Unconventional oil and gas spills: materials, volumes and risks to surface waters in four states of the U.S.

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ABSTRACT

Extraction of oil and gas from unconventional sources, such as shale, has dramatically increased over the past ten years, raising the potential for spills or releases of chemicals, waste materials, and oil and gas. We analyzed spill data associated with unconventional wells from Colorado, New Mexico, North Dakota and Pennsylvania from 2005-2014, where we defined unconventional wells as horizontally drilled into an unconventional formation. We identified materials spilled by state and for each material we summarized frequency, volumes and spill rates. We evaluated the environmental risk of spills by calculating distance to the nearest stream and compared these distances to existing setback regulations. Finally, we summarized relative importance to drinking water in watersheds where spills occurred. Across all four states, we identified 21,300 unconventional wells and 6,622 reported spills. The number of horizontal well bores increased sharply beginning in the late 2000s; spill rates also increased for all states except PA where the rate initially increased, reached a maximum in 2009 and then decreased. Wastewater, crude oil, drilling waste, and hydraulic fracturing fluid were the materials most often spilled; spilled volumes of these materials largely ranged from 100–10,000 L. Across all states, the average distance of spills to a stream was highest in New Mexico (1,379 m), followed by Colorado (747 m), North Dakota (598 m) and then Pennsylvania (268 m), and 7.0, 13.3, and 20.4% of spills occurred within existing surface water setback regulations of 30.5, 61.0, and 91.4 m, respectively. Pennsylvania spills occurred in watersheds with a higher relative importance to drinking water than the other three states. Results from this study can inform risk assessments by providing improved input parameters on volume and rates of materials spilled, and guide regulations and the management policy of spills.

1. Introduction

Development of oil and gas from unconventional shale sources (unconventional oil and gas, or UOG) has dramatically increased over the past ten years in large part due to the combination of horizontal drilling and hydraulic fracturing. Horizontal drilling refers to the process where a wellbore aligns horizontally with the target formation, thus increasing contact with the reservoir, and hydraulic fracturing refers to the process that stimulates oil and gas within the reservoir by expanding fractures in shale through injection of fracturing fluid (i.e., water, proppant and chemicals) (USDOE 2009). The U.S. is currently the leader in developing UOG resources, where from 2000 to 2016 daily production of shale gas (dry) increased by 20-fold (2.2 to 44.0 billion cubic feet) and tight oil increased by more than 10-fold (0.4 to >4.5 million barrels) (USEIA 2016). Other countries are beginning to commercially produce oil and gas from shale and low-permeability formations (USEIA 2015), and by 2040, unconventional gas production is projected to triple to account for almost a third of global natural gas production (IEA 2015). Given the rapid, recent development of UOG, data are scarce on its long-term environmental impacts, and there is a need to better quantify risk to people and nature (Finkel and Hays 2013, Small et al. 2014, Souther et al. 2014, Werner et al. 2015).

UOG development can affect species, ecosystems and the services they provide to people. In central North America, estimates suggest that oil and gas development (including coal bed methane) reduced net primary productivity, an important measure of a region's ability to provide ecosystem services, by ~4.5 Tg of carbon from 2000 – 2012 (Allred et al. 2015). Further, land application of hydraulic fracturing fluid resulted in leaf drop and 56% mortality of trees where the application occurred (Adams 2011). Forest interior bird counts increased with distance from a well pad in Pennsylvania (Barton et al. 2016), abundances of sagebrush

songbirds decreased with increased well density in Wyoming (Gilbert and Chalfon 2011), and mule deer have been documented to avoid well pads with active drilling by at least 800 m in Colorado (Northrup et al. 2015). In Kentucky, an accidental release of hydraulic fracturing fluid into a stream increased gill lesions and other indicators of stress in fish (Papoulias and Velasco 2013), and in Pennsylvania, juvenile mussels below a brine treatment plant had lower survival rates than mussels located above the plant (Patnode et al. 2015). Streambed microbial diversity was lower below an oil and gas waste injection plant in West Virginia (Akob et al. 2016), and water downstream from this site had higher endocrine-disrupting activities than reference water (Kassotis et al. 2016). Despite the emerging evidence, studies establishing causal relationships between environmental changes and UOG activities are scarce; this is particularly true for spills and releases of materials used in and produced by UOG development.

