Unconventional Oil and Gas Spills: Risks, Mitigation Priorities, and State Reporting Requirements

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Supporting Information

20 pages

Table of Contents

Figure S1: Number of new wells drilled and cumulative number of wells over time.
Figure S2: Timeline of changes in reporting volumes, methods, and content.
Figure S3: Boxplot showing the volume spilled by life-year of the well
Figure S4: Boxplot showing the volume spilled by pathway

A. Federal laws requiring unconventional oil and gas spills to be reported

The Clean Water Act requires reporting of oil discharges (including oil mixed with other wastes) into "waters of the United States", or discharges that cause a sheen, discoloration, sludge, or a violation of water quality standards (33 U.S.C. § 1321(b)(3), (5); 40 C.F.R. § 110.3). The federal "Superfund" law – the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) - requires reporting of "releases" (42 U.S.C. §9601(22); 40 C.F.R. §300.5) of hazardous substances above threshold quantities (42 U.S.C. §9602; 40 C.F.R. §302.4), but exempts oil and gas exploration and production wastes, as well as oil, from these requirements (42 U.S.C. §9601(14)). (Despite the oil and gas reporting exemption under CERCLA, spills of fracturing fluid chemicals, some of which are hazardous, might trigger Superfund reporting requirements.) Federal transportation rules require reporting if a hazardous material being transported "in commerce" (across state lines) causes death or hospitalization, a public evacuation or the closing of a major transportation artery or facility for at least an hour, or if there is an unintentional release of a hazardous material or discharge of hazardous waste of any size (49 C.F.R. §171.15, 16).

B. Data

Here we describe data sources and how unconventional oil and gas (UOG) wells were selected. As stated in the paper, the distinctions between conventional and UOG wells were not always clear and we were conservative to ensure the spills we assessed were linked to UOG activity.

Colorado

Colorado provides oil and gas, as well as spills, data through its Oil & Gas Conservation Commission (COGCC) housed in the Department of Natural Resources (http://cogcc.state.co.us/#/home). However, the well data did not provide sufficient information to discern which wells were unconventional; therefore, we relied on the IHS Enerdeq database (https://www.ihs.com/Info/en/a/unconventional/e-p-data.html) for UOG wells. We included only those wells that had a horizontal orientation or reported more than 3,785 m^3 (1 Mgal) of water used for completion. Many of Colorado's wells have been re-drilled and re-fractured between 1995 and 2014. We assessed the data based on the first date of completion. There were 9,436 new UOG wells with a spud date between1995 and 2014 in Colorado (Figure S1; Table S1).

New Mexico

We obtained data pertaining to New Mexico oil and gas wells from the State of New Mexico's Oil Conservation Division (OCD; http://www.emnrd.state.nm.us/OCD/ocdgis.html). The dataset included over 114,781 wells. We included only those wells with a horizontal orientation as UOG wells. Not including vertical wells will omit some UOG wells, but ensured that we avoided including non-fractured wells. The dataset had several missing values (n=3,239) for well direction (vertical, horizontal, or deviated). Well API's were entered into the online OCD permitting database to obtain well direction. If well direction was still missing but the well name contained an "H" at the end, it was given a horizontal direction. There were 3,624 horizontal wells with a spud date between 2005 and 2014, with the number of new wells annually continuing to increase (Figure S1; Table S1). New Mexico spill data were scraped from the NMOCD website on spills (https://wwwapps.emnrd.state.nm.us/ocd/ocdpermitting/Data/Incidents/Spills.aspx). We matched the spill API to the horizontal well API's and kept only those spill records that matched to an UOG well.

North Dakota

We obtained a shapefile of North Dakota oil and gas wells from the North Dakota Industrial Commission, Department of Mineral Resources, Oil and Gas Division (https://www.dmr.nd.gov/oilgas/). The dataset included 28,155 wells. We included only those oil and gas wells with a spud date between 1995 and 2014 that had a horizontal orientation as indicated by the well name (include "H", "HR", "HZ", or "HOR") to ensure the wells were unconventional. There were 11,860 wells identified as oil and gas and 10,068 wells that were also labeled as having a horizontal orientation (Figure S1; Table S1). Spill data in North Dakota were obtained from the oilfield environmental incident summary reports held on the North Dakota Department of Health – Environmental health website (https://www.ndhealth.gov/EHS/Spills/).

