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

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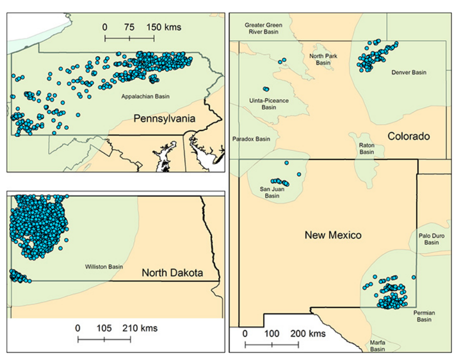
HIGHLIGHTS

- Analyzed data from 6622 spills from horizontal UOG wells in four U.S. states
- Wastewater, crude oil, HF solution and drilling waste were most often spilled
- Average distance of spills to the nearest stream was smallest in Pennsylvania
- Some spills in all states occurred within current surface water setback regulations
- Pennsylvania spills occurred in watersheds of higher importance to drinking water

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)).

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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 to 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 6622 reported spills. The number of horizontal well bores increased sharply beginning in the late 2000s; spill rates also

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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 to 10,000 L. Across all states, the average distance of spills to a stream was highest in New Mexico (1379 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 >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 to 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 Chalfoun, 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 (< 1000 gal, 3785 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 (Entrekin 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)