WORKING PAPER · NO. 2023-06

Internalizing Externalities: Disclosure Regulation for Hydraulic Fracturing, Drilling Activity and Water Quality

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JANUARY 2023

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INTERNALIZING EXTERNALITIES:
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We would like to thank Wes Austin, Jenn Baka, Marianne Bertrand, Thomas Bourveau, Susan Brantley, Matthias Breuer, Thomas Covert, Aytekin Ertan (discussant), Michael Greenstone, Chris Hansen, Elaine Hill (discussant), Ginger Jin, Ryan Kellogg, Sendhil Mullainathan, Felix Oberholzer-Gee, Joseph Shapiro, Luigi Zingales and workshop participants at the AEA 2022 Annual Meeting, Bocconi, Chicago Booth Micro Lunch, Columbia Business School, EPA, FARS, Frankfurt School of Finance & Management, Goethe University Frankfurt, HEC Paris, University of Mannheim, University of Maryland, LMU München, University of San Diego, University of St Gallen, the UN PRI Seminar Series and the Shale Gas Network Conference for helpful comments. We also gratefully acknowledge the excellent research assistance of Patricia Breuer, Tom Kim, Igor Kuznetsov, Alessandro Maimone, Fabian Nagel, Christopher Nance, Claudia Serra, and Zirui Song.

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JEL No. D62,G38,K22,K32,L71,L72,M41,M48,Q53

ABSTRACT

The rise of shale gas and tight oil development has triggered a major debate about hydraulic fracturing (HF). In an effort to mitigate risks from HF, especially with respect to water quality, many U.S. states have introduced disclosure mandates for HF wells and fracturing fluids. We use this setting to study whether targeting corporate activities that have dispersed environmental externalities with disclosure regulation to create public pressure reduces their environmental impact. We find significant improvements in water quality, examining salts that are considered signatures for HF impact, after the disclosure mandates are introduced. We document effects along the extensive and the intensive margin, though most of the improvement comes from the latter. Supporting this interpretation, we find that, after the disclosure mandates, operators pollute less per unit of production, use fewer toxic chemicals, and cause fewer spills and leaks of HF fluids and wastewater. We also show that disclosure enables public pressure and that this pressure facilitates internalization.

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"Publicity is justly commended as a remedy for social and industrial diseases. Sunlight is said to be the best of disinfectants." (Justice Louis D. Brandeis, Harper's Weekly 1913)

1. Introduction

In this study, we pose the question in Brandeis' famous article and ask what publicity (or transparency) can do when it comes to environmental externalities. This question is highly relevant as transparency regulation has become a key policy tool in many areas (Weil *et al.*, 2006, Dranove and Jin, 2010, Weil *et al*., 2013, Leuz and Wysocki, 2016). Recently, disclosure requirements have been proposed for corporate GHG emissions and other sustainability issues (Christensen *et al.*, 2021, SEC, 2022). Targeting corporate environmental impacts with disclosure has a long tradition in the U.S., going back to the 1986 Emergency Planning and Community Right-to-Know Act (e.g., Oberholzer-Gee and Mitsunari, 2006). However, we still have relatively little evidence as to whether mandated disclosure works for behaviors with dispersed negative externalities as well as how it produces the intended effects.

We investigate these questions in the context of unconventional oil and gas (O&G) development, which combines horizontal drilling with hydraulic fracturing (HF) to extract shale gas and tight oil in deep formations. HF is considered the most important innovation in the energy sector since the introduction of nuclear energy, which has dramatically increased U.S. energy production and lowered consumer prices (e.g., Mason *et al.*, 2015, Bartik *et al.*, 2019, Black *et al.*, 2021). But the rise of HF has also been very controversial due to the associated health and environmental risks, including air and water pollution (e.g., Jackson *et al.*, 2014, Currie *et al.*, 2017, Bonetti *et al.*, 2021). Chief among them are concerns about the chemicals in the HF fluids (e.g., EPA, 2016, Vengosh *et al.*, 2017) and the large amounts of wastewater generated by HF (Vidic *et al.*, 2013, Vengosh *et al.*, 2014). In contrast, the industry maintains that environmental and health risks of HF are limited (API, 2017; 2019).

In an effort to shed light on HF practices and given the lack of federal regulation (Maule *et al.*, 2013, Fink, 2019), many U.S. states have introduced mandatory disclosure rules for newly fractured wells starting around 2010. The rules require HF operators to disclose details on their drilling activity and the chemical composition of the HF fluids. These mandates were hailed as bringing more transparency to controversial practices of an industry with a long history of regulatory exemptions (Konschnik, 2014, Fink, 2019).[1] Yet, many voiced skepticism that the disclosure rules would make HF safer or reduce its environmental impacts, especially considering the trade secret exemptions and the lack of penalties for non- or misreporting (e.g., McFeeley, 2012, Maule *et al.*, 2013, Konschnik, 2014, Tiemann and Vann, 2015).

Conceptually, the effect of state rules is not obvious either. On one hand, disclosure could enable stakeholders and the public to impose costs (or an implicit tax) on HF operators, which in turn should incentivize them to reduce pollution or to invest in cleaner practices (Pigou, 1920, Baumol and Oates, 1988, Goolsbee, 2004, Acemoglu *et al.*, 2012). On the other hand, whether disclosure is effective depends on the accessibility and dissemination of the information and the extent to which the publicity creates pressure or allows users to take actions that are costly to firms (Tietenberg, 1998, Weil *et al.*, 2006, Weil *et al.*, 2013).

Thus, our study analyzes the effectiveness of transparency targeting environmental externalities and the public pressure that disclosure regulation creates. The analysis provides the first empirical analysis of state disclosure rules for HF operators with respect to drilling activity and surface water pollution and, more generally, an assessment of the impact of HF on U.S. water quality over time. We focus on water pollution given its substantial environmental and social costs (Entrekin *et al.*, 2011, Keiser and Shapiro, 2019a, Keiser and Shapiro, 2019b, Hill and Ma, 2021). Further, several recent studies document the impact of HF wells and spills on water quality (Hill and Ma, 2017, Agarwal *et al.*, 2020, Bonetti *et al.*, 2021). Thus, rather than examining the required information or the composition of the HF fluids, which would

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[1] For example, although the Underground Injection Control provision of the Safe Drinking Water Act (SDWA) normally regulates the use (and disclosure) of the fluids injected into the ground, HF is exempt from this provision (except when using diesel fuel).

limit our analysis to the post-disclosure period for most wells,[2] we analyze surface water quality to assess changes in the environmental impact and practices of unconventional O&G development resulting from the HF disclosure rules.

Our sample comprises a large geo-coded database of 154,324 HF wells from 16 states and 325,351 surface water-quality observations from 2,209 watersheds (HUC10s)[3] with and without HF activity. The sample spans 14 years (2006-2019). Our water quality analysis focuses on the concentrations of four ions: bromide (Br^-), chloride (Cl^-), barium (Ba) and strontium (Sr). These four ions are the likely mode of detection if and when surface water impact exists (Vidic *et al.*, 2013, Brantley *et al.*, 2014). For one, they are usually found in high concentrations in flowback and produced water from HF wells and therefore considered signatures (Vengosh *et al.*, 2014, Rosenblum *et al.*, 2017). Moreover, unlike some organic components of HF fluids, the four ions do not biodegrade, and their presence can and has been measured several years after HF spill events (Lauer *et al.*, 2016, Agarwal *et al.*, 2020). They are also measured in many locations with reasonable frequency, so that baseline chemical concentrations can be reliably estimated (Bonetti *et al.*, 2021).

The disclosure rules for HF wells were imposed by the states at different points in time allowing us to perform staggered difference-in-differences analyses for water quality and drilling activity. We estimate panel regressions with monitoring station fixed effects to control for differences in local water quality. In addition, we use state×month×year fixed effects or, alternatively, HUC8×month×year fixed effects to flexibly control for regional or sub-basin changes over time. Thus, the identification of the disclosure effects comes from differences in the pre- and post-disclosure evolution of ion concentrations between watersheds (HUC10) with

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[2] Some operators provided chemical disclosures voluntarily before the mandates, which we exploit in one analysis. However, the sample of voluntary disclosures is limited and likely selected. See Fetter *et al.* (2018).

[3] HUC10s (or watersheds) are homogenous geologic areas that drain or shed surface water into a specific waterbody. There are roughly 22,000 watersheds in the U.S. The average size of a watershed is 230 square miles. Prior work shows that the impact of HF wells on surface water are detectable at the watershed level (Agarwal *et al.*, 2020; Bonetti *et al.*, 2021), which is why we perform our analysis at this level.

HF activity and close-by control watersheds without HF activity that are in the same state or in the same sub-basin (HUC8). To further reduce heterogeneity between treatment and control watersheds, we also restrict the analysis to watersheds that are situated over shales.

We find that HUC10s with pre-disclosure HF activity exhibit a significant decrease in ion concentrations after the state disclosure mandates become effective. Based on the average ion concentrations in watersheds with HF activity, the estimated coefficients correspond to watershed-level decreases in chemical concentrations of 8,469.83 μg/l for Cl^-, 5.73 μg/l for Ba, and 20.59 μg/l for Sr. These effects imply meaningful declines in ion concentration levels relative to their baselines, ranging from 4.4 percent for Sr to 17.8 percent for Cl^-.

Reassuringly, we do not find such declines in three other water quality proxies (dissolved oxygen, phosphorus and fecal coliforms) that are not signatures for HF-related water impacts but should reflect changes in economic activity related to unconventional O&G development as well as other potential confounds, such as agriculture. In a similar spirit, we examine water quality changes related to conventional drilling, to which the HF disclosure rules do not apply, and find that the estimated effects do not mimic the results for HF wells. Additionally, we search for other state regulatory changes that apply to HF activity, such as wastewater management rules (e.g., on injection wells and pit lining) and HF drilling standards (e.g., for well casings and blowout controls). These other rules could confound our analysis of the disclosure rules, but we find that controlling for a broad range of other HF regulations, individually or jointly, does not alter our inferences with respect to HF disclosure regulation. We also perform extensive tests with respect to the timing of the state adoption dates, as it is an important source of identification.

Next, we analyze the margins along which HF operators adjust their practices after the disclosure mandate. We examine whether the documented improvements in water quality come from less HF drilling activity (extensive margin) or from changes in operator practices and technology that reduce the per-well impact on water quality (intensive margin). For the former, we find that the rate of new HF well entry declines by roughly 5 percent. This decline contributes roughly 14% of the overall decrease in water pollution in the post-disclosure period.

For HF operator adjustments along the intensive margin, we provide four sets of analyses to shed light on how operators adjust practices. First, we investigate whether wells spudded in the post-disclosure period exhibit smaller per-well effects on ion concentrations than wells spudded in the pre-disclosure period. We find that, after the disclosure mandates come into force, the per-well impact decreases. Even more convincingly, we see changes in the ion concentration patterns shortly after well spudding. Bonetti *et al.* (2021) document spikes in all four HF-related ion concentrations between 91 and 180 days after spudding. These spikes are not only an order of magnitude larger than the long-run impacts but also occur when HF wells generate large amounts of wastewater. We show that these concentration spikes are attenuated after mandatory disclosure.

Second, we analyze the environmental performance of O&G production, relating output to the ion concentration level by watershed. Consistent with our per-well analyses, which suggest improvements in HF practices, we find that O&G production per unit of water pollution increases after the disclosure mandates come into force. Third, we examine changes in the HF fluids around the introduction of the disclosure regulation. We document a decrease in the use of hazardous chemicals and chloride-related chemicals in HF fluids after the disclosure mandate, albeit relative to voluntary disclosures in the pre-period. Fourth, we study changes in HF-related incidents (e.g., spills, leaks and accidents related to wastewater), which are likely a key pathway by which HF wells affect water quality (Agarwal *et al.*, 2020; Bonetti *et al.*, 2021). The new disclosure requirements could make HF operators exercise more caution in their practices, including the handling of wastewater. Consistent with this idea, we detect a decline in the number of HF-related incidents, especially those related to the handling of wastewater and fracking pits. Taken together, our evidence suggests that, after mandatory disclosure, HF practices improve in material ways, reducing the surface water impact from new HF wells.

In our final set of analyses, we show more explicitly that targeted transparency operates through public pressure. This pressure can take many forms. Disclosure regulation can enable social movements, environmental groups, local communities, and the media to exert pressure on HF operators (Pargal and Wheeler, 1996; Freedman *et al.*, 2012, Johnson, 2020). For instance, social movements can shame operators for their use of toxic chemicals. Moreover, NGOs and watershed groups monitor surface waters and look for chemical signatures of HF flowback and produced water to identify contamination (Shale Network, 2020, Watson, 2022). They can also put pressure on regulators with respect to enforcement. In addition, HF disclosures can stimulate public debate about new stricter HF regulation, including bans, which in turn creates incentives for industry to improve HF practices.

Using several different proxies, we find that water quality improvements after the disclosure mandate are greater in areas where public pressure is higher. We find larger decreases in HF-related ion concentrations in areas with a greater presence of local environmental NGOs and in counties with more local newspapers. We show that public pressure, measured by media coverage and internet searches, intensifies after disclosure regulation and that the improvements in water quality are more pronounced in states with more news articles discussing HF and water pollution, and with more Google searches for HF after the disclosure mandate. Furthermore, we document larger ion declines in areas where a larger fraction of wells is owned by publicly traded firms, consistent with the idea that listed firms likely face more public scrutiny than private operators. We also find incremental water quality improvements when the dissemination of the HF disclosures to the public further improves after the state mandates are in place. All these results underscore the central role of public pressure created by disclosure regulation, as Justice Brandeis predicted for publicity.

To connect the reduced environmental impact with features of the disclosure mandates, we exploit variation in how easy it is to obtain trade secret exemptions or how quickly operators have to file the disclosures, as both features plausibly affect the effectiveness of the mandates.

Consistent with this notion, we find larger increases in water quality for states where disclosure mandates offer fewer trade secret exemptions and require timelier disclosure. This evidence is consistent with work in regulatory economics, highlighting the importance of implementation and enforcement for regulatory outcomes (Magat and Viscusi, 1990, Djankov *et al.*, 2003, Shleifer, 2005, Christensen *et al.*, 2016).

Our study makes two primary contributions. First, we contribute to a burgeoning literature studying the use of disclosure regulation in public policy, in particular, to drive changes in firm behavior (e.g., Weil *et al.*, 2006, Dranove and Jin, 2010, Christensen *et al.*, 2021).[4] Much of this literature examines information dissemination about "negative" firm behaviors, such as violations of standards or rules, mining accidents or tax avoidance (e.g., Bennear and Olmstead, 2008, Delmas *et al.*, 2010, Dyreng *et al.*, 2016, Christensen *et al.*, 2017, Chen *et al.*, 2018, Johnson, 2020, Rauter, 2020; Buntaine *et al.*, 2022) or quality disclosures to consumers, such as restaurant hygiene (e.g., Jin and Leslie, 2003). But disclosure rules do not always work as intended (e.g., Bui and Mayer, 2003, Dranove *et al.*, 2003, Weil et al, 2006). Moreover, it is not obvious that the real effects documented in prior studies carry over to settings where publicity targets corporate actions with dispersed negative externalities (such as air and water pollution), for which Coasian bargaining might be difficult.

In this regard, our paper is closer to recent studies on mandated disclosure of greenhouse gas emissions (GHG). Downar *et al.* (2021), Yang *et al.* (2021) and Tomar (2022) examine mandatory reporting of corporate GHG emissions in the UK and in the U.S., documenting reductions in GHG emissions between 7 and 15 percent. Tomar (2022) attributes the effects primarily to inter-firm benchmarking and learning. In our setting, the HF disclosure form does not reveal pollution per se. Instead, it provides transparency about the underlying activity and the question is whether such information can create sufficient pressure to alter corporate

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[4] There is also a growing accounting literature on the real effects of disclosure and reporting regulation. See Leuz and Wysocki (2016) and Roychowdhury *et al*. (2019) for extensive reviews of this literature.

behavior. Our study documents that transparency about the underlying activities contributes to the internalization of negative external effects. It also provides extensive evidence on how HF operators change their practices and the public pressure mechanism.

