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The potential for spills and leaks of contaminated liquids from shale gas developments

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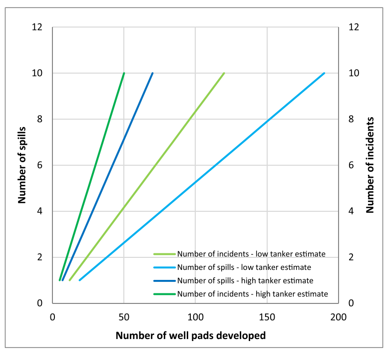
HIGHLIGHTS

- First article on the probability of spills associated with a UK shale gas industry
- Spills occur on the well pads and during fluid transportation to and from the site.
- A spill during transportation is predicted for every 19 well pads developed.
- A spill onsite is predicted for every 16 well pads developed.

GRAPHICAL ABSTRACT

The predicted number of incidents and spills that are likely to occur during the transportation of fracking related fluids from the development of a UK shale gas industry.



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ABSTRACT

Rapid growth of hydraulic fracturing for shale gas within the USA and the possibility of shale developments within Europe has created public concern about the risks of spills and leaks associated with the industry. Reports from the Texas Railroad Commission (1999 to 2015) and the Colorado Oil and Gas Commission (2009 to 2015) were used to examine spill rates from oil and gas well pads. Pollution incident records for England and road transport incident data for the UK were examined as an analogue for potential offsite spills associated with transport for a developing shale industry.

The Texas and Colorado spill data shows that the spill rate on the well pads has increased over the recorded time period. The most common spill cause was equipment failure. Within Colorado 33% of the spills recorded were found during well pad remediation and random site inspections. Based on data from the Texas Railroad Commission, a UK shale industry developing well pads with 10 lateral wells would likely experience a spill for every 16 well pads developed. The same well pad development scenario is estimated to require at least 2856 tanker movements over two years per well pad. Considering this tanker movement estimate with incident and spill frequency data from UK milk tankers, a UK shale industry would likely experience an incident on the road for every 12 well pads developed and a road spill for every 19 well pads developed. Consequently, should a UK shale industry be developed it is important that appropriate mitigation strategies are in place to minimise the risk of spills associated with well pad activities and fluid transportation movements.

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1. Introduction

Increased global demand for energy is driving a rapid increase in the use of hydraulic fracturing and horizontal drilling (Gross et al., 2013; Patterson et al., 2017). Hydraulic fracturing allows for enhanced oil and gas extraction from unconventional formations such as low-permeability shale and source rock (McLaughlin et al., 2016). The process involves high-volume fluid injection of fracturing fluid into a shale reservoir at a sufficient rate to raise downhole pressure above the fracture pressure of the formation rock, when the shale is pressurised fissures and interconnected fractures are formed enabling greater flow rates of gas into the well (Gregory et al., 2011; Wilson et al., 2017). Once the hydraulic fracturing processes are performed the pressure is relieved and the fracturing fluid returns to the surface through the borehole, the returning fluid is termed flowback fluid (Gregory et al., 2011).

Within the USA, fracturing fluids are typically composed of about 90% water, 9% proppant (e.g. sand), and 0.5–1% chemical additives (McLaughlin et al., 2016; Vidic et al., 2013). Additives are generally delivered to the well site in a concentrated form and stored until they are mixed with the base fluid and proppant and pumped down the production well (USA EPA, 2016). Within the USA additives are often stored in multiple, closed containers and moved around the site in specially designed hoses and tubing (USA EPA, 2016).

Flowback fluid is typically highly saline, reaching five times the salinity of sea water (Gregory et al., 2011). It can also contain high levels of dissolved and suspended solids, heavy metals, fracking chemicals, naturally occurring radioactive materials of varying concentrations and hydrocarbons extracted from the formation (Edminston et al., 2011). The volume of flowback that returns to the surface is variable, with between 10 and 50% of the fracturing fluid returning to the surface (Akob et al., 2015) during the 'flowback period' (the first two weeks after hydraulically fracturing the rock) (Howarth et al., 2011). During the active gas production stage, aqueous and non-aqueous liquid continue to be produced in considerably lower volumes than the fracking and flowback fluids over the lifetime of the well (known as produced water - Gregory et al., 2011). Typically within the USA, flowback water and produced water flow from the well to onsite tanks or pits through a series of pipes or flowlines before being transported offsite via trucks or pipelines for disposal or reuse (USA EPA, 2016). Therefore, for the development and exploitation of shale gas resources there would be three types of potentially polluting liquids to consider: the fracking fluid; the flowback water; and the produced water. In addition undiluted chemical additives also need to be considered.

In the USA it is common for the majority of these potentially hazardous fluids (fracking fluid, flowback and production waters - Drollette et al., 2015; DiGiulio et al., 2011) to be transported considerable distances by truck on public roads to and from the drilling sites, this can lead to incidents and spillages on the road (Eshleman and Elmore, 2013). In addition to the risks associated with transport, as with other outdoor practises, well pad sites (the area required for the borehole, drilling equipment, piping and storage) are exposed to extreme weather and environmental conditions (e.g. heavy rainstorms, severe windstorms, floods and freezing conditions) which can also lead to spills and leaks of potentially hazardous fluids on the well site (Eshleman and Elmore, 2013). Even with appropriately designed storage equipment for additives, blended hydraulic fracturing fluids, flowback fluids and produced water, spills could occur.

Currently there is no shale gas production within Europe, however exploration wells are underway and the public have expressed many concerns regarding the potential for water contamination. Included in the perceived risk to water is the potential for polluting spills and leaks to contaminate land, surface water and groundwater, which if severe may lead to polluted fluid being exposed to humans and natural ecosystems (Eshleman and Elmore, 2013; Vengosh et al., 2014). Based on our review there have been no studies published in the peer-reviewed scientific literature addressing the potential for spills and leaks, either onsite or offsite, from possible hydraulic fracturing sites within Europe.

Within the USA a number of studies have considered the risk to the surface and subsurface environment from spills and leaks. Gross et al. (2013) examined the Colorado Oil and Gas Commission's database of incidents and found surface spills were associated with <0.5% of the active wells. Drollette et al. (2015) found that groundwater near the Marcellus shale gas operations in north eastern Pennsylvania had been contaminated by diesel-range organic compounds via accidental release of fracturing fluid chemicals, derived from the hydraulic fracturing activities at the surface. DiGiulio et al. (2011) found leakages from storage and disposal pits were responsible for the high concentrations of benzene, xylenes, gasoline range organics, diesel range organics and total purgeable hydrocarbons found in shallow ground water around the Pavillion field in Wyoming. The USA Environmental Protection Agency (EPA) assessed data from nine state agencies, nine oil and gas production well operators, nine hydraulic fracturing service companies and determined 457 hydraulic fracturing-related spills occurred between January 2006 and April 2012 (USA EPA, 2015). More recently Patterson et al. (2017) considered spills from unconventional oil and gas wells, in Colorado, New Mexico, North Dakota and Pennsylvania from 2005 to 2014, recording that between 2 and 16% of wells reported a spill each year.

These reviews of spills and leaks have only considered onsite incidents, not those occurring offsite. The average multi-stage well in the USA requires hundreds to more than a thousand round trips to transport equipment, chemicals, sand and water required for well development and hydraulic fracturing (Adgate et al., 2014; Muehlenbachs and Krupnick, 2013). Muehlenbachs and Krupnick (2013) found a significant increase in the total number of accidents and accidents involving heavy trucks in counties with a relatively large degree of shale gas development, compared to those counties with less (or no) development: they found one additional well drilled per month raised the frequency of an accident by approximately 2% and increased the risk of a fatality by 0.6%. The Texas Department of Transportation also noted that the influx of traffic from the development of the Permian Basin had generated an increase in the number of road traffic accidents: a 27% increase in roadway fatalities, trucks were involved in 7% of these reported crashes (Texas Department of Transportation, 2013). These studies did not consider the potential for spills and leaks from these offsite incidents.

