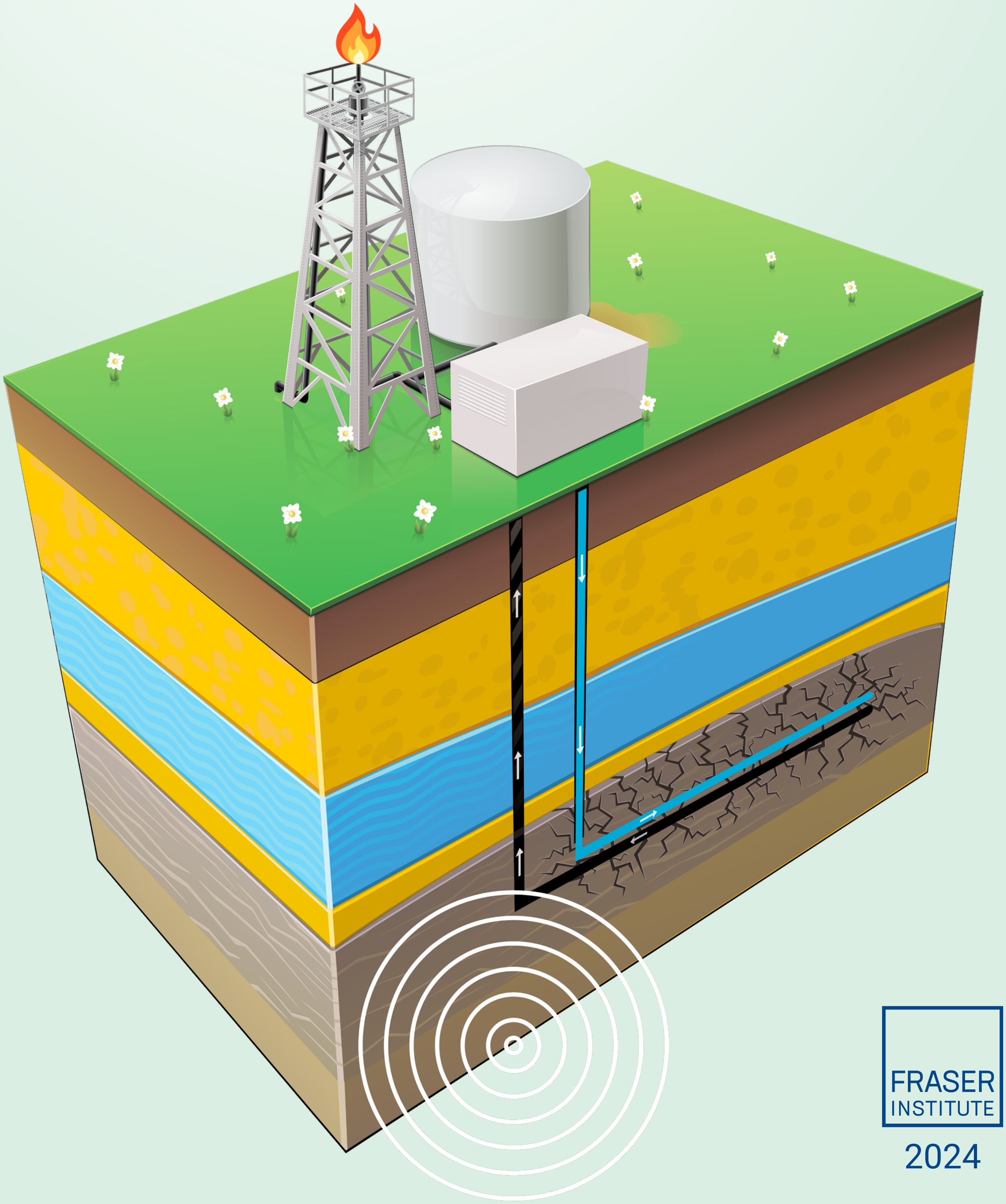
Hydraulic Fracturing

Risks and Management

Kenneth P. Green



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Executive Summary

- Hydraulic fracturing, a technique used in oil and gas production, has faced strong opposition from environmental groups in the several decades since the practice came into widespread use.

- Opponents of hydraulic fracturing assert that the process poses innumerable risks to the environment and human health—and have lobbied governments to impose moratoria and outright ban hydraulic fracturing entirely.

- Since 2014 Fraser Institute researchers have conducted periodic surveys of the literature assessing the environmental and health risks of hydraulic fracturing. Generally, they found that while the risks posited by opponents of hydraulic fracturing are real, they are neither high nor overly frequent and could be mitigated with various technological changes and changes to the hydraulic fracturing practice.

- In 2014, we reviewed nine high-profile studies and reviews of the impacts of hydraulic fracturing; an additional five studies were added in 2015; and nine additional studies were incorporated in 2020. Again, we concluded that hydraulic fracturing should continue as we improve the current system of governmental and industry self-regulation (Green, 2014: iii–iv).