Pennsylvania

The Pennsylvania Department of Environmental Protection (PADEP) Oil and Gas reporting website provides production data for unconventional oil and gas wells (https://www.paoilandgasreporting.state.pa.us/). There were 8,353 UOG wells spudded between 1995 and 2014 Figure S1; Table S1. Pennsylvania does not have a separate spill dataset, therefore spill data were pulled from the PADEP's notice of violations (NOV) database for UOG. This data included information regarding the violation, violation type, violation code, and comments regarding the inspection and ensuing violations. This necessarily limits the spill data to those that resulted in some sort of enforcement action, likely understating the number of reported spills in the Commonwealth. Using the violation code and comments in the NOV dataset, we categorized the violations as Environmental Health and Safety, Encroachment, Notifications, Paperwork and Planning, Permit Violation, Restoration, Signage, Spills and Potential Spills, Well Casing and Other following a peer-reviewed framework.[S1] We included in our analysis only those NOV's categorized as having a spill or the potential to result in a spill (n = 1,293). Based on the description provided by the inspector we included information regarding volume spilled, material spilled, and the cause of the spill. Since this information was not required in the inspection report, many spills do not provide any of this additional information.

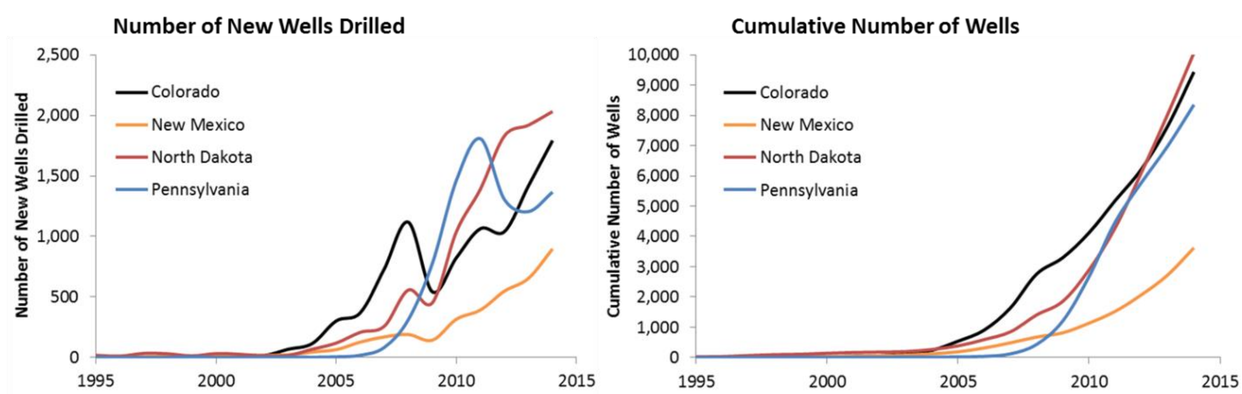

Figure S1: Number of new wells drilled and cumulative number of wells over time

Table S1: Number of new UOG wells drilled each year. See section B of SI for data sources.

Year	Life-Year	Colorado	New Mexico	North Dakota	Pennsylvania
1995	19	4	2	18	1
1996	18	2	3	11	0
1997	17	2	5	34	0
1998	16	2	6	30	0
1999	15	3	0	13	5
2000	14	3	11	32	0
2001	13	20	11	26	0
2002	12	16	17	14	1
2003	11	68	22	17	4
2004	10	115	45	68	2
2005	9	302	65	119	5
2006	8	369	127	208	18
2007	7	732	170	258	83
2008	6	1,118	190	557	312
2009	5	542	143	452	777
2010	4	824	316	1,039	1,463
2011	3	1,064	392	1,391	1,807
2012	2	1,040	548	1,830	1,304
2013	1	1,418	654	1,919	1,205
2014	0	1,792	897	2,032	1,366
Total		**9,436**	**3,624**	**10,068**	**8,353**

Table S2: Cumulative number of UOG wells. See section B of SI for data sources.

Year	Colorado	New Mexico	North Dakota	Pennsylvania
1995	4	2	18	1
1996	6	5	29	1
1997	8	10	63	1
1998	10	16	93	1
1999	13	16	106	6
2000	16	27	138	6
2001	36	38	164	6
2002	52	55	178	7
2003	120	77	195	11
2004	235	122	263	13
2005	537	187	382	18
2006	906	314	590	36
2007	1,638	484	848	119
2008	2,756	674	1,405	431
2009	3,298	817	1,857	1,208
2010	4,122	1,133	2,896	2,671
2011	5,186	1,525	4,287	4,478
2012	6,226	2,073	6,117	5,782
2013	7,644	2,727	8,036	6,987
2014	9,436	3,624	10,068	8,353
***Well Years**	**41,749**	**13,558**	**36,486**	**30,083**

*Only the cumulative sum of wells between 2005 and 2014 (when spills data were available) were used in the calculation of well years. Spills may have occurred prior to 2005; however, we do not have that information and don't want to include those well years in the denominator.