With the possibility of a shale gas industry emerging within the UK Goodman et al. (2016) determined the number of truck visits required over the lifetime of a single-well pad with six-wells, and from this, the impact upon local air quality, greenhouse gas emissions and noise emissions. However the number of incidents and spillages were not considered. Lacey and Cole (2003) used information from UK databases on vehicular flow of tankers, accident rate and the probability that an accident would result in a spill; from this they predicted the expected number of spills per year. Their analysis predict the likelihood of a spill which exceeds 150 kg of chemical load spilling on a 2 km section of road is once in 370 years, with a range of 75 to 1800 years.

Thus, the aim of this study was to assess the probability of surface spills and leaks of undiluted additives, fracturing fluid, flowback water and produced water, assessing the probability of spills occurring both onsite (on the well pad) and offsite (during fluid transportation). Secondly we have assessed volumes spilt and the underlying cause of spills in analogue developments to help generate mitigation strategies for potential future sites in the UK.

2. Approach and methodology

A leak is a way for fluid to escape a container or fluid-containing system. The word leak usually refers to a gradual loss; whilst a sudden loss is usually called a spill. For simplicity this study refers to any accidental and undesired escape of fluid as a spill. Additionally we have not distinguished between the different types of fluids spilt (e.g. flowback water, fracking fluid, produced waters), we are aware that the toxicity of the type of fluid spilt and therefore the impact of the spill can vary considerably, for example spilling a highly saline flowback water is very different to spilling produced waters contaminated with BTEX or crude oil. However, within this study we have focused on the probability of an incident occurring rather than the consequence.

Without a shale gas industry currently operating within Europe information has been drawn from both onsite and offsite experiences in the USA and analogues from within the UK. Due to differences in the source and occurrence of the spills this study has analysed onsite and offsite incidents separately. Two USA state data sources were considered: the Texas Railroad Commission (Texas RRC – RRC, 2017a) and the Colorado Oil and Gas Commission (COGCC - COGCC, 2017a, 2017b). The recorded spills have been evaluated to assess the type, volume and reasons for the currently occurring spills. From this spill analysis the probability of spills onsite for potential shale gas developments within Europe has been assessed. In England, spills from oil and gas sites are reported to the Environment Agency (EA) and recorded in the pollution incident database. This was analysed to access the number of incidents that have occurred on conventional well pads within England.

Without a fully developed shale industry within the UK, fracking fluid, produced water and flowback fluid will be transport to and from the site via tanker trucks. It is currently believed the new development at the Preston New Road site in Lancashire will require produced and flowback fluid to be transported over 80 km by truck to the Davyhulme wastewater treatment works in Manchester. With increased transportation from Preston New Road to Davyhulme there is an increased chance of an incident or spill offsite. With a lack of information in Europe and the USA for incidents offsite, UK milk and fuel (petrol and diesel) tanker incidents were analysed as an analogue to determine the probability of an incident related to hydraulic fracturing occurring on the road for different shale gas development scenarios. These vehicle types have been identified within the records and were considered a good analogue for the transport required within a UK shale industry, as they often operate on rural roads carrying liquid that is a pollutant with respect to surface waters. Recorded tanker incidents have been cross-correlated with the pollution incident database for England to determine their environmental impact.

2.1. Onsite

2.1.1. Texas Railroad Commission (Texas RRC) database

The Texas RRC enforces the delineation and reporting of any spill of 0.8 m^3 or more within the state of Texas (RRC, 2017b). The dataset includes surface spills of crude oil, gas well liquid[1], products[2] and combined[3] (RRC, 2017a). This data is publically available and documents the number of spills, volume spilt, spill type, facility type the loss was from and the cause for all spills from 2009 to 2016. The data indicates the gross loss per spill, the amount of spill recovered and the net loss. The data were evaluated for each year individually and then compiled to assess trends within the whole dataset. The statistical significance of trends was assessed using a *t*-test and in all cases significance was judged at a probability of not being zero of 95%. The Texas RRC also records the number of wells active per year and the volumes of crude oil produced; from these the percentage of produced crude oil spilt was calculated. From the average number of spills per year and the average number of active wells per year, the average number of spills per well has also been calculated.

2.1.2. Colorado Oil and Gas Commission (COGCC) database

The COGCC require operators to fully report: (1) spills of any size that impact or threaten to impact waters of the state (streams, lakes, ponds, drainage ditches), structures, livestock, public byways; (2) spills >0.2 m^3 that released exploration and production (E&P), or produced water outside of the berm or other secondary containment; (3) spill of 0.8 m^3 or more, regardless of whether the spill was contained within the berms or other secondary containments (COGCC, 2015). The COGCC has two spill databases, due to considerable changes in processing and data collection these databases are not comparable and have been analysed separately, these two datasets are henceforward referred to as: “1999–2015 spill data”; and “2014–2015 spill data” (COGCC, 2017a, 2017b). Both datasets included data for 2016; however, data were only available for the first two quarters of 2016, as the dataset for 2016 was incomplete it was not included in this study. The “2014–2015 spill dataset” provides the following information on each spill; timing, location, type and volume, facility type (where breach occurred) and the impact on land and surrounding environment. Conversely the “1999–2015 spill dataset” is less comprehensive, only consisting of the number of active wells, the annual volume of oil and water spilt and produced and the percentage of the produced oil and water spilt. From the “1999–2015 spill data” we have assessed the changes and patterns in oil and water spill numbers and volumes over the 17 years recorded. Using the number of active wells per year and the “1999–2015 spill data” the average number of spills per well has been calculated.

2.1.3. Pollution incident database

The Environment Agency records the pollution incidents in England and classifies them according to their impact on the population, the environment and level of response required (EA, 2017). Each incident is recorded by date and location and is categorised on pollution type and impact. The pollution impact category system is 1 (major) to 4 (no impact). The pollution incident database for England contains 12,335 incidents recorded between March 2001 and December 2016 (EA, 2017).

To determine the number and cause of incidents related to well integrity failure within England, Davies et al. (2014) analysed the pollution incident database. Davies et al. (2014) only reported incidents which could be confirmed as being due to well integrity failure, whereas as this study considered all incidents reported, from any well pad. Identification and analysis of the cause of releases in currently operating industries allows for lessons to be learnt and mitigation strategies to be put in place avoiding repeating these incidents.

2.1.4. Onsite industrial development scenarios

The UK's Institute of Directors (IoD) have suggested several shale gas development scenarios for the UK, the first is based on the development of a 10-well pad of 10 laterals (one well pad with 10 wells each with one lateral) (Taylor et al., 2013). The second involved the development of a 10-well pad of 40 laterals (one well pad with 10 well each with four laterals) (Taylor et al., 2013). These two scenarios have been used along with the calculated number of spills per well (based on data from the Texas RRC, the COGCC and the pollution incident database) to determine the likely number of spills that would occur on a single site, and how many sites would be developed before we would likely experience a spill. As it is unlikely only one site would be developed these results highlight the accumulative risk of a number of well sites.

2.2. Offsite

2.2.1. Milk tankers

Without a shale gas industry currently operating within Europe, this study has used an analogue of UK milk tanker journeys to predict the

[1] Condensate or other hydrocarbons produced from a gas well.

