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Human-Induced Earthquakes from Deep-Well Injection: A Brief Overview

Peter Folger
Acting Section Research Manager

Mary Tiemann
Specialist in Environmental Policy

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Summary

The development of unconventional oil and natural gas resources using horizontal drilling and hydraulic fracturing has created new demand for disposal wells that inject waste fluids into deep geologic formations. Deep-well injection has long been the environmentally preferred method for managing produced brine and other wastewater associated with oil and gas production. However, an increasing concern in the United States is that injection of these fluids may be responsible for increasing rates of seismic activity. The number of earthquakes of magnitude 3.0 or greater in the central and eastern United States, where there are many injection wells, has increased dramatically since about 2009. For example, over 60 earthquakes of magnitudes 4.0 to 4.8 have occurred in central Oklahoma from 2009 to mid-year 2016. Some of these earthquakes may be felt at the surface. The largest earthquake in Oklahoma history (magnitude 5.8) occurred on September 3, 2016, near Pawnee, causing damage to several structures. Central and northern Oklahoma were seismically active regions before the recent increase in the volume of waste fluid injection. However, the sharp uptick in earthquake activity does not seem to be due to typical, random changes in the rate of seismicity, according to several studies.

The relationship between earthquake activity and the timing of injection, the amount and rate of waste fluid injected, and other factors are still uncertain and are current research topics. Despite increasing evidence linking some deep-well disposal activities to human-induced earthquakes, only a small fraction of the more than 30,000 U.S. wastewater disposal wells appears to be associated with damaging earthquakes. However, the U.S. Geological Survey (USGS) deemed the increase in earthquake hazard in the central United States—likely from deep-well injection—sufficient to release a new one-year seismic hazard forecast for 2016 that includes contributions from both induced and natural earthquakes.

The potential for damaging earthquakes caused by hydraulic fracturing, as opposed to deep-well injection of wastewater from oil and gas activities, appears to be much smaller. Hydraulic fracturing intentionally creates fractures in rocks to increase the flow of oil and gas. The technique induces microseismicity, mostly of less than magnitude 1.0—too small to feel or cause damage at the surface. In a few cases, however, hydraulic fracturing has led directly to earthquakes larger than magnitude 2.0, including at sites in Oklahoma, Ohio, and England. In western Canada, earthquakes greater than magnitude 3.0 have been associated with hydraulic fracturing activities, although only from a very small percentage of hydraulic fracturing wells.

The Environmental Protection Agency's (EPA) Underground Injection Control (UIC) program under the Safe Drinking Water Act (SDWA) regulates the subsurface injection of fluids to protect underground drinking water sources. EPA has issued regulations for six classes of injection wells, including Class II wells used for oil and gas wastewater disposal and enhanced recovery. Most oil and gas producing states administer the Class II program. Although the SDWA does not address seismicity, EPA rules for certain well classes require evaluation of seismic risk. Such requirements do not apply to Class II wells; however, EPA has developed a framework for evaluating seismic risk when reviewing Class II permit applications in states where EPA administers this program.

Although only a small fraction of U.S. wastewater disposal wells appears to be problematic for causing damaging earthquakes, the potential for injection-related earthquakes has raised an array of issues and has affected oil and gas wastewater disposal in some areas. In response to induced seismicity concerns, both EPA and state work groups have issued recommendations for best practices to minimize and manage such risks. Several states have increased regulation and oversight of Class II disposal wells. Congress may be interested in oversight of EPA's UIC

program or in federally sponsored research on the relationship between energy development activities and induced seismicity.

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Introduction

Human-induced earthquakes, also known as induced seismicity, are an increasing concern in regions of the United States where the produced fluids and wastewaters from oil and natural gas production are being injected into the subsurface through deep disposal wells. The immediate concern is that injection of these fluids underground may cause damaging earthquakes in regions that typically do not experience much seismic activity. Induced seismicity has garnered increased attention partly as a result of the rapid development of unconventional oil and gas resources using hydraulic fracturing (often referred to as "fracking"). Specifically, the use of high-volume hydraulic fracturing has contributed significantly to the volume of wastewater requiring disposal and has also created demand for disposal wells in new locations. In examining these issues, it is important to distinguish between seismic activity possibly related to hydraulic fracturing itself and the possibility of seismic activity related to injecting fluids down disposal wells, which may not be located near where wells were fracked.

Human activities have long been known to have induced earthquakes in some instances: impoundment of reservoirs, surface and underground mining, withdrawal of fluids such as oil and gas, and injection of fluids into subsurface formations. With the increase in the use of horizontal drilling and hydraulic fracturing to extract oil and gas from shale, and the concomitant increase in the amount of fluids that are injected for high-volume hydraulic fracturing and for disposal, there are several indications of a link between the injected fluids and unusual seismic activity.

The principal seismic hazard that has emerged from increased oil and gas production in the United States appears to be related to disposal of wastewater using deep-well injection in some regions of the country. For example, one study showed the central United States has experienced a sharp increase in seismicity since 2009, increasing from an average of 24 earthquakes per year of magnitude 3.0 (M 3.0) or greater prior to 2009,[1] to an average of 193 earthquakes of M 3.0 or greater through 2014.[2] The number of M 3.0 or greater earthquakes in the central United States has continued to increase; **Figure 1** shows that the central United States experienced an average of 330 earthquakes of M 3.0 per year or greater from 2009 through January 2016.

Earthquake Magnitude and Intensity[3]

Earthquake magnitude is a number that characterizes the relative size of an earthquake. It was historically reported using the *Richter* scale. Richter magnitude is calculated from the strongest seismic wave recorded from the earthquake based on a logarithmic (base 10) scale: for each whole number increase in the Richter scale, the ground motion increases by 10 times. The amount of energy released per whole number increase, however, goes up by a factor of 32. The *moment magnitude* (M) scale is another expression of earthquake size, or energy released during an earthquake, that roughly corresponds to the Richter magnitude and is used by most seismologists because it more accurately describes the size of very large earthquakes. Sometimes earthquakes will be reported using qualitative terms, such as Great or Moderate. Generally, these terms refer to magnitudes as follows: Great (M>8); Major (M>7); Strong (M>6); Moderate (M>5); Light (M>4); Minor (M>3); and Micro (M<3). This report uses the moment magnitude scale, which is generally consistent with the Richter scale.

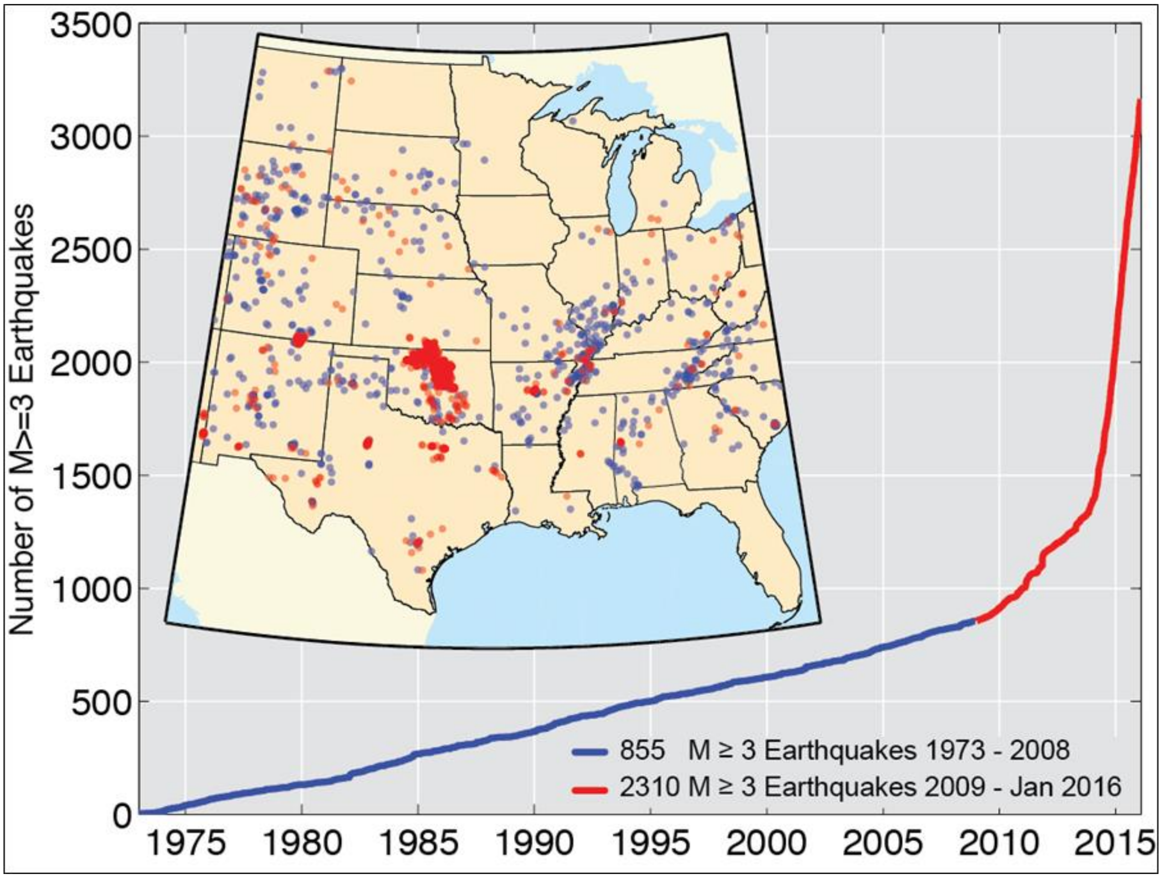
Source: U.S. Geological Survey FAQs, http://earthquake.usgs.gov/learn/faq/; and Magnitude/Intensity Comparison, at http://earthquake.usgs.gov/learn/topics/mag_vs_int.php.

[1] Earthquakes of magnitude 3.0 or more can typically be felt at the ground surface. See Box: Earthquake Magnitude and Intensity, above.

[2] Justin L. Rubinstein and Alireza Babaie Mahani, "Myths and Facts on Wastewater Injection, Hydraulic Fracturing, Enhanced Oil Recovery, and Induced Seismicity," *Seismological Research Letters*, vol. 86, no. 4 (July/August 2015), p. 1060. Hereinafter Rubinstein and Mahani, 2015.

[3] For a more general discussion of earthquakes, see CRS Report RL33861, *Earthquakes: Risk, Detection, Warning, and Research*, by Peter Folger.

Figure 1. Cumulative Number of Magnitude 3.0 or Greater Earthquakes in the Central and Eastern United States, 1973-2016



Source: U.S. Geological Survey, Earthquake Hazards Program, http://earthquake.usgs.gov/research/induced/.

Notes: The graph included earthquakes through January 2016. Starting around 2009, the long-term rate of approximately 29 M 3.0 or greater earthquakes per year increased significantly. Between 2009 and January 2016 the region experienced approximately 330 M 3.0 or greater earthquakes per year.

Many studies suggest that the most important contributing factor to this rising trend likely is deep-well injection of oil-and-gas-related wastewater.[4] However, the precise relationships between earthquake activity and the timing of injection, the amount and rate of fluid injected, and other factors are still not well understood, although a better understanding of these complex relationships appears to be emerging.[5] Several studies have pointed out that, of the more than 30,000 wastewater disposal wells classified by the Environmental Protection Agency (EPA) as

[4] See, for example, Rubinstein and Mahani, 2015; A. McGarr et al., "Coping with Earthquakes Induced by Fluid Injection," *Science*, vol. 347, no. 6224 (February 20, 2015), p. 830, hereinafter McGarr et al., 2015; William L. Ellsworth, "Injection-Induced Earthquakes," *Science*, vol. 341, July 12, 2013, http://www.sciencemag.org/content/341/6142/1225942.full, hereinafter Ellsworth, 2013.

[5] See, for example, F. Rall Walsh III and Mark D. Zoback, "Oklahoma's Recent Earthquakes and Saltwater Disposal," *Science Advances*, vol. 1 (June 18, 2015), hereinafter Walsh and Zoback, 2015.