Summary reports on UOG spills are starting to emerge; however, they are typically restricted to a single state, short on detail regarding materials spilled or reasons for spills, or are characterized by a small sample size. For example, the Colorado Oil and Gas Conservation Commission (COGCC, 2014) reported that equipment failure and human error were the two main causes of spills, most spills occurred during the production stage, process piping, pipelines and tanks were the main sources of spills, and the volume of 12% of the spills were > 100 barrels (15,900 L); however no detailed analysis on spilled material was presented. Brantley et al. (2014), using the Pennsylvania Notice of Violation (NOV) database, reported that one-fifth of wells were given a non-administrative violation from 2005 to 2013, and Rahm et al. (2015) reported that Pennsylvania NOVs (2007-2013) related to spills and erosion were the most common NOV issued. Neither study, however, conducted a detailed analysis on volumes or materials spilled or their potential impacts to surface waters in Pennsylvania. Finally, the U.S.

Environmental Protection Agency (USEPA; 2015a) reviewed over 36,000 spill records from nine states but was able to confidently identify only 457 incidents associated with hydraulic fracturing (~12,000 contained insufficient information and ~24,000 were not related to hydraulic fracturing). The USEPA reported most spills were small (< 1,000 gallons, 3,785 L), flowback and produced waters were the most commonly spilled material, human error was the most common cause of a spill, storage units were the common source of spills, and 300 of the spills reached an environmental receptor; however, the study did not include spills that occurred during the drilling stage.

The objectives of this study were to characterize the volumes and compositions of the materials spilled from horizontal, hydraulically fractured oil and gas wells, and evaluate the risk that spills posed to streams and surrounding watersheds important to human drinking water. Our first objective aimed to fill the knowledge gap on the materials and volumes spilled during UOG development. Our second objective focuses on streams because they provide habitat that supports a high level of biodiversity (Meyer et al. 2007), are particularly vulnerable to UOG development due to their tight coupling with upstream catchments (Hynes 1975), and are sensitive to small changes in catchment conditions from anthropogenic activities (Maloney et al. 2012). Further, over 1/3 of the U.S. population uses public drinking water systems that rely, at least in part, on intermittent, ephemeral or headwater streams (USEPA 2009). The spatial position of anthropogenic activities within the catchment often affects these relationships (King et al. 2005), which is especially important for UOG because wells are frequently located in close proximity to streams (Entekin et al. 2011). We therefore evaluated the risk of spills to streams by quantifying the spatial position of spills to the nearest stream and how these distances related to current setback regulations. Because a large population relies on surface water for domestic

use, our second objective also explored risks to drinking water using the U.S. Forest Service's Forest to Faucets data set. We provide a broad analysis of spill features to improve understanding of the potential environmental risks of spilled materials from UOG development and to inform management practices and policy formulation.

2. Study Site and Methods

2.1. Study Sites and Setback Regulations

We sampled state databases on spill records for four states (Colorado – CO, New Mexico – NM, North Dakota – ND, and Pennsylvania – PA) that have accessible oil and gas spill data. Each of the states experienced an increase in horizontal hydraulic fracturing over the past decade (Fig. S1); however, they vary in production type from ND being primarily an oil producer to PA being primarily a gas producer. These states provide a representative range in information on spills related to UOG, which should be applicable to many geographic and ecological settings. Each state's laws and reporting requirements also vary for when (volume threshold or potential impact to people or water) and how spills are reported (verbal or written and reporting requirements) (CDPHE 2009, NM Admin Code R. 19.15.29, ND Admin. Code R. 43-02-03-30, 25 Pa. Code § 78.66). These differences drive the quantity and quality of spills data reported in each state; therefore, a higher spill rate in a state may just reflect a more robust reporting system.

