Project Acronym and Title:

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

REVIEW OF IMPACT OF WELL SITE INFRASTRUCTURE

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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 impact of the infrastructure that would be developed as a result of shale gas exploitation in Europe. The infrastructure here includes: the well pad, pipelines, access roads and boreholes. The review is largely based upon the experience of the US shale gas industry but draws from projections from Europe and the experience from possible comparator industries. The study has considered issues for public safety, including: spills and leaks; and site safety and concludes that mitigation strategies from existing industries could be readily-translated to any shale gas industry. With respect to footprint it is important to note that in Europe and given the state of the current shale gas technology it would be expected that well pads would larger but with many more wells than is typical in the US. The footprint of a 6-well pad would be expected to be 2 ha. Access roads would be expected to shorter than in the US but values between 40 and 900 m long and occupy 1.3 hectares. In addition to the direct well pad footprint the setback vary between 30 and 300 m which could mean the total footprint nearer 9 ha. Given the infrastructure this review suggests that there would be between 800 and 2000 additional truck movements associated with development and fracking of a 6-well pad. The infrastructure of shale gas exploitation will leave a legacy of structures that we would be expected to be decommissioned but the industry is not at that stage in the US and we will have to learn from the European onshore oil and gas industry in order to predict the legacy impacts of any shale gas industry.

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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 Study objectives

- Review the average footprint (in acres) for a well pad and its associated infrastructure based on currently developed well pads in the U.S.
- Review the potential risks to public safety from infrastructure due to pollution incidences and accidents; compare these instances to comparator industries.
- Review the impact of developing well pads on the land with regards to cultural, historical and recreational resources, agriculture land and aesthetic values.
- Review the impact of traffic generated by shale gas activities on general traffic networks (primarily road, but also possibly rail or other modes).
- Review if mitigation strategies could be implemented to reduce impact from infrastructure in the issue areas expressed above.

1.3 Aims of this report

The rapid growth of shale gas developments within the U.S. and now the possibility of developments in Europe, have raised concerns on the impact and the environmental costs of shale gas extraction. Currently there are few papers that fully address the footprint impact of well site infrastructure, thus this report hopes to answer some of the public concerns with regard to the physical implication of developing well pads and their associated infrastructure on the land. This report will also highlight some of the potential the risks associated with shale gas sites and how these could potentially be mitigated. In addition to the above this report will aim to review the impact of traffic generated by shale gas activities on general traffic networks.

2 APPROACH AND METHODOLOGY

2.1 Introduction

To review the impact of well site infrastructure with regards to public safety, footprint and transport 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 regards to the impacts of shale gas extraction throughout Europe, and to date there are relatively few exploratory wells completed. Consequently there is little information available with regards to the impact of well site infrastructure within the 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 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 as to ensure an unbiased approach to the review.

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 wastes which require 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 public risks 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 related with spills and leaks, we will also discuss site security and assess potential hazards and precautions that can be put in place to limit associated risks. This chapter will also review if the public safety risks associated shale gas development is comparable to other industries or activities currently operating in Europe, 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 groundwater (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) highlight 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 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 bare it in mind when reviewing the few publications that do comment on changes in ground water quality since the development of shale gas sites.

An area of concern and researched quite considerably relates to elevated levels of methane and other aliphatic hydrocarbons (e.g. ethane and propane) in groundwater and especially in drinking water. There are discussions as to whether 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 groundwater debate, nor will we discuss the other suggested mechanisms as to how groundwater 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 Pennsylvannia Depat 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 groundwater (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 highly 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 groundwater 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 groundwater in County (Gross et al., 2013). To varying degrees the groundwater samples were reported to contain benzene, toluene, ethylbenzene, and xylene (BTEX) components that exceeded National Drinking Water maximum contaminant levels and can potentially impact 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 levels. Of the 77 reported spills 10 were reportedly due to corrosion/equipment failure, whilst 15 were reported due to historical failure (e.g. discovery of a spill during inspection), with just 3 due to human error. There was no background knowledge on the remaining recorded spills.