[2] Derived from petroleum hydrocarbons, for example, crude oil, processed crude petroleum, residue from crude petroleum, fuel oil, natural gas gasoline, gas oil, waste oil, blended gasoline, lubricating oil, blends or mixtures of petroleum, and/or any and all liquid products or by-products derived from crude petroleum oil or gas, whether hereinabove enumerated or not.

[3] Combination of crude, condensate, and/or other produced water.

probability of spills during the transportation of fracking fluid, produced water and flowback water to and from the well site. Within this study milk tankers are defined as vessels used to transport large quantities (approximately 30 m^3) of milk. This study does not include references to milk floats, vans or lorries. Assuming an average milk tanker size of 30 m^3, some 366,667 milk tanker journeys are required to transport the 11 million m^3 of milk produced by British farmers each year (Taylor et al., 2013). A search for local media reports involving milk tanker incidents in the UK between 1998 and 2016 was carried out. The data collection involved searching for all online media articles that mentioned "milk", "tanker", "accident", "incident", "road", "crashes", "overturned", "UK" and "spillage". There was no discrimination on the type of report or article, authorship or publisher used. Incidents due to engine fires were not recorded. The number of milk tanker incidents that were reported was recorded; those that resulted in a spillage of milk or flammable liquid (e.g. diesel) were logged; as were the volumes spilt if documented and cause of incident. If the incident resulted in injuries or fatalities these were noted.

Where possible incidents reported in the media were matched to those recorded in the pollution incident database, and the type and scale of the pollution caused by the spill incidents assessed. As this database only includes incidents from England, only these have been matched.

2.2.2. Fuel tankers

The UK road fuel (petrol and diesel) tanker fleet is estimated to be around 1000–1500 vehicles, these are estimated to travel some 220,000 km each year (Robinson et al., 2014). The size and volume capacity of fuel tanker trucks varies considerably. Commonly large tanker trucks with capacities of 21–44 m^3 are used to transport petrol and diesel to filling stations (Madigan, 2017). Fuel tankers have been studied, as similarly to milk tankers they are a good analogue for the truck movements that would be associated with a UK shale industry. Unlike milk tankers the average number of journeys required each year to transport the nations fuel is undocumented in the literature. Therefore, the number of fuel tanker journeys has been determined from the known volume of motor fuel consumed by the UK, recorded by the Department for Business, Energy and Industrial Strategy (BEIS, 2017) and the average tanker size used. This estimate was then used to determine the probability of an incident or spill per year.

The Transport Research Laboratory (TRL) compiled data on all tanker accidents by carrying out a search of local BBC news reports involving tanker incidents which occurred in the UK between 2009 and 2014 (Robinson et al., 2014). Their data collection involved searching for all media articles that mentioned "tanker" and "accident" on the BBC news website. These were then assessed on whether a spill occurred; a flammable liquid was spilt; an injury resulted; the incident was caused by a collision or the tanker overturned; and if the tanker overturning led to a spillage (Robinson et al., 2014). This study continued the search for 2015 and 2016 in the same manner to the method used by TRL. In a similar manner to milk tankers a broader search was then conducted just for fuel tankers between 2009 and 2016, using the same search terms to check for milk tanker accidents, with the addition of "milk" being substituted for "fuel", "petrol" and "diesel". As with milk tankers, where possible, spill incidents related to fuel tankers were matched to incidents recorded in the pollution incident database.

2.2.3. Offsite industrial development scenarios

The development scenarios proposed by Taylor et al. (2013), along with the annual number of incidents and spills per milk and fuel tanker on the road for 2016 have been used to calculate the potential number of incidents and spills related to a future UK shale industry. Data for 2016 was used to generate the following scenarios as this was deemed the most accurate, being the most up to date.

Taylor et al. (2013) first scenario, based on the development of a single 10-well pad of 10 laterals, would potentially produce 0.9 km^3 of gas, requiring 136,000 m^3 of water per well. Initially it is likely that the water will be trucked to the site rather than piped, thus requiring between 2856 and 7890 tankers over a 20 year period (Taylor et al., 2013). If tanker movement was concentrated in the early years of drilling activity, which is most likely, this would average out at 3.9–10.8 tanker movements per day over two years, or if spread over 20 years decreasing to 0.4–1.1 per day (Taylor et al., 2013). The second scenario, based on a single 10-well pad of 40 laterals, potentially producing 3.6 km^3 of gas and using 544,000 m^3 of water per pad equates to between 11,155 and 31,288 tanker movements over 20 years, or 1.5–4.2 tanker movements per day (Taylor et al., 2013): when averaged out over five years this equals 6.1–17.1 truck movements per day (Taylor et al., 2013). As it is unlikely that just one well pad would be developed the probability of an incident or spill occurring from a number of well pads was estimated.

3. Results

The analysis of the results has been split into incidents that occurred onsite and incidents that occur offsite, during transportation.

3.1. Onsite

3.1.1. Texas Railroad Commission

The number of reported spills between 2009 and 2015 has increased each year with 675 reported in 2009 and 1485 in 2015 (Table 1). Over the same period the number of producing wells has also increased from 157,807 in 2009 to 193,807 in 2015. The number of spills per producing well increased at an average rate of 0.0006 spills/yr^2, the *t*-test showed that the increase in spill rate is significant at 95% probability. Of the 7820 spills recorded during the study period the majority (83%) involved the loss of crude oil (Table 1). The most common cause of leakage was due to equipment failure; the second was due to corrosion (rust) of equipment, followed by 'Acts of God' and human error. The most common location for a spill to occur was around the tank battery (70% of the spills), followed by the flow line (10%) and pipe line (8%).

The number of crude oil spills has increased year on year since 2009, with 549 crude oil spills reported in 2009 and 1270 in 2015. The average number of crude oil spills per year was 924. The number of crude oil spills per producing well increased at a rate of 0.0001 spills/yr^2 - significant at the 95% probability (Table 1). The total annual volume of crude oil spilt varied from 6713 m^3 (2009) to 14,158 m^3 (2015) (Table 1). The average rate of change over this seven year period was 805 m^3/yr^2 which is statistically significant at the 95% probability. Clean-up operations recover some of the lost fluid, however much is left unrecovered. Annually between 50 and 76% of the crude oil spilt is recovered, with an annual average of 59% (Table 1). The largest spill was recorded in 2010 with 3975 m^3 of crude oil escaping in one incident; however, 99.7% of this was recovered (Table 1). The largest reported net loss of crude oil for a single spill was 1069 m^3 (Table 1).

Between 2009 and 2015, 715 producing wells reported gas well liquid spills. The number of spills involving gas well liquid decreased over the time period analysed, this trend was not statistically significant (Table 1). The total annual volume of gas well liquid spilt ranged from 489 m^3 in 2015 to 2438 m^3 in 2013 (Table 1). The annual average percentage of gas well liquid recovered was 30% of the amount spilt.

The number of spills involving product varied year on year, from five spills in 2015 to 95 in 2013 (Table 1). Although there has been an increase in the number of wells and spills per year the trend was not statistically significant. The annual percentage recovery rates show that 65% of the product is recovered after a spill (Table 1). The annual average minimum and maximum recovery ranged from 16% in 2012 to 94% in 2010 (Table 1).

For the loss of combined liquids there has been a statistically significant trend over the period of record: in 2009 three cases were recorded,

Table 1
The annual number of active wells, and associated gross loss, fluid recovered, net loss and percentage recovered for crude oil, gas well liquids or associated products. Data recorded by the Texas Railroad Commission (RRC, 2017a, 2017c).