Second, our study presents new evidence on the environmental impact of HF on U.S. surface waters, covering an extended time period and much of the HF boom as well as documenting a post-disclosure reduction in this impact. Such evidence is not only important in light of the public controversy about HF, but also when considering its role for U.S. energy supply. This evidence complements other work in environmental economics showing that major regulatory initiatives, like the Clean Air Act or the Clean Water Act, have been effective at limiting environmental pollution (Greenstone, 2002, Greenstone, 2004, Keiser and Shapiro, 2019a, Keiser and Shapiro, 2019b). Our results are different and important because, unlike the aforementioned acts, mandating disclosure does not directly regulate quantities (e.g., economic activity or environmental pollution).

In terms of the setting, our paper is closely related to studies by Fetter (2017) and Fetter *et al.* (2018). The former shows that, after the introduction of the state disclosure rules, well operators report using fewer hazardous chemicals in their HF fluids, relative to prior voluntary disclosures. The latter examines whether the disclosure rules facilitate learning and imitation across operators, using the chemical mix of HF fluids. Fetter *et al.* (2018) find that firms' chemical choices converge to the mix of more productive wells. These findings are complementary to ours. However, convergence of operator practices does not necessarily imply lower environmental impact. Towards this end, we present evidence on water pollution, HF-related incidents and drilling activity.

2. Empirical Setting and Institutional Details

2.1 Hydraulic Fracturing and Water Quality

Unconventional development has tapped into large O&G reserves that sit in low-permeability formations and require HF for extraction. In the U.S., the production of shale gas and tight oil is projected to expand to 29.0 trillion cubic feet (tcf) by 2040, up from 13.6 tcf produced in 2015 (EIA, 2018). However, despite its important role for energy production and independence, unconventional development has been controversial due to its potential negative effects on human and ecological health (Colborn *et al.*, 2011, Entrekin *et al.*, 2011, Mason *et al.*, 2015, Currie *et al.*, 2017, Hill and Ma, 2022). Among the environmental risks, water pollution is a key concern for at least two reasons (McKenzie *et al.*, 2012, Vidic *et al.*, 2013, Vengosh *et al.*, 2014, EPA, 2016). First, aside from water and propping agents like sand, HF fluids contain a series of additives (e.g., friction reducers, surfactants, scale inhibitors, biocides, gelling agents, gel breakers, and inorganic acid), which are potentially toxic or harmful (Vidic *et al.*, 2013, Vengosh *et al.*, 2014). Second, HF wells produce large amounts of wastewater, initially the partial flowback of HF fluids and over time increasingly produced water from the deep formations. The latter brine is naturally occurring water into which organic and inorganic constituents from the deep formations have dissolved, resulting in very high salt concentrations (Rosenblum *et al.*, 2017).

In light of these concerns, the Environmental Protection Agency (EPA) reviewed and synthetized available scientific evidence concerning the impact of HF on U.S. water resources, following a request by the U.S. Congress. The final report concludes that “hydraulic fracturing activities can impact drinking water resources under some circumstances” (EPA, 2016). Contamination of groundwater has been ascribed to either cementing failures or the migration of stray gas and deep formation brines through faults (Osborn *et al*., 2011, Jackson *et al*., 2013, Darrah *et al*., 2014, Llewellyin *et al*., 2015). In Pennsylvania, Hill and Ma (2017, 2022) document increases in shale gas-related contaminants at ground-water intake locations of community water systems that are in close proximity and downstream to gas wells. For surface water, there are a number of studies documenting contaminations after spills and leaks (e.g., Lauer *et al*., 2016, Maloney *et al.*, 2017, Agarwal *et al*., 2020) and two large-scale studies on the link between unconventional O&G development and surface water quality. Olmstead *et al*.

(2013) estimate the effects of HF and wastewater treatment facilities on downstream chloride concentration and total suspended solids (TSS) in Pennsylvania. They find higher chloride concentration in surface water downstream from treatment facilities and that HF well density within a watershed is associated with increased TSS concentrations (but not chloride concentrations). Using a large geo-coded database of water quality observations and HF wells for the U.S., Bonetti *et al*. (2021) examine the association between new HF wells and ion concentrations in surface water that are specific to HF (barium, bromide, chloride and strontium). They find evidence of elevated ion concentrations for several shales (or states) and in many watersheds. The estimated association is larger for wells with large amounts of produced water, for wells located in areas with high-salinity formations and for wells that are located upstream and in proximity of water monitoring stations. Potential pathways for surface water contamination are accidents, leaks and spills of HF fluids, flowback or produced water (on-site, related to HF pits or brine trucking), and the direct disposal of untreated wastewater from HF operations (unauthorized or permitted) (Vidic *et al.*, 2013, Vengosh *et al.*, 2014, EPA, 2016, Agarwal *et al.*, 2020, Bonetti *et al.*, 2021).

2.2 HF Chemicals Disclosure Regulation

Although HF is subject to the Clean Water Act, it is exempted from the SDWA provision on underground injections, which regulates monitoring, recordkeeping and reporting requirements for any injection of chemicals endangering drinking water sources (except for diesel fuel). Because of this exemption, granted by Section 322 of Energy Policy Act (2005), HF operators had no obligation to disclose the components used in the HF fluids. As public concerns about the environmental and health effects of HF grew, some operators started voluntarily disclosing the composition of the HF fluids. Beginning in 2010, several states mandated the disclosure of the chemical components used in HF on a well-by-well basis. There are currently eighteen states with significant hydraulic fracturing activity and chemical disclosure laws for the HF fluids (Konschnik and Dayalu, 2016).[5] These rules were adopted at different points between 2010 and 2015 (Table 1, Panel A and Figure 1).[6]

The HF forms require information on the operator, well identification number, exact location (state, county, latitude, longitude), job start and end dates, some drilling information, such as the vertical well depth and the volume of water used, as well as details on HF fluids. The required fluid information varies only slightly across states. Typical disclosures are the ingredient name (plus trade name if applicable), the chemical abstract service number, the concentration in the fluid (typically the maximum concentration in any fracturing stage), and the supplier name (see Appendix for an example). All states allow operators to obtain trade secrets exemptions for chemicals that are considered confidential business information under the Uniform Trade Secrets Act. The prerequisites and procedures to obtain such exemptions vary across states (McFeeley, 2012, Jiang, 2022).[7] If granted, the form still discloses the chemical concentration, but the name and chemical abstract service number are omitted.

The disclosure forms have to be filed with a state agency or, predominantly, with the FracFocus registry,[8] which is a web-based database created by the Groundwater Protection Council and the Interstate Oil and Gas Conservation Commission. State rules stipulate when the disclosure must be made, typically between 30 and 120 days after the spudding or the completion of the HF well. In addition, all states require HF operators to submit well

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[5] California and Michigan have disclosure rules but are not included in our sample because we lack water quality data (California) or data on drilling activity (Michigan). Our well databases provide information for only 18 wells in Michigan. In California, our databases include 212 wells, but all of them are located in two watersheds without water quality observations.

[6] In Pennsylvania, operators had to report *to the regulator* information on the chemicals used in the drilling process starting 14 months before the adoption of the public disclosure rules. In Colorado, beginning from April 2009, operators had to keep a record of the chemicals used in the drilling process and the regulator had the right to access to these records during inspections. In the other states, we are not aware of such reporting requirements by the regulators.

[7] The prerequisites and procedures to claim a trade secret exemption can entail the following: (1) a formal request is required; (2) the submission requires a factual justification; (3) operators have to provide supporting information; (4) there is a process for evaluating the trade secret claim; (5) operators must follow a specific standard to show that the trade secret exemption is justified. We provide more details on states' trade secret exemptions in the Online Appendix OA4.

[8] State rules specify where the HF disclosures must be filed. In our sample, only Arkansas and New Mexico require operators to file with the state agency without mentioning FracFocus, although the majority of operators in these states still submit their forms also to FracFocus (Konschnik and Dayalu, 2016).

completion reports to their respective state agencies. These reports include the well identification number, location, completion date, and basic information on the drilling process. Many states introduced this requirement prior to the HF disclosure mandate, but initially the filings were difficult to access (e.g., as hard copies at the state agencies) and it was not until later that they moved to online portals.[9]

In sum, the state disclosure mandates substantially change the public information environment for HF activities in three ways. First, the mandates make it much easier and quicker for the public to obtain information about the location and timing of drilling activity and the operator identity. Second, the disclosure forms reveal the composition of the HF fluids and, in particular, provide information about potentially harmful chemicals used in HF fluids. Third, the public dissemination of this information via FracFocus is much wider. All these changes imply that the transparency of HF activities substantially increases.

2.3 Disclosure Regulation and Public Pressure

Unlike traditional regulatory approaches to pollution control, disclosure regulation does not restrict or prescribe specific practices. Instead, the idea of targeted transparency is to enlist market forces and public pressure to change corporate behavior (Weil *et al.*, 2013), which goes beyond right-to-know policies justified on ethical grounds (Tietenberg, 1998). Viewed through this lens, HF disclosure requirements could change the behavior of HF operators and the environmental impact of HF wells by increasing transparency and enabling stakeholders or the public to impose pressure and ultimately costs on HF operators, which in turn could incentivize operators to drill less, change the composition of the HF fluids or to operate in a cleaner and safer fashion.

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[9] Three states (Colorado, Montana, and Utah) made these filings available online around the same time as the HF fluid disclosures. For them, the two disclosure changes are essentially bundled. Four states (Arkansas, Kentucky, Ohio, and Pennsylvania) introduced online completion reports after their HF disclosure mandates. The remainder provided them earlier. In robustness analyses, we explore whether online well completion reports play a role in the water quality effects. We find little evidence of that, which is not surprising as they are even more technical and did not receive much public attention.

However, for disclosure rules to work in this way, they need to provide relevant information about the environmental risks, they need to disseminate or publicize the information widely and finally users need to be able to act on this information (Tietenberg, 1998; Weil *et al*., 2006). As discussed in Section II.B, the HF disclosure rules likely satisfy the first two criteria. But it is not obvious that the rules create enough pressure for HF operators to change their practices. Conceptually, public pressure can arise in a number of ways.

First, given the contentious public debate about HF, operators could expect the public to react negatively to the disclosure of toxic chemicals in the HF fluids. For instance, the well-specific disclosures could facilitate protests nearby HF activity by local communities and environmental NGOs (see Pargal and Wheeler, 1996; for community influence). Public pressure can impose reputational costs on HF operators (e.g., shaming) as well as increase regulatory enforcement (see Johnson, 2020; Leonelli, 2022; for workplace safety violations). In addition, NGOs monitor surface waters and look for the chemical signatures of HF flowback and produced water (Shale Network, 2020).[10] Knowing the composition of the HF fluids could increase regulatory and liability risks for HF activity to the extent it facilitates regulatory enforcement actions or private litigation (Olmstead and Richardson, 2014).[11]

Second, public debate about HF and opposition to unconventional O&G development from near or far could lead to stricter regulation, including bans (see Dokshin, 2021, for the public discourse in New York state). The threat of such regulation could motivate operators to adjust their behaviors. Third, investors in O&G companies could use the disclosures to pressure

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[10] The HF disclosures and the composition of HF fluids also received considerable attention from the scientific community (e.g., Tollefson, 2013), which in turn can further increase public pressure.

[11] However, identifying the responsible operator for contamination is very difficult, even when the HF fluids are known. Wells are typically located close to each other, and their produced water composition is not publicly available. Moreover, the burden of proof in litigation is high, which often leads to the dismissal of tort cases (Tsekerides and Lowney, 2015). For example, a tort case in Colorado was the first to be dismissed for non-compliance with the "*Lone Pine* order" (which is a court order that requires the plaintiffs among other things to demonstrate some evidentiary support for their key claims at the outset, usually strict *causality evidence* of damages). An appellate court later reversed this decision, holding that *Lone Pine* orders are prohibited under Colorado law. The *Lone Pine* order has also been used in Texas and Louisiana; in Ohio and Pennsylvania it has been denied (Watson, 2022).

firms to change their practices, especially if the practices entail regulatory or litigation risks that are ultimately borne by investors (e.g., Yang *et al.*, 2021, Bellon, 2022). For the same reason, investors could demand higher returns when financing HF operators. In addition, investors could have non-financial preferences (e.g., Fama and French, 2007), including preferences to use fewer hazardous chemicals in the HF process.

In the Online Appendix OA1, we provide anecdotal evidence illustrating the demand for information on the HF fluids by local communities, environmental groups, policymakers and regulators, investors, the media as well as plaintiffs in HF-related lawsuits. In addition, Online Appendix OA2 provides anecdotes from the regulatory and public debate on HF disclosure regulation illustrating public pressure.

In addition to the public pressure channel, it also possible that disclosure facilitates benchmark learning, i.e., HF operators learn from the other operators' disclosures and imitate high-productivity practices and fluid mixes (e.g., Fetter *et al.*, 2018, Tomar, 2022). However, it is not clear that higher productivity practices have less environmental impact. Moreover, the competitive costs from the disclosures (e.g., the imitation of practices) can reduce HF operators' incentives to innovate (e.g., Fetter *et al.*, 2018, Breuer *et al.*, 2022). Thus, at least in the long-run, the direction of the learning effect on pollution is unclear.

3. Data

We analyze patterns in surface water quality using the concentrations of four ions: Br^-, Cl^-, Ba, and Sr. These ions are regarded as specific signatures of flowback and produced waters (Entrekin *et al.*, 2011, Vidic *et al.*, 2013, Rosenblum *et al.*, 2017) because deep formation brines mobilized by HF contain high concentrations of all these four ions (Vengosh *et al.*, 2014, Brantley *et al.*, 2014, Blondes *et al.*, 2018). Thus, elevated concentrations of these ions could indicate contamination related to HF wells, if and when it exists.[12] Furthermore, these ions

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[12] The four ions (salts) are tied to several environmental and health concerns (Vidic *et al.*, 2013). Cl^- increases the corrosivity of water and the leaching of lead from pipes (Stets *et al.*, 2018). High concentrations of Br^- can lead to the formation of bromine, which can subsequently react with organic matter to form brominated

have been measured and tracked with reasonable frequency over a long period in publicly available data, allowing us to estimate reliable baseline concentrations.

Water quality data come from the EPA (STORET), USGS (NWIS), the Shale Network (Shale Network, 2020), Susquehanna River Basin Commission, and from the PA DEP (SAC046). STORET and NWIS data contribute by far the most observations to our sample. Surface-water observations include rivers, lakes, streams, and ponds. The data sets provide information on the latitude and longitude of each water monitoring station, the ion, the type of surface water (e.g., rivers, lakes), the sampling method, and the agency in charge of the monitoring station.[13] We downloaded the data in September 2021.

We obtain data on the location and spud date of HF wells from three sources: (1) the WellDatabase; (2) Enverus (formerly Drillinginfo); and (3) the Pennsylvania Department of Environmental Protection (PADEP) and the Pennsylvania Department of Conservation of Natural Resources (PADCNR). WellDatabase and Enverus are data sources that are widely used in many empirical studies on the O&G industry. They collect O&G production information from various state agencies for each well. For Pennsylvania, PADEP and PADCNR provide comprehensive information, which we use to complement WellDatabase and Enverus information. The three databases provide information on the latitude and longitude of each well, the type of each well (horizontal vs. vertical), the production type of each well, and the spud date. By combining the three databases we make our sample of wells as comprehensive as possible. If a well appears in only one of the three databases, we use the spud date from the respective database. If a well appears in more than one database but is recorded with different spud dates in the databases, we first rely on the spud date in PADEP and

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trihalomethanes (THMs), known to be associated with increased cancer risk (Brantley *et al.*, 2014). High concentrations of Ba can have health effects such as increased blood pressure (WHO, 2016). Although Sr is not currently regulated under the SDWA and hence there are no EPA limits, high concentrations may cause harm for skeletal health, especially in children and adolescents (Health Canada, 2018).

