Project Acronym and Title:

M4ShaleGas - Measuring, monitoring, mitigating and managing the environmental impact of shale gas

REVIEW OF SPILLS AND LEAKS FROM NORMAL SHALE GAS OPERATIONS

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Public introduction
M4ShaleGas stands for *Measuring, monitoring, mitigating and managing the environmental impact of shale gas* and is funded by the *European Union's Horizon 2020 Research and Innovation Programme*. The main goal of the M4ShaleGas project is to study and evaluate potential risks and impacts of shale gas exploration and exploitation. The focus lies on four main areas of potential impact: the subsurface, the surface, the atmosphere, and social impacts. The European Commission's Energy Roadmap 2050 identifies gas as a critical fuel for the transformation of the energy system in the direction of lower CO_2 emissions and more renewable energy. Shale gas may contribute to this transformation. Shale gas is – by definition – a natural gas found trapped in shale, a fine grained sedimentary rock composed of mud. There are several concerns related to shale gas exploration and production, many of them being associated with hydraulic fracturing operations that are performed to stimulate gas flow in the shales. Potential risks and concerns include for example the fate of chemical compounds in the used hydraulic fracturing and drilling fluids and their potential impact on shallow ground water. The fracturing process may also induce small magnitude earthquakes. There is also an ongoing debate on greenhouse gas emissions of shale gas (CO_2 and methane) and its energy efficiency compared to other energy sources. There is a strong need for a better European knowledge base on shale gas operations and their environmental impacts particularly, if shale gas shall play a role in Europe's energy mix in the coming decennia. M4ShaleGas' main goal is to build such a knowledge base, including an inventory of best practices that minimise risks and impacts of shale gas exploration and production in Europe, as well as best practices for public engagement. The M4ShaleGas project is carried out by 18 European research institutions and is coordinated by TNO-Netherlands Organization for Applied Scientific Research.

Executive Report Summary
This review considers the potential for leaks and spills of contaminants from infrastructure that would be developed as a result of shale gas exploitation in Europe. Specific information from shale gas operations in the US is rare and non-existent from Europe. Most information is for near well activities and for shallow ground water contamination that was being ascribed to well integrity failure. For Europe there is information from analogue industries, including: onshore conventional oil and gas; and wastewater treatment works. A range of mitigation strategies have been proposed, including: site setbacks; zero-discharge well pads and site safety plans.

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1 INTRODUCTION

1.1 Context of M4ShaleGas

Shale gas source rocks are widely distributed around the world and many countries have now started to investigate their shale gas potential. Some argue that shale gas has already proved to be a game changer in the U.S. energy market (EIA 2015[1]). The European Commission's Energy Roadmap 2050 identifies gas as a critical energy source for the transformation of the energy system to a system with lower CO_2 emissions that combines gas with increasing contributions of renewable energy and increasing energy efficiency. It may be argued that in Europe, natural gas replacing coal and oil will contribute to emissions reduction on the short and medium terms.

There are, however, several concerns related to shale gas exploration and production, many of them being associated with the process of hydraulic fracturing. There is also a debate on the greenhouse gas emissions of shale gas (CO_2 and methane) and its energy return on investment compared to other energy sources. Questions are raised about the specific environmental footprint of shale gas in Europe as a whole as well as in individual Member States. Shale gas basins are unevenly distributed among the European Member States and are not restricted within national borders, which makes close cooperation between the involved Member States essential. There is relatively little knowledge on the footprint in regions with a variety of geological and geopolitical settings as are present in Europe. Concerns and risks are clustered in the following four areas: subsurface, surface, atmosphere and society. As the European continent is densely populated, it is most certainly of vital importance to understand public perceptions of shale gas and for European publics to be fully engaged in the debate about its potential development.

Accordingly, Europe has a strong need for a comprehensive knowledge base on potential environmental, societal and economic consequences of shale gas exploration and exploitation. Knowledge needs to be science-based, needs to be developed by research institutes with a strong track record in shale gas studies, and needs to cover the different attitudes and approaches to shale gas exploration and exploitation in Europe. The M4ShaleGas project is seeking to provide such a scientific knowledge base, integrating the scientific outcome of 18 research institutes across Europe. It addresses the issues raised in the Horizon 2020 call LCE 16 – 2014 on *Understanding, preventing and mitigating the potential environmental risks and impacts of shale gas exploration and exploitation.*

[1] EIA (2015). Annual Energy Outlook 2015 with projections to 2040. U.S. Energy Information Administration (*www.eia.gov*).

1.2 Objectives

The objectives of this review are:

- Review the potential risks to public safety from infrastructure due to pollution incidences and accidents; compare these instances to comparator industries.
- Review the long term legacy from shale gas developments with regards to public safety.
- Review if mitigation strategies could be implemented to reduce impact from infrastructure in the areas expressed above.

1.3 Aim

The rapid growth of shale gas developments within the U.S. and the possibility of developments within Europe have raised concerns on the impact and environmental cost of shale gas extraction. Currently there are few papers that fully address the impact of well site footprints and associated infrastructure. This report hopes hopes to highlight some of the possible risks to public safety associated with shale gas sites and how these could potentially be mitigated.

2 APPROACH AND METHODOLOGY

2.1 Introduction

To review the impact of well site infrastructure with regards to public safety the literature has been extensively studied. Generally peer reviewed literature in this relatively new industry is limited. However, in the last couple of years more papers on this topic have been published.

At the time of writing this report there is widespread concern with regard to the impact of shale gas extraction throughout Europe, to date there are relatively few exploratory wells completed. Consequently little information is available regarding the impact of dhale gas within Europe. Thus the majority of this review is derived from literature based on the more exploited U.S. shale plays, such as the Marcellus and Barnett shales. However, comparable industries such as onshore conventional oil and gas well pads, petrol stations and sewage works have been in existence within Europe for many years, allowing for a clear assessment of their impact within Europe.

2.2 Documentary analysis

A structured approach was undertaken to determine the source of material for review. Peer-reviewed and independent governmental reports were the main source of information and data. Searches for peer-reviewed journal articles and independent governmental reports were conducted using a systemic approach to ensure an unbiased methodology.

3 PUBLIC SAFETY

3.1 Introduction

Shale gas operations require substantial use of hazardous materials, toxic chemical substances and hydraulic fracturing fluid; it also generates contaminated waste requiring storage and subsequent transport (Broderick et al., 2011; Eshleman & Elmore, 2013). It is common for the majority of these fluids and materials to be transported considerable distances by truck on public roads to the drilling sites (Eshleman & Elmore, 2013). In addition to the public risk associated with transport, as with other outdoor activities, well pad sites are exposed to extreme weather and environmental conditions (e.g. heavy rainstorms, severe windstorms, floods and freezing conditions) which makes working on site difficult and also elevate the risk of accidents, spills, or leakages (Eshleman & Elmore, 2013). Unless these spills and accidents are prevented and/or quickly and carefully contained, contamination of land, surface water and groundwater may result, which if severe may lead to potentially highly toxic chemicals being exposed to humans and natural ecosystems (Eshleman & Elmore, 2013).