Year	Number of producing wells	Number of spills	Number of spills by type				Combined				Crude				Gas well liquid				Products			
			Combined	Crude	Gas well liquid	Products	Gross loss (m^3)	Recovered (m^3)	Net loss (m^3)	% Recovered	Gross loss (m^3)	Recovered (m^3)	Net loss (m^3)	% Recovered	Gross loss (m^3)	Recovered (m^3)	Net loss (m^3)	% Recovered	Gross loss (m^3)	Recovered (m^3)	Net loss (m^3)	% Recovered
2009	157,807	675	3	549	91	32	20	10	10	52	6713	3418	3296	51	1049	384	665	37	1120	920	200	82
2010	158,451	796	5	630	123	38	351	320	31	91	12,414	9449	2964	76	1522	617	905	41	3074	2878	197	94
2011	161,402	869	8	724	101	36	101	20	81	20	9698	4863	4835	50	1158	409	749	35	956	460	496	48
2012	167,864	1236	19	1028	128	61	252	170	82	68	12,015	6934	5081	58	1883	497	1387	26	6463	1062	5401	16
2013	179,797	1354	29	1105	125	95	418	268	151	64	12,548	7289	5259	58	2438	581	1857	24	3376	2153	1223	64
2014	190,331	1405	122	1160	91	32	2850	1208	1642	42	11,099	6118	4981	55	761	143	618	19	2044	1531	513	75
2015	193,807	1485	154	1270	56	5	4441	2750	1691	62	14,156	8759	5397	62	489	133	356	27	34	26	8	77
Total	1,209,459	7820	340	6466	715	299	8433	4746	3686		78,643	46,830	31,813		9300	2764	6536		17,068	9030	8038	

whilst in 2015 154 cases were recorded (Table 1). The annual average minimum and maximum recovery ranges from 20% in 2011 to 91% in 2010 (Table 1).

3.1.2. Colorado Oil and Gas Commission

The 1999–2015 spill data does not distinguish between whether it was oil or water being spilt. It records a total of 6617 spills, the maximum and minimum numbers of spills per year were 789 in 2014 and 193 in 2002 (Table 2). The average number of spills per year was 389. Between 1999 and 2015 there has been an increase in the number of active producing wells and the number of spills at a rate of 0.00017 spills/yr^2, however, this increase is not statistically significant. A total of 0.11 km^3 of oil and 0.88 km^3 of water were produced between 1999 and 2015. Of this 8670 m^3 of oil and 81,200 m^3 of water were spilt, equivalent to 0.008% and 0.009% of the oil and water produced (Table 2). For this dataset there is no information on recovery rate or reasons for the spills.

Of the 2009–2015 spill data, only years 2014 and 2015 are complete, therefore only those years have been studied. Of the 2893 spills recorded during this period; 563 were oil, 401 condensate, 50 flowback water, 1399 produced water, 78 E&P waste and 129 drilling fluid (Table 3). The volume spilt varies considerably; 188 spills were recorded between >0 and <0.2 m^3, 1201 were between ≥0.2 m^3 and <0.8 m^3, 1051 were between ≥0.8 m^3 and <16 m^3 and 180 were ≥16 m^3 (Table 3). The average length and width of a spill was 33 m and 10 m, whilst the maximum was 1416 m and 152 m. The average depth to groundwater in the spill locality was 28 m and the average depth the spill impacted was 2.5 m, with a maximum depth impact of 22 m. Just over 73% (2112) of spills had ≥0.16 m^3 of fluid leak outside the berm of the well pad, with three sites requiring an emergency pit to be constructed. The average volume of soil that needed to be excavated due to pollution from a spill was 220 m^3, with a maximum of 10,780 m^3 being removed from one site. Polluted soil was excavated offsite from 471 sites; 62 sites treated the soil onsite, whilst 74 sites had the soil disposed of by alternative methods. The average volume of groundwater removed was 42 m^3, with 484 m^3 being the maximum quantity removed from one site. At two sites 1 m^3 and 6 m^3 of surface water was removed. Of the spills documented; 1107 impacted soil, 260 groundwater, 16 surface water and 30 dry drainage features.

Of the spills 1946 were termed 'recent', thus recent or ongoing at the time of discovery. Whereas 947 were termed 'historical', therefore the spill occurred at a time unknown or was discovered during activities such as plugging and abandonment or site reclamation. Of the spills 653 were reportedly due to equipment failure, 254 human errors, 186 were historical and 46 were recorded as "other". Examples of "other" include weather, vandalism and external sources of interference such as cattle. In 2014, one instance involved cattle rubbing against the valve handle of the wellhead partially opening the valve allowing produced water to spill out. In 2015, there was a report of wild horses pushing open a 2.5 cm valve, this was determined by tracks and faeces left in the area. The most common location facility type from which spills originated from was the tank battery, with 36% of spills initiating there, whereas 6% of the spills were associated with pipelines.

3.1.3. Pollution incident database

Based on data provided by DECC, Davies et al. (2014) comments that there were 143 onshore oil and gas wells producing at the start of the year 2000. Between 2000 and 2013 the Environment Agency recorded nine pollution incidents involving the release of crude oil within 1 km of an oil and gas well. Two of the spills were recorded at the Singleton Oil Field and were caused by borehole cement failure. The other seven pollution incidents were due to leaks from pipework linked to the well (Davies et al., 2014). Between 2000 and 2013 the pollution incident rate was 0.0045 incidents/well/yr.

Table 2
The annual number of active wells, number of spills and volumes of oil and water produced and spilt for Colorado. Data recorded by the Colorado Oil and Gas Commission (COGCC, 2017a).

Year	Number of active wells	Number of spills	Oil spilled (m^3)	Water spilled (m^3)	Oil produced (m^3)	% Produced oil spilled	Water produced (m^3)	% Produced water spilled	Average oil spilled (m^3) per incident	Average water spilled (m^3) per incident	Average oil produced (m^3) per incident	Average water produced (m^3) per incident	% Of active wells that spilled
1999	21,745	263	363	6576	3,131,683	0.01	36,590,207	0.02	1	25	11,908	139,126	1.21
2000	22,228	254	569	3584	3,183,339	0.02	40,227,601	0.01	2	14	12,533	158,376	1.14
2001	22,879	206	308	1682	3,208,682	0.01	42,335,137	0.00	1	8	15,576	205,510	0.90
2002	23,711	193	509	9196	3,270,789	0.02	45,013,104	0.02	3	48	16,947	233,229	0.81
2003	25,042	213	465	3105	3,434,841	0.01	48,137,113	0.01	2	15	16,126	225,996	0.85
2004	26,968	222	637	5898	3,588,455	0.02	46,985,899	0.01	3	27	16,164	211,648	0.82
2005	28,952	326	797	3917	3,692,872	0.02	55,177,628	0.01	2	12	11,328	169,257	1.13
2006	31,096	336	414	5317	3,894,915	0.01	63,313,559	0.01	1	16	11,592	188,433	1.08
2007	33,815	376	648	4308	4,163,614	0.02	62,628,307	0.01	2	11	11,073	166,565	1.11
2008	39,944	408	508	11,441	4,759,933	0.01	58,431,321	0.02	1	28	11,667	143,214	1.02
2009	37,311	368	443	3532	4,827,681	0.01	57,129,268	0.01	1	10	13,119	155,243	0.99
2010	41,010	499	521	5349	5,243,162	0.01	57,559,586	0.01	1	11	10,507	115,350	1.22
2011	43,354	501	522	5374	6,271,776	0.01	54,762,143	0.01	1	11	12,519	109,306	1.16
2012	46,835	407	716	2334	7,869,668	0.01	52,857,376	0.00	2	6	19,336	129,871	0.87
2013	50,067	633	627	2281	10,397,330	0.01	52,203,721	0.00	1	4	16,425	82,470	1.26
2014	51,737	789	388	2847	15,230,669	0.00	53,356,073	0.01	0	4	19,304	67,625	1.53
2015	53,054	623	233	4468	20,038,113	0.00	52,190,327	0.01	0	7	32,164	83,773	1.17
Total	599,748	6617	8670	81,208	106,207,523	0.01	878,898,369	0.01					1.10
Average		389	510	4777	6,247,501		51,699,904						
Maximum		789	797	11,441	20,038,113		63,313,559						
Minimum		193	233	1682	3,131,683		36,590,207						