[13] Following Keiser and Shapiro (2019a), we identify each monitoring site by latitude and longitude because monitoring sites are often assigned different codes and names in different repositories.

PADCNR, then use the date recorded in the WellDatabase, and finally use the Enverus spud date if the well exists only in the latter.[14]

We obtain the adoption dates of the state disclosure mandates from state websites. We carefully review the text of the laws introducing the disclosure requirements and cross-validate these dates with those reported in the FracFocus repository. We also search for adoption dates for other (potentially concurrent) regulations related to HF drilling and wastewater disposal. Specifically, we consider regulations regarding wastewater discharge, injection wells for wastewater, design of wastewater pits as well as standards for well casing, blowout control and mechanical integrity testing. These rules and their adoption dates are reported in the Online Appendix (OA3). We use these dates to construct controls for these regulations.

To assemble the estimation sample, we assign each monitoring station and HF well to a watershed (HUC10)[15] through a QGIS geographical software. Watersheds are homogenous geologic areas defined by the US Geological Survey (USGS) that channel surface water to creeks, streams, and rivers, and eventually to a common outflow point. The literature shows that water impacts of HF wells are detectable within watersheds (Agarwal *et al.*, 2020, Bonetti *et al.*, 2021). For this reason, we analyze cross-sectional and time-series variation in ion concentrations across watersheds with and without HF activity.

We retain water readings from monitoring stations that are located in states that have adopted HF fluids disclosure mandates and belong to HUC4s (sub-regions) that have at least one HF well spudding during the sample period. With these restrictions, we focus on sub-regions for which unconventional O&G development is relevant, but we do not impose the

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[14] We use this order after carefully reviewing the three databases. PADEP and PADCNR appear to be the most reliable source followed by WellDatabase and Enverus.

[15] Data on the watershed boundaries come in *shapefile* formats from the Watershed Boundary Dataset (WBD) provided by the Natural Resources Conservation Service (NRCS) at the Geospatial Data Gateway (GDG). A watershed is uniquely identified by a 10-digit hydrologic unit code (HUC). The United States is divided and sub-divided into successively smaller hydrologic units. There are six levels in the hierarchy, represented by codes (HUC) that are 2 to 12 digits long, called regions (HUC2), sub-regions (HUC4), basins (HUC6), sub-basins (HUC8), watersheds (HUC10), and sub-watersheds (HUC12).

presence of HF activity in all watersheds within these sub-regions. We require non-missing information on the latitude/longitude of each monitoring station, the measurement date, the unit of measurement, the type of surface water (rivers, lakes), the ion sampled, and the amount of the ion measured. Furthermore, we require at least two water measurements per ion×sub-basin×month×year to estimate the ion concentration baselines in our models and remove HUC10s that have water measurements in the post-disclosure period only. These requirements yield a sample of 325,351 surface water quality measurements from January 2006 to September 2019, over 2,209 watersheds and 16 states with HF disclosure mandates. To our knowledge, this is the longest panel for which the impact of HF on water quality has been analyzed.

Table 1 reports the distribution of water quality observations and HF activity across these states with HF disclosure mandates. Figure 1 plots the time trend in HF activity in our sample, along with the staggered adoption timing of the disclosure regulation across states. Figure 2 shows HUC10s with and without HF activity and the locations of water monitoring stations.

Daily precipitation and temperature data come from Schlenker (2020) for Contiguous United States.[16] For the 2.5×2.5 mile grid, in which a particular monitoring station is located, we compute the average temperature on the day of the water measurement and the cumulative precipitation over the last three days including the day of water measurement.

Our final estimation sample consists of two sub-samples: (i) treatment HUC10s with at least one active HF well in the pre-disclosure period; (ii) control HUC10s without HF activity in the pre-disclosure period but located in treated states and within HUC4s that have HF activity in some HUC10s.[17] We provide descriptive statistics for the ion concentrations in the two sub-

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[16] The raw data files give daily minimum and maximum temperature as well as total precipitation on a 2.5x2.5 mile grid for the contiguous United States from 1900-2019. The data are based on the PRISM weather dataset. The use of Schlenker (2020)'s Daily Weather Data allows us to measure the local weather conditions at the time and location of water measurement with greater precision than we could with other databases (e.g., National Oceanic and Atmospheric Administration National Climatic Data).

[17] The assignment of watersheds is based on the existence of HF activities in the pre-disclosure period. Thus, it is possible that, in some control watersheds, HF activities start during the post-disclosure period. In fact, we have 85 watersheds (with 12,758 water measurements) without HF activity in the pre-disclosure period but some HF activity in the post-disclosure period. Keeping these watersheds in the control group could overstate our estimates. Thus, we exclude them from the main analyses. As a robustness, we re-run our analyses

samples in Table 2, Panels A and B. All ion concentrations are reported in microgram per liter (μg/L). To limit the influence of outliers due to measurement or recording errors, we truncate the sample at the 99th percentile, computed per ion at the HUC4 level to allow for some regional variation in ion concentrations. Most of our surface water observations come from rivers and streams: 96.32% for Br^{-}, 93.34% for Cl^{-}, 93.87% for Ba and 96.42% for Sr. We take the natural logarithm of the ion concentrations to account for their highly skewed distributions.[18] We provide descriptive statistics for the distribution of monitoring stations and water measurements per ion and HUC10 in Table 2, Panel C. Ion concentration measurements can be sparsely distributed, except for Cl^{-}. On average, there are 15 monitoring stations per HUC10, ranging from 8 for Br^{-} to 17 for Sr. The average number of measurements per ion in a HUC10 ranges from 37 for Br^{-} to 85 for Cl^{-}.

4. Research Design

In our primary analysis, we test whether the adoption of the HF disclosure mandates are associated with reduced surface water impact of HF, as indicated by changes in the concentrations of Br^{-}, Cl^{-}, Ba, and Sr. We test this prediction using the panel data set of ion concentrations described in Section III. We exploit variation in the entry-into-force dates of the disclosure mandates across U.S. states as well as variation in HF activity across time and watersheds. We estimate the following model:

$$\begin{aligned} C_{ikd} = {} & station_i + \boldsymbol{\alpha HUC10\_HF_k} \times \boldsymbol{POST_{sd}} + state_s[or\ HUC8_h] \times month_m \times year_t \\ & + HUC8_h \times month_m + \beta p_{ikd} + t_{ikd} + \varepsilon_{ikd} \qquad (1) \end{aligned}$$

where C_{ikd} is the natural logarithm of ion concentration, measured at monitoring i on day d located in HUC10 k, $station_i$ is the monitoring station fixed effect, $States_s(HUC8_h)$×month$_m$×

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including these 85 watersheds and obtain results that are indistinguishable from those reported in the paper.

[18] There is no consensus in the literature on how to model concentrations in regressions. Keiser and Shapiro (2019a) model concentrations in raw levels and provide robustness in logs. Hill and Ma (2017) model concentrations in logs. Olmstead *et al*. (2013) model concentration in raw levels. We explore the sensitivity of our inferences to alternative specification and truncation choices in Online Appendix (OB3).

$year_t$ is (alternatively) state (or sub-basin)×month×year fixed effect, $HUC8_h$×$month_m$ is a sub-basin×calendar month fixed effect, p_{ikd} the 3-day cumulative precipitation registered on the day a water quality observation is drawn, t_{ikd} is the average temperature (in Celsius) on the day a water quality measurement is drawn,[19] and ε_{ikd} is the error term. *HUC10_HF* is a binary and time-invariant indicator variable marking watersheds with at least one HF well in the pre-disclosure period (treated HUC10s). *POST* is a binary indicator variable marking water measurements taken after the disclosure regulation has come into force. The key variable of interest is the interaction term, *HUC10_HF×POST*. It estimates the impact of the state disclosure mandates on ion concentrations in HUC10s with HF activity relative to changes in ion concentrations in HUC10s without HF activity. If HF disclosure regulation leads to less surface water impact of HF activity, be it via adjustments along the intensive or the extensive margin, we expect a negative coefficient on *HUC10_HF×POST*. Our inferences are based on standard errors that are clustered at the HUC10 level.

The described fixed effect structure controls flexibly for arbitrary monthly changes in the average concentration in a state (or HUC8) and the average concentration at the monitoring station. Thus, the model in Eq. (1) controls for: (i) cross-sectional and time-series heterogeneity in background ion concentrations in a state (or sub-basins) due to seasonal changes, including the effects of road de-icing or agriculture, as well as the effects of economic development associated with the rise of HF, including changes in the O&G prices, (ii) time-invariant heterogeneity of the water monitoring stations, including local ion concentrations, the way they are measured, the type of monitor, the type of water body, the location of the monitor, natural brine migration at the monitoring station location, and (iii) local weather (precipitation and temperature) at the time of the water measurement.[20]

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[19] We model daily temperature in a categorical form to allow for non-monotonic relations between ion concentration and temperature. Specifically, we code up five binary variables marking the following temperature brackets, in Celsius: $[< -10]$, $[-10; 3]$, $[3; 15]$, $[15; 25]$, $[> 25]$.

[20] In the Online Appendix OB1, we provide a visualization of the identification strategy for Oklahoma.

The model essentially estimates the impact of the individual state disclosure mandates comparing the pre-and post-disclosure evolution in ion concentrations of treated HUC10s and control HUC10s within the same state (or same HUC8) and month. The estimated coefficient for *HUC10_HF×POST* is the average over all state mandates. This identification strategy assumes that the watersheds within a state or within a sub-basin (HUC8) are good controls for each other and exhibit similar trends in water quality but for the disclosure mandates. Thus, it is important that the state adoption dates are not selected in response to trends in water quality, changes in operator practices, or public pressure that would have changed HF practices regardless. In essence, the staggering of the dates needs to be plausibly exogenous. We later gauge this assumption as well as the assumption of parallel trends. We also explore recent econometric concerns about staggered difference-in-differences analyses (Goodman-Bacon, 2021, de Chaisemartin and D'Haultfoeuille, 2022).

5. Results

5.1 Water Quality Changes after the Introduction of Disclosure Regulation

We present results estimating Eq. (1) in Table 3. The explanatory power of the regressions is very high, suggesting that our models capture most of the background variation in ion concentrations across watersheds and within watersheds through time. We first estimate the effect of the disclosure mandates, *HUC10_HF×POST*, for each ion separately. We find significant reductions in the concentrations of Cl^{-}, Ba, Sr in the within-state model (Columns (3), (5) and (7)) and of Cl^{-} and Ba in the within-HUC8 model (Column (4) and (6)). For Br^{-}, the coefficients are not statistically significant at conventional levels.

The results indicate that in some models, statistical power can be low, likely due to the sparsity of water measurements for some ions. We therefore pool the water measurements for all ions in one regression to harness power.[21] In these pooled models, the coefficients on

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[21] See also Hill and Ma (2017). When we pool all the ions, we estimate one regression for all ions and include a fixed effect for each ion as well as interactions of this ion indicator with the controls and fixed effects, so that the coefficients are specific to each ion. This model is akin to running a seemingly unrelated regression model.

HUC10_HF×*POST* are negative and statistically significant, irrespective of the fixed effects structure (Columns (9) and (10)). We also estimate models restricting the control watersheds to those located over shales in order to further reduce potential differences between treated and control watersheds. The findings in Columns (11) and (12) are essentially the same as those in Columns (9) and (10). Taken together, the results in Table 3 suggest that the introduction of the HF disclosure mandates is followed by improvements in water quality.

The magnitudes of the estimated reductions in ion concentrations are meaningful in terms of water quality. Using the within-state models, the reductions range between 4.4 percent for Sr and 17.8 percent of Cl^-. We also translate the percentage changes into ion concentration changes measured in μg/l. The estimated coefficients imply ion concentration declines in treated HUC10s of 8,469.83 μg/l for Cl^-, 5.73 μg/l for Ba, and 20.59 μg/l for Sr. Even relatively small ion concentration changes can be economically relevant because surface waters serve as intake for community water systems. For instance, higher Cl^- concentrations in source water raise lead leaching from pipes (Stets *et al.*, 2018). Small increases in Br^- in source water of treatment plants raise disinfectant by-product formation in drinking water, which in turn has been linked to increased bladder cancer rates (Regli *et al.*, 2015).

Next, we map out the estimated impact of disclosure regulation on ion concentrations over time. This allows us to gauge the existence of differential trends between treated and control HUC10s prior to the mandates, which would question the parallel trends assumption. We estimate Eq. (1) replacing *POST* with separate indicator variables, D_t, for each year, coded relative to the entry-into-force date of the disclosure regulation in the respective state. That is, D_1 is equal to one for any water measurement taken within 365 days of the date the state disclosure rule becomes effective (and zero otherwise), D_2 marks water measurements taken in the second year, and so on. We omit D_{-1} (i.e., the indicator for measurements taken in the

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The model produces an estimate for the average concentration change over all ions.

365 days before the effective date), which serves as a benchmark. We use the within-HUC8 model shown in Column (12) of Table 3.

Figure 3 plots the coefficients from this temporal analysis for the model that pools all ions, together with their 90% confidence intervals. The coefficient on D_{-1} is zero and has no confidence interval; all other coefficients are estimated relative to it. Importantly, Figure 3 does not indicate any differences in the pre-trends for treated and control HUC10s. The figure shows that the decrease in ion concentrations starts after the disclosure regulation comes into force and continues to increase the following year; thereafter it stays fairly constant. Well operators typically have between 30 and 120 days from the spud date or well completion to provide the HF disclosures. Moreover, prior evidence suggests that the water impact of new HF wells does not occur until 90 days after well spudding (Bonetti *et al.*, 2021). Thus, we would not expect to see the full effect until a year after the mandate becomes effective.[22]

We gauge the robustness of the results with respect to: (i) sample composition and selection; (ii) clustering of the standard errors; (iii) truncation of the ion concentrations; (iv) alternative ways of dealing with ion measurements that are reported as below detection levels; and (v) estimating WLS models that give more weight to areas with more data and hence better baselines. These sensitivity analyses are presented in the Online Appendix (Sections OB2, OB3 and OB7) and show that our findings and estimated magnitudes are robust to a wide range of alternative design choices. Given recent studies in econometrics showing that staggered difference-in-differences analyses and two-way fixed effect structures can produce biased estimates in the presence of heterogeneous treatment (Goodman-Bacon, 2021, de Chaisemartin and D'Haultfoeuille, 2022), we also use a “stacked” regression approach and ascertain that our inferences are the same (Cengiz *et al.*, 2019, see Section OB9 for details).

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[22] In Table 3 and Figure 3, the post-rule indicators mark water measurements after the state-specific effective dates. However, to better take into account when the information becomes public and contamination could show up, we could instead mark post-rule water measurements considering whether the rule applies to the spud or the completion date, how long it takes to complete a well, and how many days operators have to file the disclosure form. When we account for this timeline, we find a slightly sharper impact in year 1.

5.2 Assessing Alternative Explanations for the Effects on Water Quality

We conduct several analyses to assess alternative explanations for our results in Table 3. An important concern is the adoption dates of the mandates are endogenous, for instance, because states choose to adopt the disclosure requirements in response to local shocks to water quality (e.g., related to spills or accidents). Similarly, lawmakers might pass the disclosure rules in response to local public pressure. It is conceivable that these local shocks or pressures by themselves would have led to changes in operator practices that reduced HF water impact, rather than the disclosure rules. We perform a series of tests to gauge this alternative explanation but do not find evidence supporting it.[23]

Next, we conduct two "placebo" tests. First, we examine changes in the concentration of analytes that are not specific to HF water impact and unlikely to be directly affected by HF activity. Concentrations in these analytes, however, can reflect other economic activities, e.g., agriculture, as well as economic or housing growth due to HF activity in the local area. Thus, in using these analytes, we gauge how well our models control for these other potentially confounding effects on water quality.[24] Specifically, we use: (i) Dissolved oxygen (DO), (ii) Fecal Coliforms, (iii) Phosphorus. We do not find consistent patterns in the concentrations of these three analytes around the introduction of the disclosure mandates and all the estimated coefficients (except for one) are statistically insignificant (Table 4, Panel A).

