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

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Summary

The development of unconventional oil and natural gas resources using horizontal drilling and hydraulic fracturing (fracking) has created new demand for wastewater disposal wells that inject waste fluids into deep geologic strata. 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 has increased dramatically since about 2009, from an average of approximately 20 per year between 1970 and 2000 to over 100 per year in the period 2010-2013. Some of these earthquakes may be felt at the surface. For example, 20 earthquakes of magnitudes 4.0 to 4.8 have struck central Oklahoma since 2009. The largest earthquake in Oklahoma history (magnitude 5.6) occurred on November 5, 2011, near Prague, causing damage to several structures nearby. Central and northern Oklahoma were seismically active regions before the recent increase in the volume of waste fluid injection through deep wells. However, the recent earthquake swarm does not seem to be due to typical, random, changes in the rate of seismicity, according to the U.S. Geological Survey.

The relationship between earthquake activity and the timing of injection, the amount and rate of fluid injected, and other factors are still uncertain and are current research topics. Despite increasing evidence linking some deep-well disposal activities with 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.

The potential for damaging earthquakes caused by hydraulic fracturing itself, 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, and induces microseismicity, mostly of less than magnitude 1.0, too small to feel or cause damage. In a few cases, however, fracking has led directly to earthquakes larger than magnitude 2.0, including at sites in Oklahoma, Ohio, England, and Canada.

The Environmental Protection Agency's (EPA's) Underground Injection Control (UIC) program under the Safe Drinking Water Act (SDWA) regulates the subsurface injection of fluids to prevent endangerment of drinking water sources. 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. Most oil and gas states administer the UIC Class II program. The SDWA does not address seismicity, although EPA regulations for certain classes of injection wells require some 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. How Congress shapes EPA or other agency efforts to address and possibly mitigate human-caused earthquakes may be an issue in the 114th Congress.

In 2011, in response to seismic events in Arkansas and Texas thought to be associated with wastewater disposal wells, EPA authorized a national UIC technical work group to develop recommendations to address the risk of Class II disposal-induced seismicity. EPA plans to issue a document outlining technical recommendations and best practices in early 2015. At the state level, several states have increased oversight of Class II wells in response to induced seismicity concerns. In 2014, state oil and gas and groundwater protection agencies established a work group to discuss Class II disposal wells and recent seismic events occurring in multiple states.

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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 activities are being injected into the subsurface through deep disposal wells. The immediate concern is that injection of these fluids into underground formations may be responsible for damaging earthquakes in regions that typically do not experience much seismic activity. Induced seismicity has garnered increased attention because of the rapid development of unconventional oil and gas resources, in part due to the use of hydraulic fracturing (often referred to as fracking). It is important to distinguish between seismic activity possibly related to hydraulic fracturing itself and the possibility of human-induced earthquakes 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. **Figure 1** illustrates conceptually the processes of deep-well injection and the linkage to triggering earthquakes.

The principal seismic hazard that has emerged from the increased amount of oil and gas activity in the United States appears to be related to disposal of wastewater using deep-well injection in some regions of the country. For example, in a May 2, 2014, joint statement between the Oklahoma Geological Survey and the U.S. Geological Survey (USGS), researchers reported a 50% increase in the rate of earthquakes in Oklahoma since 2013.[1] A USGS analysis of the rising trend suggested that a likely contributing factor was deep-well injection of oil-and-gas-related wastewater.[2] But the relationship between earthquake activity and the timing of injection, the amount and rate of fluid injected, and other factors are still uncertain and are current research topics. A 2013 article that reviewed the current understanding of human-caused earthquakes noted that, of the more than 30,000 wastewater disposal wells classified by the Environmental Protection Agency (EPA) as Class II,[3] only a small fraction appears to be associated with damaging earthquakes.[4]

The potential for damaging earthquakes caused by hydraulic fracturing itself, as opposed to deep-well injection of wastewater from fracking and other oil and natural gas production, appears to be much smaller. The 2013 review article indicated that the vast majority of wells used for hydraulic fracturing itself cause microearthquakes—the results of fracturing the rock to extract natural

[1] U.S. Geological Survey/Oklahoma Geological Survey joint statement, "Record Number of Oklahoma Tremors Raises Possibility of Damaging Earthquakes," May 2, 2014, http://earthquake.usgs.gov/regional/ceus/products/newsrelease_05022014.php.

[2] Ibid.