- In this update, six high-level reviews or summary publications shedding additional light on the risks of hydraulic fracturing have been included—particularly pertaining to seismicity and water overuse/contamination, but also several studies examining direct effects on human health.

- As with previous reviews, this one finds increased knowledge about the risks of hydraulic fracturing continues to accumulate, with indications that some of the risks—increased seismicity and impacts to groundwater—may warrant greater mitigation efforts than previously thought necessary.

- Monitoring of air and water quality as well as induced seismicity in areas engaging in hydraulic fracturing may need to be increased, and exposure notification systems strengthened to ensure that nearby populations are enabled to manage their risk exposures from hydraulic fracturing operations.

Background

Since 2014, the Fraser Institute has published studies examining the state of knowledge regarding the potential risks and benefits of hydraulic fracturing in producing Canadian unconventional natural gas resources. We have also assessed the potential for managing those risks while allowing for hydraulic fracturing to be employed in developing Canada's unconventional natural gas resources.

Our first such study, in 2014, summarized the findings of nine high-profile scientific and technical studies and reviews of the impacts of hydraulic fracturing. Our conclusions in the 2014 study acknowledged that there is no question that the technology poses risks to water quality, air quality, and ecosystem health. But, we concluded that "continuing to allow hydraulic fracturing while improving on the current system of governmental and industry self-regulation would seem to be indicated" (Green, 2014: iii–iv).

Our 2015 study provided an update, incorporating the findings of five new studies and reviews, and concluded that "additional research on the safety of hydraulic fracturing confirms that while there are indeed risks from this process ... they are for the most part readily managed with available technologies and best practices" (Green and Jackson, 2015: 13). Our 2015 update concluded that "Calls for bans and moratoria are passionate, and no doubt heartfelt by those who fear the technology or oppose the product of that technology (hydrocarbons), but policymakers should ignore the siren song of the simplistic solution" (p. 14).

Robert P. Murphy (2020) continued the update process, summarizing the findings of nine additional studies and reviews, focusing on fracking's potential impact on drinking water quality and availability, methane emissions, induced seismicity (earthquakes), and noise pollution. Murphy's conclusions mirrored those of the preceding publications published by the Fraser Institute. He found that while the scientific understanding of the mechanisms by which fracking may affect human welfare—specifically, impacts on drinking water and seismicity—had improved over time, these particular impacts seemed more significant than the findings of the 2015 literature update. Even so, Murphy concluded, "actual demonstrated harm to human welfare from fracking is still extremely modest, despite the enormous boom in fracking operations and the passage of many years to allow for an assessment of its effects. In particular, the latest research shows that fracking actually reduces methane emissions once we adjust for the volume of natural gas produced, and especially if we consider the displacement of coal-fired power plants. The noise pollution from fracking on nearby residences has been documented, but appears to be comparable to the noise generated by a refrigerator" (Murphy, 2020: i).

Murphy observes that fracking's potential impacts on drinking water and seismicity are not the result of fracking itself but that of wastewater storage and disposal. He found that amending these operations by improving the lining of storage pits and changing the depths at which wastewater is injected underground can reduce these risks. Murphy concludes that “Although there are some genuine risks associated with fracking, the existing research leads us to conclude that they are manageable. Explicit government bans (or moratoria) at this point are a gross overreaction to the actual concerns documented in the literature” (p. ii).

This study will continue the process of reviewing the risks, and potential benefits of hydraulic fracturing for the production of unconventional Canadian natural gas, focusing on the three risks that continue to generate significant research interest: induced seismicity, human health risk, and risks to the environment. In this update, I located six high-level reviews or summary publications shedding additional light on the risks of hydraulic fracturing—particularly regarding seismicity and water overuse/contamination—and several studies examining direct effects on human health.

A Short Review of Hydraulic Fracturing

Hydraulic fracturing (colloquially called “fracking,” but more often now referred to by an acronym of HF) is a technique for extracting natural gas and other hydrocarbons from shale (rock) and tight sand formations—such as sandstone, carbonates, and siltstone—or for increasing pore space and cracks for geothermal fluid transfer and heat extraction. While often presented as a recently developed technology, hydraulic fracturing is best understood as a combination and refinement of two well-known techniques: horizontal drilling of boreholes underground, and utilization of pressurized fluids to enhance the productivity of oil wells and the fluid capture of gas molecules. Horizontal drilling, the process of drilling underground shafts horizontally, was first implemented in the US in the 1920s. Hydraulic fracturing, the injection of pressurized fluids to enhance oil and gas recovery, dates back to the late 1940s in the US (Green, 2014).

In the hydraulic fracturing process, wells are first drilled downward to a depth of up to several kilometres, and once the vertical well reaches a depth containing an identified gas-bearing geologic formation (such as a layer of gas/oil -bearing shale), the bore is curved to the horizontal, and a transverse well is drilled. These horizontal legs can also extend several kilometres in length.