The figure below summarizes the description of state regulatory requirements for reporting oil and gas related spills in the Spill Data section.

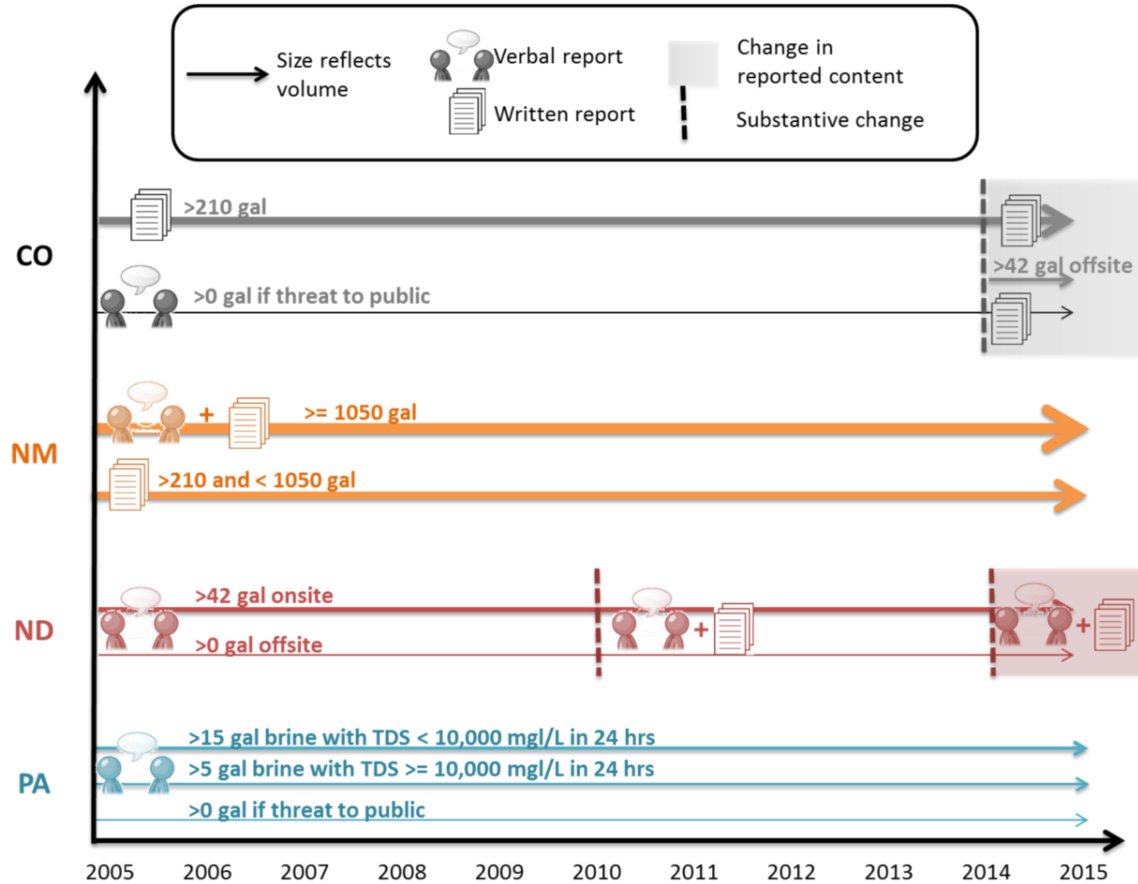

Figure S2: Timeline of changes in reporting volumes, methods, and content

C. *Pathways*

Blowouts are uncontrolled fluid releases that typically occur when unexpectedly high pressures are encountered in the sub-surface and/or due to the failure of valves or other equipment such as blowout preventers (BOP) that shut down fluid flow when the well kicks. Blowouts can occur as a result of a failure of well casing or communication with a nearby well and may occur at the surface or sub-surface.

Drilling Equipment is required for well drilling and well casing. Leaks and spills tied to drill rigs, shakers, and active mud systems were all classified under this category. This pathway does not include spills of drilling materials that occurred at pits, flowlines, or via transportation.

Completion Equipment includes blenders, flowback equipment, chemical totes, and storage containers for chemicals. This pathway is only for those spills clearly related to completion equipment. Spills related to tanks, pits, transportation, or pumps are categorized under those pathways as there often was not consistently reported to differentiate between completion and production related spills. Few spills were tied directly to completion equipment; however spills of completion materials have the potential for high toxicity and impact to the environment.

