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A little more than a decade ago, industry learned to combine hydraulic fracturing and horizontal drilling in ways that make it potentially profitable to drill for natural gas in low-permeability ("tight") formations where drilling would not have been economic before. Within a few years, these techniques were being applied in tight ***oil*** formations also. This has had several effects. One was a substantial increase in domestic drilling and another has been significantly higher rates of ***oil*** and gas production (though drilling rates are now down because the increased production has driven down prices).

Other effects have been a greater public awareness of hydraulic fracturing and an increase in public concern regarding the potential for ***oil*** and gas activity to cause adverse impacts to groundwater and surface water resources-either by contaminating those resources or by using such large quantities of water that the amount of water available for other users might be curtailed. There has been sharp disagreement regarding the level of risk that ***oil*** and gas activities actually pose to water quality and availability, and regarding the number of times, if any, that particular steps in the overall process of ***oil*** and gas development have caused contamination in the past. The disagreement has been fueled in part by a shortage of data and studies regarding potential impacts of ***oil*** and gas activity.

In the last few years, however, a number of studies have been published, and many studies still are ongoing. This paper provides an overview of many of the studies published in 2015 and early 2016, as well as a few studies that were published in 2014. Some excellent studies were published earlier, but this paper will focus on the more recent studies.

**Introduction**

There are a wide variety of studies that are relevant to the potential for ***oil*** and gas activities to impact water resources. Many of the early studies focused on whether ***oil*** and gas activities had contaminated a particular source of groundwater or whether a correlation could be found between the proximity of a water well to ***oil*** and gas activity on the one hand and the likelihood that the water well will contain methane or some other source of contamination on the other. Those sorts of studies are still being done, but some studies are now addressing a variety of other issues. Some of the ongoing and recently-published studies examine very broad questions-for example, what are the potential impacts of ***oil*** and gas activities on water resources-and they conduct the examination on a nationwide level. Other studies focus on a smaller geographic area or they focus on narrower issues, such as how effectively a particular type of regulatory program works, or whether particular substances used in some hydraulic fracturing operations can have toxic effects at certain concentrations.

These new studies that look at water-related impacts beyond private water well contamination events show both a shift in attention and an increased level of knowledge and interest from the public and researchers in learning more about other, perhaps equally important, potential impacts. Recent studies have asked more detailed and directed scientific questions, and are beginning to dive more deeply into specific questions. While studies continue to look at groundwater contamination events, interest has expanded to include subjects like surface water impacts, chemical characteristics of produced wastewater, induced seismicity, and toxicity and human health impact analyses.

This expansion in interest has been accompanied by an expansion in entities conducting in-depth research and investigation into key questions. The past year has seen a number of publications not only from academic institutes, but also from state and federal agencies, and national independent groups.

A broader audience and broader range of subject-matter interest has resulted in a wide variety of publications, and a growing pool of resources to advance the public's understanding of the potential impacts to water resources from ***oil*** and gas development. Advanced research is equally important to the development of sound policies and effective regulations. As scientific and technical data continues to expand, lawyers, regulators, and legislators alike have the opportunity to advance our practice and policies along with this growth in knowledge. A number of studies shared within this paper will likely have policy and regulatory implications, and perhaps legal implications in future cases and controversies on the subject of water contamination.

This paper contains three parts. Part 1 gives an overview of five national studies. These studies have a broad geographic scope and generally look at a broad range of issues. Part 2 discusses studies sponsored at the state level. Some of these studies cover a broad range of issues associated with development, namely hydraulic fracturing, while others focus on a key issue of concern for the particular state agency. Finally, Part 3 provides brief discussions of a number of academic studies, which are organized by topic. Many of those studies examine fairly narrow issues. The aim of the paper is provide readers with some information regarding the results of these studies, but also to serve as a resource to make readers aware of studies that they may wish to read in full. Finally, it is important to note that while the authors have included a number of important studies on a wide range of topics, this paper is not a full literature review of relevant publications over the past year.

**Part 1: National Studies**

Part 1 of this paper discusses "national studies." These studies typically examine evidence relating to ***oil*** and gas activities across the nation and evaluate a relatively broad set of issues. In the past two years, the national studies include: (a) the Environmental Protection Agency (EPA)'s draft assessment of the potential impacts of hydraulic fracturing and related activities on drinking water; (b) a study that estimates the volume of produced water generated by ***oil*** and gas activities nationwide and on a state-by-state basis, and also estimates the relative portions of this water that are managed in particular ways (e.g., injection disposal, surface discharge, etc.); (c) a broad-based report on induced seismicity and ways to minimize risks relating to induced seismicity; (d) a 27-state study of regulations that are designed to protect groundwater against potential impacts from ***oil*** and gas activities, along with a discussion of how those regulations changed between 2009 and 2013; and (e) a report that seeks to identify issues that merit research relating to potential impacts of ***oil*** and gas activities on the environment and communities.

**A. EPA Study Relating to Drinking Water Resources**

In response to a request made by the United States Congress in Fiscal Year 2010, the EPA is conducting a study of the potential impacts of hydraulic fracturing and other associated activities on drinking water resources. [[1]](#footnote-2)1 The study does not consider other potential impacts hydraulic fracturing on the environment or communities, but with respect to potential impacts on drinking water, the study is a broad-based effort.

For example, for purposes of the study, the definition of "[d]rinking water resources" is not limited to resources actually used to supply drinking water or even to resources that would meet most federal and state regulatory definitions of "drinking water."[[2]](#footnote-3)2 Instead, the study considers drinking water resources to encompass "any body of ground water or surface water that now serves, or in the future could serve, as a source of drinking water for public or private use," including "both fresh and non-fresh bodies of water."[[3]](#footnote-4)3

Further, although the name of the report refers to impacts of "hydraulic fracturing," the study also considers potential impacts of certain other "activities" associated with ***oil*** and gas development, particularly those that are closely related to hydraulic fracturing. For example, the study considers: the acquisition of water for hydraulic fracturing; the mixing of chemicals at the well pad in preparation for hydraulic fracturing; hydraulic fracturing itself; well integrity issues; and the handling, storage, and management of both flowback and produced water (including the potential for spills).[[4]](#footnote-5)4 These are collectively deemed stages in the "hydraulic fracturing water cycle."[[5]](#footnote-6)5

In 2015, the EPA published several reports in connection with its study, including reports that discuss the chemical composition of the water used in hydraulic fracturing (based on data from FracFocus),[[6]](#footnote-7)6 well construction and integrity,[[7]](#footnote-8)7 fluid spills,[[8]](#footnote-9)8 five retrospective case studies that were performed at locations where there was either a known release of fluids into the environment or complaints about alleged changes in groundwater quality,[[9]](#footnote-10)9 and other subjects.[[10]](#footnote-11)10 But the EPA report that is getting the most attention is a document that still is in draft form and undergoing peer review-a report entitled *Assessment of the Potential Impacts of Hydraulic Fracturing for* ***Oil*** *and Gas on Drinking Water Resources* (the "*Assessment*"), which was released in June 2015. The *Assessment* relied on a variety of data and scientific literature, including EPA's own studies cited above.[[11]](#footnote-12)11

The introduction to the *Assessment*'s Executive Summary section entitled "Major Findings" has drawn particular attention from the media, the public, industry, and EPA's Scientific Advisory Board (SAB) in their ongoing peer review of the report. The authors of this paper believe it is important to share the three high-level, overall summary paragraphs in full:

From our assessment, we conclude there are above and below ground mechanisms by which hydraulic fracturing activities have the potential to impact drinking water resources. These mechanisms include water withdrawals in times of, or in areas with, low water availability; spills of hydraulic fracturing fluids and produced water; fracturing directly into underground drinking water resources; below ground migration of liquids and gases; and inadequate treatment and discharge of wastewater.

We did not find evidence that these mechanisms have led to widespread, systemic impacts on drinking water resources in the United States. Of the potential mechanisms identified in this report, we found specific instances where one or more mechanisms led to impacts on drinking water resources, including contamination of drinking water wells. The number of identified cases, however, was small compared to the number of hydraulically fractured wells.

This finding could reflect a rarity of effects on drinking water resources, but may also be due to other limiting factors. These factors include: insufficient pre- and post-fracturing data on the quality of drinking water resources; the paucity of long-term systematic studies; the presence of other sources of contamination precluding a definitive link between hydraulic fracturing activities and an impact; and the inaccessibility of some information on hydraulic fracturing activities and potential impacts.[[12]](#footnote-13)12

There has been some debate about what these findings mean. Of particular note, the statement "[w]e did not find evidence that these mechanisms have led to widespread, systemic impacts on drinking water resources in the United States" has been widely highlighted, discussed, debated, and interpreted.

For example, some industry headlines interpreted the "widespread, systemic impacts" statement to mean that EPA's review "confirms safety"[[13]](#footnote-14)13 of hydraulic fracturing activities, or summarized the statement to say that EPA's report "finds fracking has not led to widespread water contamination."[[14]](#footnote-15)14 On the other hand, some environmental blogs led with headlines focusing on other details of the findings, noting that the EPA study concludes "fracking has contaminated drinking water"[[15]](#footnote-16)15 or that "fracking puts drinking water supplies at risk of contamination."[[16]](#footnote-17)16 Other environmentalists criticized the headline statement as potentially misleading when taken out of context and not sufficiently clear to reflect the nuances of the full report, like local impacts or data gaps and limitations - leading to confusion in interpretation and coverage.[[17]](#footnote-18)17 Perhaps confusing the matter even further, EPA's own press release leads with a headline that deletes the "we did not find evidence" aspect of the statement and leads with "[a]ssessment *shows* hydraulic fracturing activities have not led to widespread, systemic impacts," [[18]](#footnote-19)18 and this conclusion has been widely cited.

It is worth noting that a number of media outlets gave thorough, more nuanced coverage to the full scope of the report and comments from stakeholders, which are worth reviewing for further dialogue.[[19]](#footnote-20)19

Hearing opinions from both sides from public comment, and based on their own expert review and analysis, the SAB itself - which is currently in the process of conducting a peer-review of the report[[20]](#footnote-21)20 - published a draft review of the *Assessment* in January, echoing some of these concerns.[[21]](#footnote-22)21 Relevant to the headline statement, in a section of the SAB review titled "Revisions to Statements on Major Findings," the reviewers state:

The SAB finds that this statement [referring to the "widespread, systemic impacts" statement] does not clearly describe the system(s) of interest (e.g., groundwater, surface water) nor the definitions of 'systemic,' 'widespread,' or 'impacts.' The SAB is also concerned that this statement does not reflect the uncertainties and data limitations described in the body of the Report associated with such impacts. The statement is ambiguous and requires clarification and additional explanation."[[22]](#footnote-23)22 The SAB also notes ambiguity and the need for clarification for language other parts of the Major Findings introduction, including the statement "the number of identified cases, however, was small compared to the number of hydraulically fractured wells.[[23]](#footnote-24)23

The SAB report goes on to discuss and review in detail the full report in over 100 pages of text and citations. The report is in draft form as of January 2016.

It's important to distinguish these criticisms of the headline statement regarding widespread, systemic impacts from criticisms of the full report, or even, the full three paragraphs introducing the major findings. For example, the full EPA report does describe a scope and system of interest, referring to "impacts on drinking water resources" and defining drinking water resources as "any body of ground water or surface water that now serves, or in the future could serve, as a source of drinking water for public or private use."[[24]](#footnote-25)24 The EPA report also emphasizes data gaps, limitations, and uncertainties at the close of every chapter covered. Most critics of the language most commonly excerpted from the report share concern that the headline alone may not be sufficiently clear to reflect the nuances of the full report, and could lead to potential confusion in interpretation.

This debate continues as the SAB continues its review, and will likely be ongoing until EPA publishes a final *Assessment*, potentially expected this year. The draft *Assessment* covers a wide range of material in over 1,000 pages of text, sharing currently available data on multiple aspects of the "hydraulic fracturing water cycle." The *Assessment* is divided into chapters analyzing each state of this water cycle. The authors of this paper have included here an extremely limited overview of some of the reports topics and conclusions. The *Assessment* itself should be referenced for more detailed discussion of subjects of interest.

The draft *Assessment* states that hydraulic fracturing operations in the eastern United States generally rely on surface water, while operations in the more semi-arid to arid western states generally use mixed supplies of surface and ground water."[[25]](#footnote-26)25 The vast majority of water used is fresh water, though some operators use lower-quality water, including wastewater from ***oil*** and gas operations. Nationally, about 5% of the water used in fracturing operations is recycled wastewater, but the average varies widely by region.[[26]](#footnote-27)26 For example, in portions of Pennsylvania, about 18% of the water used in fracturing operations is recycled from other ***oil*** and gas operations.[[27]](#footnote-28)27

Nationwide, about 44 billion gallons of water was used each year in 2011 and 2012.[[28]](#footnote-29)28 This represented less than 1% of the nation's water use, but in some counties hydraulic fracturing accounted for a much larger portion of water use.[[29]](#footnote-30)29 Of course, many counties had no hydraulic fracturing activity during that period, but in some of the counties that did have hydraulic fracturing activity, such activity accounted for a significant portion of water use. For example, in 6.5% of those counties, fracturing accounted for 10% of all water use.[[30]](#footnote-31)30

The EPA stated the areas most likely to suffer impacts to drinking water resources from water withdrawals for hydraulic fracturing are in areas such as southern and western Texas, where there is significant hydraulic fracturing activity and low water availability.[[31]](#footnote-32)31 The EPA "found excessive drawdown of local groundwater" in approximately 6% of the area of the Eagle Ford Shale.[[32]](#footnote-33)32 The EPA did detailed case studies in western Colorado and northeastern Pennsylvania, and did not find impacts there from water withdrawals, though the EPA concluded that "streams could be vulnerable."[[33]](#footnote-34)33

The *Assessment* acknowledges that the chemical additives used in fracturing constitute a small percentage of the fracturing fluid, but the Assessment also noted that, during mixing of the fracturing fluid and prior to mixing, thousands of gallons of chemicals may be stored on site.[[34]](#footnote-35)34 This, plus the handling and storage of flowback, or produced water on site, creates the possibility of spills that could impact drinking water resources.

The *Assessment* stated that the EPA did not have sufficient data to estimate the frequency of spills in most areas. Based on data and literature regarding the frequency of spills in two states, Colorado and Pennsylvania (whether spills of fracturing additives, flowback, or produced water), EPA noted that the nationwide rate "could range from approximately 100 to 3,700 spills annually, assuming 25,000 to 30,000 new wells are fractured per year."[[35]](#footnote-36)35 But the EPA emphasized that it is unknown whether the rates of spills in Colorado and Pennsylvania are representative of the rates of spills in other places, and the EPA's Science Advisory Board cautioned against extrapolating such limited data to estimate the number of spills occurring across the nation (moreover, the annual number of wells being drilled and fractured has declined as drilling and fracturing rates have declined significantly in the last couple of years).[[36]](#footnote-37)36 Based on the spill incidents that the EPA was able to characterize, the *Assessment* reported that the median volume of spills of fracturing fluids or chemicals was 420 gallons,[[37]](#footnote-38)37 whereas the median volume of spills of produced water was 990 gallons.[[38]](#footnote-39)38

The *Assessment* discussed well integrity issues, noting that appropriate casing and cementing-particularly cemented surface casing-are important features for protecting underground sources of drinking water.[[39]](#footnote-40)39 If casing or cementing is not adequately designed or constructed, adverse impacts to groundwater can occur. Indeed, the *Assessment* notes that there are "several examples" in which well integrity problems "have or may have resulted in impacts to drinking water resources."[[40]](#footnote-41)40 The *Assessment* also stated that the fracturing of older wells may pose greater risks than fracturing newer wells. The Assessment explains that "older wells may not have been built or tested to the same specifications" as newer wells and that aging of a well can contribute to casing degradation that may lessen the wells' ability to withstand stresses associated with hydraulic fracturing.[[41]](#footnote-42)41

The *Assessment*'s discussion of wastewater management noted that produced water and flowback are managed in several different ways, including: disposal in injection wells; reduction in volume in evaporation ponds; reuse in hydraulic fracturing after little or no treatment; treatment in centralized wastewater treatment (CWT) facilities, followed by reuse or discharge to either the surface or publicly owned treatment works (POTWs); and land spreading or application to roads for deicing or dust suppression.[[42]](#footnote-43)42 In most areas of the country, injection disposal is the most common management technique.[[43]](#footnote-44)43 The Marcellus region is an exception. There, relatively few injection disposal wells are available and a substantial portion of water is reused, often after treatment.[[44]](#footnote-45)44

Although some CWTs have the capability to remove the total dissolved solids (TDS)- primarily salts-that are common in produced water and flowback, most CWTs accepting such water in Pennsylvania are not capable of significantly reducing TDS.[[45]](#footnote-46)45 Similarly, most POTWs are not designed to effectively reduce TDS.[[46]](#footnote-47)46 The *Assessment* noted that hydraulic fracturing wastewater has been sent to POTWs in Pennsylvania in the past, but that this practice "decreased sharply" after new state requirements were imposed and the Pennsylvania Department of Environmental Protection made a request that ***oil*** and gas operators stop sending such wastewater to POTWs.[[47]](#footnote-48)47

The final substantive chapter of the draft *Assessment* examines what is known and what is still unknown regarding the potential toxicological hazards that different chemicals might pose via oral exposure if they were to enter drinking water resources.[[48]](#footnote-49)48 The *Assessment* noted that the EPA has identified 1,173 chemicals that either are used in hydraulic fracturing fluids or that appear in produced water or flowback.[[49]](#footnote-50)49 These chemicals include chemicals deliberately added to fracturing fluids, chemicals naturally found in formations to which operators drill, and products that might be formed by reactions of the other chemicals.[[50]](#footnote-51)50

The EPA then examined available toxicological data. The *Assessment* notes that toxicity information is available from a wide range of sources, and that the data differs with respect to its "extent, quality and reliability."[[51]](#footnote-52)51 For purposes of its analysis in Chapter 9 of the *Assessment*, the EPA selected data from sources that satisfy certain criteria described in Chapter 9.[[52]](#footnote-53)52 Data from other sources was not included in the evaluation.[[53]](#footnote-54)53

The EPA was particularly interested in two types of data-so-called "reference values" ("RfV") and "oral slope factors" ("OSF"). An RfV is an estimate of an exposure for a given duration to the human population that is likely to be without appreciative risk of adverse health effects over a lifetime.[[54]](#footnote-55)54 An OSF is an upper bound (within an approximately 95% confidence limits) on the increased cancer risk from a lifetime oral exposure to an agent.[[55]](#footnote-56)55 Further, noted the *Assessment*, toxicology data can be based on acute levels of exposure or chronic, low levels of exposure.[[56]](#footnote-57)56

The *Assessment* reported that chronic RfVs or OSFs were available from the sources selected by EPA for only 147 (13%) of the 1,173 chemicals that the Agency identified as being either used in fracturing fluid or present in produce water or flowback.[[57]](#footnote-58)57 For the chemicals for which data was available, the EPA found that some pose potential health hazards-either carcinogenesis or some other hazard.[[58]](#footnote-59)58

The information noted above is only a small portion of the content in the EPA's draft *Assessment*. Readers can obtain a copy of the draft *Assessment* (the full draft contains 998 pages) or its Executive Summary or particular chapters at: http://cfpub.epa.gov/ncea/hfstudy/recordisplay.cfm?deid=244651. Readers can obtain the SAB's January 7, 2016 draft evaluation of the EPA's draft Assessment at: http://yosemite.epa.gov/sab/sabproduct.nsf/fedrgstr\_activites/HF%20Drinking%20Water%20Assessment?OpenDocument&TableRow=2.2#2.