In contrast with depth and horizontal length, the well diameters are quite small: an initial borehole only seven inches in diameter is drilled downward, and then lined with layers of concrete and steel pipe at the upper levels where the well might pass through groundwater formations. The final pipe that will return gas and associated liquids to the surface is only four inches in diameter.

Once both wells (horizontal and vertical) are drilled, a mixture of water, sand (proppant), and a small percentage of chemicals is injected into the well under high pressure (up to 10,000 PSI) in a series of stages moving backward from the end of the transverse well toward the horizontal leg of the well.

The pressurized water introduces fractures into the shale formation surrounding the horizontal borehole; the sand introduced into the fractures under pressure keeps them from closing back up during operations.

The fractures newly propped open allow gas and liquid hydrocarbons to flow into the transverse shaft and up the vertical well shaft. The chemicals in the hydraulic fracturing slurry (primarily detergents used to reduce friction) account for a small fraction (half to two percent) of the total fluid used. The overall hydraulic fracturing process for an individual well takes between a week and 10 days.

In *A Comprehensive Review on Water Contamination and Seismic Activity in the United States,* Hwang et al. summarize the typical hydraulic fracturing process as practiced today:

> The workflow of shale gas reservoir development consists of distinct steps. Starting with exploration, experts utilize seismic surveys to identify potential reservoir locations. After selecting a suitable site, drilling operations commence, first vertically and then transitioning to horizontal drilling to tap into the shale formation. Upon successful drilling, hydraulic fracturing or 'fracking' is applied, a technique that involves injecting a fluid mixture under high pressure to create fractures in the rock, thereby enhancing its permeability. After fracturing, flowback fluids, which are a source of recycled fracturing comprising fluid and water, are managed, and may be reinjected as waste or treated for other uses. (2023, internal sourcing removed)

Wollin et al. (2020), identify six distinct phases to hydraulic fracturing processes, which

> …involve (1) the identification of possible production sites (exploration); (2) site selection and construction of a drilling place; (3) drilling, casing and cementing; (4) hydraulic stimulation; (5) production; (6) dismantling of the drilling place and renaturation. Application of frac fluids requires the following processes: (i) removing large volumes of ground- or surface water for the production of frac fluids—between 3 and 50 million L of water are pumped into each individual well; (2) production of frac fluid, i.e., proppants and frac fluid additives are stored and mixed at the drilling site; (3) injection of frac fluids into the borehole, (4) storage and processing of the produced water; (5) disposal of the flow-back from the drilling site and produced water. (Internal sourcing removed.)

Hydraulic-Fracturing Induced Seismicity

It has been known for some time that hydraulic fracturing, used in the production of unconventional natural gas, is associated with increased seismic activity. What has been less well understood are the mechanisms which trigger the additional seismicity, the areal extent of the additional seismicity, and the proximal cause of the induced seismicity which can be caused by the direct high-pressure hydraulic fracturing activities, and also triggered by the re-introduction of fracturing liquids back down into the fractured formation for disposal. The seismicity that has been seen has been largely contained to the proximity of the fracturing itself, and not propagated far from those operations, which are not generally in proximity to large populations or developed areas. However, there have been some instances of greater distancing and somewhat stronger earthquakes noted in some hydraulic fracturing locations. As the way that seismicity is discussed has evolved since our prior reviews, a short refresher may help interpret the studies to be discussed here.

Historically, earthquakes were measured using a Richter Scale, likely most familiar to readers of this study. Table 1 explains the Richter Scale, from the Magnitude of the Earth's movement to the earthquake effects associated with a given movement scale reading and the estimated number of earthquakes per year at a given Richter scale reading.

The Richter scale has fallen into some disuse in the technical literature regarding seismicity because it was deemed insufficient for measuring larger earthquakes accurately. Today, a scale named the Moment Magnitude Scale, abbreviated "Mw," is more commonly used. According to a primer on earthquakes from Michigan Technological University (Michigan Tech):

> The moment magnitude scale is based on the total moment release of the earthquake. Moment is a product of the distance a fault moved and the force required to move it. It is derived from modeling recordings of the earthquake at multiple stations. Moment

Table 1: Earthquake Magnitude Scale

Magnitude	Earthquake Effects	Estimated Number Each Year
2.5 or less	Usually not felt, but can be recorded by seismograph.	Millions
2.5 to 5.4	Often felt, but only causes minor damage.	500,000
5.5 to 6.0	Slight damage to buildings and other structures.	350
6.1 to 6.9	May cause a lot of damage in very populated areas.	100
7.0 to 7.9	Major earthquake. Serious damage.	15-Oct
8.0 or greater	Great earthquake. Can totally destroy communities near the epicenter.	One every year or two

Source: Michigan Tech, n.d.-a.

