Earthquakes Induced by Underground Fluid Injection and the Federal Role in Mitigation

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SUMMARY

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Human activities, including underground fluid injection activities, may cause earthquakes (known as *induced earthquakes*). Underground fluid injection activities, such as hydraulic fracturing for oil and gas production, enhanced oil and gas recovery wells, and wastewater disposal wells, have increased in the central and eastern United States since about 2008, in part due to advancements in horizontal drilling. The number of earthquakes of magnitude 3.0 or greater in the same region increased from 2009 to 2015, and these earthquakes are correlated in space and time with injection activities. For example, over 1,000 earthquakes of magnitude 3.0 or greater occurred in the central and eastern United States in 2015 (more than the annual historic rate of magnitude 3.0 or greater earthquakes of less than 25). Disposal wells induced the largest earthquake recorded in Oklahoma, a magnitude 5.8, in 2016, causing property damage and lawsuits.

The U.S. Geological Survey (USGS), state agencies, and universities have increased seismic monitoring and research near underground fluid injection activities since 2008 to understand what causes induced earthquakes and to mitigate the risks of these activities. In general, one or more fluid injections may change the geologic conditions of a fault, causing the fault to slip in an induced earthquake. Current research topics include identifying unstable faults and understanding how injection operations may cause a fault to slip. The USGS released one-year seismic hazard forecasts for the central and eastern United States for 2016, 2017, and 2018, which included naturally occurring and induced earthquakes.

Under the Safe Drinking Water Act (SDWA), the U.S. Environmental Protection Agency (EPA) regulates the underground injection of fluids to protect underground drinking water sources. EPA has issued Underground Injection Control (UIC) regulations for six classes of injection wells. Class II wells, primarily wastewater disposal wells, have caused most of the induced earthquakes in the central and eastern United States. SDWA authorizes states that meet program requirements to administer the federal UIC programs in lieu of EPA, and most oil and gas producing states administer a UIC program for their state. Although 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 developed a framework for evaluating seismic risk when reviewing Class II well permit applications in states where EPA administers the UIC program.

Although a small fraction of underground fluid injection wells, primarily disposal wells, in the central and eastern United States may induce earthquakes, potential seismic risk persists. Federal agencies, state agencies, and other stakeholders continue to study, monitor, regulate, and mitigate this risk. Mitigation may include stopping, pausing, or changing underground fluid injection operations. The study of induced seismicity caused by these fluid injection activities may inform USGS and Department of Energy (DOE) efforts to develop an understanding of how other underground fluid injection activities may induce earthquakes, such as enhanced geothermal energy and geologic carbon sequestration systems.

Congress may consider the adequacy of federally funded research on induced seismicity. Congress also may consider amending the statutory authorities of the UIC program to require consideration of induced seismicity. In addition, Congress may consider whether the federal government should have a role in regulating underground fluid injection activities for induced seismicity and whether current EPA or DOE requirements, reports, or guidance regarding induced seismicity from underground fluid injection activities are sufficient. Some in Congress have expressed interest in changing regulations for hydraulic fracturing for oil and gas production wells through measures introduced in the 117th Congress. Although these measures did not mention induced seismicity, any changes to the regulation of one underground fluid injection activity may affect the regulatory structure for other types of wells and how federal agencies and state agencies deal with the risks of induced seismicity.

Contents

Figures

Tables

Appendixes

Contacts

Introduction

Human activities, such as dam building, mining, and injecting fluids via underground wells, may cause earthquakes (also known as *induced earthquakes* or *induced seismicity*).[1] Underground fluid injection activities that may induce earthquakes include *hydraulic fracturing oil and gas production wells* (HF), *enhanced oil and gas recovery wells*, *wastewater disposal wells*, some *enhanced geothermal energy production wells*, and *geologic sequestration wells* for liquid carbon dioxide storage.[2] HF, recovery, and disposal well activity has increased in the central and eastern United States since 2008 (CEUS, defined as the area on the inset map of **Figure 1**), in part due to advances in horizontal drilling to recover oil and gas from unconventional resources.[3] A small fraction of tens of thousands of HF, recovery, and disposal wells induce tens to hundreds of earthquakes in the CEUS.[4] Wastewater disposal accounts for the majority of induced earthquakes

[1] National Research Council (NRC), *Induced Seismicity Potential in Energy Technologies* (Washington, DC: National Academies Press, 2013), doi:10.17226/13355 (hereinafter NRC, *Induced Seismicity*, 2013).

[2] *Hydraulic fracturing oil and gas production wells* inject fluids via horizontal drilling into producing formations to fracture the rock and release the oil and gas. *Enhanced oil and gas recovery wells* inject fluids into an existing producing formation to flush out the remaining oil or gas. *Wastewater disposal wells* inject oil- and gas-produced wastewaters and *geologic sequestration wells* inject carbon dioxide-captured liquids deep underground for permanent disposal. *Enhanced geothermal wells* inject fluids via horizontal drilling into producing formations to fracture the rock and release heated fluid. *Geologic sequestration wells* inject carbon dioxide-captured liquids into targeted underground formations for permanent storage; geologic sequestration is a strategy to capture carbon dioxide emissions before they can be released into the atmosphere to mitigate the impacts of climate change. EPA, "Protecting Underground Sources of Drinking Water From Underground Injection (UIC)," at https://www.epa.gov/uic for short descriptions of injection well types and USGS, "Energy Resources Program," at https://www.usgs.gov/programs/energy-resources-program for more on hydraulic fracturing, geothermal and geologic carbon sequestration. See also Ground Water Protection Council (GWPC) and Interstate Oil and Gas Compact Commission (IOGC), *Potential Induced Seismicity Guide: A Resource of Technical and Regulatory Considerations Associated with Fluid Injection*, March 2021, at https://www.gwpc.org/sites/gwpc/uploads/documents/publications/.FINAL_Induced_Seismicity_2021_Guide_33021.pdf (hereinafter GWPC/IOGC, *Induced Seismicity Guide*, 2021).

[3] Most oil and gas activities produce wastewaters. In the central and eastern United States (CEUS), wastewater disposal wells inject some of these produced wastewaters underground. An increase in oil and gas activities results in an increase in wastewater disposal activities in some areas. GWPC/IOGC, *Induced Seismicity Guide*, 2021. The number of hydraulic fracturing oil and gas production (HF) wells, particularly in the CEUS, has been increasing since 2007. For example, the Energy Information Administration (EIA) estimates there were fewer than 10,000 HF wells in the United States in 2000 and that the number of HF wells began to increase in 2007, reaching 159,000 HF wells in 2020. EIA, *The Distribution of U.S. Oil and Natural Gas Wells by Production Rate*, January 2022, at https://www.eia.gov/petroleum/wells/pdf/full_report.pdf (hereinafter EIA, *Wells*, 2022), Figure 2. More than 2 billion gallons of fluids are injected into the subsurface in wastewater disposal and enhanced oil and gas recovery wells every day in the United States, according to the EPA. There are about 156,000 Class II wells (most are wastewater disposal and enhanced oil and gas recovery wells) in operation in the United States in 2022 (EPA, "Class II Oil and Gas Related Injection Wells," at https://www.epa.gov/uic/class-ii-oil-and-gas-related-injection-wells). See Table A-1 in the **Appendix** for the number of oil and gas and disposal wells by state. See also CRS Report R46723, *U.S. Energy in the 21st Century: A Primer*, coordinated by Melissa N. Diaz.

An *unconventional resource* (also called *tight* or *continuous-type deposit)* consists of an impermeable shale formation, an organic-rich sedimentary rock that is the source and reservoir for oil and/or natural gas. An impermeable rock formation is composed of fine-grained minerals tightly held together with little to no open pore space between grains. CRS Report R43148, *An Overview of Unconventional Oil and Natural Gas: Resources and Federal Actions*, by Michael Ratner and Mary Tiemann. Most onshore unconventional resources are located in the central and eastern U.S. See USGS, "USGS Domestic Continuous (Unconventional) Oil & Gas Assessments, 2000-Present," at https://certmapper.cr.usgs.gov/data/apps/noga-summary/.

[4] See Table A-1 in the **Appendix** for the number of wells by state. Summary reports and some specific studies that have identified induced earthquakes associated with oil and gas plus wastewater disposal activities and in some cases the pre-existing faults via space and time correlations with these fluid injection activities include GWPC/IOGC, *Induced Seismicity Guide*, 2021; Ryan Schultz et al., "Hydraulic Fracturing-Induced Seismicity," *Reviews of Geophysics*, vol.

in the CEUS since 2009.[5] Some of these induced earthquakes have caused damage and led to lawsuits against well operators, motivating a variety of stakeholders to consider ways to mitigate induced earthquakes.[6]

The number of induced earthquakes in the CEUS since 2009 correlates in space and time with some underground fluid injection activities, such as oil and gas activities and wastewater disposal, and in many cases research has identified a fault prone to slipping that may be the source of these earthquakes near these injection activities (**Figure 1**).[7] The number of magnitude 3.0 or larger (M 3.0+) earthquakes increased every year from 2009 to 2015 and reached a peak of 1,010 events in 2015 compared to an average number of M3.0+ earthquakes in the CEUS of 25 or fewer events per year from 1973 to 2008.[8] Since 2015, the annual number of M 3.0+ earthquakes has declined from this peak, but remains above 25 earthquakes per year. In addition, there has been a small increase in M 3.0+ earthquakes in 2020 and 2021 (**Figure 1**). As the annual number of earthquakes in the CEUS has increased since 2009, so too has the magnitude of some of these events, with more earthquakes greater than M 4.0. Some communities are feeling ground shaking from these events and five earthquakes of M 4.8+ caused property damage in Colorado, Oklahoma, and Texas between 2011 and 2016.

58 (June 2020), e2019RG000695, doi: 10.1029/2019RG000695 (hereinafter Schultz, HF-Induced Seismicity, 2020); and Iason Grigoratos, Alexandros Savviadis, and Ellen Rathje, "Distinguishing the Causal Factors of Induced Seismicity in the Delaware Basin: Hydraulic Fracturing or Wastewater Disposal?," *Seismological Research Letters*, (2022), pp. 1-19, doi: 10.1785/0220210320 (hereinafter, Grigoratos, Causal Factors of Induced Seismicity, 2022).