There is also considerable variability in stream setback regulations for UOG across the states examined in this study. In CO, new oil and gas development must generally avoid “restricted surface occupancy areas”, which are defined to include areas within 300 feet (91.4 m) of the ordinary high water mark of any stream segment located within designated Cutthroat Trout habitat, or streams or lakes designated by the Colorado Parks and Wildlife as “Gold Medal” (2

Colo. Code Regs. 404-1:100, 404-1:1205). Operators proposing to drill a well on a previously undisturbed site must first obtain a location assessment from the Colorado Oil and Gas Conservation Commission and must indicate on the form provided for this assessment that the proposed site is within a restricted surface occupancy area (2 Colo. Code Regs. 404-1:303b(3)(P)). Further, no new well may be drilled within 300 feet (91.4 m) of a public water system without a variance and consultation with the CO Department of Public Health and the Environment (2 Colo. Code Regs. 404-1:317B(c), and a well may only be located between 301 and 2,640 feet (91.7 and 804.7 m) from a public water system if additional security measures are taken and baseline water quality testing is conducted (2 Colo. Code Regs. 404-1:317B(d)(4), (e)(2)).

In NM, wellhead protection areas include 200 feet (61.0 m) of a private, domestic freshwater well or spring used by less than five households or within 1000 feet (304.8 m) of any other freshwater well or spring (NM Admin Code R. 19.15.2.7(W)(8)). Further, permanent waste pits (NM Admin. Code R. 19.15.17.10(A)(5)) and recycling containments (NM Admin. Code R. 19.15.34.11) are not to be located within 300 feet (91.4 m) from a continuously flowing watercourse or 200 feet (61.0 m) from any other significant watercourse or lakebed, sinkhole or playa lake. Operators may obtain a waiver from these requirements if the state determines that waters will be protected from the permanent waste pit. Permanent waste pits and recycling containments also may not be located within 500 feet (152.4 m) of a spring or freshwater well, 500 feet (152.4 m) of a wetland, or within the 100 year floodplain.

In ND, Admin. Code R. 43-02-03-19 states that “[w]ell sites and facilities shall not be located in or hazardously near, bodies of water, nor shall they block natural drainage”. However, no setback distances are specified.

In PA, the edge of the disturbed area associated with an UOG well previously had to be set back 100 feet (30.5 m) or the vertical portion of the well must be 300 feet (91.4 m) from the edge of any “solid blue lined stream, spring or body of water as identified on the most current 7 1/2 minute topographic quadrangle map of the United States Geological Survey.” (58 Pa. Stat. § 3215(b)). However, this setback requirement was enjoined in *Robinson Township v. Commonwealth*, 83 A.3d 901, 1000 (Pa. 2013) and is not in effect. Pennsylvania’s Act 13 also allowed the Department of Environmental Protection to require that hazardous chemicals and materials used in UOG be stored 750 feet (229 m) from blue lined streams (58 Pa. Stat. § 3215(d.1)). Finally, the Commonwealth restricts well site placement within floodplains (58 Pa. Stat. § 3215(f)).

2.2. Spill Data and Rates

We analyzed spill data from 01 January 2005 through 31 December 2014 for NM, ND, and PA, and from 01 January 2005 through 31 December 2013 for CO because of a significant change in CO spill reporting in 2014 (COGCC 2014) a time period that encompassed the majority of horizontal UOG well development in these states (Fig. S1). Colorado spill data were obtained on 2 September 2014 from the state’s online incident report Form 19/19A (<http://cogcc.state.co.us/data.html#/cogis>). Spill data within NM were accessed on 25 June 2015 from the New Mexico Oil Conservation Division website on spills (<https://wwwapps.emnrd.state.nm.us/ocd/ocdpermitting/Data/Incidents/Spills.aspx>). North Dakota spill data were collated on 26 August 2015 from the oilfield environmental incident reports on the North Dakota Department of Health – Environmental health website (<https://www.ndhealth.gov/EHS/Spills/>). Pennsylvania does not have a spill database; instead

spills are reported in a Notice of Violation (NOV) database

(http://www.depreportingservices.state.pa.us/ReportServer/Pages/ReportViewer.aspx?/Oil_Gas/OG_Compliance). We downloaded all PA NOVs from this site on 03 April 2015 and using the “violation codes” listed classified each violation as a “spills, potential spills” similar to Rahm et al. (2015, Table S1).