In addition to the public safety risks, relating to spills and leaks this chapter will include the ongoing risk represented by the legacy of shale gas extraction, and where possible consider affective mitigation strategies, specifically focusing on emergency response plans for the risks identified.

3.1.1 Contamination from infrastructure

Well site infrastructure such as pipelines and boreholes need to be well constructed, monitored and maintained to avoid leakage into surface water and ground water. Brantley et al. (2014) recall that through March 2013, 3.4% of gas wells were issued with notices of violation for well construction issues and 0.24% of gas wells received notices of violation related to methane migration into ground water (Brantley et al., 2014). Jackson et al, (2013) also commented on elevated levels of methane, ethane and hydrocarbons in a subset of shallow drinking water in northeastern Pennsylvania. Jackson et al. (2013) describe several explanations for higher than expected dissolved gas concentrations in the wells including, poor well infrastructure such as faulty or inadequate casing and poor cementation or sealing of the annulus or gaps between casing and rocks (Jackson et al., 2013). Other publications such as Vengosh et al. (2014) also indicate how stray gas migration into shallow aquifers can potentially occur via the release of hydrocarbons through leaking casing or along the well annulus. Jackson et al. (2013) highlights that in 2010, 90 violations for faulty casing and cementations on 64 Marcellus shale gas wells were issued by the Pennsylvania Department of Environmental Protection, a further 119 similar violations were issued in 2011.

There are many additional studies that remark further upon well integrity and how poor well borehole construction and maintenance, along with failure to comply with regulations can lead to contamination of both ground water and surface water. The aim of this review however, is not to discuss well integrity, which is well documented but to review the impact of well site infrastructure, thus we will comment no further on this aspect.

3.1.2 Subsurface contamination of ground water

There are few confirmed cases of ground water contamination from activities such as production wells and hydraulic fracturing, and fewer publications documenting them (Goldstein et al., 2014; Wright et al., 2012; Brantley et al., 2014; Jackson et al., 2013). Brantley et al. (2014) indicate that this could be due to the fact that incidents are rare or that contaminants were quickly diluted. However, of the studies performed there are limits to their validity, as for the majority, there is a lack of baseline information as to what the water quality was like before shale gas drilling began, therefore it is difficult to clearly distinguish between levels and sources of potential contamination. To draw a definitive conclusion about the origin of elevated element concentrations in ground water, one would require a focused study of groundwater before, during and after natural gas extraction activities. Having made the above clear, one has to bear it in mind when reviewing the few publications that do comment on the changes in ground water quality after the development of shale gas sites.

An area of concern researched quite considerably relates to the elevated levels of methane and other aliphatic hydrocarbons (e.g. ethane and propane) in ground water, and especially in drinking water. There are discussions as to whether the methane identified in well water is due to nearby hydraulic fracturing activities or older conventional wells, or is present due to subsurface coal bed methane, bacterial decomposition, or other sources (Vengosh et al., 2014; Osborne et al., 2011). In this review we will not be joining the methane in ground water debate, nor will we discuss the other suggested mechanisms as to how ground water is potentially polluted (e.g. hydraulic fracturing potentially enhancing deep-to-shallow hydraulic connections and intersecting abandoned oil and gas wells etc.) as it is beyond the scope of this report (Jackson et al., 2013). With regards to reviewing subsurface ground water contamination, we will assess this topic simultaneously with surface water and soil contamination, as there is much overlap in the mechanisms that generate the pollution.

3.1.3 Surface water and soil contamination

The impact on surface water and the potential for land contamination from shale gas well site infrastructure is a major concern with regards to public safety. The Canadian Water Network (2015) specifically reports that surface contaminant exposure due to spills or the poor handling of wastewater could represent more immediate or short-term risks than ground water exposures. The risks associated with surface spills are similar to those related to chemical and wastewater handling issues connected with other oil and gas or industrial processes (Canadian Water Network, 2015).

Entrekin et al. (2011) comments that contamination of surface water from hydraulic fracturing fluids and produced water is most likely to occur through accidental spills and leaks during hydraulic fracturing or treatment and disposal processes. In addition to this, Entrekin et al. (2011) remarks that contamination from hydraulic fracturing wastes can potentially occur through inadequate waste treatment practices, inappropriate waste storage, poorly constructed impoundments or well casings, and improper disposal of solid wastes that may leach into nearby surface waters. Entrekin et al. (2011) comments on the Pennsylvanian Department of Environmental Protection (PADEP) recording more than 1400 drilling violations between January 2008 and October 2010 in Pennsylvania alone, nearly half of these were related to surface water contamination and included direct discharge of pollutants, improper erosion control, or failure to sufficiently contain waste (Entrekin et al., 2011).

3.1.4 Spills and leaks

Within the U.S. the frequency of spillage events related to shale gas developments is not well known, there have been a number of media reports citing spills but there is a lack of robust data on the frequency, cause and impact on public safety of such events (Broomfield, 2012). Typically spills and leaks tend to occur near the drilling location, with occurrence and frequency linked to the density of the shale gas drilling developments (Vengosh et al., 2014; Gross et al., 2013). Spills and leaks of hydraulic fracturing and flowback water (often containing organics, salts, metals, and other constituents) can pollute soil, surface water, and shallow ground water (Vengosh et al., 2014). In addition to this Vengosh et al. (2014) indicates that leaks, spills and releases of hypersaline flowback and produced waters are more likely to impact the inorganic quality of surface water because these brines contain high levels of salts (e.g. Cl, Br), alkaline earth elements (e.g. Ba, Sr), metalloids (e.g. Se, As), and radionuclides (e.g. Ra).

Gross et al. (2013) is one of the few papers to document ground water contamination from surface spills associated with hydraulic fracturing operations from both oil and gas developments. Their study discovered that the majority of spills were located in Weld County, Colorado and from July 2010 to July 2011, 77 reported surface spills impacted the ground water in Weld County (Gross et al., 2013). To varying degrees the ground water samples were reported to contain benzene, toluene, ethylbenzene, and xylene (BTEX), components that exceeded maximum National Drinking Water contaminant levels, potentially impeding public safety (Gross et al., 2013). Since May 2012 remediation has reported to have taken place, reducing BTEX levels in at least 84% of the cases to levels acceptable in accordance to the National Drinking Water standards. Of the 77 reported spills, 47 were reportedly due to equipment failure, 10 were allegedly due to corrosion/equipment failure, 15 were reportedly due to historical failure (e.g. discovery of a spill during inspection), with just 3 due to human error. Of the remaining 2 spills, one was due to multiple leaks in the dump line system and the other's origin is unknown (Gross et al., 2013).