Class II,[6] only a small fraction appears to be associated with damaging earthquakes.[7] However, even though it is only a small fraction, the overall number of disposal wells is so large that the total seismic hazard, at least for the central United States, appears to have increased measurably (see "National Issues—Changes to the U.S. Earthquake Hazard Maps").[8]

The potential for damaging earthquakes caused by injection of fluids for hydraulic fracturing operations, as opposed to deep-well injection of wastewater from fracking and other oil and natural gas production, appears to be much smaller. Multiple studies indicate that the vast majority of fluid injections into production wells for hydraulic fracturing cause microearthquakes—the results of fracturing the rock to extract oil or natural gas—which are typically too small to be felt or cause damage at the surface.[9] There are some cases where fracking caused detectable earthquakes felt at the surface, but most were too small to cause damage (see "Hydraulic Fracturing" below).

This report reviews the current scientific understanding of induced seismicity, primarily in the context of Class II oil and gas wastewater disposal wells. The report also outlines the regulatory framework for these injection wells and identifies several federal and state initiatives responding to recent events of induced seismicity associated with Class II disposal.

Congressional Interest

How deep-well injection is linked to induced seismicity, and state and federal efforts to address that linkage, are of interest to Congress because of the potential implications for continued development of unconventional oil and gas resources in the United States. If the current boom in onshore oil and gas production continues, then deep-well injection of waste fluids is likely to also continue and may increase in volume. Also, what Congress, the federal government, and the states do to address and mitigate possible human-caused earthquakes from deep-well injection of oil-and-gas-related fluids may provide some guidance for the injection and sequestration of carbon dioxide. Carbon dioxide sequestration—intended to reduce greenhouse gas emissions—would involve ongoing, long-term, high-volume, high-pressure injection via deep wells. Several large-scale injection experiments are currently underway; however, the relationship between long-term and high-volume carbon dioxide injection and induced earthquakes is not known.

The federal Safe Drinking Water Act (SDWA) authorizes EPA to regulate underground injection activities to prevent endangerment of underground sources of drinking water. The SDWA does not address seismicity; however, EPA underground injection control (UIC) program regulations include seismicity-related siting and testing requirements for hazardous waste and carbon sequestration injection wells. Such requirements are not included in regulations governing oil and gas wastewater disposal (Class II) wells, although regulators have discretionary authority to add conditions to individual permits. In February 2015, EPA released a document outlining technical recommendations and best practices for minimizing and managing the impacts of induced seismicity from oil and gas wastewater disposal wells.[10]

[6] EPA has established regulations for six classes of injection wells, including Class II wells used for the injection of fluids for enhanced oil and gas recovery and wastewater disposal. See section on "EPA Regulation of Underground Injection" for more information.

[7] See, for example, Ellsworth, 2013; McGarr et al., 2015; Rubinstein and Mahani, 2013.

[8] McGarr et al., 2015, p. 830.

[9] See, for example, Rubinstein and Mahani, 2015; Ellsworth, 2013; and Walsh and Zoback, 2015.

[10] U.S. Environmental Protection Agency, *Minimizing and Managing Potential Impacts of Injection-Induced Seismicity from Class II Disposal Wells: Practical Approaches*, Underground Injection Control National Technical Workgroup,

In the 114th Congress, no legislation has been introduced to address induced seismicity associated with oil and gas wastewater disposal or other injection activities. The Fracturing Responsibility and Awareness of Chemicals (FRAC) Act of 2015 was introduced in the House (H.R. 1482) and the Senate (S. 785). Among other things, the bills would amend the SDWA term "underground injection" to include the injection of fluids and proppants used in hydraulic fracturing operations, thus authorizing EPA to regulate this process under the SDWA. It is unclear whether the legislation would affect EPA regulatory authority regarding the potential for induced seismicity from hydraulic fracturing, unless it could be shown that induced seismicity caused by the hydraulic fracturing process posed a threat to underground sources of drinking water. As discussed, the potential for damaging earthquakes caused by hydraulic fracturing appears to be much smaller than deep-well injection of wastewater from oil and gas production activities.

Current Understanding of Induced Seismicity in the United States

Since about the 1920s, it has been known that pumping fluids in and out of Earth's subsurface has the potential to cause earthquakes.[11] In addition, a wide range of other human activities have been known to cause earthquakes, including the filling of large reservoirs, mining, geothermal energy extraction, and others.[12] The mechanics of how human industrial activities may cause earthquakes are fairly well known: The human perturbation changes the amount of stress in Earth's crust, and the forces that prevent faults from slipping become unequal. Once those forces are out of equilibrium, the fault ceases to be locked and the fault slips, sending shock waves out from the fault that potentially reach the surface and are strong enough to be felt or cause damage.

Even knowing that human activities can cause earthquakes, and the mechanics of the process, it is currently nearly impossible to discriminate between man-made earthquakes and those caused by natural tectonic forces through the use of modern seismological methods.[13] Other lines of evidence are required to positively link human activities to earthquakes. That linkage is becoming increasingly well understood in parts of the United States where activities related to oil and gas extraction—deep-well injection of oil and gas wastewater and hydraulic fracturing—have increased significantly in the last few years, particularly in Oklahoma, Texas, Arkansas, Ohio, Colorado, and several other states.[14] Nevertheless, the majority of deep-well injection and hydraulic fracturing activities are not known to cause earthquakes; most are termed "aseismic" (i.e., not causing any appreciable seismic activity, at least for earthquakes greater than M 3.0).[15]

Scientists currently have limited capability to predict human-caused earthquakes for a number of reasons, including uncertainty in knowing the state of stress in the earth, rudimentary knowledge of how injected fluids flow underground after injection, poor knowledge of faults that could potentially slip and cause earthquakes, limited networks of seismometers (instruments used to

November 12, 2014 (released February 6, 2015), http://www.epa.gov/r5water/uic/ntwg/pdfs/induced-seismicity-201502.pdf.

[11] National Research Council (NRC), "Induced Seismicity Potential in Energy Technologies," 2013, p. vii.

[12] Ellsworth, 2013.

[13] Ibid.

[14] According to the NRC report, seismic events likely related to energy development have been documented in Alabama, Arkansas, California, Colorado, Illinois, Louisiana, Mississippi, Nebraska, Nevada, Ohio, Oklahoma, and Texas. NRC, "Induced Seismicity Potential in Energy Technologies," p. 6.

[15] Ibid.

measure seismicity) in regions of the country where most oil-and-gas-related activities are occurring, and difficulty in predicting how large an earthquake will grow once it is triggered.[16]

Despite these uncertainties, a simple conceptual model for understanding how deep-well injection may be triggering earthquakes is starting to evolve, particularly for Oklahoma, which has experienced the greatest change in seismicity since about 2009. In the conceptual model, injecting oil and gas wastewater into the sedimentary formation increases its pore pressure.[17] Over time the increase in pore pressure propagates into pre-existing faults in the crystalline basement rocks underlying the sedimentary formation[18] (see **Figure 2**). Some of the faults in the crystalline basement rocks are "critically stressed," meaning that any change to the pre-existing pressure regime has the potential to initiate "slip" along the fault. Slip along a fault creates an earthquake; the size of the earthquake is generally related to the amount of slip and the length of the fault. Furthermore, studies indicate that even small pressure perturbations have the potential to cause relatively large earthquakes along these critically stressed pre-existing faults in crystalline basement rocks.[19] This may have been the case for the large, M 5.6 and M 5.8 earthquakes in Oklahoma in 2011 and 2016, respectively.[20]

[16] William Leith, Senior Science Advisor for Earthquakes and Geologic Hazards, U.S. Geological Survey, "USGS Research into the Causes & Consequences of Injection-Induced Seismicity," presentation at the U.S. Energy Association, October 30, 2014, http://www.usea.org/sites/default/files/event-/Leith%20induced%20for%20DOE-USEA%20Oct14.pdf.

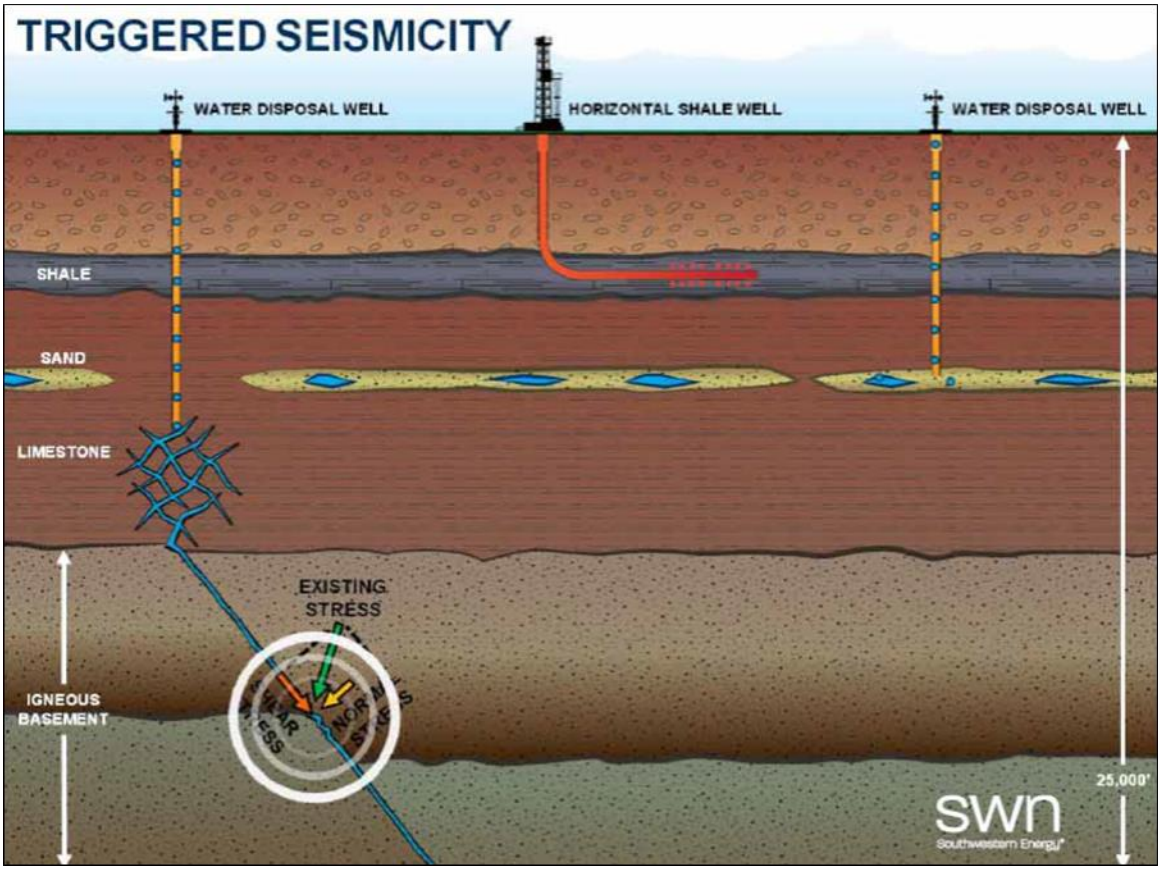
[17] Pore pressure refers to the measure of hydrostatic pressure of the fluid trapped in the pores of a rock. In the case of deep-well injection, the increase in pore pressure caused by the injection of fluids can be transmitted into the basement crystalline rocks if the fluids in pre-existing faults in the basement rocks are hydraulically connected to the sedimentary rocks where the well is located. The injected fluid itself does not necessarily have to travel into the crystalline basement faults to trigger an earthquake; the pressure wave induced by the deep-well injection is potentially sufficient to perturb the stresses on the fault and induce an earthquake.

[18] Simply, crystalline basement rocks refer to older igneous or metamorphic rocks that lie beneath younger sedimentary rocks. Oil and gas wastewaters are typically injected into the overlying sedimentary rocks.

[19] See, for example, Walsh and Zoback, 2015.

[20] Ibid.