> magnitude estimates are about the same as Richter magnitudes for small to large earthquakes. But only the moment magnitude scale is capable of measuring M8 (read "magnitude 8") and greater events accurately. Magnitudes are based on a logarithmic scale (base 10). What this means is that for each whole number you go up on the magnitude scale, the amplitude of the ground motion recorded by a seismograph goes up ten times. Using this scale, a magnitude 5 earthquake would result in ten times the level of ground shaking as a magnitude 4 earthquake (and about 32 times as much energy would be released). (Michigan Tech, n.d.-b)

A third scale, the Modified Mercalli Intensity Scale, measures earthquake strength non-mechanically based on damage seen and reported historically. Table 2 shows the scale, associated perceptions of observers, and damages registered to structures.

Table 2: Modified Mercalli Intensity Scale

Intensity	Witness Perceptions and Damage
I	Felt by very few people; barely noticeable.
II	Felt by a few people, especially on upper floors.
III	Noticeable indoors, especially on upper floors, but may not be recognized as an earthquake.
IV	Felt by many indoors, few outdoors. May feel like heavy truck passing by.
V	Felt by almost everyone, some people awakened. Small objects moved. Trees and poles may shake.
VI	Felt by everyone. Difficult to stand. Some heavy furniture moved, some plaster falls. Chimneys may be slightly damaged.
VII	Slight to moderate damage in well built, ordinary structures. Considerable damage to poorly built structures. Some walls may fall.
VIII	Little damage in specially built structures. Considerable damage to ordinary buildings, severe damage to poorly built structures. Some walls collapse.
IX	Considerable damage to specially built structures, buildings shifted off foundations. Ground cracked noticeably. Wholesale destruction. Landslides.
X	Most masonry and frame structures and their foundations destroyed. Ground badly cracked. Landslides. Wholesale destruction.
XI	Total damage. Few, if any, structures standing. Bridges destroyed. Wide cracks in ground. Waves seen on ground.
XII	Total damage. Waves seen on ground. Objects thrown up into air.

Source: Michigan Tech University, n.d.-c.

Recent Studies on Induced Seismicity

Ryan Schultz et al. (2020). Hydraulic Fracturing-Induced Seismicity.

Ryan Schultz et al. in *Hydraulic Fracturing-Induced Seismicity* observe that "It has been well documented that subsurface disposal has the potential to induce earthquakes." They note that other anthropogenic activities also have the potential to cause induced earthquakes, including "underground mining, deep artificial water reservoirs, oil and gas extraction, geothermal power generation, and wastewater disposal."

Of primary interest to Canadian readers, Schultz et al. documents the history of hydraulic fracturing-related seismicity in several Canadian jurisdictions where hydraulic fracturing is commonly practiced. They observe that the first documented case of multiple earthquakes induced by HF occurred in the Horn River Basin, which straddles the border between the Northwest Territories and British Columbia (BC), in northwestern Canada. The Horn River Basin, Schultz observes, holds an estimated marketable dry gas resource of more than 70 trillion cubic feet (2.0 × 1012 m3), making it one of the largest shale gas plays in North America (Schulz et al., 2020).

Also, potentially of interest to Canadian readers is induced seismicity seen in the Wabamun/Exshaw/Banff Formation in the Alberta Basin, Canada. Schutlz et al. report that more than 60 small earthquakes (up to 3.0 ML) with similar waveforms were detected from December 2011 to March 2012 north of Cardston, Alberta. This area had no prior documented seismic activity of comparable magnitude or frequency. Per Schultz et al., the timing of these earthquakes followed five stages of hydraulic fracturing operation stimulation, and Schultz et al. concluded they were induced by the contemporaneous HF well completion. Induced seismicity is also well-documented in the Duvernay Formation in the Alberta Basin, and the Montney Formation in the Western Canada Sedimentary Basin (Schultz et al., 2020).

In their findings, Schultz et al. (under the "Plain Language Summary") conclude that "The widespread use of HF has resulted in a significant increase in induced earthquakes. In this paper, we provide a review of all the reported cases of HF-induced earthquakes: in Canada, the United States, the United Kingdom, and China. Some of these cases are exceptional [China], having events as large as 5.7 ML or earthquakes triggered up to 1.5 km away. That said, there are common themes that are repeated in all of the cases: similar waveforms, swarm-like sequences, proximity to HF stimulation in time and space, and that only the small minority of HF wells induced earthquakes."

Allan R. Chapman (2021). Hydraulic Fracturing, Cumulative Development and Earthquakes in the Peace River Region of British Columbia, Canada.

In a 2021 review of hydraulic fracturing and the induction of earthquakes in the Peace River region of British Columbia, Allan R. Chapman observes that unconventional petroleum development involving large-volume fluid injection into horizontal wellbores began in the Montney Trend of northeast British Columbia, Canada, in 2005, quickly initiating earthquakes. Earthquake frequency increased substantially in the Montney by 2008 in relation to the number of wells fracked and the volume of injected frack water.

Chapman (2021) used a "spatiotemporal filter" to associate earthquakes with hydraulically fractured wells, finding that "a total of 439 earthquakes (M 1.0 – 4.6) during 2013–2019 have close association with HF activity, of which 77% are associated with three operators. Fifteen percent of HF wells in the Montney are associated with these earthquakes, while 1.7% of HF wells are associated with M ≥ 3.0 earthquakes."