Readers should note that, because the draft *Assessment* is not final, it is subject to change. The same is true for the SAB's draft evaluation of the *Assessment*.

**B. John Veil's Report on U.S. Produced Water Volumes**

In April 2015, the Ground Water Protection Council[[59]](#footnote-60)59 published a study by John Veil entitled *U.S. Produced Water Volumes and Management Practices in 2012*.[[60]](#footnote-61)60 Veil was the co-author of a similar study published in 2009 that examined 2007 water management practices.[[61]](#footnote-62)61 In the recent study, Veil estimates the total volume of "produced water" that was generated in the United States in 2012, using data he obtained by contacting state ***oil*** and gas regulators in the 31 states that have active ***oil*** and gas wells, and by contacting federal officials that have regulatory jurisdiction over federal lands, Indian lands, and federal offshore areas.[[62]](#footnote-63)62

Some agencies had thorough data regarding produced water volumes, but many did not. For the jurisdictions whose agencies did not have thorough data, Veil estimated volumes of produced water using alternative data, assumptions, or extrapolations from available data.[[63]](#footnote-64)63 For purposes of his study, Veil used the phrase "produced water" to refer to both the initial return of hydraulic fracturing fluids after completion (often called flowback) and the sort of water that is more traditionally called "produced water."[[64]](#footnote-65)64

The recent study concluded that onshore wells generated about 20.6 billion barrels[[65]](#footnote-66)65 of produced water in 2012, and that offshore wells produced another 0.6 billion barrels, for a total of 21.2 billion barrels of produced water in 2012. This compares to an estimated 21 billion barrels of produced water in 2007.[[66]](#footnote-67)66 Thus, the estimated annual quantity of produced water increased by about 1% from 2007 to 2012. During the same period, however, U.S. production of ***oil*** increased by about 29% and U.S. natural gas production increased by about 22%.[[67]](#footnote-68)67 Much of the increased ***oil*** and gas production was due to unconventional production. Further, in three states with large, recent increases in unconventional production, the proportional increase in ***oil*** (in North Dakota) or gas (in Arkansas and Pennsylvania) was much larger than the increase in the production of water.[[68]](#footnote-69)68 This led Veil to the conclusion that "at least in those three states, unconventional wells may generate less produced water per unit of hydrocarbon output than conventional wells."[[69]](#footnote-70)69

The report notes that many ***oil*** wells generate a larger volume of produced water than of ***oil***. The report calculated a national weighted average water-to-***oil*** ratio ("WOR") of 9.2.[[70]](#footnote-71)70 That is, for every barrel of ***oil*** that is produced by U.S. ***oil*** wells, about 9.2 barrels of water are produced from the same wells. Veil calculated a weighted average water-to-gas ratio ("WGR") of 97 barrels of water per million standard cubic feet of natural gas.[[71]](#footnote-72)71 He cautioned, however, that the actual WORs and WGRs vary so much from one area to another that average WOR and WGR calculations have limited utility.[[72]](#footnote-73)72 The limited utility a nationwide average WOR is illustrated by comparing state-by-state average WORs. For example, California has an average WOR of about 15.5, while North Dakota has an average WOR of 1.2.[[73]](#footnote-74)73

In addition, Veil examined practices for managing produced water, and he calculated the fraction of total produced water that was managed in various ways. Based on his calculations, he estimated that, in 2012, approximately 45.1% of produced water was managed by injecting it for enhanced ***oil*** recovery (EOR), about 38.9% was managed by injection disposal, 6.7% by offsite commercial disposal,[[74]](#footnote-75)74 5.4% by surface discharge, 3.4% by evaporation, and 0.6% by beneficial reuse.[[75]](#footnote-76)75

Management techniques do not appear to have changed dramatically since 2007. The six management techniques identified by Veil as being used in 2012 also were in use in 2007, the year of the earlier study that he co-authored. In his earlier study, he did not collect data on evaporation, offsite commercial disposal, or beneficial reuse, but he did collect data on three of the most common management techniques-injection disposal, injection for enhanced ***oil*** recovery, and surface discharge. Considering only the water managed by the three techniques for which they collected data in the earlier study, Veil and his co-author estimated that in 2007 approximately 57.8% of produced water was managed by injection for enhanced ***oil*** recovery, 38.8% by injection disposal, and 3.6% by surface discharge.[[76]](#footnote-77)76 In broad terms, these numbers are somewhat similar to the 2012 data.

Although management techniques may not have changed much with time between 2007 and 2012, management techniques vary substantially by location. For example, in 2012, about 80% of produced water from offshore wells was treated and discharged into the ocean.[[77]](#footnote-78)77 In contrast, only about 3% of produced water from onshore wells was discharged to the surface.[[78]](#footnote-79)78 Management practices also differ substantially between different offshore areas and between different onshore areas. For example, about 90% of produced water from the Gulf of Mexico outer continental shelf is treated on offshore platforms and discharged into the Gulf in 2012, while about 10% is sent to injection wells.[[79]](#footnote-80)79 In contrast, on the Pacific outer continental shelf, only about 44% of water was treated and discharged, while 56% was injected.[[80]](#footnote-81)80

With respect to onshore practices for the management of produced water, several differences are notable between different areas. For example, about 3.4% of the nation's produced water is managed by evaporation nationwide, but in many states, evaporation does not seem to be used at all as a tool for managing produced water.[[81]](#footnote-82)81 Predictably, for example, evaporation is not used in humid Louisiana. On the other hand, evaporation is a significant management tool in some less humid states, primarily in the west.[[82]](#footnote-83)82 Indeed, evaporation is used to manage about 21% of the produced water in California in 2012, about 20% in Colorado, and about 9% in Nebraska.[[83]](#footnote-84)83

The rate of beneficial reuse also varies widely by state. The report calculates that the nationwide average rate of beneficial reuse was 0.6% in 2012 (the report states that the actual amount of beneficial reuse probably is higher than the 0.6% that is calculated, but that data is not available to provide a better quantification).[[84]](#footnote-85)84 But Pennsylvania-the state with, by far, the highest portion of beneficial reuse-had a beneficial reuse rate of 85% in 2012 (the beneficial reuse rate was slightly more than 85% for produced water from unconventional operations and about 80% for water from conventional operations).[[85]](#footnote-86)85 Pennsylvania's high rate of beneficial reuse probably is driven by the lack of other available options-Pennsylvania has few injection disposal wells and there are no enhanced recovery operations in the state.[[86]](#footnote-87)86

And when produced water is put to beneficial reuse, how is it used? Veil's report notes that much of it was used as the supply water for subsequent hydraulic fracturing operations.[[87]](#footnote-88)87 In some areas, produced water was used for dust control or de-icing of roads, and in some places produced water with low salinity was used for irrigation.[[88]](#footnote-89)88

Finally, it should be noted that Veil's report has a great deal of other information, including a discussion of the pros and cons of various water management techniques,[[89]](#footnote-90)89 and state-by-state numbers for produced water volumes,[[90]](#footnote-91)90 water-***oil*** ratios,[[91]](#footnote-92)91 water-gas ratios,[[92]](#footnote-93)92 and the amount of produced water managed by various techniques.[[93]](#footnote-94)93 The report also has a few pages of discussion regarding the composition of produced water.[[94]](#footnote-95)94

**C. GWPC & IOGCC Primer on Induced Seismicity**

The term "induced seismicity" refers to earthquakes that are triggered by human activity. Scientists have known for several decades that certain types of human activity can trigger earthquakes.[[95]](#footnote-96)95 These activities include impounding water behind dams, mining, underground nuclear tests, the withdrawal of fluids from the earth's subsurface, and the injection of fluids into the subsurface.[[96]](#footnote-97)96

In the last few years, induced seismicity has attracted a great deal of attention because the rate of seismicity has increased significantly in some areas, and many scientists and regulators believe that at least some of the increase is triggered by subsurface injections associated with ***oil*** and gas activity. In the United States, this typically has meant injections for purposes of wastewater disposal, but on rare occasions injections performed for purposes of hydraulic fracturing itself are believed to have induced seismicity.[[97]](#footnote-98)97

The most dramatic increase in the rate of seismic activity has occurred in Oklahoma. For decades, Oklahoma averaged about 1.6 earthquakes per year of magnitude 3.0 or greater. But the number of Oklahoma earthquakes of that magnitude increased to 20 in 2009. In 2013, the state experienced 109 such quakes. In 2014, Oklahoma experienced 584 earthquakes of that magnitude, and in 2015 Oklahoma saw about 883 earthquakes of magnitude 3.0 or greater.[[98]](#footnote-99)98 Many scientists are convinced that injection disposal operations are responsible for much of the increase. Although no other state has seen such a dramatic increase in seismicity, several other states have experienced earthquakes that scientists believe were probably induced by injection disposal operations. These states include Arkansas, Kansas, Ohio, and Texas.[[99]](#footnote-100)99

These seismic events have prompted public concern, regulatory responses, and numerous academic studies. Some of those studies are briefly discussed in Part III of this paper. The increased concern about seismicity also prompted the Ground Water Protection Council (GWPC)[[100]](#footnote-101)100 and the Interstate ***Oil*** and Gas Compact Commission (IOGCC)[[101]](#footnote-102)101 to form a working group to study the issue and produce a report that is national in scope. The working group, which was dubbed the StatesFirst Induced Seismicity by Injection Work Group, included representatives from state and federal agencies, industry, academia, and non-profit organizations. In 2015, the group published a 141-page report entitled *Potential Injection-Induced Seismicity Associated with* ***Oil*** *& Gas Development: A Primer on Technical and Regulatory Considerations Informing Risk Management and Mitigation* (herein, the "*Induced Seismicity Primer*" or the "*Primer*").

In brief, the *Primer* recognizes that injection can be a contributing factor to induced seismicity and provides advice from experts on what can be done to address this issue. The *Primer* was a first-of-its-kind joint effort and moved the scientific and regulatory dialogue forward by recognizing the issues and aiming to seek effective solutions.[[102]](#footnote-103)102 The *Primer* focuses on four topics.

The first is an explanation of induced seismicity. Chapter 1 of the *Primer* explains how injections of fluids can induce seismicity, and discusses such things as the locations, depths, and magnitudes of recent earthquakes that are suspected of having been induced. Further, for the benefit of readers who are not familiar with the basics of seismology, the *Primer*'s Appendix A explains such things as what an earthquakes is, how the various scales for measuring the magnitude of earthquakes work, the number of seismic events of various magnitudes that typically occur worldwide during the course of a year, and how large a magnitude an earthquake typically must have in order for it to be felt; for it to cause light damage; or for it to cause significant damage.

The second topic covered by the *Primer* is the question of how scientists evaluate whether a particular earthquake was induced or natural. Chapter 2 addresses this subject. Chapter 3 addresses the third topic-strategies to minimize and mange risks-and Appendix G complements Chapter 3 by giving more detailed discussion of tools for risk management and mitigation. Finally, the fourth topic is strategies that regulators can use for external communications and engagement relating to induced seismicity. This is the subject of Chapter 4.

The *Primer* provides an excellent overview of induced seismicity. It notes that most injection disposal wells in the United States do not pose a risk for inducing seismicity, but that the operation of such wells can induce seismicity under certain geologic conditions, and that "a limited number of injection wells have been determined to be responsible for induced earthquakes with felt levels of ground shaking."[[103]](#footnote-104)103

Whenever, an induced seismic event occurs, it generally occurs at a critically stressed fault.[[104]](#footnote-105)104 A fault is "critically stressed" when subsurface stresses are almost sufficient to cause movement or "slip" at the fault.[[105]](#footnote-106)105 Several factors determine whether a fault will be critically stressed, including the magnitude of subsurface stresses, whether those stresses are in a direction perpendicular to or parallel to the fault (stresses perpendicular to a fault tend to stabilize the fault, rather than make it prone to movement), and the amount of friction between the rocks at opposing faces of the fault.[[106]](#footnote-107)106 As explained in the *Primer*, there will be slippage or movement along a fault when subsurface stresses that tend to make a fault move are sufficient to overcome friction at the face of the fault (and it is the sudden movement associated with such slippage that causes a shaking of the earth).[[107]](#footnote-108)107

The *Primer* also explains the reason why, in some circumstances, a subsurface injection can induce seismicity-namely, because an injection can reduce friction at the face of a fault.[[108]](#footnote-109)108 A popular misconception is that the injection lubricates the fault.[[109]](#footnote-110)109 It does not. Instead, the injection can increase the pressure in the pore spaces along the face of the fault. This increased pressure pushes back against the stresses that are perpendicular to the fault, and which therefore tend to "clamp" or press the two sides of the fault together.[[110]](#footnote-111)110 This reduces the effective stress that tends to clamp or press the two sides of the fault together, and it is this factor that decreases friction. The Primer, speaking metaphorically, states that the injection "unclamps" the fault.[[111]](#footnote-112)111

A simple household analogy that one of the authors of this paper frequently uses is a cardboard box that is filled with books and placed on the tile floor. It will be difficult to push the heavy, book-filled box across the floor because gravity presses the bottom of the box against the floor with significant force, and the friction between two surfaces increases if the two surfaces are pressed together with more force. But returning to the box, if you remove the books, it will be easier to push the empty box across the floor. But you did not lubricate the floor or the bottom of the box. Instead, by removing the books, you decreased the weight of the box. Thus, gravity presses the bottom of the floor with less force and this result in decreased friction. The *Primer* uses the analogy to two surfaces that are clamped together. The force of a clamp can press two surfaces together, thereby increasing friction and preventing movement. But if the clamp is loosened, friction is reduced and the previously clamped surfaces can move. Increasing the pore pressures along the face of the fault has an effect similar to removing the books from the box or unclamping two surfaces because the pore pressure counteracts the subsurface stresses that press the fault together.

