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# Characterization of Accidental Spills and Releases Affecting Groundwater in the Greater Wattenberg Area of the Denver-Julesburg Basin in Northeastern Colorado

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## Abstract

Public concern about the potential effects of unconventional oil and gas development on water quality has grown in recent years. In this study, we considered accidental spills and releases that occurred from 2007 to 2014 in the Greater Wattenberg Area (GWA), an area of intensive oil and gas extraction located within the Denver-Julesburg Basin in northeastern Colorado. Our objective was to quantify the occurrence rates of (1) all spills and (2) spills determined by the operator to have caused groundwater impacts. Additionally, for spills affecting groundwater, we analyzed characteristics including facilities and equipment involved, causes, and resolution times in order to identify recommendations for improved regulatory or operational practices.

Spills and releases were identified from publicly-available reports collected by the Colorado Oil and Gas Conservation Commission (COGCC). Spills were identified as having potentially impacted groundwater based on an operator-reported field present on the reports. Groundwater impacts were verified for this subset of spills by reviewing the narrative description of the incident and the supporting documents (e.g., consultant reports, laboratory data) available in the COGCC database. Additional information collected included the causes of the spills, the facility types, and the time required for resolution of spills. To determine spill occurrence rates, the number of annual spills was compared to several annual indicators of oil and gas development, including the volumes of oil and water produced and the number of active producing wells in the GWA.

The annual spill count remained relatively stable from 2007 to 2011, but increased each year from 2011 to 2014. From 2007 to 2014, spill occurrence rates decreased or remained steady when compared to oil and water production volumes, respectively; however, the occurrence rate increased compared to the number of active producing wells. These trends suggest that fewer spills occurred for a greater volume of fluids produced and handled in the GWA, but that more spills occurred per active well. For all three normalization metrics, we observed that the occurrence rate of groundwater-impacting spills remained steady or decreased. The percentage of spills impacting groundwater compared to total spills decreased by a factor of two from

2010 (54%) to 2014 (27%). Among groundwater-impacting spills, the most common facility types were tank batteries and lines (including flow lines, gathering lines, load lines, and pipelines), and the most common cause was equipment failure. Based on our observations of spills in the GWA from 2007 to 2014, we have suggested several strategies for regulators and operators to improve spill reporting practices and to reduce the likelihood of surface spills that result in persistent impacts to shallow groundwater.

## Introduction

The rapid expansion of unconventional oil and gas development facilitated by technical advances in horizontal drilling and hydraulic fracturing has raised concerns about the potential contamination of drinking water resources (Adgate et al. 2014; Vengosh et al. 2014; Shrestha et al. 2017). This work investigates the frequency and characteristics of spills affecting groundwater from 2007 to 2014 in the Greater Wattenberg Area (GWA) of the Denver-Julesburg Basin in northeastern Colorado (Fig. 1).

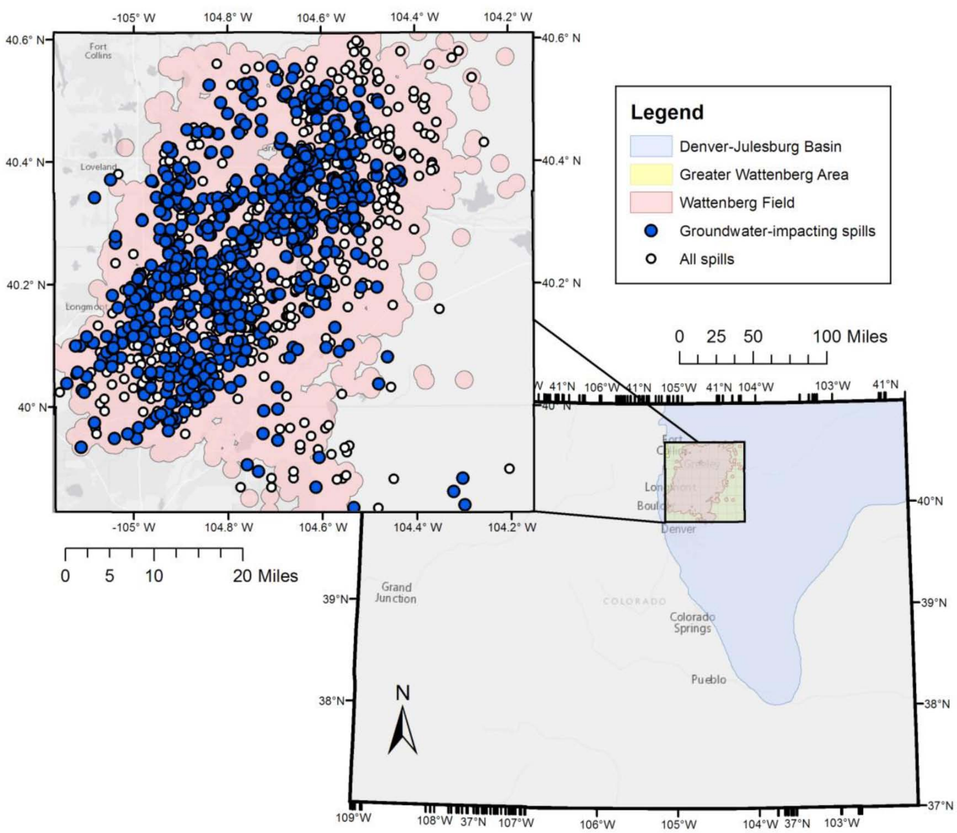


**Figure 1—Map of Colorado, the Denver-Julesburg Basin, the Greater Wattenberg Area, the Wattenberg Field, and spills reported in the Greater Wattenberg Area from 2007 to 2014.**