Induced seismicity in the Montney Formation seems somewhat higher than in other Canadian unconventional gas-bearing regions. Chapman (2021: 61) reports that "the Canadian National Earthquake Database contains 175 earthquakes for the 2000–2012 period (M 1.0 – 4.2) with epicentres in the Montney, of which 37 earthquakes were M ≥ 3.0, with a maximum magnitude of M 4.2. For just the 2013–2019 period, following the enhancement of the seismic monitoring network, 975 earthquakes were recorded (M 1.0 – 4.6) across the Montney, 647 in the North Peace Ground Motion Monitoring Area (NPGMMA), 227 in the Kiskatinaw Seismic Monitoring and Mitigation Area (KSSMA) and 101 across the remainder of the Montney. Fifty-six earthquakes (6%) were M ≥ 3.0. Five earthquakes exceeded M 4.0 (three in the KSMMA and two in the NPGMMA)."

Chapman notes that earthquakes with magnitudes ≥ 3.0 are generally felt at ground level, "at some distance from the earthquake epicentre; at magnitudes ≥ 4.0 the surface manifestation can be substantial, with damage to buildings and infrastructure." Chapman notes that these M ≥ 3.0 earthquakes are a threshold magnitude for events of particular interest, as they are the drivers of public safety and infrastructure risk (Chapman, 2021). For this reason, as we will discuss later in this update, conventional risk management techniques (a traffic-light monitoring system described below) applied to control induced seismicity used in other hydrocarbon formations might be insufficient to manage this risk in parts of the Montney formation, and, as Chapman concludes, "There may be locations and values in NEBC [North East British Columbia] where hazard avoidance, such as no-fracking zones, is essential and necessary."

Germán Rodríguez-Pradilla et al. (2022). Basin-Scale Multi-Decadal Analysis of Hydraulic Fracturing and Seismicity in Western Canada Shows Non-Recurrence of Induced Runaway Fault Rupture.

Rodríguez-Pradilla et al. examine the relationship between hydraulic fracturing and seismicity in Western Canada between January 1, 2000 and January 1, 2020. While finding evidence of hydraulic fracturing-induced seismicity, including episodes of "runaway fault rupture" in which seismicity travels along and disrupts fault structures a significant distance from the fracturing operations, their findings contain some counter-intuitive elements which suggest that fracturing-induced seismicity may not have a linear relationship with the extent of hydraulic fracturing in an area, nor the injection volumes of hydraulic fracturing liquid.

As they summarize, “We fit a seismic efficiency ratio (SEFF), the ratio of the net seismic moment release and the forecasted maximum moment, and find that the obtained SEFF exhibits a complex evolution in such areas, with anomalously high seismic activity arising from inferred runaway rupture processes on pre-existing faults. In 93% of cases where exceedance of SEFF = 0.5 occurred (i.e., in 13 out of 14 cases), representing the presumed onset of stored tectonic stress release, continued injections within the same 0.2° × 0.1° area (in Latitude x Longitude, of approximately 13 × 11 km) did not lead to further seismicity with characteristics of runaway rupture” (Rodríguez-Pradilla et al., 2022: 11). As they detail elsewhere, it seems that seismicity risks actually diminish over time as gas-bearing formations are hydraulically fractured during development and production of oil and gas.

Recent Studies on Environmental Degradation

Bohyun Hwang et al. (2023). Environmental Implications of Shale Gas Hydraulic Fracturing: A Comprehensive Review on Water Contamination and Seismic Activity in the United States.

In a 2023 systematic review of the literature regarding the risks of water contamination and seismic activity in the United States, Hwang et al. reveals “multiple areas of concern, including water and soil contamination, seismic activity, and air pollution. A notable finding is the average use of 2.4 million gallons of water per well in hydraulic fracturing, of which only 15–35% is typically retrieved.”

Hwang et al. also reveal concerns about local water overutilization due to the large volumes of water consumed in hydraulic fracturing processes. “This large volume of water used in each well not only poses risks of becoming severely contaminated when retrieved but also impacts local water availability. Typically, only 15–35% of the water used for extraction is actually retrieved, increasing the risk of groundwater pollution and local water shortages” (Hwang et al., 2023).

With regard to the risk of contaminating shallow drinking water aquifers, Hwang et al. find that “While there has been limited direct evidence tying shallow potable aquifer contamination specifically to deep hydraulic fracturing, there are documented cases of contaminants, such as stray natural gases and drilling-related fluid spillages in close proximity to fracking sites.” Soil contamination is also a risk recognized in the Hwang review. “Soil pollution associated with hydraulic fracturing can result from the accumulation of various contaminants, including metals, salts, organic compounds, and naturally occurring radionuclides (NORM). The presence of NORM, such as radium isotopes, in wastewater fluids from hydraulic fracturing operations can pose significant risks to the environment and human health” (Hwang et al., 2023).

