Hydraulic fracturing near domestic groundwater wells

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Hydraulic fracturing operations are generating considerable discussion about their potential to contaminate aquifers tapped by domestic groundwater wells. Groundwater wells located closer to hydraulically fractured wells are more likely to be exposed to contaminants derived from on-site spills and well-bore failures, should they occur. Nevertheless, the proximity of hydraulic fracturing operations to domestic groundwater wells is unknown. Here, we analyze the distance between domestic groundwater wells (public and self-supply) constructed between 2000 and 2014 and hydraulically fractured wells stimulated in 2014 in 14 states. We show that 37% of all recorded hydraulically fractured wells stimulated during 2014 exist within 2 km of at least one recently constructed (2000–2014) domestic groundwater well. Furthermore, we identify 11 counties where most (>50%) recorded domestic groundwater wells exist within 2 km of one or more hydraulically fractured wells stimulated during 2014. Our findings suggest that understanding how frequently hydraulic fracturing operations impact groundwater quality is of widespread importance to drinking water safety in many areas where hydraulic fracturing is common. We also identify 236 counties where most recorded domestic groundwater wells exist within 2 km of one or more recorded oil and gas wells producing during 2014. Our analysis identifies hotspots where both conventional and unconventional oil and gas wells frequently exist near recorded domestic groundwater wells that may be targeted for further water-quality monitoring.

groundwater well | hydraulic fracturing | water quality | drinking water

United States (US) natural gas production derived from hydraulically fractured wells increased 10-fold between 2000 and 2015 (1). Hydraulic fracturing has enabled production of reserves that were otherwise uneconomic to extract with conventional oil and gas technologies. Although hydraulic fracturing technologies have been used to enhance hydrocarbon production for decades, concerns that hydraulic fracturing operations may contaminate groundwater have gained traction with the public in recent years (2, 3). As unconventional oil and gas reserves become more accessible economically (4), characterizing risk from hydraulic fracturing operations to groundwater will be critical for safeguarding groundwater quality and addressing public concerns (5).

To begin understanding, managing, and communicating (6) hydraulic fracturing risks to the public, it is important to understand both the (*i*) likelihood that mechanisms with the potential to contaminate groundwaters may occur, and (*ii*) potential population affected by a contamination event. Hydraulic fracturing is a stimulation process that pumps fluid through a well (henceforth referred to as a hydraulically fractured well) to fracture hydrocarbon-bearing rock to increase oil and gas production; the fluid is most often composed of water, sand, and chemical additives (https://fracfocus.org/chemical-use). There are a variety of mechanisms that have the potential to contaminate groundwater aquifers before, during, or after the hydraulic fracturing process (e.g., Table 1). Although the likelihood that each mechanism may occur is relatively small, the population using groundwater for domestic purposes that may be exposed to a potential contamination event associated with hydraulic fracturing operations has yet to be quantified, limiting our understanding of hydraulic fracturing risks (1).

According to the US Environmental Protection Agency (EPA), when hydraulically fractured wells are located near domestic water resources, "there is a greater potential for activities in the hydraulic fracturing water cycle to impact those resources" (1). Literature focused on individual case studies supports this sentiment: The proximity of groundwater wells to a contamination mechanism associated with hydraulic fracturing operations is important to identify potentially contaminated well waters (7–10). In 2016, the EPA evaluated the proximity of hydraulically fractured wells to public water supplies on a national scale (1). Citing a lack of aggregated groundwater well construction data, the EPA did not assess the proximity of hydraulically fractured wells to private, self-supply groundwater wells. Self-supply groundwater wells provide drinking water to 45 million US residents (1), and, unlike public water utilities, self-supply groundwater well owners are not required to monitor water quality regularly under the Safe Drinking Water Act (42 USC, §300f; ref. 11). Consequently, contamination in self-supply wells may be more likely to go unnoticed than contamination in public-supply wells. To understand contamination risks that hydraulic fracturing may pose to drinking-water wells, it is important to characterize the proximity of hydraulic fracturing operations to self- and public-supply groundwater wells.

The central objective of our study is to evaluate the horizontal proximity and vertical offset of recorded hydraulically fractured wells stimulated in 2014 and recorded domestic self- and public-supply groundwater wells constructed between 2000 and 2014. We recognize that (*i*) hydraulically fractured wells are but one type of well used to produce oil and gas, and (*ii*) some potential groundwater contamination mechanisms identified in

Significance

Millions of Americans rely on self-supply groundwater wells for drinking water, but the number of these wells that are located near hydraulic fracturing operations is unknown. Here, we show that approximately half of all hydraulically fractured wells stimulated in 2014 exist within 2–3 km of one or more domestic (public and self-supply) groundwater wells. Our finding that many hydraulically fractured and domestic groundwater wells are colocated emphasizes that determining how frequently hydraulic fracturing activities impact groundwater quality is important to maintaining high-quality water in many domestic wells.

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Table 1. Estimated frequency of some potential contamination mechanisms from hydraulic fracturing jobs or wells

Potential contamination mechanism	Approximate frequency (1)
Spills	2.6% (0.4–12.2%) of wells
“Frac hit” of nearby well	1% (0.4–4%) of wells
Well integrity failure	0.5% (0.1–2%) of jobs

See also *SI Appendix*, Table S22.

unconventional oil and gas operations are identified also in conventional oil and gas operations [e.g., spills (12)]; therefore, we also evaluate the proximity between recorded oil and gas wells producing hydrocarbons in 2014 and recorded domestic self- and public-supply groundwater wells constructed between 2000 and 2014.