### Greater Wattenberg Area and the Colorado Oil and Gas Conservation Commission (COGCC)

The Denver-Julesburg Basin has a long history of oil and gas development. Hydraulic fracturing has been utilized since the 1950s to stimulate production from vertical wells in the Sussex, Codell and J Sand formations, and in 2010 horizontal drilling was expanded to target the Niobrara Formation (Sherwood et al. 2016).

For this study, we focused on the GWA, a geographical unit defined by the COGCC that encompasses the Wattenberg Field. Wells drilled in the GWA are subject to special well location, spacing, and baseline monitoring requirements under Rule 318A (COGCC 2016). We considered spills reported between 1 January 2007 and 31 December 2014 because this period brackets a sharp rise in production volumes in the GWA (Fig. 2a), which was the result of increased unconventional oil and gas extraction. Most of the oil and gas wells in the GWA were hydraulically fractured, and since 2009, most new production wells were drilled horizontally and completed with high-volume hydraulic fracturing (Fig. 2b).

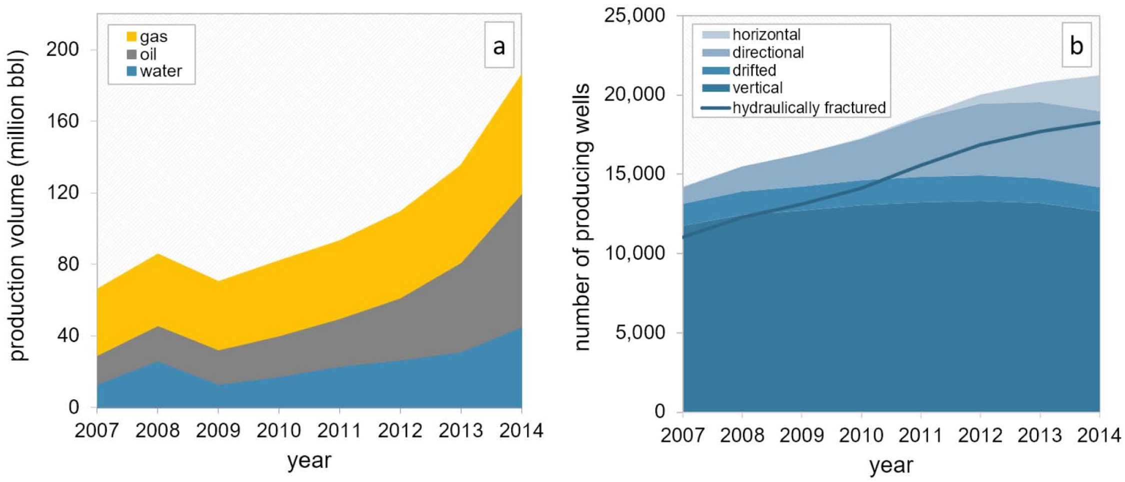


**Figure 2—(a) Annual production volumes volumes of oil, gas, and produced water in the Greater Wattenberg Area. Gas volumes were converted from thousand cubic feet (MCF) to barrels of oil equivalent (BOE) using a conversion factor (6,000 ft$^3$ = 1 BOE; Klett 2005); (b) Number of producing oil and gas wells in the Greater Wattenberg Area by wellbore direction (shaded areas) and number of hydraulically fractured oil and gas wells (line).**

The Colorado Oil and Gas Conservation Commission (COGCC) oversees operations in the GWA, including regulation of accidental spills and releases. The COGCC defines a release as "any unauthorized discharge of exploration and production waste to the environment" and further defines a spill as any unauthorized "sudden discharge" of waste (COGCC 2016). For simplicity, we refer to both spills and releases collectively as "spills." The COGCC's spill data are among the most detailed in the United States (Gross et al. 2013; Burden et al. 2015) and are available to the public in an online database.