In order for an injection to induce seismicity, four circumstances generally must be present simultaneously. In particular, (1) a critically stressed fault must be located somewhere in the vicinity of the injection disposal; (2) the injection must increase subsurface pore pressures by an amount sufficient to cause a decrease in friction large enough to allow the previously stable (though critically stressed) fault to move; (3) there must be a pathway by which the increase in subsurface pressure can be transmitted from the point of injection to the location of the fault; and (4) the injection must be of sufficient duration that that the increased pressure actually reaches the fault.[[112]](#footnote-113)112

The *Primer* notes that induced earthquakes typically occur at shallower depths than natural earthquakes, often in the shallow portions of the basement rock that lie beneath the sedimentary formations.[[113]](#footnote-114)113 Earthquakes typically must be about 2.5 or higher in magnitude to be felt[[114]](#footnote-115)114 and typically must have a magnitude of 5.0 or more to cause structural damages to modern engineered buildings.[[115]](#footnote-116)115 Most induced earthquakes have been small magnitude events,[[116]](#footnote-117)116 but a few of the recent earthquakes that scientists suspect were induced had magnitudes between 4.8 and 5.7.[[117]](#footnote-118)117

More seismic networks have been installed recently in response to concerns about earthquakes, but since the 1970s, the U.S. has had a sufficient seismic network in place that most earthquakes of 3.0 magnitude or greater are detected.[[118]](#footnote-119)118 Thus, the recently observed increase in seismic events of magnitude 3.0 and larger in some areas indicates a true increase in seismicity, not merely an increase in the number of events being detected. But smaller earthquakes sometimes go undetected, and the increased number of seismic networks can lead to detection of a greater portion of those small magnitude earthquakes.[[119]](#footnote-120)119 Thus, comparisons that shown an increase in the annual number of earthquakes with magnitude greater than 0.0 may reflect, in part, better detection.[[120]](#footnote-121)120 In addition to helping detect a greater fraction of small earthquakes, the installation of more seismic networks can increase the accuracy of scientists' estimates of the location and magnitude of earthquakes.[[121]](#footnote-122)121

The *Primer* also notes that, although most earthquakes suspected to be linked to ***oil*** and gas activity in the United States are suspected of being linked to injection disposal, a few earthquakes are suspected of being linked to hydraulic fracturing itself.[[122]](#footnote-123)122 The relatively short duration of any given hydraulic fracturing operation may be the reason that hydraulic fracturing seems to have induced far fewer seismic events in the United States than injection disposal has.[[123]](#footnote-124)123

At present, scientists find it difficult to determine definitively whether a particular seismic event was induced.[[124]](#footnote-125)124 But scientists look at a number of factors relating to the earthquake, past seismicity in the area, the existence and operating conditions (injection pressures and rates) of injection activities, and the location and timing of those activities relative to the location and timing of an earthquake in evaluating whether the earthquake likely was natural or induced.[[125]](#footnote-126)125

The *Primer* states that the methods of managing the risk of induced seismicity associated with injection disposal can begin at the site selection stage, when planning the location of a prospective injection disposal well.[[126]](#footnote-127)126 A company planning an injection disposal well can examine an area's history of seismic activity-past seismic events may indicate the existence of one or more critically-stressed faults.[[127]](#footnote-128)127 Also, although most induced seismic events have occurred at previously unknown faults,[[128]](#footnote-129)128 the company can attempt to determine whether any known faults of potential concern (not all faults will pose an induced seismicity risk) are in the vicinity of a site being considered for an injection disposal well.[[129]](#footnote-130)129

Because many of the earthquakes suspected of having been induced have occurred in basement rock, a company can avoid injecting into the basement rock, and the company can evaluate whether pathways exist that would allow pore pressure increases to be transmitted from the prospective injection depth to the deeper basement rock.[[130]](#footnote-131)130 Further, once operations are underway, the operator of an injection well can monitor injection pressures and injection rates, monitor seismic activity in the area, and can follow a protocol that provides for adjusting or halting operations if seismic events of a specified magnitude occur within a specified distance of the injection well.[[131]](#footnote-132)131 A protocol for reducing injection rates if earthquakes of a particular magnitude occur within a specified distance of the injection well, and for halting operations if earthquakes of a larger magnitude (or closer proximity) occur is sometimes called a "traffic light" approach.[[132]](#footnote-133)132

**D. GWPC: State *Oil* & Gas Regulations Designed to Protect Water Resources**

In 2014, the Ground Water Protection Council (GWPC)[[133]](#footnote-134)133 published *State* ***Oil*** *& Gas Regulations Designed to Protect Water Resources* ("*State Regulations*").[[134]](#footnote-135)134 The study provides an overview of regulations in place in 2013 to protect water resources in 27 states that have ***oil*** and gas activity.[[135]](#footnote-136)135 The study also examines how such regulations changed between 2009 and 2013, and identifies regulatory trends.

*State Regulations* concludes that, "[s]ince 2009, states have made considerable progress" with respect to the issues examined.[[136]](#footnote-137)136 The study further concludes that "[e]specially notable" progress has been made in "requirements for chemical disclosure of hydraulic fracturing fluids, enhancements to mechanical integrity testing, improved pit siting and lining requirements, and advances in data management."[[137]](#footnote-138)137 And, "[o]verall, state and natural regulatory agencies have been diligent in addressing the technological, legal and practical changes that have occurred in ***oil*** and gas E&P over the last four years."[[138]](#footnote-139)138

One of the trends identified by *State Regulations* is a movement toward more rigorous permitting. The study stated that the number of states requiring public notice prior to the issuance of certain types of permits increased from 7 to 13 between 2009 and 2013, the number allowing regulators to deny permits based on an applicant's past non-compliance increased from 11 to 20, and the number allowing revocation of permits for non-compliance increased from 9 to 10.[[139]](#footnote-140)139 Also, several states have added "area of review" analyses to permit applications.[[140]](#footnote-141)140 Such evaluations, modeled after the area of review evaluations used in Safe Drinking Water Act Underground Injection Control permitting, requires analyses to determine that adequate stratigraphic confinement will protect underground sources of drinking water from contamination during hydraulic fracturing, and that no nearby, pre-existing wellbores will provide a pathway for contamination.[[141]](#footnote-142)141

As in the past, "well integrity regulations remain the primary tool that regulators use to protect the environment," but there is a trend toward using additional tools, including monitoring and reporting of pressures during hydraulic fracturing, and mandatory baseline testing of groundwater before ***oil*** and gas activity, as well as additional requirements relating to well integrity.[[142]](#footnote-143)142 For example, the number of states requiring that cement evaluation logs or other evaluation techniques be used in certain circumstances increased from 9 to 14, and there appears to be a trend toward more state inspects witnessing casing and cementing operations more frequently.[[143]](#footnote-144)143

The study noted that most states allow operators to temporarily abandon wells that are not active, but which may have future value. But this raises the possibility that operators will abuse the temporary abandonment status to delay the plugging of wells have no future use. *State Regulations* found that, between 2009 and 2013, two additional states took steps to prevent such abuses by imposing time limits on the time that a well can be in a temporary abandonment status before it must be restored to use or permanently plugged.[[144]](#footnote-145)144 Also, more states are specifying the method of plugging and requiring more detailed reports on the plugging of wells.[[145]](#footnote-146)145

The number of states with "competency" standards for pit liners increased from 15 to 22, and the number requiring a minimum freeboard between the water level and the top of the pit to avoid overflows during heavy rains increased from 16 to 20.[[146]](#footnote-147)146 Also, the states that require soil sampling after pit closure went from 3 to 8, and more states set limits on the length of time a pit can be used.[[147]](#footnote-148)147 The study also found that several states are requiring that some method of leak detection be used during the life of pits.[[148]](#footnote-149)148

*State Regulations* also identified a growing trend toward recycling and reuse of produced water.[[149]](#footnote-150)149

*State Regulations* is a good resource for an overview of regulated ***oil*** and gas activities and for information regarding how those activities are regulated across producing states, as well as for data and discussion of new trends or gaps in regulations. The report highlights key considerations for regulators in each area covered: permitting, fracturing, well integrity, temporary abandonment, well plugging, storage in pits, storage in tanks, produced water, exempt waste disposal, spill response, regulatory coordination, data management, and foundational scientific research needs.[[150]](#footnote-151)150 These considerations are worth reviewing to understand key areas for improvement in regulations on each subject.

**E. Health Effects Institute Research Agenda**

In October 2015, the Health Effects Research Institute's[[151]](#footnote-152)151 Special Scientific Committee on Unconventional ***Oil*** and Gas Development[[152]](#footnote-153)152 published a *Strategic Research Agenda on the Potential Impacts of 21st Century* ***Oil*** *and Natural Gas Development in the Appalachian Region and Beyond* (the "*Research Agenda*" or "*Agenda*").[[153]](#footnote-154)153 The *Research Agenda* does not make any factual findings that ***oil*** and gas development has actually caused adverse impacts-a point that the document repeats multiple times-but instead the *Agenda* seeks to identify potential impacts and "knowledge gaps" relating to potential impacts, encourage research and the funding of research relating to potential impacts, and set priorities for future research.[[154]](#footnote-155)154

The *Research Agenda* identifies 35 research questions.[[155]](#footnote-156)155The HEI Special Scientific Committee on Unconventional ***Oil*** and Gas Development (the "Committee") "deemed all research questions to be important topics of inquiry, although not necessarily of equal importance."[[156]](#footnote-157)156 Accordingly, and because funding for research is limited, the Committee sought to set priorities for research[[157]](#footnote-158)157 based on various criteria, including whether particular research topics relate to decisions being made in the next few years, whether research could be completed and published in time to be used by industry or regulators in planning and decision-making, whether the research is feasible, whether it has broad applicability, and whether the research concerns a potential adverse impact that is likely to be severe or affect a large area or large number of people.[[158]](#footnote-159)158

The *Research Agenda* grouped the 35 research questions[[159]](#footnote-160)159 that it identified into three broad categories, with those areas relating to whether exposures or incidents of potential concern are occurring, whether adverse impacts to health are occurring, and what practices could minimize or prevent adverse impacts.[[160]](#footnote-161)160 The *Agenda* identified and prioritized 13 of the 35 questions as being of questions as being of "overarching importance."[[161]](#footnote-162)161 Those 13 "questions," which read more like topics, are: chemical toxicity (human and ecological); emissions and air quality; total human exposure; water quality; ecological health effects of landscape changes (such as habitat fragmentation); public health effects relating to airborne exposure; public health effects relating to water-based exposure; public health effects on nearby communities; social and psychosocial effects; worker health effects (including from chemical and radiation exposure); the most-effective practices relating to accidental releases; most-effective practices relating to permitted waste management; and most-effective practices relating to wellbore integrity.[[162]](#footnote-163)162

As previously noted, the *Research Agenda* makes no factual findings regarding potential adverse impacts associated with ***oil*** and gas development. The importance of the *Research Agenda* is its potential to encourage academics to pursue priority research regarding potential adverse impacts of ***oil*** and gas development, and to encourage government, foundations, and others to fund such research.

Further, it encourages research into a broader array of questions than some of the "first generation" studies that focused on such questions as whether contamination is or is not found near sites of ***oil*** and gas activity. Thus, in a potential "second generation" of studies, some of the same attention to detail that results in studies addressing such questions as whether drinking several cups of coffee daily is bad for health, whether having a desk near an office printer can have an adverse effect on health, and whether several hours per day of sitting in a chair can adversely affect a person's health even if that person gets plenty of exercise, may now be directed at various potential impacts of ***oil*** and gas activity.

**Part 2: State-Sponsored Studies**

In addition to the academic work, and studies of national scope evaluating ***oil*** and gas production discussed in other sections of this paper, several reports and research papers commissioned by states and relevant regulatory agencies were released in 2015. State-sponsored studies addressed risks associated with hydraulic fracturing generally, as well as specific areas of public concern, such as Technologically Enhanced Radionuclide Materials (TENORM) and brine spills. In some cases, the studies were designed to identify and fill gaps in existing knowledge on a given subject, and in other cases the studies explicitly informed potential regulatory action. Research commissioned by the state agencies of California, New York, North Dakota and Pennsylvania are discussed below.

**A. Comprehensive State-Wide Reviews**

**1. California Council on Science and Technology**

On July 9, 2015, the California Natural Resources Agency released to the public a multivolume report detailing the results of an independent scientific assessment of well stimulation by the California Council on Science and Technology (CSST).[[163]](#footnote-164)163 The report was commissioned in 2013, pursuant to Senate Bill 4 in order to "evaluate the hazards and risks and potential hazards and risks that well stimulation treatments pose to natural resources and public, occupational, and environmental health and safety."[[164]](#footnote-165)164 An interdisciplinary steering committee, chaired by Dr. Jane C. Long,[[165]](#footnote-166)165 and composed of independent technical experts representing various specialties reviewed existing literature and data. The report was peer reviewed, and also received public comment.

The first volume of the final report outlined the status of hydraulic fracturing and other well stimulation techniques in California.[[166]](#footnote-167)166 The study authors noted that information regarding "where, when, and how operators conduct well stimulation in the state were not collected thoroughly or consistently across the state prior to 2014."[[167]](#footnote-168)167 In the absence of full information, the study authors relied on published literature and official and voluntary databases and noted specific instances where incomplete and unverified data limited their analysis and conclusions.

The authors noted that over the last decade, approximately twenty percent of ***oil*** produced in California came from wells that had been hydraulically fractured, and from wells located in the San Joaquin Basin. According to this study, hydraulic fracturing practices in California differ from practices elsewhere; typically occurring in shallower wells that are vertical, as opposed to deep, horizontal wells common in other states. The authors of the study predicted these trends would continue.[[168]](#footnote-169)168

The second volume evaluated potential impacts of well stimulation, including hydraulic fracturing, on water, atmosphere, seismic activity, wildlife, vegetation and human health, based on available data.[[169]](#footnote-170)169 Again, the authors identified data gaps that constrained their analysis.[[170]](#footnote-171)170 With respect to hydraulic fracturing and potential impacts on drinking water, authors identified several plausible mechanisms for release of produced water contaminants into surface and groundwater, including disposal of produced water in unlined pits, injection of produced water into potentially protected groundwater, reuse of produced water for irrigation, disposal of produced water into sewer systems and accidental releases.[[171]](#footnote-172)171 The authors noted that the potential for contamination from fractures was more significant than elsewhere in the country-although still of "medium priority" - because typical fracturing depths are much shallower in California.[[172]](#footnote-173)172

The CSST study authors cited the lack of information regarding chemicals in produced water and their respective toxic effects as a major data gap inhibiting full evaluation of well stimulation's impacts on drinking water.[[173]](#footnote-174)173 Literature and data review identified 316 chemical additives used in hydraulic fracturing operations, but approximately one-half of chemicals used did have publicly available results from standard aquatic toxicity tests, and more than one-half lack biodegradability, water-octanol partitioning analysis, or other characteristic measurements needed for understanding hazards and risks associated with chemicals.[[174]](#footnote-175)174 Accordingly, the study recommended that "[t]he overall number of different chemicals should be reduced, and the use of more hazardous chemicals and chemicals with poor environmental profiles should be reduced, avoided, or disallowed."[[175]](#footnote-176)175

The CSST study also evaluated the intensity and potential sources of water used in various types of well stimulation, characterized wastewater, identified management and disposal practices and proposed best and alternative practices for well stimulation to avoid or mitigate impacts on water resources. Alternative management practices recommended include limit and phasing out disposal through unlined evaporation pits.[[176]](#footnote-177)176

Volume III of the CSST presents four case studies assessing environmental issues and qualitative risks for specific geographic regions in California: offshore, the Monterey Formation, the Los Angeles Basin, and the San Joaquin Basin.[[177]](#footnote-178)177

**2. New York Final Supplemental Generic Environmental Impact Statement (May 2015)**

In May, 2015, New York State's Department of Environmental Conservation (DEC) issued its final comprehensive review of "high-volume hydraulic fracturing" (HVHF).[[178]](#footnote-179)178 The DEC's Supplemental Generic Environmental Impact Statement (SGEIS) was initiated in 2008 pursuant to the State Environmental Quality Review Act (SEQRA), to review environmental impacts associated with HVHF that had not previously been considered during the 1992 review of DEC's existing rules. The SGEIS was intended to inform an evaluation of whether the Department of Environmental Conservation's ***Oil***, Gas and Solution Mining Regulatory Program should issue permits to drill, deepen, plug back or convert wells that use HVHF to develop natural gas resources in the Marcellus Shale and other low-permeability gas reservoirs underlying New York State. Numerous revisions of the SGEIS (draft versions were published in 2009 and 2011) to incorporate public comments and consider more deeply whether proposed mitigation measures were adequate to protect public health.

DEC evaluated short and long term impacts from HVHF. Long term, lasting impacts evaluated include construction of natural gas pipelines, gathering lines and compressor states and other infrastructure off the well pad. The DEC evaluated significant adverse impacts to of water resources, ecosystems and wildlife, air resources and greenhouse gas emissions, naturally occurring radioactive material and seismicity, noise and visual resources, as well as impacts to socioeconomics and community character, special and unique places and public health.

Mitigation measures identified and evaluated include setbacks and buffers, site specific environmental review for wells constructed in sensitive areas, groundwater monitoring, road and wellpad planning, use of cleaner engines in the drilling and fracturing equipment, Reduced Emission Completion, and limited venting and flaring, as well as requiring operators to develop a Greenhouse Gas Mitigation Plan. The DEC also considered expanded disclosure requirements for chemicals used in HVHF, and would have prohibited drilling activity in Catskill Park.

DEC incorporated the SGEIS impacts evaluation in its SEQRA Findings Statement for HVFR, published on June 29, 2015.[[179]](#footnote-180)179 In the SEQRA Findings Statement, DEC concluded that potential significant adverse environmental and public health impacts associated with HVHF "cannot be adequately avoided or minimized to the maximum extent practicable," and "significant uncertainty remains regarding the level of risk to public health and the environment" outweighed the "limited economic and social benefits that would be derived from HVHF."[[180]](#footnote-181)180 Based on these findings, the DEC selected a No-Action alternative, and recommended that HVHF should not be permitted in New York.[[181]](#footnote-182)181

**B. TENORM Studies**

Underground rock formations from which ***oil*** and gas wastes are produced may contain naturally occurring radionuclides, such as uranium, thorium, radium, strontium and potassium-40.[[182]](#footnote-183)182 The radiation contained in shales varies among the various plays, but in some cases, shales contain radiation above background concentrations.[[183]](#footnote-184)183 Where ***oil*** and gas activities bring radionuclide-containing substances to the surface, these materials are called technologically enhanced naturally occurring radioactive materials (TENORM).