Tanks are used to temporarily store wastewater and crude oil. Tank batteries are a group of tanks used for storing produced water and crude oil during various stages of separation. In Colorado, buried produced water vaults were included under the tank category. Tanks are a primary location for spills to occur as overflows may happen at a tank due to problems with the heater treater, pump, separator, or other equipment failures further down the line. However, since the spill occurred at the tank, the tank is the primary pathway with equipment failure being the causal mechanism.

Pits are dug into the ground and are used to temporarily store drill cuttings, wastewater, and crude oil. Regulations related to pits include requirements for pit liners to avoid leaks and freeboard space to avoid overflows.

Flowlines carry fluids from the wellhead to and between equipment such as tanks, blenders, pits, and injection wells. Flowlines can be constructed with different levels of permanence, located above or underground, and composed of materials such as steel or fiberglass. Spills reports appeared to use terms interchangeably such as: pipeline, injection line, production line, gathering line, dump lines, and water lines. Due to the lack of consistency in the spill data, we included all of these together under the pathway of flowlines since the spill occurred in the process of transferring materials between vessels.

Transportation refers to the loading and unloading of materials between trucks and a tank or pit. This category was sub-divided into spills that occurred during the loading and unloading process, illegal dumping of materials, and spills that occurred while the vehicle was in transit between locations.

Pumps are used to move fluid or gas by pressure or suction. Spills can occur at the pump location or away from the pump. For example, a tank may overflow due to a pump failure. In this case the pathway would be linked to the tank since that is where the spill occurred, with the underlying cause being equipment failure. As a result, the number of spills related to pumps is conservative.

Heater Treater is a vessel that uses heat to break oil-water emulsions to prepare oil for transportation.

Stuffing Box is a device that prevents leakage at the wellhead if a polish rod is used to lift fluids out of the well, as well as leaks from valves, pistons, etc.

Wellhead is the point where oil is extracted from the ground. Some spills are linked to a valve at the wellhead while other spills are linked to specific types of equipment around the wellhead such as the blowout preventer, free water knockout, and separator.

Table S3: Pathways and causes assessed in this analysis

Pathway	More Detail	Category of Cause	Examples
Blowout			
Completion Activity	Blender Manifold Storage Container	Equipment Failure	Corrosion, Valve...
		Human Error	Punctured with Forklift, Valve Position...
		Unknown	
Drilling Activity	Active Mud System Drill Rig Shaker	Equipment Failure	
		Human Error	Improperly Stored
		Environmental Conditions	Formation Breakdown, Excessive Pressure, Lost Circulation...
		Unknown	
Heater Treater		Equipment Failure	Popoff Valve
		Human Error	Valve Position, Vandalism
		Environmental Conditions	Froze, Lightening
		Unknown	Fire
Flowline		Equipment Failure	Connection, Corrosion, Fused Joint, Weld Failed...
		Human Error	Construction Broke Line, Disconnected Line, Line Position, Valve Position, Vandalsim...
		Environmental Conditions	Animal, Froze, Groundwater Rising, Rockslide
		Unknown	
Pits	Overflow Leak	Equipment Failure	Liner tear, pump, gauge...
		Human Error	Improperly Lined, Inattention, Not Lined...
		Environmental Conditions	Flood, Heavy Rain, Snow Melt...
		Unknown	Not structurally sound
Pump		Equipment Failure	
		Human Error	
		Unknown	
Stuffing Box		Equipment Failure	Packing Failed, Polish Rod...
		Human Error	
		Environmental Conditions	Froze
		Unknown	
Tanks	Overflow Leak	Equipment Failure	Corrosion, Gasket, Gauge, Heater Treater, Line Plugged, Valve...
		Human Error	Miscommunication, Transport Delay, Valve Position, Well Communication...
		Environmental Conditions	Animal, Froze, Flood, Unanticipated Volume, High Wind, Lightening, Rock Slide...
		Unknown	
Transport	Loading/Unloading In Transit Illegal Dumping	Equipment Failure	Gauge, Leak, Seal, Valve...
		Human Error	Driver Inattention, Valve Position, Vehicle Accident...
		Unknown	
Wellhead	Blowout Preventor Free Water Knockout Separator Well Casing Well Communication Wellhead	Equipment Failure	Corrosion, Gasket, Fire Tube, Valve
		Human Error	Valve Position
		Environmental Conditions	Froze, High Wind
		Unknown	

D. Results

Table S4: Number of spills reported each year. See section B of SI for data sources.

Year	Colorado	New Mexico	North Dakota	Pennsylvania
2005	7	2	10	0
2006	25	5	58	0
2007	31	2	59	3
2008	35	6	108	38
2009	43	9	150	176
2010	39	13	263	374
2011	63	36	673	260
2012	50	52	788	190
2013	88	95	1,155	131
2014	95	206	1,189	121
Total	**476**	**426**	**4453**	**1293**

Table S5: Number of spills reported each year. Expected values were taken from binomial probabilities of a well experiencing more than one spill.