3.2. Application

Using data from the Texas RRC and values from the first scenario (based upon well pads with 10 laterals) the probability of a spill occurring on a developed site in the UK was calculated at 0.06 spills/well pad; therefore there would likely be a spill onsite for every 16 well pads developed (Fig. 1). When the COGCC 1999–2015 spill data and values from the first scenario are used the likelihood of a spill is 0.11 spills/well pad; therefore a spill would likely occur for every 10 well pads developed (Fig. 1).

Using data from the Texas RRC and values from the second scenario (based upon well pads with 10-wells, each with four laterals) the likelihood of a spill onsite was 0.26 spills/well pad; therefore it is likely that a spill would occur for every four well pads developed (Fig. 1). Using the COGCC 1999–2015 spill data and values from the second scenario the likelihood of a spill is 0.44 spills/single-well pad, therefore there would likely be a spill for every three well pads developed (Fig. 1).

Using data from the Environment Agency's pollution incident database the results for the first scenario showed that the likelihood of a spill onsite was 0.045 incidents/single-well pad; therefore a spill would likely occur for every 23 well pads developed. Using data from the pollution incident database and values from the second scenario the likelihood of a spill onsite was 0.18 incidents/well pad; therefore there would likely be a spill for every six well pads developed.

3.3. Offsite

3.3.1. Milk tankers

Between 1998 and 2016 122 milk tanker incidents were recorded, 54 of these were reported to have spills associated with them. The last four years studied saw the highest number of annual incidents, between 1998 and 2016 the number of incidents per year increased at a rate of 0.6 incidents/yr^2. The rate of change over this 19 year period was statistically significant at the 95% probability. The greatest number of milk spills recorded in a year was six, in 2016. The number of spills per year has increased at a rate of 0.5 spills/yr^2 - statistically significant at the 95% probability. Of the spills 89% consisted of milk and 24% flammable liquid, and where mentioned it was diesel, implying that the accident had been severe enough to rupture a fuel tank. The largest spill involved 20 m^3 of milk escaping from the tanker. However many media reports have not recorded the quantity of milk spilt, nor were the volumes of flammable liquid spilt commented on. Of the incidents assessed 61% were caused by a collision, this was most commonly milk tankers with other cars, but also with central reservations, hedges, houses and in one incident a bridge. Tankers rolled over in 43% of the reported cases, often due to a collision but also due to tankers jack knifing, tankers breaking away from the drivers cab and drivers losing control. One of the spills was caused by a faulty valve. Injuries were reported in 58% of incidents, 16% of these resulted in death.

Table 3
The type of fluid and volume of fluid spilt for 2014 and 2015 in the State of Colorado. Data from Colorado Oil and Gas Commission (COGCC, 2017b).

Volume spilt (m^3)	Number of oil spills	Number of condensate spills	Number of flowback water spills	Number of produced water spills	Number of E&P waste spills	Number of drilling fluid spills	Total number of spills
0	2083	2125	2801	912	2778	2094	
>0 and <0.2	98	41	0	43	1	5	188
≥0.2 and <0.8	265	259	15	607	24	31	1201
≥0.8 and <15.9	191	90	30	606	46	88	1051
≥15.9	9	11	5	143	7	5	180
unknown	247	367	42	582	37	670	1945
Total number of spills	563	401	50	1399	78	129	

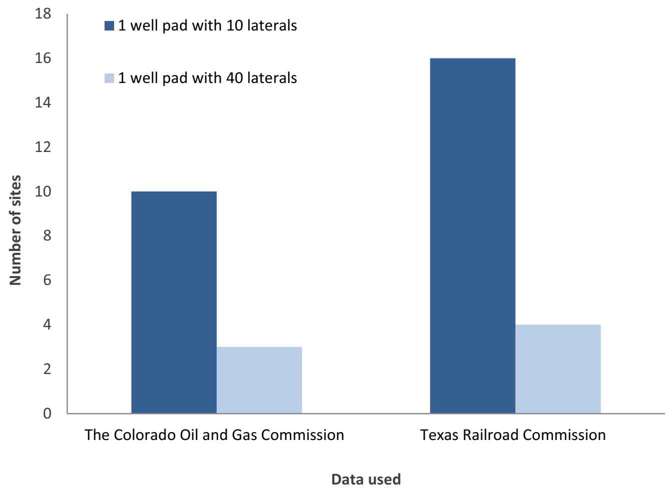

Fig. 1. The number of sites that need to be developed before a spill is likely to occur onsite, based on data from the Texas RRC and COGCC. Scenario 1 (dark blue bars): Single-well pad with 10-wells, each well is a lateral; Scenario 2 (light blue bars): Single-well pad with 10-wells, each well has four laterals. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Six milk tanker incidents reported in media reports correlated with an incident in the pollution incident database, i.e. 48 milk spills were not found to be recorded in the pollution incident database. Air pollution was recorded in two of the incidences; the impacts of these events were reported as being minor and "significant" (note that the term significant is as used within the database and implies no statistical significance as is the case in the rest of this study). Two incidents were reported as causing land pollution; one was considered as having minor impact and the other 'significant'. All the incidents were recorded as polluting a water system; two were determined minor and four as "significant". Pollutant type has been determined for each incident, three spills were categorised as oils and fuel, the other three were recorded as; organic chemicals or product, general biodegradable material and wastes, and specific waste materials, i.e. each of these could be a description of a milk tanker incident.

3.3.2. Fuel tankers

From the review of the local BBC media reports TRL identified 59 incidents involving a variety of vehicles (both rigid and articulated) and loads (foodstuff, chemicals and fuels) between 2009 and 2014 (Robinson et al., 2014). Of those recorded 42% were found to be spillage incidents, with 80% of those cases involving flammable liquids (Robinson et al., 2014). A tanker overturned in 37% of the media reported incidents (Robinson et al., 2014). Of these 64% were then reported to have spilled their load. When this study continued the search for 2015 no additional media stories were recorded, however, when the media search was conducted using the broader approach, as used for identifying milk tanker incidents, the reported fuel tanker incident numbers for 2015 and 2016 were 14 and 17 respectively. Of these 36% and 53% resulted in a fuel spillage. The largest known spill volume was 8 m^3 in 2016, however this could be far higher as many of the media reports did not record the volume spilt. When assessing the media reports between 2009 and 2016 with the broader search terms, 61 incidents were recorded, of these 44% had associated spills. The incident rate increased annually by 1.7 incidents/yr^2, whilst the spill rate increased annually by 0.96 spills/yr^2, these rates were statistically significant at the 95% probability. Of the incidents reported 51% involved an injury, whereas 23% were associated with a fatality. All incidents were caused by some sort of collision, with 28% of the incidents resulting in the tanker overturning. There was no correlation between the fuel tanker incidents recorded in the media and the pollution incident database.