Materials and Methods

We analyzed hydraulic fracturing records downloaded from FracFocus (fracfocus.org/data-download) and oil and gas records downloaded from FracTracker (https://www.fractracker.org/map/national/us-oil-gas/; ref. 13). Our analysis of hydraulic fracturing operations assessed wells likely stimulated in 2014, whereas our analysis of oil and gas wells assessed wells producing hydrocarbons in 2014. The FracFocus dataset contains $n = 119{,}223$ records; we identified $n = 28{,}950$ records indicating possible stimulation during the year 2014, $n = 28{,}154$ (97%) of which report nonzero well depths. We analyzed wells with records of hydraulic fracturing where the time interval defined by “JobStartDate” and “JobEndDate” encompassed at least 1 day during the year 2014; 97% of the analyzed records had a time interval contained entirely within 2014. We removed duplicate records of hydraulically fractured wells on the basis of identical American Petroleum Institute numbers, retaining the record with the largest recorded value of “TotalBaseW”. In total, we analyzed $n = 26{,}983$ hydraulically fractured well records in 14 states where domestic water well data were available, and where >100 records of hydraulically fractured wells stimulated in 2014 existed in FracFocus. We acknowledge that FracFocus well depths are total vertical depths (Fig. 1*A*) and do not account for perforations that may occur hundreds of meters above the reported total vertical depth (14). The FracTracker dataset contains $n = 1{,}193{,}575$ records of oil and gas wells, compressors, and processors, 99% ($n = 1{,}182{,}278$) of which are oil and gas well records analyzed in this study. FracTracker records wells that were actively producing in the year 2014, which was the most recent year for which records were available. We did not combine the 2014 FracTracker dataset with earlier datasets, because FracTracker’s record-keeping methodology has evolved. FracTracker does not include oil and gas well depth data, and it was not possible to link activities in FracTracker to FracFocus records with high confidence. We constrained our analysis to the year 2014 so that we could better compare our analyses of (*i*) hydraulically fractured well proximity to water wells and (*ii*) oil and gas well proximity to water wells.

Groundwater well data quality is heterogeneous among the states identified for our analysis, because each state manages individual well construction record repositories (15). We collected, aggregated, and analyzed groundwater well construction data in 14 states where >100 wells were hydraulically fractured in 2014: Arkansas, California, Colorado, Montana, Louisiana, Nebraska, New Mexico, North Dakota, Ohio, Oklahoma, Pennsylvania, Texas, Utah, and Wyoming. One other state hosted >100 recorded hydraulically fractured wells stimulated in 2014: West Virginia. Unfortunately, digitized groundwater well construction data were unavailable for West Virginia as of September 2017. We screened the data to focus our analysis on groundwater wells constructed between 2000 and 2014, with a well depth (Fig. 1*B*) and with a “domestic” well purpose (e.g., household self-supply, municipal, public-supply, or fire protection and recreational purposes). The year 2000 was selected to avoid limitations associated with state-level well construction record datasets (*SI Appendix*, Table S2) and to increase the potential that the groundwater well was in use during 2014. Domestic water wells constructed during 2014 were excluded to ensure the analyzed water wells were constructed before the analyzed hydraulically fractured wells were stimulated. Abandoned water wells were removed where possible; some states had individual records for well construction and abandonment that could not be reconciled, and some states did not provide information on abandonment (*SI Appendix*, section S2.2). It is possible that any given domestic groundwater well may not actually be used for domestic purposes (*SI Appendix*, section S2). Notable groundwater well database quality variations included: (*i*) Texas, where records were limited before 2002; (*ii*) North Dakota, where many records lacked purpose information and were therefore excluded from our analysis; (*iii*) Wyoming, where we used groundwater priority dates as a proxy for well construction dates; and (*iv*) West Virginia, where groundwater well data were not available (*SI Appendix*, Table S2). *SI Appendix* provides details about each of the 14 state groundwater well datasets included in our analysis (*SI Appendix*, Tables S5–S17).

We used the aforementioned datasets to calculate the (*i*) horizontal distances between recorded domestic groundwater wells and their nearest recorded hydraulically fractured well; (*ii*) horizontal distances between recorded hydraulically fractured and recorded domestic groundwater wells; (*iii*) vertical offset between the depth of recorded domestic groundwater wells and the depth of nearby (<2 km) recorded hydraulically fractured wells; (*iv*) horizontal distances between recorded domestic groundwater wells and recorded oil and gas wells; and (*v*) horizontal distances between recorded oil and gas wells and recorded domestic groundwater wells. These distances were determined by using North America Equidistant Conic coordinates. We selected 2 km as a threshold distance because: (*i*) Some records that were submitted before extensive use of global positioning systems were accurate only within ±1 mile (±1.6 km), and (*ii*) previous work suggested that chemicals may be able to migrate horizontal distances of between 1 km (8, 10) and 3 km (7, 9). Our vertical offset calculation used total vertical depth as recorded, and we did not account for differences