Figure 2. Illustration of the Possible Relationship Between Deep-Well Injection and Induced Seismicity



Source: North Carolina General Assembly, presentation by the Arkansas Oil and Gas Commission, *Fayetteville Shale Overview, for the North Carolina Delegation*, slide 33, prepared by Southwestern Energy, November 21, 2013, http://www.ncleg.net/documentsites/committees/BCCI-6576/2013-2014/5%20-%20Feb.%204.%202014/Presentations%20and%20Handouts/Arkansas%20Site%20Visit%20Attachments/Att.%205%20-%20AOGC%20Presentation%2011-21-13%20%283%29.pdf.

Notes: The figure is for illustrative purposes only and does not depict any specific location or geological formation. The term "triggered" in the figure is synonymous with the term induced as used in this report.

A Historical Example: The Rocky Mountain Arsenal

Prior to the M 5.6 earthquake that occurred on November 6, 2011, in central Oklahoma, an M 4.8 earthquake that struck northeast Denver, on August 9, 1967 was generally accepted as the largest recorded human-induced earthquake in the United States. The M 4.8 earthquake was part of a series of earthquakes that began within several months of the 1961 start of deep-well injection of hazardous chemicals produced at the Rocky Mountain Arsenal defense plant. The earthquakes continued after injection ceased in February 1966.[21] The disposal well was drilled through the flat-lying sedimentary rocks into the underlying older crystalline rocks more than 12,000 feet deep, and injection rates varied from 2 million gallons per month to as much as 5.5 million gallons per month.[22] Earthquake activity declined after 1967 but continued for the next two

[21] J. H. Healy et al., "The Denver Earthquakes," *Science*, vol. 161, no. 3848 (September 27, 1968), pp. 1301-1310.

[22] Ibid.

decades. Scientists concluded that the injection triggered the earthquakes. Even after injection ceased, the migration of the underground pressure front continued for years and initiated earthquakes along an ancient fault system many miles away from the injection well.[23] As discussed below, the Rocky Mountain Arsenal earthquakes had many similarities to the recent increased earthquake activity in some deep-well injection activities of the United States, including, for example, injection near or in underlying crystalline bedrock, activation of fault systems miles away from the well, and migration of the pressure front away from the point of injection months or years after injection stopped.

Deep-Well Injection of Oil and Natural Gas Wastewaters

As stated above, the number of earthquakes of M greater than 3.0 in the central and eastern United States has increased dramatically since about 2009 (**Figure 1**). The steep increase in the frequency of M 3.0 or greater earthquakes indicates an increasing likelihood that, in some instances, deep-well injection is linked to earthquakes, some greater than M 5.0. A human-induced M 6.0 or greater earthquake considered to be linked to deep-well injection has not yet been observed, although the September 3, 2016, M 5.8 earthquake northwest of Pawnee, OK, was the largest ever recorded in the state and may be associated with deep-well injection (see text box on p. 11).

Many observers conclude that most wells permitted for deep-well injection are in geologic formations that likely have a low risk of failure that could lead to damaging earthquakes if the injected fluids remain in the intended geologic structure.[24] The largest earthquakes apparently triggered by deep-well injection involved faulting that was deeper than the injection interval, suggesting to some that transmitting pressure from the injection point to deeper zones in basement rocks—below the sedimentary layers—increases the potential for triggering earthquakes.[25]

States experiencing higher levels of seismic activity compared to the pre-2005 average include Arkansas, Colorado, Texas, New Mexico, Ohio, Oklahoma, and Virginia.[26] Seismic activity has also increased in south-central Kansas compared to levels in 2013 and before, where there may be a link to deep-well injection of produced waters from unconventional oil and gas development.[27] For some of these states, there is an increasing realization of a potential linkage between deep-well injection of oil and gas wastewaters and earthquakes, as the number of wells and volume of disposed wastewater have increased concomitant with increased domestic oil and gas production, particularly since about 2008 and 2009.[28] Several instances of suspected human-induced earthquakes that garnered media and national attention include the following:

- October 2008/May 2009: M 2.5-3.3 earthquakes near Dallas-Fort Worth, TX;[29]

[23] Ellsworth, 2013.

[24] Rubinstein and Mahani, 2015.

[25] Walsh and Zoback, 2015.

[26] Ellsworth, 2013.

[27] Rex C. Buchanan et al., Kansas Geological Survey, "Induced Seismicity: The Potential for Triggered Earthquakes in Kansas," Public Information Circular 36, April 10, 2014, http://www.kgs.ku.edu/Publications/PIC/pic36.html.

[28] Rubinstein and Mahani, 2015.

[29] Cliff Frohlich et al., "Dallas-Fort Worth Earthquakes Coincident with Activity Associated with Natural Gas Production," *The Leading Edge*, vol. 29, no. 3 (2010), pp. 270-275.

- August 2010/February 2011: earthquake swarm in central Arkansas, with an M 4.7 earthquake on February 27, 2011, near Greenbrier, AR;[30]
- August 2011: M 5.3 earthquake in the Raton Basin, northern New Mexico/southern Colorado;[31]
- November 2011: M 5.7 earthquake near Prague, OK;[32]
- December 2011: M 3.9 earthquake near Youngstown, OH;[33] and
- September 2016: M 5.8 earthquake near Pawnee, OK.[34]

These examples are summarized below.

Colorado and New Mexico

An investigation of the seismicity in the Raton Basin of northern New Mexico and southern Colorado concluded that increased seismic activity since August 2001 was associated with deep-well injection of wastewater related to the production of natural gas from coal-bed methane fields.[35] The study linked the increased seismicity to two high-volume disposal wells that injected more than seven times as much fluid as the Rocky Mountain Arsenal well in the period leading up to an August 2011 M 5.3 earthquake in the Raton Basin.

Arkansas

A study of a 2010-2011 earthquake swarm in central Arkansas noted that the study area experienced an increase in the number of M 2.5 or greater earthquakes since 2009, when the first of eight deep-well injection disposal wells became operational.[36] The rate of M greater than 2.5 earthquakes increased from 1 in 2007 to 2 in 2008, 10 in 2009, 54 in 2010, and 157 in 2011, including a M 4.7 earthquake on February 27, 2011.[37] Although the area has a history of seismic activity, including earthquake swarms in the early 1980s, the study noted that 98% of the earthquakes during the 2010-2011 swarm occurred within six kilometers of one of the waste disposal wells. In response, the Arkansas Oil and Gas Commission (AOGC) imposed a moratorium on oil and gas wastewater disposal wells in a 1,150-square-mile area of central

[30] U.S. Geological Survey, Earthquake Hazards Program, "Poster of the 2010-2011 Arkansas Earthquake Swarm," http://earthquake.usgs.gov/earthquakes/eqarchives/poster/2011/20110228.php.

[31] J. L. Rubinstein, W. L. Ellsworth, and A. McGarr, "The 2001-Present Triggered Seismicity Sequence in the Raton Basin of Southern Colorado/Northern New Mexico," talk delivered at the Seismological Society of America Annual Meeting, Salt Lake City, UT, April 19, 2013, pp. Abstract #13-206.

[32] Danielle F. Sumy et al., "Observations of Static Coulomb Stress Triggering of the November 2011 M 5.7 Oklahoma Earthquake Sequence," *Journal of Geophysical Research—Solid Earth*, vol. 119, no. 3 (March 2014), http://onlinelibrary.wiley.com/doi/10.1002/2013JB010612/abstract.

[33] Won-Young Kim, "Induced Seismicity Associated with Fluid Injection into a Deep Well in Youngstown, Ohio," *Journal of Geophysical Research—Solid Earth*, vol. 118, no. 7 (July 19, 2013), pp. 3506-3518.

[34] Oklahoma Geological Survey, *Pawnee Earthquake Fact Sheet*, http://www.ou.edu/content/dam/ogs/documents/statements/OGS-Fact_Sheet_Pawnee_Earthquake_2016-09-03.pdf.

[35] Rubinstein, Ellsworth, and McGarr, "The 2001-Present Triggered Seismicity Sequence." ...

[36] S. Horton, "Disposal of Hydrofracking Waste Fluid by Injection into Subsurface Aquifers Triggers Earthquake Swarm in Central Arkansas with Potential for Damaging Earthquake," *Seismological Research Letters*, vol. 83, no. 2 (2012), pp. 250-260.

[37] U.S. Geological Survey, Earthquake Hazards Program, "Poster of the 2010-2011 Arkansas Earthquake Swarm."

Arkansas. Four disposal wells were shut down following injection of wastewater from the Fayetteville Shale.

Texas

A study of increased seismicity near Dallas-Fort Worth and Cleburne, Texas, identified a possible linkage between high injection rates of oilfield-related wastewater and earthquakes of M 1.5 or greater. The study found that all 24 of the most reliably located earthquake epicenters occurred within about 1.5 miles of one or more injection wells.[38] The study examined earthquakes occurring between 2009 and 2011 and noted that it was possible that some of the earthquakes had a natural origin, but that it was implausible that all were naturally occurring. The investigation showed a probable linkage between earthquakes and some high-volume injection wells but also pointed out that in other regions of the study area there exist similar high-volume injection wells but no increased seismic activity. The study hypothesized that injection might trigger earthquakes only if the injected fluids reach suitably oriented nearby faults under regional tectonic stress.

Ohio

A study reported that the Youngstown, Ohio, area, where there were no known past earthquakes, experienced over 100 small earthquakes between January 2011 and February 2012.[39] The largest among the six felt earthquakes was an M 3.9 event that occurred on December 31, 2011. The study concluded that the earthquakes, which occurred within the Precambrian crystalline rocks lying beneath sedimentary rocks, were induced by fluid injection from a deep injection well. The study noted that the level of seismicity dropped after periods when the injection volumes and pressures were at their lowest levels, indicating that the earthquakes may have been caused by pressure buildup and then stopped when the pressure dropped.

Oklahoma

Figure 1 shows that the earthquake rate in the central and eastern United States has increased significantly since 2009; more than 50% of those earthquakes since 2009 have occurred in central Oklahoma.[40] **Figure 3** shows the rate of increase in M 3.0 or greater earthquakes in Oklahoma, in particular the steep increases during 2014 and 2015. As of 2014, the earthquake rate for M 3.0 or greater earthquakes in Oklahoma exceeded the rate for earthquakes of a similar magnitude in California.[41] The rate for M 3.0 earthquakes since 2009 is nearly 300 times higher than for previous decades.[42]

In the past, Oklahoma has experienced earthquakes large enough to be felt at the surface, including two earthquakes in the range of M 5.0 or greater in 1918 and 1952.[43] However, studies indicate that it is highly improbable that the increase in earthquake activity since 2009 is part of a

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[38] Cliff Frohlich, "Two-Year Survey Comparing Earthquake Activity and Injection-Well Locations in the Barnett Shale, Texas," *Proceedings of the National Academy of Sciences*, vol. 109, no. 35 (August 28, 2012), pp. 13934-13938.

[39] Won-Young Kim, "Induced Seismicity Associated with Fluid Injection into a Deep Well in Youngstown, Ohio," *Journal of Geophysical Research—Solid Earth*, vol. 118, no. 7 (July 19, 2013), pp. 3506-3518.

[40] D.E. McNamara et al., "Efforts to Monitor and Characterize the Recent Increasing Seismicity in Central Oklahoma, " *The Leading Edge*, June 2015, pp. 628-639.

[41] Ibid, p. 629.