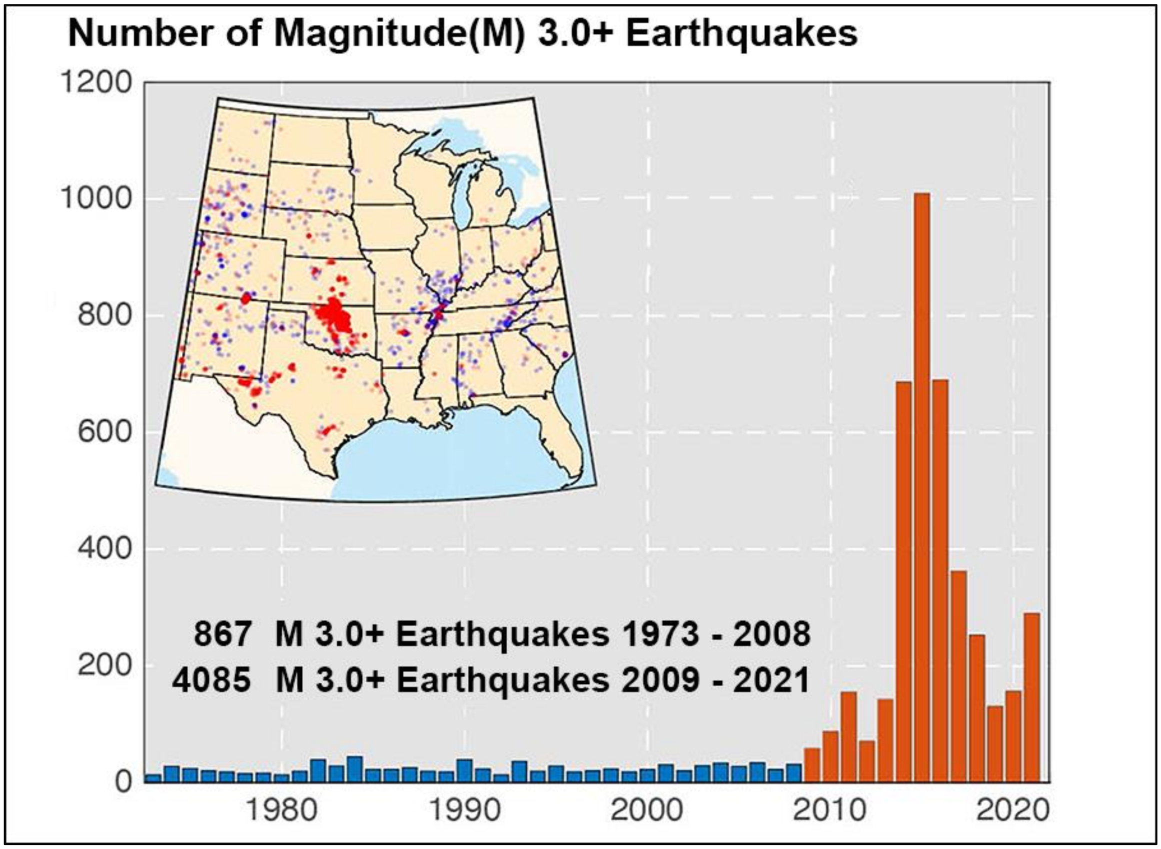
[5] Estimates of the percentage of induced earthquakes caused by wastewater disposal versus enhanced oil and gas recovery and HF wells in the CEUS since 2009 varies depending on the area considered, the range of earthquake magnitudes considered (e.g., magnitude greater than 2.0 or magnitude greater than 3.0), and percentages of different well operations occurring in the area of concern. USGS, "Myths and Misconceptions About Induced Earthquakes," at https://www.usgs.gov/programs/earthquake-hazards/myths-and-misconceptions-about-induced-earthquakes; GWPC/IOGC, *Induced Seismicity Guide*, 2021, p. 11, 20, and 34; Schultz, HF-Induced Seismicity, 2020; and Grigoratos, Causal Factors of Induced Seismicity, 2022.

[6] Stakeholders include federal and state agencies, associations and organizations, earthquake science researchers, and industry involved in underground fluid injection activities. Involvement may include research, monitoring, regulation, guidance, or operation of underground fluid injection activities.

[7] See footnote 4.

[8] USGS, "Induced Earthquakes Overview," at https://www.usgs.gov/programs/earthquake-hazards/science/induced-earthquakes-overview. Magnitude refers to the size of an earthquake and the scale is logarithmic, meaning that a magnitude 5.0 earthquake is 10 times the size (and about 32 times more energy) than a magnitude 4.0 earthquake. USGS, "Earthquake Magnitude, Energy Released, and Shaking Intensity," at https://www.usgs.gov/programs/earthquake-hazards/earthquake-magnitude-energy-release-and-shaking-intensity.

Figure 1. Number of Magnitude 3.0 of Greater Earthquakes in the Central and Eastern United States, 1973-2021



Source: U.S. Geological Survey (USGS), "Induced Earthquakes," at https://www.usgs.gov/programs/earthquake-hazards/induced-earthquakes.

Notes: The inset map defines the area included as the central and eastern United States (CEUS) for the purposes of this report. The USGS notes the rate of M 3.0+ earthquakes per year in this area was 25 or fewer events from 1973 to 2008 (blue bars), and this may be considered the average geologic rate (i.e., the expected average rate of earthquakes in the CEUS related to natural geologic processes based on recorded events). Since 2009, the annual rate of earthquakes in the CEUS has increased to at least 58 events per year from 2009 to 2012 and at least 100 events per year since 2013 (orange bars). The peak annual number in 2015 was 1,010 events. The purple dots on the map (which correspond to blue bars on the graph) are earthquakes of magnitude 3.0 or greater that occurred between 1973 and 2008. The red dots on the map (which correspond to the orange bars on the graph) are earthquakes of M 3.0+ that occurred between 2009 and 2021.

Under the Safe Drinking Water Act (SDWA; 42 U.S.C. §§300f-300j), EPA is authorized to regulate underground injection activities (except for most HF activities) to prevent endangerment of underground sources of drinking water (USDW). EPA has issued Underground Injection Control (UIC) regulations for six classes of wells, including wastewater disposal, enhanced oil and gas recovery, some geothermal energy, and carbon sequestration.

SDWA does not require EPA to address seismicity directly; however, EPA UIC program regulations include seismicity-related siting and testing requirements for hazardous waste and carbon dioxide sequestration injection wells.[9] Such requirements are not included in regulations

[9] See EPA, "Underground Injection Control Regulations," at https://www.epa.gov/uic/underground-injection-control-regulations.

governing oil and gas wastewater disposal wells, although regulators (either EPA or a state) have discretionary authority to add conditions to individual permits. In 2015, EPA published technical recommendations and best practices for minimizing and managing the impacts of induced seismicity from oil and gas wastewater disposal wells.[10]

The USGS, universities, and state agencies have conducted seismic monitoring and research to identify the causes and assess the risks of induced seismicity in the CEUS. These studies, in addition to EPA guidance and state mitigation measures, may have contributed to decreasing the annual number of earthquakes in the CEUS since the peak in 2015.[11] Even so, the annual number of induced earthquakes (M 3.0+) in the CEUS remains high (e.g., eight times higher in 2021 than the historic annual rate before 2009) and more research and mitigation may help to reduce earthquake risks.

Understanding induced earthquakes caused by underground fluid injection in the CEUS may help the U.S. Geological Survey (USGS), the Department of Energy (DOE), and other stakeholders understand fault mechanisms and the potential for induced earthquakes caused by similar underground fluid injection processes used for geothermal energy production or geologic carbon sequestration.[12] Some in Congress are interested in increasing these activities for energy production and for reducing the amount of carbon dioxide in the atmosphere.

In the 117th Congress, there was support for more research on induced seismicity to understand the causes and reduce the risks. The House Committee on Appropriations, for example, in its report accompanying the FY2023 Department of the Interior, Environment, and Related Agencies appropriations bill, called for $3.1 million for the USGS Earthquake Hazards Program for induced seismicity.[13] Other measures introduced in the 117th Congress would have changed the federal role in the regulation of some underground fluid injection activities. Congress may consider whether the federal government should play any role in regulating induced seismicity from underground fluid injection activities.

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[10] EPA, *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 6, 2015), at https://www.epa.gov/sites/default/files/2015-08/documents/induced-seismicity-201502.pdf (hereinafter EPA, *Minimizing and Managing*).

[11] Oklahoma Corporation Commission, *Annual Report Fiscal Year 2018*, 2018, pp. P. 48-49, https://oklahoma.gov/content/dam/ok/en/occ/documents/ajls/about/Annual_Report-FY18.pdf, Oklahoma Corporation Commission, "Response to Oklahoma Earthquakes," at https://oklahoma.gov/occ/divisions/oil-gas/induced-seismicity-and-uic-department/response-oklahoma-earthquakes.html, and GWPC/IOGC, *Induced Seismicity Guide*, 2021.

[12] CRS Report R44902, *Carbon Capture and Sequestration (CCS) in the United States*, by Angela C. Jones and Ashley J. Lawson.

[13] U.S. Congress, House Committee on Appropriations, *Department of the Interior, Environment, and Related Agencies Appropriations Bill, 2023*, report with minority views to accompany H.R. 8262, 117th Cong., 1st sess., H.Rept. 117-400, July 1, 2022, p. 43, at https://www.congress.gov/117/crpt/hrpt400/CRPT-117hrpt400.pdf#page=47. Note the committee-recommended amount of $3.1 million for induced seismicity research for the Earthquake Hazards Program is the same as requested in the President's FY2023 budget request. This amount does not include an additional $3.5 million requested in the President's FY2022 budget request, for a joint investigation by USGS Energy Resources Program and the Earthquake Hazards Program. The investigation would identify the potential for induced seismicity in underground areas that may be used for carbon sequestration; USGS, *Budget Justifications and Performance Information Fiscal Year 2023*, pp. 59, 72, at https://d9-wret.s3.us-west-2.amazonaws.com/assets/palladium/production/s3fs-public/media/files/FY23-USGS-Greenbook.pdf.

Understanding, Monitoring, and Assessing the Risk of Induced Seismicity

Scientists and others have known, since the 1920s, that pumping fluids in and out of Earth's subsurface has the potential to cause earthquakes.[14] Some wells pump fluids into a target rock formation in the subsurface to permanently contain waste products deep underground, such as wastewater disposal wells and carbon sequestration wells (see text box titled "A Historical Example: The Rocky Mountain Arsenal"). Other wells pump fluids into a target rock formation in the subsurface to extract oil and gas (e.g., enhanced oil and gas recovery wells or HF wells) or to extract energy as heat (e.g., enhanced geothermal wells).[15] The underground fluid injection may change the amount of local stress in Earth's crust, and the forces that prevent faults from slipping may become unequal. Once those forces are out of equilibrium, the fault may become unstable and may slip. The sudden movement on the fault leads to an earthquake, which releases energy and sends seismic waves out from the fault; these waves may reach the surface with enough energy to cause shaking at the surface and the shaking may cause damage.