COGCC regulations mandate that operators have 24 hours to verbally notify the COGCC of spills of any volume that "impact(s) or threaten(s) to impact any waters of the state, a residence or occupied structure, livestock or public byway." After conducting a preliminary site investigation and, in some cases, initial mitigation and remediation actions (e.g., excavation of soils, application of a carbon soil amendment), the operator is required to submit the Form 19 Spill/Release Report (referred to as "Form 19") to the COGCC (COGCC 2016). If the spill is found to have no impacts or the initial remediation action is shown to have mitigated any contamination, the COGCC considers the spill resolved. If the spill is found to cause "threatened or actual" adverse environmental impacts, including non-compliance with soil and water quality standards established by the COGCC, the operator may be required to submit a Form 27 "Site Investigation and Remediation Workplan" (referred to as "Form 27") at the discretion of the Director of the COGCC (COGCC 2016). At this point, the spill's Form 19 file is closed, the remediation project becomes the active file for the site, and any necessary remediation or monitoring activities are initiated or continued. Sites are sampled quarterly, and operators typically submit monitoring results annually to the COGCC. Following four consecutive quarters of compliance with the COGCC's soil and water quality standards, the operator submits a request for "no further action," and the Form 27 report is considered resolved. The COGCC's regulatory process for spills was relatively consistent throughout our study period, with one exception. Effective February 1, 2014, the reporting requirement was lowered from 5 barrels to 1 barrel for spills occurring *outside of berms of other secondary containment* (the 5 barrel threshold was maintained for spills entirely within secondary containment; COGCC 2016). Additionally, the Form 19 was updated in April 2014 to an electronic version, the "eForm 19," with slightly modified reporting requirements. The effects of these changes on our data collection methods and potential implications for our results are addressed in detail.

### Objectives

This work investigates the frequency and characteristics of spills affecting groundwater in the GWA for the period 2007–2014. Our objective was to quantify the occurrence rates of (1) all spills and (2) spills determined by the operator to have caused groundwater impacts. Additionally, for spills affecting groundwater, we analyzed characteristics including facilities and equipment involved, causes, and resolution times in order to identify recommendations for improved regulatory or operational practices.

## Methods

### Data Sources

Spill and remediation records (Form 19 and Form 27, respectively) from individual sites were compiled from the COGCC incident/inspection database using an automated extraction procedure. This bulk download is publicly available online via the AirWaterGas COGCC Database Query Tool (https://data.airwatergas.org/cogcc/query). After April 2014, spills were reported to the COGCC using the electronic Form 19 ("eForm 19") submitted via the COGCC website. Following the adoption of the eForm 19, complete spill data could no longer be retrieved by our extraction procedure because the format of reported data had changed. Therefore, spill data from April 2014 to December 2014 were acquired via a public bulk spill data download updated monthly by the COGCC.

### Spatial and Temporal Range

Spills reported within the Greater Wattenberg Area (GWA) from 1 January 2007 to 31 December 2014 were considered. The GWA is a geographical area defined by the COGCC to encompass the Wattenberg Field and includes townships 2 South to 7 North and ranges 61 West to 69 West (Fig. 1).

### Counting Spills

We determined the total number of annual spills in the GWA based on the incident dates assigned to spill records. We determined the number of annual groundwater-impacting spills in the GWA by performing a detailed screening of spill and remediation records. We flagged Form 19 and 27 records for review of potential groundwater impacts if the operator identified groundwater as an impacted medium and filled the accompanying field with the letter "Y" (positively indicating impact to groundwater) or left the field blank. For spills reported using the updated eForm 19, two checkboxes were reviewed: (1) if "groundwater" was checked under the list of impacted media in the "spill/release detail reports" section of the form, we flagged the spill for further review of potential groundwater impacts, and (2) if "groundwater" was left unchecked or a list of impacted media was not provided, but "waters of the state" was checked as "impacted or threatened" in the initial section of the form, we flagged the spill.

For the subset of spills that were flagged for further review, we verified groundwater impacts through a manual review of spill and remediation files and associated supporting documents in the COGCC database. Spill records were reviewed first. If the COGCC indicated that remediation activities were required for a spill, the spill record was linked with its corresponding remediation project (Form 27). If no remediation project number was readily available in the spill file, a manual search was performed in the database for remediation projects sharing spatial and facility information with the spill record in question. Spill records typically lacked a corresponding remediation record because initial remedial action (e.g., application of carbon-based amendment to groundwater in the base of an excavation) was sufficient for COGCC to consider the spill resolved. After reviewing spill records, any remediation records which could not be linked to a spill record were reviewed separately. Remediation records typically lacked a corresponding spill record because they were initiated by a complaint, inspection, facility closure, or Notice of Alleged Violation (NOAV; issued by the Director of the COGCC to seek penalties from operators accused of violating a COGCC rule; COGCC 2016).

We considered a spill to have impacted groundwater if the operator checked the groundwater impact box on the original Form 19 or the original Form 27, even if no corroborating evidence (e.g., a qualitative description of impacts, laboratory analytical report) was provided. Additionally, we considered a spill to have impacted groundwater if the operator left the groundwater impact box unchecked on either or both the original Form 19 and Form 27, but provided other evidence of impacts to groundwater (qualitative descriptions or laboratory analysis) in the spill or remediation files.

Spills were also screened for association with a historic flood generated by copious rainfall in September 2013 (Gochis et al. 2015). We removed flood-related spills from our annual spill count for 2013 because the flood-related spills were not representative of normal operating conditions in the GWA.