An investigation into ground water contamination by the U.S. Environmental Protection Agency in the Wind River Formation above the Pavilion gas field was conducted in response to complaints by domestic well owners, regarding objectionable taste and odour problems in well water (DiGiulio et al., 2011). The combination of shallow and deep monitoring wells in the area allowed distinction between shallow sources of contamination (pits), and deeper sources of contamination (production wells) (DiGiulio et al., 2011). DiGiullo et al. (2011) found increased concentrations of benzene, xylenes, gasoline range organics, diesel range organics and total purgeable hydrocarbons in ground water samples from shallow monitoring wells (DiGiulio et al., 2011). Further investigation indicated that shallow ground water contamination was connected in part to surface pits used for storage and disposal of drilling wastes and produced water (DiGiulio et al., 2011).

During April and May 2012 the U.S. Geological Survey completed a follow up to the work completed by the Environmental Protection Agency in 2010 (Wright et al., 2012). They found similar results, thus methane, ethane and propane levels were greater than expected; however they also recorded organic compounds levels were lower than expected (Wright et al., 2012). This later study did not give any suggestions as to the reasons behind these elevated gas levels.

The U.S. Geological Survey initiated a multidisciplinary investigation to determine the fate and effects of the disposal of produced water on the near surface environment (Kharaka & Otton, 2003). The two sites of investigation were located on the Osage Reservation in Osage County, N E Oklahoma (Kharaka & Otton, 2003). Oil and gas production in Osage county has occurred for over 100 years, with the development of around 39000 wells, mostly at shallow depths of around 300 to 700 m. Due to a lack of strict water disposal practices in the past, land here is affected by salt scarring, tree kills, soil salinization and brine and petroleum contamination. This is due to the leakage of produced water and associated hydrocarbons from brine pits, and accidental release from active and inactive pipes and tank batteries (Kharaka & Otton, 2003). The long term effects of spills and leaks in this area indicate significant amounts of salts from produced water releases, petroleum hydrocarbons still remain in the rocks and soil of the affected area more than 60 years after the incident (Kharaka & Otton, 2003).

3.1.5 Site security

The presence and operation of heavy equipment and the large quantities of hazardous chemicals used on shale gas sites present similar risks to other industrial facilities, making site security extremely important to ensure public safety (Eshleman & Elmore, 2013). Well sites and their associated infrastructure should be treated like any other industrial site and made to adhere to securing these facilities so they can operate in a safe manner (Eshleman & Elmore, 2013). Security is site specific, demanding different levels and types of security at the varying life stages of the well (Eshleman & Elmore, 2013). Consideration needs to be assessed for incidents of accidental trespassing (e.g. someone accidentally wondering onsite) and people purposely trying to trespass to cause damage.

3.2 Impacts from comparable industries

This chapter has reviewed a number of potential public safety concerns relating to shale gas development. To put these into context this section will briefly outline current practice activities, such as petrol stations and sewage works that pose similar public safety risks.

3.2.1 Petrol stations

Surface water and soil pollution from petrol stations is known to occur and happens in much the same way as it would arise from shale gas development sites, including failure of ground or below ground storage tanks, pipeline failure and from associated activities such as delivery and fuel dispensing (DEFRA, 2002; Mariano et al., 2007). As with shale gas sites underground tanks may be used to store the hydrocarbons, it is essential that these are installed in suitable ground conditions and protected from corrosion and premature degradation by chemical attack (PELG, 2009). Leaking underground storage tanks are a major problem, in mid-2008 there were more than 625000 active underground petroleum storage tanks in the U.S., with an additional 1.7 million inactive ones. From these there were more than 475000 confirmed releases, and clean ups had been performed at over 95% of them (Prince & Douglas, 2010). PELG, (2009) comments poorly installed, inadequately maintained or old tanks and pipelines are the main causes of petrol leaks and ground water contamination.

There are few publications that discuss the effect of petrol stations on the contamination of surface water and soil environments. However, Borowiec et al. (2008) studied several soil samples in Poland in an attempt to analyse the crude oil derivative substance content and the presence of organic carbon in soil samples 5 m, 10 m, 100 m, and 200 m from the fuel tank (Borowiec et al., 2008). At the time of writing their paper they record approximately 6700 petrol stations and 56 fuel bases in Poland, with 27000 fuel tanks in operation. They discovered that in the vicinity of petrol stations fuel spills and their penetration into deep soil layers were the main contributor to soil contamination (Borowiec et al., 2008). They also concluded that elevated levels of crude oil were observed up to 10 m away from the fuel tanks, concluding that in this location this was the furthest distance attributable to migration of petrol from precipitated water (Borowiec et al., 2008).

Karakitsios et al. (2006) studied leaks from petrol stations in Ioannina, Greece, and found that petrol stations contribute to increased levels of total benzene concentrations in their surroundings. They stated that it is possible the increase concentration is enough to increase the risk of the inhabitants getting cancer, specifically mentioning that the risk of leukaemia caused by benzene alone could increase by 3% to 21% (Karakitsios et al., 2006). The study indicated that the health risk to the public could be reduced by improving evaporation recovery systems, reducing the leaks of the fuel tanks, and if possible relocating petrol stations away from urban areas (Karakitsios et al., 2006).

The British Geological Society reiterates how precautions should be taken with regard to storage tanks, including installations of multi-layered storage systems. Good practice would also include installation of double-skinned tanks in a concrete vault, lined with synthetic polymer membranes and compacted clay (BGS, no date). They also comment that long term maintenance needs to monitor component deterioration, potential cracks in cement, and breaches in synthetic membranes (BGS, no date). These are the same precautions that need to be incorporated into shale gas development.

Petrol stations require a large number of deliveries of potentially hazardous hydrocarbons in a similar manner to shale gas sites; transport planning is therefore an important factor to consider when discussing all the public safety risks associated with petrol stations. As with any transported load carrying potentially toxic chemicals there is a risk of hazardous chemical spills, fires, and possibly even explosions (Eshleman & Elmore, 2013). However, unlike shale gas sites, petrol stations tend to be located on well-established public roads, so the quality of the roads and bridges used for transportation should be suitable for the load.

3.2.2 Sewage works

Similarly to shale gas sites ground water contamination from leaking sewers is a great concern as contaminants can include nitrates, heavy metals, and organic compounds (Bishop et al., 1998) which can lead to serious health implications. For example in Bramham, Yorkshire, a leak from a surcharged sewer contaminated a borehole exploiting the Magnesian limestone aquifer, causing 3000 cases of gastro-enteritis (Short, 1988; Bishop et al., 1998). There have been further reports of leaks into surface water from sewage works within the UK, but incidents remain relatively rare. Over the past 60 years there have been roughly 70 officially documented sewer-related waterborne disease outbreaks in the UK (Blackwood et al., 2001; Ellis et al., 2004).