Waste streams from ***oil*** and gas activities that may contain TENORM include produced water, scale on pipes or other solid production equipment, sludge and filter cake, filter socks, synthetic proppants and contaminated soils, sediments, water or equipment. As ***oil*** and gas production from shale formations increased, the volume of TENORM waste increased, causing management and disposal challenges where shale formations contained high radiation concentrations. In part to evaluate the sufficiency of rules governing ***oil*** and gas TENORM, and to respond to public concern surrounding TENORM, regulatory agencies in North Dakota and Pennsylvania initiated research to determine whether, and to what extent, ***oil*** and gas TENORM poses risks to the public, workers and the environment.

**1. North Dakota**

On behalf of North Dakota's Department of Health, Argonne National Lab evaluated the potential for exposure to workers and the general public resulting from the management and disposal of technologically enhanced naturally occurring radioactive material (TENORM).[[184]](#footnote-185)184 The study first evaluated the disposal of TENORM wastes in permitted Industrial Waste and Special Waste landfills, including transportation, during landfill operations, and considering future use of landfill property. Next, the study examined exposure risks during oilfield activities, such as worker exposures from wellsite operations and accidental public exposures to mismanaged TENORM-containing wastes.

Argonne labs evaluated carcinogenic risk posed by TENORM exposure associated with various management and disposal scenarios using several modeling methodologies and analysis (rather than actual site measurements). Researchers identified potential environmental pathways, including on-site direct exposure, air concentration, water contamination and soil contamination and indirect pathways such as exposure via plant foods, livestock and aquatic foods. Corresponding methods of exposure, such as external radiation, inhalation and ingestion, were estimated for each of the environmental exposure pathways. Potential effective dose equivalent for exposed persons were compared to health-based dose limits to determine whether, and to what extent, a given management or disposal scenario posed health risks.

Based on this analysis, Argonne determined that for many well site operations, the risk of radiation exposure to workers can be effectively reduced through the use of personal protective equipment, and in some cases, limits to exposure time. Risks to the public from accidental exposure and from transportation of TENORM wastes were deemed low.

With respect to regulation of TENORM-containing ***oil*** and gas wastes, Argonne made several recommendations. Researchers estimated that public exposures exceeding a health-based limit of 100 mrem/year could be avoided so long as:

No more than 25,000 tons of TENORM wastes were disposed of in a single landfill per year.

The average thorium activity concentration in the waste did not exceed 24 pCi/g.

TENORM wastes were covered by at least 2 m (6 ft) of clean cover material.

Following the release of this TENORM study, the North Dakota Department of Health proposed new rules to govern ***oil*** and gas wastes containing TENORM. The proposed rules would require that:

TENORM waste up to 50 picocuries per gram (up from 5 picocures per gram) may be disposed of at approved Oilfield Special Waste Landfills and Large Volume Industrial Waste Landfills;

TENORM generators must register with the NDDoH;

TENORM must be tracked from production to disposal;

Any facility approved by the NDDoH to accept TENORM of up to 50 picocuries per gram will be limited to no more than 25,000 tons/year of TENORM waste; and

TENORM waste must be buried a minimum of 10 feet below the top of the closed landfill.

The Department of Health adopted the final rules on 2015.[[185]](#footnote-186)185

**2. Pennsylvania**

The subsurface formations underlying Pennsylvania, including the Marcellus Shale, contain relatively high concentrations of naturally occurring radioactive material (NORM).[[186]](#footnote-187)186 As ***oil*** and gas development activity expanded, the Pennsylvania Department of Environmental Protection (DEP) observed a "steady increase in the volume of [***oil*** and gas] waste containing TENORM."[[187]](#footnote-188)187 To address this increase in TENORM-containing waste, Pennsylvania DEP contracted with Perma-Fix Environmental Services (PESI) to conduct a study of TENORM associated with various ***oil*** and gas operations activities in the Marcellus Shale. Beginning in 2013, PESI gathered samples of solids, liquids, natural gas, ambient air, and surface radiation from wellpads, disposal facilities and water treatment plants for analysis. Based on these direct measurements, PESI evaluated the potential for radiation exposure to the public, workers and the environment.

This Pennsylvania assessment identified little potential for additional radiological exposure to human populations due to activities associated with ***oil*** and gas development, production and disposal. However, the assessment did reveal the potential for radiological environmental impacts associated with produced water and the waste byproducts of its treatment.[[188]](#footnote-189)188 Specifically, the data supported a finding of potential impacts associated with (1) spills and the long-term disposal of filter cake, and other concentrated residual waste; (2) spills of influent and effluent water at ***oil*** and gas wastewater treatment facilities; and (3) limited potential for radiation exposure to recreationists using roads treated with brine.[[189]](#footnote-190)189

Based on these findings, PESI recommended that DEP undertake certain regulatory actions and further study.

Radium should be added to the Pennsylvania spill protocol to ensure cleanups adequately characterize radiological risk.

Potential environmental impacts from the use of produced water for dust suppression and road stabilization should be evaluated.

Facilities that treat ***oil*** and gas wastes should be further evaluated to detect elevated discharge limitations, and to determine whether any sites require remediation.

TENORM disposal protocols should be reviewed to ensure the safety of long-term disposal of waste containing TENORM.

On December 15, 2015, the Pennsylvania DEP modified TENORM tracking and disposal protocols through a letter sent directly to landfills.[[190]](#footnote-191)190 The new protocols, which became effective January 1, 2016, revise the Residual Waste Codes, adjust the multiplier for wastewater treatment sludge, and change method of calculating annual TENORM loads. According to DEP, these alterations reflect landfill experience with the tracking spreadsheet, disposal trends and input from the Pennsylvania Waste Industries Association and the Marcellus Shale Coalition.[[191]](#footnote-192)191

Specifically, DEP adjusted the multipliers used to equalize exposure rate and radioactive concentrations for TENORM containing wastes. For materials classified under Residual Waste Codes 804 and 812, which includes wastewater treatment sludge and filters, filter socks and other filter media used in the treatment of ***oil*** and gas wastewater, respectively, the DEP decreased the multiplier from 3 to 1.5. The multiplier reflects DEP's determination that the radioactive concentration (pCi/g) of these types of ***oil*** and gas waste is approximately 1.5 times higher than indicated by the measured exposure rate (μR/hr). Effectively, this means that 1 ton of waste designated under Residual Waste Codes 804 and 812 will count towards a landfill's allotment as 150 tons. For all TENORM-containing wastes other than wastewater treatment sludge and filter material, DEP set the multiplier at 0.38.

Additionally, DEP revised the TENORM protocols to "reduce the TENORM allocation by a greater proportion compared to the 2015 calendar year" by altering the method a facility calculates its TENORM allocation, using pCi tons/g rather than μR/hr.[[192]](#footnote-193)192 The new protocols also require facilities to report total waste tonnages for the past three years, instead of tonnage from only the previous year.

Finally, DEP revised Residual Waste Codes in the 800-series to allow for more detailed tracking of ***oil*** and gas wastes. Sludge generated during ***oil*** and gas wastewater treatment will be classified under its own Residual Waste Code (804), and additional wastes should be reported using new codes for materials such as synthetic liner materials, contaminated soils, filters and other ***oil*** and gas wastes (806, 811, 812, and 899, respectively).[[193]](#footnote-194)193

**C. North Dakota Energy & Environmental Research Center Pipeline Study**

Expansion of North Dakota's ***oil*** industry has been accompanied by an equally dramatic increase in produced water generation. Infrastructure necessary to manage this produced water has also expanded; nearly 23,000 miles of gathering pipeline have been installed in North Dakota since 2008. The expanding volume of produced water and size of the management system have, in part, contributed to a greater number of spills, including North Dakota's largest spill - 3 million barrels of brine - in 2015.[[194]](#footnote-195)194

In response to growing public concern about brine spills, and the need to evaluate existing regulations and identify best management practices for temporary pipelines, North Dakota's 64th Legislative Assembly passed House Bill No. 1358 during its 2015-2016 session. Section 8 of H.B. 1358 provided funding for research in these areas, and directed the University of North Dakota's Energy & Environmental Research Center (EERC) to provide a report with recommendations to the North Dakota Industrial Commission (NDIC) and the Energy Development and Transmission Committee (EDTC).

On December 1, 2015, the EERC issued its report and recommendations.[[195]](#footnote-196)195 The study includes a survey of pipeline materials, maintenance practices, inspection methods, monitoring and leak detection, as well as a comparison of pipeline and spill regulation from several other ***oil***-producing states.

Key findings:

Liquid gathering lines in North Dakota are largely unregulated. The North Dakota Department of Mineral Resources (DMR) has authority to administer punitive actions but does not have authority to shepherd the installation and operation of gathering lines. It may be beneficial to reconsider DMR's role in the implementation and enforcement of a pipeline safety management system for North Dakota operators.

Robust standard practices for construction and installation exist for steel pipelines. However, far less standardization and regulation governing installation practices exist for plastic pipelines. This is especially true for the spoolable pipe produces widely used in North Dakota.

Anecdotal evidence suggests line strikes, poor workmanship, and lack of inspection are the root cause of many gathering line leaks. However, analysis of spill statistics data could not substantiate nor refute this statement, in part due to the poor quality of spill data.

Most pipeline leaks are discovered visually by people who happen to be in the area of the spill. Sensor and software technology is evolving to meet the needs of leak detection, but they have not been demonstrated as reliable.

A modest investment in advanced systems to decrease the impact of pipeline spills is easily justified when a company recognizes that costs of remediation efforts may be larger by orders of magnitude.

In addition to this pipeline study, H.B. 1358 also mandated a demonstration study to evaluate leading leak detection systems and pipeline construction practices. In the near future, the North Dakota Division of Mineral Resources and EERC will partner with one or more pipeline operators to examine performance and cost efficiency of commercially available leak detection technologies and advanced pipeline monitoring.[[196]](#footnote-197)196 It is anticipated that the demonstration project will provide further information on the potential and efficacy of various methods of and leak detection systems. The study design and partners are currently under review.

**Part 3: Selected Academic Publications by Topic**

Heightened research interest by organizations, states, and governments was echoed, if not amplified, by academia over the past year. As industry advanced, regulations expanded, and public attention increased, academic publications supplemented the dialogue with scientific and research contributions on a number of areas of interest. A majority of these publications focused on areas where water-related environmental and geological impacts were concerned.

In 2015, a number of publications revealed a shift in attention away from inquiries into groundwater contamination events toward more broad areas of interest tied to specific aspects of industry operations - particularly areas where new issues were surfacing or novel practices were being deployed.

This Part will be divided into smaller, subject-focused subsections. Each subsection will include a discussion of the topic generally, followed by a citation and summary for a number of selected publications on each topic. Topics include: general water impact studies; groundwater contamination; water consumption and production; characterization, management, and disposal of produced water and flowback fluids; induced seismicity; and, regulatory oversight and enforcement. Where appropriate, these topics are broken down into further thematic subsections.

Finally, it is important to know that this Part is not intended to serve as a comprehensive literature review of all academic publications on these subjects. For the sake of utility and brevity, this review is focused on highlighting trends in research and providing citations and high-level, brief discussion on select publications of interest within each trend topic. For more thorough literature review of all publications related to drilling, hydraulic fracturing, and water disposal, see the Draft EPA Assessment reviewed above, and keep a lookout for the Final EPA Assessment, which will likely include updated research through the end of 2015 and early 2016.

**A. General Water Impact Studies**

Some research groups aim to look at a broad range of potential water resource impacts from hydraulic fracturing in certain regions or even nationally. A few relevant examples of such studies - although published in 2014, rather than 2015 - are worth sharing.

Brantley, S.L., Yoxtheimer, D., Arjmand, S., Grieve, P., Vidic, R., Pollak, J., Llewellyn, G.T., Abad, J., Simon, C. (2014). Water resource impacts during unconventional shale gas development: The Pennsylvania experience. *International Journal of Coal Geology, 126*(140).

This team of researchers reviewed publicly available databases in Pennsylvania to track evidence of contamination of surface and groundwater. Their review looked at everything from reported violations and complaints to contamination concerns associated with surface discharge and drinking water supply problems. The researchers concluded that the publicly available databases show relatively rare incidences of significant environmental impact compared to the number of wells drilled in the state. However, the team emphasized that firm conclusions on actual impacts are difficult to assess due to a lack of transparent and accessible data.

Vengosh, A., Jackson, R. B., Warner, N., Darrah, T. H., & Kondash, A. (2014). A critical review of the risks to water resources from unconventional shale gas development and hydraulic fracturing in the United States. *Environmental Science & Technology, 48*(15), 8334-48.

Dr. Vengosh and his team undertook a review of four possible risks to water sources from unconventional shale gas development and hydraulic fracturing and provided potential solutions to reduce those risks. The risks discussed include groundwater contamination, surface water contamination, the environmental legacy of chemical residues in areas of disposal and leaks, and water scarcity. For groundwater contamination, the authors propose enforcing a safe zone of 1 kilometer (km) between new shale gas sites and existing drinking water wells; mandatory baseline monitoring of water quality including isotopes of water and methane; and transparency and data sharing. When it comes to the possible legacy of chemical residues, the authors stress that full disclosure of all hydraulic fracturing chemicals is needed. For surface water, the authors propose a zero discharge policy for untreated wastewater, and development and use of adequate treatment technologies. In terms of water limitation, the authors propose use of alternative water sources including: gel, marginal waters, and acid mine drainage.

**B. Groundwater Contamination**

One of the first questions of academic interest associated with hydraulic fracturing was stray gas migration. To date, there have been no studies that have conclusively tied hydraulic fracturing itself (the physical action of injecting water, chemicals, and proppant at high pressure into a well) to a groundwater contamination event, although there are a number of alleged cases of water well contamination related to hydraulic fracturing activities that have not been definitively settled. Well construction failures - failures of the cement or casing that act as barriers to fluid or gas flow outside of the wellbore - are most often tied to groundwater contamination events, rather than the practice of hydraulic fracturing itself. There is increasing interest in the precise mechanism for contamination - ranging from research into aqueous and gas phase transport, to the impact of surface spills and leaks on groundwater. Researchers, regulators, and operators alike continue to debate the appropriate methodologies for conclusively tying contamination events to particular operations or operators.

Some studies are particularly relevant to liability in that they focus on the growing science of isotopic signatures or "fingerprinting." This research aims to identify unique, signature qualities of gases or liquids associated with ***oil*** and gas production in specific basins. Advances in this area of research intend to close key gaps in our ability to definitively tie a particular release or contamination event to a development activity, or definitively rule out development activity (or even a certain operator) as the source of contamination. Those in the legal industry should monitor these cases and scientific advancements for their important tie to liability claims.

A number of researchers studied samples of groundwater in specific regions of development activity:

Li, H., Son J-H., Carlson, K.H. (2016). Concurrence of aqueous and gas phase contamination of groundwater in the Wattenberg ***oil*** and gas field of northern Colorado. *Water Research 88:* 458-466.

This Colorado research team examined possible concurrent transport of gas and aqueous phases from an ***oil*** and gas formation into an aquifer by comparing the ionic character (or chloride to total dissolved solid ratio) from three sets of water samples: an uncontaminated deep confined aquifer; suspected contaminated groundwater from a deep confined aquifer containing thermogenic methane; and produced water from nearby ***oil*** and gas wells (representing aqueous phase contaminants). The researchers found that the produced water's ionic character did not have similarities to the "thermogenic methane contaminated" groundwater - concluding that there was no aqueous phase transport. The team hopes the results will provide additional insight on contamination mechanisms "since improperly sealed casing may result in stray gas but not aqueous phase transport."

Hildenbrand, Z. L., et al. (2015). A Comprehensive Analysis of Groundwater Quality in The Barnett Shale Region. *Environmental Science & Technology 49*(13): 8254-8262.

In an effort to expand contamination research beyond dissolved gases, researchers analyzed 550 groundwater samples in the Barnett Shale Play region in Texas and detected volatile organic carbon compounds, various alcohols, the BTEX family of compounds (benzene, toluene, ethylbenzene, and xylenes), and a number of chlorinated compounds in several samples. The researchers emphasized that although these constituents are associated with unconventional ***oil*** and gas (UOG) extraction techniques, their detection does not necessarily identify UOG as the source of potential contamination. The team concluded that their results "provide a strong impetus" for ongoing and expanded monitoring and analysis of groundwater contamination in the region.

Darrah, T.H., Vengosh, A., Jackson, R.B., Warner, N.R., and Poreda, R.J. (2014). Noble gases identify the mechanisms of fugitive gas contamination in drinking-water wells overlying the Marcellus and Barnett Shales. *PNAS 111*(14076).

Darrah and team analyzed samples from drinking water wells in the Marcellus and Barnett Shales for hydrocarbon abundance and isotopic composition along with a comprehensive analysis of noble gases and their isotopes in the groundwater near shale-gas wells. The team identified discrete clusters of fugitive gas contamination. Their noble gas and isotope data linked four clusters to failures of intermediate annulus casing, three to target production gases implicating faulty production casing, and one to an underground gas well failure. Their data appeared to rule out contamination by upward migration triggered by horizontal drilling or hydraulic fracturing.