State		Wells with 0 or 1 spill	Wells with >1 spill	Rate above expected
Colorado	Expected	9424.4	11.6	4.57
	Observed	9383	53	
	Chi-square P-value			*<0.0001*
New Mexico	Expected	3600.9	23.1	2.94
	Observed	3556	68	
	Chi-square P-value			*<0.0001*
North Dakota	Expected	9330.7	737.3	1.31
	Observed	9104	964	
	Chi-square P-value			*<0.0001*
Pennsylvania	Expected	8267.8	90.2	2.51
	Observed	8132	226	
	Chi-square P-value			*<0.0001*

Table S6: Annual spill rates. See section B of SI for data sources.

Year	Colorado	New Mexico	North Dakota	Pennsylvania
2005	1.3%	1.1%	2.6%	0%
2006	2.8%	1.6%	9.8%	0%
2007	1.9%	0.4%	7.0%	2.5%
2008	1.3%	0.9%	7.7%	8.8%
2009	1.3%	1.1%	8.1%	14.6%
2010	0.9%	1.1%	9.1%	14.0%
2011	1.2%	2.4%	15.7%	5.8%
2012	0.8%	2.5%	12.9%	3.3%
2013	1.2%	3.5%	14.4%	1.9%
2014	1.0%	5.7%	11.8%	1.4%
Weighted Frequency	**1.1%**	**3.1%**	**12.2%**	**4.3%**

The weighted frequency is the quotient of the sum of Table 4 by the sum of Table 2.

Table S7: Number of spills by life-year of the well. See section B of SI for data sources.

Life-Year	Colorado	New Mexico	North Dakota	Pennsylvania
0	244	125	1,452	689
1	103	114	1,226	452
2	44	80	666	117
3	23	61	405	39
4	19	22	240	19
5	18	10	141	13
6	10	5	117	5
7	4	3	57	1
8	6	2	39	0
9	3	2	24	1
10	1	1	20	0
11	0	0	15	1
12	0	0	16	0
13	0	0	15	0
14	0	0	5	0
15	0	0	4	0
16	0	1	8	0
17	0	0	2	0
18	0	0	1	0
19	0	0	0	0

Table S8: Spill rate by life-year. See section B of SI for data sources.

Life-Year	Colorado	New Mexico	North Dakota	Pennsylvania
0	2.6%	3.4%	14.4%	8.2%
1	1.3%	4.2%	15.3%	6.5%
2	0.7%	3.9%	10.9%	2.0%
3	0.4%	4.0%	9.4%	0.9%
4	0.5%	1.9%	8.3%	0.7%
5	0.5%	1.2%	7.6%	1.1%
6	0.4%	.07%	8.3%	1.2%
7	0.2%	.06%	6.7%	0.8%
8	0.7%	.06%	6.6%	0%
9	0.6%	1.1%	6.3%	5.6%
10	0.4%	.08%	7.6%	0%
11	0%	0%	7.7%	9.1%
12	0%	0%	9.0%	0%
13	0%	0%	9.1%	0%
14	0%	0%	3.6%	0%
15	0%	0%	3.8%	0%
16	0%	6.3%	8.6%	0%
17	0%	0%	3.2%	0%
18	0%	0%	3.4%	0%
19	0%	0%	0%	0%

Table S9: Volume of reported spills. See section B of SI for data sources.

Percentile Less Than	Unit	Colorado	New Mexico	North Dakota	Pennsylvania
0.1%	m3	0.2	0.0	0.0	0.0
	gal	40	10	1	1
10%	m3	0.6	1.2	0.1	0.0
	gal	168	307	30	10
20%	m3	1.1	1.9	0.2	0.1
	gal	294	504	59	20
30%	m3	1.6	2.9	0.3	0.1
	gal	420	752	84	36
40%	m3	2.1	3.2	0.5	0.2
	gal	546	840	126	50
50%	m3	3.0	4.9	0.8	0.5
	gal	798	1,302	210	120
60%	m3	4.0	8.0	1.0	0.8
	gal	1,050	2,100	252	210
70%	m3	6.4	12.7	1.6	1.6
	gal	1,680	3,360	420	420
80%	m3	11.1	19.1	3.5	3.2
	gal	2,898	5,040	924	840
90%	m3	23.9	32.4	9.5	12.4
	gal	6,300	8,547	2,520	3,287
100%	m3	731.3	372.0	3,752.1	66.8
	gal	193,200	98,280	991,200	17,640
Number reported		**438**	**414**	**4,343**	**232**

The majority of the spills were consistent between life-years within states. The maximum reported volume spilled occurred within the first year of a well in Colorado and New Mexico, and within the fourth life-year of the well in North Dakota and Pennsylvania.