Each spill or NOV record was individually examined for duplication, errors, and a description of material and volume spilled. We grouped materials into ten main categories: chemicals, condensate, crude oil, diesel fuel, drilling waste, freshwater, hydraulic fracturing solution, natural gas, sediment, and wastewater. Materials not falling into these ten categories were grouped under “other”. For consistency across states, we had to group some of the reported material classifications into these more general categories. Drilling mud, cuttings, and drilling fluid were not consistently reported across states so these were grouped together as “Drilling waste”; similarly brine, flowback, and produced water were grouped as “Wastewater”. Hydraulic fracturing solution and frac fluid were reclassified as “HF Solution”, and chemicals used in the development process (e.g., HCl, antifreeze, surfactant, and glycol) were classified as “Chemicals”. For some records more than one material was reported; for these we treated each material as a separate spill. In ND, 20 records had no material spilled and were removed from analysis. North Dakota also had three records with a zero value for volume spilled; we classified these records as no volume reported.

We obtained well information from 01 January 1995 through 31 December 2014 from the IHS Enerdeq database (IHS 2016), a private source for well information that synthesizes and independently quality assures data from state agencies and organizes it in a user-friendly searchable format. We used this single, private source for well information to minimize data

inconsistencies among states. Because there was no clear designation of what constituted an UOG well in this database, we used geologic province name, play type, well status, and well bore orientation to identify UOG wells. UOG geologic provinces included the Denver Basin, Green River Basin and Piceance Basin in CO; Williston Basin for ND; Permian Basin and San Juan Basin for NM and Appalachian Basin for PA. We therefore considered wells as UOG if they 1) overlapped with the mentioned geological provinces, 2) had a play type classified as Shale Gas, Tight Gas, or Tight Oil, 3) had a well status of oil, gas, abandoned, pilot or suspended designation, and 4) had a horizontal hole direction.

We merged the entire spills dataset to the UOG well dataset using the American Petroleum Institute (API) number, a unique number for all oil and gas wells drilled in the U.S. This resulted in a dataset that contained only those spills associated with horizontally drilled UOG wells since 1995. We calculated spill rates by material for each state using the number of spills for a given year divided by the cumulative number of spudded wells since 1995. We used the cumulative number of wells because we wanted to examine the risk of spills throughout the life of a well. We multiplied the resulting rates by 100 thus report spill rates per 100 wells.

2.3. Potential risks to people and nature

Because streams support numerous freshwater taxa, including those for human consumption, and provide a source of drinking water for humans we assessed the potential risks of spills to these ecosystems two ways. First, we compared distances of spills to the nearest stream among states by measuring proximity (linear geographic distance) of spills to a stream using the NHDplusV2 high resolution flowline dataset (McKay et al. 2012) and the Near Tool in

ArcGIS 10.2.2 (ESRI, Redlands, California, USA). We assumed that spills occurring closer to streams can pose a higher risk than spills occurring further away. Geospatial information of spills was not available in the state spill reports; therefore we used the latitude and longitude of wells as the spatial location of the spill. We acknowledge that some spills associated with supporting infrastructure and equipment of the well, e.g., storage tanks and flowlines, may not be located at close proximity to the well head, however locational data for such structures were not available for this analysis. We therefore used the well head coordinates as a surrogate, potentially over- or under-estimating actual distance of spills to streams; however we have no reason to believe there would be a systematic bias for over- or under-estimation of distances. Second, using the distance to stream data, we calculated the number of spills in each state that occurred within the various state setback distances from streams listed above (30.5 m, 61.0 m, 91.4 m, 152.4 m and 228.6 m).

However, the importance of streams as sources of drinking water varies greatly across the U.S. Therefore, we also explored risks to drinking water among states using the U.S. Forest Service's Forest to Faucets data set (Weidner and Todd 2011). Based on water production and water use, the Forest to Faucets data produced a Hydrologic Unit Codes (HUC) 12 watershed level index of relative importance to surface drinking water, which ranks relative importance from least important, 0, to most important, 100. We used this importance index to examine potential risk of UOG spills to surface drinking waters. All data analyses and figures were performed in R (R Development Core Team 2015) or ArcGIS 10.2.2.