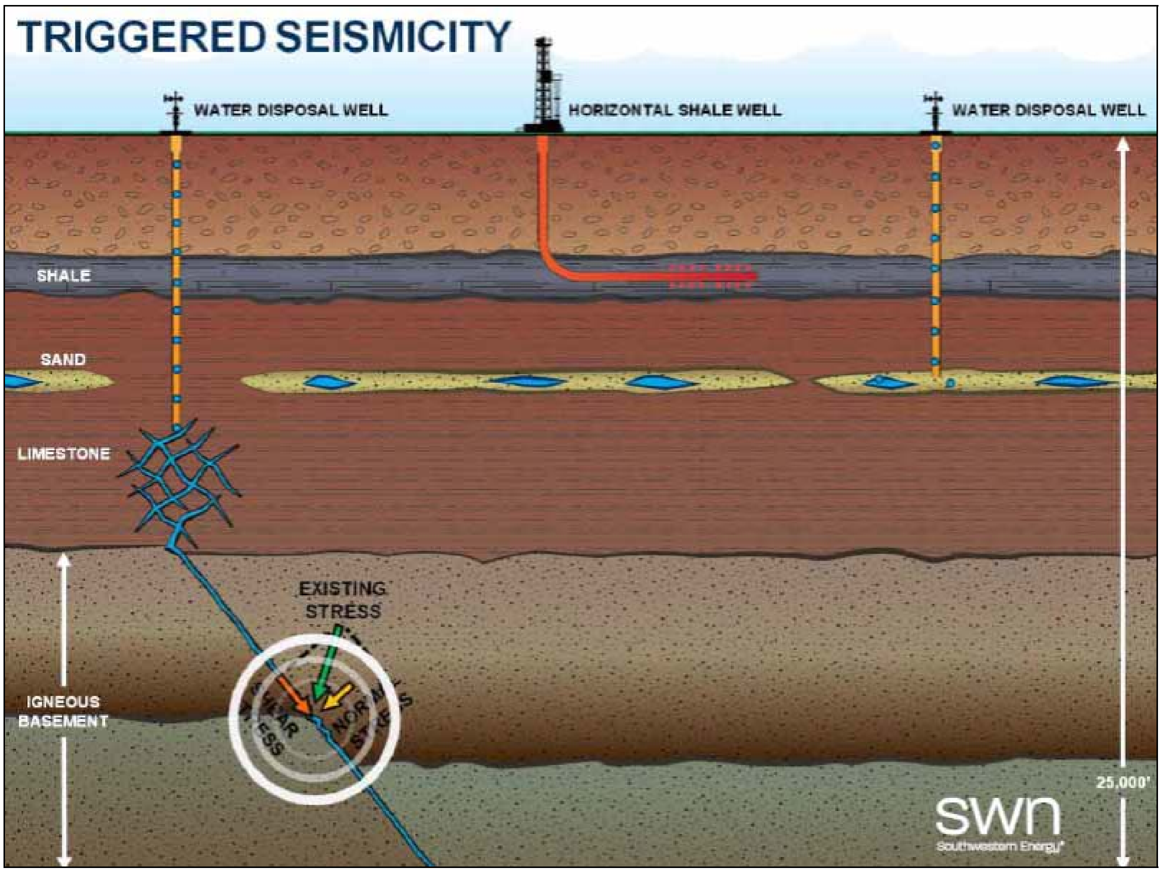
[3] EPA has established regulations for six classes of injection wells, including Class II wells used for the injection of fluids for enhanced oil and gas recovery and wastewater disposal. See section on "EPA Regulation of Underground Injection Activities" for more information.

[4] William L. Ellsworth, "Injection-Induced Earthquakes," *Science*, vol. 341, July 12, 2013, http://www.sciencemag.org/content/341/6142/1225942.full. Hereinafter Ellsworth, 2013.

gas—which are typically too small to be felt or cause damage at the surface. The 2013 review documented a few cases where fracking itself caused detectable earthquakes felt at the surface, but these were too small to cause damage.

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.

Figure 1. 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.

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 implications to 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 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.

Current Scientific Understanding of Induced Seismicity in the United States

Since about the 1920s, it has been known that pumping fluids in and out of the Earth's subsurface has the potential to cause earthquakes.[5] 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.[6] The mechanics of how human industrial activities may cause earthquakes are fairly well known: the human perturbation changes the amount of stress in the 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.[7] 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.[8] Nevertheless, the majority of these 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 magnitude 3).[9] (See text box below for a brief description of earthquake magnitude and intensity.)

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 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.[10]

[5] National Research Council, "Induced Seismicity Potential in Energy Technologies," 2013, p. vii. Hereinafter referred to as NRC, 2013.