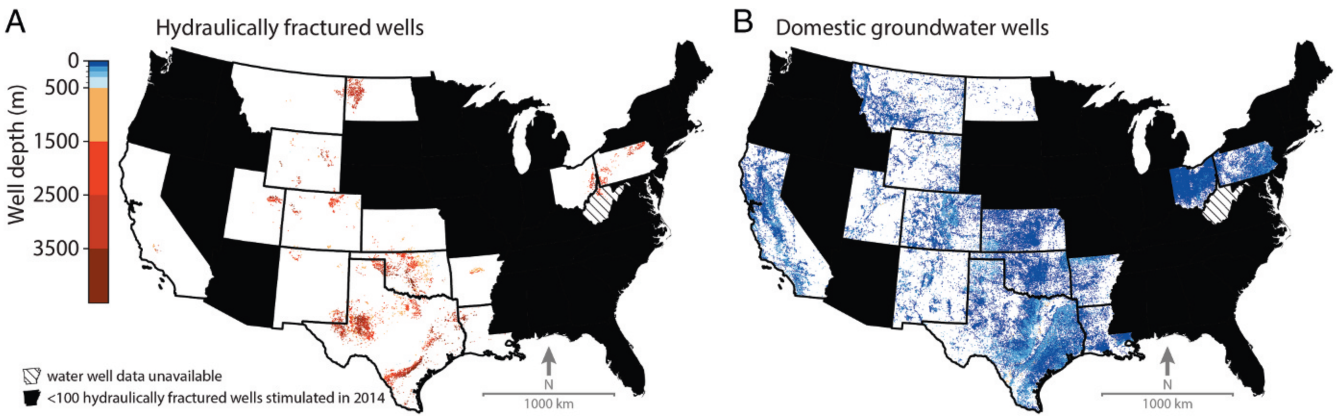

Fig. 1. Reported depths of hydraulically fractured (stimulated during 2014) (*A*) and domestic (constructed between 2000 and 2014) (*B*) wells across 15 US states with >100 hydraulic fracturing events during 2014 (FracFocus database). Hydraulically fractured well depths have a median of 2,482 m, an interquartile range of 1,894–3,246 m, a 5th- to 95th-percentile range of 863–3,858 m, and a 1st- to 99th-percentile range of 453–4,572 m. Most (>95%) domestic wells are shallower than 200 m. Known limitations with state-level water well datasets are acknowledged in *SI Appendix*.

in land-surface elevations. We emphasize that groundwater well, hydraulically fractured well, and oil and gas well data are not comprehensively collected, and limitations exist. Our analysis and results were limited by the quality and completeness of available well data (*SI Appendix*, Table S21), and only represent recorded well information for domestic groundwater wells, hydraulically fractured wells, and oil and gas wells.

Results

Horizontal Distance from Water Wells to Hydraulic Fracturing. Many domestic groundwater wells constructed between 2000 and 2014 exist within 2 km of one or more hydraulically fractured wells stimulated in 2014 (Fig. 2 *A* and *B*). High concentrations of colocated groundwater and hydraulically fractured wells were in areas where oil and gas occur in low-permeability formations. At the county level, domestic groundwater wells located within 2 km of one or more hydraulic fracturing wells comprised more than half of all domestic groundwater wells in 11 counties (8 in Texas, 2 in North Dakota, and 1 in Oklahoma); more than one-third of domestic groundwater wells in 20 counties (15 in Texas, 2 in North Dakota, 2 in Oklahoma, and 1 in Pennsylvania); and >10% of domestic groundwater wells in 96 counties (50 in Texas, 22 in Oklahoma, 6 in Pennsylvania, 6 in Ohio, 3 in Colorado, 3 in North Dakota, 2 in Arkansas, 1 in Louisiana, 1 in Utah, 1 in Kansas, and 1 in Montana).

Horizontal Distance from Hydraulic Fracturing to Water Wells. Our second finding is that hydraulically fractured wells stimulated in 2014 are often located nearby at least one domestic groundwater well (Fig. 2 *C* and *D*). Among all recorded hydraulically fractured wells stimulated in 2014 in the 14 states we analyzed ($n = 26{,}983$), recorded locations of $n = 4{,}653$ (17%) hydraulically fractured wells were within 1 km of at least one domestic groundwater well; $n = 10{,}089$ (37%) were within 2 km of at least one domestic groundwater well; and $n = 13{,}962$ (60%) were within 3 km of at least one domestic groundwater well.

Most (>50%) hydraulically fractured wells stimulated in 2014 were within 2 km of one or more domestic groundwater wells in Ohio (89% of hydraulically fractured wells), Colorado (60%), Kansas (57%), Oklahoma (53%), and Louisiana (51%). Between 10 and 50% of hydraulically fractured wells stimulated in 2014 were within 2 km of a recorded domestic groundwater well in Pennsylvania (49%), Texas (40%), Montana (39%), and Arkansas (36%). The actual fraction of hydraulic fracturing that takes place near to domestic groundwater wells may differ from those reported, where domestic groundwater well data and hydraulically fractured well data gaps exist.