3.4. Application

3.4.1. Milk tankers

The results for the first scenario (based on well pads with 10-wells, each with one lateral) with the lower tanker movement estimate (2856 tankers) concentrated over the first two years of drilling resulted in the probable number of incidents and subsequent spills being between 0.043 and 0.118 incidents/year and 0.027 and –0.075 spills/year. When spread over 20 years the probable number of incidents was between 0.004 and 0.012 incidents/year, with the predicted number of spills being between 0.003 and 0.008 spills/year. The accumulative risk of an incident or spill over the lifetime of a well (in this case 20 years as assumed in Taylor et al., 2013) for this scenario was between 0.086 and 0.237 incidents/lifetime of the well pad and 0.055–0.151 spills/lifetime of the well pad. Based on the milk tanker data and the lower tanker movement estimate spread over two years, there would likely be one incident on the road for every 12 well pads developed and a spill for every 19 well pads developed (Fig. 2). This is equivalent to one 30 m^3 tanker truck spilling part of its load out of the 54,264 required to transport the 1,628,000 m^3 of fluid needed for 19 well sites.

The likely annual number of incidents and spills for the second scenario (based upon well pads with 10-wells per pad, each with four laterals) if the lower tanker estimate (11,155 tankers) movements were concentrated over five years would be between 0.067 and –0.118 incidents/year, and 0.043 and –0.119 spills/year. When truck movements are spread over 20 years the probability of an incident or spill was between 0.017 and –0.047 incidents/year and 0.011 and –0.03 spills/year. The accumulative risk of an incident or spill over the lifetime of a well for this scenario would be between 0.304 and –0.853 incidents/lifetime of the well pad and 0.183 and –0.512 spills/lifetime of the well pad. Based on the milk tanker data and the lower tanker movement estimate spread over five years, there would likely be an incident on the road for every three well pads developed and a spill for every five well pads developed (Fig. 2). This is equivalent to one tanker truck out of the 55,775 required for five wells sites spilling part load.

3.4.2. Fuel tankers

For 2016 the recorded volume of motor spirit (gasoline/petrol) and Derv (road diesel) used were 11,951 KT and 24,648 KT (BEIS, 2017): or 15,800,000 m^3 of gasoline, 29,200,000 m^3 of diesel and a total of 45,000,000 m^3 of hydrocarbon road fuels. A large tanker generally used for fuel transportation has a capacity of between 21 and 44 m^3, we have averaged this value for our study. Therefore, with an average fuel tanker capacity of 32.5 m^3, 1,384,415 fuel tanker journeys would be required annually.

The results for the first scenario (based on a well pad with 10-wells, each with one lateral) with tanker movement concentrated over the first two years of drilling resulted in the probable number of incidents and subsequent spills being between 0.018 and –0.048 incidents/year and 0.009 and –0.026 spills/year. When tanker movement is spread over 20 years the probable annual number of incidents and spills was between 0.002 and –0.005 incidents/year and 0.001 and –0.003 spills/year. The accumulated risk of an incident or spill over the lifetime of a well would be between 0.035 and –0.097 incidents/lifetime of the well pad and 0.019 and –0.051 spills/lifetime of the well pad, therefore there would likely be an incident on the road for every 29 well pads developed and a spill for every 55 well pads developed (Fig. 3).

The likely annual number of incidents and spills for the second scenario (a single-well pad with 10-wells, each with four laterals) if tanker movement was concentrated over five years would be between 0.027 and –0.077 incidents/year, and 0.015 and –0.041 spills/year. When tanker movement was spread over 20 years the probability of an incident and spill was between 0.007 and–0.019 incidents/year and 0.004 and –0.010 spills/year. The accumulated risk of an incident or spill over the lifetime of a well for this scenario would be between

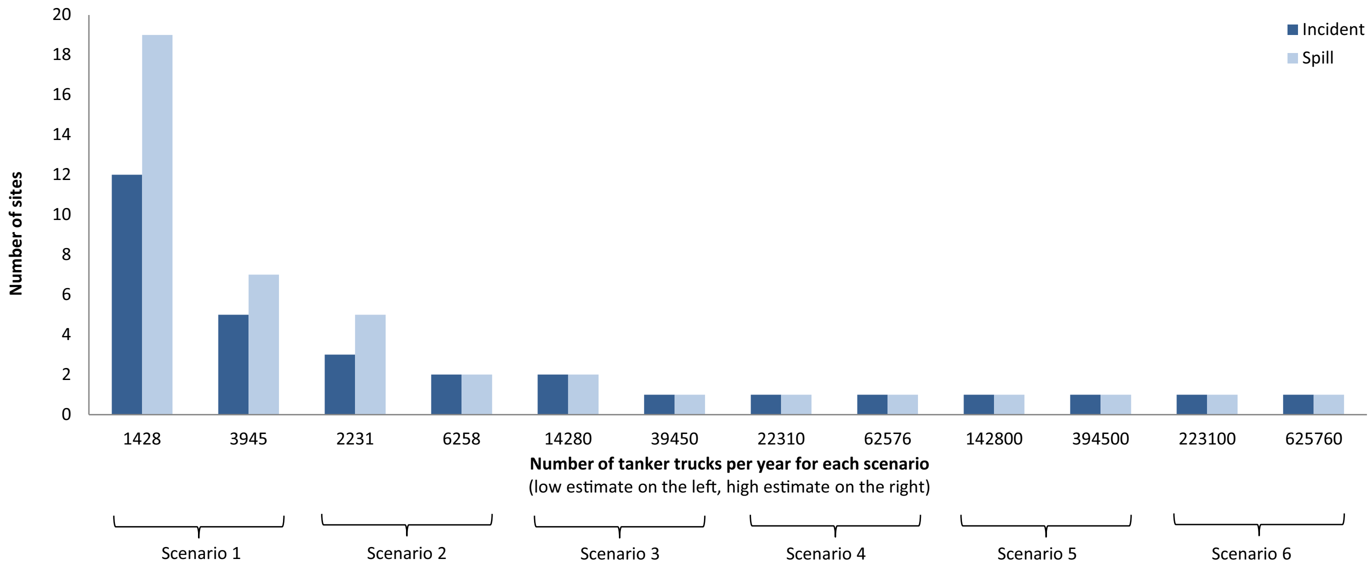

Fig. 2. The number of sites that need to be developed before an incident or spill is likely to occur based on the milk tankers data and minimum and maximum tanker numbers from the IoD report. Scenario 1: Single-well pad with 10-wells with 10 laterals developed over two years; Scenario 2: Single-well pad with 10-wells with 40 laterals developed over five years. Scenario 3: 10 well pads with 10-wells with 10 laterals developed over two years; Scenario 4: 10 well pads with 10-wells with 40 laterals developed over five years. Scenario 5: One hundred well pads with 10-wells with 10 laterals developed over two years; Scenario 6: One hundred well pads with 10-wells with 40 laterals developed over five years.

0.137 and –0.384 incidents/lifetime of the well pad and 0.073 and – 0.203 spills/lifetime of the well pad. Based on the fuel tanker data and the lower tanker movement estimate spread over five years, an incident on the road would likely occur for every seven well pads developed and a spill would likely occur for every 13 well pads developed (Fig. 3).