[6] Ellsworth, 2013.

[7] Ibid.

[8] According to the National Research Council 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, 2013, p. 6.

[9] Ibid.

[10] William Leith, Senior Science Advisor for Earthquakes and Geologic Hazards, U.S. Geological Survey, "USGS (continued...)

Earthquake Magnitude and Intensity[11]

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, and is 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.[12]

A Historical Example—The Rocky Mountain Arsenal

Prior to the moment magnitude (M) 5.6 earthquake that occurred on November 6, 2011, in central Oklahoma (discussed below), an M 4.8 earthquake that struck northeast Denver on August 9, 1967, was generally accepted as the largest recorded human-induced earthquake. 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.[13] 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.[14] Earthquake activity declined after 1967, but continued for the next two decades. Scientists concluded that the injection triggered the earthquakes, and that 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.[15] 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

The number of earthquakes of M >3.0 in the central and eastern United States has increased dramatically since about 2009, from an average of approximately 20 per year between 1970 and 2000 to over 100 per year in the period 2010-2013.[16] **Figure 2** shows this increase in earthquake

(...continued)

Research into the Causes & Consequences of Injection-Induced Seismicity," presentation at the U.S. Energy Association, Oct. 30, 2014, http://www.usea.org/sites/default/files/event-/Leith%20induced%20for%20DOE-USEA%20Oct14.pdf.

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

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

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

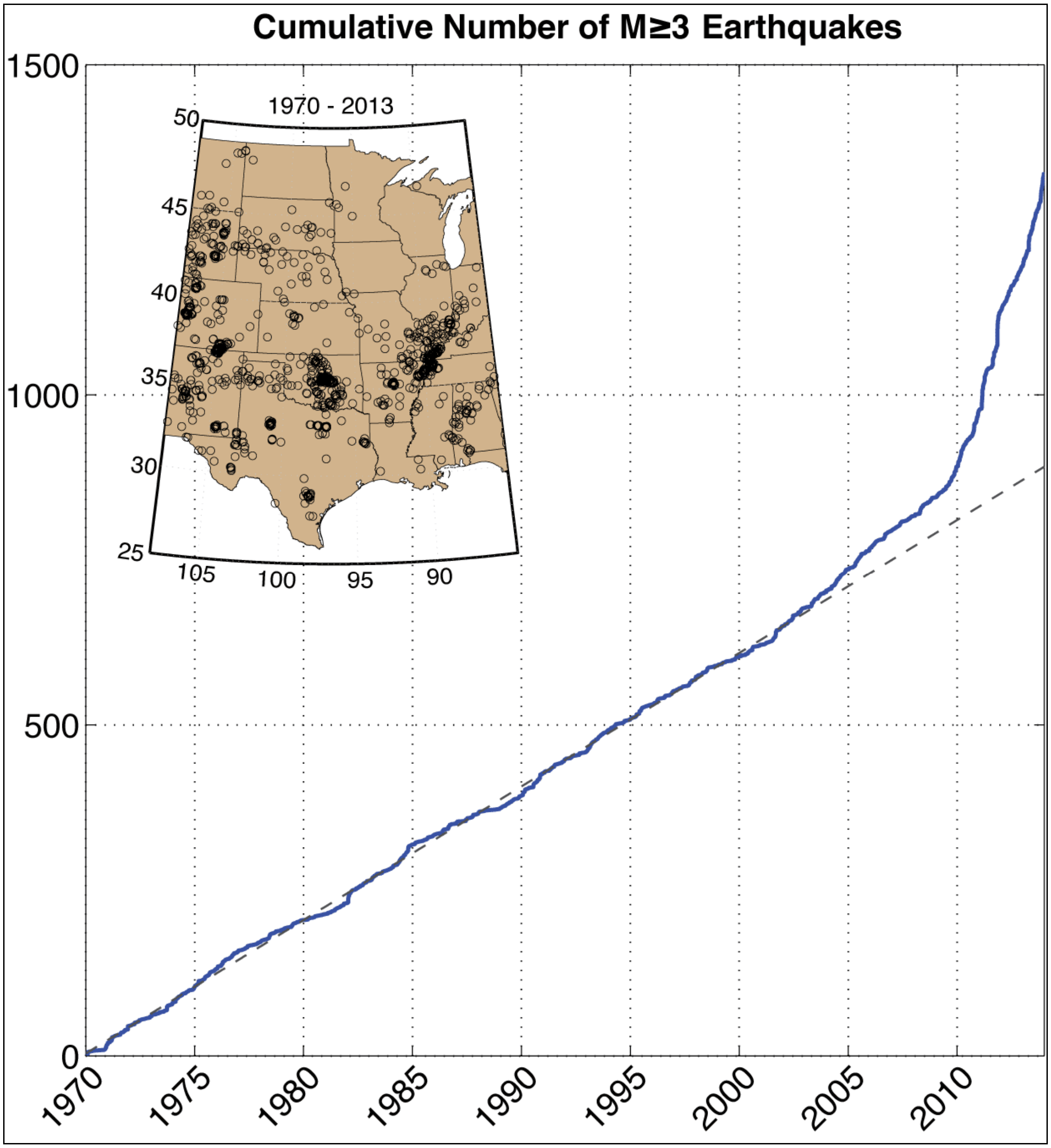
[14] Healy et al., 1968.