Vertical Offset from Water Wells to Hydraulic Fracturing. Among domestic groundwater wells located near (<2 km) hydraulically fractured wells, we estimated percentiles for each states' vertical offset, or the difference between the recorded depth of the groundwater well and the recorded depth of the shallowest nearby (<2 km) hydraulically fractured well (Fig. 3*A*). The offset was <600 m for <1% of these analyzed domestic

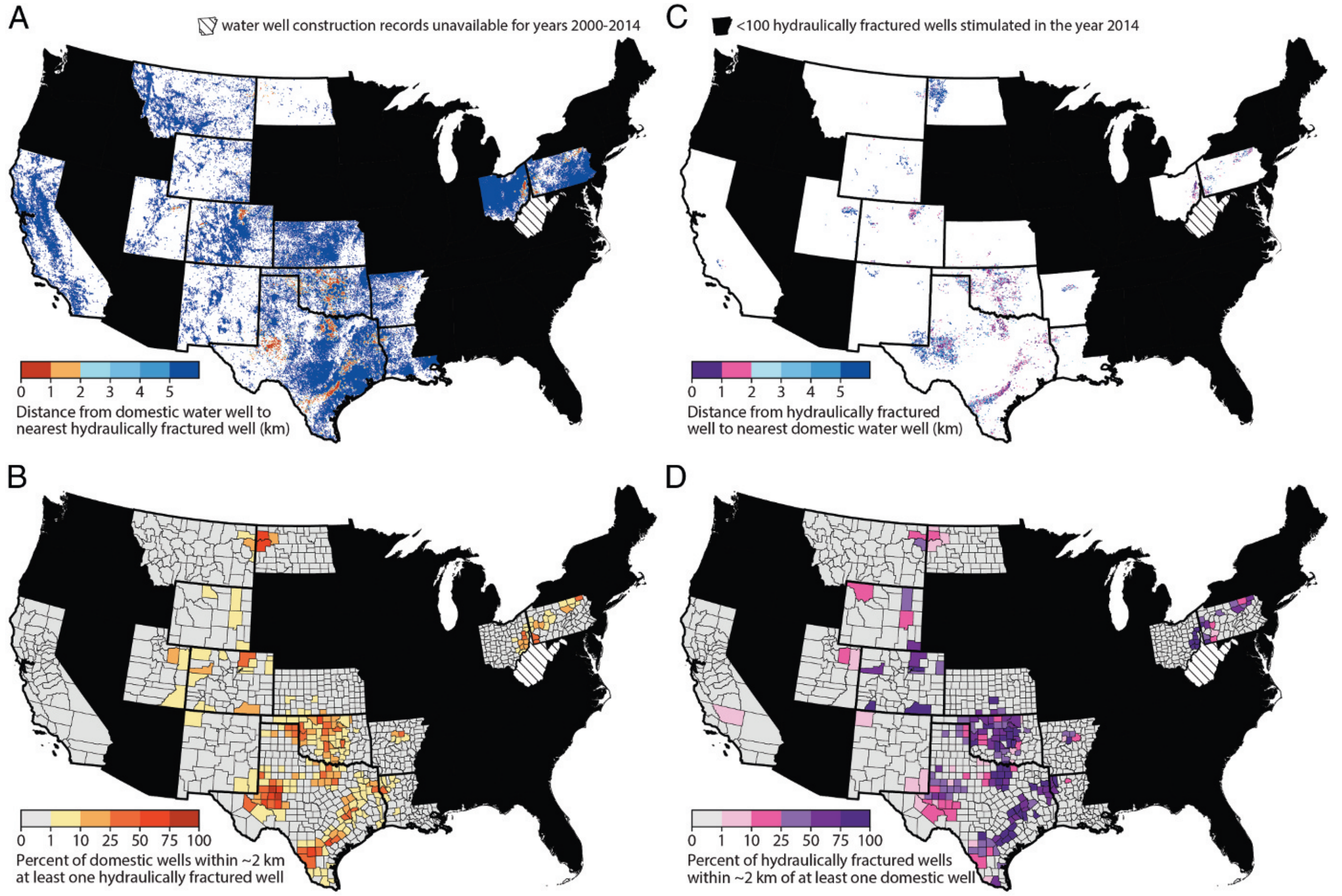

Fig. 2. Horizontal proximity among domestic groundwater wells (2000–2014) and the nearest hydraulic fracturing well stimulated in 2014. (*A*) Domestic water well proximity to nearest hydraulically fractured well. (*B*) County-level percent of domestic wells near (<2 km) hydraulically fractured well(s). (*C*) Hydraulically fractured well proximity to nearest domestic water well. (*D*) County-level proportions of hydraulically fractured wells near (<2 km) domestic water well(s). Only counties with $n > 10$ records are shown in *B* and *D*.