Recently, in September 2015, Severn Trent Water Limited was fined almost £500,000 for allowing raw sewage to leak into a farmer's field and a pond on private land (Environment Agency, 2015). The Severn Trent pipeline that transported raw sewage to a treatment plant ruptured repeatedly, leading to four incidents within a single year (Environment Agency, 2015). The leaks directly led to fish dying; the Environment Agency also suggests that the episode affected the local invertebrate community including freshwater shrimps (Environment Agency, 2015).

In the U.S. similar incidents have been recorded, including a rupture in the sewer mains serving a large municipal waste system on the East Coast (Mallin et al., 2007). The rupture caused approximately 11,355,000 litres of raw human waste into a tidal creek estuary (Mallin et al., 2007). The high discharge of sewage led to high fecal coliform bacteria concentrations in the creek causing the death of larger fish and several algal blooms (Mallin et al., 2007).

The causes of leaks like these are often due to structural defects such as cracks, fractures, joint displacement, unsealed connections and deformational gaps (Ellis et al., 2004). Ellis et al. (2004) indicates the cause of these structural defects can be attributed to poor construction and materials (especially joint fracturing pre-1978), heavy traffic loading, as well as operational and service damage (Bishop et al., 1998). It has been suggested that up to 40% of UK sewers have structural defects, with one in twelve having serious defects (Ellis et al., 2010). In addition to this some 5000 sewer pipe collapses per annum are being recorded in urban areas within the UK (Ellis et al., 2010).

Bishop et al. (1998) suggests a number of recommendations to reduce ground water contamination, including, (1) modifying the existing criteria for the service performance grading of existing sewers, (2) improving construction of new sewers, (3) increase ground water monitoring, and (4) risk assessments for new ground water sources. Several of these recommendations can be adapted for the infrastructure (e.g. pipelines and storage tanks) used in shale gas developments.

3.3 Mitigation measures

New York State has declared that shale gas well pads and all associated onsite infrastructure should be treated like all other industrial facilities (Eshleman & Elmore, 2013). With this in mind they recognise that protection of homes, businesses, public buildings, and places with high levels of recreational activity is paramount (Eshleman & Elmore, 2013). The first step in aiding the protection of these sites is locating the areas at risk and then developing the shale gas sites as far away from these areas as possible (Eshleman & Elmore, 2013). This can be achieved through careful planning and permit restrictions, and where necessary significant setback requirements should be made compulsory (Eshleman & Elmore, 2013).

Good practice for industrial activities that have a risk associated with them is to have a carefully composed site specific emergency response plan (ERP) (Eshleman & Elmore, 2013). A carefully drawn up and site specific ERP that includes appropriate advance planning, safety training, and coordination deployment of company and community assets can help protect lives, property and the environment (Eshleman & Elmore, 2013). It should describe, in writing, specifically how one should respond to different emergencies (e.g. spills or leaks) that may arise during each phase of shale gas development (Eshleman & Elmore, 2013).

3.3.1 Water contamination

Osborn et al. (2011) comment that compared to other fossil fuel extraction methods, hydraulic fracturing is currently poorly regulated in the U.S. and more research is required on mechanisms and consequences of contamination. They comment that long term, coordinated sampling and monitoring of the industry and private homes is required to assess groundwater quality (Osborn et al., 2011). Entrekin et al. (2011) agrees with Osborn et al. (2011) remarking that the rapid growth and expansion of U.S. gas drilling has made regulation of sites difficult and violations common.

Gross et al. (2013) recognised the risks associated with surface spills from produced water, especially with regard to the release of BTEX chemicals in excess of the advised national levels. To aid further production they gave a number of recommendations for future activities. Their initial recommendation was to identify and evaluate the hazard and exposure potential posed by specific chemicals and chemical mixtures used in the hydraulic fracturing process (Gross et al., 2013). From this chemical footprinting one can then evaluate and safeguard against negative environmental characteristics, including biopersistence, bioaccumulation potential, mobility and exposure potential by multiple routes (Gross et al., 2013). Once the chemicals with the greatest risk have been identified, operators may choose to employ alternative chemicals or enhance the safety measures (e.g. increase monitoring for certain chemicals on a regular basis) (Gross et al., 2013).

Factors such as the variation of water table depth should be considered when selecting the location of drilling site operations (Gross et al., 2013). Especially when considering placement of storage tanks and production facilities, as Gross et al. (2013) found these were common causes for high concentrations of BTEX in surface spills with groundwater impact. Further to this, Gross et al. (2013) suggests that as most spills were reported due to equipment failure rather than operation error, equipment safety systems on the surface at drilling site should be carefully considered and enhanced where needed. They acknowledge that many of the drilling sites in the Weld County are in remote locations and continuous onsite personnel monitoring of each well is not feasible (Gross et al., 2013). Therefore, in some locations improvements of remote monitoring capabilities and an increase in the redundancy of spill prevention measures may be required (Gross et al., 2013).

3.3.2 Site security

Site security required is site specific, and different levels and types of security are essential at the varying life stages of the well (Eshleman & Elmore, 2013). Several examples of best practice, possibly advised by an operator would include: (1) sufficient perimeter fencing (at least 1.8 m high), lighting, gates (with keyed locks), and signage in place around drill rigs, engines, compressors, tanks, impoundments, and separators, to restrict access: and (2) use of safety or security guards to further control access (particularly important during active drilling and completion phases of an operation) (Eshleman & Elmore, 2013).

4 CHAPTER 4 - TRANSPORT

4.1 Introduction

Aside from the spills and leaks that can directly be associated with the well pad and its interconnections it is possible that spills and leaks will result from the increased road traffic due to the work of the well pad. and associated access to that site, the impact of traffic generated by shale gas activities on general traffic networks (primarily road, but also possibly rail or other modes) need to be considered.

In the UK, many of the above elements form part of 'routine' 'Transport Assessment', 'Transport Plan', 'Environmental Risk Assessments' or 'Environmental Impact' statements for industrial developments (e.g. see Arup 2014a; 2014b; 2014c, 2014d relating to Cuadrilla activities in Lancashire, UK). Other EU member states have their own legislation, generally derived from EC Directives in force (EP DGIP, 2011; AEA, 2012). In the United States approaches to the above are more complicated, given the diverse policies and legislation of individual states, and overarching Federal legislation (Andrews et al., 2009).

4.1.1 Scale of the problem

In the previous review it was possible to estimate the breakdown of truck movements based largely on EP DGIP (2011) and NYCDEC (2009) – Table 4.1. Further, Goodman et al. (2016) have agreed with Broderick et al. (2011) that the truck movements will represent a 60 km round trip and so given the data below this means that each well there is an additional 48000 to 120000 km driven by trucks per well.