An investigation by the U.S. Environmental Protection Agency into groundwater contamination 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 groundwater samples from shallow monitoring wells (DiGiulio et al., 2011). Further investigation indicated that shallow groundwater 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, northeastern Oklahoma (Kharaka & Otton, 2003). Oil and gas production in Osage county has occurred for over 100 years, with the development of around 39,000 wells, mostly at shallow depths of around 300 to 700 m. Due to a lack of 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 effect of spills and leaks in this area indicate significant amounts of salts from produced water releases, and 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, thus 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, and demands 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 related to shale gas development. To put these into context this section will briefly outline current practiced 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 625,000 active underground petroleum storage tanks in the U.S., with an additional 1.7 million inactive ones. From these there were more than 475,000 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 groundwater contamination.

There are few publications that discuss the effect of petrol stations on the contamination of surface water and soil environment. However, Borowiec et al. (2008) studied several soil samples in Poland to 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 in their paper they record approximately 6700 petrol stations and 56 fuel bases in Poland, with 27,000 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 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 state that it is possible the increase concentration is enough to increase the risk of the inhabitants getting cancer, they specifically mention 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 risks to the public can be reduced by improving the 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 regards to storage tanks, including installations of multi-layered storage systems. Good practice would be 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, 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 groundwater 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, with about 70 officially documented sewer-related waterborne disease outbreaks in the UK over the past 60 years (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 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 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 these leaks 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) indicate the causes of these structural defects can be 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 UK urban areas (Ellis et al., 2010).

Bishop et al. (1998) suggest a number of recommendations to reduce groundwater contamination including, (1) modifying the existing criteria for the service performance grading of existing sewers, (2) improve construction of new sewers, (3) increase groundwater monitoring, and (4) risk assessments for new groundwater 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 those 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 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 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 with further production they gave a number of recommendations for future activities. There initial recommendation was to identify and evaluate the hazard and exposure potential posed by the 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 6 ft high), 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 FOOTPRINT

4.1 Introduction

With the development of shale gas landscape disturbance is inevitable as numerous wells from many well pads are required to intersect the gas bearing formation(s) in order to be economic. The amount of land disturbed will vary depending on, amongst other considerations, the well pad size, the number of wells per pad, the well pad density and the specifics of the shale play that is being developed (Baranzelli et al., 2015). The increased development of shale gas exploitation in the U.S. has led to advancements in drilling technology; a common approach in recent times is drilling multiple horizontal wells from a single pad. This method along with optimising placement of these multi-well pads reduces cost, time and minimise the number of surface locations required while increasing the bottom hole contact of the shale resource (Yu & Sepehrnoori., 2013). However, even with these technological advancements the footprint from well site infrastructure is still significant and causes natural landscapes to be interrupted, and has a substantial impact on agricultural and forested land.

Few scientific studies have recorded the footprint and impact on the land from shale gas sites. However, there appear to be four exceptions that investigate the impact of land use and land cover change and the accompanying ecological, physical and aesthetic changes that can result from well site development and associated infrastructure. These studies are Drohan et al. (2012); Johnson et al. (2010); Slonecker et al. (2012) and Jantz et al. (2014), these will be carefully reviewed in this chapter.

4.1.1 Potential impacts from infrastructure

In this chapter we review the average total footprint of a well site, this is achieved by assessing the average well pad size and how much additional land is required for pads infrastructure, such as access roads, pipelines etc. We then review the literature to assess the impact of the well site footprint on the land, with particular focus on existing cultural, historical and recreational resources, agriculture and biodiversity. Finally we review if the footprint impact from shale gas development is comparable to other industries and what mitigations processes industry currently uses to reduce the impact on the land.