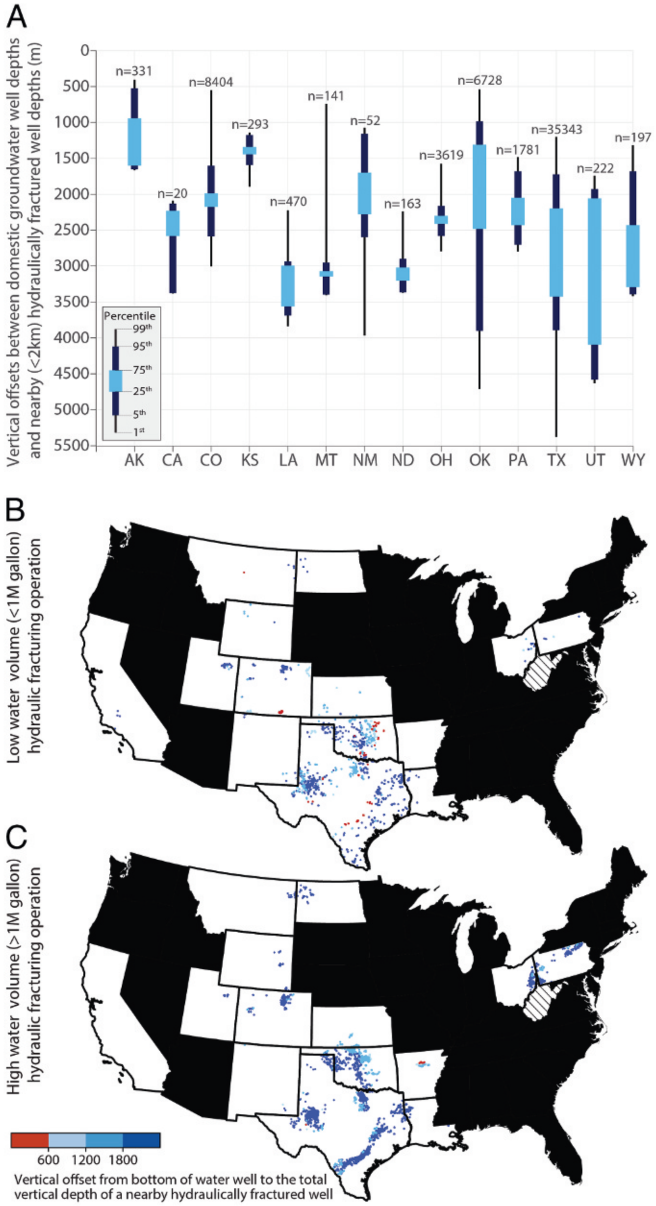

Fig. 3. Vertical offsets between domestic water well depths (wells constructed during 2000–2014) and depths of nearby (<2 km) hydraulically fractured wells (wells stimulated in 2014) presented as percentiles by state (*A*) and locations for low (*B*) and high (*C*) water volume stimulations. M, million.

groundwater wells; nearly all (i.e., >99%) of these occurrences were in four states: Arkansas, Colorado, Oklahoma, and Texas. Records suggested that <1 million gallons of water were injected into hydraulically fractured wells in most cases where the hydraulically fractured well depth was within 600-m vertical distance of a nearby (<2 km) groundwater well depth (Fig. 3 *B* and *C*).

Horizontal Distance from Water Wells to Oil and Gas Wells. Our analysis indicated that the majority (>50%) of recorded domestic groundwater wells exist within 2 km of one or more producing oil and gas wells in 236 counties (Fig. 4 *A* and *B*). Most (91%) of these counties are located in Texas ($n = 104$ counties), Ohio (42 counties), Kansas (39 counties), Pennsylvania (22 counties), or Arkansas (9 counties). The number of counties where most domestic groundwater wells exist near at least one oil and gas well producing in 2014 ($n = 236$) was much larger than the number of counties where most domestic groundwater wells were near at least one hydraulically fractured well stimulated during 2014 ($n = 11$).

Horizontal Distance from Oil and Gas Wells to Water Wells. We showed that 20% of oil and gas wells producing in 2014 in the 14 states exist within 1 km of at least one recently constructed (2000–2014) domestic water well; 38% exist within 2 km; and 52% exist within 3 km (Fig. 4*C*). Most (>50%) oil and gas wells were within 2 km of at least one domestic water well in 315 US counties in these 14 states (Fig. 4*D*). Our findings highlight that conventional oil and gas wells, more broadly, often exist close to domestic water wells.

Discussion

Risks to Groundwater Quality from Hydraulic Fracturing. Quantifying and communicating risks of hydraulic fracturing to groundwater resources is challenging because of the lack of consistently cataloged information about the (*i*) frequency and severity of spills and leaks linked to hydraulic fracturing (16); (*ii*) integrity of active and decommissioned wells (17, 18); (*iii*) groundwater quality before vs. following the initiation of a hydraulic fracturing operation (16); and (*iv*) environmental profile, including toxicity, of chemicals used for oil and gas production. Mounting a nationwide assessment of hydraulic fracturing fluid spill frequencies and severities or decommissioned oil and gas well integrities would require substantial resources (19). We identify multiple regions where domestic groundwater wells constructed between 2000 and 2014 exist within 2 km of one or more hydraulically fractured wells stimulated in 2014. In these areas, assessing spill frequency and well integrity continually may prove to be a useful way of allocating limited resources, while informing risks to groundwater quality from hydraulic fracturing. We emphasize that physical proximity of groundwater wells and hydraulically fractured wells does not alone imply groundwater well contamination.

Increasing water-quality monitoring efforts before, during, and after the construction of hydraulically fractured wells can improve our understanding of how hydraulic fracturing operations may affect groundwater resources in different hydrogeologic settings over time (20). The lack of field-based hydrogeologic studies (21), combined with the variability in hydraulic fracturing operations and hydrogeology across the United States, makes it difficult to identify “one-size-fits-all” exposure pathways, should a contamination event occur. Approximately half of all hydraulically fractured wells in our dataset were within 2–3 km of at least one domestic groundwater well. A recent study in Pennsylvania (Marcellus Formation) found that methane concentrations in drinking-water supplies were six times higher in homes within 1 km of a natural gas well (8). In another study in Pennsylvania (also focused on the Marcellus Formation), chemicals likely migrated horizontal distances of 1–3 km from hydraulically fractured wells into a groundwater aquifer used for drinking water (9). Nevertheless, given the wide range of factors impacting contaminant migration rates (e.g., aquifer heterogeneity and permeability and contaminant retardation), it is unclear whether a water-quality monitoring distance of 1–3 km from hydraulically fractured wells is an appropriate monitoring radius in other hydrogeologic settings.