Second, we examine changes in the four HF-specific ion concentrations around the disclosure mandates, but in watersheds with conventional drilling. Given that the disclosure mandates apply only to HF wells, watersheds with conventional wells should not exhibit the

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[23] First, we add lagged changes in the respective ion concentration to the model. This control mitigates concerns about mean reversion in water quality if states introduce the disclosure requirements in response to shocks to local water quality (Table B10). Second, we show that public pressure, economic or political differences and HF drilling intensity does not predict the relative timing of state disclosure rules (Table B11). We also find that, in most states (13 out of 16), Google searches peak after the start of the legislative process (not before). Third, we run tests based on Altonji *et al.* (2005) and Oster (2019) using proxies for local factors that could prompt lawmakers to pass the disclosure rules (Table B12). See Online Appendix for details.

[24] In Section OB4, we also report an additional test that explicitly considers whether our results reflect trends in water pollution due to agricultural activity.

same patterns. To check this, we re-estimate the analyses in Table 3, but define the treatment HUC10s as those with conventional (i.e., vertically drilled) wells in the pre-disclosure period but no HF activity. The control sample comprises HUC10s without conventional or HF wells in the pre-disclosure period. Consistent with our expectation, we do not find significant effects for the disclosure mandates in HUC10s with conventional drilling (Table 4, Panel B).

A common concern in regulatory studies such as ours is that there are other concurrent events that could also affect the outcome variables or the relevant corporate behavior. The staggering of the HF disclosure mandates in our setting alleviates this concern with respect to general changes in water quality that are unrelated to HF (e.g., federal regulation) as well as common trends in HF or drilling practices (e.g., technological change). However, almost all states in our sample have other regulations for HF activity that were introduced before or over the sample period. The ones that are particularly relevant for our analysis are rules on wastewater management and HF drilling standards. To the extent that the states introduced such HF regulations around the same time as their disclosure mandates, these other regulations could contribute to the water quality effects documented in Table 3.[25]

To explore this possibility, we create three interaction variables for these other regulations: (i) *HUC10_HF×CUM_WASTEWATER* represents the number of regulations related to wastewater handling at a given point of time in watersheds with HF wells (i.e., the variable increases by one when a new regulation for wastewater handling is introduced in a state); (ii) *HUC10_HF×CUM_HF_STANDARDS* represents the number of HF drilling standards at a point in time in watersheds with HF wells (i.e., the variable increases by one when a new

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[25] To identify relevant regulatory changes for the O&G industry, we read the respective administrative codes and laws adopted by the states in our sample. Relevant regulations include provisions prohibiting the discharge of wastewater, regulating injection wells, imposing pit siting, liners, freeboard and overflow requirements, leak detection and blowout prevention systems, as well as well casing requirements. Some of these provisions have been adopted well before the start of our sample period and others were introduced only very recently. These cases pose little threat to our analysis. However, some have been adopted around the time of the disclosure mandates and five states (Ohio, Pennsylvania, Montana, North Dakota, and Utah) have introduced their HF disclosure requirements along with other regulatory amendments. Online Appendix OA3 describes these regulatory changes in more detail and provides their respective implementation dates.

drilling standard is introduced in a state); (iii) *HUC10_HF×CUM_HF_REG* represents the joint number of wastewater handling rules and drilling standards at a given point in time (i.e., the variable is the sum of the previous to two variables). If the documented changes in water quality primarily reflect these other regulatory changes, rather than the disclosure mandates, then the estimated coefficient for the disclosure mandates, *HUC10_HF×POST*, should be attenuated when we also include the control variables for the other regulations.

In Table 5, Columns (1)–(3) as well as (7)–(9), we report results for each of the new variables separately.[26] We find that changes in the other HF regulations are also associated with improvements in water quality. However, these results do not account for the disclosure mandates.[27] We therefore estimate models jointly introducing variables marking the disclosure mandates and the other regulatory changes. In these models, Columns (4)–(6) as well as (10)–(12), we find that the coefficients on *HUC10_HF×POST* are still negative and significant in all specifications. More importantly, we see little attenuation in the coefficient magnitudes relative to the estimates for the disclosure mandates reported in Table 3. This evidence makes it unlikely that the improvements in water quality are mainly driven by other regulatory changes that are concurrent or close in time to the disclosure mandates. The coefficients on the other HF regulations are now insignificant and close to zero. These results could reflect that some of the other HF rule changes during our analysis period are fairly minor, e.g., amendments to existing and initially more major rules that were put in place earlier.[28]

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[26] For the sake of brevity, we report only the results for the "all ions pooled" specification.

[27] As noted in Fn. 25, a few states introduce other regulatory changes around the time of HF disclosure mandate. This overlap could boost the coefficients for other HF regulations if the indicator for the disclosure mandates is missing from the model. Generally speaking, however, the disclosure mandates and the other HF regulations are fairly "distant." The mean (median) absolute difference between the dates for the disclosure mandate and the other HF regulations is 52 months (27 months). For details, see Online Appendix OA3.

[28] The insignificant results for the other regulatory changes should thus be interpreted cautiously. Our tests intend to gauge the potentially confounding role of these other regulations, rather than to provide an estimate for their impact. For the latter, we would have to choose a sample period that includes the initial introduction of wastewater rules or HF drilling standards (as opposed to using a period centered on the disclosure mandates).

5.3 *Changes in Operator Behavior: HF Drilling Activity and Per-Well Pollution*

The evidence provided so far shows improvements in water quality after the introduction of the disclosure mandates. We now examine which margins HF operators adjust. The increase in water quality in the post-disclosure period could come from less HF activity (extensive margin) or from less water impact of each HF well (intensive margin).

We expect drilling activity to be driven primarily by market factors, e.g., energy prices and demand, as well as existing supply and new drilling opportunities in an area. It is important to control for these first-order forces when teasing out the impact of disclosure regulation on the extensive margin (i.e., on new HF wells). Thus, we restrict the analysis to HUC10s over shales, i.e., areas where HF is feasible. We further restrict the analysis to watersheds in sub-basins that are partially located in contiguous states (i.e., HUC8s that cross state borders), so that we compare the rate of well entry in watersheds of a state that introduced disclosure with the rate of entry in watersheds of the neighboring state without disclosure. We measure entry by taking the natural logarithm of the number of new HF wells spudded in a HUC10-month-year. We include HUC10 fixed effects to account for location-specific factors to well entry, and either region×month×year FE or shale×month×year FE to account for regional or shale-specific trends in unconventional O&G development as well as local price variation.[29]

Table 6, Columns (1)–(4), documents a decrease in well entry, irrespective of the fixed effects or the estimation sample. To further tighten the analysis, we also estimate the change in HF wells entry around the disclosure mandate relative to well entry for conventional wells (Table 6, Columns (5)–(6)). Since the latter wells are not subject to the disclosure rules, they represent a useful control to account for changes in the O&G industry broadly and local trends. We recode the dependent variable as the difference between the number of new HF wells and the number of new conventional wells spudded in a HUC10-month-year. We again include

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[29] There are 30 shales in our sample. These shales can be further classified into five regions: North-East, South-Mid-West, South-West, Mountain, North-West. The extensive margin analysis focuses on watersheds with HF, which is why we change the fixed effects structure and conduct analyses within region or within shale.

controls for other HF regulations, *CUM_HF_REG*. Even in this specification, we still observe a significant decrease in HF wells entry. Figure 4 plots coefficients from the model in Column (6) of Table 6, mapping out the effect by quarter relative to the disclosure mandate. Figure 4 indicates parallel trends in the pre-disclosure period and a decline afterwards. The estimated coefficient in Column (4), which is the tightest model before differencing vertical wells, implies 0.04 fewer new HF wells per HUC10-month-year, relative to an average well entry of 0.74 per HUC10-month-year. Thus, on a percentage basis, the response on the extensive margin is smaller than the overall reduction in ion concentrations, which suggests additional improvements along the intensive margin.[30]

To quantify the impact of HF disclosure regulation along the intensive margin, we estimate the per-well effect on ion concentrations for the pre- and post-disclosure periods, separately. We restrict the estimation sample to HUC10s with HF in both the pre-and post-disclosure periods and modify Eq. (1), replacing *HUC10_HF×POST* with two cumulative well count variables, one that counts the total number of HF wells that were spudded within a HUC10 up to 120 days before a given water reading for the pre-disclosure period and one for the post-disclosure period. Over time, these well counts increase by one as new wells are spudded.

Table 7 reports the results. We find positive and significant per-well effects on ion concentrations before the disclosure mandates for Br^{-}, Cl^{-}, Sr and for all ions pooled together. For HF wells spudded in the post-period, the coefficients are smaller and at times no longer significant. Thus, relative to the pre-period, there are sizeable declines in the per-well effects. The estimated coefficients imply an average per-well decrease of 1.53 μg/l for Br^{-}, 9.55 μg/l for Cl^{-}, 0.24 μg/l for Sr. Overall, the results suggest significant improvements in water quality along the intensive margin as a result of the disclosure mandates.

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[30] For robustness, we study well entry at different aggregation levels. The results are weaker and not statistically significant if we instead aggregate the dependent variable at the county-level. However, if we aggregate the dependent variable at the 5-digit zip code-level, we obtain similar patterns to those reported in Table 6.

Prior research suggests that mishandling of flowback and produced waters is likely a key mechanism by which HF could pollute surface water (Vidic *et al.*, 2013, Vengosh *et al.*, 2014). Consistent with this mechanism, Bonetti *et al*. (2021) find significant spikes in the four ion concentrations between 90 and 180 days after well spudding, which is when HF wells generate large amounts of flowback and produced water that need to be collected. Thus, the ion increases are directly tied to critical phases of HF. We explore changes in these patterns after the introduction of disclosure regulation by plotting the coefficients for HF well counts calculated over fixed time intervals around the well spud dates, both for the pre- and the post-period, respectively (Figure 5). Consistent with Bonetti *et al*. (2021), we find concentration spikes for the [91, 180]-day window. Importantly, this spike becomes less pronounced after mandatory disclosure. This (graphical) result is consistent with the documented improvements along the intensive margin, and closely ties the improvements to the HF process.

To assess the relative role of the intensive and the extensive margin adjustments for the decrease in ion concentrations, we perform a magnitude decomposition exercise. For Cl^-, we first multiply the average per-well decrease in pollution after the disclosure mandate (9.55 μg/l) with the average number of wells per HUC10 in the pre-disclosure period (41.40) to obtain an estimate for the total decrease in Cl^- concentration due to adjustments on the intensive margin (395.21 μg/l). We then compare this estimate with the estimated decrease in Cl^- concentrations due to adjustments on the extensive margin. We obtain this estimate by multiplying the per-well Cl^- concentration effect in the pre-disclosure period (38.17 μg/l) with the decrease in the number of wells in the post-disclosure period relative to the pre-period HUC10 average number of wells (1.65). Our estimate for the extensive margin is 63.04 μg/l. Comparing the two estimates, we conclude that around 86 percent of the decline in Cl^- concentrations comes from the intensive margin.

5.4 Specific Changes in HF Operators' Practices

In this section, we study specific changes in HF operator practices that could explain or contribute to the increase in water quality after mandatory disclosure. First, we examine changes in the environmental performance of HF wells, which could indicate investments in better HF well technology. We cannot directly observe the technological changes of HF operators, but we can compute the ratio between the O&G production volume, in barrels, and the local ion concentrations, in μg/l, all at the HUC10-month-year level. This ratio is a reasonable proxy for the environmental performance of HF wells (Wang and Shen, 2016). Table 8 reports OLS estimates of the impact of disclosure regulation on environmental performance. We provide results for a treatment sample that includes HUC10s with HF in the pre-disclosure period (Columns (1)-(2)) and for a treatment sample that includes HUC10s with HF in the pre- and post-disclosure periods (Columns (3)-(4)). For brevity, we report the results for the model pooling all ions. We find that, after mandatory disclosure, HF wells have higher environmental performance, i.e., the same production is associated with lower ion concentrations. This evidence is consistent with our earlier intensive margin results.

Second, we examine whether HF operators reduce the use of hazardous chemicals after the HF fluid disclosures become mandatory. We use data on the chemicals used in HF from Konschnik and Dayalu (2016) and create a variable that captures the combined percentage share of all hazardous chemicals used in the HF fluids. We first compute for each well the ratio of the total amount of hazardous chemicals to total fluids injected, and then average over all wells at the HUC10-month-year level. Hazardous chemicals are those (i) regulated as primary contaminants by the SDWA; (ii) regulated as Priority Toxic Pollutants for ecological toxicity under the Clean Water Act; or (iii) classified as diesel fuel under EPA guidance on fracturing operations (EPA, 2014). For the pre-disclosure period, we have to use voluntarily disclosed information about the share of hazardous chemicals to calculate the HUC10-month-year averages.[31] Assuming that operators using a larger fraction of hazardous chemicals were more reluctant to provide information prior to the mandates, the use of voluntary disclosures in the pre-period is likely to bias against us finding a reduction in the share of hazardous chemicals. In addition, we compute the fraction of hazardous chemicals using only those related to chloride to better link the HF fluid analysis here with our earlier water quality analyses using chloride concentrations in surface waters. Table C1 lists the most common hazardous chemicals in HF fluids and Table C2 provides descriptive statistics for the two hazardous chemical variables. We estimate changes in the use of hazardous chemicals after the HF disclosure mandates using watershed and month×year fixed effects to flexibly control for broader changes in the composition of HF fluids. Table 9 reports the results. We find that operators disclose using fewer hazardous chemicals, both overall and chloride-related, after disclosure regulation. These results are consistent with the documented decline in chloride and, more generally, ion concentrations in surface waters.

Third, spills, leaks and accidents related to HF wastewater are likely a key pathway for surface water contamination. Transparency and public pressure should provide operators with incentives to improve the safety of the drilling process and the management of HF wastewater. Thus, we examine the effect of the disclosure regulation on the occurrence of such HF-related incidents. We use data on recorded major HF-related spills from Brantley *et al.* (2014) and Patterson *et al.* (2017). As these data extend only to 2015 and are confined to Pennsylvania as well as Colorado, New Mexico, and North Dakota, respectively, we restrict the analysis accordingly. We count the number of HF-related incidents for each HUC10-month-year using either all HF-related incidents or all HF incidents related to wastewater management. Table C3 reports descriptive statistics for these incidents. We estimate changes in these incidents after the introduction of disclosure regulation for all HUC10s over shales using watershed and

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[31] Not all watersheds have HF wells, for which voluntary disclosures are available in the pre-period. Thus, we first compute pre-disclosure averages at the HUC8 level using voluntary disclosures and then use these averages for watersheds (HUC10s) without voluntary disclosures in the pre-period.

month×year fixed effects. Table 10 reports the results. Consistent with our water quality results in Table 3, we find statistically and economically significant declines in the number of HF-related incidents in general and in those related to wastewater management.

5.5 The Role of Public Pressure for the Observed Improvements in Water Quality

As discussed in Section II.C, disclosure regulation can enable social movements, environmental groups, local communities, and the media to exert pressure on HF operators (see Online Appendix OA1 and OA2 for anecdotal evidence from various sources). In this section, we provide more formal evidence that targeted transparency indeed operates through public pressure.[32] We measure public pressure using several proxies and present a series of tests.