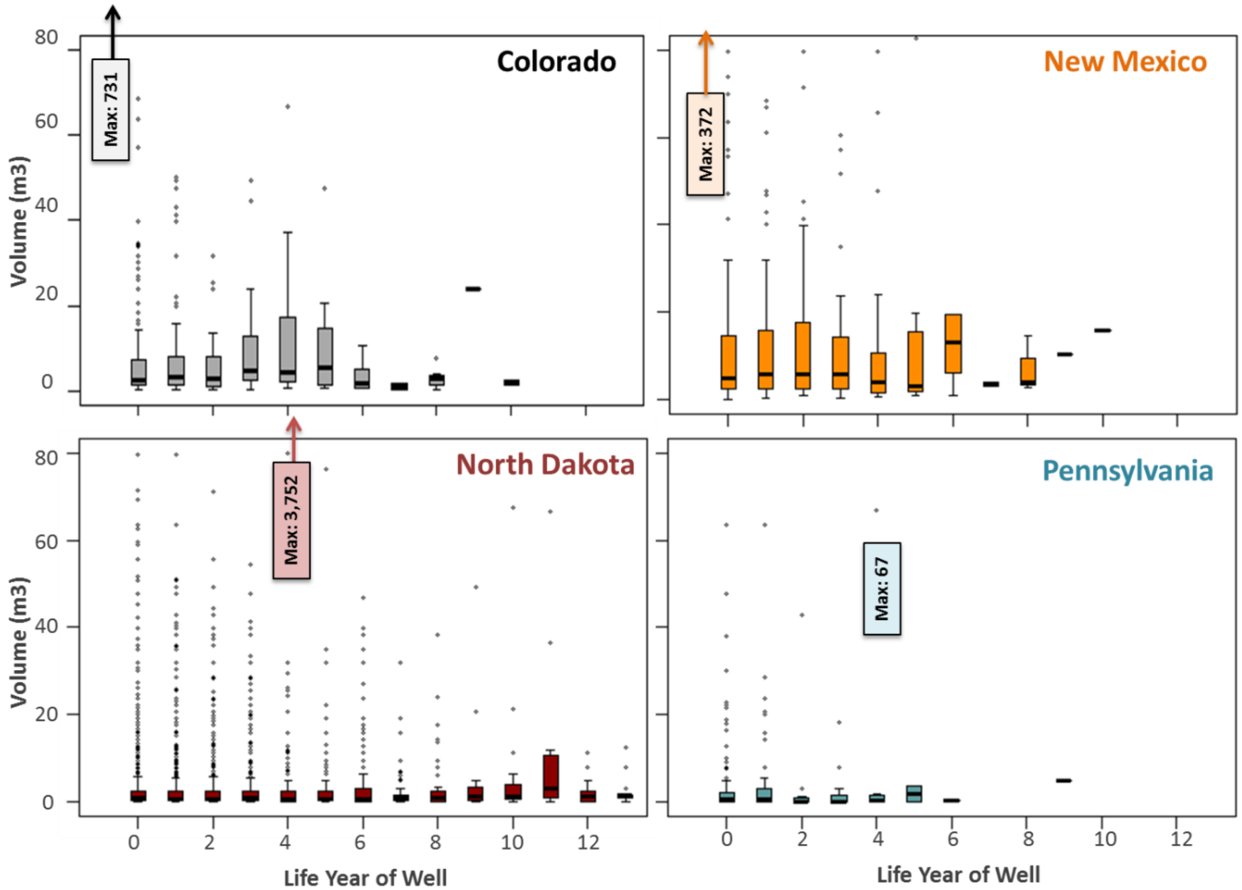

Figure S3: Boxplot showing the volume spilled by life-year of the well. Bars represent the interquartile range of spills. Y-axis is constant across states to enable comparison. The maximum spill is shown at the life-year of occurrence. Several spills exceeded the y-axis; however the majority of spills are visible at this scale.