Table 4.1: Estimated quantities of materials and truck movements for a single well [Sources: EP DGIP (2011); summarised from NYCDEP (2009) with conversion of US Imperial values to SI units)[1].

Activity	Materials	Volume	Associated Truck movements	Implied truck capacity/rate
Site access and pad construction	Cleared earth and vegetation	0.8 to 2.0 ha site, plus access roads	20 to 40	0.04-0.05 ha/truck
Drill rig set up/initial Drilling Chemicals	Drill equipment Various chemicals	-	40	N/A
Drilling water (in)	Water	40 m^3 to 400 m^3	5 to 50	8 m^3/truck
Casing	Pipe	2100 – 4600 m of casing (60 – 130 t). Each truck will carry 15 x 6 m of casing.	25 to 50	84 – 92 m of casing/truck (2.4 – 2.6 tonnes/truck)
	Cement (grout)	14 to 28 m^3	5 to 10	2.8m^3 /truck
Drill cuttings	Rock/Earth/Formation Material	71 to 156 m^3	Depends on the fate of the cuttings	
Drilling water (waste)	Water waste	40 m^3 to 400 m^3	5 to 50	8m^3/truck
Casing perforation	Explosives	Single 25g charge, number of charges used per length of lateral	1	
Fracturing fluid water (in)	Water	11355 m^3 to 34065 m^3	350 to 1000	32 - 34m^3/truck
Fracturing fluid chemicals	Various	Assume 1 to 2% of fracture fluids are chemicals: 114 m^3 to 681 m^3	5 to 20	22.8 – 34m^3/truck
Fracturing fluid water (out)	Waste fracturing fluids	Assume 100% of initial water: 11355 m^3 to 34065 m^3	350 to 1000	32 - 34 m^3/truck
Well pad completion	Equipment	N/A	10	N/A
Gas collection	Produced water	57m^3 per year/ per well	2 to 3	19 – 29 m^3/truck
TOTAL			800 to over 2000	

[1]*All truck trips in the original NYCDEP (2009) document were assumed to be by '18-wheeler semi- trucks or 9,000 gallon (34 m^3) tankers.*

4.1.2 Leaks and Spills

Leaks and spills from road accidents have been demonstrated to be a threat to surface water (eg. Eg. Price et al., 1992). Lacey and Cole (2003) have estimated tht based upon British roads then there would be 1 tanker spill every 740 years per km of trunk road in a rural setting. The values of Lacey and Cole (2003) use a value of 0.52 accidents per million vehicle km and the probability that any accident results in spill of sufficient concern to water resources of 0.043. Therefore, given that 48000 and 120000 vehicle km are driven per well over its lifetime then the probability of a water resource threatening spill of 0.002 per well over its lifetime. Given that in the UK the scale of industry is predicted to be 100 well pads of upto 1000 wells then this study would suggest there will be 2 - 3 spills over this time.

4.2 Mitigation measures

A number of potential mitigation measures have been highlighted to reduce the impact of shale gas traffic – including infrastructure changes at well sites, and supporting infrastructure changes. Infrastructure measures could be expected to be increasingly effective as the industry matures, economies of scale come into effect, or as technology changes. However, Sumi (2008) notes that as time and technology have progressed, and more experience of fracturing operations at a particular gas reservoir are gained, there has also been a trend in the US for well pads to be ‘downspaced’ (i.e. operated more densely in a particular area).

4.2.1 Pipelines

The most fundamental mitigation measure lies in achieving a reduction in the need to transport large quantities of water to and from well sites. This may be primarily done through the utilisation of either existing water supply networks, or the construction of new pipeline facilities. Whilst piping water could mitigate a large volume of traffic associated with shale gas activities, the following issues need to be considered:

- If well pad sites are too remote from the water supply network, requiring the construction of new pipelines, it may be more cost effective for the industry to use road haulage, at least in the initial stages of industrial development. Construction of new pipelines would entail needs for separate construction traffic (and attendant impacts);
- Flowback waste/produced water from well pad sites may require specialist tanker transportation to waste facilities (or separate, dedicated pipeline networks).

Depending on infrastructure, rail freight may also be able to take some of the burden of water transportation away from roads (NYSDEC, 2011; 2015a).

4.2.2 On-site storage

The use of on-site lined ponds to store waste water may also be used to 'buffer' transportation requirements, to spread the temporal intensity of demand for waste removal over a longer period, reducing overall traffic impacts.

4.2.3 Other traffic mitigation measures

Other traffic mitigation measures suggested in the NYSDEC documentation include:

- Scheduling of operations to avoid conflicts in areas where multiple pads are operational;
- Efficient route selection to maximise 'efficient driving and public safety';
- Avoidance of operations:
  - in peak traffic hours;
  - wherever movements could disrupt school bus traffic;
  - wherever community events could be disrupted;
  - in overnight quiet periods;
- Coordination with local authorities, especially highway departments and emergency services (e.g. to put into place plans in the event of emergencies or breakdowns blocking highways);
- Upgrades or improvements to roads and bridges that will be frequently used to transport water to sites with many well and pads, or roads that will bear the brunt of traffic from multiple sites;
- Advance notice to the public of detours and road closures if necessary;
- Adequate provision of off-road parking and site delivery areas;
- Use of rail and air travel, over road, to move large numbers of temporary workers

5 CHAPTER 5 - LEGACY

5.1 Introduction

The recent rapid growth of shale gas developments in the U.S. raises concerns about the legacy of the wells required for shale gas exploitation and their potential long term impact on the environment. A number of issues can arise if wells are left improperly sealed, for example, legacy oil and gas wells have the potential to create pathways for unwanted migration of fluids (e.g. brine, drilling and stimulation fluids, oil and gas - Dilmore et al., 2015). In this chapter the legacy of abandoned wells has been reviewed, along with the long term consequence of spills and leaks, especially with regard to potential chemical accumulation within the soil and groundwater. In addition to risks associated with public safety, the long term impact of well site footprints on the land has been studied. This chapter also reviews mitigation methods that might reduce the public safety issues and the disruption caused by the well site footprint.

5.1.1 Public safety

There are a number of public safety issues that need to be considered with regard to legacy from shale gas well sites. This section reviews issues related to abandonment and plugging, and spills and leaks.

5.1.1.1 Abandoned wells

Plugging and well abandonment is most common when the well is no longer required, thus logs determine there is insufficient hydrocarbon potential for production, or production operations have drained the reservoir the well taps (Schlumberger Limited, 2015). Although decommissioning varies depending on different operators, most require cement plugs to be places and tested across any open hydrocarbon-bearing formations, across all casing shoes, across freshwater aquifers, and perhaps several other areas near the surface, including 6 to 15 m (20’ to 50’) of the wellbore (Schlumberger Limited, 2015).