4.1.1.1 Footprint Assessment

Well pad size:
The size of a well pad is dependent on site topography, number of wells per pad and pattern layout, with consideration given to the ability to stage, move and locate needed drilling and hydraulic fracturing equipment (DEC, 2015).

In recent years the mean and maximum number of wells per pad has increased (Drohan et al., 2012), due to the advancements in technology and the gas industry understanding that greater consolidation of infrastructure is more efficient and economical (Johnson et al., 2010). Johnson et al. (2010) documents a mean of 2 producing wells per pad, whereas Drohan et al. (2012) reported more than 75% of pads to have just 1 or 2 wells per pad. Jantz et al. (2014) found a slightly higher mean of 2.45 producing wells per pad, with a standard deviation of 1.45 wells per pad. For producing and permitted wells they recorded a slightly higher mean of 4.67 wells per pad, with a standard deviation of 2.64 wells per pad (Jantz et al., 2014). It is worth noting that Jantz et al. (2014) study focuses on the recently developed Bradford County, thus these results represent a more accurate picture of current patterns in development and consolidation of infrastructure.

Although it is common to have single well pads in the U.S. it is unlikely this will be the case in Europe. As unlike the U.S. there is less land available and land is more densely populated, especially in countries such as the UK, and so small footprints are essential and revelant restrictions will be put emplace. In the UK, Cuadrilla who are investigating potential production in to the Bowland Shale in Lancashire has already stated if they get permission to continue they intend to have 10 wells per pad at its site to reduce the footprint (Regeneris, 2011).

As mentioned the number of possible wells associated with a pad, overall site and pad sizes are variable, with ICF (2009) reporting site dimensions (pad and lined pits for water storage, but excluding access roads) for horizontal well pads in the range 300’ by 250’ (91 m x 76 m / 0.69 ha) to 500’ by 500’ (152 m x 152 m / 2.3 ha). A ‘rule-of-thumb’ was suggested, based on discussion with operators of assuming an initial, single-well pad size of 350’ by 400’ (106 m x 122 m / 1.3 ha), which increased the largest dimension of the pad by 50’ (15 m) for each well present (i.e. an increase of 400’ x 50’ (122 m x 15m / 0.18 ha) per well) – to give a total of 2.1 hectares for a 6-well pad. Broderick et al. (2011) suggested a range for a 6 well pad of between 1.5 – 2.0 hectares, but land taken for a single-well pad being 0.7 hectares. Regeneris (2011) states that a single test well pad of 0.7 hectares could eventually support commercial operation of 10 wells spaced out across the total site area. King (2012) states that a single 2.4 hectare pad supporting multiple wells could collect gas from an area 1000x larger than its footprint (2400 ha).

Access roads:

The location of the well pads and proximity to existing roads impacts considerably on the amount of additional road infrastructure required and thus the footprint on the land. The actual size of an access road is determined by the size of equipment to be transported to the well, distance of the well pad from existing roads and the route dictated by property access rights and environmental concerns (DEC, 2015).

Access road widths tend to range from 20’ to 40’ (6.2 to 12.4 m) during the drilling and fracturing phase and from 10’ to 20’ during the production phase (DEC, 2015). It has been calculated that for every 150’ by 30’ wide access road adds about one-tenth of an acre to the total surface acreage distribution attributed to the well site (DEC, 2015).

Permit applications for Marcellus horizontal wells prior to 2009 recorded road lengths ranging from 130’ to approximately 3,000’ (DEC, 2015).

It is difficult to accurately review the additional footprint required for well site access roads because a number of publications have not distinguished between acreage required for general infrastructure (e.g. pipelines and storage ponds etc.) and acreages specifically required for roads. However, a few publications have made this distinction including Jantz et al. (2014), they found the mean additional acreages for access roads to be 3.01 acres, with a range of 0.05 to 16.90 acres (0.02 to 6.8 ha). Whilst Jiang et al. (2011) recorded a slightly lower average of 1.43 acres, with a range of 0.1 to 2.75 acres.