[15] Ellsworth, 2013.

[16] U.S. Geological Survey, "Man-Made Earthquakes Update," January 17, 2014, http://www.usgs.gov/blogs/features/usgs_top_story/man-made-earthquakes/.

frequency as a steep increase in slope of the line of cumulative number of earthquakes starting in about 2004 but increasing sharply from about 2009, and departing from the relatively unchanging slope of the average number of earthquakes from 1970 to 2000, depicted as a dashed line.

Figure 2. Cumulative Number of Magnitude 3.0 or Greater Earthquakes in the Central and Eastern United States, 1970-2013



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

Notes: The dashed line corresponds to the long-term rate of about 20 earthquakes of M 3.0 or greater per year. A significant increase in the rate of these >M 3.0 earthquakes started around 2009.

States experiencing higher levels of seismic activity compared to the pre-2005 average include Arkansas, Colorado, Texas, New Mexico, Ohio, Oklahoma, and Virginia.[17] 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.[18] Several instances of suspected human-induced earthquakes that garnered media and national attention include:

- October 2008/May 2009—M 2.5-3.3 earthquakes near Dallas-Fort Worth, Texas;[19]
- August 2010/February 2011—earthquake swarm in central Arkansas, with M 4.7 earthquake on February 27, 2011, near Greenbrier, Arkansas;[20]
- August 2011—M 5.3 earthquake in the Raton Basin, northern New Mexico/southern Colorado;[21]
- December 2011—M 3.9 earthquake near Youngstown, OH;[22] and
- November 2011—M 5.6 earthquake near Prague, OK.[23]

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.[24] 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.

[17] Ellsworth, 2013.

[18] Ibid.

[19] 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.

[20] 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.

[21] 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.

[22] 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.

[23] 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.

[24] Rubinstein et al., 2013.

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.[25] The rate of M >2.5 earthquakes increased from 1 in 2007 to 2 in 2008, 10 in 2009, 54 in 2010, and 157 in 2011, culminating in a M 4.7 earthquake on February 27, 2011.[26] 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 6 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 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, and found that all 24 of the most reliably located earthquake epicenters occurred within about 1.5 miles of one or more injection wells.[27] 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 only trigger earthquakes 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.[28] 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.

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[25] 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.