First, we create a variable indicating the presence of local environmental NGOs. We obtain a list of local anti-fracking NGOs from *America Against Fracking*, *Pennsylvania Against Fracking Coalition*, and *Frack Action*. We augment this list with data from GuideStar, which contains nonprofit organizations filing Form 990. To identify local environmental groups that focus on water quality issues, we retain nonprofits with the NTEE codes, C01, C02, C03, C011, C12, C20, C30, C32, C34, and institutional names that include the words: *watershed*, *river*, *water*, *creek*, *lake*, or *stream*. We remove from this list four NGOs with more than 100 employees, as they are unlikely to operate locally only. We then assign environmental groups to a local community based on their address to Census Core-Based Statistical Areas (and counties if the address is not within any CBSA). We ensure that the environmental NGOs are active in the year before the state disclosure mandate is adopted.

We analyze whether the results in Table 3 differ across locations with or without the

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[32] We recognize that public pressure could also be a confounding factor if state legislators adopt the disclosure rules in response to public pressure. We perform several tests to gauge this possibility. First, we show that public pressure measured by Google searches does not predict the timing of the disclosure rules (Table B11). See also OB8 for additional tests examining the potential endogeneity of the adoption dates. Second, we examine the relative timing of the legislative process and Google searches. We find that, for most states in our sample (13 out of 16), Google searches peak after the legislative process has already started, consistent with disclosure regulation leading to more public pressure, rather than the other way around (see also Figure 6). Finally, we show that the results are not driven by (and if anything weaker in) the few states where Google searches peak before the state adopts the disclosure rule.

presence of an environmental group. Table 11, Column (1), shows that the effect of disclosure regulation on ion concentrations is larger in areas which have at least one active local anti-fracking or water protection NGO. We alternatively use the presence of a local newspaper to capture differences in public pressure. We code counties with at least one (no) local newspaper in the year leading up to the disclosure mandate (which assumes that media pressure is largely confined to the county in which the newspaper is published). Table 11, Column (2), shows that the effect of disclosure regulation on water quality is larger in counties with a local newspaper.

Second, we explore whether the impact of disclosure regulation is more pronounced in areas that experience larger increases in public pressure after the mandates are introduced. We measure increases in public pressure using changes in media coverage discussing HF as a source of water pollution and, alternatively, changes in Google search intensity.[33] We then use these proxies to split the treatment coefficients. In Table 11, Column (3), we report separate coefficients for counties with increases and decreases in HF-related media coverage in the year after the mandates (relative to the year before adoption). The results show that the disclosure effect is more pronounced in counties where newspaper coverage increases.

Similarly, in Table 11, Column (4), we report separate treatment coefficients for states with above and below median increases in the average number of Google searches for the term "fracking" in the post-disclosure period (relative to pre-period). The results show that the disclosure effect is larger in states with stronger increases in Google search intensity.

Third, we expect HF operators owned by publicly traded O&G firms to face greater public pressure and more scrutiny than HF operators owned by private firms (see also Table OA1 for anecdotal evidence). To explore this heterogeneity, we estimate separate treatment coefficients for watersheds, in which more (less) than 50 percent of the wells are owned by publicly traded

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[33] In the Online Appendix, Section OB5, we verify that these two proxies for public pressure increase after the disclosure mandates come into force. We find significant post-disclosure increases in the number of newspaper articles pointing to HF as a source of water pollution and also in the number of Google searches for the term "fracking." These effects are also more pronounced in counties where the population is more educated.

operators. The results in Table 11, Column (5), indicate that the disclosure effect is greater when the fraction of publicly traded HF operators is higher.

In sum, we obtain consistent results for several proxies suggesting that the improvements in water quality after the introduction of mandatory disclosure are stronger when public pressure is higher and that the mandates increase such pressure. The three final tests in Table 11 explore features of the disclosure regime.

First, we exploit improvements of the FracFocus website, which is the primary repository for the HF disclosure forms. Since its launch in 2011, the FracFocus website was revamped several times to improve the accessibility and dissemination of the HF disclosure forms. We identify three major changes during our sample period (Online Appendix OB10). To exploit these shifts, we estimate an alternative version of Eq. (1) that interacts *HUC10_HF×POST* with a count variable, *CUM_FF_CHANGES*, indicating the cumulative number of website changes implemented by FracFocus up to the respective point in time (i.e., the variable goes from 0 to 4). The results in Table 11, Column (6), indicate further decreases in the ion concentrations in HF watersheds as the dissemination of HF disclosure forms improves. This evidence supports our interpretation that the HF disclosures are the force behind the increases in public pressure and the improvements in water quality.

Second, we consider the ease with which HF operators can obtain trade secret exemptions for the chemical disclosures, as they could make the disclosure forms less effective (McFeeley, 2012). Given that the composition of HF fluids is potentially proprietary, all states allow trade secret exemptions, but differ in how easy it is to obtain them. If granted, operators can withhold the identifying name of the respective chemical, but still have to report the amount and the percentage in the HF fluid. To measure how easy it is for an operator to obtain a trade secret exemption, we consider the following five conditions that states may require to claim a trade-secret exemption (McFeeley, 2012): (1) the submission of a formal request is required to claim for a trade secret exemption; (2) a factual justification to claim for a trade secret exemption is required in the submission; (3) operators have to provide supporting information; (4) there is a process for evaluating the trade secret claim; (5) operators have to follow specific standards to prove that the trade secret exemption is justified. The more conditions are required, the more difficult it is for operators to obtain the trade secret exemption. The Online Appendix (Table OA4) describes the trade secret framework for each state in our sample.[34] In Table 11, Column (7), we report separate coefficient estimates for two state groups, splitting on whether a state has two or more (fewer) conditions for obtaining trade secret exemptions, *High Group* (*Low Group*). The results suggest that the disclosure mandates have stronger effect in states where it is more difficult to obtain a trade secret exemption.

Finally, we consider differences in how much time HF operators are given to file the disclosure forms as a proxy for the strictness of the disclosure regime. Since water impact from HF wells is best detected in the early phases of production (Bonetti *et al*., 2021), timelier disclosures should put local communities in a better informational position. The filing deadlines vary substantially across states and we split states into two groups depending on whether the number of days operators have to file the report are below (*High Group*) or above *(Low Group)* the sample median. In Table 11, Column (8), we find that larger water quality effects in states where the HF disclosure is timelier.

6. Conclusion

We study to what extent targeting corporate activities that have dispersed environmental externalities with disclosure regulation facilitates their internalization. We still have scant evidence as to whether mandated disclosure works for such activities and, if so, how it produces the intended effects. Towards this end, we study the effects of targeted transparency for HF operators in the U.S. The rise of unconventional O&G development has triggered a major and still ongoing public debate about HF. In response to significant concerns about its

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[34] Not all the states require the five conditions to be met to apply for an exemption. The sample distribution goes from 0 to 4, and five states have no requirements for the exemption.

environmental and health risks, U.S. states with unconventional O&G development passed disclosure rules for HF wells in an effort to increase the transparency of HF practices.

We study the effects of this disclosure regulation with respect to the environmental impact of HF wells on surface waters as well as the practices of HF operators. We estimate changes in water quality using four ions that are considered specific signatures of HF impact and find significant declines of these ion concentrations in surface waters after the disclosure mandates are introduced. We examine the source of these improvements in water quality and find that, aside from a minor decline in drilling activity, most changes are attributable to adjustments along the intensive margin. Specifically, we document a smaller water impact per well and per unit of O&G production, a decline in the use of hazardous chemicals, and fewer spills and accidents related to wastewater handling. Thus, our study provides detailed evidence that, with mandatory disclosure, HF operators change their practices.

The core idea of targeted transparency for corporate activities with environmental externalities is to enlist public pressure. Illustrating that this mechanism is at play in our setting, we examine several proxies for public pressure and find that water quality improvements after the disclosure mandates are greater in areas where public pressure is higher. Specifically, we find larger decreases in HF-related ion concentrations in areas with a greater presence of local environmental NGOs and in counties with more local newspapers. We show that media coverage and internet searches intensify after disclosure regulation and that the improvements in water quality are more pronounced in states with more news articles discussing HF in relation to water pollution, with more Google searches for HF after the disclosure mandate, and for publicly listed operators that face greater scrutiny. All this evidence is consistent with the idea that disclosure regulation enhances the ability of stakeholders to exert public pressure.

Finally, our study provides novel longitudinal evidence on the environmental impact of HF on U.S. surface waters. Although our analysis based on HF-related ion concentrations suggests significant improvements in water impact, readers should interpret this evidence cautiously as we lack data to study potentially more harmful chemicals.

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Figure 1 – Trends in HF Activity and the Evolution of Disclosure Mandates in the U.S.

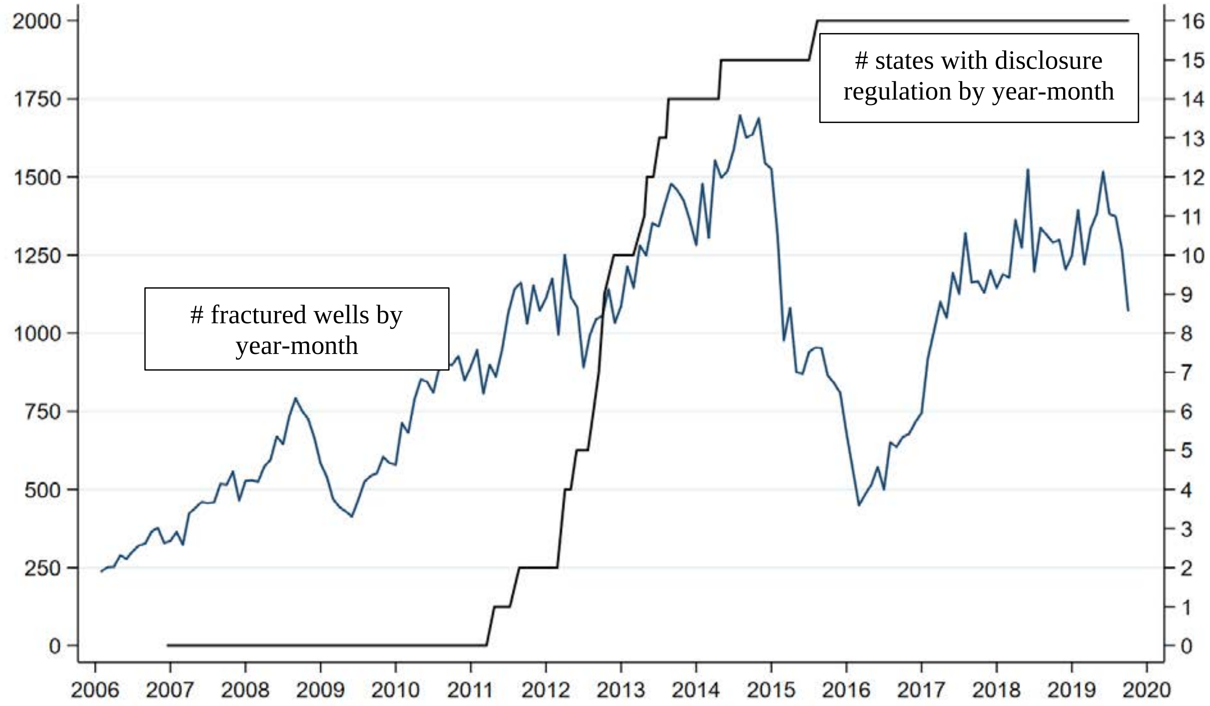
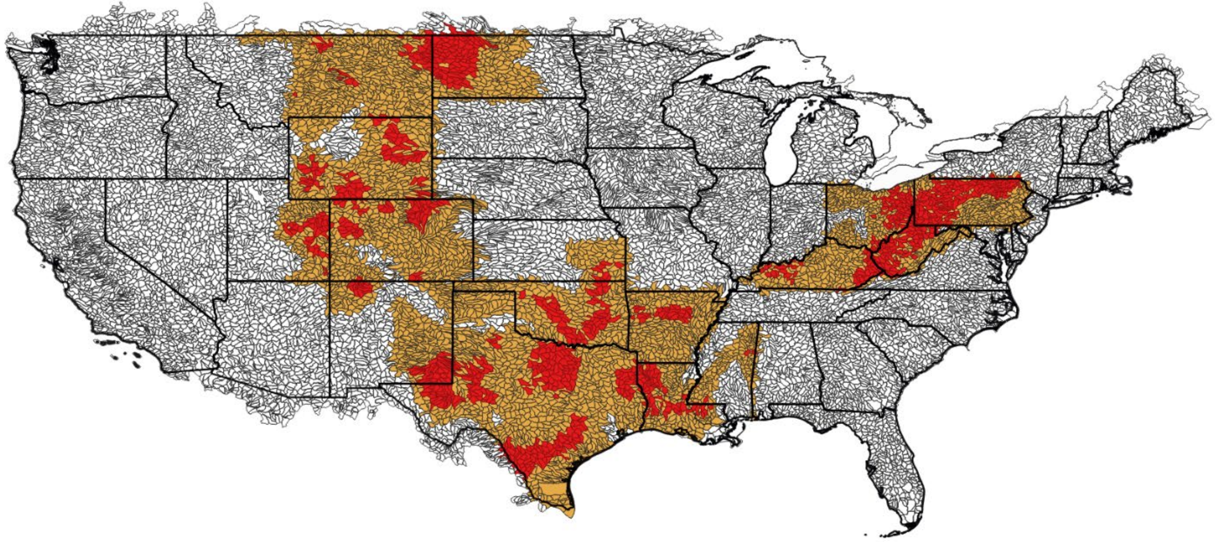


Figure 1 plots the time trend in HF activity in the U.S. along with the adoption timing of the HF disclosure regulation by the U.S. states with HF activity. The *x* axis shows the year. The *left-y* axis shows the number of new HF wells by spud year-month. The *right-y* axis shows the cumulative number of sample states adopting the disclosure regulation in a given year and month. Data on HF wells come from the WellDatabase, Enverus, the Pennsylvania Department of Environmental Protection and the Pennsylvania Department of Conservation of Natural Resources.