### Calculating Occurrence Rates

For each year, we compared (1) the number of spills overall and (2) the number of spills impacting groundwater to indicators of development in the GWA. We normalized the number of spills to annual production volumes of oil and water and to the number of producing wells in each year. These data were obtained from the COGCC.

### Characterizing Spills

Data concerning facilities and equipment, causes, and resolution times were collected from spill reports, remediation reports, and supporting documents in the course of verifying impacts to groundwater. These spill characteristics were considered only for spills determined to have impacted groundwater.

## Results

### Annual Spill Count

The number of overall spills and the number of groundwater-impacting spills are shown in Fig. 3.

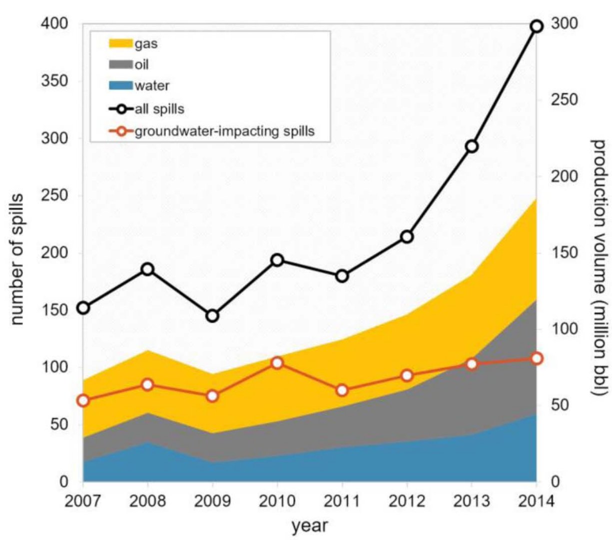


**Figure 3—Annual number of total spills ("all spills;" black symbols) and groundwater-impacting spills (red symbols) as well as annual production volumes of oil, gas, and produced water in the Greater Wattenberg Area of the Denver-Julesburg Basin in northeastern Colorado. Gas volumes were converted from thousand cubic feet (MCF) to barrels of oil equivalent (BOE) using a conversion factor (6,000 $ft^3$ = 1 BOE; Klett 2005).**

### Occurrence Rates

Annual spill counts were compared to volumes of oil (Fig. 4a) and water (Fig. 4b) produced in the GWA. Annual spill counts were also compared to the number of active producing wells in the GWA (Fig. 5).

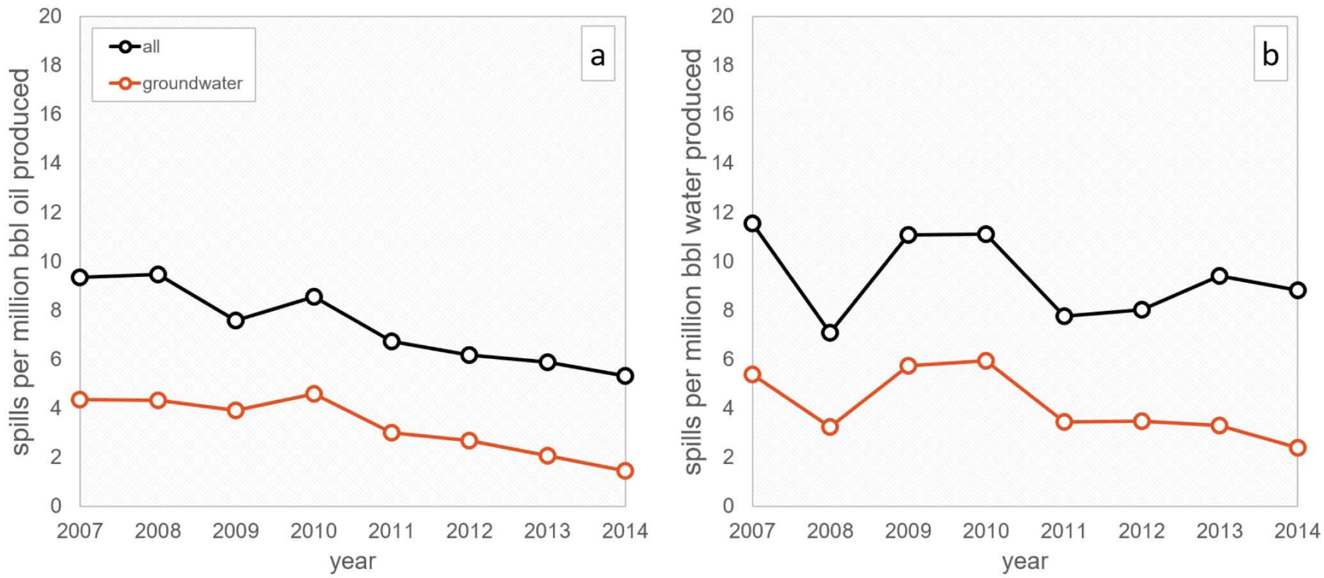


**Figure 4—Annual spill rates normalized to (a) the volume of oil produced and (b) the volume of produced water in the Greater Wattenberg Area. Rates of all spills ("all;" black symbols) and spills impacting groundwater ("groundwater;" red symbols) are indicated.**