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

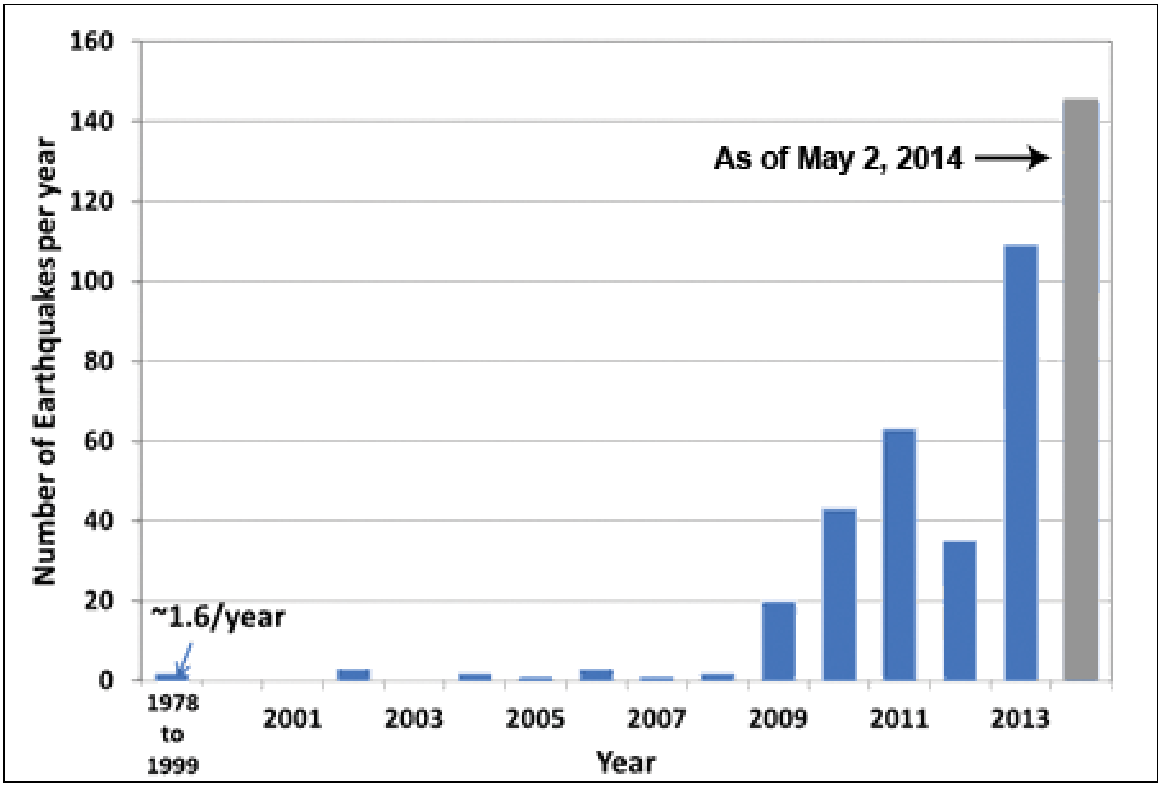
[27] Cliff Frohlich, "Two-Year Survey Comparing Earthquake Activity and Injection-Well Locations in the Barnett Shale, Texas," *Proceedings of the National Academy of Sciences*, vol. 109, no. 35 (August 28, 2012), pp. 13934-13938.

[28] 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.

Oklahoma

According to the U.S. Geological Survey and the Oklahoma Geological Survey, the rate of earthquakes in central Oklahoma increased by 50% between October 2013 and May 2014.[29] The number of M 3.0 or greater earthquakes was 145 in the first four months of 2014, which exceeded the previous record of 109 M 3.0 or greater earthquakes annually set in 2013, and which continues the trend of increasing seismic activity since about 2009 (**Figure 3**).[30]

Figure 3. Oklahoma Earthquakes of M 3.0 or Greater



Source: U.S. Geological Survey, "Record Number of Oklahoma Tremors Raises Possibility of Damaging Earthquakes," Updated USGS-Oklahoma Geological Survey Joint Statement on Oklahoma Earthquakes, May 2, 2014, http://earthquake.usgs.gov/contactus/golden/newsrelease_05022014.php. Modified by CRS.

Notes: Figure shows that 145 earthquakes of M 3.0 or greater occurred between January 1, 2014, and May 2, 2014. From 1978 through 2008, the state averaged about two M 3.0 or greater earthquakes per year.

Since 2009, 20 earthquakes of M 4.0 to M 4.8 have struck central Oklahoma. The largest earthquake in Oklahoma history—M 5.6—occurred on November 5, 2011, near Prague, causing damage to several structures nearby. Central and northern Oklahoma are seismically active regions; however, the recent earthquake swarm does not seem to be due to typical, random changes in the rate of seismicity, according to a USGS statistical analysis.[31] The statistical

[29] U.S. Geological Survey, "Record Number of Oklahoma Tremors Raises Possibility of Damaging Earthquakes," Joint USGS-Oklahoma Geological Survey joint statement, May 2, 2014, http://earthquake.usgs.gov/regional/ceus/products/newsrelease_05022014.php.

[30] Ibid.

[31] Ibid.

analysis suggested that the increased rate of seismicity could be due to deep-well wastewater injection, and that an M 5.0 foreshock that preceded the M 5.6 earthquake on November 5, 2011, may have been induced by deep-well injection.[32] The M 5.0 event could then have triggered the subsequent M 5.6 event less than a day later.

The examples above indicate 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 due to deep-well injection has not been observed, although scientists cannot rule out the possibility that one could occur in the future. However, the great majority of deep injection wells in the United States (UIC Class II) appear to be aseismic for earthquakes of M 3.0 or more.[33] Some observers conclude that most wells permitted for deep-well injection are in geologic formations that likely have a low risk of failure leading to damaging earthquakes, if the injected fluids remain in the intended geologic structure.[34] 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.[35]

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.[36] 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 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, England, and Canada. 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.[37] A subsequent investigation indicated that the seismic events were linked to fluid

[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).