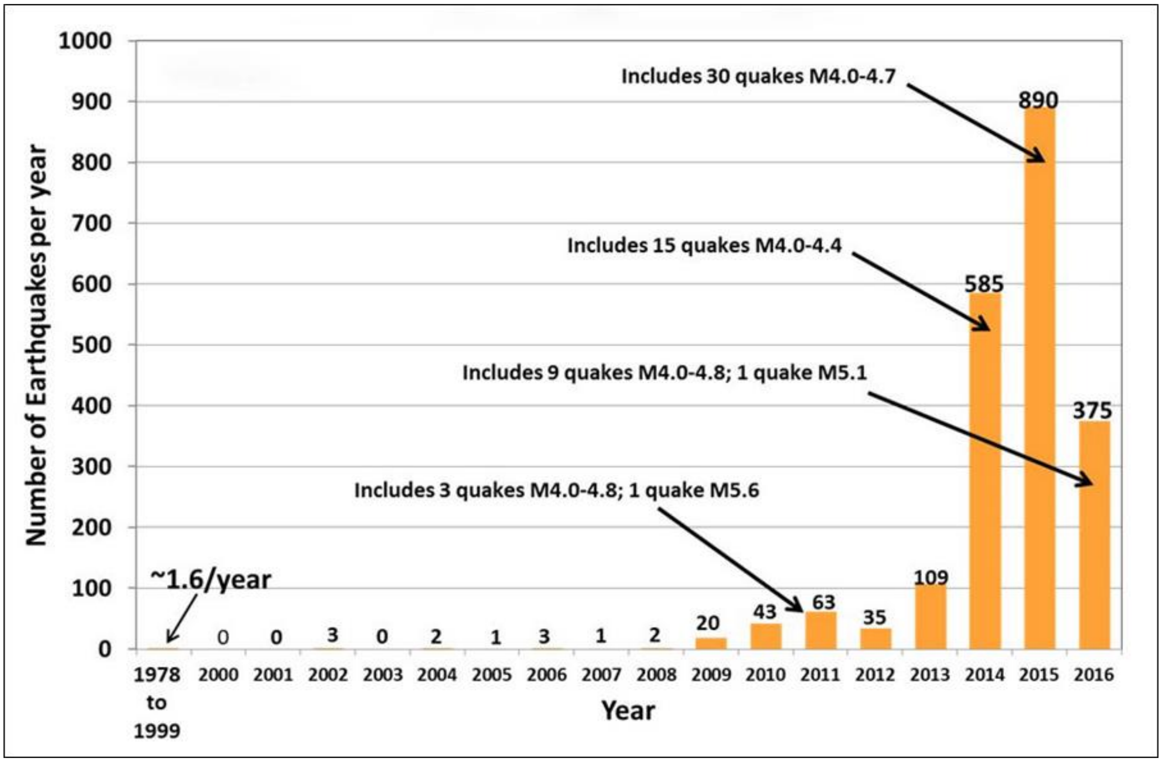
[42] D.E. McNamara et al., "Earthquake Hypocenters and Focal Mechanisms in Central Oklahoma Reveal a Complex System of Reactivated Subsurface Strike-Slip Faulting, " *Geophysical Research Letters*, vol. 42, no. 8 (April 28, 2015).

[43] Ibid.

natural fluctuation in earthquake rates.[44] Studies of the geology of central Oklahoma indicate that the region includes a complex belt of ancient, buried faults that cut through the Arbuckle Formation—the formation into which many of the oil and gas wastewater fluids are injected—and extend deeper into the older crystalline basement rocks.[45] The disposal of wastewaters into the Arbuckle Formation may be reactivating these faults and causing earthquakes.[46]

In addition to the spike of M 3.0 and greater earthquakes in Oklahoma, the state has also experienced its largest earthquakes ever recorded: a M 5.7 event near Prague on November 5, 2011, and a M 5.8 event near Pawnee on September 3, 2016. The combination of increased frequency of felt earthquakes and relatively large magnitude events has focused attention on Oklahoma and the state and federal response to the new hazard (see text box on p. 11).

Figure 3. Oklahoma Earthquakes of M 3.0 or Greater



Source: U.S. Geological Survey, email communication September 7, 2016. Modified by CRS.

Notes: The bar representing 2016 includes earthquakes through June 22, 2016. The M 5.6 event noted for 2011 has been modified to an M 5.7 earthquake by the USGS. The M 5.8 earthquake of September 3, 2016, is not included.

Kansas

According to the Kansas Geological Survey, several earthquakes were recorded in south-central Kansas in 2013 and 2014 in the vicinity of wastewater injection wells.[47] One earthquake in

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[44] Ibid.

[45] Ibid.

[46] Ibid.

[47] Rex C. Buchanan et al., Kansas Geological Survey, "Induced Seismicity: The Potential for Triggered Earthquakes in

Harper County in 2013 had a magnitude of 4.3, and three earthquakes in Sumner County in 2014 had magnitudes over 3.0.[48] Although a definitive connection to wastewater injection had not been established, increasing seismicity in Kansas near areas of wastewater injection led the Kansas governor to convene a task force on induced seismicity in January 2014.The task force resulted in an action plan for dealing with earthquakes possibly induced by deep well injection. For example, in March 2015 the Kansas Corporation Commission required operators to reduce the rate of injection in five areas where wells were disposing fluids into the deep Arbuckle Formation (the same formation that occurs in Oklahoma, discussed above).[49]

Magnitude 5.8 Earthquake Near Pawnee, OK, September 3, 2016

On September 3, 2016, a magnitude 5.8 earthquake occurred about 9 miles northwest of Pawnee, OK, and was felt throughout Oklahoma and many other states. Prior to the September 3 event, the largest earthquake to strike Oklahoma was an M 5.7 temblor on November 5, 2011, about 30 miles east of Oklahoma City near the town of Prague. In response to the September 3 earthquake, the Oklahoma Corporation Commission (OCC)—the state entity responsible for regulating oil and gas activity in Oklahoma—ordered a total of 48 injection wells within the OCC jurisdiction to shut down or reduce injection volumes. In addition, 19 wells in the vicinity of the earthquake were located in the Osage Nation Mineral Reserve, where the U.S. Environmental Protection Agency administers the UIC program: operators of these wells agreed to shut down wells consistent with actions in state jurisdiction. The authority for the OCC actions is discussed more fully below in "State Initiatives".

According to a September 12, 2016 OCC press release announcing the closures, the identification of specific injection wells to shut down or curtail injection volumes resulted from new data resulting from work by the Oklahoma Geological Survey and the U.S. Geological Survey that identified the likely fault systems responsible for the earthquake. The September 12 order amended an order issued by the OCC on the day of the earthquake to shut down and curtail operations of a different set of wells based on a preliminary evaluation of the faults responsible for the September 3 earthquake. (Similarly, EPA contacted operators of 3 additional wells in the Osage Nation Mineral Reserve and requested them to reduce injection volumes; 11 wells were allowed to resume operations at reduced injection levels, and 5 wells remained shut down.)The first order from the OCC was to shut down 37 disposal wells near the epicenter. The orders to immediately shut down or curtail injection wells reflect the OCC's current understanding of the links between injection activities and earthquakes, as manifest in their emergency authorities for issuing mandatory instructions to wells disposing wastewater into the Arbuckle Formation.

As discussed above in "Deep-Well Injection of Oil and Natural Gas Wastewaters", the Arbuckle Formation is of great interest to scientists and regulators because of its proximity to crystalline bedrock and the potential for deep-well injection to possibly reactivate existing faults. The difficulties in assigning a specific well's activities to a specific fault and subsequent earthquake did not preclude the OCC from taking immediate action to shut down or curtail the set of wells that may have a connection to the September 3 earthquake. These recent actions reflect an evolution of understanding of the relationship between deep well injection and earthquakes and the regulatory regime and actions by Oklahoma, and other states, to respond to human-induced earthquakes.

The magnitudes of the September 3, 2016, and the November 5, 2011, earthquakes focuses attention on a scientific and policy challenge: what is the relationship between the sharp increase in frequency of M 3.0 and greater earthquakes in Oklahoma since 2009 and the probability for larger and potentially damaging earthquakes. Despite the rapid uptick in earthquake frequency in Oklahoma (see **Figure 3**), most of the earthquakes have not caused damage. However, both the 2011 and 2016 larger magnitude events damaged buildings and caused injuries. The possibility of perturbing the preexisting faults in the crystalline bedrock below the Arbuckle Formation may be emerging as a mechanism for creating larger earthquakes. Whether the current scientific understanding of the link between deep-well injection and earthquakes in the crystalline basement rocks is sufficient to craft policies that eliminate the chances of large, damaging human-induced earthquakes is not clear.

Kansas," Public Information Circular 36, April 10, 2014, http://www.kgs.ku.edu/Publications/PIC/pic36.html, (revised August 2015).

[48] Ibid.

[49] Ibid.

National Issues—Changes to the U.S. Earthquake Hazard Maps

Until recently, the model for assessing the overall seismic hazard in the United States, which is used to set design provisions in building codes, intentionally excluded the seismic hazard posed by human-induced earthquakes.[50] This was done, in part, because natural seismicity is assumed to be time-independent in assessing the earthquake hazard,[51] and researchers were not sure how to treat potentially induced earthquakes in their seismic hazard analysis. The natural tectonic processes driving the earthquake hazard are assumed to be nearly constant, which is why portions of California and Alaska, parts of the mid-continent, and other areas of the country are shown on the national seismic hazard maps with only small variations from year to year.[52] In contrast, human-induced seismicity varies in time—in this case—because of changes in injection rate, location, volume, depth of the injection, and other factors. Those characteristics mean combining natural seismic hazards with human-induced seismic hazards on one map is difficult.[53]

Despite the difficulty, and because of the sharp uptick in seismic activity in the central and eastern United States since 2009, on March 28, 2016, the USGS released a one-year seismic hazard forecast for 2016 that includes contributions from both induced and natural earthquakes (revised June 16, 2016).[54] (See **Figure 4**.)

[50] A. McGarr et al., "Coping with Earthquakes Induced by Fluid Injection," *Science*, vol. 347, no. 6224 (February 20, 2015), pp. 830-831.

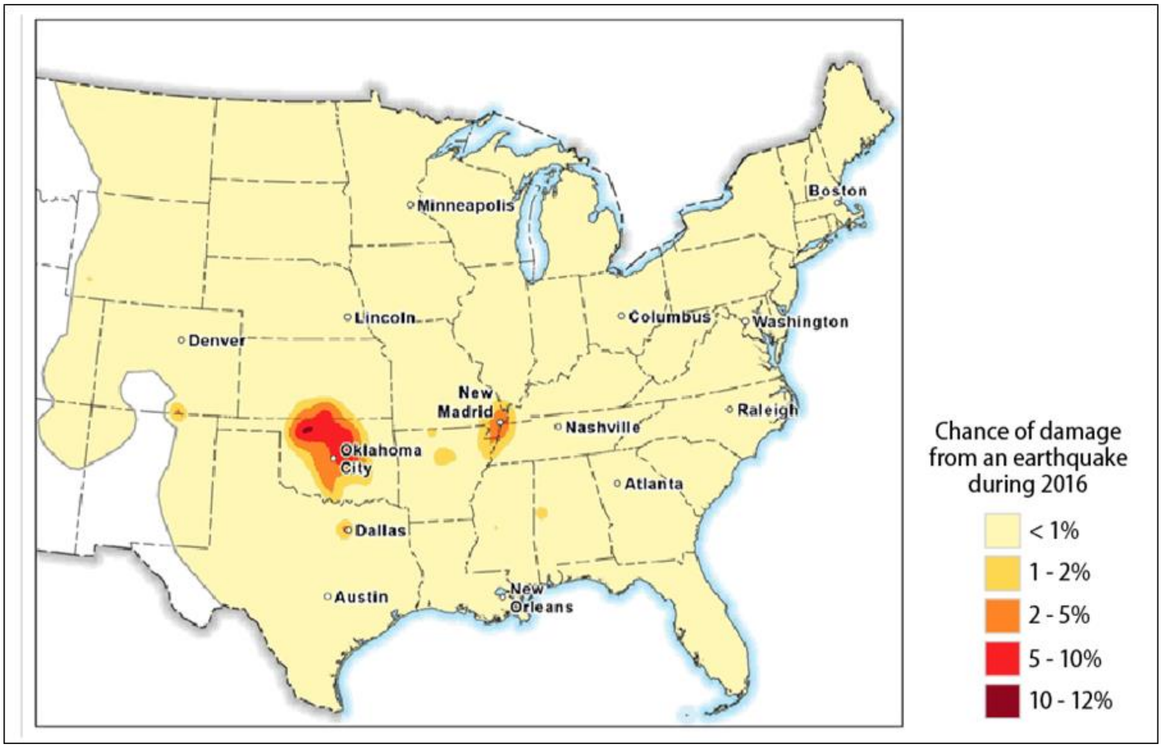
[51] Time-independent in this context means that the tectonic forces that create the earthquake hazard are assumed to be relatively non-changing over a specified time period; in this case, the U.S. Geological Survey designates a 50-year time period. The earthquake hazard caused by deep-well injection can vary on a much shorter time scale, depending on how the wells are operated.