The impact of abandoned oil and gas wells on both fluid and gas migration is a major concern, especially with regards to ground water contamination (Vidic et al., 2013; Kang et al., 2014). Darrah et al. (2014) determined well integrity failure was the likely cause of groundwater contamination of drinking water wells overlying Marcellus and Barnett shales by CH_4 due to faulty casings and migration of hydrocarbons along the well annulus because of cement failure. Vengosh et al. (2014) also identified well integrity failure as one of the four possible risks from unconventional shale gas production to water quality and that includes well failure during and after operation and includes the risk from CH_4 leaking into groundwater. When a well is abandoned it is important to plug the well appropriately as indicated above to prevent inter-zonal migration of fluids, contamination of freshwater aquifers, surface soils, and surface waters (Eshleman & Elmore, 2013). Appropriate plugging can also conserve hydrocarbon resources either in the production zone or in potential production zones (Eshleman & Elmore, 2013). Improperly plugged or abandoned wells generally contaminate through the abandoned well acting as a conduit for fluid flow between penetrated strata, underground water bodies and the surface (Eshleman & Elmore, 2013). Contaminated water can also enter the abandoned wellbore at the surface and migrate into the underground sources of drinking water (Eshleman & Elmore, 2013; API 2009b).

An example of a poorly plugged well causing contamination occurred at St Catherine Creek National Wildlife Refuge in the U.S. (Covington, 2014). The site was established in 1990 to preserve 24931 acres of Mississippi River Floodplain, and the habitats of a number of endangered species (Covington, 2014). Currently there are just a few active oil and gas wells on the Refuge, however there are over 500 inactive wells in the area, with many of these inadequately plugged and abandoned (Covington, 2014). Since well development on the Refuge site, spills and leaks from oil and gas wells and pipelines have plagued the land (Covington, 2014). An example includes a subsurface oil leak found in April 2012 which led to a thorough investigation by the Mississippi State Oil and Gas Board and the Mississippi Department of Environmental Quality (Covington, 2014). The investigation discovered the well was never properly abandoned in 1983, with the well containing just one 18 m (60 ft) concrete plug at surface level (Covington, 2014). They also discovered the well casing had deteriorated severely and complete re-plugging of the well was required. In addition to re-plugging, complete site restoration was required, including removal of all surface contaminants (Covington, 2014). The site also required seeding and covering with mulch to control erosion; the cost of the project was around $260,000 (Covington, 2014).

Deteriorated casing is not uncommon and is linked to poor cementation; the majority of leaks associated with the wellbore are in fact due to issues surrounding cementing (Watson & Bachu, 2007). Exposed (uncemented) casing is the main factor determining the occurrence of gas migration and casing failure (Watson & Bachu, 2007). Good quality cementation needs to be enforced to protect wellbores from cement degradation and casing from corrosion (Watson & Bachu, 2007).

Reported well integrity failure rates have varied between studies. For example Erno and Schmitz (1996) found of 435 wells tested for surface casing vent leakage, 22% were leaking. Chillingar and Endres (2005) found 75% leak rates of 50 wells studied in the Santa Fe Springs oilfield which was drilled in the 1920s. Watson and Bachu (2009) analysed data from 316,439 wells drilled between 1910 and 2004 for surface casing vent flow (SCVF) through wellbore annuli and soil gas migration (GM) in Alberta and determined that 4.6% of wells suffered from surface casing vent flow or gas migration. They found that the most important cause in determining wellbore failure rates was uncemented casing.

Various estimates exist of well integrity failure in Pennsylvania. Using notices of violation from the Pennsylvania Department of Environmental Protection between January 2008 and August 2011, Considine et al. (2013) determined that of 3533 wells drilled, 2.6% experienced well integrity failure. This included four instances of blowout and venting, two instances of gas migration and 85 cement and casing violations wherein gas migration was observed. Using a similar dataset but between 2008 and

March 2013, Vidic et al. (2013) found a failure rate of 3.4% from 6466 wells. Ingraffea et al. (2014) assessed 32678 producing oil and gas wells between 2000 and 2012, finding 1.9% lost integrity during that period. Beyond the well integrity failure rate, Ingraffea et al. (2014) found that unconventional wells had six times the number of cement and casing issues compared to conventional wells. Age was also likely to increase risk of failure, with the risk increasing by 18% with each additional inspection. There were geographic factors affecting hazard risk as well, with wells drilled in north east Pennsylvania 8.5 times as likely to experience problems compared to the rest of the state. Jackson (2014) suggested that local geology and different drilling practices may have been the cause of the geographical differences in hazard risk.

Davies et al. (2014) assessed 8030 wells in Pennsylvania, indicating 6.26% had well barrier or integrity failure and 1.27% leaked to the surface. Compiling a review of all the available published sources of well barrier and integrity failure rates, Davies et al. (2014) unsurprisingly found a significant range of 1.9-75%. In the UK, of the 143 active onshore wells, only two confirmed cases of well integrity failure were found yet no monitoring of abandoned wells takes place and Davies et al. (2014) called for surveying of abandoned wells to be conducted to determine whether abandoned wells show higher rates of well integrity failure than can be determined currently. Here the term abandoned is technically correct and consistent with the literature on the subject (eg. Davies et al., 2014). In most UK cases an abandoned well is defined as those that have been cut-off, sealed and then buried under soil and in the UK this means ~2 m of soil – in most circumstances an abandoned well might better be referred to as a decommissioned well.

Overtime it is expected that the condition of abandoned wells will deteriorate (Miyazaki, 2009) and Bishop (2013) stated that because of deterioration of well casings and cement over time, it is necessary to ensure that wells are not only properly plugged and abandoned but inspected and repaired when necessary. Post 1995, oil and gas wells in Alberta, Canada, have to undergo testing for SCVF and GM prior to final abandonment, for which wells are cut and capped (Watson and Bachu, 2009).

Little is known about the long-term integrity status of abandoned wells in the UK. Of 2024 onshore wells in the UK included in the analysis of Davies et al. (2014), 65.2% were not visible as they were sealed, cut and the land reclaimed, while the remaining sites (34.8% of all known wells) retained some degree of evidence of previous drilling activity at the surface – 143 of these wells were active in the past decade which means that 27.4 % (589 wells) could be better described as abandoned as opposed to decommissioned. Davies et al. (2014) suggested that surveying soils above abandoned well sites would be an important step in establishing whether there was a loss of integrity and fluid migration following well abandonment. Boothroyd et al. (2016) measured 100 abandoned across the UK and found that 30% of them has measurable leaks.

Kang et al. (2014) acknowledged very little was known about the impact of methane fluxes from abandoned oil and gas wells in Pennsylvania and so conducted a study to try and assess the methane flux at various locations. They concluded methane emissions from abandoned oil and gas wells can be considerable, with methane emissions 4 to 7% of estimated total anthropogenic methane emissions in Pennsylvania (Kang et al., 2014). Kang et al. (2014) also commented that of the millions of abandoned wells across the U.S. some are higher emitters than others. There is a lack of robust information with regards to abandoned wells and connection to subsurface methane accumulations; however it is believed that accumulations have been so great they have caused explosions (Kang et al., 2014). Obviously this is a major issue and one that requires further research, especially as the number of shale gas sites is developing so rapidly.