A Historical Example: The Rocky Mountain Arsenal

A magnitude 4.8 (M 4.8) earthquake that struck northeast Denver, CO, on August 9, 1967, was the largest recorded human-induced earthquake caused by fluid injection in the United States before 2011. 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. A disposal well, drilled through the flat-lying sedimentary rocks into the underlying older crystalline rocks more than 12,000 feet deep, injected as much as 5.5 million gallons per month. Earthquake activity declined after 1967 but continued for the next two decades. Scientists concluded the injection caused 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.

The Rocky Mountain Arsenal earthquakes have similarities to the increased earthquake activity after 2008 related to underground injection activities in the central and eastern United States. These similarities include, 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.

Sources: J. H. Healy et al., "The Denver Earthquakes," *Science*, vol. 161, no. 3848 (September 27, 1968), pp. 1301-1310; and William L. Ellsworth, "Injection-Induced Earthquakes," *Science*, vol. 341 (July 12, 2013), doi: 10.1126/science.1225942, at https://www.sciencemag.org/content/341/6142/1225942.full.

Horizontal (or directional) drilling techniques combined with HF helped spur an increase in oil and gas activities in the CEUS since about 2008,[16] where most of these economically viable unconventional resources are concentrated.[17] HF accounts for most of the onshore oil and gas production in the United States in 2021.[18] HF typically targets an impermeable shale formation

[14] NRC, *Induced Seismicity*, 2013, p. vii.

[15] An enhanced geothermal system consists of a well that pumps water into a formation, fracturing the rock and creating a hot water-rock reservoir. Another well pumps the heated water back to the surface through a different well to drive a steam turbine and generate electricity. NRC, *Induced Seismicity*, 2013.

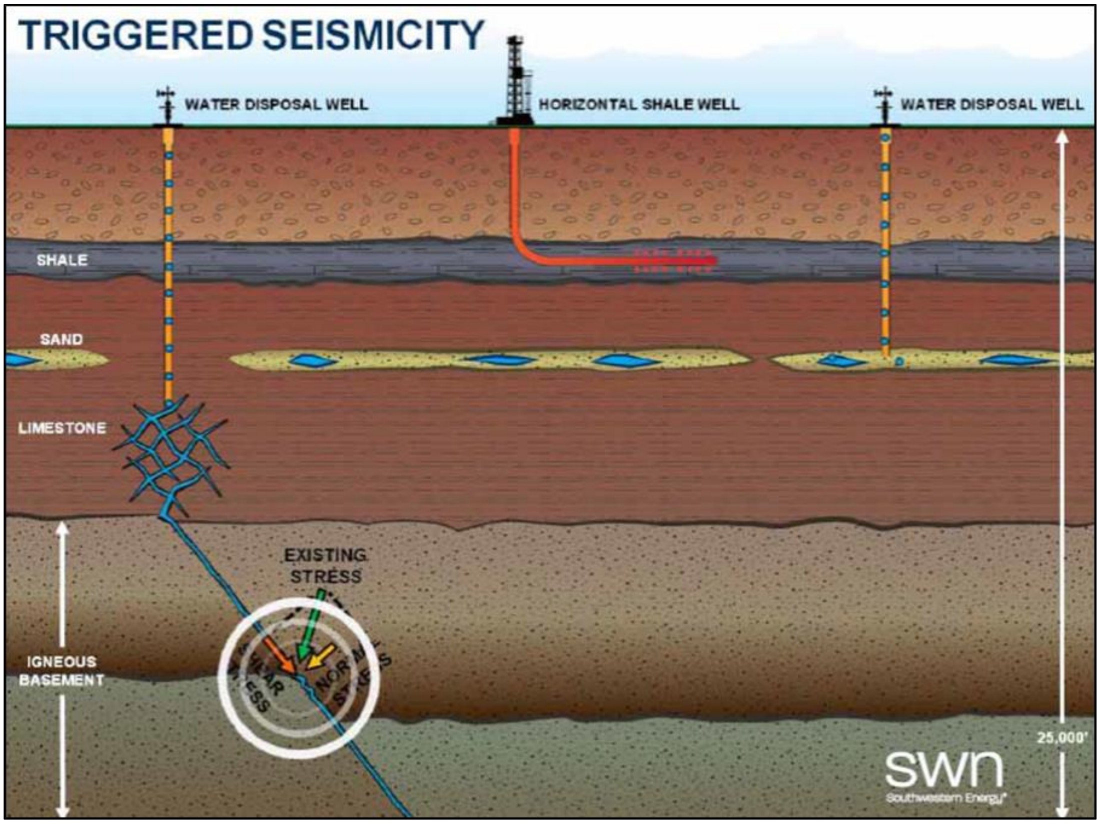
[16] EIA, *Wells*, 2022; and U.S. Energy Information Administration, *Drilling Productivity Report Supplement, Gas-to-Oil Ratios in the U.S. Primary Oil-Producing Regions*, September 2021.

[17] USGS, "USGS Domestic Continuous (Unconventional) Oil & Gas Assessments, 2000-Present," at https://certmapper.cr.usgs.gov/data/apps/noga-summary/ and **Table A-1** of oil and gas wells by state in the **Appendix**.

[18] CRS Report R46723, *U.S. Energy in the 21st Century: A Primer*, coordinated by Melissa N. Diaz; EIA, *Wells*, 2022; and EIA, "Hydraulic Fracturing Accounts for About Half of Current U.S. Crude Oil Production," at

that contains oil or gas trapped in the rock (i.e., an unconventional resource); and works by horizontal drilling into the formation (**Figure 2**).[19] Fluids injected under high pressure into a shale formation fracture the rock and enhance release of the oil and/or gas for extraction from a well.[20] The fracturing of the rock during the HF process induces micro-earthquakes of M < 1.0 that do not cause any human-felt shaking at the surface. In rare cases, where HF operations inject fluid close to a preexisting fault (e.g., a fault in the deeper crystalline basement rocks below the shale formation), the fluid may activate the fault and induce an earthquake of higher magnitude (e.g., M 3.0+) that may be felt at the surface, and if strong enough may actually cause damage.[21]

Figure 2. Illustration of the Possible Relationship Between Underground 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, at 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.

https://www.eia.gov/todayinenergy/detail.php?id=25372.

[19] See footnote 3.

[20] Enhanced geothermal energy systems use the same process as HF oil and gas production. An enhanced geothermal system works by horizontal drilling into a target formation and fracturing the rock to create permeable pathways to circulate fluids (primarily water) at depth. Earth's natural heat at depth increases the water temperature and a different well pumps the heated water to the surface to drive a turbine and generate electricity. Other geothermal systems use different techniques to generate energy and may induce earthquakes. NRC, *Induced Seismicity*, 2013.

[21] Schultz, HF-Induced Seismicity, 2020 and GWPC/IOGC, *Induced Seismicity Guide*, 2021.

Notes: The figure is for illustrative purposes only and does not depict any specific location or geological formation, which may be more complex than shown. The term *triggered* in the figure is synonymous with the term *induced* as used in this report. Likewise, *horizontal shale well* is synonymous with *hydraulic fracturing*, an unconventional oil and gas production technique, and *water disposal* is synonymous with *wastewater disposal of waste products* from oil and gas activities. Shale, sand (or sandstone), and limestone are sedimentary rocks formed from different sediments. *Shale*, formed from muds or clays on lakebeds or seabeds, may contain organic matter and oil or gas. *Igneous rocks*, such as granite, formed from magma and are sometimes called *crystalline rocks* because you can see crystals in the rock without a microscope.

HF and other oil and gas activities produce a large amount of wastewater (i.e., about 10 barrels of wastewater for every barrel of product).[22] Disposal wells inject wastewater into a sedimentary formation (typically sandstone or limestone) below shallower underground water resources. Disposal wells typically inject larger volumes of fluids for longer periods (months to years) than HF wells, so disposal wells may be more likely than HF wells to induce seismicity.[23]

Fluid injection from a disposal well may induce an earthquake on a preexisting fault. After fluid injection into a sedimentary layer (i.e., a target rock formation), the increase in pore pressure in the sedimentary layer could propagate into preexisting fault(s), most commonly located in the crystalline basement rocks underlying the sedimentary formation (**Figure** 2).[24] Slip along a fault creates an earthquake; the magnitude of the earthquake depends on the amount of slip on the fault and other factors.

Not all induced earthquakes stem from faults in the crystalline basement rocks. Some studies have identified induced earthquakes on shallower unstable faults at or above the fluid injection depth. Also, induced earthquakes may occur months or years after fluid injection (similar to the induced earthquakes that occurred years after injection at the Rocky Mountain Arsenal, see text box titled "A Historical Example: The Rocky Mountain Arsenal").[25] Induced earthquakes which occur near the Earth's surface may transfer more of their energy into ground shaking at the surface than earthquakes originating at greater depths.[26] For this reason, an M 3.0 earthquake near

[22] GWPC/IOGC, *Induced Seismicity Guide*, 2021, p. 81. The 10 barrels of wastewater for every barrel of product is an estimate and GWPC calls it a national average. EPA has noted that the amount of wastewater produced varies from 1 barrel of wastewater for 1 barrel of product to 100 barrels of wastewater for 1 barrel of product, depending on the oil and gas activities and depending on the product. Other sources, such as the Texas Alliance of Energy Producers, provide estimates of produced wastewaters for the entire state in a given year (e.g., in 2017, oil and gas activities in Texas produced more than 357 billion gallons of wastewater). EPA, *Summary of Input on Oil and Gas Extraction Wastewater Management Practices Under the Clean Water Act*, EPA-821-S19-001, May 2020, pp. 5, 7, at https://www.epa.gov/sites/default/files/2020-05/documents/oil-gas-final-report-2020.pdf. The definition of a barrel is variable and may depend on what product or waste product is in the barrel. In this report, a barrel is about 42 U.S. gallons by volume. The 42 US-gallon oil barrel is a unit of measurement of volume and no longer a physical container for holding oil. The steel drum physical containers used to hold oil in the U.S. are 55 U.S. gallons by volume. The American Petroleum Institute defines a standard barrel of oil as the amount of oil that would occupy a 42 U.S. gallon volume at a specific pressure and temperature (i.e., a unit of measurement of specific volume). All other countries use the metric system and different specific pressure and temperature for specific volume measurements. Given these differences, financial institutions and regulators may establish a standard conversion factor for converting between different units and may require a specific percentage of uncertainty in volume calculations (e.g., the measurement can only be 0.25% uncertain).