Additional studies on groundwater contamination shed new light on impacts from surface activities. As increasing attention is shifting from below ground contamination events to above ground spills, leaks, and releases studies have pointed to such incidents as causes not only of surface pollution, but also potential culprits in groundwater contamination. The first study below, out of Yale, garnered widespread media attention with headlines reading, for example, "*New Yale Study Confirms" Fracking Doesn't Contaminate Drinking Water*."[[197]](#footnote-198)197

Drollette, B.D. et al. (2015). Elevated levels of diesel range organic compounds in groundwater near Marcellus gas operations are derived from surface activities. *PNAS 112*(43), 13184-13189.

Drollette et al. analyzed shallow groundwater samples from private residential wells in the Marcellus region. Their analysis found trace levels of volatile organic carbons and low levels of gasoline range and diesel range organic compounds along with confirmed detection of bis(2- ethylhexyl) phthalate, a hydraulic fracturing additive. Through pairing their analysis with inorganic fingerprinting, isotopic analysis, and spatial relationships the researchers were able to differentiate sources of contamination. They concluded that the dominant source of organic compounds in shallow aquifers was consistent with surface spills of disclosed chemical additives, rather than subsurface flow of the fluids from the deep shale formation.

Llewellyn, G. T., Dorman, F., Westland, J. L., Yoxtheimer, D., Grieve, P., Sowers, T., Humston-Fulmer, E., Brantley, S. L. (2015). Evaluating a groundwater supply contamination incident attributed to Marcellus Shale gas development. *Proc. Natl. Acad. Sci. 112*(43): 13184-13189.

Presenting an alternative scenario of subsurface lateral migration, a second study out of *PNAS,* investigated a singular incidence of contamination of a shallow potable water source in the Marcellus Shale. The researcher's utilized highly advanced equipment to identify a mixture of organic compounds at extremely low detection levels (nanogram per liter). The authors propose that the contaminants may have traveled 1 - 3 km from the hydraulically fractured well site along shallow to intermediate depth fractures to the source aquifer. However, in line with the work of Drollete et al., one alternate explanation provided by the authors was wastewater from a pit leak reported at a nearby gas well. Samples of fluids used in drilling or hydraulic fracturing, or present in the pit may have aided in additional fingerprinting of the source of contamination but were unavailable.

**C. Water Consumption & Production**

Although ***oil*** and gas drilling and production utilizes a relatively small percentage of fresh water when compared to other industries at a large scale, water withdrawals can have local and regional impacts on communities experiencing high levels of production activity. Much public concern regarding hydraulic fracturing activity is inherently tied to concerns regarding long term availability of fresh, clean, drinkable water. While many have turned their attention to other impacts of production activities, there is ongoing interest in the issue of water scarcity as a core concern. A CERES report in 2014[[198]](#footnote-199)198 that analyzed water demand across the United States and western Canada indicated that since 2011, almost half of the wells that were hydraulically fractured were in regions with high or extremely high water stress.[[199]](#footnote-200)199 This review also highlighted areas of drought and groundwater depletion in relation to shale energy development and made more specific findings on a regional level for eight regions.

While ***oil*** and gas consumes a large amount of water each year, it also produces large quantities of produced water and flowback fluids or, collectively, wastewater. By some estimates, ***oil*** and gas operations produce over 800 billion gallons of produced wastewater each year,[[200]](#footnote-201)200 which presents a large management and disposal challenge for the ***oil*** and gas industry. Produced volumes are being increasingly scrutinized in response to stakeholder calls for increased water conservation and recycling, and in light of induced seismicity concerns associated with deep well disposal, which will be discussed in a later subsection.

A number of studies aimed at getting a better hold on the actual amount of water required by, used in, and produced as waste by ***oil*** and gas operations have been published over the past year. There are varying methodologies by each author and, as such, varying results - though all are informative in improving our understanding of the scale of the problem when it comes to water used and wastewater produced.

Chen. H. and Carter, K.E. (2016). Water usage for natural gas production through hydraulic fracturing in the United States from 2008 to 2014. *J. Envtl. Mgmt. 170:* 152- 159.

Chen and Carter compiled data on freshwater and recycled produced water used to fracture wells from 2008 to 2014 in 14 states. Their results showed average water volumes per well ranging between 1000 m3 (~ 264,000 gallons) and 30,000 m3 (~7,930,000 gallons), and the authors provided average consumption volumes state by state. As other studies have indicated, the percentage of water used for hydraulic fracturing was low compared to other industries. The authors also looked at volumes of recycled produced water and hydraulic fracturing wastewater used in operations over five years. Significantly, the authors found that wells recycling wastewater used recycled wastewater to make up more than half of their water use.

Gallegos, T. J., Varela, B. A., Haines, S. S., & Engle, M. A. (2015). Hydraulic fracturing water use variability in the United States and potential environmental implications. Water *Resources Research, 51:* 5839-5845.

Researchers found that there is relevant variability in the types of wells (horizontal, directional, and vertical) that are hydraulically fractured in shale plays. The authors conclude that these potential variations between shale plays demonstrate the need for caution in national-level assumptions about risks to water resources from hydraulic fracturing. The dataset used was a proprietary database from IHS. Water use volumes from Jan. 2011 to Aug. 2014 were then mapped by watershed using hydrologic unit codes. The highest levels of water use for that period were in the following shale plays, which generally used horizontal rather than vertical or directionally drilled wells: Eagle Ford, Bakken, Marcellus and Utica, Haynesville-Bossier, some portions of Barnett, Fayetteville, Tuscaloosa, Woodford, and only small portions of Niobrara. The study estimates that volumes of median national annual water volumes used for hydraulic fracturing of horizontal wells increased from 670 m3 (~177,000 gallons) in 2000 to more than 15,000 m3 (~3,960,000 gallons) per well in 2014, while volumes for hydraulic fracturing vertical and directional wells remained stable. Although the study reports median national annual water use volumes by hydraulic fracturing type (horizontal, vertical, or directional), the study does not scale up the results to report a national water use volume as in Kondash and Vengosh (2015), see below.

Jackson, R.B., Lowry, E.R., Pickle, A., Kang, M., Diguilio, D., Zhao K. (2015). The depths of hydraulic fracturing and accompanying water use across the United States. *Environ. Sci. Technol. 49*(15): 8969-8976.

To test reports highlighting the safety of hydraulic fracturing for drinking water if it occurs very deep underground, Jackson et al. conducted a comprehensive analysis of hydraulic fracturing depths to gain insight into how often wells are drilled within proximity of an aquifer. The researchers found that about 16% of the ~44,000 wells studied (years 2010-2013) were hydraulically fractured less than one mile from the surface, and about 6% of wells were hydraulically fractured at less than 3,000 feet below the surface. The average fracturing depth was about 8,300 feet. Average water use per well nationally was 2.4 million gallons, and differed from state to state. The researchers found that 2,000 wells shallower than one mile and 350 wells shallower than 3,000 feet were fractured with over one million gallons of water. In light of their findings, the researchers proposed that shallow wells may warrant special safeguards.

Critics of Jackson have noted that the number of shallow wells is small, compared to his statements regarding the "surprisingly common" nature of shallow hydraulic fracturing.[[201]](#footnote-202)201

Kondash A. and Vengosh A. (2015). Water footprint of hydraulic fracturing. *ES&T Letters* (accepted Aug. 21, 2015).

Kondash and Vengosh estimated unconventional shale gas and ***oil*** water use and production volumes in the United States relying on public databases and published studies. Their analysis concluded that unconventional shale gas and ***oil*** extraction used 940 billion liters (~248 billion gallons) of water between 2005 and 2014. Their annual water use rates were divided between shale gas, using 116 billion liters (~30.6 billion gallons) per year, and unconventional ***oil***, using 66 billion liters per year (~17.4 billion gallons). The researchers also reported 803 billion liters (~212 billion gallons) of produced water and flowback from all unconventional formations based on integrated data from 6 to 10 years of operation. Additionally, the authors report Produced Water Intensity (PWI), the volume of water produced per unit of energy produced, and found that the PWI for unconventional ***oil*** and gas is typically lower than for conventional ***oil***. The researchers also compared water use intensity (WUI), the amount of water used per unit of energy extracted, of unconventional ***oil*** and gas to that of other fuels including coal and uranium and concluded that shale gas and ***oil*** have much lower WUI values.

Kuwayama, Y., Olmstead, S., Krupnik, A. (2015). Water Quality and Quantity Impacts of Hydraulic Fracturing. *Curr Sustainable Renewable Energy Rep. 2:* 17-24.

Kuwayama et al. conducted a literature review of academic journal articles published 2010-2015 to provide an overview of the current state of knowledge regarding water quantity and quality concerns associated with hydraulic fracturing. The authors shared two overarching findings after their review of the literature. First, that the studies indicate water quantity impacts of unconventional development are not significantly worse than conventional impacts. Second, that recent findings suggest water quality impacts and concerns related to hydraulic fracturing may be more serious.

Scanlon, B. R., Reedy, R. C., & Philippe Nicot, J. (2014). Will water scarcity in semiarid regions limit hydraulic fracturing of shale plays? *Environmental Research Letters, 9*(12), 124011.

Researchers out of the University of Texas Bureau of Economic Geology have conducted a number of studies on water use, water demand, and water scarcity. In this study, the team concluded that impacts of hydraulic fracturing water use in the Eagle Ford Shale region are relatively small, but localized impacts can be large. Agricultural pumping has already drawn down aquifers in some areas; the added water stress of hydraulic fracturing could be reduced through use of brackish waters instead of freshwater that is needed to grow crops. The researchers project that water demand over the next 20 years will be a volume equal to about 10% of historic groundwater depletion from irrigation in the region. The 20 year projected water demand from hydraulic fracturing for the Eagle Ford Shale region represents less than 0.5% of the estimated brackish water stored in the region, compared to about 3% of the fresh water that is stored in the region. Potential for reusing or recycling flowback and produced water in the Eagle Ford is limited because of the low rate of water production compared to the rate of hydraulic fracturing water demand. However, this is not the case in the Permian basin of West Texas, where water to ***oil*** production ratios are much higher.

**D. Characterization, Management, and Disposal of Produced Water and Flowback Fluids**

Investigations in this category have garnered possibly the most new attention over the past five years for a number of reasons. Beyond characterizing these waters to identify and trace contamination events, arguably the most prominent reason for increased attention is industry's ongoing transition to increased management and disposal of produced water and flowback fluids at the surface - including reuse and recycling in the oilfield for subsequent fracturing operations, treatment and discharge to surface waters through treatment facilities, or alternative disposition options such as beneficial reuse for other purposes outside the oilfield. While the purpose for in-depth investigation into the chemical makeup of produced water and flowback fluids may have been different, results have collectively shown that characterizing and treating this wastewater is a challenge due to its complex and variable nature. Improved understanding of produced water and flowback fluids will assist regulators and operators alike in minimizing risks to water resources associated with evolving management and disposal practices. Improved understanding of produced and flowback waters will similarly inform future studies into the environmental fate and impact studies. Studies analyzing the efficacy of varying treatment technologies have not been included in this review.

**Characterization**

Efforts to thoroughly characterize the chemical constituents in produced water and flowback fluids (here, collectively "wastewater") are hampered, first, by limited knowledge regarding the precise additives utilized in the fracturing process as well as unknown character of native formation water. This unknown factor is compounded by a lack of viable analytical methods capable of identifying and quantifying chemicals at reasonably low detection levels (because potentially toxic constituents are often present in trace amounts) in an often highly saline fluid (high salt content causes interference in the analysis). Studies have investigated various methods and techniques for characterizing wastewater - looking at different types of wastewater, different analytical methods, different analytical tools, etc. Thorough knowledge of the constituents present in these wastewaters will inform reuse technologies, management techniques, development of technologies for treatment and discharge to surfaces, spill remediation standards, and a number of other important advancements in today's practices.

A select number of studies are included here, though there have been many others. Studies often focus on a particular region, a particular class of constituents (inorganic, organic, radiological), or both. The Marcellus Region has garnered particularly high attention for a number of reasons, including advanced recycling practices, the radiological nature of the shale, and the use of publicly owned and centralized facilities to treat and discharge wastewater to streams.

Akob, D.M., Cozzarelli, I.M., Dunlap, D.S., Rowan, E.L., Lorah, M.M. (2015). Organic and inorganic composition and microbiology of produced waters from Pennsylvania shale gas wells. *Applied Geochemistry*. DOI: 10.1016/j.apgeochem.2015.04.011.

Akob et al. sampled produced water from 13 shale gas wells in north central Pennsylvania. Their analysis found that organics and microbes were highly variable across the wells sampled, whereas inorganics chemistry was less variable. Notably, volatile organic compounds were detected in the range of ~1 to 11.7 ?g/L, and H2S-producing, fermenting, and methanogenic bacteria were cultured from the samples, even though biocides were present. These observations are important for understanding how to handle, treat, or reuse produced water. No broad conclusions about the composition of produced water can be drawn from this study because of the small sample size, but the results indicate potential avenues for future research.

Ferrer, I., & Thurman, E. M. (**2015**). Chemical constituents and analytical approaches for hydraulic fracturing waters. *Trends in Environmental Analytical Chemistry,* (5)*:* 18-25.

Ferrer and Thurman present an overview of known information regarding the chemical additives used in hydraulic fracturing, the natural components found in formation water, and the composition of flowback and produced water along with a discussion of advanced analytical techniques that can detect the type of compounds present. The authors note that a thorough characterization of these waters are important to understand and address the transport, environmental fate and potential health impacts, and that sophisticated analytical methodologies are necessary to detect a number of contaminants that may only be present in trace amounts. Their review presents literature on known chemical constituents, and discusses various analytical sample preparation techniques, inorganic analysis techniques, and organic analysis techniques (including both gas chromatography-mass spectrometry and liquid chromatography-mass spectrometry). The authors note important research needs in this area of analytical investigation.

Lester, Y., Ferrer, I., Thurman, E. M., Sitterley, K. A., Korak, J. A., Aiken, G., & Linden, K. G. (2015). Characterization of hydraulic fracturing flowback water in Colorado: Implications for water treatment. *The Science of the Total Environment, 512-513:* 637-644.

Lester, Ferrer, et al. used a suite of analytical tools to thoroughly evaluate the chemical composition of flowback waters from the Denver-Julesburg (DJ) basin in Colorado. In contrast to previous studies, this work identified and quantified some organic compounds present in flowback waters, which was made possible through the use of liquid and ion chromatography. A framework for evaluating hydraulic fracturing wastewaters at the site-level is provided, along with analytical methods for characterization, and guidance for choosing tailored treatment approaches based on fluid composition and desired end use.

Shih, J.S., Saiers, J.E., Anisfeld, S.C., Chu, Z., Muehlenbachs, L.A., Olmstead, S.M. (2015). Characterization and Analysis of Liquid Waste from Marcellus Shale Gas Development. *Environmental Science & Technology,* 49(16): 9557-9565.

Shih et al. compiled a dataset based on wastewater generator reports filed in Pennsylvania from 2009 - 2011. The dataset contained 160 samples of flowback, produced water, and drilling wastes and analyzed for 84 different chemicals - what the authors called the most comprehensive analysis available to date for Marcellus Shale wastewater. The authors identified very high concentrations of soluble constituents such as chloride as a particularly problematic aspect of the wastewater because they are poorly removed by wastewater treatment plants. The majority of samples analyzed exceeded relevant water quality thresholds, generally by 2-3 orders of magnitude.

Khan, N.A., Engle, M., Dungan, B., Holguin, F.O., Xu, P., Carroll, K.C. (2015). Volatile-organic molecular characterization of shale-***oil*** produced water from the Permian Basin. *Chemosphere 148:* 126-136.

Khan et al., a team from New Mexico State and the USGS, aimed to characterize the compositional variability of produced water in order to evaluate impact, treatment, and reuse potential - noting that for beneficial reuse organic contaminants must be removed. The team collected produced water from shale-***oil*** wells from the Permian Basin, where little to no organic compositional data had been gathered. The team identified approximately 1400 organic compounds, including benzene and BTEX, and were able to observe 300-400 with identifiable structures. The researchers highlighted extremely high TDS as the primary challenge for treatment and reuse. The team used a lower cost technique that allowed them to identify the presence of SVOC and VOC compounds, but high-resolution technologies were required to quantify the variability. Khan et al. concluded that their low-cost technique may be useful to fingerprint produced water for forensic evaluations.

**Geochemical and Isotopic Fingerprinting**

Often in support of efforts to better identify the precise source of potential contamination events, some research has undertaken to identify distinctive qualities of flowback and produced water associated with unconventional development. Efforts work toward development of geochemical and isotopic tracers or fingerprints that can support more robust monitoring and evaluation tools for identifying the environmental effect and specific impact of certain operations.

Vengosh, A., Warner, N.R., Kondash, A., Harkness, J.S., Lauer, N., Millot, R., Koppman, W., Darrah, T.H. (2015). Isotopic Fingerprints for Delineating the Environmental Effects of Hydraulic Fracturing Fluids. *Procedia Earth and Planetary Science (13):* 244-247.

Vengosh et al. compiled data from the USGS produced water database and new data on flowback and produced water from a number of basins across the US. They found that unconventional and conventional effluent chemistry was often indistinguishable. Flowback from the Marcellus Shale was characterized with a distinctive trace element and isotopic fingerprints that are different from conventional ***oil*** and gas wells.

Rowan, E.L., Engle, M.A., Kraemer, T.F., Schroder, K, T., Hammack, R.W., and Doughten, M.W. (2015). Geochemical and isotopic evolution of water produced from Middle Devonian Marcellus shale gas wells, Appalachian basin, Pennsylvania. *AAPG Bulletin*.