3. Results

3.1. Well and spill temporal patterns

We identified 6,622 UOG spills from 5,958 unique reports in the four states' databases (Table 1). Six hundred and fifty eight reports (11.1% of total) had more than one material reported on the same incident report. North Dakota had the most horizontal UOG wells, followed by PA, NM and then CO (Table 1). While all states showed a sharp increase in the number of horizontal wells over time (Fig. S1), the number of spills increased sharply in the late-2000s only for ND and PA; for PA, the increase was followed by a decreasing trend (Fig 1A). The maximum number of reported spills in one year was 78 in 2013 for CO, 170 in 2014 for NM, 1,374 in 2014 for ND, and 324 spills in 2010 for PA (Fig 1A, Table S2). Spill rate increased for all states except PA where the rate initially increased, reached a maximum of 20.3 spills per 100 wells in 2009 and then decreased (Fig. 1B, Table S2).

3.2. Spilled materials and volumes

We were able to identify materials for 6,082 spills (91.8% of all spills). The predominant material spilled varied across states, with wastewater in the top three spilled materials for all states (excluding unknowns for PA) and crude oil in the top two spilled materials for CO, NM and ND (Fig. 2A, Table S3). Top spilled material rates per 100 spudded wells consisted of crude oil (2.7% of wells), drilling waste (2.5%), wastewater (1.7%) and HF solution (0.5%) in CO; wastewater (6.3%), crude oil (5.5%), natural gas (1.3%) and drilling waste (0.5%) in NM; crude oil (24.1%), wastewater (14.1%), drilling waste (3.2%) and HF solution (1.4%) in ND; and unknown (6.4%), drilling waste (3.6%), wastewater (3.3%) and natural gas (1.9%) in PA (Table S3, Fig. 2B). A total of 5,466 spills (82.5%) had reported volumes ranging from 0.4 to 3,752,100 L (Table S4; mean 7,119 L, median 757 L). Volumes of the four most frequently spill materials

(wastewater, crude oil, drilling waste, and HF fluid) largely ranged from 100–10,000 L (Fig. 3). Except for condensate, the largest-volume spills of a specified material all occurred in ND (Fig. 3, Table S4). While freshwater spills were uncommon ($n = 57$ total, 56 in ND, Table S3), their median volume (7,949 L) exceeded the median volume of all other spills (715 L) by more than 10 fold.

3.3. Potential Risk to people and nature

Across all states the average distance from a spill to a stream was 580 m and ranged from a low of 0.4 m in PA to a high of 9,276 m in NM (Table S5). By state, average distance of spills (from wellhead) to the nearest stream was highest in NM (1,379 m), followed by CO (747 m), ND (598 m) and then PA (268 m) (Figure 4, Table S5). Across all states, 7% of total spills were within 30.5 m (100 feet setback) of a stream, 13.3% were within 61.0 m (200 feet setback), 20.4% were within 91.4 m (300 feet setback), and 47.1% were within 228.6 m (750 feet setback) (Table 2). Pennsylvania has the smallest setback regulation at 30.5 m and 5.3% of the spills in this state were within this distance to a stream. Colorado, NM and PA all had setbacks of 91.4 m and 11.5%, 9.8% and 17.4% of spills in these states, respectively, occurred within this distance from a stream. North Dakota had no specified setbacks from streams, and other than PA at the 228.6 m distance, had the highest percentage of spills within each setback distance (Table 2).

The overall average index of watershed importance to surface drinking water was highest in PA; PA values were on average 3.2 times higher than CO, 7.5 times higher than NM and 3.8 times higher than ND (Fig. 5A, Table S6). Concurrently, UOG spills also occurred in watersheds with highest importance to surface drinking water in PA (85.1), followed by CO (23.9) and ND (23.0), and lowest in NM (5.8) (Fig. 5B).

4. Discussion

Understanding the characteristics of spills is key to effectively evaluate environmental risk due to UOG development. Risk is a function of the frequency of spills, the type of material spilled, the volume of material spilled, and the proximity of the spill to surface waters and other ecologically sensitive systems. In our study, wastewater and crude oil were two of the most frequently spilled materials across all states, which is consistent with previous reports (COGCC 2014, USEPA 2015a). Further, a large subset of spills occurred within current setback regulation distances, which suggest some risk to streams is occurring within these distances. Spills also occurred in watersheds highly important to surface drinking water especially in PA, inferring this state's freshwater resources for drinking may be at higher risk.