[23] GWPC/IOGC, *Induced Seismicity Guide*, 2021 and USGS, "Induced Earthquakes Overview," at https://www.usgs.gov/programs/earthquake-hazards/science/induced-earthquakes-overview.

[24] Crystalline basement rocks refer to typically older igneous or metamorphic rocks, such as granite, that lie beneath younger sedimentary rocks, such as sandstone, limestone, or shale.

[25] Schultz, HF-Induced Seismicity, 2020; GWPC/IOGC, *Induced Seismicity Guide*, 2021; and Grigoratos, Causal Factors of Induced Seismicity, 2022.

[26] For example, in Oklahoma, induced earthquakes occur within 6 kilometers (3.7 miles) of the surface, whereas natural earthquakes typically occur throughout the crust to about 30 kilometers (18.6 miles) below the surface and some occur

the surface can produce more shaking and thus may cause more damage at the surface than a deeper M 3.0 event.

Underground injection in wastewater disposal wells has induced five damaging earthquakes in the United States (**Table 1**) between 2011 and 2016.[27] Stakeholders in Oklahoma sued various well operators to recover the costs of damages from an M 5.8 earthquake near Pawnee, OK, and an M 5.0 earthquake near Cushing, OK.[28] (See text box titled "Magnitude 5.8 Earthquake near Pawnee, OK, on September 3, 2016" for more details about the earthquake and subsequent mitigation efforts).

Table 1. Damage from Induced Earthquakes in the United States Caused by Wastewater Injection, 2011-2016

Year	M	Location	Damage
2011	5.7	Prague, OK	Damaged homes, broke windows, cracked masonry, and collapsed a turret at St. Gregory's University.
2011	5.3	Trinidad, CO	Caused structural damage to unreinforced masonry; cracked masonry; caused fallen chimneys, broken windows, and fallen objects.
2012	4.8	Timpson, TX	Resulted in fallen chimneys and damaged masonry walls.
2016	5.8	Pawnee, OK	Damaged brickwork and cracked sheetrock at a number of structures.
2016	5.0	Cushing, OK	Caused cracks in buildings as well as fallen bricks and facades.

Source: Ground Water Protection Council and Interstate Oil and Gas Compact Commission, *Potential Induced Seismicity Guide: A Resource of Technical and Regulatory Considerations Associated with Fluid Injection*, March 2021, p. 13, at https://www.gwpc.org/sites/gwpc/uploads/documents/publications/FINAL_Induced_Seismicity_2021_Guide_33021.pdf.

Seismic Monitoring of Induced Earthquakes

Researchers say they lack sufficient data on well operations, geologic conditions underground and in some cases sufficient monitoring of areas of concern for earthquakes with seismic instruments to identify any critically stressed faults and analyze which underground fluid injection activities may induce earthquakes on these faults.[29]

Seismic monitoring is a primary tool for estimating the state of stress and identifying faults underground.[30] The USGS Earthquake Hazards Program monitors and reports on earthquakes in the United States and globally, assesses earthquake hazards, and conducts research on the causes and effects of earthquakes under the authority of the National Earthquake Hazards Reduction

much deeper in the mantle. GWPC/IOGC, *Induced Seismicity Guide*, 2021, p. 2.

[27] GWPC/IOGC, *Induced Seismicity Guide*, 2021.

[28] Beth Wallis, "Oil Company Agrees to $850k Settlement for 2016 Oklahoma Earthquake Damages," KOSU, *Energy and Environment*, August 6, 2022, KOSU Fresh Air, at https://www.kosu.org/energy-environment/2022-08-06/oil-company-agrees-to-850k-settlement-for-2016-oklahoma-earthquake-damages (hereinafter Wallis, "Oil Company Agrees to Settlement").

[29] William Leith, Senior Science Advisor for Earthquakes and Geologic Hazards, U.S. Geological Survey (USGS), "USGS Research into the Causes and Consequences of Injection-Induced Seismicity," presentation at the U.S. Energy Association, October 30, 2014, at https://usea.org/sites/default/files/event-/Leith%20induced%20for%20DOE-USEA%20Oct14.pdf and GWPC/IOGC, *Induced Seismicity Guide*, 2021, p. 3.

[30] Seismic monitoring is a primary research tool used to image the structure of the subsurface and understand geologic processes such as earthquakes, volcanic activity, and plate tectonics.

Program.[31] The USGS has deployed seismic instruments to understand induced earthquakes related to oil and gas activities in Kansas, Oklahoma, Ohio, and Texas.[32] The USGS also deployed seismic instruments near Decatur, IL to understand induced earthquakes related to an experimental geologic carbon sequestration project.[33]

In addition to the USGS, state agencies and universities have enhanced or established short- and long-term seismic monitoring to understand induced seismicity and to mitigate seismic risks in the CEUS. For example, Arkansas, Kansas, Ohio, Oklahoma, and Texas have seismic networks operated by state agencies and/or universities to study natural and induced seismicity.[34] Researchers using these networks seek to understand which operations may cause induced seismicity and to improve the capability of regulators and operators to mitigate induced earthquakes.

One example of a state-run seismic monitoring network to understand earthquakes is the Oklahoma Geological Survey's (OGS's) Seismic Monitoring Program.[35] OGS has operated the program since 1961 and increased the size of the network and its seismic monitoring capabilities beginning in 2009 to understand the increasing number of earthquakes per year in the state. **Figure 3** shows the number of M 3.0+ earthquakes in Oklahoma from 2009 to 2021 from the OGS earthquake catalogs. The figure shows a peak in the annual number of earthquakes in 2015 and a corresponding peak in higher-magnitude events (i.e., M 4.0+). The Oklahoma Corporation Commission's (OCC) Induced Seismicity Department correlated most of these earthquakes with underground injection activities. The OCC regulates oil and gas activities and the Underground Injection Control program (on behalf of the EPA) in Oklahoma (See text box titled "Magnitude 5.8 Earthquake near Pawnee, OK, on September 3, 2016"). According to a 2018 OCC report, the annual number of induced earthquakes (M 3.0+) in Oklahoma has decreased since 2015, primarily due to regulations and directives to mitigate induced seismicity.[36]

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[31] USGS, "Earthquake Hazards," at https://www.usgs.gov/programs/earthquake-hazards and CRS Report R43141, *The National Earthquake Hazards Reduction Program (NEHRP): Issues in Brief*, by Linda R. Rowan.

[32] See USGS, "Observational Studies of Induced Earthquakes," at https://www.usgs.gov/programs/earthquake-hazards/science/observational-studies-induced-earthquakes, and a list of related publications at USGS, "Induced Earthquakes Overview," at https://www.usgs.gov/programs/earthquake-hazards/science/induced-earthquakes-overview#publications.

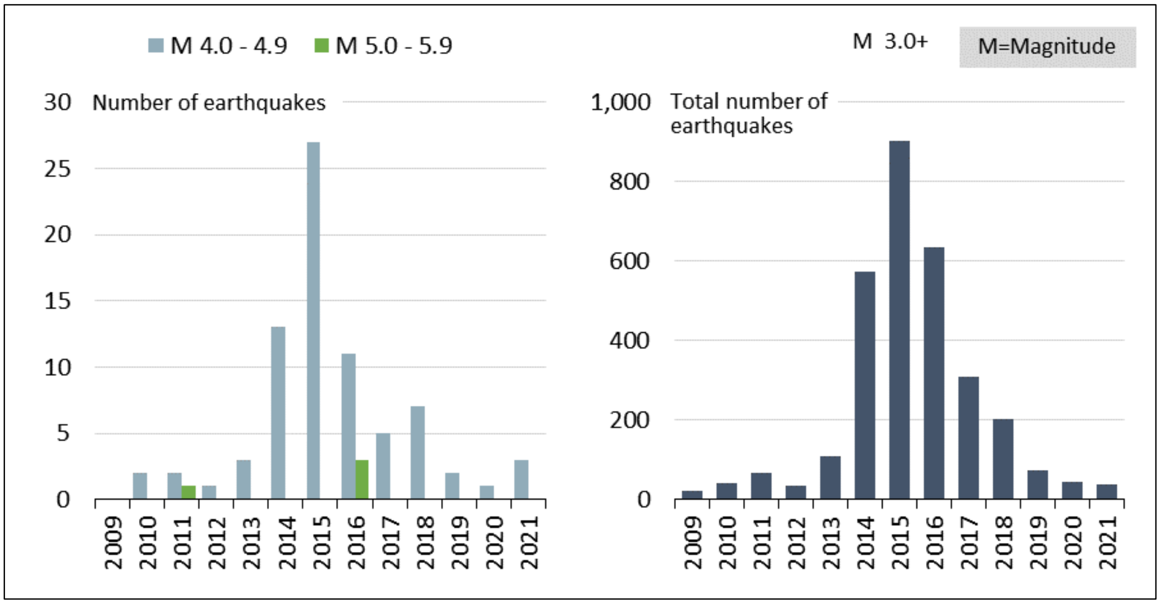
[33] J. Ole Kaven et al., "Seismic Monitoring at the Decatur, IL, CO_2 Sequestration Demonstration Site," *Energy Procedia*, vol. 63 (2014), pp. 4264-4272, doi: 10.1016/j.egypro.2014.11.461.

[34] Many states augmented or established state-managed seismic networks after the peak in induced seismicity in 2015 (see Figure 1). Arkansas Seismic Monitoring: Arkansas Geological Survey, "Earthquakes," at https://www.geology.arkansas.gov/geohazards/earthquakes-in-arkansas.html; Arkansas Geological Survey, "Arkansas Seismicity Map from 1699 to 2019," at https://www.geology.arkansas.gov/docs/pdf/maps-and-data/geohazard_maps/arkansas-seismicity-map.pdf; and University of Memphis, Center for Earthquake Research and Information, "Recent Earthquakes," at https://folkworm.ceri.memphis.edu/REQ/html/recent.html. Kansas Seismic Monitoring: Kansas Geological Survey, "Kansas Earthquakes," at https://www.kgs.ku.edu/Geophysics/Earthquakes/index.html. Ohio Seismic Monitoring: Ohio Division of Natural Resources, "The Ohio Seismic Network," at https://ohiodnr.gov/discover-and-learn/safety-conservation/about-ODNR/geologic-survey/division-of-geologic-survey/ohio-seis. Oklahoma Seismic Monitoring: Oklahoma Geological Survey, "Earthquakes," at https://www.ou.edu/ogs/research/earthquakes. Texas Seismic Monitoring: University of Texas, Bureau of Economic Geology, "TexNet Seismic Monitoring Program'" at https://www.beg.utexas.edu/texnet-cisr/texnet.