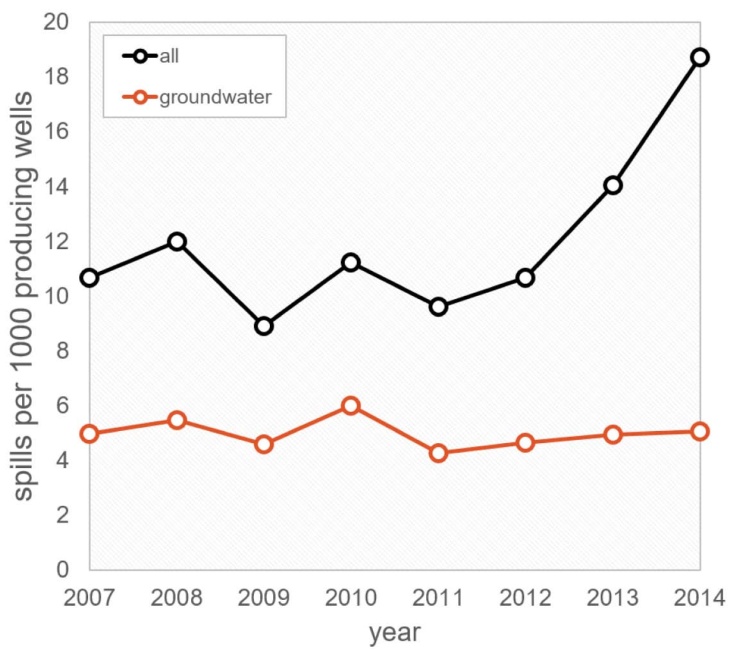


**Figure 5—Annual spill rates compared to number of producing wells in the Greater Wattenberg Area. Rates of all spills ("all;" black) and spills impacting groundwater ("groundwater;" red) are indicated.**

***Groundwater impacts.*** Approximately 30–50% of spills in the GWA from 2007 to 2014 resulted in impacts to groundwater determined from the manual review of spill and remediation records (Fig. 6).

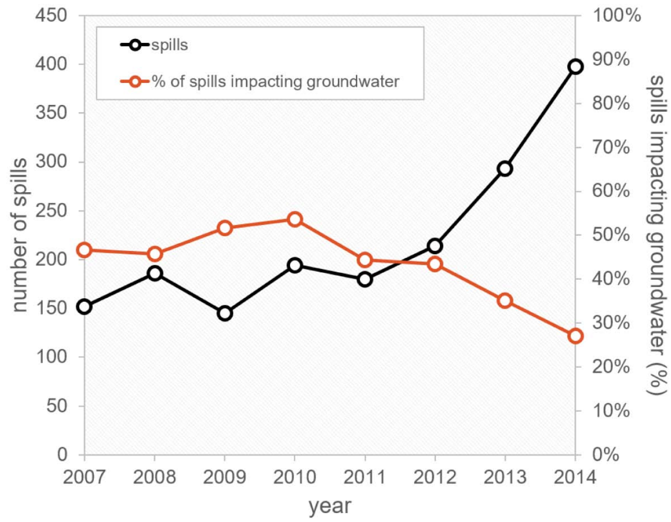


**Figure 6—Annual number of spills and fraction of spills impacting groundwater in the Greater Wattenberg Area.**

## Spill Characteristics

Spill characteristics were considered for spills that resulted in impacts to groundwater. The detailed review conducted to verify groundwater impacts facilitated the collection of these data. We did not consider temporal trends in spill characteristics, so results presented represent all groundwater-impacting spills reported from 2007 to 2014 (*n* = 729).

***Facilities and equipment.*** Tank batteries were identified most frequently as the facilities at which groundwater-impacting spills occurred (78% of groundwater-impacting spills; Fig. 7). For spills from tank batteries, "brine or produced water vessels" were the most common equipment involved (34% of spills from tank batteries), followed by "bypass/drain/dump line or other piping" (29% of spills from tank batteries).