The prevalence of wastewater and crude oil spills is likely a result of the large amount of both materials produced, stored and transported (Maloney and Yoxtheimer 2012, Kondash and Vengosh 2015). Wastewater is often high in salinity, toxic trace elements, naturally occurring radioactive materials, and other constituents depending on the producing formation and fluid mix involved in fracturing (Rowan et al. 2014, Lauer et al. 2016). Exposure to wastewater has been shown to increase plant mortality of terrestrial plants (Adams 2011), reduce juvenile mussel survival rates (Patnode et al. 2015), and lower streambed microbial diversity (Akob et al. 2016). Modeling and field studies suggest chemicals associated with wastewater spills can persist in the environment for several years (Rogers et al. 2015, Lauer et al. 2016). Similarly, crude oil spills can have long-term environmental impacts due to the tendency of waterway sediments to adsorb and retain oil's hydrophobic constituents (NASEM 2016). Besides direct mortality and alterations of community structures, crude oil toxins can negatively affect individuals by causing

genetic damage, enzymatic and hormonal changes, immuno-suppression, and bioenergetics and behavioral alterations (NASEM 2016, Perhar and Arhonditsis 2014).

Other materials that were spilled less frequently, including hydraulic fracturing fluids (HF solution) and drilling waste, may also pose environmental risks. Nearly 1000 chemicals have been used in various HF solution formulations (Konschnik and Dayalu 2016); only a small subset of chemicals are used for each individual well and the sum of these additive ingredients is frequently only 1-2% by mass of the total HF solution (USEPA 2015b). Nevertheless, the large volume of HF solution used in the fracturing process (Kondash and Vengosh 2015) increases the potential for release of these chemicals to the environment. Moreover, many of the chemicals most frequently used are hydrocarbons such as light petroleum distillates (Konschnik and Dayalu 2016), which can persist in the environment. Drilling waste, a composite of drill cutting, mud, and fluids, was mostly reported in ND and PA. These wastes, especially the cuttings, could contain low levels of naturally-occurring radioactive materials and other constituents, such as trace metals (Johnson and Graney 2015). Finally, it is interesting to note that while not necessarily as frequent, freshwater spills were on average much larger than other spills, suggesting that frequency alone may underestimate the potential effects of spills. Potential ecological effects from a freshwater spill differ from the other materials and could include increased erosion and sedimentation.

This is the first report we are aware of that reports on proximity of spills to streams. Spills in all states occurred within their smallest setback distances from streams (30.5 m in PA; 61.0 m in NM; and 91.4 m in CO). It is possible that the close proximity of these spills to streams was the result of using a dataset that contained intermittent and ephemeral streams. However, our goal was to identify any possible conduit to a stream, even if a non-flowing

system, hence the close proximity to spills indicates a potential for spilled material to reach larger streams. The number of spills within setbacks also could be because we identified the spatial position of a spill using the coordinates of the wellhead rather the supporting equipment such as flowlines or storage tanks, however as indicated before, we have no reason to believe a directional bias in over- or under-estimating spill distances. Finally, the number of spills within setbacks could be a result of waivers in some state codes (e.g., 58 Pa. Stat. § 3215(b)) that allow construction of wells within the setback; however data to evaluate this were not available for our study; a future analysis could focus on wells that were granted waivers or exemptions.

We recognize that other factors, in addition to proximity, influence the vulnerability of streams to spills. Spilled fluids may reach streams by overland flow or following infiltration and flow along subsurface pathways. The vulnerability of streams to spills that move via the subsurface track will depend, in part, on proximity, but will also reflect hydrogeologic properties that govern water-table depth, the rate and directions of groundwater flow, and whether the stream gains water from, or loses water to, the groundwater reservoir. The site-specific nature of these properties implies that assessment of threats that spills pose to stream-water quality must be conducted on a case-by-case basis.