The footprint from access road development in the U.S. is likely to be much greater than what we could expect in Europe, especially within the UK. This is mainly due to the fact that the UK is much smaller than the U.S. and nowhere is a vast distance from a road.

Setback Requirements:
Regulatory bodies enforce setback requirements on shale gas developments to provide additional protection of the most sensitive ecological species, water resources, personal property, public property and the health and safety of the public at large (Eshleman & Elmore, 2013). The additional land required for setback restrictions can greatly increase the size of the well site footprint.

Within the UK and several other European countries there is no legislative or national planning policy requirements on minimum setback distances, setbacks are designated on a site to site basis (Cave, 2015). However, in the U.S. where shale gas has been established for many decades setback restrictions have been put in place but vary from state to state. In certain locations the setbacks should be measured from the individual well pads (or disturbed areas for each pad), whilst other areas from the farthest extent of hydraulic fracturing (Eshleman & Elmore, 2013). Although the setback restrictions in the U.S. vary, most surveyed in Richardson et al (2013), (20, or about 65%) have building setback restrictions, ranging from 100 feet to 1,000 feet from the wellbore, with an average of 308 feet (Richardson et al., 2013).

Many states base their setback restrictions on the local conditions such as population density. Highly urbanised areas within Ohio and Colorado tend to have greater setback restrictions (Richardson et al., 2013). Setbacks can often be vague and complex, for example building setback regulations within the U.S. may apply to specific structures such as schools and hospitals, or it may apply to all “occupied dwellings” (Richardson et al., 2013). Wyoming’s setback restrictions include any structure “where people are known to congregate”, in Colorado a 500 foot setback is standard, however if drilling falls within a “high occupancy” building a 1,000 foot setback is required, whilst Louisiana has different setback regulations dependent on if a building is owned by a person who is a party to a gas lease on the same property (Richardson et al., 2013).

Well pad spacing:
The number of wells and well sites that exist per acre are determined by the gas reservoir, geology and productivity, planning permits and legal well spacing requirements set by the government (DEC, 2015). Investigations into well pad spacing for the Maryland Department of the Environment indicates that spacing multi-well pads in dense clusters, with well pads located as far apart as is technically feasible makes maximum use of horizontal drilling technology and could minimizes the footprint on the land (Eshleman & Elmore, 2013).

The average drilling site in the U.S. is 640 acres, well spacing within these sites is regulated by (1) specific distances between wells, and (2) minimum distance from unit boundaries (Richardson et al., 2013). In the following states of Arkansas, California, Kentucky, Maryland, New Jersey, Ohio, Oklahoma, South Dakota, Texas, Utah, and Wyoming well spacing is determined by specific minimum distances between wells, these distances range from 100 to 3,750 feet (Richardson et al., 2013). However, these specified distances can be superseded by field-specific requirements (Richardson et al., 2013).

4.1.1.2 Cultural, historical and recreational resources

The footprints of existing and would-be shale gas sites have the potential to be located close to or on a variety of cultural, historical and recreational resources. During the development of these well pad a number of these sites and resources (e.g. national and historic sites of interest, nature reserves, national parks, forests, protected wetlands and moorlands, etc) could be at risk of damage, either through physical, visual, auditory, or olfactory degradation (Eshleman & Elmore, 2013).

Many of the sites mentioned above, such as the historical landmarks and areas of natural beauty (e.g. lakes, waterfalls etc) attract tourists to the area, which in turn generates income for the nearby communities. A report by Oxford Economics, recorded Pennsylvania saw 192.9 million domestic and international travellers visit the state in 2013, generating an estimated $68.4 billion in total economic activity (Oxford Economic Company, 2015). The development of shale gas sites could upset the natural landscape leading to a decline in the quality of the resource which attracts people to the area, leading to a reduction in the number of visitors (Eshleman & Elmore, 2013). In July 2015 the UK government committed to protecting National Parks, Broad and World Heritage Sites and Areas of Outstanding Natural Beauty by commenting in their Draft Regulations that the process of hydraulic fracturing can only occur 1200 m below these sites (DECC, 2015).