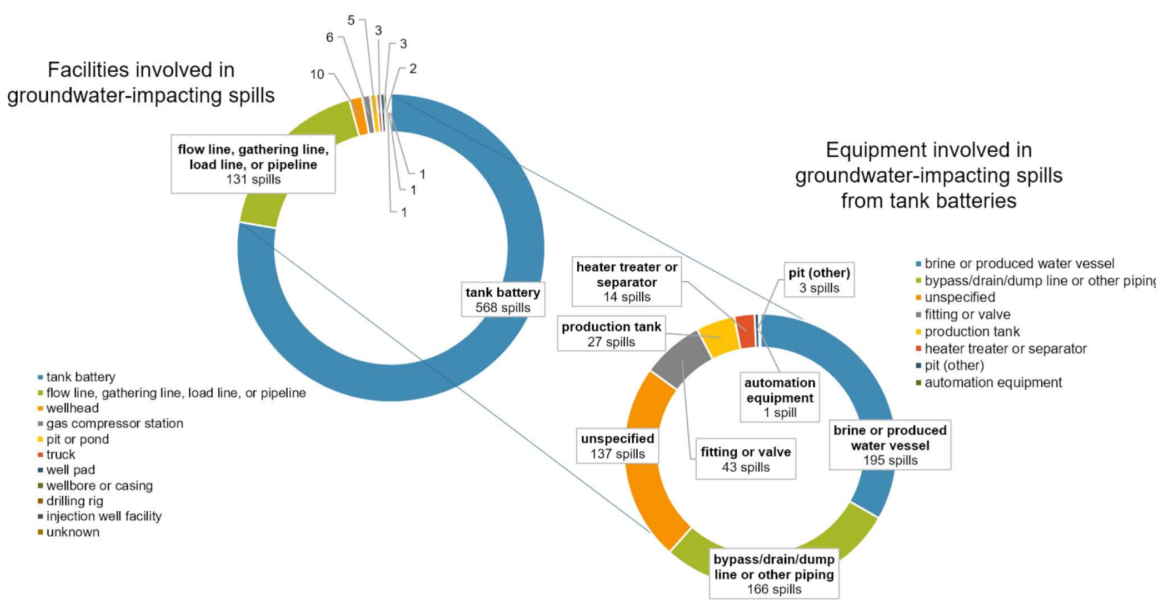


**Figure 7—Facilities and equipment involved in groundwater-impacting spills in the Greater Wattenberg Area. Equipment types are specific to tank batteries. The sum of spills for all facility types exceeds the 729 total groundwater-impacting spills observed because in some cases multiple facilities were involved in a single spill. Additionally, the sum of spills for all equipment types exceeds the 568 total groundwater-impacting spills from tank batteries because in some cases multiple pieces of equipment were involved in a single spill.**

***Causes.*** Non-historical equipment failure was the most-frequently identified cause of groundwater-impacting spills (49%), followed by historical spills (41%; Fig. 8).

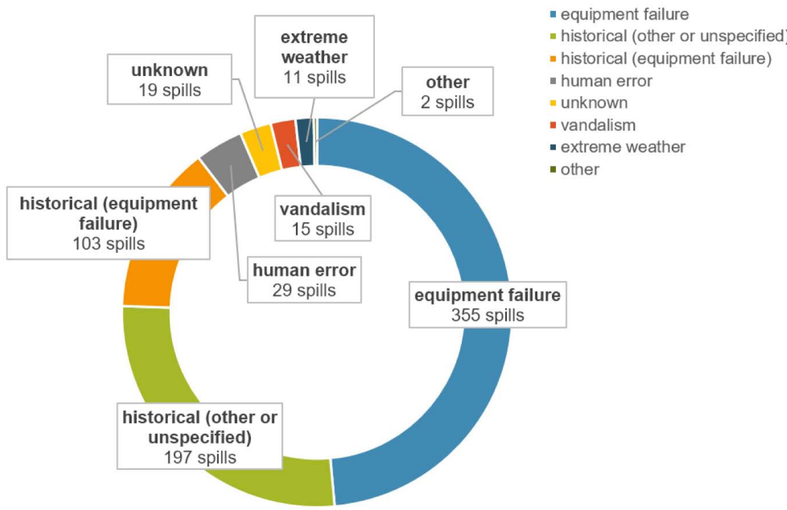


**Figure 8—Causes of groundwater-impacting spills in the Greater Wattenberg Area. The sum of spills for all causes exceeds the 729 total groundwater-impacting spills observed because in two cases multiple causes were identified for a single spill.**

***Resolution times.*** As of August 2016, up to approximately 90% of groundwater-impacting spills reported each year were identified as resolved (Fig. 9). For the spills that were resolved ($n$ = 519), the time required for resolution is shown for the most common facility types (Fig. 10).

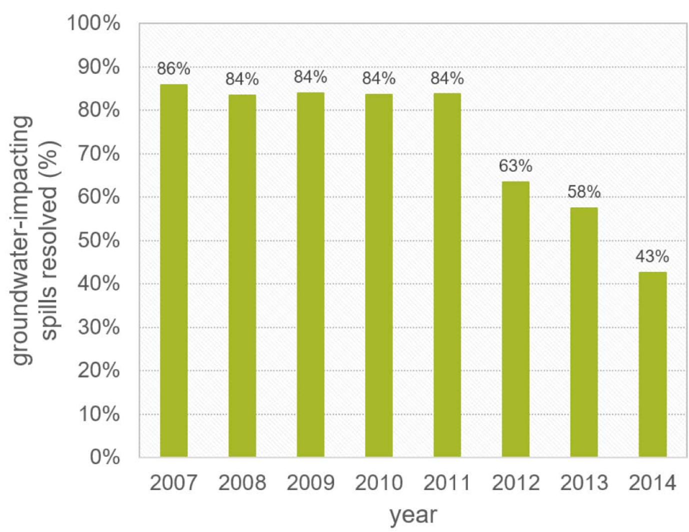


**Figure 9—Percentage of groundwater-impacting spills reported each year that have been resolved by the Colorado Oil and Gas Conservation Commission in the Greater Wattenberg Area from 2007 to 2014.**