4. Discussion

It is unrealistic to assume that all the spills within Texas and Colorado were reported, further back in time incidents may have been left unreported due to a lack of regulation, more recently incidents may have been left unreported due to lack of regulation compliance, or spills may have occurred undetected, therefore there could be bias in the results. Despite the limiting factors mentioned these values enable us to attempt to determine the annual spill rates onsite within these states. The analysis of the Texas RRC dataset from between 2009 and 2015 and the COGCC dataset from 1999 to 2015 highlight that there has been an increase in the annual rate of crude oil spills. The increased spill rate for the Texas RRC was statistically significant at 95% probability. The increase could be due to tighter and stricter enforcement on reporting of spills, or due to companies being more honest and reporting a higher number of spill incidents. Alternatively, companies are not learning from experience and are getting worse at managing site equipment (for example there is a mismatch between equipment lifetime and maintenance) leading to an increase in spill numbers.

The USA EPA (2015) determined 457 hydraulic fracturing-related spills occurred in 11 different states between January 2006 and April 2012, with spills of flowback water being the most common spill type reported. Among the spills for which the cause was reported, the most common was human error (33%) and equipment failure (27%) (USA EPA, 2015). The most common cause of a spill within both Texas and Colorado in this study was equipment failure, which like the USA EPA

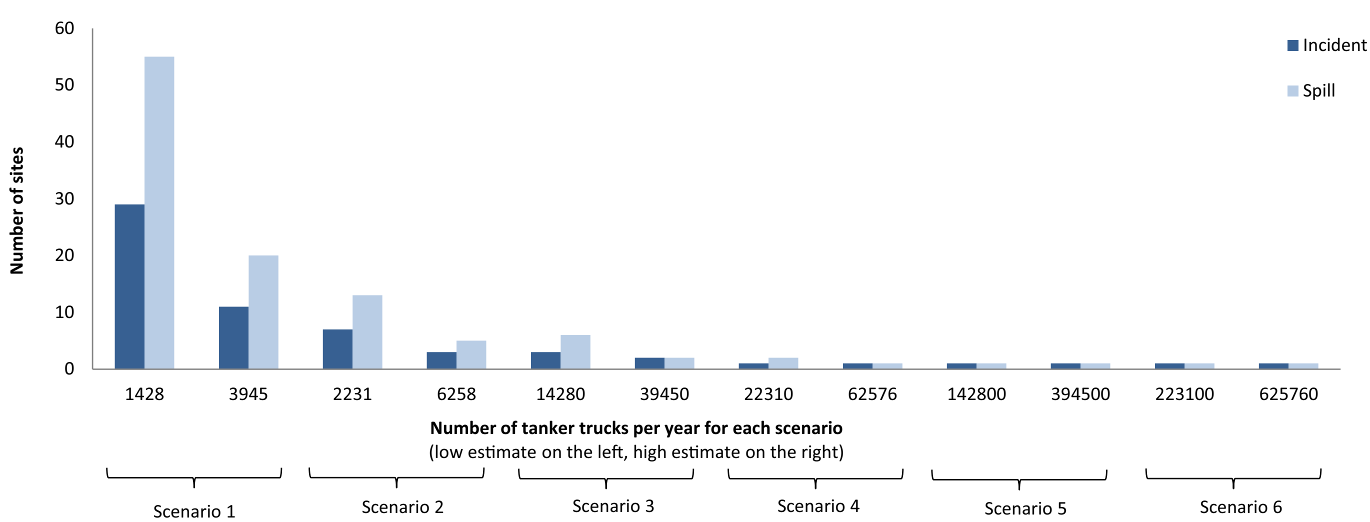

Fig. 3. The number of sites that need to be developed before an incident or spill is likely to occur based on the petrol tankers data and minimum and maximum tanker numbers from the IoD report. Scenario 1: Single-well pad with 10 wells with 10 laterals developed over two years; Scenario 2: Single-well pad with 10 wells with 40 laterals developed over five years. Scenario 3: 10 well pads with 10 wells with 10 laterals developed over two years; Scenario 4: 10 well pads with 10 wells with 40 laterals developed over five years. Scenario 5: One hundred well pads with 10 wells with 10 laterals developed over two years; Scenario 6: One hundred well pads with 10 wells with 40 laterals developed over five years.

report, indicates the need for improvements in maintenance and equipment checks onsite. Although the Texas RRC results highlight that clean-up operations recover between 5 and 76% of the crude oil spill, prevention is vital, releases into the environment pose a considerable risk to the surrounding ecosystems.

Within Patterson et al. (2017) 50% of the spills were related to storage and moving fluids via flowlines. The USA EPA study records the most common source of a spill within the 11 states assessed was from storage units (USA EPA, 2015). Within this study the results differ from the literature, with the most common location for a spill within both states being from the tank battery, with 70% of the spills in Texas being associated with tanker batteries, compared with 8% of spills being associated with pipelines.

Patterson et al. (2017) studied the states of Colorado, New Mexico, North Dakota and Pennsylvania, and found the median spill volume ranged from 0.5 m^3 in Pennsylvania to 4.9 m^3 in New Mexico; whilst the largest spills exceeded 100 m^3. Of the 457 hydraulic fracturing-related spills reported by USA EPA, 88 were of fracturing fluid, with the median spill volume being 3.1 m^3 (USA EPA, 2015). In addition there were 225 spills involving flowback and produced water, these had a median spill volume of ~3.4 m^3. Of the 2893 spills recorded in the "2009–2015 spill data" from the COGCC records, the majority were of low volumes, between ≥0.2 and <0.8 m^3. However, spills often reached considerable sizes (180 reached ≥16 m^3) and therefore impacted extensive areas. One reported spill reached a depth of 22 m. In many cases spills have led to large quantities of soil and groundwater being removed. Within the literature there are also reports of spills reaching groundwater, indicating that these incidences are not as rare as one would hope (USA EPA, 2015). EPA also reported that 7% of the hydraulic fracturing-related spills in their study reached a surface water body (often streams or creeks); the median volume per spill was ~13 m^3, with volumes per spill ranging from ~0.3 m^3 (5th percentile) to ~170 m^3 (95th percentile) (USA EPA, 2015). Within this study over 70% of the spills involved leaks outside the berm, with emergency pits often being required to prevent serious pollution incidents. The issue with regard to spills is therefore twofold. It is apparent that spills occur due to equipment failure, also the lack of spill management practise allows for the spill to continue and pollute greater areas. Given so many spills leak outside the berm highlights that well pad infrastructure is not fit for purpose, it needs to be reassessed with more appropriate infrastructure put in place. More stringent onsite spill management practises would hopefully prevent spills occurring and causing considerable, avoidable damage.

It is unrealistic to assume that all incidents involving milk and fuel tankers on UK roads were identified from the approach used in this study. Media reports were mainly produced for milk and fuel tanker incidents which were notable for a particular reason. For example: the tanker shed its load during the incident, particularly if large quantities were spilled or the load posed a threat to the public; the accident caused roads to be closed and caused severe congestion or delays; the accident had a high severity, including fatalities or injuries. The further back one searches for events, the fewer are found. Therefore the results from the media articles are likely to be low estimates of the actual number of tanker related incidents in a year. Despite the limiting factors mentioned these values enable us to attempt to determine the likely annual number of tanker incidents and spills. Using the milk tanker results as an analogue and different development scenarios given by the IoD report, our analysis shows that when (2856–7890) tanker movements for a single 10-well pad with 10 laterals is concentrated over two years the likely annual number of spills is less than one. However, the production of the low permeability shale formations decreases rapidly over the first few years of drilling; it is thought by up to 85% during the first three years (Vengosh et al., 2014). Therefore, shale gas wells are required to be drilled at high rates to overcome the rapid decline in production. If hydraulic fracturing was to go forward in the UK this would potentially mean tens to hundreds of well pads with hundreds to thousands of laterals being drilled over several years. It is worth noting that the number of well sites that could be located within the UK would be limited by the carrying capacity of the surface, thus the presence of existing infrastructure and the setbacks each well requires. Clancy et al. (2018) study found that the average carrying capacity for a well pad measuring 10,800 m^2 (average conventional UK well pad size), with a setback of 152 m and a lateral of 500 m was 26%. Therefore 26 well pads could be located on average per licence block, with a range of between 5 and 42 (Clancy et al., 2018). Our calculations show that the number of spills increases to 2–6 when 100 well sites with 10-wells per pad with one lateral each is developed.