[52] See, for example, the National Seismic Hazard Maps published by the U.S. Geological Survey, http://earthquake.usgs.gov/hazards/products/conterminous/. For more information about earthquakes generally, see CRS Report RL33861, *Earthquakes: Risk, Detection, Warning, and Research*, by Peter Folger.

[53] A. McGarr et al., "Coping with Earthquakes Induced by Fluid Injection."

[54] Mark D. Petersen et al., *2016 One-Year Seismic Hazard Forecast for the Central and Eastern United States From Induced and Natural Earthquakes*, U.S. Geological Survey, Open-File Report 2016-1035, June 17, 2016, https://pubs.er.usgs.gov/publication/ofr20161035.

Figure 4. Chance of Damage from an Earthquake in the Central and Eastern United States in 2016



Source: Mark D. Petersen et al., *2016 One-Year Seismic Hazard Forecast for the Central and Eastern United States From Induced and Natural Earthquakes*, U.S. Geological Survey, Open-File Report 2016-1035, June 17, 2016, https://pubs.er.usgs.gov/publication/ofr20161035, p. 39. Modified by CRS.

Notes: Chance of damage refers to all types of structures, including buildings, bridges, and pipelines.

The map in **Figure 4** shows two main areas of earthquake hazard: the zone near New Madrid, Missouri, and the zone extending around Oklahoma City into south-central Kansas. The New Madrid area represents primarily a zone of natural seismic hazard, whereas the zone in Oklahoma is primarily an area of induced seismicity hazard. The induced seismicity hazard from deep-well injection represents what might be considered a short-term hazard, compared with the perennial seismic hazard from natural tectonic forces, because to some degree the chance of an earthquake caused by deep-well injection depends on the injection activity.[55]

Hydraulic Fracturing

Hydraulic fracturing (often referred to as "fracking") is the process of injecting a slurry of water, chemicals, and sand at high pressure to fracture oil- and gas-bearing rocks in order to provide permeable pathways to extract hydrocarbons.[56] Fracking has been employed with increasing frequency over the past decade or so to produce oil and natural gas from "unconventional" formations (e.g., shale)—those geologic strata that contained hydrocarbons but because of natural

[55] For more information about earthquake risk in the United States generally, see CRS Report RL33861, *Earthquakes: Risk, Detection, Warning, and Research,* by Peter Folger.

[56] This process has also been used for enhanced geothermal energy development, in which rocks are fractured to create permeable pathways to circulate fluids at depth. The fluids are heated by Earth's natural heat and then recirculated to the surface to drive a turbine and generate electricity.

impermeability were not exploitable by conventional oil and gas producing methods. Fracking intentionally propagates fractures in the rocks to improve permeability. Fracking induces microseismicity, mostly less than M 1.0—too small to feel or cause damage. In some cases, fracking has led to earthquakes larger than M 2.0, including at sites in Oklahoma, Ohio, and England. In western Canada earthquakes larger than M 3.0 have been correlated to fracking.[57] Hydraulic fracturing is generally thought to present less of a risk than disposal wells for inducing large earthquakes, because the injections are short-term and add smaller amounts of fluid into the subsurface compared to most disposal wells.

Canada

Between April 2009 and July 2011, and over a five-day period in December 2011, nearly 40 seismic events were recorded in the Horn River Basin, northeast British Columbia, ranging from M 2.2 to M 3.8.[58] A subsequent investigation indicated that the seismic events were linked to fluid injection during hydraulic fracturing activities near pre-existing faults. In contrast to the vast majority of hydraulic fracturing injection activities, which cause earthquakes not felt at the surface (e.g., over 8,000 fracking completions in the Horn River Basin without any associated anomalous seismicity), these anomalous seismic events were felt at the ground surface. A statistical study associated fracking activities at 39 wells in the Western Canadian Sedimentary Basin (WCSB) with seismic events greater than M 3.0, including an earthquake of M 4.6.[59] The study indicated that most of the seismic activity in the WCSB since 1985 seems to be associated with oil and gas activity, although only a small portion of fracking operations appear to be linked to seismic activity (0.3% of wells used for hydraulic fracturing).[60] The study warned that hydraulic fracturing may have induced earthquakes in isolated cases even days after injection activities ceased, suggesting that policies that curtail injection (such as "traffic-light" protocols, discussed below in "State Initiatives") may not have an immediate effect in preventing the occurrence of injection-induced events.[61]

England

In Blackpool, England, hydraulic fracturing injection activities led to a series of small earthquakes ranging up to M 2.3, between March 28, 2011, and May 28, 2011.[62] These seismic events were not large enough to be felt at the surface but were strong enough to deform some of the well casing on the horizontal portion of the production well used for fracking the shale gas-bearing formation.

[57] Gail M. Atkinson et al., "Hydraulic Fracturing and Seismicity in the Western Canada Sedimentary Basin," *Seismological Research Letters*, vol. 87, no. 3 (May/June 2016). Hereinafter Atkinson et al., 2016.

[58] BC Oil and Gas Commission, *Investigation of Observed Seismicity in the Horn River Basin*, August 2012, http://www.bcogc.ca/node/8046/download.

[59] Atkinson et al., 2016. The Western Canadian Sedimentary Basin underlies about 540,000 square miles of western Canada, including portions of Manitoba, Saskatchewan, Alberta, British Columbia, and the Northwest Territories.

[60] Ibid.

[61] Ibid.

[62] Christopher A. Green, Peter Styles, and Brian J. Baptie, *Preese Hall Shale Gas Fracturing Review & Recommendations for Induced Seismic Mitigation*, April 2012, https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/15745/5075-preese-hall-shale-gas-fracturing-review.pdf.

Oklahoma

In south-central Oklahoma, hydraulic fracturing injections between January 16, 2011, and January 22, 2011, induced a series of 116 earthquakes of M 0.6 to M 2.9, according to one study.[63] The study concluded that the lack of similar seismic activity prior to the fracking and after fracking ceased, among other factors, linked the fracking activities to the earthquakes. More recently presented work on the link between hydraulic fracturing and earthquakes in Oklahoma seems to further strengthen the association between fracking and earthquakes that may rarely exceed M 3.0 or even M 4.0 in some cases.[64] The more recent work in Oklahoma also indicated that the vast majority of fracking operations did not create anomalous seismicity.

Ohio

Research on a series of small earthquakes in Harrison County, Ohio that occurred in 2013, indicated that hydraulic fracturing operations affected a previously unmapped fault in the Precambrian crystalline rocks lying below the sedimentary rocks that were being hydraulically fractured.[65] None of the Harrison County earthquakes exceeded magnitude 2.2, but various lines of evidence suggested that the fault responsible for the small earthquake was triggered by hydraulic fracturing operations. Some seismic activity possibly related to fracking in the Marcellus Shale and the underlying Utica Shale led to changes in how Ohio permits wells.[66] The permitting changes include requirements to install seismic monitoring equipment if drilling will take place within three miles of a known fault or in an area with seismic activity greater than M 2.0. Furthermore, if the monitors detect a seismic event greater than M 1.0, activities at the site must cease while the cause is investigated.

Other Hydraulic Fracturing Issues

One of the major shale gas plays in the United States, the Marcellus Shale—which underlies western Pennsylvania and portions of New York, West Virginia, and Ohio—occurs in a region of relatively low levels of natural seismic activity. Despite thousands of hydraulic fracturing operations in the past decade or so, only a handful of M 2.0 or greater earthquakes have been detected within the footprint of the Marcellus Shale, as measured by a regional seismographic network.[67] The earthquake activity recorded in the Youngstown, OH, region was related to deep-well injection of waste fluids from the development of Marcellus Shale gas but was not associated with hydraulic fracturing of Marcellus Shale in Pennsylvania.[68]

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[63] Austin Holland, "Earthquakes Triggered by Hydraulic Fracturing in South-Central Oklahoma," *Bulletin of the Seismological Society of America*, vol. 103, no. 3 (June 2013), pp. 1784-1792.

[64] Austin Holland, "Induced Seismicity 'Unknown Knowns': The Role of Stress and Other Difficult to Measure Parameters of the Subsurface," presentation at the U.S. Energy Association Symposium: Subsurface Technology and Engineering Challenges and R&D Opportunities, Washington, DC, October 30, 2014, http://www.usea.org/event/subsurface-technology-engineering-challenges-and-rd-opportunities-stress-state-and-induced.

[65] Paul A. Friberg, Glenda M. Besana-Ostman, and Ilya Dricker, "Characterization of an Earthquake Sequence Triggered by Hydraulic Fracturing in Harrison County, Ohio," *Seismological Research Letters*, vol. 85, no. 6 (November/December 2014), pp. 1-13.

[66] Ohio Department of Natural Resources, *Ohio Announces Tougher Permit Conditions for Drilling Activities Near Faults and Areas of Seismic Activity*, April 11, 2014, http://ohiodnr.gov/news/post/ohio-announces-tougher-permit-conditions-for-drilling-activities-near-faults-and-areas-of-seismic-activity.

[67] Ellsworth, 2013.

[68] Ibid.

The linkage between hydraulic fracturing itself and the potential for generating earthquakes large enough to be felt at the ground surface is an area of active research. It appears to be the case that hydraulic fracturing operations mostly create microseismic activity—too small to be felt—associated with fracturing the target formation to release trapped natural gas or oil. However, if the hydraulic fracturing fluid injection affects a nearby fault, there exists the potential for larger earthquakes possibly strong enough to be felt at the surface, as was the case in the Horn River Basin of western Canada and other parts of the Western Canadian Sedimentary Basin.

Overview of the Current Regulatory Structure Regarding Induced Seismicity

The National Research Council (NRC) estimates that conventional oil and gas production and hydraulic fracturing combined generate more than 800 billion gallons of fluid each year. More than one-third of this volume is injected for permanent disposal in Class II injection wells.[69] Deep-well injection has long been the environmentally preferred option for managing produced brine and other wastewater associated with oil and gas production. However, the development of unconventional formations using high-volume hydraulic fracturing has contributed significantly to a growing volume of wastewater requiring disposal and has created demand for disposal wells in new locations. Recent incidents of seismicity in the vicinity of disposal wells have drawn renewed attention to laws, regulations, and policies governing wastewater management and have generated various responses at the federal and state levels. This section of the report reviews the current regulatory framework for managing underground injection and identifies several federal and state initiatives in response to concerns surrounding Class II disposal and induced seismicity.

EPA Regulation of Underground Injection

As stated earlier, the principal law authorizing federal regulation of underground injection activities is the Safe Drinking Water Act (SDWA) of 1974, as amended.[70] The law specifically directs EPA to promulgate regulations for state underground injection control (UIC) programs to prevent underground injection that endangers drinking water sources.[71] Historically, EPA has not regulated oil and gas production wells, and as amended in 2005, the SDWA explicitly excludes the regulation of underground injection of fluids or propping agents (other than diesel fuels) associated with hydraulic fracturing operations related to oil, gas, and geothermal production activities.[72]

The SDWA authorizes states and Indian tribes to assume primary enforcement authority (primacy) for the UIC program for any or all classes of injection wells.[73] EPA must delegate this

[69] National Research Council, Committee on Induced Seismicity Potential in Energy Technologies, *Induced Seismicity Potential in Energy Technologies*, National Academy Press, Washington, DC, 2012, p. 110.

[70] The Safe Drinking Water Act of 1974 (P.L. 93-523) authorized the UIC program at EPA. UIC provisions are contained in SDWA Part C, §§1421-1426; 42 U.S.C. §§300h-300h-5.

[71] 42 U.S.C. §300h(d). SDWA §1421.