Researchers with the USGS and NETL studied produced water from Marcellus Shale gas wells to determine the origin of water and solutes produced over greater than 12 months - aiming to determine whether the water produced originated in the Marcellus Shale or was drawn, through fractures, from adjacent reservoirs. They concluded that present radium isotopes indicated an origin in the Marcellus Shale and could be used as tracers. Their timeline of analysis showed that rapid salinity increases and other changes were observed over time until a compositional plateau was reached after about one year. After that time, their review shows natural formation water originated from paleoseawater as the returning fluid, supporting a hypothesis that significant volumes of injected water were removed from circulation by imbibition.

**Treatment and Discharge to Surface Waters**

Interest in the potential environmental impact of treatment and discharge options has grown significantly in recent years as the practice expanded in a few areas. Most prominently in Pennsylvania, where operators, faced with low availability of disposal wells and high trucking costs to Ohio, utilized Publicly Owned Treatment Works (POTW) to dispose of their wastewater. It was soon determined that these facilities were not capable of managing the waste stream, resulting in a number of studied discharge impacts and regulatory changes at the state and federal level, including a voluntary ban on unconventional wastewater discharge through POTWs in Pennsylvania, and recent rule proposal from EPA that will prohibit operators from disposing of unconventional wastewater through POTWs at a national level.[[202]](#footnote-203)202 EPA's preamble for the proposed rule notes that there were no known discharges to POTW's from unconventional operations at the time of proposal.[[203]](#footnote-204)203 The use of Centralized Waste Treatment facilities (CWTs) - those facilities designed to manage specific, industrial wastewaters - is still allowed and a number of facilities are in operation or being built to treat produced water either for recycling within the oilfield or discharge.

Getzinger, G.J., O'Connor, M.P., Hoelzer, K., Drollette, B.D., Karatum, O., Deshusses, M.A., Ferguson, P.L., Elsner, M., Plata, D.L. (2015). Natural gas residual fluids: Sources, endpoints, organic chemical composition after centralized waste treatment in Pennsylvania. *Environmental Science & Technology 49*(14): 8347-8355.

Centralized waste treatment facilities (CWTFs) in Pennsylvania received 9.5% of all natural gas residual fluids in 2013. Getzinger et al. collected grab samples of discharged water from a CWT on four occasions over a two year period (CWT's with NPDES permits for surface water discharge). GC-MS and liquid chromatography were used to test the samples for approximately 900 organic compounds known to be used in high volume hydraulic fracturing. Their results revealed that only petroleum distillates and alcohol polyethoxylates (AEs) were found to be present in the samples. Although AEs are known to be degradable, their degradability in high salt, low pH conditions is not clear, and their occurrence in discharge waters could result in ecological exposure. The researchers concluded that few analytes currently targeted by regulatory agencies (like benzene and toluene) were actually observed, emphasizing the need for expanded monitoring efforts at CWT's.

**Mobility and Persistence**

Related to the discussion of groundwater contamination above, some studies have focused on analyzing the fate, transport, mobility and persistence of constituents to prioritize particular compounds of concern for increased probability of exposure.

Rogers, J.D., Burke, T.L., Osborn, S.G., Ryan, J.N. (2015). A framework for identifying organic compounds of concern in hydraulic fracturing fluids based on their mobility and persistence in groundwater. *ES&T Letters (2),* 158-164.

In this study, over 650 organic compounds known to be used in hydraulic fracturing (and containing sufficient data) were screened for mobility, persistence, toxicity, and frequency of use. The authors aimed to get an understanding of priority chemicals of concern with sufficient mobility and persistence to reach a water well under fast and slow groundwater transport scenarios. The results indicated that 15 compounds of relatively wide use (at least 50 FracFocus reports) had elevated exposure potential - including naphthalene and 2-butoxyethanol (both identified on more than 20% of FracFocus reports).

**Toxicity and Human Health Analyses**

A number of studies have analyzed toxicological aspects of chemicals used in and produced by ***oil*** and gas operations - ranging from studies on specific health hazards, such as occupational health risks, to analyses of certain toxins. EPA's Draft Assessment, summarized above, shed light (as many others have done) on the number of chemicals for which we have insufficient toxicological data. While growing attention has resulted in a number of important studies analyzing known hazards and risks associated with these chemicals and fluids, there is consensus that much work remains to be done to provide the expanded understanding necessary to fully evaluate potential threats to environmental and human health. A few exemplary studies are summarized below.

Elliott, E.G., Ettinger, A.S., Leaderer, B.P., Bracken, M.B., and Deziel, N.C. (2016). A systematic evaluation of chemicals in hydraulic fracturing fluids and wastewater for reproductive and developmental toxicity. *J. Exposure Sci. and Envtl. Epidemiology* (advanced online publication Jan. 6, 2016) DOI: 10.1038/jes.2015.81.

Researchers out of Yale University evaluated over 1,000 chemicals identified in fracturing fluids and produced water for reproductive and developmental toxicity in an effort to triage those with potential for human health impact. In their search for available data, the researchers found that toxicity information was lacking for 76% of the chemicals. Of the remaining substances, evidence suggested reproductive toxicity for 103 (43%), developmental toxicity for 95 (40%) or both for 41 (17%). Of the 157 with suggested toxicity, 67 had or were proposed for a federal water quality standard or guideline. The authors indicate that incorporation of additional data on potency, physiochemical properties, and environmental concentrations could further prioritize substances for future assessments and studies.

Wattenberg, E.V., Bielicki, J.M., Suchomel, A.E., Sweet, J.T., Vold, E.M., Ramachandran, G. (2015). Assessment of the Acute and Chronic Health Hazards of Hydraulic Fracturing Fluids. *J. Occupational Envtl. Hygiene 12*(9): 611-624.

Wattenberg et al. focused their review on hazard identification - or the type of toxicity that a substance may cause. The researchers developed an adaptable tool for hazard identification of hydraulic fracturing fluids and applied that tool to an analysis of chemicals reported to be used in 2,850 North Dakota wells between 2009 and 2013. The authors narrowed their review from 569 reported constituents to 168 that were identifiable by a Chemical Abstract Service Registration Number and were reportedly used at least 25 times. The tool then generated health hazard counts for chronic and acute endpoints. Their results showed that 11 of the most hazardous constituents identified were also in the top 30 used chemicals. It's worth noting that the top 25 constituents used in North Dakota overlap with the most used chemicals in Texas and Pennsylvania - implying that these results can be expected to be similar in those states. Notably, 24 of the constituents were associated with developmental and reproductive toxicity. 59% of the constituents studied lacked chronic toxicity information, and 35% lacked acute toxicity information.

**United States Geological Survey**

It should be noted that the USGS has an extensive Produced Water Geochemical Database and consistently publishes scientific articles devoted to improving our understanding of produced water and related investigations of hydraulic fracturing fluids, additives, chemicals, volumes and wastes. In 2015, the produced water section of the USGS published 8 relevant papers. Information including the database and publications can be found here: http://energy.usgs.gov/EnvironmentalAspects/EnvironmentalAspectsofEnergyProductionandUse/ProducedWaters.aspx#3822111-news.

**E. Induced Seismicity**

Induced seismicity incidents and investigations have ramped up exponentially over the past few years, in line with increasing seismic activity in numerous regions. In 2015, a number of key publications shed light on the ongoing inquiry into the precise cause and potential mitigation options for induced seismicity events tied to hydraulic fracturing and wastewater disposal in Class II disposal wells. There remains an ongoing debate as to why exactly these earthquakes occur and how to scientifically tie seismic events back to actual hydraulic fracturing or disposal activity. Efforts are ongoing to differentiate conclusively between natural seismic events and induced events caused either by hydraulic fracturing itself or disposal wells, with most events being tied to the latter cause.

Causes and cases have been hotly contested between researchers, industry, and government agencies alike as events increase in magnitude and frequency along with attention and concern from the public and landowners.

It is likely the most comprehensive review to date was published by the Interstate ***Oil*** and Gas Compact Commission in late 2015. A thorough discussion of that publication is included in Part I of this paper. The IOGCC publication should also be utilized as a resource for references to pertinent publications.

**Disposal Wells**

A majority of studies have focused on events associated with Class II disposal wells - where large volumes of ***oil*** and gas wastewater from both conventional and unconventional drilling are disposed of by injection into deep wells. These events have been tied to the most public outcry and regulatory investigation - particularly those in Texas and Oklahoma. The studies included here are the most recent, though there are a number of historic studies that have been valuable in building the foundation for ongoing research into the induced seismicity question.[[204]](#footnote-205)204

Goebel, T.H.W., Hosseini, S.M., Cappa, F., Hauksson, E., Ampuero, J.P., Aminzadeh, F., and Saleeby, J.B. (2016). Wastewater disposal and earthquake swarm activity at the southern end of the Central Valley, California. *Geophys. Res. Lett. 43* (online January 22, 2016). DOI: 10.1002/2015GL066948.

A team of researchers in California tied a swarm of 2005 earthquakes near the White Wolf fault in ***Kern*** County, California to wastewater injection at three nearby wells - with an event up to M4.6. The researchers conducted detailed statistical analysis and modeling to differentiate induced earthquakes from background seismicity and found evidence for deep migration within the crystalline basement between the injection wells and the fault. The researchers propose a number of possible triggering mechanisms including pressure diffusion and stress transfer. The team described a number of factors that may complicate induced seismicity in detection in California, including high background seismicity rates. In conclusion, the team noted that injection-induced earthquakes are likely to contribute marginally to the overall seismicity in California, but disposal wells in the southern Central Valley region should be monitored carefully because of the high-permeability fault structures that connect the injection area to nearby faults. Injection-induced earthquakes may remain unidentified in California if only standard seismicity catalogs are analyzed. It's worth noting that - compared to Oklahoma - wells in California inject on average 0.5 km deeper and more annual fluid volumes.

Hornbach, M.J., DeShon, H.R., Ellsworth, W.L., Stump, B.W., Hayward, C., Frohlich, C., Oldham, H.R., Olson, J.E., Magnani, M.B., Brokaw, C., and Leutgert, J.H. (2015). Causal factors for seismicity near Azle, Texas. *Nat. Commun. 6:*6728.

Researchers out of Southern Methodist University (SMU) released a highly publicized - and contentious[[205]](#footnote-206)205- study tying the combination of brine production and wastewater disposal as the most likely cause of a series of earthquakes in November 2013 near Azle, Texas. Their conclusion was based on an analysis of lake and groundwater variations in the area, porepressure models, and the absence of historical earthquakes. The SMU team stressed the need to monitor subsurface wastewater formation pressures and earthquakes with magnitude of M2 or greater - which is not standard. Despite the conclusion, the paper recognizes a number of key uncertainties and discusses them at length including uncertainties tied to modeling, permeability, brine production, bottom-hole pressure, regional structural geology, and stress magnitude and orientation.

Hough, S.E. & Page, M. (2015). A century of induced earthquakes in Oklahoma? *B. Seismological Soc. of Am. 105*(6).

Researchers Hough and Page summarize available data on background rates and rate changes for earthquakes in Oklahoma over the past century. Their research shows an increase in seismicity rates since 2009, statistically significant temporal and special correspondence of twentieth century earthquakes to disposal wells, and evidence of low level tectonic seismicity in southeastern Oklahoma associated with the Ouachita structural belt (including a M4.8 Choctaw Nation earthquake in 1882). Their research concludes that earthquakes were induced by ***oil*** production activities in Oklahoma as early as the 1920s and their research tied a majority of activity in the 1950s and 1980-1990s to induced seismicity. Despite this background, they conclude that the cluster of activity since 2009 is not consistent with the level of natural fluctuations seen in the past.

Keranen, K.M., Weingarten, M., Abers, G.A., Bekins, B.A., and Ge, S. (2014). Sharp increase in central Oklahoma seismicity since 2008 induced by massive wastewater injection. *Science 345*(6195): 448-451.

This *Science* publication concluded that four of the highest-rate disposal wells in Oklahoma were capable of inducing 20% of 2008 to 2013 central U.S. seismicity. Using seismicity and hydrogeological models they showed fluid migration from these high-rate disposal wells as potentially responsible for largest swarms, with hypocenters occurring within the disposal formations and upper basement. Specifically, they found that 45% of the region's seismicity and (at the time) 15 M>3 earthquakes per week, could be linked to disposal wells. Their conclusions regarding induced seismicity up to 35 km away from disposal wells was further than previously considered in criteria for induced seismicity. Overall they conclude that modern, very high-rate injection could cause regional seismicity, increasing seismic hazard.

McGarr, A. (2014). Maximum magnitude earthquakes induced by fluid injection. *J. Geophysical Res.: Solid Earth 119:* 1008-1019.

McGarr, of the USGS, published a paper in 2014 aiming to answer a key question of concern in light of increasing seismicity in Oklahoma and Texas - how big could these get? He concluded that the maximum seismicity was limited based on total volume injected, and provided equations capable of estimating the upper bound of a seismic moment based on a given fluid injection activity. The upper bound increases with time if injection continues, and provided an equation for the cumulative seismic moment. The study cautioned that injection could induce an earthquake larger than the upper bound. The paper recognizes that the sequence in Prague, Oklahoma could be natural, but there is a plausible interpretation of the equation to show induced seismicity.

Walsh III, F.R., Zoback, M.D. (2015). Oklahoma's recent earthquakes and saltwater disposal. *Sci. Adv. 1* (e1500195).

Walsh and Zoback found that increases over the past five years of earthquakes in Oklahoma followed 5- to 10-fold increases in the rates of saltwater disposal. From 1997 to 2013, the aggregate monthly injection volume doubled from 80 million barrels/month to 160 million barrels/month, while the seismicity increased abruptly in 2009. The team studied six special areas where the majority of earthquakes had been recorded in the state. They concluded that the deep sedimentary formations where the water is injected - particularly those in the Arbuckle Group - are in hydraulic communication with potentially active faults in the crystalline basement. Injection of high volumes of saltwater is triggering the released of stored strain energy in the Arbuckle. The researchers developed a conceptual model for induced earthquakes in Oklahoma. Significantly, the authors include a discussion on managing injection-related seismic risks and respond to a number of studies included here. Referencing the Keranen et al. conclusions regarding seismicity at a distance of 10 km from a disposal well, the team noted that reducing cumulative volume would be beneficial, but setting an arbitrary upper limit on injection rates at any single well may not reduce induced seismicity probability if lower rate wells nearby could inject that same volume. The researchers indicate a need for future research that would allow the identification of critically stressed faults so they could be avoided.

**Hydraulic Fracturing**

Hydraulic fracturing is far from the most common cause of seismicity induced by ***oil*** and gas activities. However, a few individual publications on induced seismicity case studies have looked specifically at events triggered from hydraulic fracturing itself, not the disposal of wastewater into injection wells. These studies built on others that previously recognized seismicity induced from hydraulic fracturing can and does occur.[[206]](#footnote-207)206

Schultz, R., Stern, V., Novakovic, M., Atkinson, G., Gu, Y.J. (2015). Hydraulic fracturing and the Crooked Lake Sequences: Insights gleaned from regional seismic networks. *Geophysical Res. Letters, 42*: 2750-2758.

Schultz et al. investigated a sequence of earthquakes in central Alberta, Canada and found that they were consistent with first-order observations of hydraulic fracturing induced seismicity. The team used an advanced detection algorithm to detect more than 160 events at the end of 2014 and their hypothesis that the quakes were tied to hydraulic fracturing was corroborated by the uniqueness of the waveforms. The sequences, labeled "The Crooked Lake Sequences" were close in time to hydraulic fracturing operations in the Duvernay Formation. The research team's techniques allowed them to spatially relate each of five clusters back to a unique horizontal well.

Skoumal, R.J., Brudzinksi, M.R., Currie, B.S. (2015). Earthquakes induced by hydraulic fracturing in Poland Township, Ohio. *Bulletin Seismological Soc. of Am., 105*(1): 189-197.

This team of researchers identified 77 earthquakes - ranging from M1 to M3 - in Poland Township, Ohio closely related spatially and temporally to active hydraulic fracturing operations, with the M3 being one of the largest tied to hydraulic fracturing in the US. The researchers found that the hydraulic fracturing appeared to induce slip along a pre-existing fault zone that was optimally oriented in the regional stress field. The rate of events declined following Ohio Department of Natural Resource's shut down of hydraulic fracturing at a nearby well.

Clarke, H., Eisner, L., Styles, P., Turner, P. (2014). Felt seismicity associated with shale gas hydraulic fracturing: The first documented example in Europe. *Geophysical Research Letters 41*(23): 8308-8314.

One of the first examples of hydraulic fracturing induced seismicity occurred in Blackpool, UK in 2011. The British Geological Survey published an opinion at the time tying the event to exploratory test of hydraulic fracturing of the Bowland Shale and shut down the suspected well owned by Cuadrilla Resources, who conducted further research and published this and other papers on the event. This paper concludes that the earthquakes, 2.3M and 1.7M, resulted from the interaction of hydraulic fracturing and a fault that was unknown at the time of the event.

British Columbia ***Oil*** and Gas Commission, Industry Bulletin 2015-32, August Seismic Event Determination (Dec. 15, 2015), *available at* https://www.bcogc.ca/node/12951/download.