Despite these documented risks, Hwang et al. (2023) observe that “several mitigation measures can help protect groundwater quality. These include the use of high-intensity and multiple casings, cementing, and underground water monitoring.”

Air pollution generation is also identified as a risk arising from hydraulic fracturing operations. Hwang et al. (2023) observe “Air pollution is a significant environmental concern associated with shale gas hydraulic fracturing. Despite advancements in technology and emissions reduction within the petroleum and natural gas industry, the production of shale gas still contributes to air pollution, primarily through the release of methane gas, which “can escape from various points in the production process, including wellheads, pipelines, and storage tanks.”

Hwang et al. (2023) also observe that other air pollutants are generated both in the hydraulic fracturing process, as well as the ancillary activities surrounding it, such as transportation and power generation. “Hwang notes that in addition to methane [considered a potent greenhouse gas], other air pollutants are associated with shale gas extraction and processing, and observes that volatile organic compounds (VOCs) are also emitted in HF operations, contributing to air pollution and the formation of a ground-level ozone."

Ancillary activities that support hydraulic fracturing also offer potential environmental concerns. Hwang et al. note that "…the use of diesel-powered machinery and vehicles in drilling and hydraulic fracturing activities releases air pollutants, including nitrogen oxides (NOx) and particulate matter (PM)." They further note that "fracking operations also release toxic air pollutants, such as benzene, toluene, ethylbenzene, and xylene, which pose risks to respiratory and neurological health" (2023).

Alison M. Bamber et al. (2019). A Systematic Review of the Epidemiologic Literature Assessing Health Outcomes in Populations Living near Oil and Natural Gas Operations: Study Quality and Future Recommendations.

In a 2019 article published in the open-access journal, the *International Journal of Environmental Research on Public Health,* Alison Bamber et al. conducted a systematic review of epidemiological studies that examined the public health impacts of hydraulic fracturing. They surveyed the epidemiological literature with screening criteria to identify only studies of the highest quality. Bamber et al. identified twenty studies that met their criteria of a human health epidemiologic study evaluating the potential health effects of living near oil and natural gas operations in the United States.

Bamber et al. developed weight-of-evidence conclusions from these studies regarding 32 different health effects, which ranged from "insufficient evidence to limited evidence."

On the issue of ***birth defects and birth outcomes***, the Bamber et al. (2019) review identified "nine studies comprising 12 low to moderate certainty findings that identified the relationship between women who lived near oil and natural gas operations and the likelihood that their child was born with birth defects or other types of adverse health outcomes at birth." Two of the identified studies evaluated birth defects in infants of mothers who lived at varying proximities to oil and natural gas development during pregnancy. Bamber et al. (2019) conclude that "These low-certainty studies resulted in insufficient evidence to determine if living near ONG operations during pregnancy is associated with birth defects since there was only one study per outcome."

Eight studies evaluated adverse birth outcomes pertaining to typical health indicators such as birthweight, length of gestation, infant mortality, and similar indicators. Bamber et al. (2019) found that "Overall, there are conflicting findings across studies resulting in either mixed or insufficient evidence of adverse birth outcomes associated with living near oil and natural gas operations during pregnancy."

Three of the eight studies identified along with the findings were classified as having a moderate level of certainty rating due to strength in their study designs, but were contradictory, demonstrating "both positive and null associations for multiple health outcomes. All other studies included in the Bamber review were ranked as low certainty "because of limitations within the study design or missing key elements" (Bamber et al., 2019)

With regard to ***potential cancers*** caused by proximity to oil and natural gas operations, Bamber et al. reviewed studies examining various types of adult-onset and childhood cancers. They identified three studies which met review criteria, and reviewed seven potential cancer outcomes, including such cancers as Hodgkin's lymphoma, and childhood central nervous system tumors. Overall, Bamber et al. (2019) concluded, "the weight of evidence is insufficient for all but one of the cancer outcomes since there is only one study for each. There is mixed evidence for childhood leukemia owing to conflicting study findings." None of the three cancers received a moderate level of certainty rating in the Bamber systematic review.

With regard to ***respiratory health impacts***, the Bamber et al. systematic review identified six studies which satisfied criteria for inclusion in the review. They found "There were three low to moderate rated health outcomes from six studies evaluating the associations between living near ONG and respiratory health effects. A single moderate certainty study with one study outcome indicated a limited weight of evidence for an association with asthma exacerbations" (Bamber et al., 2019).

Bamber et al. included five other low-rated studies that evaluated the occurrence of respiratory effects (symptoms and hospitalizations) but found conflicting evidence for both categories.

With regard to studies examining ***neurological health outcomes***, Bamber et al. identified four studies which satisfied their criteria for inclusion in the review. Three studies identified self-reported neurological symptoms such as severe headaches, dizziness/ depression, sleep disorders, anxiety issues, and related neurological problems. The three studies were inconsistent in identifying such health outcomes, with two studies inconclusive, and only one published study showing a "null association," with neurological health effects.