[72] The Energy Policy Act of 2005 (EPAct 2005; P.L. 109-58, §322) amended the definition of "underground injection," SDWA§1421(d), to expressly exempt hydraulically fractured oil, gas, or geothermal production wells from the UIC program unless diesel fuels are used in the fracturing fluid.

[73] For most SDWA programs, including the UIC provisions, 'state' is defined to include the District of Columbia and territories (SDWA §1401; 42 U.S.C. §§300f(14). Tribes are authorized to receive primacy under SDWA §1451; 42 U.S.C. §300j-11. Navajo Nation and the Assiniboine and Sioux Tribes of the Fort Peck Indian Reservation have

authority, provided that the state or tribal program meets certain statutory and EPA requirements.[74] If a state's UIC program plan is not approved, or if a state chooses not to assume program responsibility, then EPA implements the UIC program in that state. Tribes may also be delegated primacy for the UIC program,

For oil-and-gas-related injection operations (such as produced water disposal through Class II wells), the law allows states to administer the UIC program using state rules rather than meeting EPA regulations, provided a state demonstrates that it has an effective program that prevents underground injection that endangers drinking water sources.[75] Most oil and gas states and some tribes have assumed primacy for Class II wells under this provision.

Under the UIC program, EPA, states, and tribes regulate more than 800,000 injection wells. To implement the UIC program as mandated by the SDWA, EPA has established six classes of underground injection wells based on categories of materials injected by each class. In addition to the similarity of fluids injected, each class shares similar construction, injection depth, design, and operating techniques. The wells within a class are required to meet a set of appropriate performance criteria for protecting underground sources of drinking water (USDWs).[76] **Figure 5** provides an illustration of the six well classes established by EPA to implement the UIC program.

attained primacy for Class II wells.

[74] To receive primacy, a state, territory, or Indian tribe must demonstrate to EPA that its UIC program is at least as stringent as the federal standards. The state, territory, or tribal UIC requirements may be more stringent than the federal requirements. For Class II wells, states or tribes must demonstrate that their programs are effective in preventing endangerment of Underground Sources of Drinking Water.

[75] SDWA Section 1425 requires a state to demonstrate that its UIC program meets the requirements of Section 1421(b)(1)(A) through (D) and represents an effective program (including adequate record keeping and reporting) to prevent underground injection that endangers underground sources of drinking water. To receive approval under Section 1425's optional demonstration provisions, a state program must include permitting, inspection, monitoring, and record-keeping and reporting requirements.

[76] EPA regulations define a USDW to mean an aquifer or part of an aquifer that (a) supplies a public water system, or contains a sufficient quantity of groundwater to supply a public water system and currently supplies drinking water for human consumption, or contains fewer than 10,000 milligrams per liter (mg/L or parts per million) total dissolved solids; and (b) is not an "exempted aquifer." 40 C.F.R. 144.3.

Figure 5. Federally Regulated Underground Injection Wells

Source: U.S. Environmental Protection Agency, Underground Injection Control, Typical Injection Wells. For additional details, see http://water.epa.gov/type/groundwater/uic/wells_drawings.cfm.

Class II includes wells used to inject fluids associated with oil and gas production. Class II wells may be used for three broad purposes: (1) to dispose of brines (salt water) and other fluids associated with oil and gas production; (2) to store liquid hydrocarbons; or (3) to inject fluids to enhance recovery of oil and gas from conventional fields. There are more than 172,000 Class II wells across the United States. Based on historical averages, roughly 80% of the Class II wells are enhanced recovery wells,[77] and 20% are disposal wells (often referred to as Class IId wells).[78]

Table 1 provides descriptions of the injection well classes and subcategories and estimated numbers of wells.

Table 1. UIC Program: Classes of Injection Wells and Nationwide Numbers

Well Class	Purpose and Uses
Class I	Wells inject hazardous wastes, industrial non-hazardous liquids, or municipal wastewater beneath the lowermost underground source of drinking water (USDW). (680 wells, including 117 hazardous waste wells)
Class II	Wells inject brines and other fluids associated with oil and gas production and liquid hydrocarbons for storage. The wells inject fluids beneath the lowermost USDW. (>172,000 wells) Types of Class II wells[a]: • **Enhanced recovery wells:** Separate from, but often surrounded by, production wells, these wells are used to inject produced water (brine), fresh water, steam, polymers, or carbon dioxide (CO_2) into oil-bearing formations to recover additional oil (and sometimes gas) from production wells. These wells may also be used to maintain reservoir pressure. Approximately 80% of Class II wells are ER wells. • **Disposal wells:** Produced water and other fluids associated with oil and gas production (including flowback from hydraulic fracturing operations) are injected into these wells for permanent disposal. Approximately 20% of Class II wells are disposal (Class IId) wells. • **Hydrocarbon storage wells:** More than 100 Class II wells are used to inject liquid hydrocarbons (e.g., petroleum) into underground formations for storage.
Class III	**Class III** wells inject fluids associated with solution mining of minerals (e.g., salt and uranium) beneath the lowermost USDW. (22,131 wells)
Class IV	**Class IV** wells inject hazardous or radioactive wastes into or above USDWs. These wells are banned unless authorized under a federal or state groundwater remediation project. (33 wells)
Class V	**Class V** includes all injection wells not included in Classes I-IV, including experimental wells. Class V wells often inject non-hazardous fluids into or above USDWs, and many are shallow, on-site disposal systems (e.g., cesspools and stormwater drainage wells). Some Class V wells (e.g., geothermal energy and aquifer storage wells) inject below USDWs. (400,000-650,000 wells)
Class VI	**Class VI**, established in 2010, includes wells used for the geologic sequestration of CO_2. (Two permits were approved in 2014.)

Source: U.S. Environmental Protection Agency, *Underground Injection Control Program, Classes of Wells*, and *Class II Wells—Oil and Gas Related Injection Wells (Class II)*, http://water.epa.gov/type/groundwater/uic/wells.cfm, and UIC well surveys.

Notes: Regulations for Class I (hazardous waste) and Class VI (CO_2 sequestration) wells include evaluation of seismic risk among requirements to prevent movement of fluids out of the injection zone to protect USDWs.

a. Additionally, a Class II permit would be required for an oil, gas, or geothermal production well if diesel fuels were to be used in the hydraulic fracturing fluid.

[77] Enhanced recovery wells are separate from, but often surrounded by, production wells, these wells are used to inject produced water (brine), fresh water, steam, polymers, or carbon dioxide (CO_2) into oil-bearing formations to recover additional oil (and sometimes gas) from production wells.

[78] U.S. Environmental Protection Agency, *Class II Wells—Oil and Gas Related Injection Wells (Class II)*, http://water.epa.gov/type/groundwater/uic/class2/index.cfm, May 9, 2012.

Consideration of Seismicity in EPA UIC Regulations

The SDWA does not mention seismicity; rather, the law's UIC provisions authorize EPA to regulate underground injection to prevent endangerment of underground sources of drinking water. However, seismicity has the potential to affect drinking water quality through various means (e.g., by damaging the integrity of a well, or creating new fractures and pathways for fluids to reach groundwater). EPA UIC regulations include various requirements aimed at protecting USDWs by ensuring that injected fluids remain in a permitted injection zone. Some of these measures could also reduce the likelihood of triggering seismic events. For example, injection pressures for Class II (and other) wells may not exceed a pressure that would initiate or propagate fractures in the confining zone adjacent to a USDW.[79] As a secondary benefit, limiting injection pressure can prevent fractures that could act as conduits through which injected fluids could reach an existing fault.

EPA regulations for two categories of injection wells—Class I hazardous waste disposal wells and Class VI wells for geologic sequestration of CO_2—specifically address evaluation of seismicity risks with siting and testing requirements. For Class I wells, EPA regulations include minimum criteria for siting hazardous waste injection wells, requiring that wells must be limited to areas that are geologically suitable. The UIC Director (i.e., the delegated state or EPA) is required to determine geologic suitability based upon an "analysis of the structural and stratigraphic geology, the hydrogeology, and the seismicity of the region."[80] Testing and monitoring requirements for Class I wells state that "the Director may require seismicity monitoring when he has reason to believe that the injection activity may have the capacity to cause seismic disturbances."[81]

For Class VI CO_2 sequestration wells, EPA regulations similarly require evaluation of seismicity risks through siting and testing requirements. In determining whether to grant a permit, the UIC Director must consider various factors, including potential for seismic activity.

> Prior to the issuance of a permit for the construction of a new Class VI well or the conversion of an existing Class I, Class II, or Class V well to a Class VI well, the owner or operator shall submit ... and the Director shall consider ... information on the seismic history including the presence and depth of seismic sources and a determination that the seismicity would not interfere with containment.[82]

EPA regulations for oil and gas wastewater disposal wells (or other Class II wells) do not include these provisions or otherwise address seismicity; however, the regulations give discretion to UIC Directors to include in individual permits additional conditions as needed to protect USDWs (including requirements for construction, corrective action, operation, monitoring, or reporting).[83] Again, for the purpose of protecting drinking water sources, permits for all Class I, II, and III wells must contain specified operating conditions, including "a maximum operating pressure calculated to avoid initiating and/or propagating fractures that would allow fluid movement into a

[79] 40 C.F.R. §146.23(a)(1).

[80] 40 C.F.R. §146.62(b)(1).

[81] 40 C.F.R. §146.68(f).

[82] 40 C.F.R. §146.82(a)(3)(v).

[83] Relevant provisions for Class II wells are published at 40 C.F.R. §144.12(b) and 40 C.F.R. §144.52(a)(9) or (b)(1). See also 40 C.F.R. Part 147.

USDW."[84] Regulations for Class I wells further specify that "injection pressure must be limited such that no fracturing of the injection zone occurs during operation."[85]

Outside of regulations, EPA has recently taken steps to address induced seismicity concerns associated with Class II disposal wells. For example, EPA Region III now evaluates induced seismicity risk factors when considering permit applications for Class II wells. (Region III directly implements the UIC program in Pennsylvania and Virginia.[86]) In responding to public comments on a Class II well permit application in 2013, the regional office noted the following:

> Although EPA must consider appropriate geological data on the injection and confining zone when permitting Class II wells, the SDWA regulations for Class II wells do not require specific consideration of seismicity, unlike the SDWA regulations for Class I wells used for the injection of hazardous waste.... Nevertheless, EPA evaluated factors relevant to seismic activity such as the existence of any known faults and/or fractures and any history of, or potential for, seismic events in the areas of the Injection Well as discussed below and addressed more fully in "Region 3 framework for evaluating seismic potential associated with UIC Class II permits, updated September, 2013."[87]

Federal Initiatives to Address Induced Seismicity

As discussed above, the SDWA does not directly address seismicity; rather, the law authorizes EPA to regulate subsurface injections to prevent endangerment of drinking water sources. In 2011, in response to earthquake events in Arkansas and Texas, EPA asked the Underground Injection Control National Technical Workgroup to "develop technical recommendations to inform and enhance strategies for avoiding significant seismicity events related to Class II disposal wells." The workgroup was specifically asked to address concerns that induced seismicity associated with Class II disposal wells could cause injected fluids to move outside the containment zone and endanger drinking water sources. EPA requested that the report contain the following specific elements:

- Comparison of parameters identified as most applicable to induced seismicity with the technical parameters collected under current regulations.
- Decisionmaking model/conceptual flow chart to:
  - provide strategies for preventing or addressing significant induced seismicity,
  - identify readily available applicable databases or other information,
  - develop site characterization checklist, and
  - explore applicability of pressure transient testing and/or pressure monitoring techniques.
- Summary of lessons learned from case studies.
- Recommended measurement or monitoring techniques for higher risk areas.

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[84] U.S. Environmental Protection Agency, *Technical Program Overview: Underground Injection Control Regulations*, EPA 816-R-02-005, revised July 2001, p. 65, http://water.epa.gov/type/groundwater/uic/upload/2004_5_3_uicv_techguide_uic_tech_overview_uic_regs.pdf.

[85] Ibid., p. 66.

[86] EPA also directly implements the UIC program for other oil and gas producing states, including Kentucky, Michigan, and New York.