[35] Oklahoma Geological Survey, "Seismic Monitoring Program," at https://www.ou.edu/ogs/research/earthquakes/seismicstations.

[36] Oklahoma Corporation Commission, *Annual Report Fiscal Year 2018*, 2018, pp. P. 48-49, https://oklahoma.gov/content/dam/ok/en/occ/documents/ajls/about/Annual_Report-FY18.pdf.

Figure 3. Earthquakes of Magnitude 3.0 or Greater in Oklahoma, 2009-2021



Source: Oklahoma Geological Survey, "Earthquake Catalog Download Tool," at https://www.ou.edu/ogs/research/earthquakes/catalogs.

Notes: CRS downloaded the earthquake catalogs for the years 2009-2021. The plots show the number of earthquakes of the indicated magnitude range for each year. There were no earthquakes of M 4.0 or greater in 2009 in the Oklahoma Geological Survey earthquake catalog.

Magnitude 5.8 Earthquake near Pawnee, OK: September 3, 2016

On September 3, 2016, a magnitude (M) 5.8 earthquake occurred about 9 miles northwest of Pawnee, OK. It was the largest recorded earthquake to occur in the state and caused damage to people and property. After the earthquake, federal and state regulators required well operators to change or halt well operations in the area near the event.

Underground wastewater injections into the Arbuckle Formation induced the earthquake. The U.S. Geological Survey, working with the Oklahoma Geological Survey, identified a system of potentially unstable faults in the crystalline bedrock below the Arbuckle Formation. The underground injections likely changed conditions on the faults and at least one fault slipped, causing the earthquake.

Although it is difficult to assign a specific well's activities to a specific fault and subsequent earthquake, the Oklahoma Corporation Commission (OCC), which regulates oil and gas activities and underground fluid injection in Oklahoma, took immediate action to shut down or curtail 37 wells within a 725 square mile area of the event. Injections from those wells correlated in space and time to the September 3 earthquake.

The 725 square mile area of seismic concern included 211 square miles of Osage County, a portion of which is part of the Osage Nation Mineral Reserve. The Environmental Protection Agency (EPA) implements the Underground Injection Control program in Osage County, and the agency requested operators to shut in (temporarily shut down) 17 wastewater disposal wells after the earthquake.

On September 12, 2016, the OCC expanded the area of seismic concern to 1,116 square miles, based on new data. The OCC requested that 27 wells cease operations and 19 wells reduce disposal volumes. EPA requested that 5 wells cease operations and 14 wells reduce disposal volumes in the Osage Nation Mineral Reserve.

Since the September 3, 2016 earthquake, organizations and individuals sued different well operators for compensation for damage from the event. Part of one lawsuit was settled in August 2022.

Sources: Oklahoma Geological Survey, "Earthquakes," at https://www.ou.edu/ogs/research/earthquakes; OCC, "Media Advisory: Latest Action Regarding Pawnee Area," press release, September 12, 2016, at https://oklahoma.gov/content/dam/ok/en/occ/documents/ajls/news/2016/09-12-16pawnee-advisory.pdf; OCC, "Advisory: Pawnee," press release, November 3, 2016, at https://oklahoma.gov/content/dam/ok/en/occ/documents/ajls/news/2016/11-03-16pawnee-posting.pdf; OCC, "Earthquake Response Summary," at https://oklahoma.gov/content/dam/ok/en/occ/documents/ajls/news/2018/05-30-18earthquakeactionsummary.pdf; OCC, "Response to Oklahoma Earthquakes," at https://oklahoma.gov/occ/divisions/oil-gas/induced-seismicity-and-uic-department/response-oklahoma-earthquakes.html; and Beth Wallis, "Oil Company Agrees to $850k Settlement for 2016 Oklahoma Earthquake Damages," KOSU, *Fresh Air, Energy & Environment*, August 6, 2022, at https://www.kosu.org/energy-environment/2022-08-06/oil-company-agrees-to-850k-settlement-for-2016-oklahoma-earthquake-damages.

Seismic monitoring provides details about earthquakes that may help to identify and reduce earthquake risks.[37] For example, in Oklahoma seismic monitoring shows a slight increase in M 4.0+ events after some injection activities ceased or changed. This may signal that the fluid injections may affect geologic conditions further from the injection location (see text box titled "A Historical Example: Rocky Mountain Arsenal"). Similarly, the recently established Texas Seismic Network (TexNet, started in 2017 by the Texas state legislature) identified an annual increase in the number of M 3.0+ and M 4.0+ earthquakes from 2019 to 2021.[38] Texas regulators in consultation with seismologists at TexNet determined that wastewater disposal induced these earthquakes and some of the earthquakes occurred at or above the fluid injection site on shallower faults.[39] The occurrence of induced earthquakes on shallower faults contrasts with the illustrative

[37] GWPC/IOGC, *Induced Seismicity Guide*, 2021.

[38] Erin Douglas, "Earthquakes in Texas Doubled in 2021. Scientists Cite Years of Oil Companies Injecting Sludgy Water Underground," *Texas Tribune*, February 8, 2022, at https://www.texastribune.org/2022/02/08/west-texas-earthquakes-fracking/ (hereinafter Douglas, "Earthquakes in Texas Doubled").

[39] Texas Railroad Commission (RRC), "Seismicity Response," at https://www.rrc.texas.gov/oil-and-gas/applications-and-permits/injection-storage-permits/oil-and-gas-waste-disposal/injection-disposal-permit-procedures/seismicity-review/seismicity-response (hereinafter, RRC Seismicity Response) and Grigoratos, Causal Factors of Induced Seismicity, 2022.

model in **Figure 2** and with the identification of deeper faults in Oklahoma and Ohio, highlighting the importance of understanding the different geologic conditions in different locations.

Evaluating the Risk of Induced Earthquakes

The USGS Earthquake Hazards Program conducts research, monitors, reports, and assesses the risks of induced seismicity from many underground injection activities as a small component of its overall program.[40] The increase in seismicity since 2009 in the CEUS (**Figure 1**) is caused by underground fluid injection (primarily from wastewater disposal), according to USGS and other studies.[41] In addition to the increase in the number of earthquakes since 2009, the number of induced earthquakes of M 4.0+ increased over the same period. Larger magnitude events (4.0+) in the shallow crust increase the risk of damage from more intense ground shaking.

The USGS prepares and regularly updates U.S. Seismic Hazard Maps to assess earthquake hazards and their associated risks across the country.[42] These maps typically exclude the seismic hazard posed by induced earthquakes, because researchers are unsure how to treat potentially induced earthquakes in their seismic hazard analysis.[43] The natural tectonic processes causing earthquakes do not change much over geologic timescales of thousands to millions of years. For example, the seismic hazard in portions of California, Alaska, and other states experiencing these tectonic forces do not vary much from year to year.[44] In contrast, induced seismicity can vary over short timescales because underground fluid injection activities often change over short times (i.e., weeks, months, or a few years). Those characteristics mean assessing risk from combining natural seismic hazards with induced seismic hazards is difficult, in part because induced earthquakes are a short-term hazard, compared with the perennial seismic hazard from natural tectonic forces.[45]

Despite the difficulty, the USGS released one-year seismic hazard forecasts for the CEUS for 2016, 2017, and 2018 that included contributions from induced and natural earthquakes.[46] The

[40] USGS, "Induced Earthquakes," at https://www.usgs.gov/programs/earthquake-hazards/science/induced-earthquakes.

[41] USGS, "FAQ, Natural Hazards, Induced Earthquakes," at https://www.usgs.gov/science/faqs/natural-hazards; USGS, "Does fracking cause earthquakes?" https://www.usgs.gov/faqs/does-fracking-cause-earthquakes; Schultz, HF-Induced Seismicity, 2020; and GWPC/IOGC, *Induced Seismicity Guide*, 2021. The USGS conducted studies often in partnership with universities and/or state agencies.

[42] USGS, "National Seismic Hazard Maps," at https://www.usgs.gov/programs/earthquake-hazards/science/national-seismic-hazard-maps.

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

[44] See, for example, the National Seismic Hazard Maps published by the USGS at 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.

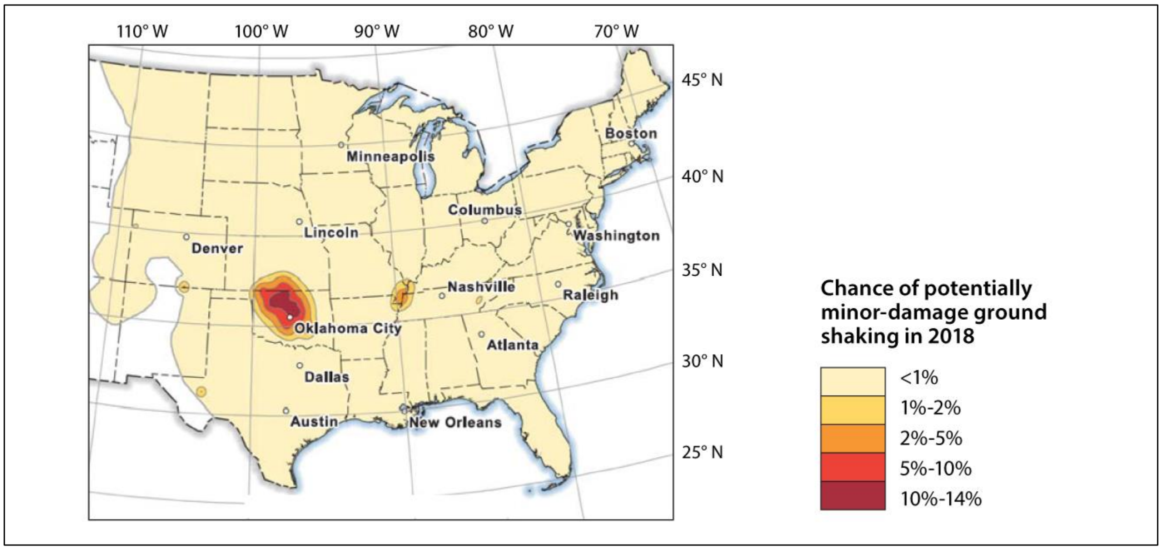
[45] The USGS designates a 50-year period for the National Seismic Hazard Maps partly because natural earthquakes are time independent (i.e., the tectonic forces that lead to earthquakes are constant over a specified time, such as 50 years). Induced seismicity caused by wastewater disposal, recovery, and HF wells can vary on a much shorter time scale (e.g., days, weeks or months).