In December of 2015, the British Columbia ***Oil*** and Gas Commission determined that a 4.6M seismic event in August of 2015 was caused by fluid injection during hydraulic fracturing from an operator in the area. The BCOGC reviewed operational and seismological data to come to their conclusion. They also considered the absence of events before and after operations, the proximity of the event epicenter to the wellbore, the fact that the event occurred during fracturing operations, and the "felt" reports strength in the vicinity of the wellbore.

**F. Regulatory Oversight and Enforcement**

Over the past five years, regulations addressing hydraulic fracturing for ***oil*** and gas, and related activities, have grows and adapted to meet changing operational practices and needs at a rapid pace. So to, have academic studies aimed at recognizing that growth, highlighting gaps, and reviewing enforcement and capacity issues. Because such articles are not directly tied to water impacts, only a few key examples have been included here.

Dundon, L.A., Abkowitz, M., Camp, J. (2015). The real value of FracFocus as a regulatory tool: A national survey of state regulators. *Energy Policy 87*, 496-504.

Dundon et al. set out to investigate the use of FracFocus as a regulatory tool, basing their research and analysis on direct feedback from state regulators. Their review criticized a 2013 report out of Harvard Law School that did not include such a survey, and concluded the FracFocus failed as a regulatory compliance tool. In countering this conclusion, Dunden and colleagues found that states were very positive about FracFocus as a tool and are using it in novel ways that go beyond the registry's original purpose.

Malone, S., Kelso, M., Auch, T., Edelstein, K., Ferrar, K., & Jalbert, K. (2015). Data inconsistencies from states with unconventional ***oil*** and gas activity. *J. Envtl. Sci. and Health, Part A: Toxic/Hazardous Substances and Environmental Engineering. 50*(5): 501-510.

This study group attempted a first methodical state-to-state comparison of the quality and availability of unconventional ***oil*** and gas data. The researchers requested, collected and assessed five categories of data from ten states with drilling activity and assessed the data based on eight data quality parameters (accessibility, usability, point location, completeness, metadata, agency responsiveness, accuracy, and cost). Scored on a scale of 100, the average score was 67.1, which the authors considered insufficient for proper data transparency. The highest and lowest scoring states were Pennsylvania and Texas, respectively.

Rahm, B.G., Vedechalam, S., Bertoia L.R., Mehta, D., Vanka, V.S., & Riha, S.J. (2015). Shale gas operator violations in the Marcellus and what they tell us about water resource risks. *Energy Policy 82*: 1-11.

Rahm et al. examined compliance data as an indicator of environmental risks and their trends and drivers over time. The group tracked over 3,000 shale gas violations and found that rates increased from 2007-2009, remained high through 2010, and dropped from 2011 through today. Relevant to water protection, the most commonly issued violations related to spills and erosion. The team found examples of one policy change that resulted in a 45% decline in environmental violation rates, and determined that for every 1% increase in wells drilled per inspections conducted, there was a 0.56% decrease in violation rates. They found that administrative violations, operator identity, price of gas and other major policies were not significantly correlated with violation rates. Interestingly for conventional versus unconventional discussions, the researchers found that shale development entails more risk for spills and solid waste management whereas conventional development was associated with increased risk due to cementing and casing issues and site restoration.

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**End of Document**

1. 1EPA, *Assessment of the Potential Impacts of Hydraulic Fracturing for* ***Oil*** *and Gas on Drinking Water Resources* (June 2015). The cited document is the draft for external review, which is still in the peer review process. It is not a final draft. [↑](#footnote-ref-2)
2. 2EPA, *Assessment of the Potential Impacts of Hydraulic Fracturing for* ***Oil*** *and Gas on Drinking Water Resources* (June 2015) at ES-3. The cited document is the draft for external review, which is still in the peer review process. It is not a final draft. [↑](#footnote-ref-3)
3. 3EPA, *Assessment of the Potential Impacts of Hydraulic Fracturing for* ***Oil*** *and Gas on Drinking Water Resources* (June 2015) at ES-3. The cited document is the draft for external review, which is still in the peer review process. It is not a final draft. [↑](#footnote-ref-4)
4. 4*Id.* at ES-3 (discussing all issues identified above, except well integrity); *id.* at (discussing well integrity); *see* also EPA (by Glen Boyd, *et al*.), *Review of Well Operator Files for Hydraulically Fractured* ***Oil*** *and Gas Production Wells: Well Design and Construction* (May 2015). [↑](#footnote-ref-5)
5. 5*Id.* at ES-4 Figure ES-2. [↑](#footnote-ref-6)
6. 6EPA (by Susan Burden *et al*.), *Analysis of Hydraulic Fracturing Fluid Data from the FracFocus Chemical Disclosure Registry 1.0* (March 2015). [↑](#footnote-ref-7)
7. 7EPA (by Glen Boyd, *et al*.), *Review of Well Operator Files for Hydraulically Fractured* ***Oil*** *and Gas Production Wells: Well Design and Construction* (May 2015). [↑](#footnote-ref-8)
8. 8EPA (by Susan Burden *et al*.), *Review of State and Industry Spill Data: Characterization of Hydraulic Fracturing-Related Spills* (May 2015). [↑](#footnote-ref-9)
9. 9EPA, *Retrospective Case Study in Northeastern Pennsylvania* (May 2015); EPA, *Retrospective Case Study in Southwestern Pennsylvania* (May 2015); EPA, *Retrospective Case Study in Killdeer, North Dakota* (May 2015); EPA, *Retrospective Case Study in the Raton Basin, Colorado* (May 2015); EPA, *Retrospective Case Study in Wise County, Texas* (May 2015). [↑](#footnote-ref-10)
10. 10*See, e.g.*, EPA, *Case Study Analysis of the Impacts of Water Acquisition for Hydraulic Fracturing on Local Water Availability* (May 2015); EPA, *Sources Contributing Inorganic Species to Drinking Water Intakes During Low Flow Conditions on the Allegheny River in Western Pennsylvania* (May 2015). [↑](#footnote-ref-11)
11. 11*Assessment* at ES-5. [↑](#footnote-ref-12)
12. 12*Id.* at ES-6. [↑](#footnote-ref-13)
13. 13Press Release, American Petroleum Institute, API: EPA hydraulic fracturing review confirms safety (June 4, 2015), *available at* http://www.americanpetroleuminstitute.com/news-and-media/news/newsitems/2015/june-2015/api-epa-hydraulic-fracturing-review-confirms-safety. [↑](#footnote-ref-14)
14. 14Katie Brown, *Long-Awaited EPA Study Finds Fracking Has Not Led to Widespread Water Contamination*, ENERGYINDEPTH BLOG (June 4, 2015, 11:11 AM), http://energyindepth.org/national/long-awaited-epa-study-finds-fracking-has-not-led-to-widespread-water-contamination/. [↑](#footnote-ref-15)
15. 15Neela Banerjee, *Fracking Has Contaminated Drinking Water, EPA Now Concludes*, INSIDECLIMATE NEWS (June 5, 2015), http://insideclimatenews.org/news/05062015/fracking-has-contaminated-drinking-water-epa-now-concludes. [↑](#footnote-ref-16)
16. 16Sharon Kelly, *EPA Study: Fracking Puts Drinking Water Supplies at Risk of Contamination*, DESMOG BLOG (June 4, 2015), http://www.desmogblog.com/2015/06/04/epa-study-fracking-contaminates-water-supplies. [↑](#footnote-ref-17)
17. 17*See, e.g.*, Clean Water Action, *Issue Brief: EPA Hydraulic Fracturing and Drinking Water Assessment*, CLEAN WATER ACTION BLOG (Winter 2016), http://blog.cleanwateraction.org/wp-content/uploads/2015/12/EPAFrackAssmt\_Brief\_Final.pdf; Hugh MacMillan, *How the Release of the EPA's Draft Assessment on Drinking Water Impacts Was Spun*, FOOD AND WATER WATCH (June 10, 2015) (noting that "The EPA's draft assessment of the effects of fracking on drinking water is being portrayed in a way that doesn't reflect the actual findings."), http://www.foodandwaterwatch.org/insight/how-release-epas-draft-assessment-drinking-water-impacts-was-spun; *and* Nichole Saunders, *What EPA Should Consider on Their Final "Fracking" Assessment*, EDF ENERGY EXCHANGE BLOG (Feb. 5, 2016), http://blogs.edf.org/energyexchange/2016/02/05/what-epa-should-consider-on-their-final-fracking-assessment/. [↑](#footnote-ref-18)
18. 18News Release, Environmental Protection Agency, EPA Releases Draft Assessment on the Potential Impacts to Drinking Water Resources from Hydraulic Fracturing Activities (June 4, 2015) (leading with the subheadline "Assessment shows hydraulic fracturing activities have not led to widespread, systemic impacts to drinking water resources and identifies important vulnerabilities to drinking water resources") (emphasis added), *available at* http://yosemite.epa.gov/opa/admpress.nsf/d0cf6618525a9efb85257359003fb69d/b542d827055a839585257e5a005a796b!OpenDocument. [↑](#footnote-ref-19)
19. 19*See, e.g.* Coral Davenport, NY TIMES, *Fracking Has Not Had Big Effect on Water Supply, E.P.A. Says While Noting Risks* (June 4, 2015), http://www.nytimes.com/2015/06/05/us/epa-hydraulic-fracking-water-supply-contamination. html?\_r=2; *and* Joby Warrick, WASHINGTON POST, *Major EPA Fracking Study Cites Pollution Risk But Sees No 'Systemic' Damage So Far* (June 4, 2015), https://www.washingtonpost.com/news/energy-environment/wp/2015/06/04/fracking/; Amy Wold, THE ADVOCATE, *EPA fracking report a mixed bag: no widespread water contamination found, but many questions remain* (June 5, 2015), http://theadvocate.com/football/lsufootball/12569901-127/epa-fracking-report-a-mixed. [↑](#footnote-ref-20)
20. 20EPA's Science Advisory Board or SAB, a group of scientists who are not affiliated with the EPA, but who provide outside advice and input to the Agency on important reports and publications. [↑](#footnote-ref-21)
21. 21Science Advisory Board (SAB) Draft Report (1/7/16) to Assist Panel Deliberations, *available at* http://yosemite.epa.gov/sab/sabproduct.nsf/ea5d9a9b55cc319285256cbd005a472e/d4210ba02ebef65185257f33005a0cc2/$ FILE/Report%20to%20Administrator-SAB%20Hydraulic%20Fracturing%20Research%20Advisory%20Panel-1-7-16%20draft.pdf. [↑](#footnote-ref-22)
22. 22*Id.* at 2. [↑](#footnote-ref-23)
23. 23*Id.* at 18. [↑](#footnote-ref-24)
24. 24*Assessment* at ES-3 (defining, for purposes of Assessment, the meaning of "drinking water resources") and ES-5 ("We did not find evidence that these mechanisms have led to widespread, systemic impacts on drinking water resources in the United States."). [↑](#footnote-ref-25)
25. 25*Assessment* at ES-7 and 10-2. [↑](#footnote-ref-26)
26. 26*Assessment* at ES-7 and 10-2. [↑](#footnote-ref-27)
27. 27*Id.* at ES-7 and ES-8; *see also Assessment* at 10-2 n.18. [↑](#footnote-ref-28)
28. 28*Assessment* at ES-6 and 10-2. [↑](#footnote-ref-29)
29. 29*Id.* at ES-9 and 10-4. [↑](#footnote-ref-30)
30. 30*Id.* at ES-9 and 10-4. [↑](#footnote-ref-31)
31. 31*Id.* at ES-9 and 10-2. [↑](#footnote-ref-32)
32. 32*Assessment* at ES-9 and 10-4. [↑](#footnote-ref-33)
33. 33*Id.* at ES-10 and 10-5. [↑](#footnote-ref-34)
34. 34*Id.* at ES-10 and 10-5. [↑](#footnote-ref-35)
35. 35*Id.* at ES-11 and 10-6. [↑](#footnote-ref-36)
36. 36*Assessment* at ES-11; Science Advisory Board (SAB) Draft Report (1/7/16) to Assist Panel Deliberations at 9, 38. [↑](#footnote-ref-37)
37. 37*Assessment* at ES-11 and 10-6. [↑](#footnote-ref-38)
38. 38*Id.* at ES-17 and 10-12. [↑](#footnote-ref-39)
39. 39*Assessment* at ES-14. [↑](#footnote-ref-40)
40. 40*Id.* at ES-14; *see also Assessment* at 10-10. [↑](#footnote-ref-41)
41. 41*Id.* at ES-15. [↑](#footnote-ref-42)
42. 42*Id.* at ES-20. [↑](#footnote-ref-43)
43. 43*Id.* at ES-20. [↑](#footnote-ref-44)
44. 44*Assessment* at ES-20. [↑](#footnote-ref-45)
45. 45*Id.* at ES-20 and ES-21. [↑](#footnote-ref-46)
46. 46*Id.* at ES-21. [↑](#footnote-ref-47)
47. 47*Id.* at ES-20; *see also Assessment* at 10-15. [↑](#footnote-ref-48)
48. 48*Id.* at 9-1 and 9-2. The *Assessment* notes that the information it considered would not necessarily apply with respect to other routes of exposure, such as inhalation or skin contact. *Assessment* at 9-2. [↑](#footnote-ref-49)
49. 49*Assessment* at 9-4. [↑](#footnote-ref-50)
50. 50*Id.* at 9-2. [↑](#footnote-ref-51)
51. 51*Id.* at 9-5. [↑](#footnote-ref-52)
52. 52*Id.* [↑](#footnote-ref-53)
53. 53*Id.* [↑](#footnote-ref-54)
54. 54*Assessment* at 9-1 n.1. [↑](#footnote-ref-55)
55. 55*Id.* at 9-1 n.2. [↑](#footnote-ref-56)
56. 56*Id.* at 9-1. [↑](#footnote-ref-57)
57. 57*Id.* at 9-7. [↑](#footnote-ref-58)
58. 58*Id.* at 9-35 thru 9-36; *see also id.* at 9-24 thru 9-28, 9-40. [↑](#footnote-ref-59)
59. 59GWPC's website states: "The Ground Water Protection Council (GWPC) is a nonprofit 501(c)6 organization whose members consist of state ground water regulatory agencies which come together within the GWPC organization to mutually work toward the protection of the nation's ground water supplies." [↑](#footnote-ref-60)
60. 60John Veil, U.S. Produced Water Volumes and Management Practices in 2012 (prepared for the Ground Water Protection Council), *available at* http://www.gwpc.org/sites/default/files/Produced%20Water%20Report%202014-GWPC\_0.pdf. [↑](#footnote-ref-61)
61. 61Clark, C.E., and J.A. Veil, 2009, Produced Water Volumes and Management Practices in the United States, ANL/EVS/R-09/1, prepared for the U.S. Department of Energy, National Energy Technology Laboratory, September, 64 pp. [↑](#footnote-ref-62)
62. 62Veil, *supra* n. 60 at 8. [↑](#footnote-ref-63)
63. 63*Id.* [↑](#footnote-ref-64)
64. 64*Id.* at 14. The subsurface formations that contain ***oil*** or natural gas often contain natural deposits of groundwater - typically, very salty groundwater, which often also contains dissolved metal ions and sometimes naturally occurring radioactive material. ***Oil*** wells often produce both ***oil*** and water, just as gas wells often produce both gas and water, even if the well is not one that has been hydraulically fractured. Such water often is called "produced water." [↑](#footnote-ref-65)
65. 65A barrel is a unit of volume equal to 42 U.S. gallons. [↑](#footnote-ref-66)
66. 66Veil, *supra* n. 60 at 7, 8. [↑](#footnote-ref-67)
67. 67*Id.* at 8. [↑](#footnote-ref-68)
68. 68*Id.* at 9. [↑](#footnote-ref-69)
69. 69*Id.* [↑](#footnote-ref-70)
70. 70Id. at 9. [↑](#footnote-ref-71)
71. 71*Id.* at 9. [↑](#footnote-ref-72)
72. 72*Id.* at 9. [↑](#footnote-ref-73)
73. 73Veil, *supra* n. 60 at 39. [↑](#footnote-ref-74)
74. 74Veil states that a majority of the offsite commercial facilities treated the water and then disposed of it via underground injection. *Id.* at 10, 45. [↑](#footnote-ref-75)
75. 75*Id.* at 9. [↑](#footnote-ref-76)
76. 76*Id.* at 9. [↑](#footnote-ref-77)
77. 77*Id.* at 10. [↑](#footnote-ref-78)
78. 78Veil, *supra* n. 60 at 10. [↑](#footnote-ref-79)
79. 79*Id.* at 111. [↑](#footnote-ref-80)
80. 80*Id.* [↑](#footnote-ref-81)
81. 81*Id.* at 42. [↑](#footnote-ref-82)
82. 82*Id.* at 10, 45. [↑](#footnote-ref-83)
83. 83Veil, *supra* n. 60 at 42, 57, 63, 79. [↑](#footnote-ref-84)
84. 84*Id.* at 10. [↑](#footnote-ref-85)
85. 85*Id.* at 42, 93, 94. [↑](#footnote-ref-86)
86. 86*Id.* at 42, 92, 93. Much of the water that is reused is first sent to centralized treatment facilities that treat the water. *Id.* at 92. A little over 12% of produced water in Pennsylvania is sent to injection disposal, some in the state and some to disposal wells in Ohio or West Virginia. *Id.* at 92, 94. Much of the produced water that is not reused or sent to injection disposal is sent to centralized waste treatment facilities that treat the water and then discharge it to surface waters. *Id.* at 92, 94. [↑](#footnote-ref-87)
87. 87*Id.* at 10. [↑](#footnote-ref-88)
88. 88*Id.* [↑](#footnote-ref-89)
89. 89Veil, *supra* n. 60 at 21-7. [↑](#footnote-ref-90)
90. 90*Id.* at 36. [↑](#footnote-ref-91)
91. 91*Id.* at 39. [↑](#footnote-ref-92)
92. 92*Id.* at 40. [↑](#footnote-ref-93)
93. 93*Id.* at 42. [↑](#footnote-ref-94)
94. 94*Id.* at 17-21. [↑](#footnote-ref-95)
95. 95Ground Water Protection Council and Interstate ***Oil*** and Gas Compact Commission, *Potential Injection-Induced Seismicity Associated with* ***Oil*** *& Gas Development: A Primer on Technical and Regulatory Considerations Informing Risk Management and Mitigation* (2015), *available at* http://media.wix.com/ugd/d3e01e\_7a12408392f240c89943d3f500039004.pdf [↑](#footnote-ref-96)
96. 96*Id.* [↑](#footnote-ref-97)
97. 97In the Canadian provinces of Alberta and British Columbia, a greater number of seismic events are believed to have been induced by hydraulic fracturing. At one location in the United Kingdom, hydraulic fracturing also is believed to have induced seismic activity. [↑](#footnote-ref-98)
98. 98These statistics can be obtained from the Oklahoma Geological Survey's website. [↑](#footnote-ref-99)
99. 99Keith B. Hall, *Induced Seismicity: An Energy Lawyer's Guide to Legal Issues and the Causes of Man-Made Earthquakes*, Proceedings of the Rocky Mountain Mineral Law Sixty-First Annual Institute § 5.01 (2015). [↑](#footnote-ref-100)
100. 100The GWPC's website states: "The Ground Water Protection Council (GWPC) is a nonprofit 501(c)6 organization whose members consist of state ground water regulatory agencies which come together within the GWPC organization to mutually work toward the protection of the nation's ground water supplies. The purpose of the GWPC is to promote and ensure the use of best management practices and fair but effective laws regarding comprehensive ground water protection." [↑](#footnote-ref-101)
101. 101The Interstate ***Oil*** and Gas Compact Commission describes itself as a "multi-state government agency." Its members include governors and state agency representatives from ***oil***-and-gas-producing states. [↑](#footnote-ref-102)
102. 102A National Academy of Sciences report had similarly broad coverage, and provided a good overview of induced seismicity, but it did not involve representatives of the various stakeholder groups. NATIONAL ACADEMY OF SCIENCES, INDUCED SEISMICITY POTENTIAL IN ENERGY TECHNOLOGIES (2013). [↑](#footnote-ref-103)
103. 103*Induced Seismicity Primer, supra* n. 95 at 1; *see also id.* at 14. [↑](#footnote-ref-104)
104. 104*Id.* at 15, 53, 54. [↑](#footnote-ref-105)
105. 105*Id.* at 15, 53, 54. [↑](#footnote-ref-106)
106. 106Id. at 15, 53, 54. [↑](#footnote-ref-107)
107. 107*Id.* at 15, 54. [↑](#footnote-ref-108)
108. 108*Induced Seismicity Primer, supra* n. 95 at 15, 54. [↑](#footnote-ref-109)
109. 109*Id.* at 15. [↑](#footnote-ref-110)
110. 110*Id.* at 18, 54. [↑](#footnote-ref-111)
111. 111*Id.* at 2, 7, 15. [↑](#footnote-ref-112)
112. 112*Induced Seismicity Primer, supra* n. 95 at 15, 17-8, 54. [↑](#footnote-ref-113)
113. 113*Id.* at 2, 15. [↑](#footnote-ref-114)
114. 114Id. at 8. [↑](#footnote-ref-115)
115. 115Id. at 11. [↑](#footnote-ref-116)
116. 116*Id.* at 8. [↑](#footnote-ref-117)
117. 117*Id.* at 10, 11. [↑](#footnote-ref-118)
118. 118*Id.* at 8. [↑](#footnote-ref-119)
119. 119*Induced Seismicity Primer, supra* n. 95 at 8. [↑](#footnote-ref-120)
120. 120*Id.* at 2. [↑](#footnote-ref-121)
121. 121*Id.* [↑](#footnote-ref-122)
122. 122*Id.* at 16. [↑](#footnote-ref-123)
123. 123*Id.* [↑](#footnote-ref-124)
124. 124*Id.* at 18. [↑](#footnote-ref-125)
125. 125*Induced Seismicity Primer, supra* n. 95 at 22-4. [↑](#footnote-ref-126)
126. 126*Id.* at 27. [↑](#footnote-ref-127)
127. 127*Id.* [↑](#footnote-ref-128)
128. 128*Id.* at 8. [↑](#footnote-ref-129)
129. 129*Id.* at 29. [↑](#footnote-ref-130)
130. 130*Id.* at 27, 29. [↑](#footnote-ref-131)
131. 131*Induced Seismicity Primer, supra* n. 95 at 29. [↑](#footnote-ref-132)
132. 132*Id.* at 28, 93. [↑](#footnote-ref-133)
133. 133The GWPC's website states: "The Ground Water Protection Council (GWPC) is a nonprofit 501(c)6 organization whose members consist of state ground water regulatory agencies which come together within the GWPC organization to mutually work toward the protection of the nation's ground water supplies. The purpose of the GWPC is to promote and ensure the use of best management practices and fair but effective laws regarding comprehensive ground water protection." [↑](#footnote-ref-134)
134. 134The study is available at: http://www.gwpc.org/sites/default/files/***Oil***%20and%20Gas%20Regulation%20Report%20Hyperlinked%20Version%20Final-rfs.pdf. [↑](#footnote-ref-135)
135. 135Ground Water Protection Council, *State* ***Oil*** *& Gas Regulations Designed to Protect Water Resources* at 5 (2014). [↑](#footnote-ref-136)
136. 136*Id.* at 6. [↑](#footnote-ref-137)
137. 137*Id.* [↑](#footnote-ref-138)
138. 138*Id.* [↑](#footnote-ref-139)
139. 139*Id.* at 7, 23. [↑](#footnote-ref-140)
140. 140Ground Water Protection Council, *supra* n. 135 at 7, 23. [↑](#footnote-ref-141)
141. 141*Id.* [↑](#footnote-ref-142)
142. 142*Id.* at 7-9. [↑](#footnote-ref-143)
143. 143*Id.* at 8, 34-5. [↑](#footnote-ref-144)
144. 144*Id.* at 9, 36. [↑](#footnote-ref-145)
145. 145Ground Water Protection Council, *supra* n. 135 at 9, 37-8. [↑](#footnote-ref-146)
146. 146*Id.* at 10, 39, 40. [↑](#footnote-ref-147)
147. 147*Id.* at 40, 41. [↑](#footnote-ref-148)
148. 148*Id.* at 39. [↑](#footnote-ref-149)
149. 149*Id.* at 26. [↑](#footnote-ref-150)
150. 150*Id.* at 7-14. [↑](#footnote-ref-151)
151. 151HEI's website states: "HEI is a nonprofit corporation chartered in 1980 as an independent research organization to provide high-quality, impartial, and relevant science on the health effects of air pollution." This statement also appears on one of the un-numbered pages of the *Research Agenda* that precedes the table of contents. [↑](#footnote-ref-152)
152. 152The HEI website states: "With funding from private foundations, the Health Effects Institute (HEI) convened a Special Scientific Committee to develop an impartial, multidisciplinary Strategic Research Agenda to help guide future research about potential adverse impacts of 21st century ***oil*** and natural gas development." Page 1 of the *Research Agenda* contains the statement regarding funding:

     This Research Agenda was produced with funding by the Richard King Mellon Foundation, the Henry L. Hillman Foundation, the Claude Worthington Benedum Foundation, and the Henry C. and Belle Doyle McEldowney Fund of The Pittsburgh Foundation. The contents of this document have not been reviewed by private party institutions, including those that support the Health Effects Institute; therefore, it may not reflect the views or policies of these parties, and no endorsement by them should be inferred. [↑](#footnote-ref-153)
153. 153Health Effects Institute, *Strategic Research Agenda on the Potential Impacts of 21st Century* ***Oil*** *and Natural Gas Development in the Appalachian Region and Beyond* (Nov. 2015) [hereinafter *Research Agenda*]. The full, approximately 240-page *Research Agenda* is available at: http://www.healtheffects.org/UOGD/UODG-Research-Agenda-Nov-4-2015.pdf. A document that contains only the Executive Summary is available at: http://www.healtheffects.org/UOGD/UODG-Executive-Summary-Nov-4-2015.pdf/. **Readers who are looking at pinpoint citations to particular pages of the Executive Summary should note that the page numbering is slightly different between the Executive Summary section of the full *Research Agenda* and the standalone Executive Summary document. The text of the Executive Summary section begins on page iii of the full *Research Agenda*, but the text begins on page ii of the standalone Executive Summary. The citations in this RMMLF/IEL paper refer to page numbers in the full *Research Agenda***. Readers who are using the standalone Executive Summary document therefore will need to "subtract 1" from the pinpoint citations (page number citations) used in this paper. [↑](#footnote-ref-154)
154. 154*Research Agenda, supra* n. 153 at ii, vi, vii, 59. [↑](#footnote-ref-155)
155. 155*Id.* at v, 18. [↑](#footnote-ref-156)
156. 156*Id.* at vii, 17, 59. [↑](#footnote-ref-157)
157. 157*Id.* at vii, 17. [↑](#footnote-ref-158)
158. 158*Id.* at 17. [↑](#footnote-ref-159)
159. 159The 35 questions appear at pages 21 through 23 of the *Research Agenda*. [↑](#footnote-ref-160)
160. 160*Research Agenda, supra* n. 153at viii. The text above paraphrases what the *Research Agenda* describes as the purpose of the questions in the three broad categories. The Agenda itself labelled the three categories of questions as: "Stressor and Exposure Characterization"; "Health and Well-Being Assessment"; and "Evaluation of Most-Effective Practices." *Id.* [↑](#footnote-ref-161)
161. 161*Id.* at vii-viii, 61. [↑](#footnote-ref-162)
162. 162*Id.* at ix, 62. [↑](#footnote-ref-163)
163. 163California Council on Sci. and Tech, *An Independent Assessment of Well Stimulation in California* (July 2015), *available at* https://ccst.us/projects/hydraulic\_fracturing\_public/SB4.php. [↑](#footnote-ref-164)
164. 164CAL. PUB. RES. CODE. div. 3, §2, art.3, § 3160. [↑](#footnote-ref-165)
165. 165Jane C. Long is a Senior Contributing Scientist for the Environmental Defense Fund. [↑](#footnote-ref-166)
166. 166California Council on Sci. and Tech, *An Independent Assessment of Well Stimulation in California: Volume 1* (July 2015), *available at* https://ccst.us/publications/2015/2015SB4-v1.pdf. [↑](#footnote-ref-167)
167. 167*Id.* at ES-iii. [↑](#footnote-ref-168)
168. 168*Id.* at ES-iii-iv. [↑](#footnote-ref-169)
169. 169California Council on Sci. and Tech, *An Independent Assessment of Well Stimulation in California: Volume 2* (July 2015), *available at* https://ccst.us/publications/2015/2015SB4-v2.pdf. [↑](#footnote-ref-170)
170. 170*Id.* at Ch.2. [↑](#footnote-ref-171)
171. 171*Id.* at 51. [↑](#footnote-ref-172)
172. 172*Id.* [↑](#footnote-ref-173)
173. 173*Id.* at 50. [↑](#footnote-ref-174)
174. 174*Id.* [↑](#footnote-ref-175)
175. 175California Council on Sci. and Tech, *supra* n. 169, at 18 (study recommendation 3.2). [↑](#footnote-ref-176)
176. 176*Id.* at 149; 151. [↑](#footnote-ref-177)
177. 177California Council on Sci. and Tech, *An Independent Assessment of Well Stimulation in California: Volume 3* (July 2015), *available at* https://ccst.us/publications/2015/2015SB4-v3.pdf [↑](#footnote-ref-178)
178. 178State of New York Department of Conservation, *Final Supplemental Generic Environmental Impact Statement: Volumes 1 & 2* (April 2015). [↑](#footnote-ref-179)
179. 179State of New York Department of Conservation, *2015 SEQR Findings Statement* (June 2015). [↑](#footnote-ref-180)
180. 180*Id.* at 5. [↑](#footnote-ref-181)
181. 181*Id.* [↑](#footnote-ref-182)
182. 182Env. Protection Agency, Radiation Protection, *TENORM:* ***Oil*** *and Gas Production Wastes*, http://www.epa.gov/radiation/tenorm-***oil***-and-gas-production-wastes. [↑](#footnote-ref-183)
183. 183Kappel, W., Williams, J.H., Szabo, Z., U.S. Geological Survey, *Water Resources and Shale Gas/****Oil*** *Production in the Appalachian Basin - Critical Issues and Evolving Developments, available at* http://pubs.usgs.gov/of/2013/1137/pdf/ofr2013-1137.pdf. [↑](#footnote-ref-184)
184. 184Argonne Nat'l Labs., ANL/EVS-14/13, *Radiological Dose and Risk Assessment of Landfill Disposal of Technologically Enhanced Naturally Occurring Radioactive Materials (TENORM) in North Dakota* (Nov. 2014). [↑](#footnote-ref-185)
185. 185N.D. CENT. CODE § 33-10-23 (Regulation and Licensing of TENORM); N.D. CENT. CODE § 33-20-01 et seq. (Solid Waste Management and Land Protection). [↑](#footnote-ref-186)
186. 186Kappel, W., Williams, J.H., Szabo, Z., U.S. Geological Survey, *Water Resources and Shale Gas/****Oil*** *Production in the Appalachian Basin - Critical Issues and Evolving Developments, available at* http://pubs.usgs.gov/of/2013/1137/pdf/ofr2013-1137.pdf. [↑](#footnote-ref-187)
187. 187Pennsylvania Dept. Env. Protection, *Technologically Enhanced Naturally Occurring Radioactive Materials (TENORM) Study Report* (Jan. 2015) at 1-1. [↑](#footnote-ref-188)
188. 188*Id.* at 9-8. [↑](#footnote-ref-189)
189. 189*Id.* [↑](#footnote-ref-190)
190. 190Pennsylvania Department of Environmental Protection, Letter to Landfill Operator, *Re: 2016 TENORM Tracking Spreadsheet*, (Dec. 15, 2015), *available at* https://www.portal.state.pa.us/portal/server.pt/document/1213244/tenorm\_disposal\_yearly\_balance\_letter\_pdf. [↑](#footnote-ref-191)
191. 191*Id.* [↑](#footnote-ref-192)
192. 192*Id.* [↑](#footnote-ref-193)
193. 193*Id.* [↑](#footnote-ref-194)
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196. 196*Id.* at 171. [↑](#footnote-ref-197)
197. 197Coloradans for Responsible Energy Development, *New Yale Study Confirms: Fracking Doesn't Contaminate Drinking Water,* CRED.org (Oct. 21, 2015), http://www.cred.org/new-yale-study-confirms-fracking-doesnt-contaminate-drinking-water/. [↑](#footnote-ref-198)
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199. 199*Id.* at ES-6. [↑](#footnote-ref-200)
200. 200Veil, John. (2015). U.S. Produced Water Volumes and Management Practices in 2012. Prepared for the Ground Water Protection Council. [↑](#footnote-ref-201)
201. 201*Stanford Univ Misses the Mark with Fracking Depths Study,* MARCELLUS DRILLING NEWS (July 30, 2105), http://marcellusdrilling.com/2015/07/stanford-univ-misses-the-mark-with-fracking-depths-study/. [↑](#footnote-ref-202)
202. 202For additional information on POTW treatment and discharge in Pennsylvania see EPA Region 3's website on ***oil*** and gas extraction in the Mid-Atlantic. ***Oil*** *and Gas Extraction in the Mid-Atlantic,* USEPA, http://www.epa.gov/foia/***oil***-and-gas-extraction-mid-atlantic. In 2015, EPA proposed an effluent limitation guideline that would prohibit discharge of unconventional ***oil*** and gas wastewater through POTWs. Effluent Limitations Guidelines and Standards for the ***Oil*** and Gas Extraction Point Source Category, 80 Fed. Reg. 18,557 (proposed April 7, 2015) (to be codified at 40 C.F.R. pt. 435). [↑](#footnote-ref-203)
203. 20380 Fed. Reg. at 18,561. [↑](#footnote-ref-204)
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206. 206Older studies of note include: Rutqvist, J., Rinaldi, A.P., Cappa, F., and Moridis, G.J. (2013). Modeling of fault reactivation and induced seismicity during hydraulic fracturing of shale-gas reservoirs. *Journal of Petroleum Science and Engineering, 107*, 31-44; Friberg, P.A., Besana-Ostman, G.M., and Dricker, I. (2014). Characterization of an earthquake sequence triggered by hydraulic fracturing in Harrison County, Ohio. *Seismological Research Letters 85(2)*: 462; Holland, A. Oklahoma Geological Survey. (2011) Examination of possibly induced seismicity from hydraulic fracturing in the Eola Field, Garvin County, Oklahoma. [↑](#footnote-ref-207)