[87] U.S. Environmental Protection Agency Region III, *Response to Comments for the Issuance of an Underground Injection Control (UIC) Permit for Windfall Oil and Gas, Inc.*, 2013, pp. 3-9, http://www.epa.gov/reg3wapd/pdf/public_notices/WindfallResponsivenessSummary.pdf.

- Applicability of conclusions to other well classes.
- Defined specific areas of research as needed.[88]

In February 2015, EPA released the National Technical Workgroup's final report, *Minimizing and Managing Potential Impacts of Injection-Induced Seismicity from Class II Disposal Wells: Practical Approaches*, which addressed the above tasks.[89] The report does not constitute formal agency guidance, nor has EPA initiated any rulemaking regarding this matter. Rather, the document includes practical management tools and best practices to "provide the UIC Director with considerations for addressing induced seismicity on a site-specific basis, using Director discretionary authority."[90] (The UIC Director is the state program director where the state has program primacy or EPA in states where EPA implements the program directly.)

Among other findings, the report identifies three key components that must be present for injection-induced seismic activity to occur:

> (1) sufficient pressure buildup from disposal activities; (2) a fault of concern; and (3) a pathway allowing the increased pressure to communicate from the disposal well to the fault.[91]

As discussed, current Class II regulations give discretion to UIC Directors to include in individual permits additional conditions and requirements as needed to protect USDWs.[92] The *Practical Approaches* document notes that, while EPA is unaware of any USDW contamination resulting from seismic events related to induced seismicity, potential USDW risks from seismic events could include

- loss of disposal well mechanical integrity,
- impact to various types of existing wells,
- changes in USDW water level or turbidity, or
- USDW contamination from a direct communication with the fault inducing seismicity or contamination from earthquake-damaged surface sources.[93]

The report includes a decision model to inform regulators on site assessment strategies and recommends monitoring, operational, and management approaches for managing and minimizing suspected injection-induced seismicity. Among the management recommendations, the report suggests that, for wells suspected of causing induced seismicity, managers should take early

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[88] U.S. Environmental Protection Agency, *Minimizing and Managing Potential Impacts of Induced-Seismicity from Class II Disposal Wells: Practical Approaches*, draft report of the Underground Injection Control National Technical Workgroup, November 27, 2012, p. A-1-2.

[89] U.S. Environmental Protection Agency, *Minimizing and Managing Potential Impacts of Injection-Induced Seismicity from Class II Disposal Wells: Practical Approaches*, Underground Injection Control National Technical Workgroup, November 12, 2014 (released February 2015), http://www.epa.gov/r5water/uic/techdocs.htm#ntwg. The report includes case studies of induced seismicity events and responses in four states: Arkansas, Ohio, Texas, and West Virginia.

[90] Ibid., ES-2.

[91] Ibid., p. 27.

[92] Relevant provisions for Class II wells are published at 40 C.F.R. §144.12(b) and 40 C.F.R. §144.52(a)(9) or (b)(1). See also 40 C.F.R. Part 147.

[93] U.S. Environmental Protection Agency, *Minimizing and Managing Potential Impacts of Injection-Induced Seismicity from Class II Disposal Wells: Practical Approaches*, p. 4.

actions (such as requiring more frequent pressure monitoring or reducing injection rates) rather than requiring definitive proof of causality.[94]

The authors also identified research needs to better understand potential for injection-related induced seismicity, including research regarding geologic siting criteria for disposal zones in areas with limited or no data. As a general principal, the workgroup recommended that future research be conducted using a holistic and multidisciplinary approach, combining expertise in petroleum engineering, geology, geophysics, and seismicity.[95]

State Initiatives

Several states and state organizations have been assessing the possible relationship between injection wells and seismic activity.[96] In March 2014, the Interstate Oil and Gas Compact Commission (IOGCC)[97] and the Ground Water Protection Council (GWPC)[98] formed an Induced Seismicity Work Group (ISWG) with state regulatory agencies and geological surveys to "proactively discuss the possible association between recent seismic events occurring in multiple states and injection wells."[99] In September 2015, the workgroup issued a primer on potential injection-induced seismicity to provide "guidance in mitigating seismic risks associated with waste water disposal wells, not hydraulic fracturing."[100]

Additionally, several states have strengthened oversight and added new operational conditions and requirements for Class II disposal wells in response to recent seismic events that appear to be injection related. Policy and regulatory developments adopted or under consideration by several states are outlined briefly below. Typically, these states have expanded their standard permit application packages to include, for example, requirements for additional existing geologic

[94] Ibid., p. 35.

[95] Ibid., pp. 31-32. In another federal initiative, the Department of Energy (DOE) is conducting a research program to promote development of the nation's geothermal resources, including development of enhanced geothermal systems (EGS). The development of EGS can enable previously uneconomical hydrothermal systems to produce geothermal energy on a large scale. However, the process of injecting fluids to enhance permeability of hydrothermal systems may trigger seismic events. In 2012, DOE released an Induced Seismicity Protocol to mitigate risks associated with the development of these systems. Some of the approaches and mitigation measures included in the DOE protocol may be applicable to issues posed by Class II disposal wells. See Emie Majer, James Nelson, and Ann Roberson-Tait et al., *Protocol for Addressing Induced Seismicity Associated with Enhanced Geothermal Systems*, U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, DOE/EE-0662, January 2012, 45 pp., https://www1.eere.energy.gov/geothermal/pdfs/geothermal_seismicity_protocol_012012.pdf.

[96] See, for example, Ground Water Protection Council, *White Paper Summarizing a Special Session on Induced Seismicity*, February 2013, http://www.gwpc.org/sites/default/files/events/white%20paper%20-%20final_0.pdf. See also Association of American State Geologists, "Induced Seismicity," http://www.stategeologist.org.

[97] The Interstate Oil and Gas Compact Commission is a multi-state agency that "serves as the collective voice of member governors on oil and gas issues and advocates states' rights to govern petroleum resources within their borders." The commission works with other stakeholders and is chartered to "efficiently maximize oil and natural gas resources through sound regulatory practices while protecting health, safety and the environment." http://iogcc.publishpath.com/.

[98] The Ground Water Protection Council represents state groundwater protection and underground injection control agencies, http://www.gwpc.org/.

[99] States First Initiative, *States Team Up to Assess Risk of Induced Seismicity*, April 29, 2014, http://www.statesfirstinitiative.org, or http://www.statesfirstinitiative.org/#!States-Team-Up-to-Assess-Risk-of-Induced-Seismicity/c8t8/72D0196F-1DAB-4617-B446-B009A1D902FB.

[100] Ground 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, September 2015, http://www.statesfirstinitiative.org/induced-seismicity-work-group.

information and studies and stricter operating requirements. Also, some states have banned the drilling of injection wells in geologic zones of known seismic risk.

Arkansas

In response to the Guy-Greenbrier earthquake swarm associated with injections of wastewater from shale gas production, the Arkansas Oil and Gas Commission (AOGC) in 2010 imposed a moratorium on new disposal wells in the vicinity of the increased seismic activity and required operators of seven existing wells in the area to report hourly injection rates and pressures bi-weekly through July 2011.[101]

In 2011, the AOGC revised rules governing Class II wells and established a permanent moratorium zone in the area of a major fault system. The state banned new disposal wells and required plugging of four existing wells within the zone.[102] (Operators voluntarily plugged the other three wells of concern.) The rules also require commission approval and a public hearing before any Class II wells within specified distances from the Moratorium Zone Deep Fault or a regional fault can be drilled, deepened, reentered, or recompleted. Class II wells proposed for disposal above or below the Fayetteville Shale formation are subject to new siting and spacing requirements, and permit applicants are required to provide information on the structural geology of an area proposed for a new disposal well. For existing disposal wells, the state required permit holders to install flow meters and submit injection volume and pressure information at least daily.[103] State officials continue to monitor disposal well operations and seismic activity. The state purchased additional seismic monitoring equipment, which supports an "early warning" system for detecting and responding to any emerging seismic activity.[104]

Colorado

The Colorado Oil and Gas Conservation Commission (COGCC) has identified in existing rules and policies various requirements that aim to reduce the likelihood of induced seismicity.[105] These safeguards, which are imposed through the permitting process, include setting limits on injection volume and rate and requiring that the maximum allowable injection pressure is set below the fracturing pressure for the injection zone.[106] In 2011, the COGCC expanded the UIC permit review process specifically to minimize risk of induced seismicity from oil and gas wastewater disposal. The changes followed a significant earthquake near wells injecting wastewater produced from a coalbed methane field. The COGCC now has the Colorado Geological Survey (CGS) review permit applications to evaluate the area for the proposed well site for seismic activity. The CGS reviews state geologic maps, the USGS earthquake database, and area-specific information.

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[101] U.S. Environmental Protection Agency, *Minimizing and Managing Potential Impacts of Injection-Induced Seismicity from Class II Disposal Wells: Practical Approaches*, p. 20.

[102] Specifically, the rules state: "Unless otherwise approved by the Commission after notice and a hearing, no permit to drill, deepen, re-enter, recomplete or operate a Class II Disposal or Class II Commercial Disposal Well may be granted for any Class II or Class II Commercial Disposal wells in any formation within [a prescribed] area ('Moratorium Zone')." AOGC Rule H-1, Section (s)(2).

[103] Arkansas Oil and Gas Commission, General Rule H—Class II Wells, Rule H-1: Class II Disposal and Class II Commercial Disposal Well Permit Application Procedures, Section (s).

[104] U.S. Environmental Protection Agency, *Minimizing and Managing Potential Impacts of Injection-Induced Seismicity from Class II Disposal Wells: Practical Approaches*, p. 20.

[105] The COGCC administers the UIC program in accordance with EPA regulations. 40 C.F.R. §§144-147.

[106] Colorado Oil and Gas Conservation Commission, *COGCC Underground Injection Control and Seismicity in Colorado*, January 19, 2011.

After reviewing the geologic history and maps of the area for faults, the CGS may recommend a more detailed review of subsurface geology or seismic monitoring prior to new drilling. Additionally, the Colorado Division of Water Resources conducts a review of the proposed injection zone. If seismicity is identified in the vicinity of the proposed injection well site, the COGCC requires the operator to define the seismic potential and the proximity to faults using the geological and geophysical data prior to approval.[107]

In 2014, the COGGC worked with the Colorado Geological Survey, USGS researchers, and state universities to establish an induced seismicity advisory group. Issues for consideration by the advisory group included development of a more comprehensive statewide seismicity monitoring network and improved guidance for managing high-volume injection. COGGC has deployed regional seismic monitoring networks and implemented a traffic light system following seismic events in the vicinity of a disposal well.[108]

Kansas

Kansas Governor Sam Brownback convened a State Task Force on Induced Seismicity in response to a significant increase in seismic activity—predominately in three counties—compared to seismic activity in 2013 and years prior. According to the task force report, Kansas has approximately 5,000 disposal wells used to inject waste fluids from oil and gas operations.[109] The action plan called for increased seismic monitoring to improve the state's ability to detect earthquakes greater than magnitude 1.5. The plan also provided a response plan, which would be triggered by earthquakes of magnitude 2.0 or greater. The plan further outlined a set of criteria under which disposal wells located within six miles of an earthquake would be evaluated and a determination made as to whether regulatory remedies under current statutory authorities would be warranted. As recommended, the state has purchased a portable seismic array and established monitor stations.

In 2015, the Kansas Corporation Commission issued an order limiting injection rates for more than 70 wells to monitor the effects of seismic activity. The order limited injection rates for all wells injecting into the Arbuckle Formation in two counties and imposed daily monitoring and monthly reporting requirements for high-volume Arbuckle wells. The order identified five areas of seismic concern based on earthquake clusters that triggered responses under the seismic action plan. Operators of affected wells were required to limit injection volumes at certain times and plug back wells that penetrated the base of the Arbuckle Formation.[110]

Ohio

Following the Youngstown earthquakes in 2011 associated with Class II disposal wells,[111] the Ohio Department of Natural Resources (ODNR) prohibited all drilling into the Precambrian

[107] Ibid.