4.1.1.3 Land use change

A major concern and threat to biodiversity in the U.S. is the disruption of agricultural land and fragmentation of forested land due to the construction of well pads, roads, pipelines and other built infrastructure. The extent to which the well site footprint will impact various land types is highly dependent on the location and the scale of the development. There are few publications that attempt to quantify the impact of well site footprints on land use change, however there are a couple of exceptions including Drohan et al. (2012), Slonecker et al. (2012), Johnson et al. (2010) and Jantz. (2014). Baranzelli et al. (2015) also attempts to assess the potential impact of different development rate scenarios in the Baltic Basin on land use if hydraulic fracturing were to go ahead in Northern Poland.

Agricultural Land

Drohan et al. (2012) studied the effects of drilling in Pennsylvania on land cover changes due to well pad development with specific emphasis on forest fragmentation and forest loss in headwater. They also considered whether the developments were on private or public lands (Drohan et al., 2012). They found that in Pennsylvania the majority of shale gas developments were built on private land, with only 10% occurring on public lands (Drohan et al., 2012). They also concluded that since June 3, 2011 there have been 2931 wells drilled and 1465 pads constructed, of these developments approximately 45-62% pads occur on agricultural land and 38-54% in forested land (Drohan et al., 2012).

Between 2004 and 2010 the U.S. Geological Survey studied the Pennsylvanian counties of Bradford and Washington with regards to changes in land cover and land use related to natural gas extraction (including hydraulic fracturing and coalbed methane) within the Marcellus Shale. The report focused on investigating the impact on the ecosystem at landscape and watershed scales. Slonecker et al. (2012), analysed land use change associated with the development of well pads and their associated infrastructure (e.g. roads, pipelines and water storage facilities) using aerial photographs (Slonecker et al., 2012). They concluded that within Bradford County a total of 3213.11 acres of land had been disturbed, of which 1834.51 acres was caused by well site infrastructure and roads, a further 3030.5 acres by water impoundments (Slonecker et al., 2012). With regards to land cover change within the two counties, they found that natural gas development had the largest impact on agricultural and forest lands (Slonecker et al., 2012).

Similar to Slonecker et al. (2012), Jantz et al. (2014), also assessed the land use changes due to natural gas drilling in the Marcellus Shale within Bradford County (the county with the most permitted gas wells in Pennsylvania). To access the land use changes associated with Marcellus Shale drilling their study utilized publically available data sets, aerial photography and other remotely sensed data (Jantz et al., 2014). Their study concluded that agricultural land was the most favoured land type to be converted and based on the aerial imagery from 2010 about 459 acres (67% of total change) of primary agricultural land had been cleared for well pads, access roads, and impoundment ponds

(Jantz et al., 2014). In terms of future change they estimated that if all the permitted wells in the county were drilled and developed roughly 620.60 and 3983.50 hectares of additional land use change could occur (Jantz et al., 2014).

Baranzelli et al. (2015) developed different scenarios related to the rate at which shale gas development in the Baltic Basin, Northern Poland might impact land use (Baranzelli et al., 2015). Their conclusion indicated that in the final year of their simulations, between 7% and 12% of the land taken for industrial activities could be taken up by shale gas development (Baranzelli et al., 2015). The majority of this land will be existing arable land, followed by forest and other natural areas, and to a lesser extent pastures (Baranzelli et al., 2015). They indicate that land competition with regards to change of agricultural land could potentially become important at a local level (Baranzelli et al., 2015).

Forest fragmentation

Slonecker et al. (2012) highlighted in their study on Bradford and Washington Counties that pipeline infrastructure and construction was the greatest contributor to forest loss and fragmentation (Slonecker et al., 2012). They concluded that interior forest loss is approximately twice that of overall forest loss, and the gain in edge forest approximates that of overall forest loss (Slonecker et al., 2012).