Bamber et al. identified 20 published epidemiologic studies that evaluated potential associations between oil and natural gas operations and health outcomes. These studies assessed 32 different health outcomes, ranging from self-reported symptoms to confirmed disease diagnoses. Because only a few outcomes were covered by multiple studies, Bamber et al. concluded there was insufficient weight of evidence for most health outcomes.

While Bamber et al. identified studies of populations living near ONG operations which provided limited evidence of harmful health effects, including asthma exacerbation, for all other health outcomes, they found "conflicting evidence (mixed), insufficient evidence, or in some cases, a lack of evidence of the possibility for harmful health effects" (2019).

Bamber et al. further observed that the majority of the findings reported in the 20 studies they identified were ranked as having low certainty, with study designs which made it difficult to establish clear links between exposures to substances potentially emitted directly from oil and natural operations and the health outcomes evaluated. Such limitations Bamber et al. note "are inherent to observational epidemiologic studies and include indirect exposure measurements, confounding bias, and subjective methods to determine health outcomes."

Finally, Bamber et al. (2019) note that "Taken together, these studies make it clear that the identities and exposure levels of substances people are exposed to when living, working, or going to school near ONG development have not been well characterized."

Klaus-Michael Wollin et al. (2020). Critical Evaluation of Human Health Risks due to Hydraulic Fracturing in Natural Gas and Petroleum Production.

As with seismicity and environmental degradation, risks to human health posed by hydraulic fracturing centre around water utilization throughout the fracturing process, notably, contamination of groundwater that is subsequently reused as drinking water. Klaus-Michael Wollin et al. offer a review of these risks.

Groundwater

Regarding groundwater pollution caused by hydraulic fracturing, Wollin et al. summarize: "The question of whether HF leads to widespread and systematic groundwater pollution is a matter of controversy" (Wollin, 2020) (internal referencing removed from quotes), and observe that in its draft on the *Assessment of the Potential Impacts of Hydraulic Fracturing for Oil and Gas on Drinking Water Resources* from 2015, the US EPA concluded that there was no such impact, though that conclusion was softened in the final report after objections from outside reviewers.

Wollin et al. observe that several studies have examined whether shale gas development systematically impacts public drinking water in Pennsylvania, where HG operations are common. They report that one 2017 study examined 424 community groundwater systems (with intakes lying within 10 km of at least one HF well pad) over five years (2011–2016), looking for chemicals related to hydraulic fracturing: 54,809 water samples were analyzed. Drilling an additional well pad within 1 km of groundwater intake locations increased shale gas-related contaminants by an average of 1.5–2.7 percent. The authors of this 2017 study concluded from their results that the health impacts of HF through water contamination remain an "open question."

Surface water

Wollin et al. (2020) report on a comprehensive study of the Marcellus Shale formation to clarify whether hazardous compounds used in HF can reach shallow groundwater aquifers and affect local water quality after being injected into deep shale horizons. They cited a 2015 study that detected hydrocarbons from diesel in "23 of 41 analyzed groundwater samples at concentrations ranging up to 157.6 μg/L." The study found that concentrations of benzene, toluene, ethylbenzene, and xylene were below the US EPA maximum contamination levels for drinking water and identified the presence of bis(2-ethylhexyl) phthalate, a known HF additive.

Health Risk

Wollin et al. also survey the literature on human health risks caused by proximity to oil and gas operations, but find that “So far, the scientific investigation of possible health risks mediated by hydraulic fracturing operations has led to inconsistent results. The most critical part of risk assessment in this context is the exposure assessment which is hampered by the unavailability of data from qualified baseline monitoring before the start of frac operations. Hence, when assessing the HF impact on the environment and human health it is often difficult or practically impossible to estimate the proportion of HF which is contributing to the existing exposure” (2020).

They also note that although available epidemiological studies have identified significant links between emissions from hydraulic fracturing processes and observed health effects, even extensive studies have been unable to establish clear causality.

Recent Studies on Risk Mitigation

Several studies in this latest update on the risks of hydraulic fracturing also discuss current mitigation techniques and possible improvements.

Earthquake risk mitigation

Risk management methods for mitigating induced seismicity risk have evolved from efforts to control the number and magnitude of seismic activity triggered toward systems that aim to manage the risk of such events to people and the built environment (Verdon, 2021). The "Traffic Light System," or TLS, is the most commonly used today.

In a TLS, extensive monitoring of seismic activity accompanies hydraulic fracturing processes, and thresholds are established to determine whether a fracturing operation can continue (green light), whether fracturing operators need to be more cautious/less vigorous in fracturing operations (yellow light); or whether fracturing operations need to be suspended (red light). In *Green, Yellow, Red, or Out of the Blue? An Assessment of Traffic Light Schemes to Mitigate the Impact of Hydraulic Fracturing-Induced Seismicity,* the pioneers in TLS development Verdon and Bommer (2021: 307), explain that "TLS thresholds have varied significantly between different jurisdictions. in the UK the red-light threshold was M 0.5, whereas in Fox Creek area of the WCSB it is M 4. Within Alberta, the regulator has also imposed red-light thresholds of M 2.5 in the vicinity of the Brazeau Dam, and M 3.0 near to the town of Red Deer. Other thresholds for HF-IS include Illinois, M 4; Oklahoma, M3.5; California, M 2.7; and Ohio, M 1.0."