[46] Mark D. Petersen et al., *2016 One-Year Seismic Hazard Forecast for the Central and Eastern United States from Induced and Natural Earthquakes*, USGS, Open-File Report 2016-1035, June 17, 2016, at https://pubs.er.usgs.gov/publication/ofr20161035 (hereinafter Petersen, *2016 One-Year Seismic Hazard Forecast)* . USGS, "Hazard Estimation for Induced Earthquakes," at https://www.usgs.gov/programs/earthquake-hazards/science/hazard-estimation-induced-earthquakes. Jason L. Rubinstein, Andrew J. Barbour, and Jack H. Norbeck, "Forecasting Induced Earthquake Hazard Using a Hydromechanical Earthquake Nucleation Model," *Seismological Research Letters*, vol. 92 (2021), pp. 2206-2220, doi: 10.1785/0220200215 (hereinafter Rubinstein, Barbour, and Norbeck, "Forecasting," 2021).

2018 map in **Figure 4** shows two main areas of earthquake hazard in the CEUS: the natural seismic zone near New Madrid, MO, and the induced seismic zone extending around Oklahoma City, OK.[47]

The risks from induced earthquakes is ultimately dependent on local geologic conditions and local fluid injection activities.[48] Oklahoma state agencies monitor induced earthquakes at the local level and understand that fluid injections may cause earthquakes on preexisting faults in the deeper crystalline basement below the injection site soon after injection or the earthquakes may be delayed for reasons that are not fully understood. Oklahoma's monitoring identifies different fault risks for Oklahoma regulators to consider and they may adjust their response regarding fluid injection activities that may induce earthquakes. Similarly Texas state agencies recognize that induced earthquakes may occur on preexisting faults in the shallow layers above or at the same level as the injection site as well as in the deeper crystalline basement based on TexNet monitoring. Texas regulators have posted plans to respond to the seismicity in shallow and deep areas to reduce risks.[49]

Figure 4. Chance of Damage from an Earthquake in the Central and Eastern United States in 2018



Source: USGS, "Hazard Estimation for Induced Earthquakes," at https://www.usgs.gov/programs/earthquake-hazards/science/hazard-estimation-induced-earthquakes. Modified by CRS.

Notes: One-year forecast for 2018 of potential earthquake shaking in the central and eastern United States based on past induced and natural earthquakes. The natural seismic zone near New Madrid, MO, and the induced seismic zone near Oklahoma City, OK, had the highest potential for shaking in 2018.

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[47] The New Madrid Seismic Zone experienced high-magnitude earthquakes (M 7.0+) in 1811-1812 and continues to experience smaller-magnitude earthquakes recorded on modern seismic instruments. See USGS, "The New Madrid Seismic Zone," at https://www.usgs.gov/programs/earthquake-hazards/new-madrid-seismic-zone. For more information about earthquake risk in the United States generally, see CRS Report RL33861, *Earthquakes: Risk, Detection, Warning, and Research*, by Peter Folger; and CRS Report R43141, *The National Earthquake Hazards Reduction Program (NEHRP): Issues in Brief*, by Linda R. Rowan.

[48] GWPC/IOGC, *Induced Seismicity Guide*, 2021.

[49] RRC, Seismicity Response.

Overview of the Current Regulatory Structure Regarding Induced Seismicity

According to a National Research Council report, conventional oil and gas production and hydraulic fracturing combined generate more than 800 billion gallons of fluid each year. Underground injection control (UIC) Class II injection wells dispose of more than one-third of this volume deep underground.[50] 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 and growth of HF production 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 near 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

The principal law authorizing federal regulation of underground injection activities is the Safe Drinking Water Act (SDWA), as amended.[51] The law specifically directs EPA to promulgate regulations for state UIC programs to prevent underground injection that endangers drinking water sources.[52] Historically, EPA has not regulated oil and gas production wells. Further, as amended in 2005, 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.[53]

SDWA authorizes states and Indian tribes to assume primary enforcement authority (*primacy*) for the UIC program for any or all classes of injection wells.[54] EPA must delegate this authority, provided the state or tribal program meets certain statutory and EPA requirements.[55] If EPA does not approve a state's UIC program plan or if a state chooses not to assume program responsibility, then EPA implements the UIC program in that state.

[50] NRC, Committee on Induced Seismicity Potential in Energy Technologies, *Induced Seismicity Potential in Energy Technologies* (Washington, DC: National Academy Press, 2012), p. 110.

[51] The Safe Drinking Water Act of 1974 (SDWA; 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.

[52] 42 U.S.C. §300h(d). SDWA §1421.

[53] The Energy Policy Act of 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. A *propping agent* is a material, such as sand, that is injected along with hydraulic fracturing fluid to "prop" open the cracks in the formation.

[54] 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 attained primacy for Class II wells.

[55] 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.

For oil and gas-related injection operations (e.g., produced water disposal through Class II wells), the law allows states or tribes to administer the UIC program using state rules rather than meeting EPA regulations, provided a state demonstrates it has an effective program that prevents underground injection that endangers drinking water sources.[56] 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 700,000 injection wells. To implement the UIC program as mandated by 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 USDW.[57]

Class II injection wells include wells (1) to inject fluids to enhance recovery of oil and gas from conventional fields (*Class IIR*), (2) to dispose of brines (saltwater) and other fluids (wastewater) associated with oil and gas production (*Class IID*), and (3) to store liquid hydrocarbons. There are more than 156,000 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.[58] Class II injection wells, specifically Class IID disposal wells, have caused the most induced earthquakes in the CEUS since 2009 (see **Table A-1** in the **Appendix** for the number of oil and gas wells and Class II wells by state in operation in 2019 or 2020).

[56] SDWA §1425 requires a state to demonstrate that its UIC program meets the requirements of §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 §1425's optional demonstration provisions, a state program must include permitting, inspection, monitoring, and record-keeping and reporting requirements.

[57] EPA regulations define an *underground source of drinking water* (USDW) to mean an aquifer or part of an aquifer that (1) 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 (2) is not an "exempted aquifer." 40 C.F.R. 144.3.

[58] Enhanced recovery wells are separate from, but often surrounded by, production wells. Recovery wells 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 former production wells. EPA, "Class II Oil and Gas Related Injection Wells," at https://www.epa.gov/uic/class-ii-oil-and-gas-related-injection-wells. See **Table A-1** in the **Appendix** for the number of disposal and recovery wells by state, as the percentages of each per state are more variable then the 80%/20% average for the total number of wells in the United States.

Table 2. Underground Injection Control Program: Classes of Injection Wells and Nationwide Numbers

Well Class	Purpose and Uses	Number of Wells
Class I	Inject hazardous wastes, industrial nonhazardous liquids, or municipal wastewater beneath the lowermost underground source of drinking water (USDW).	903, including 135 hazardous waste wells
Class II	Inject brines and other fluids associated with oil and gas production and liquid hydrocarbons for storage. Inject fluids beneath the lowermost USDW. Types of Class II wells include the following:[a] • **Enhanced Recovery Wells:** Separate from but often surrounded by production wells, enhanced recovery 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. This category includes hydraulic fracturing wells when diesel fuels, however, most hydraulic fracturing wells do not use diesel fuels and are excluded from the EPA UIC program. Approximately 80% of Class II wells are enhanced recovery (*Class IIR*) wells. • **Disposal Wells:** Produced water and other fluids associated with oil and gas production (including flowback from hydraulic fracturing operations) are injected into disposal 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.	>156,000
Class III	Inject fluids associated with solution mining of minerals (e.g., salt and uranium) beneath the lowermost USDW.	28,465
Class IV	Inject hazardous or radioactive wastes into or above USDW. Banned unless authorized under a federal or state groundwater remediation project.	169
Class V	All injection wells not included in Classes I-IV, including experimental wells. Often inject nonhazardous fluids into or above USDW. Many are shallow, on-site disposal systems (e.g., cesspools and stormwater drainage wells). Some Class V wells (e.g., geothermal energy) inject below USDW.	>549,000
Class VI	Used for the geologic sequestration of CO_2.	4

Sources: U.S. Environmental Protection Agency (EPA), *Underground Injection Control Program, Classes of Wells*, *and Class II Wells—Oil and Gas Related Injection Wells,* at http://www.epa.gov/uic/class-ii-oil-and-gas-related-injection-wells; and EPA, "FY2019 State UIC Injection Well Inventory," accessed September 22, 2022.

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 USDW. New York and New Jersey did not submit data for EPA's UIC well inventory. This table does not include tribal wells, which include Class 1, Class II, and Class V wells (totaling 6,945 wells, according to EPA's FY2019 Tribal UIC Injection Well Inventory). See **Table A-1** in the **Appendix** for the number of Class IID and Class IIR wells by state.

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

Consideration of Seismicity in EPA UIC Regulations

SDWA does not mention seismicity; rather, the law's UIC provisions authorize EPA to regulate underground injection to prevent endangerment of USDW. 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 USDW by ensuring injected fluids remain in a permitted injection zone. Some of these measures also could reduce the likelihood of inducing 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.[59] As a secondary benefit, limiting injection pressure could prevent fractures that may 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 be limited to geologically suitable areas. The UIC director (i.e., EPA or the delegated state or tribe) is required to determine geologic suitability based on an "analysis of the structural and stratigraphic geology, the hydrogeology, and the seismicity of the region."[60] 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."[61]

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.[62]

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 USDW (including requirements for construction, corrective action, operation, monitoring, or reporting).[63] 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

[59] 40 C.F.R. §146.23(a)(1).

[60] 40 C.F.R. §146.62(b)(1).

[61] 40 C.F.R. §146.68(f).

[62] 40 C.F.R. §146.82(a)(3)(v).

[63] 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."[64] Regulations for Class I wells further specify that "injection pressure must be limited such that no fracturing of the injection zone occurs during operation."[65]

Outside of regulations, EPA has taken steps to address induced seismicity concerns associated with Class II disposal wells. For example, EPA Region III, which directly implements the UIC program in Pennsylvania and Virginia, evaluates induced seismicity risk factors when considering permit applications for Class II wells.[66] 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."[67]

Recommendations to Mitigate Induced Seismicity Related to Class II Disposal Wells

As discussed above, 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 could 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 a site characterization checklist, and
    - explore applicability of pressure transient testing and/or pressure monitoring techniques.

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

[65] Ibid., p. 66.

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

[67] EPA 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, at http://www.epa.gov/sites/default/files/2020-12/documents/windfall-pas2d020bcle_response_to_comments_final_0.pdf.