[108] Ground 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*, September 2015.

[109] Kansas Department of Health and Environment, Kansas Corporation Commission, Kansas Geological Survey, *Kansas Seismic Action Plan*, September 26, 2014, p. 1, http://kcc.ks.gov/induced_seismicity/state_of_kansas_seismic_action_plan_9_26_14_v2_1_21_15.pdf.

[110] Kansas Corporation Commission, Commission Order, Docket No. 15-CONS-770-CMSC (order), http://www.kcc.state.ks.us/induced_seismicity/index.htm.

[111] Ohio Department of Natural Resources, *Preliminary Report on the Northstar Class II Injection Well and the Seismic Events in the Youngstown, Ohio, Area* , March 2012, http://oilandgas.ohiodnr.gov/portals/oilgas/downloads/northstar/

basement rock and added new permit requirements for Class II disposal wells to improve site assessment and collection of more comprehensive information. The rules became effective in October 2012 and are implemented on a well-by-well basis through the permitting process. The supplemental permit application requirements could include pressure fall-off testing, geological evaluation of potential faulting, seismic monitoring program (baseline and active injection), minimum geophysical logging suite, radioactive tracer or spinner survey, and any other tests deemed necessary by the Division of Oil and Gas Resources Management.[112] Before approving a new Class II disposal well, state officials now review existing geologic data for known faulted areas. ODNR will also require companies to run a complete suite of geophysical logs on newly drilled Class II disposal wells. Companies are required to give ODNR a copy of the log suite and may be required to provide analytical interpretation of the logging. For all new Class II permit applications, ODNR requires installation of monitoring technologies, including a continuous pressure monitoring system and an automatic shutoff system.[113] Additionally, the state has purchased portable seismic units and implemented a proactive approach to seismic monitoring around deep Class II wells.[114]

Hydraulic Fracturing

In 2014, ODNR drafted new rules and imposed new drilling requirements for construction of horizontal production wells that would be hydraulically fractured (i.e., shale gas and oil wells) in response to seismic activity the state determined had a "probable connection to hydraulic fracturing near a previously unknown microfault."[115] The rules include standards for design, approval, and construction of horizontal well sites and strengthen drilling permit conditions for wells located near faults or areas linked to previous seismic activity.[116]

New permits for horizontal drilling within 3 miles of a known fault or area of seismic activity greater than a 2.0 magnitude, now include requirements for companies to install seismic monitors. If the monitors detect a seismic event in excess of 1.0 magnitude, the well operator would be required to halt activities while the cause is investigated. If a probable connection to hydraulic fracturing is identified, then the operator would be required to suspend hydraulic fracturing operations.[117]

Oklahoma

Oklahoma has more than 11,600 Class II wells, including 4,626 Class II disposal wells and 7,037 enhanced oil recovery wells. As discussed above, seismicity events have increased markedly in recent years as Class II disposal wells have been used to manage large volumes of produced water

reports/northstar-executive_summary.pdf.

[112] Ohio Department of Natural Resources, Division of Oil and Gas Resources, Underground Injection Control (UIC), http://oilandgas.ohiodnr.gov/industry/underground-injection-control.

[113] Ohio Department of Natural Resources, Class II Disposal Well Reforms/Youngstown Seismic Activity Questions and Answers, https://oilandgas.ohiodnr.gov/portals/oilgas/pdf/YoungstownFAQ.pdf.

[114] U.S. Environmental Protection Agency, *Minimizing and Managing Potential Impacts of Injection-Induced Seismicity from Class II Disposal Wells: Practical Approaches*, pp. 24-25.

[115] Ohio Department of Natural Resources, "Ohio Announces Tougher Permit Conditions for Drilling Activities near Faults and Areas of Seismic Activity," press release, April 11, 2014, http://ohiodnr.gov/news/post/ohio-announces-tougher-permit-conditions-for-drilling-activities-near-faults-and-areas-of-seismic-activity.

[116] Ch. 1501:9-2-02 OAC, http://codes.ohio.gov/oac/1501%3A9-2.

[117] Ohio Department of Natural Resources, Division of Oil and Gas Resources Management, "Shale Well Drilling and Permitting: Seismic Restrictions," http://oilandgas.ohiodnr.gov/shale#SEIS.

from oil and gas production activities. In 2015, the state reported that most of the wastewater disposed of in the state is the naturally occurring saltwater brine that is brought to the surface along with the oil and gas, and a relatively small portion is flowback from hydraulically fractured wells.[118]

In 2013, in response to injection-related induced seismicity concerns, the Oklahoma Corporation Commission (OCC) initiated a "traffic light" permitting system for Class II disposal wells. The system is based on National Academy of Sciences recommendations[119] and has continued to evolve to reflect new information. Under the system, all disposal well permit applications must be reviewed for proximity to faults and seismicity in the area of the proposed well. For applications for new wells, regulators must determine whether a location of a proposed well is within three miles of a stress fault, within six miles of a seismic cluster, or within another "area of interest." If so, the well operator is asked to demonstrate level of risk of induced seismicity and to provide more technical data, and a public hearing must be held on the permit application.[120] In 2015, the OCC greatly expanded "areas of interest" where injection wells are subject to additional requirements to include seismic clusters.

The "yellow light" permitting requirements apply to proposed wells in areas where some seismicity concerns exist but do not meet prescribed "red light" criteria. Among other conditions that may be imposed, "yellow light" permits are granted for only six months, and permit language may be made more stringent at any time. Additionally, operators may be required to monitor for background seismicity and shut down wells every 60 days for bottom hole pressure readings. A shutdown is mandatory in the event of defined seismic activity.[121]

In March 2015, the OCC announced new directives for disposal well operators currently operating in "areas of interest" that inject into the Arbuckle Formation. Under the directives, operators were required to provide to the Oil and Gas Conservation Division (OGCD), by April 18, 2015, information showing that Class II disposal wells in the area of interest were not in contact or communication with the crystalline basement rock. Wells that met the criteria were allowed to resume normal operations. For any wells found to be in contact/communication with basement rock, operators were required to plug back the wells to a shallower depth and meet specified criteria. Operators who did not provide the requested information or did not have an approved plugging schedule were required to reduce injection volumes by 50%.[122] Since April 2015, the OCC has used the traffic light system multiple times to impose restrictions on well operations in prescribed areas following seismic events.

Following the seismic event on September 3, 2016, the OCC used its emergency authorities to issue mandatory instructions for wells injecting into the Arbuckle Formation. The OGCD required operators to shut in (temporarily shut down) all Arbuckle disposal wells within a 725 square-mile area. Wells within five miles of the location of the earthquake were required to shut

[118] Oklahoma Geological Survey, "Statement on Oklahoma Seismicity," summary statement, April 21, 2015, http://earthquakes.ok.gov/wp-content/uploads/2015/04/OGS_Summary_Statement_2015_04_20.pdf.

[119] NRC, "Induced Seismicity Potential in Energy Technologies," ch. 6, "Steps Toward a 'Best Practices' Protocol," pp. 151-164. See also Mark D. Zoback, "Managing the Seismic Risk Posed by Wastewater Disposal," *Earth Magazine,* April 2012, pp. 38-43.

[120] Tim Baker, Director, Oil and Gas Conservation Division, Oklahoma Corporation Commission Town Hall Presentation on Seismicity/Updates to the Traffic Light System, http://earthquakes.ok.gov/wp-content/uploads/2015/04/OGCD_Presentation.pdf.

[121] Office of the Oklahoma Secretary of Energy and Environment, "Oklahoma Corporation Commission," http://earthquakes.ok.gov/what-we-are-doing/oklahoma-corporation-commission/.

[122] Oklahoma Corporation Commission, "Media Advisory—Ongoing OCC Earthquake Response," press release, March 25, 2015, http://www.occeweb.com/. The directives apply to 347 of 900 Arbuckle disposal wells.

in no later than September 10, 2016, and wells located between 5 and 10 miles of the earthquake were required to shut in by September 13, 2016. The 725 square-mile area included 211 square miles of Osage County, a portion of which is part of the Osage Nation Mineral Reserve. EPA implements the UIC program in Osage County, and the agency requested operators to shut in 17 disposal wells. EPA reports that these operators agreed to do so consistent with the state's directives.

On September 12, 2016, OCC expanded the seismicity impact area of concern to 1,116 square miles based on new data. The total number of wells of interest increased to 67, including 48 wells under OCC jurisdiction and 19 under EPA jurisdiction. Of these, 27 in OCC jurisdiction were required to cease operations with the remainder operating at reduced disposal volumes. EPA requested operators at 14 wells to reduce injection volumes by 25% of recent levels. Five wells in the Osage Nation Mineral Reserve remained shut in.

Texas

In November 2014, the Texas Railroad Commission (RRC) published amendments to the state's oil and gas rules to incorporate requirements related to seismic events in connection with wastewater disposal permits, monitoring, and reporting.[123] Several of the new requirements are listed below.[124]

- Applicants for disposal well permits are required to provide information from the USGS regarding the locations of any historical seismic events within 100 square miles of the proposed well site.
- A permit for a Class II disposal well "may be modified, suspended, or terminated if injection is likely to be or determined to be contributing to seismic activity."[125]
- The RRC may require permit applicants to provide additional information (e.g., logs, geologic cross-sections, and pressure front boundary calculations) if the well is to be located in an area where conditions may increase the risk that fluids will not be confined in the injection interval. (Such conditions may include complex geology, proximity of the basement rock to the injection interval, transmissive faults, and/or a history of seismic events using available USGS information.)
- Operators may be required to conduct more frequent monitoring and reporting of disposal well injection pressures and rates if certain conditions are present that could increase the risk that fluids will not be confined to the injection interval.

Although states have taken various actions in response to recent seismic events and wastewater injection, additional regulatory actions could result as experience is accrued from current approaches. Additional developments might also result from the IOGCC and GWPC Induced Seismicity Work Group initiative, as state regulatory agencies and geological surveys continue to evaluate this issue.

[123] *Texas Register*, 39 *TexReg N*8988, November 14, 2014, amending 16 T.A.C. §3.9, §3.46, http://www.sos.state.tx.us/texreg/pdf/backview/1114/1114adop.pdf.

[124] 39 *TexReg* 8996-9005, 16 T.A.C. §3.9.

[125] 16 T.A.C. §3.9(6)(A)(vi).

Conclusion

The scientific understanding of linkages between deep-well injection of waste fluids from oil and gas production, and from hydraulic fracturing operations, is rapidly evolving. This poses a challenge to state and federal policy makers who are tasked with making policy, regulatory, and permitting decisions in a relatively short time frame, concomitant with the evolving scientific study and understanding, and given public concern over the possibility of damaging earthquakes from some of the deep disposal wells. Some states have already implemented changes to their regulatory and permitting requirements, as discussed above. The vast majority of Class II disposal wells (and hydraulic fracturing wells) do not appear to be associated with significant seismic events; however, due to the growing volumes injected by these wells and increased seismicity in some disposal areas, an increasing concern in the United States is that injection of these fluids may be responsible for increasing rates of seismic activity. Additional geologic studies and reviews adopted by some states should address some potential risks; however, it is likely that states and possibly the federal government will continue to explore ways to understand and mitigate against the possibility of damaging earthquakes caused by a small number of wells.

In February 2015, EPA published a report outlining best practices to minimize and manage seismic events associated with oil and gas wastewater injection. The agency has not issued related guidance or initiated any regulatory actions.

Congress may be interested in oversight of EPA's UIC program or, more broadly, in federally sponsored research on the relationship between energy development activities and induced seismicity. Although only a small fraction of the more than 30,000 U.S. wastewater disposal wells appears to be problematic for causing damaging earthquakes, such incidents may raise questions as to whether other energy-related activity—specifically, underground injection for carbon dioxide sequestration—may present similar risks.

Author Contact Information

Peter Folger
Acting Section Research Manager
[redacted]@crs.loc.gov, 7-....

Mary Tiemann
Specialist in Environmental Policy
[redacted]@crs.loc.gov, 7-....