Figure 2 – Location of HF Wells and Water Monitoring Stations

Panel A – Location of HF Activity by Watershed



Panel B – Location of Water Monitoring Stations by Watershed

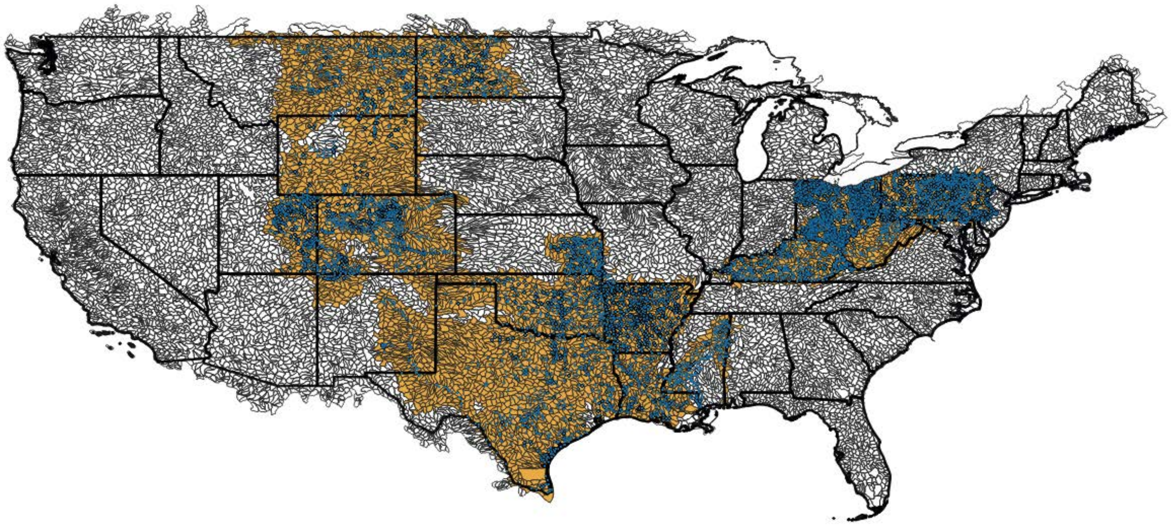
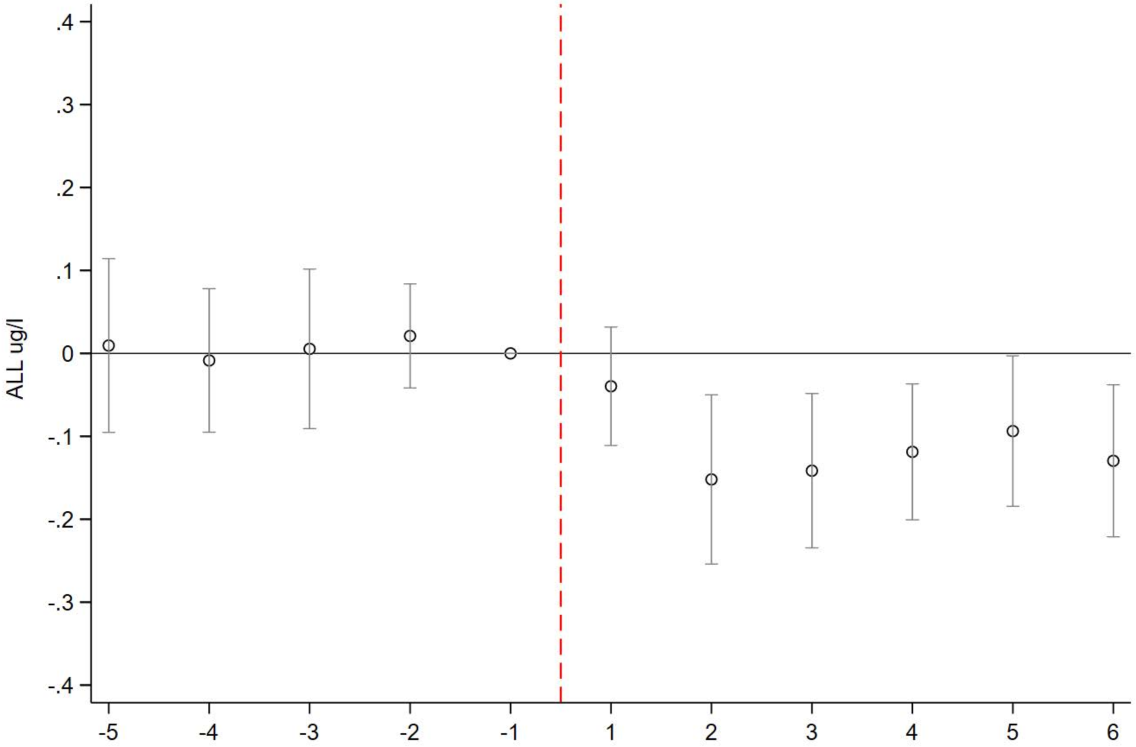


Figure 2 shows the location of HF activity (Panel A) and the location of water monitoring stations (Panel B) across watersheds (HUC10s). Watersheds in the treatment sample are colored in red. Watersheds in the control sample are colored in ocher. Blue dots mark the location of monitoring stations. Data on the location of wells come from the WellDatabase, Enverus, the Pennsylvania Department of Environmental Protection and the Pennsylvania Department of Conservation of Natural Resources. Data on the location of water monitoring stations come from the EPA (STORET data), USGS (NWIS data), Susquehanna River Basin Commission, Shale Network, and from the Pennsylvania DEP. Thin black lines outline HUC10 boundaries; thick black lines depict state boundaries.

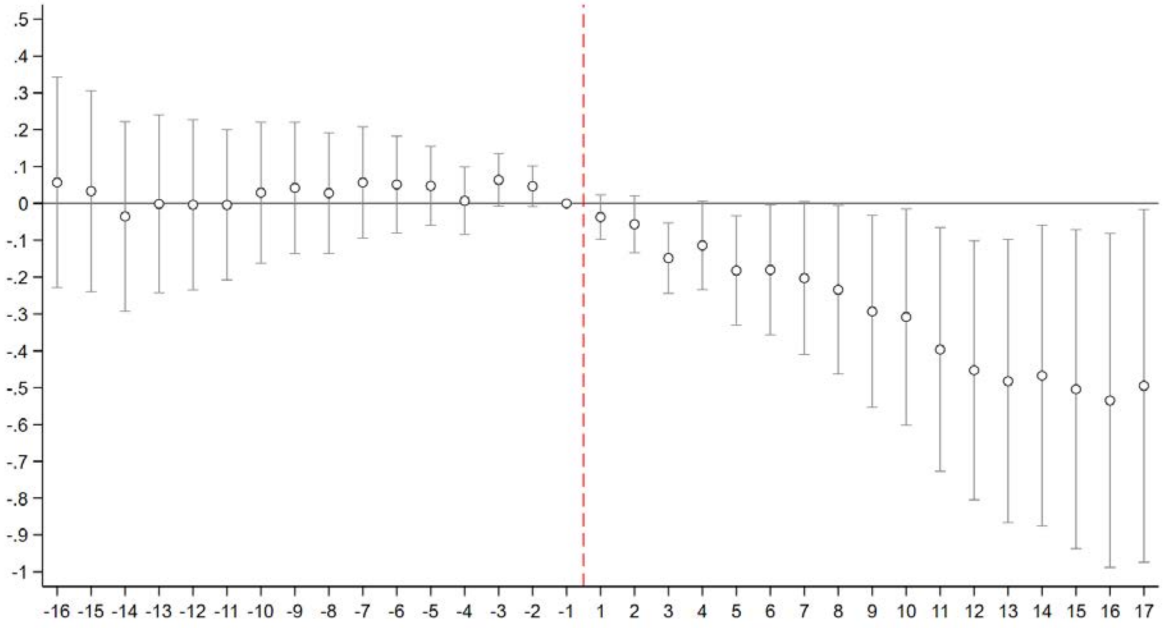
Figure 3 – Mapping Out the Effect of HF Disclosure Regulation



Year Relative to Disclosure Mandate

Figure 3 plots coefficients from the estimation of Eq. (1), together with the respective 90% confidence intervals, adding indicators for the years relative to the introduction of the disclosure mandate. Year 1 comprises all water measurements that take place within the first 365 days from the state-specific entry-into-force date. Year -1 comprises measurements in the 365 days before the entry-into-force date. The coefficient for the year before the disclosure mandate (-1) is omitted from the regression and therefore serves as benchmark. We use the within-HUC8 model shown in Column (12) of Table 3.

Figure 4 – Extensive Margin: Changes in HF Activity after Disclosure Regulation



Quarter Relative to Disclosure Mandate

Figure 4 plots coefficients from estimating the model shown in Column (6) of Table 6, together with the respective 95% confidence intervals, adding indicators for the quarter relative to the introduction of the disclosure mandate. Quarter 1 comprises all new wells that are spudded within the first 90 days from the state-specific entry-into-force date. Quarter -1 comprises wells spudded in the 90 days before the entry-into-force date. The coefficient for the quarter before the disclosure mandate (-1) is omitted from the model and therefore serves as benchmark. The sample is restricted to observations from HUC8s that cross state lines (border design).

Figure 5 – Mapping Out the Per-Well Impact Before and After Disclosure Regulation

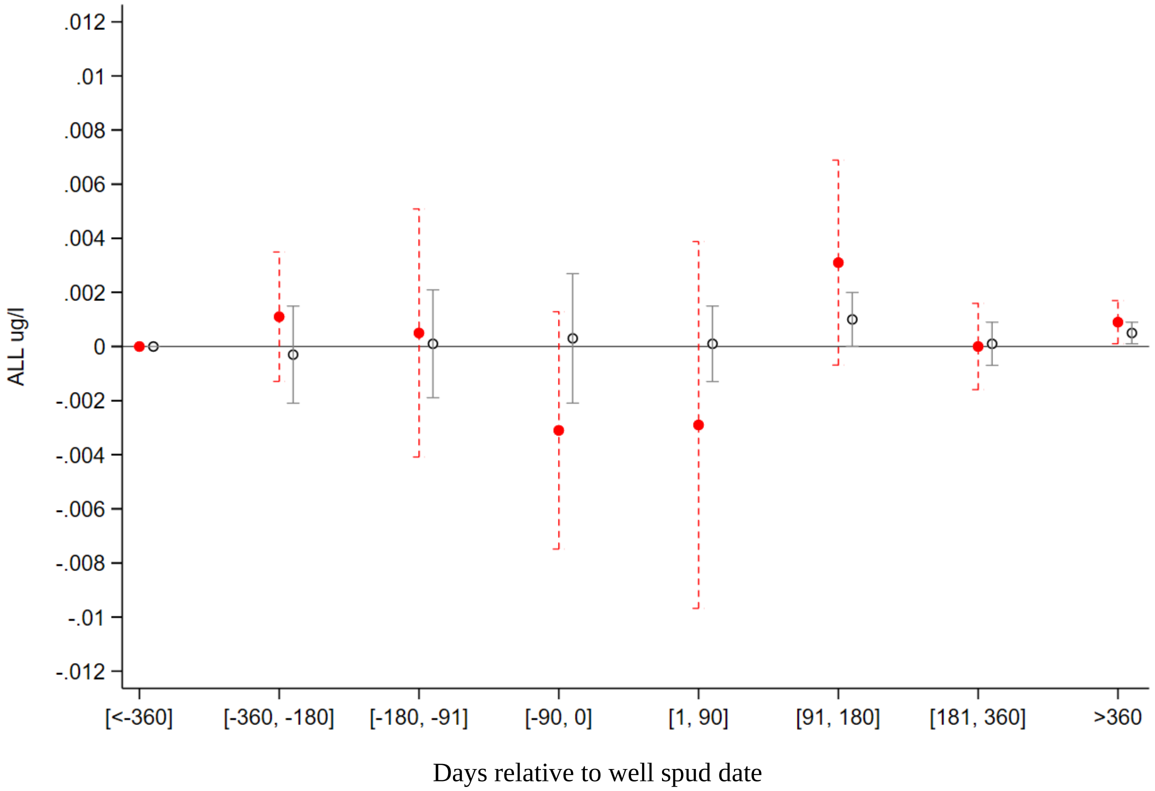
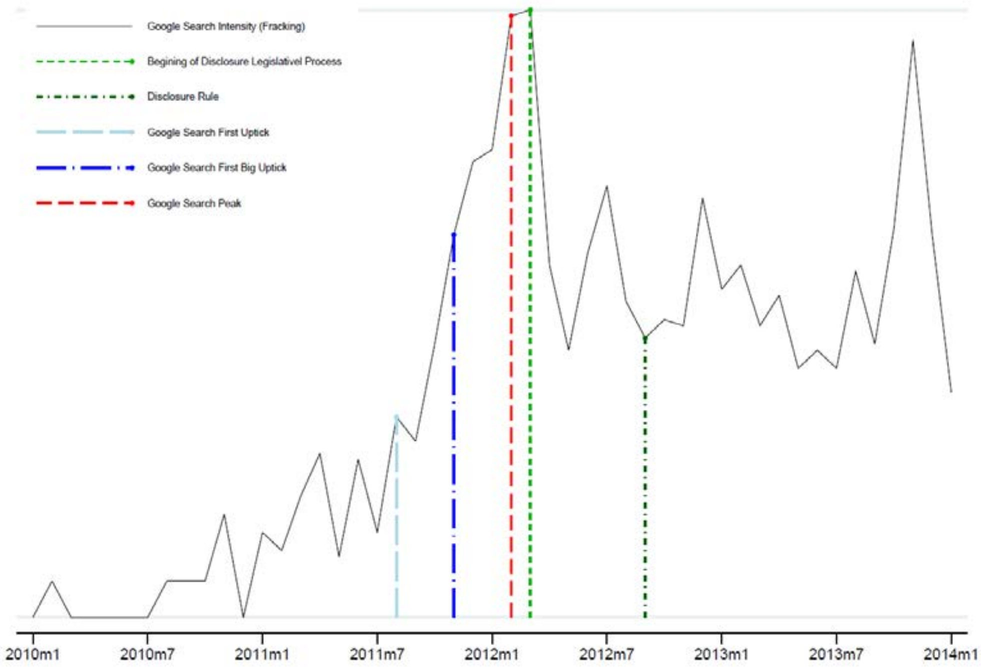
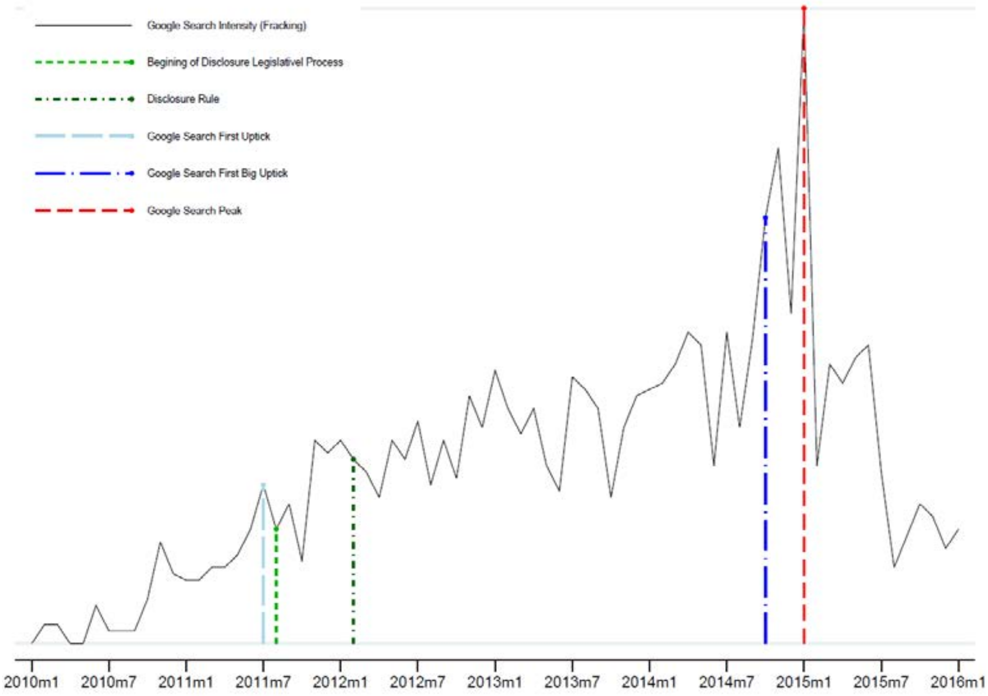


Figure 5 plots coefficients from estimating the model shown in Column (5) of Table 7, together with the respective 95% confidence intervals, using separate HF well counts calculated over fixed time intervals around the well spud dates. We estimate the coefficients for the pre- and post-disclosure period separately. The red (gray) dots are the coefficients for HF wells spudded in the pre-disclosure (post-disclosure) period.

Figure 6 – Google Search Trends around the Introduction of the Disclosure Rules



Ohio



Texas

Figure 6 plots the evolution of Google searches of the term “fracking” for Ohio and Texas, respectively. We superimpose the key legislative events for the disclosure rule (i.e., the beginning of the legislative process and the adoption date). We have performed the same exercise for the remaining states in the sample. In total, 13 out of the 16 sample states have a pattern like Texas (i.e., Google searches peak after adoption).