[33] Ellsworth, 2013.

[34] Ibid.

[35] Ellsworth, 2013.

[36] 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 the Earth's natural heat, and then recirculated to the surface to drive a turbine and generate electricity.

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

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.

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.[38] 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.

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.[39] 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.[40] The more recent work in Oklahoma also indicated that the vast majority of fracking operations did not create anomalous seismicity.

Ohio

Recently published research on a series of small earthquakes in Harrison County, Ohio, 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.[41] 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.[42] The permitting changes

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[38] 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.

[39] 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.

[40] 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.

[41] 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.

[42] 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.

include requirements to install seismic monitoring equipment if drilling will take place within 3 miles of a known fault, or in an area with seismic activity greater than M 2.0. Further, if the monitors detect a seismic event greater than M 1.0, activities at the site must cease while the cause is investigated.

Other 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 were detected within the footprint of the Marcellus Shale, as measured by a regional seismographic network.[43] 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.[44]

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.

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.[45] Deep-well injection has long been the environmentally preferred option for managing produced brine and other wastewater associated with oil and gas production poses. However, the development of unconventional formations using high-volume hydraulic fracturing has contributed significantly to a growing volume of wastewater requiring disposal. 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.

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[43] Ellsworth, 2013.

[44] Ibid.

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

EPA Regulation of Underground Injection Activities

The principal law authorizing federal regulation of underground injection activities is the Safe Drinking Water Act (SDWA) of 1974, as amended.[46] The law specifically directs EPA to promulgate regulations for state underground injection control (UIC) programs to prevent underground injection that endangers drinking water sources.[47] 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.[48]

The SDWA authorizes states to assume primary enforcement authority (primacy) for the UIC program for any or all classes of injection wells. EPA must delegate this authority, provided that the state program meets certain statutory and EPA requirements. 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.

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 following EPA regulatory requirements, provided a state demonstrates that it has an effective program that prevents underground injection that endangers drinking water sources.[49] Most oil and gas states 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).[50] **Figure 4** provides an illustration of the six well classes established by EPA to implement the UIC program.

[46] 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.

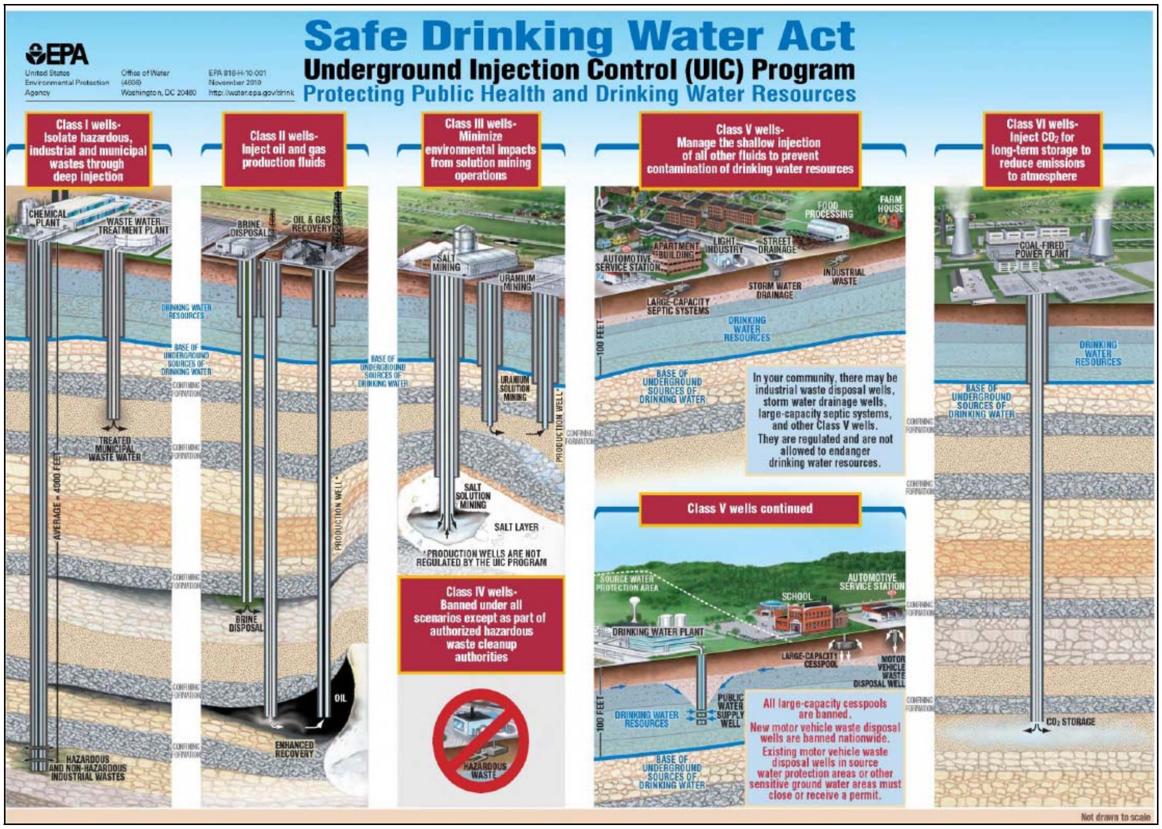
[47] 42 U.S.C. §300h(d). SDWA Section 1421.