Increasing water-quality monitoring efforts before, during, and after hydraulic fracturing operations may also help protect self-supply well water quality. Unlike domestic groundwater wells operated through public utilities, self-supply domestic groundwater wells are not required to perform routine water-quality tests under the Safe Drinking Water Act. Individual states can advise more stringent monitoring, but routine water-quality testing of self-supply domestic groundwater well waters is voluntary for all

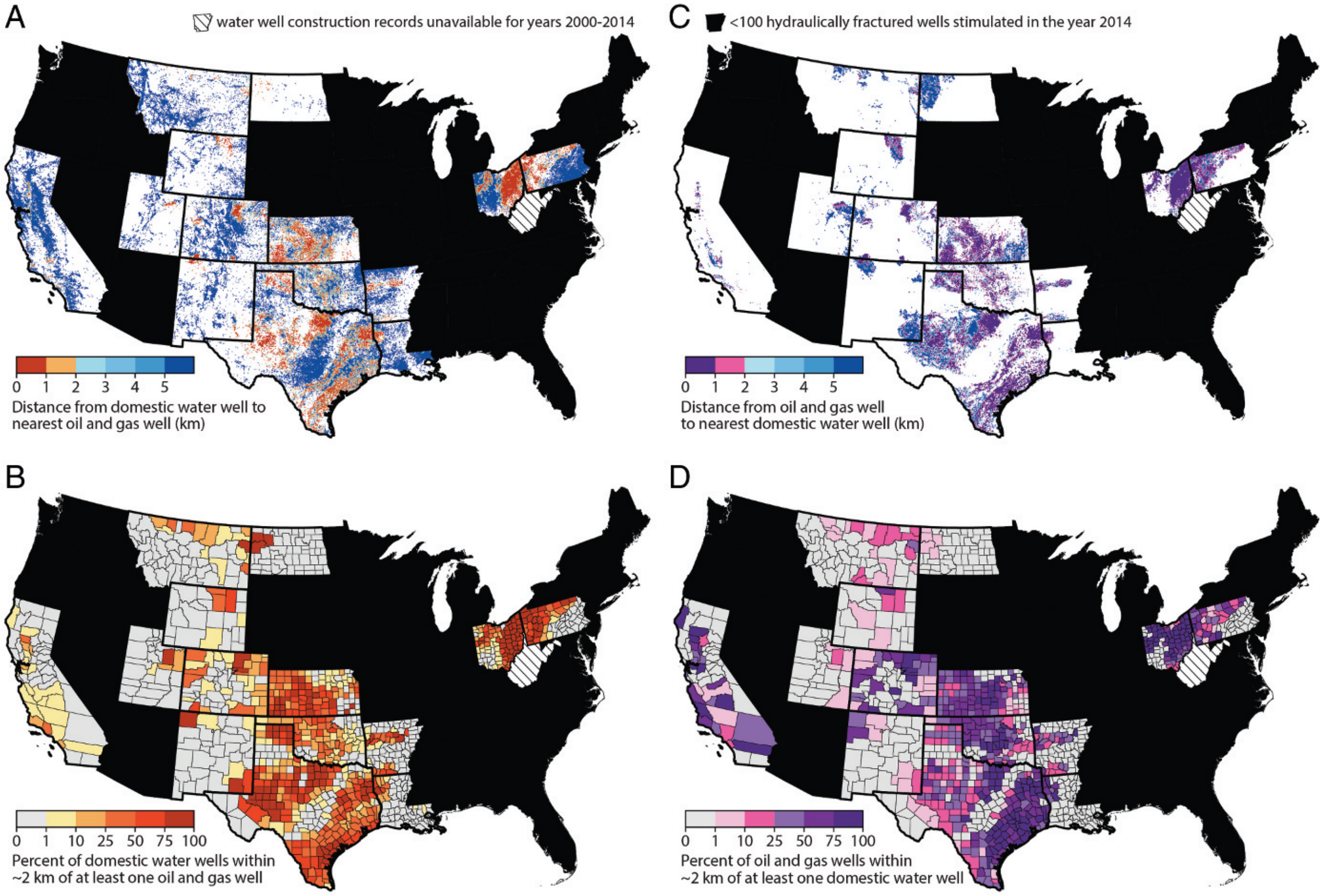

Fig. 4. Horizontal proximity among domestic water wells (2000–2014) and oil and gas wells producing in 2014. (*A*) Domestic water well proximity to nearest oil and gas well (see limitations in *SI Appendix*). (*B*) County-level percent of domestic wells near (<2 km) oil and gas well(s). (*C*) Oil and gas well proximity to nearest domestic water well. (*D*) County-level percent of oil and gas wells near (<2 km) domestic water well(s). Only counties with $n > 10$ records are shown in *B* and *D*.

of the states analyzed in this study (*SI Appendix*, Table S1; in some states, water-quality testing is required when drilling a new groundwater well or when transferring property ownership). Similarly, the federal government does not require routine ambient groundwater monitoring in the aquifers adjacent to oil and gas wells. Individual states can advise more stringent water-quality monitoring for areas surrounding hydraulically fractured wells or more stringent well construction standards. For example, in California, domestic well owners within 457 m of the wellhead and 152 m of any subsurface portion of the well may request water-quality testing before and after hydraulic fracturing operations (AB-7 §3203.1; ref. 22); it is unclear if these distances are appropriate in other hydrogeologic systems. Increasing water-quality monitoring efforts may prove futile until we have more information about chemicals used in hydraulic fracturing operations and their toxicity. There likely exist chemical additives used by hydraulic fracturing operations that cannot be detected by common and relatively inexpensive water-quality tests (1, 9, 23, 24).