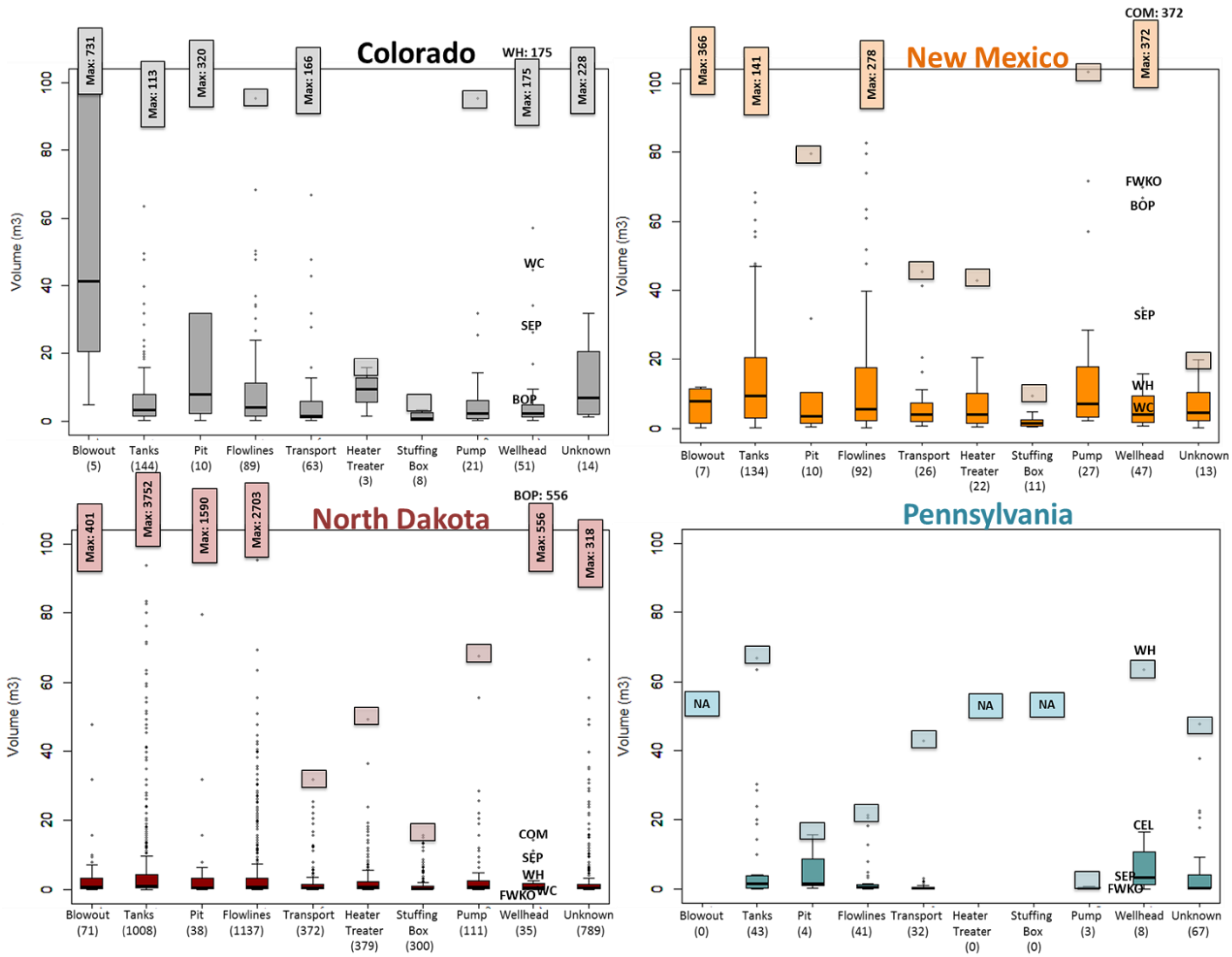

Figure S4: Box plots comparing the volume spilled by pathway. Bars represent the interquartile range of spills. The maximum spill is highlighted by a box. If the maximum spills box goes beyond the y-limit the value is reported. The maximum volume for components of the wellhead is provided: blowout preventer (BOP), free water knockout (FWKO), separator (SEP), well casing (WC), well cellar (CEL), well communication (COM), and wellhead (WH).

E. Data Insights

When spill pathways are identified the data can be used to inform risk identification and improved regulation. From the data, we concluded that the most prominent pathway for spills to occur was related to storage of materials in tanks or pits (30% of reported spills) (Table 1). Additional details allowed us to discern that while leaking tanks were less prevalent than overflowing tanks, the spills from leaks tended to be larger (Table S10). In Colorado, 72% of leaks were due to equipment failure (31% corrosion) while 51% of overflow events were caused by human errors. In New Mexico, equipment failure was the prominent cause for both leaks (54%) and overflows (44%), while all spills related to environmental conditions, such as lightning strikes and flooding, released nearly twice the volume of material (~22.4 m^3). Neither North Dakota nor Pennsylvania provided sufficient information to determine causal mechanisms (90% and 80% unknown), respectively.