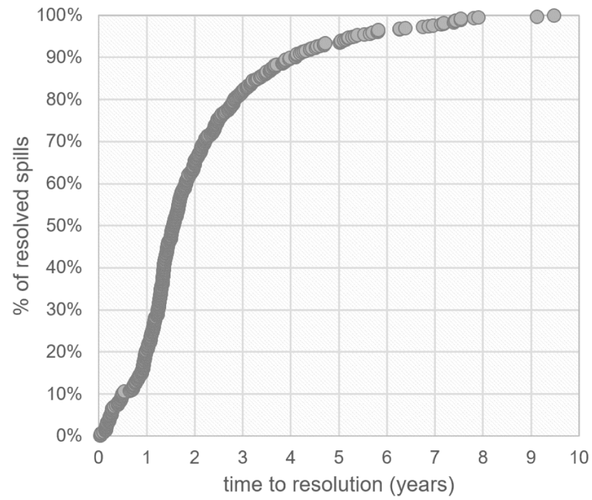


**Figure 10—Time to resolution for all groundwater-impacting spills in the Greater Wattenberg Area from 2007 to 2014.**

# Discussion

### Annual Spill Count and Production Activity

The annual spill count remained relatively stable from 2007 to 2011, but increased each year from 2011 to 2014 (Fig. 3). About twice as many spills were reported in 2014 as in 2011. The number of producing wells also increased from 2007 to 2014 (Fig. 2b), and the volumes of oil, gas, and water produced in the Greater Wattenberg Area (GWA) increased steadily from 2009 to 2014 (Fig. 2a). The volume of oil produced in 2014 roughly doubled from the volume produced in 2012 and quadrupled from the volume produced in 2009. The sharpest increase in the spill count occurred from 2013 to 2014, which corresponds to a sharp increase in production volumes during the same period. Some of this increase in the spill count may be attributable to the reduced volume threshold for spill reporting that took effect on February 1, 2014. The number of groundwater-impacting spills per year remained steady from 2007 to 2014.

### Occurrence Rates

Oil and water production volumes as well as the number of active producing wells were each investigated as indicators of overall activity in the GWA. When the number of spills was normalized to oil production volumes, we observed an overall decreasing trend in the total spill occurrence rate from 2007 to 2014 (Fig. 4a). When normalized to water production volumes, the total spill occurrence rate was relatively steady from 2007 to 2014, with some year-to-year variability observed (Fig. 4b). Thus, the total number of annual spills increased more *slowly* than the increase in oil production volumes and around the same rate as the increase in water production volumes over the period of rapid oil and gas developmentin the GWA. However, when compared to the number of producing wells, the total rate of spills was relatively steady until 2012, when it doubled from an average of approximately 10 spills per 1000 producing wells to approximately 20 (Fig. 5). Thus, the increase in total number of annual spills was *faster* than the increase in the number of producing wells. These trends suggest that fewer spills occurred for a greater volume of fluids produced and handled in the GWA, but that more spills may be occurring per active well. This result is consistent with greater volumes of oil and gas being produced using newer horizontal wells, compared with older vertical or deviated wells. Whether the occurrence rate of total spills became more or less frequent during the study period, then, depends on the normalization metric. We did not have access to the necessary data for an analysis of the operational phases during which spills occurred, but an investigation to this effect could assist in analyzing the relationship between overall activity and spill occurrence.

All three normalization metrics indicate that the occurrence rate of groundwater-impacting spills remained steady or decreased from 2007 to 2014. We also observed that the percentage of spills impacting groundwater compared to total spills decreased by a factor of two from 2010 (54%) to 2014 (27%; Fig. 6). Notably, the increase in production volumes associated with the expansion of unconventional development in the GWA starting in 2010 did not result in an increase in the occurrence rate of groundwater-impacting spills, regardless of the normalization metric used. A number of possible factors may affect the likelihood of groundwater impact, including spill volumes, material released, the quality of storage vessels, the effectiveness with which berms contain spills, the time between a spill's occurrence and its discovery, and the depth to groundwater. Further research is required to determine which of these factors, if any, resulted in a decrease in the frequency of groundwater-impacting spills in the GWA.

### Spill Characteristics

We identified several common characteristics for spills that impacted groundwater.

***Facilities and equipment.*** Tank batteries (including equipment like produced water vessels, production tanks, and process piping) and lines (including flow lines, gathering lines, load lines, and pipelines) were the facilities that experienced groundwater-impacting spills most frequently (Fig. 7). As a result, these two types of facilities may warrant more frequent or more detailed inspections than other facilities in order to reduce the likelihood of spills that can impact shallow groundwater.