- Summary of lessons learned from case studies.
- Recommended measurement or monitoring techniques for high-risk areas.
- Applicability of conclusions to other well classes.
- Defined specific areas of research, as needed.[68]

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.[69] 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."[70]

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.
3. A pathway allowing the increased pressure to communicate from the disposal well to the fault.[71]

As discussed, current Class II regulations give discretion to UIC directors to include in individual permits additional conditions and requirements as needed to protect USDW.[72] The *Practical Approaches* document notes that, although 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.[73]

The report includes a decision model to inform regulators on site assessment strategies and recommends monitoring, operational, and management approaches to manage and minimize suspected injection-induced seismicity. Among the management recommendations, the report suggests that, for wells suspected of causing induced seismicity, managers should take early actions (e.g., requiring more frequent pressure monitoring and reducing injection rates) rather than requiring definitive proof of causality.[74]

The technical workgroup also identified research needs to better understand the 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

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[68] EPA, *Minimizing and Managing*, p. 5.

[69] EPA, *Minimizing and Managing*. The report includes case studies of induced seismicity events and responses in four states: Arkansas, Ohio, Texas, and West Virginia. The UIC director is the state program director where the state has program primacy or EPA in states where EPA implements the program directly.

[70] EPA, *Minimizing and Managing*, ES-2.

[71] EPA, *Minimizing and Managing*, ES-2.

[72] 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.

[73] EPA, *Minimizing and Managing*, p. 4.

[74] EPA, *Minimizing and Managing*, p. 35.

recommended that future research be conducted using a holistic, multidisciplinary approach, combining expertise in petroleum engineering, geology, geophysics, and seismicity.[75]

State Initiatives Regarding Induced Seismicity

Several organizations and states in the CEUS are monitoring, assessing, guiding, and regulating Class II wells (i.e., waste and recovery) and HF operations that may induce seismicity.[76] In 2014, the Interstate Oil and Gas Compact Commission and the Ground Water Protection Council formed an Induced Seismicity Work Group (ISWG) with state regulatory agencies and state geological surveys to "proactively discuss the possible association between recent seismic events occurring in multiple states and injection wells."[77] The ISWG issued its first primer about induced seismicity in 2015, a second primer in 2017, and a guide in 2021. The 2015 and 2017 primers focused on induced seismicity associated with Class II wells. The 2021 guide updated its summary of the scientific understanding of induced seismicity and "expanded on the topic of induced seismicity related to hydraulic fracturing."[78]

States regulate oil and gas activities within their state boundaries, and in some cases the state oil and gas activities program includes the state UIC program. In other cases, a different state agency runs the UIC program.

States in the CEUS that have experienced increased induced seismicity related to oil and gas activities have instituted mitigation strategies. Strategies may include requiring underground injection operators to (1) assess seismic risks before beginning operations, (2) provide details about their operations, and (3) monitor injection sites with seismic instruments for any earthquakes. If induced seismicity is attributed to certain wells, regulators may ask or require the operators to change their operations (e.g., reduce the volume or pressure of fluid injections or change the depth of the injections), or to stop their operations.[79] For example, Oklahoma has

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[75] EPA, *Minimizing and Managing*, 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. The development of these systems can enable previously uneconomical hydrothermal systems to produce geothermal energy on a large scale; the process of injecting fluids to enhance permeability of hydrothermal systems may also induce earthquakes. 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 Tait et al., *Protocol for Addressing Induced Seismicity Associated with Enhanced Geothermal Systems*, DOE, Office of Energy Efficiency and Renewable Energy, DOE/EE-0662, January 2012, at https://www1.eere.energy.gov/geothermal/pdfs/geothermal_seismicity_protocol_012012.pdf.

[76] GWPC/IOGC, *Induced Seismicity Guide*, 2021.

[77] The Interstate Oil and Gas Compact Commission is a multistate agency that states that it "works to champion the conservation and efficient recovery of our nation's oil and natural gas resources while protecting health, safety and the environment." The commission asserts it does so by "providing member states with a clear and unified voice and serving as the authority on issues surrounding these vital resources," and says it "assists states in balancing a multitude of interests through sound regulatory practices." According to the commission, its "unique structure offers a highly effective forum for states, industry, Congress and the environmental community to share information and viewpoints to advance our nation's energy future" (Interstate Oil and Gas Compact Commission, "About Us," at https://iogcc.ok.gov/about-us.) The Ground Water Protection Council is "a nonprofit 501(c)6 organization whose members consist of state ground water regulatory agencies which come together ... to mutually work toward the protection of the nation's ground water supplies" (Ground Water Protection Council, "About Us," at https://www.gwpc.org/about-us/overview/). States First Initiative, *States Team Up to Assess Risk of Induced Seismicity*, April 29, 2014, at http://www.statesfirstinitiative.org or http://www.statesfirstinitiative.org/#!States-Team-Up-to-Assess-Risk-of-Induced-Seismicity/c8t8/72D0196F-1DAB-4617-B446-B009A1D902FB.

[78] GWPC/IOGC, *Induced Seismicity Guide*, 2021.

[79] Ibid.

regulations and directives to mitigate induced seismicity while allowing oil and gas activities in the state.[80] In addition, some states have banned the drilling of underground injection wells in geologic zones of known seismic risk. The 2021 guide provides examples of state efforts to regulate activities to reduce potential seismic risks and mitigate induced seismicity related to oil and gas activities and concomitant wastewater disposal.

Options for Congress

Interest in policies or regulations to mitigate induced seismicity caused by underground fluid injection in the CEUS may change in accordance with the number of induced earthquakes per year, which peaked in 2015, then decreased from 2016 to 2019, and increased again in 2020 and 2021 (**Figure 1**). Other reasons for renewed interest include several M 5.0 or larger events in Texas in 2020 and 2022 and an M 4.5 earthquake near Clyde, OK, in 2022; news reports and public concern about induced seismicity damage and related litigation; increasing oil and gas activities related to higher oil prices; and increasing interest in the development of enhanced geothermal systems and geologic carbon sequestration.[81] Underground fluid injection activities associated with advancing geothermal energy systems, and injecting liquid carbon dioxide for geologic sequestration may induce earthquakes and may require mitigation strategies similar to those for oil and gas activities to reduce earthquake risks.

Congress may consider whether to support federal agency efforts in research, risk assessment, response, and/or mitigation strategies to understand and reduce induced seismicity caused by underground fluid injection activities. In the past, the USGS has studied induced seismicity caused by underground fluid injections (e.g., oil and gas activities, wastewater disposal, and geologic carbon sequestration) in the CEUS and issued one-year earthquake hazard forecasts for the CEUS for 2016, 2017, and 2018 (see "Understanding, Monitoring, and Assessing the Risk of Induced Seismicity").[82] The USGS has partnered with states in the CEUS to monitor earthquakes with USGS and state-led seismic networks.[83] The FY2022 and FY2023 President's budget requests called for increased funding for the USGS to study induced seismicity caused by geothermal or geologic carbon sequestration activities, and for a one-year earthquake hazard forecast for the CEUS similar to those produced in 2016-2018.[84] The House Appropriations Committee agreed with some of the Administration's proposals to support induced seismicity

[80] Oklahoma Corporation Commission, "Response to Oklahoma Earthquakes," at https://oklahoma.gov/occ/divisions/oil-gas/induced-seismicity-and-uic-department/response-oklahoma-earthquakes.html.

[81] The M 5.0 or larger earthquakes in Texas include a M 5.0 event near Metone, TX on March 26, 2020, a M 5.4 event near Coalson Draw, TX on November 16, 2022, and a M 5.3 event near Range Hill, TX on December 16, 2022 (see USGS, "M 5.3 – Range Hill, Texas," at https://earthquake.usgs.gov/earthquakes/eventpage/tx2022yplg/executive). Erin Douglas, "Earthquakes in Texas Doubled"; Wallis, "Oil Company Agrees to Settlement"; and Anthony Faiola, "Earthquakes for Ukraine: Dutch Gas Drilling Tests What Countries Will Accept," *Washington Post*, September 1, 2022, at https://www.washingtonpost.com/world/2022/09/01/natural-gas-europe-ukraine-earthquakes/.

[82] See USGS, "Observational Studies of Induced Earthquakes," at https://www.usgs.gov/programs/earthquake-hazards/science/observational-studies-induced-earthquakes, and a list of related publications at USGS, "Induced Earthquakes Overview," at https://www.usgs.gov/programs/earthquake-hazards/science/induced-earthquakes-overview#publications. See also USGS, "Induced Seismicity Associated with Carbon Dioxide Geologic Storage," at https://www.usgs.gov/centers/geology-energy-and-minerals-science-center/science/induced-seismicity-associated-carbon. Petersen, *2016 One-Year Seismic Hazard Forecast* and USGS, "Hazard Estimation for Induced Earthquakes," at https://www.usgs.gov/programs/earthquake-hazards/science/hazard-estimation-induced-earthquakes.

[83] See footnote 34.

[84] USGS, *Budget Justifications and Performance Information Fiscal Year 2023*, 2022, at https://d9-wret.s3.us-west-2.amazonaws.com/assets/palladium/production/s3fs-public/media/files/FY23-USGS-Greenbook.pdf.

research at the USGS in FY2023 (H.Rept. 117-400).[85] The Senate Appropriations Committee did not express support for any specified induced seismicity work by the USGS in FY2023.[86] The FY2023 Consolidated Appropriations Act does not include any specific funding for induced seismicity research or assessment by the USGS (P.L. 117-328). Congress may consider whether to direct the USGS to specifically study or provide earthquake hazards assessment for induced seismicity and whether to specify any funding for such work.

Congress may consider whether EPA or DOE requirements, reports, or guidance regarding induced seismicity from underground fluid injection activities are sufficient to reduce the risks of induced earthquakes. Especially given earthquake activity in the CEUS in the past few years and ongoing research and seismic monitoring by federal, state, or local entities (e.g., USGS, state geological surveys, state regulators, and universities). The EPA requires induced seismicity risk assessment for Class I hazardous waste disposal wells and Class VI geologic carbon sequestration wells, but not for Class II wells. EPA issued a report in 2015 on induced seismicity risk assessment and management for Class II wastewater disposal wells (see "Consideration of Seismicity in EPA UIC Regulations"), but the report has no regulatory authority and did not discuss Class II enhanced oil and gas recovery wells. In addition, DOE supports research and demonstration projects for enhanced geothermal systems and geologic carbon sequestration; these underground fluid injection activities may induce earthquakes.[87] DOE issued a report in 2012 on induced seismicity protocols to mitigate earthquake risks associated with the development of enhanced geothermal systems.[88] Congress may provide oversight as to whether these past requirements, reports, and guidance are sufficient to reduce the risks of induced earthquakes.