The depths targeted for injection by hydraulic fracturing operations in 2014 were often >1,000 m below the depth of nearby domestic water wells constructed between 2000 and 2014, a vertical offset exceeding the extent that vertical hydraulically induced fractures typically propagate. Vertical propagations of fracture networks created by hydraulic fracturing typically extend no more than 600 m above well perforations (25–27). These results corroborate and build upon recent evaluations of the vertical distribution of hydraulic fracturing (28) and industry disclosures of vertical offsets of groundwater resources and hydraulically fractured wells (1). We emphasize that our analysis used total depths of hydraulically fractured wells, as opposed to depth of first perforation; depth to the top of the perforated interval were not available in the FracFocus dataset. Many wells used for hydraulic fracturing in central California, for example, use vertical wells that are perforated 220 m above the total depth on average (14).

Our analysis only examined groundwater wells constructed between 2000 and 2014 and hydraulically fractured wells stimulated in 2014; examining wells constructed and stimulated over a different time interval may illuminate different results. For example, near Pavillion (Wyoming), formations were being stimulated within 500 m of the ground surface during the early 2000s; many of the well stimulations occurred at depths similar to those of groundwater wells (29). Additional safeguards for groundwaters have been recommended in areas where shallow hydraulic fracturing occurs (28).

Risks to Groundwater Quality from Oil and Gas Wells. Perceptions about unconventional oil and gas risks to groundwater are likely influenced by the rapid emergence of hydraulic fracturing (2) and the undisclosed chemicals used in some hydraulic fracturing operations (30). Nevertheless, on-site spills and well-integrity failures associated with hydraulic fracturing operations may be more likely to impact groundwater quality than the direct injection of fluids into potable and shallow groundwater aquifers by hydraulic fracturing operations (30). We stress that on-site spills and well-integrity failures are not unique to unconventional oil and gas wells; these risks also arise during conventional oil and gas production activities. We show that oil and gas wells—some hydraulically fractured, some not—are frequently situated near domestic groundwater wells (Fig. 4). Our main finding highlights that hydraulic fracturing takes place in close proximity to domestic groundwater wells in many cases (Fig. 2); we also emphasize that conventional oil and gas activities, more broadly, commonly occur close to domestic groundwater wells (Fig. 4). Conventional oil and gas wells in close proximity to water wells may also pose risks to groundwater quality in many counties, and should be considered along with hydraulically fractured wells.

Addressing Data Gaps. Existing gaps in hydraulically fractured and groundwater well data limited our ability to comprehensively map which domestic groundwater wells were the most likely to be impacted by hydraulic fracturing. Hydraulically fractured well data derived from FracFocus provided valuable information, but they were incomplete both in time and in space. State-level groundwater well record management has resulted in a patchwork of well data that were both difficult to collect and difficult to catalog with consistency (*SI Appendix*, Table S2). Data constraints were further impacted by the lack of field-based hydrogeologic studies in regions where hydraulically fractured wells are common (21). Our analysis only targeted groundwater wells constructed between 2000 and 2014 and only hydraulically fractured wells that were stimulated during 2014; extrapolating our results forward in time may prove problematic, especially where groundwater wells are being constructed to deeper depths over time (31). Furthermore, there exist deep groundwaters not being accessed currently for domestic water use that may be accessed in the future, particularly in areas where shallow aquifers are being depleted (32). Deep groundwater reserves may be susceptible to contamination through a variety of mechanisms (31, 32).

Although hydraulic fracturing has been used to enhance hydrocarbon production for decades, concerns that hydraulic fracturing operations may contaminate groundwater have gained traction in recent years (5). A key strategy of risk management is to communicate with the public and involve them as legitimate partners when resolving problems (6). Quantifying and communicating actual risks remains challenging because of the lack of publicly available and consistently cataloged information about (*i*) hydraulically fractured and groundwater well locations, (*ii*) frequency and severity of spills and leaks linked to hydraulic fracturing (16), (*iii*) integrity of decommissioned wells (18), (*iv*) toxicity of hydraulic fracturing fluids, and (*v*) groundwater quality before and following hydraulic fracturing operations (16). Our analysis identifies hotspots that may be targeted for future fieldwork to better understand the potential for contamination events and possible contaminant migration rates in aquifers. As more shale oil and gas reservoirs become economically and technologically feasible to access with hydraulically fractured wells (4), understanding the frequency that groundwater resources are contaminated will be critical to allocating resources for safeguarding groundwater and addressing public concerns.