[48] 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.

[49] 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.

[50] 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 4. Federally Regulated Underground Injection Wells



Source: U.S. Environmental Protection Agency, Underground Injection Control, Typical Injection Wells.

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 petroleum natural gas; or (3) to inject fluids to enhance recovery of oil and gas from conventional fields. There are roughly 180,500 Class II wells across the United States. Based on historical averages, roughly 80% of the Class II wells are enhanced recovery wells, and 20% are disposal wells (Class IId wells).[51]

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

[51] 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.

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 hydrocarbons for storage. The wells inject fluids beneath the lowermost USDW. (>180,000 wells) Types of Class II wells:[a] • **Enhanced Recovery (ER) 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 also may 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 hydrocarbons (petroleum and natural gas) 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 are typically shallow, on-site disposal systems (e.g., cesspools and stormwater drainage wells). Some deep Class V wells (e.g., geothermal energy and aquifer storage wells) inject below USDWs. (>450,000 wells)
Class VI	**Class VI**, established in 2010, includes wells used for the geologic sequestration of carbon dioxide (CO_2). (2 permits 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. 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.

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 also could 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.[52] 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."[53] 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."[54]

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.[55]

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 requirements as needed to protect underground sources of drinking water.[56] 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 USDW."[57] Regulations for Class I wells further specify that "injection pressure must be limited such that no fracturing of the injection zone occurs during operation."[58]

Outside of regulations, EPA recently has 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

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[52] 40 C.F.R. §146.23(a)(1).

[53] 40 C.F.R. §146.62(b)(1).

[54] 40 C.F.R. §146.68(f).

[55] 40 C.F.R. §146.82(a)(3)(v).

[56] 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).

[57] 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.

[58] Ibid., p. 66.

directly implements the UIC program in Pennsylvania and Virginia.)[59] In responding to public comments on a Class II well permit application, 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."[60]

EPA expects that seismic activity is likely to be induced by Class II well injections only when several conditions are present: "(1) there is a fault in a near-failure state of stress; (2) the fluid injected has a path of communication to the fault: and (3) the pressure exerted by the fluid is high enough and lasts long enough to cause movement along the fault line."[61]

Federal Initiatives to Address Induced Seismicity

As discussed above, the Safe Drinking Water Act 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 specifically was 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 has not initiated any rulemaking to address this issue.)

The UIC workgroup completed a draft report in late 2012.[62] EPA plans to release the final report in early 2015. The final report is expected to include practical tools and best practices to address injection-induced seismicity: it will not constitute formal agency guidance. 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.
- Decision-making model/conceptual flow chart to:
    - provide strategies for preventing or addressing significant induced seismicity,

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

[60] 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.

[61] Ibid., p. 4.

[62] 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.

- identify readily available applicable databases or other information,
- develop site characterization check list, 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.
- Applicability of conclusions to other well classes.
- Define specific areas of research as needed.[63]

The Department of Energy (DOE) conducts 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 uneconomic hydrothermal systems to produce geothermal energy on a large scale. However, the process of injecting fluids to enhance permeability of hydrothermal systems may trigger a seismic event. In 2012, DOE released an Induced Seismicity Protocol to mitigate risks associated with the development of these systems.[64] Some of the approaches and mitigation measures included in the DOE protocol may be applicable to issues posed by Class II disposal wells.