Table S10: Spill rates and volumes associated with tanks

	Tanks	**Colorado**	**New Mexico**	**North Dakota**	**Pennsylvania**
Percent of Spills	Leak	13	25.5	27.4	37.3
	Overflow	43.2	52.6	70.7	32.7
	Unknown	43.8	21.9	2	30
Median Volume (m3)	Leak	3.4	15.5	1.6	1.7
	Overflow	4	6.4	1	1.2
	Unknown	3.2	9.5	1.6	1

Pits, similar to tanks, had greater volumes released through leaks than overflows. The majority of pit leaks were due to liner issues: either a tear in the liner (equipment failure) or the pit was improperly lined (human error). Pits were also more susceptible to spills resulting from environmental conditions such as flooding, heavy rain, and snow melt. For example, in 2011 North Dakota reported 18 pits overflowed due to snow melt.

Tanks and pits were particularly susceptible to large volume spills during the initial stages of completion when large volumes of flowback and produced water are coming to the surface. Several wells in Colorado mentioned overflows due to unanticipated volumes.

One caveat regarding why tanks and pits may appear as the most prominent pathway is due to how spills were reported, at least with respect to overflows due to equipment failure or unknown reasons, and our definition of pathway. For example, the spill was released to the ground at a tank due to the tank overflowing. However, in the description of the spill the root cause may be due to equipment failure at the heater treater. We defined this spill as a tank overflow due to equipment failure. However, others might have defined the pathway not as the location at which the spill occurred, but the reason behind the spill (i.e. the pathway would have been directly linked to the heater treater).

The second most prominent pathway was related to the movement of fluids between locations via flowlines (Table 1). Equipment failure was the predominant cause for spills in all four states (Table S11). The majority of leaks occurred from corrosion or where valves and connections are located along the flowline. Flowline spills due to human error most commonly result from accidentally breaking a line that is not clearly marked during construction, excavating around the well pad, or leaving a valve in an incorrect position.

Table S11: Spill rates and volumes associated with flowlines by causal mechanism

		Colorado	**New Mexico**	**North Dakota**	**Pennsylvania**
Percent of spills	Equipment Failure	60.9	79.8	68.2	55.7
	Human Error	28.3	11.7	1.6	11.5
	Environmental Conditions	10.9	2.1	0.8	8.2
	Unknown	0	6.4	29.3	24.6
Median Volume (m3)	Equipment Failure	2.7	6.4	0.8	0.7
	Human Error	4	4.8	0.8	0.2
	Environmental Conditions	5.6	1.3	0.6	0.1
	Unknown	NA	12.7	0.8	0.4

Transportation was another common pathway in all four states. Seventy-three percent of transportation spills occurred during the process of loading or unloading materials. In Colorado and New Mexico, 88% of spills were attributed to human error, most often due to drivers' inattention or leaving valves in an open position. Each state had 5 to 10% of their reported releases caused by issues of unloading waste in non-approved areas. Spills that occurred in transit were relatively rare, but those spills could also be under-reported since they occurred offsite.

F. Links to spill forms used by states

Colorado: http://cogcc.state.co.us/forms/PDF_Forms/form19.pdf
New Mexico: http://www.emnrd.state.nm.us/OCD/documents/C-14120110808.pdf
North Dakota: https://www.dmr.nd.gov/oilgas/mvc/wincident/Incident/Create
Pennsylvania: No forms are used

PADEP recently updated its regulations. Once they go into effect, the new rules will require a written report if the release is more than 42 gallons (1 barrel) that pollute or threaten to pollute Pennsylvania waters[S2]. The new written report requires information about the "nature of the contaminant", the location of the incident, and the *effect* (not the cause) of the spill.

G. Limitations

The lack of consistency in how spills are reported within a state will lead to inconsistent findings between studies because different analysts interpret descriptions of events differently. For example, using the same database in Pennsylvania, four studies found four different rates of well leakage: 5%[S3], 3.4%[S4], 6.2%[S5], and 2.6%[S6]. These variations resulted from different interpretations of events and whether violation codes matched the description provided. While the results are similar, they should ideally be identical given they all use the same dataset. However, data curations of descriptive narratives will likely lead to different conclusions.

The spill data reported here do not cover the entire life cycle of the well; it focuses only on those spills that occur on or near the well pad. Additional spills may occur during the transportation of sand and chemicals to a well pad, as well as the transportation of wastewater for disposal by truck or injection lines. This data additionally does not take into account spills that occur as oil and natural gas are transported to refineries. Capturing the rate and volume of spills is challenging due to the lack of data collected: "Data limitations also preclude a quantitative analysis of the likelihood or magnitude of chemical spills or impacts. Spills that occur off-site, such as those during transportation of chemicals or storage of chemicals in staging areas, are out of scope."[S7]

H. References

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