5.1.1.2 Spills and Leaks

The environmental legacy of spills and leaks at surface level is an important factor to consider with regards to long term public safety (Vengosh et al., 2014). Obviously spills and leaks should be avoided at all cost, however inevitably they will occur. As mentioned in Chapter 3 shale gas sites should be treated like any other industrial facility, so should a spill or leak occur it should be dealt with appropriately in accordance with the emergency response plan (Eshleman & Elmore, 2013). However, Gross et al. (2012) highlights that even though spills and leaks have been identified and clean-ups initiated they are often inadequate and still leave considerable contamination.

Gross et al. (2012) record 77 spills that impacted ground water in Weld County, Colorado, between July 1, 2010, and July 1, 2011. Of the 77 only 13 reported spills with the specific volume of oil spilled (average 24; range 1-177 barrels) and of these only one operator indicated that all oil spilled was recovered (Gross et al., 2012). Six incidents reported that no oil was recovered with another six indicating that some of oil was recovered (42-84%) (Gross et al., 2012). In addition to the 13 oil spills, five of the operators recorded spills of produced water (Gross et al., 2012). Of the five, one operator indicated all the produced water was recovered, two operators reported no recovery, and two recorded that some of the water was recovered (50-96%) (Gross et al., 2012). These results clearly indicate that even when spills and leaks are identified and clean ups completed it is difficult to recover all that is spilt and soil remains contaminated.

In addition to the above, Gross et al. (2010) paper indicate that of the 77 spills 15 were historic and discovered during onsite inspections, highlighting that spills are occurring unnoticed. This is of great concern because essential clean-ups of the impacted area are delayed and possibly do not occur. Also, repairs to faulty equipment and prevention of further leaks and spills cannot be carried out.

The severity of the legacy from a spill is dependent upon the composition of what and how much is spilt. Over time, metals, salts and organics from spills and leaks may build up in sediments and soil (Vengosh et al., 2014). Whether constituents will be absorbed onto the soil, stream, river or pond/lake sediments and potentially cause long term environmental and health risks is determined by a number of factors (Vengosh et al., 2014). Including the physicochemical conditions of surface waters and the distribution coefficient of each compound, this will determine how it will interact with particulate matter or river sediments (Vengosh et al., 2014). Leaks and spills of NORM-rich flowback and produced water are of particular concern as discharge in high volumes can lead to a build-up of radium, and radiation in sediment and soils (Vengosh et al., 2014). Kharaka & Otton (2003) results show important amounts of salts from spills and leaks of produced water still remain in the soils and rocks of the impacted area after more than 60 years of natural attenuation.

5.2 Impacts from comparisons industries

Several comparable industries including petrol station and sewage treatment works were reviewed so the legacy from shale gas sites could be put in prospective. Our review found that there is a considerable gap in the literature with regards to the documented legacy from petrol stations and sewage treatment works within Europe. The UK Environment Agency does go into some detail about the risks associated with petrol station decommissioning but there is very little literature on the long term impacts on land previously used for petrol stations. Likewise there is little information on the long term implications of past sewage treatment works on the land, however there are a couple of papers on site redevelopment.

5.2.1 Petrol station

In a similar manner to shale gas site, petrol stations are prone to spills and leaks. As with shale gas sites these could potentially lead to long term pollution and accumulation of pollutants in the land and ground water. Spills and leaks at petrol stations are often caused during the installation, decommissioning and removal of underground storage tank (UST) (EA, no date). A number of serious pollution incidents have occurred as a result of damage to UST systems during installation, inappropriate decommissioning or during the removal of systems which have not been decommissioned properly (EA, no date). These incidents have been known to cause serious soil and ground water contamination and, in some cases, have contaminated surface waters (EA, no date).

5.2.1.1. Mitigation methods

Spills and leaks occur at petrol station sites and although there is a lack of literature to support this claim, the clean ups are likely similar to shale gas sites. That is, although spills and leaks have been identified and the clean-up process performed, it is unlikely that the spill was cleaned up in its entirety. In addition to this, as with shale gas sites, spills and leaks may have occurred undetected. To avoid long term environmental issues during decommissioning samples of soil and groundwater (if present) should be taken and checked for subsurface contamination (EA, no date). If soil or groundwater contamination is discovered, further investigations should be performed to determine the need for remediation (EA, no date).

USTs are decommissioned on either a temporary or permanent basis (EA, no date). Often tanks are decommissioned on a temporary basis and then forgotten about (EA, no date). To avoid this issue and risk of associated pollution, the UK Environment Agency recommends complete removal of tanks that are unlikely to be used again (EA, no date).

Best practice methods include removal and appropriate disposal of all remaining products in the tanks and pipelines, followed by the careful removal of the UST (EA, no date). As the main polluters have been removed before the decommissioning of the tank the risk of pollution should be reduced (EA, no date). As mentioned above, once the tank has been removed surface sampling should be performed to check for contamination (EA, no date).

5.2.2 Sewage works

Sewage treatment works comprise of a complex system of pipelines, tanks, open channels and drying/irrigation beds (DOEI, 1995). Soil contamination may arise through leakages from pipelines and tanks, leading to localised higher concentrations of contaminants, and from poor equipment management, e.g. from the land being used for temporary storage of screening, grits and used filter media (DOEI, 1995). Although not supported by any publications, presumably as with petrol stations, soil contamination could also potentially occur during substandard site decommissioning.

As with spills and leaks from other industries the level of contamination and legacy of the spill depends on what and how much was spilt, and if it was adequately remediated (DOEI, 1995). Land contamination from sewage treatment works can arise from the biodegradable material in the sludge, chemicals used to treat the sludge and fuel oils used in pumps, heating systems, plant or vehicles possibly stored on site (DOEI, 1995). However, the Department of the Environmental Industry indicate that sludge and liquid effluents are the most significant sources of potential metal contamination, which in a similar manner to other industries, if in higher enough quantities, has the potential to cause long term land pollution if it is not carefully cleaned up (DOEI, 1995).

5.2.2.1. Mitigation methods

There is a lack of literature to support this claim; however it is logical to derive that best practise mitigation method regarding spills and leaks from sewage treatment works are similar to those documented for petrol stations above. Thus the key to reducing long term contamination from old sewage treatment works is to monitor land quality whilst the plant is in operation and on decommissioning test the soil for contamination and if required remediate appropriately.