State Initiatives

Several states and state organizations have been assessing the possible relationship between injection wells and seismic activity. In 2013, the Ground Water Protection Council (GWPC)[65] published a white paper on assessing and managing risk of induced seismicity by underground injection.[66] In March 2014, the Interstate Oil and Gas Compact Commission (IOGCC)[67] and the GWPC formed an Induced Seismicity Work Group with state regulatory agencies and geological surveys to "proactively discuss the possible association between recent seismic events occurring in multiple states and injection wells."[68]

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[63] Ibid, p. A-1-2. *Technical Recommendations to Address the Risk of Class II Disposal Induced Seismicity*, Office of Ground Water and Drinking Water, UIC National Technical Workgroup Project Topic #2011-3, July 2011.

[64] 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.

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

[66] 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.

[67] 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/.

[68] States First Initiative, *States Team Up to Assess Risk of Induced Seismicity*, April 29, 2014, http://www.statesfirstinitiative.org.

Additionally, several states have strengthened 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 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 provide bi-hourly injection rates and pressures.[69]

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.[70] 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 to the state information on the structural geology of an area proposed for a new disposal well. For existing disposal wells, permit holders must install flow meters and submit injection volume and pressure information at least daily.[71]

Colorado

The Colorado Oil and Gas Conservation Commission (COGCC) has identified in existing rules and policies various requirements that reduce the likelihood of induced seismicity.[72] 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.[73] In 2011, 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 State Geologist (CGS) review permit

[69] 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. 15.

[70] 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)."

[71] 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).

[72] The Colorado Oil and Gas Conservation Commission (COGCC) administers the UIC program in accordance with EPA regulations. 40 C.F.R. §§144-147.

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

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. 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 Division of Water Resources conducts a review of the proposed injection zone.[74]

In July 2014, the COGGC reported that the commission is working with the Colorado Geological Survey, USGS researchers, and state universities to establish an induced seismicity advisory group. Issues for consideration by the advisory group include development of a more comprehensive statewide seismicity monitoring network and improved guidance for managing high volume injection.

Ohio

Following the Youngstown earthquakes in 2011 associated with Class II disposal wells, the Ohio Department of Natural Resources (ODNR) prohibited all drilling into the Precambrian 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.[75] 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 where required, 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.[76]

In 2014, ODNR drafted new rules for construction of horizontal production wells that are to be hydraulically fractured (i.e., shale oil and gas wells) in response to seismic activity the state determined had a "probable connection to hydraulic fracturing near a previously unknown microfault."[77] The draft rules include standards for design, approval, and construction of horizontal well sites, and would strengthen drilling permit conditions for wells located near faults or areas linked to previous seismic activity.[78]

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[74] Colorado Department of Natural Resources, "COGCC Underground Injection Control and Seismicity in Colorado," Colorado Oil and Gas Conservation Commission, January 19, 2011.

[75] http://www.aipg.org/Seminars/HFMS14/presentations/Dick_Jeffrey.pdf.

[76] https://oilandgas.ohiodnr.gov/portals/oilgas/pdf/YoungstownFAQ.pdf.

[77] 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.

[78] Ohio Department of Natural Resources, Division of Oil and Gas Resources Management, Draft Rules and Review (Ch. 1501:9-2-02 OAC), http://oilandgas.ohiodnr.gov/.

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.[79] Several of the new requirements are listed below.[80]

- 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."[81]
- 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 from the IOGCC and GWPC Induced Seismicity Work Group as state regulatory agencies and geological surveys continue to evaluate this issue.

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 deep-well injection wells and hydraulic fracturing wells do not appear to be associated with significant seismic events. 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

[79] Railroad Commission of Texas, Ch. 3. Oil and Gas Division, 39 *TexRegN*8988, November 14, 2014, Texas Register, amending 16 T.A.C. §3.9, §3.46, http://www.sos.state.tx.us/texreg/pdf/backview/1114/1114adop.pdf.

[80] 39 *TexReg* 8996-9005, 16 T.A.C. §3.9.

[81] 16 T.A.C. §3.9(6)(A)(vi).

continue to explore ways to understand and mitigate against the possibility of damaging earthquakes caused by a small number of wells.

In early 2015, EPA plans to publish a report outlining best practices to address seismic events associated with oil and gas wastewater injection. Congress may be interested in oversight of EPA's UIC program and, more broadly, in federally sponsored research on the relationship between energy development activities and induced seismicity

Only a small fraction of the more than 30,000 U.S. wastewater disposal wells appears to be problematic for causing damaging earthquakes. However, such incidents may raise questions as to whether other energy-related activity—specifically, underground injection for carbon dioxide sequestration—may present similar risks.

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