The majority of the reported traffic incidents were caused by collisions, most commonly milk tankers with cars. Research suggests that drivers who drive for business purposes are at an above average risk of accident involvement relative to the general driving population (Clarke et al., 2005). Generally heavy goods vehicles such as milk tankers are 7.5 times more likely to present an accident risk to other road user per kilometre (Copsey et al., 2010). Different explanations are put forward in the literature to explain the higher number of accidents involving commercial road transport, it is important to understand these so appropriate mitigation strategies can be developed. Several suggested explanations why heavy goods vehicle drivers are at a higher risk are, they undertake longer journeys, often drive late at night or during the early hours when fatigue and drowsiness is more likely to occur (Copsey et al., 2010; RoSPA, 2001). Truck drivers are often driving under time pressure and are more likely to carry out distracting tasks whilst driving, such as making phone calls, eating and drinking (Copsey et al., 2010; Broughton et al., 2003). Milk tankers are also required to carry heavy loads down small country tracks which are often unfit for purpose and sometimes made worse by bad weather conditions or heavy traffic. To minimise the likelihood of an incident occurring there are a number of mitigations strategies that could be put in place, these include regular vehicle inspections and maintenance of vehicles, specialised training and instructions for drivers, selecting appropriate route and planning trips according to weather and road conditions. It is also important for the employer to avoid tight schedules for drivers and to make sure a sufficient number of rest stops are planned.

The study has focused on estimating the number of spills from potential shale gas developments but not the consequences of these spills. The consequence of surface spills associated with hydraulic fracturing is a complex issue and one that is difficult to measure as there have been few incidents documented in the peer-reviewed scientific literature. Papoulias and Velasco (2013) record a leak of fracking chemical into a 2 km stretch of Acorn Fork Creek in Kentucky (USA) in May and June 2007. The incident led to the streams pH dropping to 5.6, the conductivity increasing to 35,000 μS/cm, aquatic invertebrates and fish dying and those that were not killed being left in distress (Papoulias and Velasco, 2013). Fish examination from the polluted stretch of the river by the USA Geological Survey showed that of the 45 fish examined all had severe gill lesions, consistent with exposure to low pH and toxic concentrations of heavy metals (Papoulias and Velasco, 2013). Bamberger and Oswald (2012) documented several experiences farmers have had with regards to shale gas operations leading to environmental concerns. One example involved a release of fracturing fluid due to a worker shutting down a chemical blender during the fracturing process (Bamberger and Oswald, 2012). The fluids released flowed into an adjacent cow pasture which was then reported to have led to the death of 17 cows within one hour (Bamberger and Oswald, 2012). Another reported example was caused by a defective value on a hydraulic fracturing fluid tank, the fault led to hundreds of litres of hydraulic fracturing fluid leaking onto a goat pasture (Bamberger and Oswald, 2012). The goats exposed to the fluid were later reported to have issues reproducing over the following two years (Bamberger and Oswald, 2012). However, it should be noted that the studies of Papoulias and Velasco (2013) and Bamberger and Oswald (2012) had no control to know what might have happened had no spill occurred, or if another fluid type had been spilt. Furthermore, it should be noted that these examples are not unique to a shale gas industry.

In Europe, hydraulic fracturing is still in the exploratory stage; however, a report in the German Tax De newspaper reported a leak which occurred in 2007 (Kummetz, 2011). The report claimed that a waste water pipe leaked at a tight gas field in Söhlingen, Germany, causing groundwater contamination with benzene and mercury (Kummetz, 2011). Similarly, on the 24th July 2002, 19 m^3 of milk was spilt into a stream flowing into Rudyard Lake near Leek in Staffordshire, this incident correlates with an 'organic chemicals/products' spillage in the pollution incident database. The impact of the incident were classified as follows; air pollution category 2 ('significant'); land pollution category 4 (no impact); water pollution category 3 (minor). A BBC news report commented that 50,000 fish were in danger if the milk entered the reservoir after a milk tanker crashed into a bridge (BBC news, 2002).

Given the highlighted risks of spills from shale gas operations, mitigation methods are a necessity. Procedures need to be in place to identify, evaluate and mitigate potential risks associated with the transportation, handling, storage and disposal of hydraulic fracturing related fluids. Patterson et al. (2017) comments that enhanced and standardised regulatory requirements for reporting spills could improve the accuracy and speed of analyses to identify and prevent spill risks and mitigate potential environmental damage. Additionally, baseline, site and monitoring after plugging and abandonment are essential. Initial baseline monitoring at the site and in the surrounding area allows for comparisons to be made to the original environment so deviations from the norm can be recognised. Systematic equipment checks and regular site monitoring should allow for any equipment failures to be acknowledged and dealt with rapidly, thus avoiding future spills. Long term monitoring after plugging and abandonment allows for equipment failures to be recognised so any issues that do arise can be dealt with appropriately. It is important that those responsible for the above monitoring are confirmed and adequate monetary provisions are made prior to drilling so all concerned are aware of who is responsible for the long term maintenance of the wells. Transparent and consistently measured data sharing allows for insights to be gained into when and where spills are most likely to occur, and the underlying causes. Better understanding of these factors would provide regulatory bodies and industry makers with important information on where to target efforts for locating and preventing future spills (Patterson et al., 2017). All equipment should be fit for purpose and investments must be made into sourcing the most up to date and appropriate technologies. Well sites and equipment should also be appropriately designed for adverse weather conditions, including severe flooding. On large-scale development projects pipeline construction should be considered instead of trucking the fluid required for hydraulic fracturing, although it is worth noting that pipelines can also leak and spillages are often difficult to identify. Within the UK a common practise carried out by water treatment works is site contained drainage, the site is lined with an impermeable membrane and any fluid discharged is directed towards carefully located drains and collected in tanks underground. The fluids collected can therefore be appropriately dealt with. This practise should be introduced at all sites within Europe to contain any spill that do occur.

5. Conclusion

Results from Colorado and Texas show that spill rate is increasing, and within Texas this increase is statistically significant. Based on data from Texas RRC, a UK shale industry consisting of well pads with 10 laterals would likely experience a spill for every 16 well pads developed. When 40 laterals are developed on a single well pad, a spill would likely occur for every four well pads developed. The datasets these values are based upon specify the leading cause of a spill is equipment failure, followed by human error. With 33% of the spills recorded in Colorado being found during site remediation and random site inspections it is important that regular site inspections are performed by an appropriately trained work force and where possible constant onsite monitoring is carried out.

Based on the milk tanker data and tanker movement estimates of 2856 tankers over two years, a well pad of 10 laterals would likely experience an incident for every 12 well pads developed and a spill for every 19 well pads developed. Consequently, should a shale industry go forward within the UK, or anywhere else in Europe, it is important that appropriate mitigation strategies are in place to minimise the risk of spills associated with well pad activities and fluid transportation movements.

Acknowledgements

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2018.01.177.

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