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1. Environmental Protection Agency (2016) *Hydraulic Fracturing for Oil and Gas: Impacts from the Hydraulic Fracturing Water Cycle on Drinking Water Resources in the United States* (Environmental Protection Agency, Washington, DC), Report EPA/600/R-16/236F.
2. Small MJ, et al. (2014) Risks and risk governance in unconventional shale gas development. *Environ Sci Technol* 48:8289–8297.
3. Vengosh A, Jackson RB, Warner N, Darrah TH, Kondash A (2014) A critical review of the risks to water resources from unconventional shale gas development and hydraulic fracturing in the United States. *Environ Sci Technol* 48:8334–8348.
4. Sidder A (2016) Largest ever U.S. shale oil deposit identified in Texas. *Eos*, 10.1029/2016EO063225.
5. Howarth RW, Ingraffea A, Engelder T (2011) Natural gas: Should fracking stop? *Nature* 477:271–275.
6. Abkowitz MD (2008) *Operational Risk Management: A Case Study Approach to Effective Planning and Response* (Wiley, New York), p 278.
7. Fontenot BE, et al. (2013) An evaluation of water quality in private drinking water wells near natural gas extraction sites in the Barnett shale formation. *Environ Sci Technol* 47:10032–10040.
8. Jackson RB, et al. (2013) Increased stray gas abundance in a subset of drinking water wells near Marcellus shale gas extraction. *Proc Natl Acad Sci USA* 110:11250–11255.
9. Llewellyn GT, et al. (2015) Evaluating a groundwater supply contamination incident attributed to Marcellus shale gas development. *Proc Natl Acad Sci USA* 112:6325–6330.
10. Osborn SG, Vengosh A, Warner NR, Jackson RB (2011) Methane contamination of drinking water accompanying gas-well drilling and hydraulic fracturing. *Proc Natl Acad Sci USA* 108:8172–8176.
11. 42 USC, §300f (1974).
12. Cooley H, Donnelly K (2014) Hydraulic fracturing and water resources: What do we know and need to know? *The World's Water*, ed Gleick PH (Island, Washington, DC), Vol 8, pp 63–82.
13. Rubright S (2016) Data from "2016 U.S. Oil & Gas Activity." FracTracker. Available at https://www.fractracker.org/map/national/us-oil-gas/. Accessed April 12, 2017.
14. California Council on Science and Technology (2014) Advanced well stimulation technologies in California: An independent review of scientific and technical information (California Council on Science and Technology, Sacramento, CA).
15. Perrone D, Jasechko S (2017) Dry groundwater wells in the western United States. *Environ Res Lett* 12:104002.
16. Brantley SL, et al. (2014) Water resource impacts during unconventional shale gas development: The Pennsylvania experience. *Int J Coal Geol* 126:140–156.
17. Ingraffea AR, Wells MT, Santoro RL, Shonkoff SBC (2014) Assessment and risk analysis of casing and cement impairment in oil and gas wells in Pennsylvania, 2000–2012. *Proc Natl Acad Sci USA* 111:10955–10960.
18. Jackson RB (2014) The integrity of oil and gas wells. *Proc Natl Acad Sci USA* 111:10902–10903.
19. Council NR (2009) *Science and Decisions: Advancing Risk Assessment* (National Academies, Washington, DC).
20. Hildenbrand ZL, et al. (2016) Temporal variation in groundwater quality in the permian basin of Texas, a region of increasing unconventional oil and gas development. *Sci Total Environ* 562:906–913.
21. Jackson RE, et al. (2013) Groundwater protection and unconventional gas extraction: The critical need for field-based hydrogeological research. *Groundwater* 51:488–510.
22. Oil and gas: Hydraulic fracturing, The California Code, Chapter AB-7, Sect. 3203.1 (2013).
23. Cahill AG, et al. (2017) Mobility and persistence of methane in groundwater in a controlled-release field experiment. *Nat Geosci* 10:289–294.
24. Drollette BD, et al. (2015) Elevated levels of diesel range organic compounds in groundwater near Marcellus gas operations are derived from surface activities. *Proc Natl Acad Sci USA* 112:13184–13189.
25. Davies RJ, Mathias SA, Moss J, Hustoft S, Newport L (2012) Hydraulic fractures: How far can they go? *Mar Pet Geology* 37:1–6.
26. Fischer M, et al. (2014) *Potential Direct Environmental Effects of Well Stimulation* (California Council on Science and Technology, Lawrence Berkeley National Laboratory, Pacific Institute, Sacramento, CA).
27. Flewelling SA, Tymchak MP, Warpinski N (2013) Hydraulic fracture height limits and fault interactions in tight oil and gas formations. *Geophys Res Lett* 40:3602–3606.
28. Jackson RB, et al. (2015) The depths of hydraulic fracturing and accompanying water use across the United States. *Environ Sci Technol* 49:8969–8976.
29. DiGiulio DC, Jackson RB (2016) Impact to underground sources of drinking water and domestic wells from production well stimulation and completion practices in the Pavillion, Wyoming, field. *Environ Sci Technol* 50:4524–4536.
30. Adgate JL, Goldstein BD, McKenzie LM (2014) Potential public health hazards, exposures and health effects from unconventional natural gas development. *Environ Sci Technol* 48:8307–8320.
31. Jasechko S, et al. (2017) Global aquifers dominated by fossil groundwaters but wells vulnerable to modern contamination. *Nat Geosci* 10:425–429.
32. Kang M, Jackson RB (2016) Salinity of deep groundwater in California: Water quantity, quality, and protection. *Proc Natl Acad Sci USA* 113:7768–7773.