Ecosystems provide many benefits to people, including food and water, regulating floods and diseases, and recreation (Millennium Ecosystem Assessment, 2005). We evaluated the potential effects of UOG spills on ecosystem services by focusing on surface drinking water, using an importance index developed by the US Forest Service. We found that spills in Pennsylvania occurred in watersheds with a much higher value to surface water than the other states, a result of higher population density and reliance on surface waters as drinking water in this area (Weidner and Todd 2011). The other three states had spills in watersheds with lower

importance values, which likely reflects a greater reliance on groundwater or that drinking water is sourced from streams and reservoirs of distal watersheds. Nevertheless, in these states a localized spill that affects water reservoirs and treatment plants can negatively impact communities near UOG development.

Several approaches to model the risk of UOG development have been recently implemented, from probability modeling (Rozell and Reaven 2012) to expert risk assessments (Walker et al. 2016). Our results suggest that modeling the risk of hydraulic fracturing will require region-specific parameterizations. For example, North Dakota had the highest spill rates for both crude oil and wastewater as well as the largest reported spill volumes for these materials. The Bakken is the largest producer of crude oil (USEIA 2016) and wastewater (Kondash and Vengosh 2015) for plays in our study, which could be one reason for the higher spill rates. Another reason may be development rate, where ND had over twice the number of spudded horizontal wells in 2012, 2013 and 2014 than the other three states. Finally, differences in reporting are also a factor; ND requires reporting at a lower threshold (1 barrel; 159 L) than either CO or NM (5 bbls, 795 L), and its dataset also had the most complete records in terms of materials and volumes associated with spills. Unifying reporting requirements across states would aid future broad-scale data analyses and risk modeling.

Finally, we acknowledge that all spills may not have been reported or included in the available state databases. Data were not available to estimate the frequency of these “missing” spills and we are unaware of any study that has directly examined missing spills (but see Wiseman 2013). To deter under-reporting, states in our study have penalties for failing to report a required spill that include maximum civil penalties that range across the states from \$12,500 (ND) to \$15,000 (CO) per day to \$75,000 plus \$5,000 per day (PA); NM, ND, and PA

also categorize a failure to report as a possible criminal act (Colorado House Bill 14-1356, Section 1, 34-60-121; North Dakota Century Code Section 38-08-16.1; New Mexico House Bill 286 Section 70-2-31(B); 58 Pa State § 3255, 3256). Further, our large sample size ($n = 6,622$) from four states over ten years likely averages any effects of under- or over-reporting, and missing spills are thus not likely to affect overall patterns.

5. Conclusions

Concerns over potential environmental issues resulting from UOG development have spurred a flurry of recent articles on its potential ecological effects to associated ecosystems (Brittingham et al. 2014, Evans and Kiesecker 2014, Souther et al. 2014). An important gap in our understanding of potential effects of UOG on associated ecosystems is the surface release of chemicals, waste materials and oil and gas. We found that wastewater, crude oil, drilling waste and hydraulic fracturing solution are the materials most often involved in a spill incident, and that most spills ranged between 100 L and 10,000 L. We also found that some spills occurred in very close proximity to streams and in watersheds of high importance to drinking water. Further, spills occurred within current setback requirements. As UOG activity continues in the U.S. and commences in other countries around the world, our findings can be used to better understand the risk of spills from UOG development and help inform management decisions, policy, and regulations.

Competing financial interest declaration

The authors declare no competing financial interests.

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Appendix A. Supplementary data

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Table 1. Number of wells and spills by state. “With Volumes” column indicates the number of spills with volume data; “With Materials” column shows the number of spills with materials spilled data. Numbers in parentheses indicate percentage of the number of wells (Unique Records, Total) or percentage of total spills (With Volumes, With Materials). The Unique Records column indicates the number of unique spill reports; the Total column does not show total unique spills because we considered spill reports with more than one material as separate spills.