Congress may consider the federal role in regulating underground fluid injection activities to mitigate induced seismicity. EPA has some regulatory authority regarding induced seismicity for Class I and VI wells, while USGS and DOE have no regulatory authority regarding induced seismicity for any underground injection activities (see "Overview of the Current Regulatory Structure Regarding Induced Seismicity"). The EPA allows states and Indian tribes to operate the UIC program in their state or tribal land if they meet the program criteria (see "EPA Regulation of Underground Injection"). Most induced earthquakes in the CEUS are correlated with Class II wastewater disposal and HF wells (excluded from the EPA UIC program, except when diesel fuel is used) that are not regulated for induced seismicity by EPA. In the 117th Congress, some Members introduced bills that would have regulated HF wells through EPA or the Bureau of Land Management (BLM). Such measures could potentially include a federal role for regulating induced earthquakes. For example, the Fracturing Responsibility and Awareness of Chemicals Act of 2021 (H.R. 2202) proposed to repeal the exemption for HF activities in SDWA including the underground injection of fluids for HF activities under SDWA Section 1421(d)(1). The Restoring Community Input and Public Protections in Oil and Gas Leasing Act of 2021 (H.R. 1503) proposed to give the BLM authority to regulate HF activities on federal lands. The Safe Hydration is an American Right in Energy Development Act of 2021 (H.R. 2164) and the

[85] The committee called for $3.1 million for the USGS Earthquake Hazards Program for induced seismicity and did not specify whether the work should focus on any particular underground injection activities or hazard forecast.

[86] United States Senate Committee on Appropriations, Explanatory Statement for the Department of the Interior, Environment, and Related Agencies Appropriations Bill, 2023, p. 46-47, https://www.appropriations.senate.gov/imo/media/doc/INTFY23RPT.PDF.

[87] DOE Office of Energy Efficiency and Renewable Energy, "Geothermal Technologies Office," at https://www.energy.gov/eere/geothermal/geothermal-technologies-office and DOE Office of Fossil Energy and Carbon Management, "Carbon Storage Research," at https://www.energy.gov/fecm/science-innovation/carbon-capture-and-storage-research.

[88] See footnote 75.

CLEAN Future Act (H.R. 1512) proposed to amend SDWA to require EPA to revise regulations for state UIC programs to require testing of USDW that are within access of HF activities. None of these measures would have required EPA to regulate Class II wells for induced seismicity.

Congress may consider allowing states to continue to regulate oil and gas and underground fluid injection activities with support for research, monitoring, hazard assessment, and risk management from federal agencies. Another bill introduced in the 117th Congress would have specified state primacy in regulating HF wells. The Fracturing Regulations Are Effective in State Hands Act (S. 2393) proposed to clarify that the state has sole authority to regulate HF activities on federal land within state boundaries. Oklahoma provides an example of a state regulating oil and gas activities and the UIC program in the state while working with federal agencies.[89] The Oklahoma Corporation Commission (OCC) regulates oil and gas activities and has primacy for the UIC program in the state. As the number and magnitude of earthquakes on annual basis increased in Oklahoma (**Figure 3**), the state began to address the issue. Oklahoma agencies enhanced seismic monitoring, established regulations and protocols for induced seismicity, and issued directives requiring well operators to change their operations or cease operations where induced earthquakes posed a risk (see "Seismic Monitoring of Induced Earthquakes", "State Initiatives Regarding Induced Seismicity", and the text box titled "Magnitude 5.8 Earthquake near Pawnee, OK: September 3, 2016"). Oklahoma worked with the USGS on seismic monitoring and earthquake science and with the EPA on managing the UIC program. In addition, Oklahoma worked with EPA, which has primacy over the Osage Nation UIC program in Oklahoma to deal with the aftermath of the M 5.8 earthquake near Pawnee, OK.[90] The EPA issued directives similar to the OCC directives, requesting well operators within the Osage Nation to change their operations or cease operations near the M 5.8 event. The OCC attributed a decrease in the number of induced earthquakes per year in Oklahoma after 2015 to their monitoring, research, regulations, and directives.[91]

[89] The Oklahoma Corporation Commission (OCC) has authority to regulate oil and gas activities under Oklahoma Administrative Code (OAC) Title 52:3-139. Oklahoma Secretary of State, "Oklahoma Administrative Code," at https://rules.ok.gov/code. The OCC operates the Underground Injection Control (UIC) program in Oklahoma. Most regulations for oil and gas activities, including wastewater disposal, are in OAC Title 165 Corporation Commission, Chapter 10: Oil and Gas Conservation (OAC 165:10). These rules generally require operators to apply for permits for underground injection operations in the state and to notify the OCC of the status of operations. OCC publishes additional instructions regarding induced seismicity as directives or notices, OCC, "Response to Oklahoma Earthquakes," at https://oklahoma.gov/occ/divisions/oil-gas/induced-seismicity-and-uic-department/response-oklahoma-earthquakes.html. The OCC has an Oil and Gas Conservation Division (OGCD) that includes an Induced Seismicity Department and a UIC Department. Together, these state agencies deal with any potential induced seismicity caused by underground fluid injection activities. The OCC has established areas of seismic concern, where induced seismicity has occurred in the past related to underground fluid injection activities. Special directives govern well operations in these areas. For example, OCC, "Clyde Earthquake Directive," at https://oklahoma.gov/occ/news/news-feed/2022/clyde-earthquake-directive.html. The OCC established induced seismicity protocols for Oklahoma's largest oil and gas production area, including for HF wells, OCC, "Well Completion Protocol Updated, 02-27-2018," at https://oklahoma.gov/content/dam/ok/en/occ/documents/og/02-27-18protocol.pdf.

[90] EPA has primacy over some tribal UIC programs and the Osage Nation has by far the largest number of Class II wells of any EPA-administered UIC tribal program (Osage Nation had 993 wastewater disposal wells and 1390 enhanced oil and gas recovery wells in 2019), EPA, "UIC Injection Well Inventory," at https://www.epa.gov/uic/uic-injection-well-inventory.

[91] Monitoring and research helped to identify the critically stressed faults near underground injection activities. Regulations and directives identified well operations causing induced earthquakes on these faults and directed the well operators to cease or change their operations to mitigate additional induced earthquakes. Oklahoma Corporation Commission, *Annual Report Fiscal Year 2018*, 2018, pp. P. 48-49, https://oklahoma.gov/content/dam/ok/en/occ/documents/ajls/about/Annual_Report-FY18.pdf.

Appendix. Onshore Oil and Gas Production and Disposal Wells By State

The U.S. Energy Information Administration estimates the amount of oil and gas production and the number of oil and gas wells accounting for this production for the country. **Table A-1** shows that most of the onshore oil and gas production per state by total number of oil and gas wells and by HF wells is in the central and eastern United States. The Environmental Protection Agency estimates the number of Class II disposal and recovery wells for the country. **Table A-1** shows that most of the Class II wells are in the central and eastern United States.

Table A-1. Number of Oil and Gas and Disposal Wells By State

2019 or 2020

State	Oil and Gas Wells	HF Wells	Disposal Wells	Recovery Wells
AK	2,326	19	51	1,499
AL	5,946	14	89	188
AR	11,047	5,417	800	226
AZ	17	0	0	0
CA	47,898	1,815	1,698	34,990
CO	47,861	8,813	417	569
CT	^	^	0	0
DC	^	^	0	0
DE	^	^	0	0
FL	66	0	17	49
HI	^	^	0	0
IA	^	^	4	0
ID	^	^	0	0
IL	*	*	1,106	6,914
IN	*	*	215	949
KS	68,137	4	4,954	11,160
KY	18,594	1,209	117	3,004
LA	32,998	4,892	2,631	461
MA	^	^	0	0
MD	1	0	0	0
ME	^	^	0	0
MI	8,063	264	770	658
MN	^	^	0	0
MO	30	0	9	425
MS	2,987	258	575	769
MT	9,609	1,685	272	989
NC	^	^	0	0

State	Oil and Gas Wells	HF Wells	Disposal Wells	Recovery Wells
ND	17,643	16,075	674	772
NE	1,664	2	146	484
NH	^	^	0	0
NJ	^	^	*	*
NM	57,533	8,654	983	3,249
NV	67	0	12	5
NY	10,046	47	*	*
OH	38,439	2,719	2,208	128
OK	71,779	15,909	4,337	6,688
OR	10	0	4	5
PA	78,769	10,109	17	1,642
RI	^	^	0	0
SC	^	^	0	0
SD	195	122	18	90
TN	1,864	20	3	30
TX	293,316	73,792	13,731	37,193
UT	11,960	462	86	694
VA	8,118	119	13	0
VT	^	^	0	0
WA	^	^	1	0
WI	^	^	0	0
WV	55,528	3,692	55	650
WY	31,121	2,663	459	4,537
Total	931,306	158,756	36,421	117,518

Source: Numbers for columns two (Oil and Gas Wells) and three (HF Wells) are from U.S. Energy Information Administration, "U.S. Oil and Natural Gas Wells by Production Rate, Release Data: January 13, 2022" Appendix B: Selected summary tables, at https://www.eia.gov/petroleum/wells/. Numbers for columns four (Disposal Wells) and five (Recovery Wells) are from United States Environmental Protection Agency, "UIC Injection Well Inventory," FY2019 State UIC Inventory table, at https://www.epa.gov/uic/uic-injection-well-inventory.

Notes: Oil and Gas Wells includes conventional vertical wells, unconventional horizontal wells, enhanced oil and gas recovery wells and other wells as defined in the EIA supplementary tables. HF Wells means hydraulic fracturing oil and gas production wells. The United States Energy Information Administration (EIA) refers to HF Wells as Horizontal Wells in supplementary tables. Disposal Wells means wastewater disposal wells. The Environmental Protection Agency (EPA) refers to Disposal Wells as Class IID Wells. Recovery Wells means enhanced oil and gas recovery wells. EPA refers to Recovery Wells as Class IIR Wells. ^ means no well counts were collected for these states because the states do not have any oil and gas well activity. * means no data was submitted for these states, even though there is well activity in these states. IL and IN did not report their well data for any year according to EIA. The EIA numbers are from 2020, except MD is from 2016, MO is from 2019, and TN is from 2016. The EPA numbers are from 2019. NJ and NY did not submit any data to EPA. The well numbers are estimates as states and other data sources may count wells in different ways (e.g., a well pad with multiple individual wells may be counted as one well).

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