***Causes.*** Equipment failure was the most frequently-cited cause of the spills that impact groundwater, followed by historical spills. For about one-third of historical spills, equipment failure was identified as the most likely cause (Fig. 8). A COGCC report similarly noted that equipment failure was the most frequent cause for all Colorado spills from January 2010 through August 2013, and that human error was the next most frequent spill cause, accounting for 23% of all spills (S.S. Papadapulos & Associates, Inc. 2013). We observed that human error accounted for only 4% of spills that impacted groundwater in the GWA in the study period, which may indicate that spills caused by human error are less likely to impact groundwater than other spills. The report to COGCC also identified about 18% of spills as historical, while our analysis indicated that about 41% of groundwater-impacting spills were historical. This suggests that historical spills are more likely to impact groundwater than non-historical spills, which highlights the importance of quickly identifying that a spill has occurred through inspections or monitoring.

***Resolution times.*** Of groundwater-impacting spills reported in 2014, 43% were reported to be resolved as of August 2016 (Fig. 9). Given that half of spills required more than 1.5 years for resolution, it is likely that insufficient time has passed for many of the 2014 spills to be resolved. However, for groundwater-impacting spills that were reported earlier in the study period (2007 to 2011), about 16% remained unresolved by the COGCC as of August 2016 (Fig. 9). Most of these spills remain unresolved because groundwater quality is not in compliance with the COGCC's Table 910-1 concentrations (COGCC 2016). We did not analyze the remediation strategies used to address all groundwater-impacting spills, but we observed that passive strategies (i.e., monitored natural attenuation) were prevalent among these unresolved spills. For the groundwater-impacting spills that were reported resolved as of August 2016, about 50% required less than 1.5 years for resolution, and about 90% were resolved in less than 4 years.

## Uncertainties and Challenges

### Reporting Details

During our manual verification process of groundwater-impacting spills and their supporting documents we experienced challenges in obtaining spill data because of inconsistent reporting practices. Reporting of groundwater impacts was one of the most common discrepancies between spill reports and their corresponding remediation reports. For about 11 spills per year, operators did not indicate on the Form 19 that groundwater was impacted, but later indicated on the Form 27 or in supporting documentation that groundwater was impacted. We also noted the reverse case, albeit infrequently: operators indicated on the

Form 27 or in supporting documentation that groundwater was not impacted, even though groundwater impacts were indicated on the Form 19. The need to review both spill and remediation records to capture the number of groundwater-impacting spills significantly increased the time required to review each spill.

The most significant data gap we observed was the absence of reported volumes. In the COGCC database, 54% of all spills had no volume reported. We could not determine a volume for 82% of groundwater-impacting spills, even after performing a manual review of supporting documents. Furthermore, we identified only 49% of groundwater-impacting spills with unknown volumes as historical spills, which suggests that the lack of volume data cannot be entirely attributed to a lack of ability to estimate the volume of historical spills.

**Factors Contributing to Groundwater Impacts**

In this study, we identified several characteristics that were common among spills that resulted in impacts to groundwater; however, we were unable to clearly determine why only some spills impacted groundwater. We hypothesized that spills with larger volumes were more likely to impact groundwater, but not enough data on spill volumes were available to perform a robust analysis. Our analyses were also limited by the fact that we only reviewed the characteristics of groundwater-impacting spills. Determining the detailed characteristics of all spills in our spatial and temporal range would have required a manual review of more than 1,000 additional spill records.

## Conclusions

While we observed varying temporal trends in the rate of total spills depending on the normalization metric used to describe overall activity in the Greater Wattenberg Area (GWA), we also observed that the rate of groundwater-impacting spills remained relatively stable in comparison to oil production volumes, produced water volumes, and the number of producing wells.

Based on our observations of spills in the GWA from 2007 to 2014, we suggest the following strategies for regulators and operators to improve the quality of reported spill data and to reduce the likelihood of surface spills that result in persistent impacts to shallow groundwater.

**Reporting**

The volumes of non-historical spills should be consistently reported because the lack of these data is a significant obstacle to a comprehensive analysis of spills. A similar recommendation was made to the COGCC in 2013 for development of the eForm 19 (S.S. Papadapulos & Associates, Inc. 2013). Reported data would also be improved by minimizing irregularities in the submission of spill reports (e.g., duplicate spill reports and reports describing multiple spills) and by identifying impacted media as early in the reporting process as possible. Finally, reporting the operational phase during which a spill occurred could improve understanding of spill occurrence rates and further inform strategies to reduce spill occurrence.

**Spill Prevention**

We recommend that operators consider performing monitoring or inspections of particular facility types and equipment at which groundwater-impacting spills appear to be more likely. For instance, fewer groundwater-impacting spills originated from pipelines compared to tank batteries in the GWA. Thus, piping produced liquids to centralized facilities which could be continuously monitored rather than storing them at individual well pads could potentially reduce the number of groundwater-impacting spills or lessen their impacts. While centralized facilities may require a substantial investment in new infrastructure which may not be practical or feasible for all operators, they could offer other benefits, like reduction in truck traffic related to transportation of produced liquids from tank batteries.

## Acknowledgements
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