State	Number of Wells	Number of Spills			
		Total	Unique Spill Records	With Volumes	With Materials
Colorado	1753	139 (7.9)	125 (7.1)	135 (97.1)	136 (97.8)
New Mexico	2197	316 (14.4)	265 (12.1)	276 (87.3)	312 (98.7)
North Dakota	10881	4986 (45.8)	4428 (40.7)	4859 (97.5)	4868 (97.6)
Pennsylvania	6469	1181 (18.3)	1140 (17.6)	196 (16.6)	766 (64.9)
Totals	21300	6622 (31.1)	5958 (28)	5466 (82.5)	6082 (91.8)

Table 2. Number of spills within specified distance of streams corresponding to existing setback regulations. Numbers in parentheses indicate the percentage of spills within the setback distance out of total spills (see Total column in Table 1). Grey shading represent setback distances specified for each state depending on regulation, where North Dakota had no setback distances specified.

State	Distance (m)				
	30.5	61.0	91.4	152.4	228.6
Colorado	2 (1.4)	7 (5.0)	16 (11.5)	28 (20.1)	41 (29.5)
New Mexico	13 (4.1)	25 (7.9)	31 (9.8)	47 (14.9)	78 (24.7)
North Dakota	388 (7.8)	736 (14.8)	1095 (22.0)	1722 (34.5)	2410 (48.3)
Pennsylvania	63 (5.3)	116 (9.8)	206 (17.4)	378 (32.0)	589 (49.9)
Totals	466 (7.0)	884 (13.3)	1348 (20.4)	2175 (32.8)	3118 (47.1)

Figures:

Figure 1. Number of identified unconventional oil and gas spills (A) and number of spills per 100 wells spudded cumulatively since 1995 (B) in Colorado, New Mexico, North Dakota and Pennsylvania from 01 January 2005 through 31 December 2014. Note: numbers do not denote unique spills because we considered spill reports with more than one material as separate spills. Data for both graphs are located in Table S2.

Figure 2. Number of spills by material for each state (A) and number of spills by material per 100 wells spudded cumulatively since 1995 (B). “Other” includes all materials not included in the 10 listed, and “Unknown” indicates no material was listed in the spill reports. We note that data on the y-axis in panel A are presented on a log scale for display purposes. In panel A, bars below 1 line indicate no spills. Data for both graphs are located in Table S3.

Figure 3. Volume (L) of spills for the four most often reported spilled materials by state. Box lower and upper hinges correspond to the 1st and 3rd quartiles (25th and 75th percentiles), solid horizontal line are medians, lower whiskers extend from the hinge to the lowest values within 1.5 times the interquartile range (difference between first and third quartiles) of the hinge, the upper whiskers extend from the hinge to the highest value that is within 1.5 times the interquartile range of the hinge, and points beyond whiskers are outliers. We note that data on the y-axis are presented on a log scale for display purposes. Data for graph are located in Table S4.

Figure 4. Distance of spills to the nearest stream (NHDplus high resolution flowline) by state. Numbers below boxplots signify sample size. Box lower and upper hinges correspond to the 1st and 3rd quartiles (25th and 75th percentiles), solid horizontal line are medians, lower whiskers extend from the hinge to the lowest values within 1.5 times the interquartile range (difference

between first and third quartiles) of the hinge, the upper whiskers extend from the hinge to the highest value that is within 1.5 times the interquartile range of the hinge, and points beyond whiskers are outliers. We note that data on the y-axis are presented on a log scale for display purposes, and we included common setback distances discussed in text. Data for graph are located in Table S5.

Figure 5. Forest to Faucet index of importance to surface drinking water for all HUC12 watersheds in the Forest to Faucet data set in each state (A) and for the subset of these HUC12 watersheds in which a UOG spill occurred (B). Number within or above boxplots are sample size. Box lower and upper hinges correspond to the 1st and 3rd quartiles (25th and 75th percentiles), solid horizontal line are medians, lower whiskers extend from the hinge to the lowest values within 1.5 times the interquartile range (difference between first and third quartiles) of the hinge, the upper whiskers extend from the hinge to the highest value that is within 1.5 times the interquartile range of the hinge, and points beyond whiskers are outliers. Data for graph are located in Table S6.

Figure 1.

Figure 2.

Figure 3.

Figure 4.

Figure 5.

Graphical Abstract

Distribution of spills attributed to unconventional oil and gas wells by state. Light green polygons indicate shale basins (basin nomenclature and shapefile from USEIA 2011).