Table 1 – Sample Composition and Descriptive Statistics

Panel A: Sample composition and entry-into-force dates of the state disclosure mandates

State	Unique monitors	Unique wells	N	Entry-into-force
Arkansas	1,156	6,472	51,898	15-Jan-2011
Colorado	1,298	10,343	23,438	01-Apr-2012
Kansas	379	132	10,341	02-Dec-2013
Kentucky	601	695	8,079	19-Mar-2015
Louisiana	303	4,467	5,764	20-Oct-2011
Mississippi	128	163	2,252	04-Mar-2013
Montana	499	1,381	6,799	26-Aug-2011
New Mexico	119	11,470	1,368	15-Feb-2012
North Dakota	519	17,243	13,904	01-Apr-2012
Ohio	3,768	3,036	68,148	10-Sep-2012
Oklahoma	473	8,254	12,732	01-Jan-2013
Pennsylvania	2,066	12,319	88,122	16-Apr-2012
Texas	723	65,468	10,411	01-Feb-2012
Utah	650	1,421	12,982	01-Nov-2012
West Virginia	92	4,053	1,080	29-Aug-2011
Wyoming	176	7,407	8,033	17-Aug-2010

Panel B: Number of watersheds in the treatment and control samples

	Bromide	**Chloride**	**Barium**	**Strontium**
# HUC10s w/ HF in pre-period	163	573	358	216
# HUC10s w/o HF in pre-period	268	1,618	884	409

Table 1, Panel A, provides the number of water monitoring stations, HF wells and water quality measurements per state as well as the date when the disclosure of the HF fluid composition became mandatory. Panel B shows the number of watersheds in the treatment and control samples for the respective ion. HUC10s are assigned to treatment and control depending on the existence of HF activity in the pre-disclosure period.

Table 2 – Descriptive Statistics for Surface Water Measurements (μ/l)

Panel A – Treated HUC10s with HF in the pre-disclosure period

Bromide	N	Mean	p25	p50	p75	SD
Concentration	6,216	121.303	31.480	60.000	100.000	333.849
Ln(Concentration)	6,216	4.139	3.481	4.111	4.615	1.090
Chloride						
Concentration	46,269	49,130.850	5,620.000	15,000.000	39,680.000	177,371.300
Ln(Concentration)	46,269	9.588	8.634	9.616	10.589	1.691
Barium						
Concentration	26,001	53.147	31.000	43.800	63.000	75.472
Ln(Concentration)	26,001	3.696	3.466	3.802	4.159	0.895
Strontium						
Concentration	21,484	296.759	49.000	146.000	290.000	523.933
Ln(Concentration)	21,484	4.895	3.912	4.990	5.673	1.250

Panel B – HUC10s without HF in the pre-disclosure period

Bromide						
Concentration	9,567	221.260	20.300	43.682	101.250	1,798.698
Ln(Concentration)	9,567	3.962	3.060	3.800	4.629	1.165
Chloride						
Concentration	142,060	103,213.10	4,680.00	14,165.63	35,800.00	980,708.70
Ln(Concentration)	142,060	9.298	8.451	9.559	10.486	2.114
Barium						
Concentration	46,702	64.121	30.000	47.000	71.000	524.401
Ln(Concentration)	46,702	3.700	3.434	3.871	4.277	1.059
Strontium						
Concentration	27,052	705.277	81.000	251.000	654.000	1,360.458
Ln(Concentration)	27,052	5.366	4.407	5.529	6.485	1.734

Table 2 presents descriptive statistics for surface water ion concentrations. Panel A reports statistics for the ion concentrations in treatment watersheds (HUC10s) with HF activity in the pre-disclosure period. Panel B reports statistics for the ion concentrations in control watersheds (HUC10s) without HF activity in the pre-disclosure period, that are located in treatment states and within sub-regions (HUC4s) that had HF activity in some HUC10s. The panels report statistics for the raw ion concentrations and after applying the natural logarithm (ln).

Panel C – Distribution of surface water measurements

Unique # of HUC10s by state	**N**	**Mean**	**p25**	**p50**	**p75**	**SD**
	2,209	182	136	192	242	67

Unique # of HUC10s by state/ion	**N**	**Mean**	**p25**	**p50**	**p75**	**SD**
Bromide	431	77	36	70	149	55
Chloride	2,209	179	135	171	242	71
Barium	1,247	141	101	134	199	64
Strontium	628	147	29	183	230	88

Unique # of monitoring stations by HUC10	**N**	**Mean**	**p25**	**p50**	**p75**	**SD**
	12,950	15	5	12	22	13

Unique # of monitoring stations by HUC10/ion	**N**	**Mean**	**p25**	**p50**	**p75**	**SD**
Bromide	1,453	8	3	5	8	8
Chloride	12,577	15	6	11	21	13
Barium	6,995	14	5	11	20	12
Strontium	4,829	17	7	14	22	13

Water quality observations by HUC10/ion	**N**	**Mean**	**p25**	**p50**	**p75**	**SD**
Bromide	15,783	37	4	12	37	62
Chloride	188,329	85	12	34	107	152
Barium	72,703	58	11	34	81	72
Strontium	48,536	77	15	49	107	91

Panel C presents distributional information on the number of HUC10s by state and by state and ion, the number of water quality monitoring stations by HUC10 and by HUC10 and ion as well as the number of surface water measurements quality by HUC10 and ion.

Table 3 – Disclosure Mandates and Water Quality

	Bromide		Chloride		Barium		Strontium		All Ions pooled			
	(µg/l)		(µg/l)		(µg/l)		(µg/l)		(µg/l)			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
HUC10_HF×POST	-0.1108	0.0449	**-0.1955*****	**-0.1183****	**-0.0969*****	**-0.0589****	**-0.0448****	-0.0382	**-0.1509*****	**-0.0928****	**-0.1476*****	**-0.0925****
	[0.0714]	[0.1232]	**[0.0557]**	**[0.0520]**	**[0.0352]**	**[0.0346]**	**[0.0223]**	[0.0290]	**[0.0386]**	**[0.0363]**	**[0.0418]**	**[0.0365]**
Observations	15,783	14,538	188,329	176,729	72,703	65,812	48,536	46,308	325,351	303,387	220,208	206,389
R-squared	0.860	0.915	0.865	0.903	0.834	0.867	0.968	0.976	0.961	0.971	0.961	0.971
Treatment Sample	HUC10s with HF activity in the pre-disclosure period											
Full Sample	All HUC10s in sub-regions (HUC4s) in treated states with some HF activity										HUC10s over shales in treated states	
Monitoring station FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Weather controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
State×Month×Year FE	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No
HUC8×Month	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No
HUC8×Month×Year FE	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes

Table 3 reports OLS coefficients estimating Eq. (1) to assess the impact of the state disclosure mandates on the respective ion concentrations. The models in Columns (9)-(12) pool all four ion concentrations in one model, as described in Section IV. In Columns (1)-(10), the sample consists of treatment HUC10s with HF activity in the pre-disclosure period and control HUC10s without HF activity in the pre-and post-disclosure period that are located in treated states and within sub-regions (HUC4s) with some HF activity. In Columns (11)-(12), the sample consists of treatment HUC10s with HF activity in the pre-disclosure period, but the control HUC10s without HF activity in the pre- and post-disclosure period are restricted to those located over shales in treated states. *HUC10_HF* is a binary indicator marking watersheds with HF activity (treated HUC10s). *POST* is a binary variable marking water quality measurements taken in the post-disclosure period. The sub-panel at the bottom indicates the fixed effects (FE) included in the model. Standard errors (in parentheses) are clustered by HUC10 and reported below the coefficients. *, **, *** denote statistical significance at the 10%, 5%, and 1% level (two-tailed), respectively.

Table 4 – Disclosure Mandates and Water Quality: Non-HF Specific Analytes and Vertical Wells

Panel A – Analytes that are not specific to HF impact

	Dissolved oxygen		Fecal Coliform (μg/l)		Phosphorus (μg/l)		All Analytes pooled	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
HUC10_HF×POST	0.0141 [0.0475]	-0.0402 [0.0533]	-0.1567 [0.1809]	0.1475 [0.5896]	**-0.0309**** **[0.0150]**	0.0189 [0.0141]	-0.0190 [0.0273]	-0.0046 [0.0319]
Observations	110,339	103,769	26,729	25,472	111,956	106,069	249,024	235,310
R-squared	0.760	0.818	0.555	0.620	0.524	0.650	0.911	0.933
Treatment Sample	HUC10s with HF activity in the pre-disclosure period							
Monitoring station FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Weather controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
State×Month×Year FE	Yes	No	Yes	No	Yes	No	Yes	No
HUC8×Month	Yes	No	Yes	No	Yes	No	Yes	No
HUC8×Month×Year FE	No	Yes	No	Yes	No	Yes	No	Yes

Table 4, Panel A, reports OLS coefficients estimating Eq. (1) for three water quality proxies that are not specific to HF impact. The models in Columns (7) and (8) pool all analytes in one model, as described in Section IV. The sample consists of treatment HUC10s with HF activity in the pre-disclosure period and control HUC10s without HF activity in the pre- and post-disclosure period that are located in treated states and within sub-regions (HUC4s) with some HF activity. *HUC10_HF* is a binary indicator marking watersheds with HF activity (treated HUC10s). *POST* is a binary variable marking water quality measurements taken in the post-disclosure period. The sub-panel at the bottom indicates the fixed effects (FE) included in the model. Standard errors (in parentheses) are clustered by HUC10 and reported below the coefficients. *, **, *** denote statistical significance at the 10%, 5%, and 1% level (two-tailed), respectively.

Panel B – Conventional drilling

	Bromide (µg/l)		Chloride (µg/l)		Barium (µg/l)		Strontium (µg/l)		All Ions pooled (µg/l)	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
HUC10_Conv×POST	0.0110 [0.1461]	0.0107 [0.0170]	-0.0499 [0.0379]	-0.0593 [0.0570]	-0.0260 [0.0170]	-0.0504 [0.0275]	-0.0157 [0.0401]	-0.0587 [0.0528]	-0.0409 [0.0289]	-0.0567 [0.0394]
Observations	9,637	8,686	141,131	130,536	45,915	40,027	26,631	24,627	223,314	203,876
R-squared	0.879	0.929	0.870	0.905	0.838	0.864	0.968	0.975	0.956	0.967
Treatment Sample	HUC10s with conventional drilling activity in the pre-disclosure period									
Monitoring station FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Weather controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
State×Month×Year FE	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No
HUC8×Month	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No
HUC8×Month×Year FE	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes

Table 4, Panel B, reports OLS coefficients estimating Eq. (1) for HUC10s with conventional, i.e., vertically drilled, wells around the introduction of the disclosure mandates. The sample consists of treatment HUC10s with conventional drilling in the pre-disclosure period (and not HF) and control HUC10s without conventional drilling (and not HF activity) in the pre- and post-disclosure period that are located in treated states and within sub-regions (HUC4s) with some conventional drilling activity. *HUC10_Conv* is a binary indicator marking watersheds with conventional drilling activity (treated HUC10s). *POST* is a binary variable marking water quality observations in the post-disclosure period. The sub-panel at the bottom indicates the fixed effects (FE) included in the model. Standard errors (in parentheses) are clustered by HUC10 and reported below the coefficients. *, **, *** denote statistical significance at the 10%, 5%, and 1% level (two-tailed), respectively.

Table 5 – Disclosure Mandates and Water Quality: Controlling for other HF Regulations

	All Ions pooled (μg/l)											
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
HUC10_HF×POST				**-0.1364*****	**-0.1907*****	**-0.1600****				**-0.0874****	**-0.0919***	**-0.0871***
				[0.0481]	**[0.0672]**	**[0.0626]**				**[0.0415]**	**[0.0491]**	**[0.0491]**
HUC10_HF×CUM_WASTEWATER	**-0.0331*****			-0.0072			**-0.0181****			-0.0027		
	[0.0076]			[0.0092]			**[0.0075]**			[0.0077]		
HUC10_HF×CUM_HF_STANDARDS		**-0.0265*****			0.0159			**-0.0197****			-0.0005	
		[0.0058]			[0.0133]			**[0.0079]**			[0.0109]	
HUC10_HF×CUM_HF_REG			**-0.0179*****			0.0020			**-0.0121*****			-0.0014
			[0.0036]			[0.0067]			**[0.0046]**			[0.0057]
Observations	325,351	325,351	325,351	325,351	325,351	325,351	303,387	303,387	303,387	303,387	303,387	303,387
R-squared	0.961	0.961	0.961	0.961	0.961	0.961	0.971	0.971	0.971	0.971	0.971	0.971
Coef. *HUC10_HF×POST* (Table 3)				**-0.1509**	**-0.1509**	**-0.1509**				**-0.0928**	**-0.0928**	**-0.0928**
Treatment Sample	HUC10s with HF activity in the pre-disclosure period											
Monitoring station FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Weather controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
State×Month×Year FE	Yes	Yes	Yes	Yes	Yes	Yes	No	No	No	No	No	No
HUC8×Month	Yes	Yes	Yes	Yes	Yes	Yes	No	No	No	No	No	No
HUC8×Month×Year FE	No	No	No	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes

Table 5 reports OLS coefficients estimating Eq. (1), but adding controls for other HF regulations using three alternative variables: (i) *HUC10_HF×CUM_WASTEWATER*, which represents the cumulative number of regulations related to wastewater handling at a given point of time (i.e., the variable increases by one when a new regulation for wastewater handling is introduced in a state) in watersheds with HF wells in the pre-disclosure period; (ii) *HUC10_HF×CUM_HF_STANDARDS*, which represents the number of HF drilling standards at a point in time (i.e., the variable increases by one when a new drilling standard is introduced) in watersheds with HF wells in the pre-disclosure period; (iii) *HUC10_HF×CUM_HF_REG*, which represents the joint number of wastewater handling rules and drilling standards at a given point in time (i.e., the variable is the sum of the previous to two variables) in watersheds with HF wells in the pre-disclosure period The sample consists of treatment HUC10s with HF activity in the pre- and post-disclosure period and control HUC10s without HF activity in the pre- and post-disclosure period that are located in treated states and within sub-regions (HUC4s) with some HF activity. *HUC10_HF* is a binary indicator marking watersheds with HF activity (treated HUC10s). *POST* is a binary variable marking water quality measurements taken in the post-disclosure period. We report the respective coefficient of interest from Table 3 for comparison. The sub-panel at the bottom indicates the fixed effects (FE) included in the model. Standard errors (in parentheses) are clustered by HUC10 and reported below the coefficients. *, **, *** denote statistical significance at the 10%, 5%, and 1% level (two-tailed), respectively.

Table 6 – Disclosure Mandates and Well Entry: Extensive Margin Analysis

	#HF wells (1)	#HF wells (2)	#HF wells (3)	#HF wells (4)	#[HF – V] wells (5)	#[HF – V] wells (6)
POST	**-0.0554***** **[0.0162]**	**-0.0629***** **[0.0213]**	**-0.0559***** **[0.0196]**	**-0.0506*** **[0.0285]**	**-0.0505**** **[0.0257]**	**-0.0692*** **[0.03721]**
CUM_HF_REG					**0.0575***** **[0.0107]**	**0.0687***** **[0.0160]**
Observations	199,962	112,644	199,773	112,455	199,773	112,455
R-squared	0.383	0.408	0.468	0.461	0.480	0.492
Sample	ALL	HUC8s across two or more states	ALL	HUC8s across two or more states	ALL	HUC8s across two or more states
HUC10 FE	Yes	Yes	Yes	Yes	Yes	Yes
Region×Month×Year FE	Yes	Yes	No	No	No	No
Shale×Month×Year FE	No	No	Yes	Yes	Yes	Yes

Table 6 reports OLS coefficients estimating the impact of the state disclosure mandates on HF well entry. The sample comprises HUC10s in treatment states over shales. In Columns (1)-(4), the dependent variable is the natural logarithm of one plus the number of new HF wells spudded in a given HUC10-month-year. In Columns (5)–(6), the dependent variable is the natural logarithm of one plus the number of new HF wells minus the number of new conventional (or vertical) wells. In these models, we also control for changes in other HF regulations. In Columns (2), (4) and (6), the sample is restricted to HUC10s within HUC8s that are partially located in at least two states (i.e., are crossing state lines). *POST* is a binary variable equal to one in the post-disclosure period. In Columns (1)–(2), we include region×month×year fixed effects in the model. In Columns (3)–(6), we include shale×month×year fixed effects. There are 30 shales in our sample that can be classified into five regions: North-East, South-Mid-West, South-West, Mountain, North-West. Standard errors (in parentheses) are clustered by HUC10 and reported below the coefficients. *, **, *** denote statistical significance at the 10%, 5%, and 1% level (two-tailed), respectively.