Johnson et al. (2010) evaluated forest loss and fragmentation due to drilling in the Marcellus shale, and its impacts on habitats of rare species and freshwater in Pennsylvania. This study used aerial photos to assess the current impact and project the impact of possible future natural gas developments. They determined that the total average spatial disturbance for the Marcellus Shale well pads in forested area was roughly 30 acres, this was calculated by the direct impact of a well pad being assessed at 9 acres and the indirect impact being assessed at 20 acres (Johnson et al., 2010). In this case study ‘direct impact’ refers to the actual forest cleared for the well pad itself and the associated infrastructure, whilst ‘indirect impact’ refers to the effects on adjacent land not necessarily directly cleared but impacted due to the creation of new forest edges (Johnson et al., 2010). They concluded that as of 2010, 3500 acres of Pennsylvania forest had been cleared for shale gas development (Johnson et al., 2010). An additional 8500 acres of land located within 91.4 m (300’) of well pads, roads, and other infrastructure, was also disturbed, highlighting the impact on habitats and the extent of forest fragmentation due to hydraulic fracturing in the area (Johnson et al., 2010). From these results they then went on to project impacts from future developments. These projections were based on the predicted number of drilling rigs in the area, the number of wells per pad, and an analysis of areas most likely to be targeted (Johnson et al., 2010). Johnson et al. (2010) calculated by 2030 between 34000 and 82000 acres of forested land could be cleared by new Marcellus gas development in the state of Pennsylvania.

Jantz et al. (2014) recorded forest land being the second most converted land type for well pads in Bradford County, with roughly 198 acres (29% of total change) having been converted. More than 50% of Bradford County is covered by forested land yet only 29% of the time this is converted, compared to 67% of agriculture. It is apparent that gas companies prefer to develop agricultural land as it is more cost effective, it is cheaper to and less invasive to clear and restoration and reclamation post-drill is significantly easier (Jantz et al., 2014).

Total Suspended Sediments

As with traditional construction, well site development (including changes to local roads, pipeline construction and other shale gas development activities) can lead to an increase in the level of total suspended substances in local water bodies (Olmstead et al., 2013). Well pads and their associated footprint are often located close to streams, increasing the probability of potential damage to surface waters, and the potential for sedimentation (Entrekin et al., 2011).

Williams et al. (2007) evaluated the sediment runoff from gas well sites in Denton County, Texas. They reported that Texas gas well sites produced sediment loads of 54 t/ha/year, these results are comparable to small traditional construction sites. Pad sites exhibit a “site stabilisation” effect, this is characterised by construction causing an initial pulse of sediment runoff but over time the amount of mobilised sediment decreases (Williams et al., 2007). However, the disturbed area surrounding the pad sites appear to supply a greater amount of sediment runoff for a longer period of time (Williams et al., 2007).

McBroom et al. (2012) assessed the impact of natural gas developments on soil erosion and surface water quality in East Texas. They found that in the well site study areas there was a significant increase in bare, compacted soil surface, and thus runoff was much more frequent. In addition, the significantly higher bulk density on these well sites resulted in less infiltration (McBroom et al., 2012). Unlike Williams et al. (2007), McBroom et al. (2012) found that the well site footprint continued to cause erosion years after the initial development of the site, with little evidence of natural stabilization and natural vegetation returning due to the poor quality of the fill material.

Soil compaction

The development of a well pad, involves repeated truck and equipment traffic, along with pipeline and road development and maintenance which lead to land disturbance and soil compaction. Jantz et al. (2014) comments on how disruption and subsoil compaction can lead to structural changes within the soil, upsetting natural biological processes. This disruption can have significant implication for farmers, lowering crop production and causing severe environmental degradation (Jantz et al., 2014). Topsoil compaction can reduce plant productivity in the short term, whilst subsoil compaction can modestly reduce productivity for many decades (Duiker and Micsky., 2009). As mentioned above, subsoil compaction can also contribute to prolonged periods of surface soil saturation and conversely surface runoff and erosion (Duiker and Micsky., 2009).