Little is published with regards to the methods of decommissioning sewage treatment works and remediation of the land. However, Davies (1991) comment on a trail programme used in Beaumont Leys area in the 1970s (Davies, 1991). Between the 1890's to 1966 the Beaumont Leys area to the North of Leicester was home to the City of Leicester's sewage treatment works (Davies, 1991). The closure of the site led to a comprehensive redevelopment programme, involving trail land remediation techniques. This included stripping and respreading contaminated soil to reduce maximum concentrations of metals in the soil (Davies, 1991). The process involved a detailed soil analyses being untaken before the remediation began and then to assess the success another on its completion (Davies, 1991). Land remediation involved removing the highly contaminated topsoil from the sludge spreading area, this soil was contaminated with high levels of Cadmium, in excess of 20 mg/kg (Davies, 1991). To put that in perceptive local authorities recommended level of Cadmium in garden areas should not exceed 5 mg/kg (Davies, 1991). The highly contaminated soils were removed and recycled. In this case the soil was used as a base material for nearby landscaping projects where it was covered with less contaminated topsoil before being seeded to form open grassy parkland areas (Davies, 1991). The trial project found that soil stripping and re-spreading was an effective mechanism for increasing soil homogeneity and modestly reducing Cadmium concentrations in the soil (Davies, 1991). It is believed if other metals were tested the same results would occur (Davies, 1991).

As mentioned previously there is a general lack of literature, whether that is peered reviewed or not, on the topic of mitigation methods and remediation techniques used on the land impacted by sewage treatment works. Although the method of stripping and respreading has been mentioned above no doubt other methods are utilised which have not been covered in this report.

5.3 Mitigation methods

5.3.1 Abandoned wells

Avoiding improper abandonment of gas wells which otherwise might threatening public safety, as well as potentially causing air and water pollution (Mitchell & Casman, 2011) is of primary importance.

Plugging needs to be adequate to prevent surface water runoff (which may contain contaminants from agriculture, industry, or municipal activities) from seeping into the wellbore and migrating into drinking water (Eshleman & Elmore 2013; API 2009). Additionally plugging needs to be sufficient and prevent fluids within the well seeping into surface soils and water (Eshleman & Elmore 2013). Eshleman & Elmore (2013) therefore recommend that operators set a cement plug at the base of the lowermost freshwater aquifer during the plugging and abandonment operations. Besides this many U.S. states and federal agencies require cement plugs across the base of the surface casing and in, or between, each producing and potential producing zone (Eshleman & Elmore 2013; API 2009b).

As previously mentioned, Dusseault & Jackson (2014) recognise that gas migration outside the casing is typically a result of cementing failure, either through incomplete cementing or the formation of microannuli within or on the periphery of the cement sheath because of cement shrinkage. They suggest leaks can be avoided with; (1) more stringent mitigation methods such as better initial cementation quality control; (2) initially installing long life expanding packers; (3) ensuring methods to force induced leak-off into deep saline aquifers to avoid interaction with shallow aquifer; (4) better casing perforation and squeeze corrective actions if leakage does develop (Dusseault & Jackson, 2014). Eshleman & Elmore (2013) supports Dusseault & Jackson (2014) indicating special procedures such as perforating casing and circulating cement, may be necessary to isolate certain potential production or injection formations which might not be protected due to uncemented or poorly cemented casing (Eshleman & Elmore, 2013).

To avoid inter-zonal flow Eshleman & Elmore (2013) indicate operator should: (1) set the required surface plugs; (2) remove the wellhead; (3) weld a steel plate on the surface casing stub; (4) fill in any well cellar; and (5) level the area (Eshleman & Elmore, 2013). Eshleman & Elmore (2013) recommend regulations with respects to plugging of wells that are consistent with API recommendations. Within the U.S. different states have varying regulations, for example Pennsylvania and Colorado have installed regulations that appear to be consistent with API's suggested practices; however West Virginia and Ohio have not (Eshleman & Elmore, 2013). Watson & Bachu (2007) comment that enforced regulations are crucial in monitoring and detecting wellbore leakage from annular flow (e.g. gas migration), casing failure or zonal abandonment failure. Good practice in Europe would require enforcing appropriate regulations on well decommissioning and making sure these are upheld (Eshleman & Elmore, 2013). Due to the significant growth in shale gas developments in recent times one of the biggest problems in the U.S. is ensuring operators are held accountable for maintaining their wells and have sufficient assets to do so (Eshleman & Elmore, 2013). The cost of plugging wells that are poorly constructed in the first place can be extremely high (Mitchell & Casman, 2011), highlighting again that wells need to initially be constructed to the highest standards (Eshleman & Elmore, 2013).

5.3.2 Spills and leaks

General mitigation against leaks and spills has been mentioned in Chapter 3, so will not be repeated within this chapter. However, it is clear that spills and leaks have occurred and there is evidence that these have not being adequately cleaned up leading to subsequent well site remediation being required.

There are several common soil remediation techniques that can be employed to clear up contaminated soil (SEPA, no date). Some methods work better in certain environments, for example methods (e.g. bioremediation) that require natural heat, moisture, or sunshine, which is not abundant in low temperature areas having long winter seasons, so they are not going to work in areas that have cooler climates (ADEC, 2009). The type of treatment that will work best can be determined by several factors, including the type of contaminant(s), presence of permafrost, groundwater flow, location of the site, and the interaction of these variables (ADEC, 2009). Remediation methods can broadly be divided into engineering methods (e.g. excavation and removal, or cover systems) and process-based methods (e.g. bioremediation or soil washing) (SEPA, no date). SEPA comment each method has a different specificity, effectiveness, cost and potential of risk to the environmental and human health.

Ground water is extremely difficult to clean up and can take a considerable amount of time (EPA, 2006). Therefore, whilst the long-term clean-up is underway it is imperative that human exposure in the short term is prevented (EPA, 2006). Ground water can be treated in a number of ways, including natural attenuation, bioremediation and air sparging (ADEC, 2009). However, the most common process to treat contaminated ground water is to extract the water, treat it at the surface, and discharge the treated water (SEPA, no date). This method is known as “pump and treat”. The treated water is disposed of in a variety of ways; one includes re-injecting it into underground aquifers (SEPA, no date).

5.4 Improvements

There are many concerns that the development of shale gas sites and the associated increase in traffic will negatively impact local roads and bridges (Drohan et al., 2012). However, although there is a lack of evidence from the literature, there are also a number of potential long term benefits from new shale gas developments. For example, well-made roads to areas that are poorly assessable could improve local transport systems. In addition to this, road quality in many areas has been known to improve as government regulations imposed on operators forces them to maintain good quality roads. It is also in the operator’s best interest to maintain road quality to avoid unnecessary damage to the trucks and equipment being transported.

In addition to potential improvements in infrastructure, improvements might be seen in forest management. Shale gas sites located in forested areas will require the forest to be maintained, as a poorly managed forest could lead to damage of on-site (e.g. well pads, storage tanks etc.) and off-site (e.g. roads) infrastructure.

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