Table 7 – Disclosure Mandates and Water Quality: Intensive Margin (Per-Well) Analysis

	Bromide (µg/l) (1)	Chloride (µg/l) (2)	Barium (µg/l) (3)	Strontium (µg/l) (4)	All Ions Pooled (µg/l) (5)
#WELL_HUC10_HF_POST	0.0005	**0.0006****	-0.0001	0.0004	**0.0005***
	[0.0020]	**[0.0003]**	[0.0001]	[0.0003]	**[0.0003]**
#WELL_HUC10_HF_PRE	**0.0075*****	**0.0008****	-0.0003	**0.0009****	**0.0007****
	[0.0020]	**[0.0003]**	[0.0002]	**[0.0004]**	**[0.0003]**
Observations	4,797	32,917	16,989	15,886	70,589
R-squared	0.894	0.922	0.893	0.973	0.986
F-Test	0.077	0.784	0.651	0.386	0.664
Treatment Sample	HUC10s with HF in the pre & post disclosure period				
Monitoring station FE	Yes	Yes	Yes	Yes	Yes
Weather controls	Yes	Yes	Yes	Yes	Yes
HUC8×Month×Year FE	Yes	Yes	Yes	Yes	Yes

Table 7 reports OLS coefficients estimating the per-well effects of new HF wells on ion concentrations, separately for the pre- and the post-disclosure periods. The sample consists of HUC10s with HF activity in the pre-disclosure and the post-disclosure periods. *#WELL_HUC10_HF_POST* (*PRE*) is a cumulative well count variable, which increases by one when a new HF well in the respective HUC10 is spudded. Given the findings in Bonetti et al. (2021), we align water measurements on a given day with well counts that are lagged by 120 days. Standard errors (in parentheses) are clustered by HUC10 and reported below the coefficients. *, **, *** denote statistical significance at the 10%, 5%, and 1% level (two-tailed), respectively.

Table 8 – Environmental Performance (Production per Unit of Pollution)

	O&G Production / All Ions (μg/l) (1)	O&G Production / All Ions (μg/l) (2)	O&G Production / All Ions (μg/l) (3)	O&G Production / All Ions Pooled (μg/l) (4)
HUC10_HF×POST	**40.4681****	**23.2152***	**49.0126*****	**31.7463***
	[16.4891]	**[14.1630]**	**[18.4847]**	**[18.5015]**
Observations	269,473	251,912	249,685	231,869
R-squared	0.946	0.962	0.946	0.962
Treatment Sample	HUC10s with HF activity in the pre	HUC10s with HF activity in the pre	HUC10s with HF activity in pre & post	HUC10s with HF in activity in pre & post
Monitoring station FE	Yes	Yes	Yes	Yes
Weather controls	Yes	Yes	Yes	Yes
State×Month×Year FE	Yes	No	Yes	No
HUC8×Month	Yes	No	Yes	No
HUC8×Month×Year FE	No	Yes	No	Yes

Table 8 reports OLS coefficients estimating Eq. (1) for an alternative dependent variable: the ratio of the average O&G production (bbl) in a given HUC10-month-year and the sum of the four ion concentrations (μg/l). In Columns (1)-(2), the sample consists of treatment HUC10s with HF activity in the pre-disclosure period (and non-missing O&G production data) and control HUC10s without HF in the pre- and post-disclosure period that are located in treated states and within sub-regions (HUC4s) with some HF activity. In Columns (3)-(4), the sample consists of treatment HUC10s with HF activity in the pre- *and* post-disclosure period (and non-missing O&G production data) and control HUC10s without HF in the pre- and post-disclosure period that are located in treated states and within sub-regions (HUC4s) with some HF activity. *HUC10_HF* is a binary indicator marking treated watersheds (HUC10s). *POST* is a binary variable marking water quality measurements taken in the post-disclosure period. Standard errors (in parentheses) are clustered by HUC10 and reported below the coefficients. *, **, *** denote statistical significance at the 10%, 5%, and 1% level (two-tailed), respectively.

Table 9 – Chemicals used in the HF Fluids

	All Hazardous Chemicals (1)	Chloride-related Chemicals (2)
POST	**-0.0097***** **[0.0024]**	**-0.0034***** **[0.0013]**
Observations	15,607	15,607
R-squared	0.335	0.157
Sample	HUC10s over shales	
HUC10 FE	Yes	Yes
Month×Year FE	Yes	Yes

Table 9 reports OLS coefficients estimating the impact of the disclosure mandates on the chemicals used in HF fluids. Data on the chemicals disclosed by well operators are from Konschnik and Dayalu (2016). The dependent variable is constructed at the HUC10 level, averaging over all HF well disclosures for each HUC10-month-year. We compute averages for the amount of all hazardous chemicals, chloride-related chemicals, respectively. For each HF well, we scale the respective amount by the total amount of fluids injected. Hazardous chemicals are those (i) regulated as primary contaminants by the Safe Drinking Water Act; (ii) regulated as Priority Toxic Pollutants for ecological toxicity under the Clean Water Act; or (iii) classified as diesel fuel under EPA guidance on HF operations (USEPA, 2012a, 2014). For the pre-period, we use voluntary disclosures to calculate HUC10-month-year averages, following Fetter (2017). *POST* is a binary variable equal to one in the post-disclosure period. Standard errors (in parentheses) are clustered by HUC10 and reported below the coefficients. *, **, *** denote statistical significance at the 10%, 5%, and 1% level (two-tailed), respectively.

Table 10 – HF-Related Incidents

	All Incidents		Wastewater Incidents	
	(1)	(2)	(3)	(4)
POST	**-0.1623****	-0.0758	**-0.1443*****	**-0.0894****
	[0.0754]	[0.0781]	**[0.0308]**	**[0.0371]**
Observations	7,562	5,001	6,440	4,280
R-squared	0.319	0.351	0.190	0.209
Sample	HUC10s over shales			
	ALL	HUC8s across two or more states	ALL	HUC8s across two or more states
HUC10 FE	Yes	Yes	Yes	Yes
Month×Year FE	Yes	Yes	Yes	Yes

Table 10 reports OLS coefficients estimating the impact of the state disclosure mandates on HF-related incidents such as spills, leaks and accidents (sample up to Dec 2015). The sample comprises HUC10s over shales in states covered in Brantley *et al*. (2014) and Patterson *et al.* (2017). The dependent variable is the logarithm of one plus the number of HF-related incidents in a given HUC10-month-year. Columns (1)-(2) report results for all HF-related incidents. Columns (3)-(4) report results using only spills related to the disposal of wastewater. In Columns (2) and (4), the sample is restricted to HUC10s within HUC8s that are located in at least two neighboring states, i.e., are crossing state lines. *POST* is a binary variable equal to one in the post-disclosure period. Standard errors (in parentheses) are clustered by HUC10 and reported below the coefficients. *, **, *** denote statistical significance at the 10%, 5%, and 1% level (two-tailed), respectively.

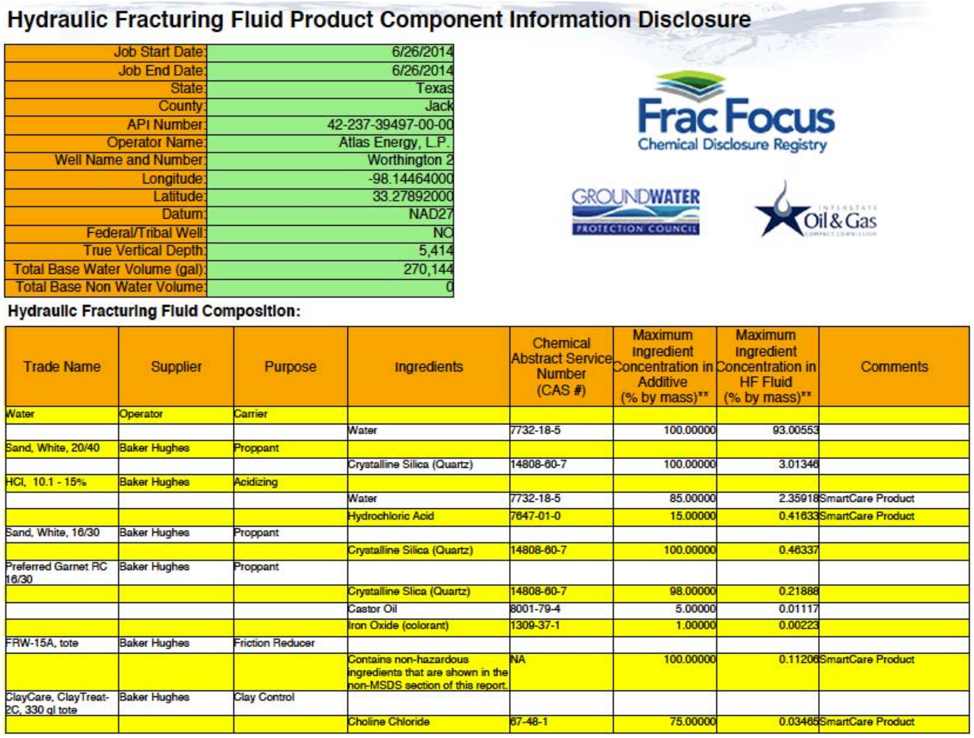
Table 11 – HF Activity and Water Quality: Role of Public Pressure

	All Ions Pooled (μg/l)							
	Role of public pressure – partitioning on:						*Features of the disclosure regime – partitioning on:*	
	NGOs (1)	*Media Scrutiny* (2)	*Increase in media coverage* (3)	*Increase in Google searches* (4)	*Publicly Owned Operators* (5)	*FracFocus Dissemination* (6)	*Trade Secret Exemptions* (7)	*Disclosure Timeliness* (8)
POST×HUC10_HF×High Group	**-0.1992****	**-0.1908*****	**-0.2734*****	**-0.1195****	**-0.1633*****		**-0.1275****	**-0.1536*****
	[0.0893]	**[0.0686]**	**[0.0601]**	**[0.0563]**	**[0.0587]**		**[0.0508]**	**[0.0586]**
POST×HUC10_HF×Low Group	**-0.0893****	**-0.0906****	**-0.0656****	**-0.0580****	**-0.0844****		-0.0582	-0.0161
	[0.0367]	**[0.0365]**	**[0.0325]**	**[0.0260]**	**[0.0362]**		[0.0446]	[0.0269]
POST×HUC10_HF						**-0.0774****		
						[0.0378]		
POST×HUC10_HF× CUM_FF_CHANGES						**-0.0255***		
						[0.0152]		
Observations	303,387	303,387	303,387	303,387	303,387	303,387	303,387	303,387
R-squared	0.971	0.971	0.971	0.971	0.971	0.971	0.971	0.971
Treatment Sample	HUC10s with HF activity in the pre-disclosure period							
F-Test	0.1967	**0.0998**	**0.0001**	0.2995	**0.0870**	NA	**0.2881**	**0.0364**
Monitoring station FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Weather controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
HUC8×Month×Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Table 11, Panel A, Columns (1)-(5) reports coefficients from an alternative version of Eq. (1), for which we split *POST×HUC10_HF* by two non-overlapping variables marking observations in the post-disclosure period that fall into a *High Group* and into a *Low Group*, respectively. The high/low partitions are as follows: (1) core-based statistical areas/counties with *at least one* (*no*) local anti-fracking NGO active in the year before the adoption of the disclosure mandate; (2) counties with an *at least one* (*no*) local newspapers active in the 360 days leading up to the adoption of the disclosure mandate; (3) counties with an *increase* (*decrease*) in the number of newspapers articles pointing to HF as a source of water pollution between the pre- and post-disclosure period; (4) states with an *above* (*below*) sample median of the change in the state-specific average Google search trend for the term "fracking" between the pre- and post-disclosure periods; (5) HUC10s with an *above* (*below*) 50 percent of wells owned by publicly traded operators. *HUC10_HF* is an indicator variable marking treated watersheds (HUC10s). In Column (6), we estimate an alternative version of Eq. (1), in which we include the cumulative number of website changes implemented by FracFocus to implement accessibility and dissemination, *CUM_FF_CHANGES* interacted with *HUC10_HF×POST*. Columns (7)-(8) reports coefficients from an alternative version of Eq. (1), for which we split *POST×HUC10_HF* by two non-overlapping variables marking observations in the post-disclosure period that fall into a *High Group* and into a *Low Group*, respectively. The high/low partitions are as follows: (7) states in which it is *more difficult* (*easier*) to obtain trade secret exemptions for the disclosure of HF fluids. The former (latter) group includes states with two or more (none or one) conditions for trade secret exemptions; (8) states, for which the required disclosures need to be timelier, based on a *below* (*above*) the sample median split on the #days between the spud date and the required regulatory filing date. The sample includes treatment HUC10s with HF activity in the pre-disclosure period and control HUC10s without HF in the pre- and post-disclosure period that are located in treated states and within sub-regions (HUC4s) with some HF activity. *POST* is a binary variable marking water quality measurements taken in the post-disclosure period. We report results with HUC8×Month×Year FE. The results with HUC8×Month×Year FE are very similar. Standard errors (in parentheses) are clustered by HUC10 and reported below the coefficients. *, **, *** denote statistical significance at the 10%, 5%, and 1% level (two-tailed), respectively.

Appendix

Example of HF Fluid Disclosures



Hydraulic Fracturing Fluid Product Component Information Disclosure

Job Start Date:	6/26/2014
Job End Date:	6/26/2014
State:	Texas
County:	Jack
API Number:	42-237-39497-00-00
Operator Name:	Atlas Energy, L.P.
Well Name and Number:	Worthington 2
Longitude:	-98.14464000
Latitude:	33.27892000
Datum:	NAD27
Federal/Tribal Well:	NO
True Vertical Depth:	5,414
Total Base Water Volume (gal):	270,144
Total Base Non Water Volume:	0

Hydraulic Fracturing Fluid Composition:

Trade Name	Supplier	Purpose	Ingredients	Chemical Abstract Service Number (CAS #)	Maximum Ingredient Concentration in Additive (% by mass)**	Maximum Ingredient Concentration in HF Fluid (% by mass)**	Comments
Water	Operator	Carrier					
			Water	7732-18-5	100.00000	93.00553	
Sand, White, 20/40	Baker Hughes	Proppant					
			Crystalline Silica (Quartz)	14808-60-7	100.00000	3.01346	
HCl, 10.1 - 15%	Baker Hughes	Acidizing					
			Water	7732-18-5	85.00000	2.35918	SmartCare Product
			Hydrochloric Acid	7647-01-0	15.00000	0.41633	SmartCare Product
Sand, White, 16/30	Baker Hughes	Proppant					
			Crystalline Silica (Quartz)	14808-60-7	100.00000	0.46337	
Preferred Garnet RC 16/30	Baker Hughes	Proppant					
			Crystalline Slica (Quartz)	14808-60-7	98.00000	0.21888	
			Castor Oil	8001-79-4	5.00000	0.01117	
			Iron Oxide (colorant)	1309-37-1	1.00000	0.00223	
FRW-15A, tote	Baker Hughes	Friction Reducer					
			Contains non-hazardous ingredients that are shown in the non-MSDS section of this report.	NA	100.00000	0.11206	SmartCare Product
ClayCare, ClayTreat-2C, 330 gl tote	Baker Hughes	Clay Control					
			Choline Chloride	67-48-1	75.00000	0.03465	SmartCare Product

The figure displays an example for HF fluid disclosures. It is taken from a well spudded in Texas after the state adopted the disclosure mandate. The figure shows the information provided by the disclosure, including the start date of the on-site operations, well ID, operator name, the coordinates of the well and information on the water consumed along with the chemicals used by the operator drilling the well. Some of the ingredients and chemicals CAS numbers are not disclosed because of trade secret exemptions. In this example, the operator still has to report the trade name, the purpose of the chemical and the quantity used.