4.1.1.4 Aesthetic values

The visual impact from well site footprint is determined by the overall levels of drilling activity, the spacing restrictions between wells, the distance of drilling sites from other sites of interest and the effort drilling companies go to minimise drilling activities, e.g. camouflaged infrastructure. Little has been written in the literature to the extent of the impact on the landscape but is a cumulative impact, drilling across large areas will produce a more pronounced impact on the visual environment.

The visual impact from shale gas sites reduces with time, once the development phase is complete land reclamation will occur and well pad dimensions are thought to reduce to 200' by 250' (61m x 76 m / 0.46 ha) (ICF, 2009).

4.2 Impact from comparable industries

The impact on the land from wind power varies depending on turbine spacing and their configuration (Fthenakis & Kim., 2009).

Similar to shale gas development wind farms require significant infrastructure which leave a footprint on the land. Wind farms comprise of the wind turbines themselves, interconnecting cables, transformer stations, meteorological masts and ancillary infrastructure including onshore access roads and occasionally visitor centres (Drewitt & Langston, 2006). An onshore wind turbine can have a tower height of 80 m and a rotor diameter of 90 m, resulting in an overall height of 125 m (400 feet) (Drewitt and Langston, 2006).

The 'direct impact' from forest clearance for the wind turbine and associated infrastructure was calculated at 1.4 acres and 0.5 acres respectably (Johnson, 2010). Whilst 'indirect' forest impact from new edges is thought to affect 13.4 acres.

The development of wind turbines require heavy cranes and trucks carrying heavy components, thus access roads are required and need to be sufficiently wide (typically 15 feet) with strong pavements to allow for such transport (Van Haaren & Fthenakis., 2011). The development of these roads typically involves flattening and compressing the ground surface and then depositing gravel on top to restrict "slipperiness" (Van Haaren & Fthenakis., 2011). The size of the facility will heavily influence the size of the footprint, thus a facility with hundreds of turbines will require a larger and more complex road network which will negatively impact the land and biodiversity (Kuvlesky et al., 2007).

The impact of wind turbines on cultural, historical and recreational resources is much the same as the impact from shale gas sites. In a similar manner the spatial disturbance for wind energy development in a forested area can be compared with the land disturbed for the development of shale gas extraction (Johnson, 2010).

As with the development of shale gas sites, the visual impact of wind turbines is subjective and impacted by sociological factors. Whilst some people view them negatively others believe they are pleasant and add to the local landscape. As with shale gas there is a concern that the turbines damage local tourism.

4.3 Mitigation measures

To reduce the impact of well site footprint on the land a number of mitigation strategies can be put in place and regulations can be enforced. Eshleman and Elmore (2013) study on the Marcellus Shale gas development in Maryland has been extremely useful when reviewing mitigations strategies and best management practices. Their report goes into detailed recommendations on a number of areas of concern.

4.3.1 Footprint size

Minimising the number and density of well pads along with careful consideration to spacing (e.g. co-location of infrastructure wherever possible, using existing right of ways) could allow for development that disturbs less than 1-2% of the land surface, even when including additional infrastructure such as access roads, pipelines etc. (Eshleman & Elmore, 2013). The Maryland Department of the Environment reassure that a disturbance of 1-2% of the land surface is quite low compared to other types of development (e.g. suburban residential, surface mining, etc.) (Eshleman & Elmore, 2013).

Restrictions on the number of wells pads allowed to be developed also reduce the impact of well site footprint on the land. Pennsylvania's newer leases hold operators to a maximum number of well pad locations, or total disturbance of predefined acreage, whichever happens to occur first (Eshleman & Elmore, 2013). If an operator wishes to deviate from the well pad number or acreage, these newer leases require a waiver or possibly state forest approval to be obtained (Eshleman & Elmore, 2013).