In *A Risk-Based Approach for Managing Hydraulic Fracturing–Induced Seismicity,* Schultz et al. (2021a: 505) develop geographically specific thresholds for a TLS based on "an iso-nuisance tolerance of a 50% chance of 300,000 households being impacted by a community decimal intensity (CDI) of 3. CDI is a questionnaire-based measure that quantifies the degree of earthquake shaking felt by a person, with levels 2 to 6 roughly corresponding to the subjective criteria of just felt, exciting, somewhat frightening, frightening, and extremely frightening, respectively. Our nuisance tolerance was chosen to keep the number of exciting (CDI 3) felt reports at a manageable level [because only ~0.2% of the population reports their experience]. We chose an iso-damage tolerance of a 50% chance of 30 households being impacted at a damage state (DS) of 1. DS is a measure that quantifies the degree of building damage received from earthquake shaking, with levels 1 to 4 corresponding to damage that is slight or minor, moderate, extensive, and complete, respectively. This damage tolerance was chosen to minimize the chances that even cosmetic damage (DS 1) would occur. These tolerance choices are subjective value judgments. In practice, tolerances should be selected on the basis of input from all stakeholders" (internal sourcing removed).

Applying their risk-based methods to the Eagle Ford formation in the United States, Schultz et al. (2021a) generated a TLS which defines red light situations in the event of a range of 1–28 earthquakes in different areas of an oil and gas region being hydraulically fractured. A yellow light situation would be triggered where seismicity was 2 moments of magnitude lower than the level triggering a red light. Below this level of movement, operations would be considered in a green-light condition. Schultz et al observe that their geographically specific, risk-based approach to setting TLS thresholds should have broad applicability for hydraulic fracturing operations worldwide, as well as have applicability for use in managing earthquake risks from non-HF activities such as enhanced geothermal power generation projects (Shultz et al., 2021b).

Mitigating health risks

Having shown that risks to human health from hydraulic fracturing have not been well defined, Bamber et al. (2019) make suggestions for how such studies and understanding might be improved, by, for example:

- Suggesting regulators and policymakers work with public health researchers to pose specific questions that need to be answered, and partner with public health officials to evaluate the public's concerns.
- Public health officials should continue to monitor health concerns in areas with substantial oil and natural gas operations through centralized data collection and analysis.

Multi-state collaborations should be considered to collect consistent data from differing oil and gas basins across the United States to evaluate comprehensively the potential for adverse effects.

Mitigating environmental degradation

Air pollution: As mentioned above, air pollution increases in areas with hydraulic fracturing operations. However, there is limited evidence that these emissions cause ill health in nearby populations. Nonetheless, these risks might be mitigated via increased monitoring in areas engaged in HF activities and increased awareness campaigns (air pollution alerts) issued by those conducting HF operations. These measures would ensure that affected populations are informed and empowered to take measures to reduce their exposure and risk.

Water contamination: As one of the recent studies examining water impact observes, "several mitigation measures can help protect groundwater quality. These include the use of high-intensity and multiple casings, cementing, and underground water monitoring" (Hwang et al., 2023). As we noted in the 2020 update (Murphy, 2020), fracking's potential impacts on drinking water and seismicity are not the result of fracking in itself, but rather certain procedures in wastewater storage and disposal. Amending operations (such as the lining of storage pits and the depths to which wastewater is injected) can reduce these risks. The potential overuse of local water supplies, which places a strain on water availability in some local communities, can be ameliorated through the introduction of flexible pricing for water. This can help avoid waste and ensure that the available water supply is channelled to its high-valued uses.

Summary

In this latest update, the fourth assessment of the current state of knowledge regarding the risks of hydraulic fracturing and their mitigation includes six high-level reviews or summary publications. These publications shed additional light on the risks of hydraulic fracturing, particularly pertaining to seismicity and water overuse/contamination, as well as several studies examining direct effects on human health.

As with previous reviews, this one finds that knowledge about the risks of hydraulic fracturing continues to accumulate. There are indications that some risks, such as increased seismicity and impacts on groundwater, may warrant greater mitigation efforts than previously thought necessary.

Monitoring of air and water quality in areas engaging in hydraulic fracturing may need to be increased, and exposure notification systems strengthened to ensure that nearby populations are enabled to manage their risk exposures from hydraulic fracturing operations. In the case of seismicity, again, increased monitoring of seismic activity around hydraulic fracturing operations may be required, with operations being limited in scale and speed to prevent higher-order seismicity. In at least one area, parts of the Montney Formation in British Columbia, seismic sensitivity to hydraulic fracturing might even justify putting certain areas off limits for hydraulic fracturing activities entirely.

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