To reduce the well site footprint wherever possible existing roads should be used, however, where new roads are essential potential footprint impacts should be assessed and an attempt to minimise further surface exposure should be a primary concern (Eshleman & Elmore, 2013). If possible single track roads should be developed rather than double track, although single tracks require better coordination via radios with regard to passing they can significantly reduce surface footprint (Eshleman & Elmore, 2013). Roads need to be planned and constructed appropriately to avoid potential environmental impacts, especially in environmentally sensitive areas and location where erosion potential is higher. In addition to this, roads can be replaced by pipelines to help reduce drilling related traffic, dust and street erosions (Jenner & Lamadrid, 2013).

Although there are concerns with regard to potential negative impacts from the footprints well site infrastructure creates. There is the capacity for the well site developments to have a positive impact on nearby wildlife, habitats, ecosystems and biodiversity in the area (Eshleman & Elmore, 2013). For example, through developments there is the opportunity to make improvements through land management, land restoration and habitat creation (Eshleman & Elmore, 2013).

4.3.2 Cultural, historical and recreational resources

Eshleman & Elmore, (2013) best practise management in Maryland report clearly states that protection of cultural and historical resources begins with the careful process of identifying all the relevant sites that could potentially be affected by the shale gas development (Eshleman & Elmore, 2013). They recognise there is often a lack of knowledge with regards to the location and the existence of many cultural and historical sites. To aid in the identification of sites it is recommended that operators consult with the local historical trusts, the planning departments, and other county and local historic preservation offices during the planning and permit application process to ensure that no eligible or existing cultural or historical sites could potentially be disturbed or damaged by any aspect of the shale gas development (Eshleman & Elmore, 2013).

Eshleman & Elmore, (2013) indicate the impact of the well site footprint on public recreational resources can also be controlled via identification and mapping of all the sites potentially at risk. National parks, local parks, scenic trails, forests, protected wetlands and moorlands etc. require careful documentation so that mitigation practises such as the introduction of setback restrictions can be put in place (Eshleman & Elmore, 2013). The Pennsylvania DCNR Bureau of Forestry requires a 300' setback from any state picnic area, trail road of historic value, tree plantation, overlook, vista, fire tower site, or existing right of way; these precautions also give forested recreational areas additional protection of public safety through conflict avoidance (Eshleman & Elmore, 2013).

New York State, suggested oil and gas sites are reviewed on a case by case basis. When permits are granted they come with a number of restrictions and mitigation requirements to protect the impacts on cultural, historical and recreational resources (Eshleman & Elmore, 2013). Depending on the location and the type of resource the following mitigation actions may be required: (1) visual screening of drilling operations; (2) an increase in minimum setback restrictions for specific resources; (3) operation times restrictions (e.g. avoid operations that are noisy in peak tourist seasons etc.); and (4) landscaping reclamation requirements (Eshleman & Elmore, 2013). Additional mitigation actions are known to include, relocation of infrastructure found damaging by local residence or resource managers, use of camouflage on the infrastructure to try to reduce visual impact, paint schemes, evergreen buffers, maintain low facility profiles, downsizing the scale of a project, using alternative technologies, using non-reflective materials and monitoring off-site lighting (Eshleman & Elmore, 2013).

4.3.3 Land use change

The extent to which shale gas extraction should be permitted to fragment natural areas and forest needs to be limited and carefully regulated. To a certain extent this can be achieved during the planning and permit application process. To protect prime soil in the U.S. it has been advised that soil conditions be evaluated as part of the planning process (Eshleman & Elmore, 2013). Thus when prime agricultural soils and prime farmland are detected they can be avoided. Soil found to be highly erodible can also be detected and precautions can be put in place to prevent erosion and sedimentation problems occurring in these locations (Eshleman & Elmore, 2013). In addition to well sites being carefully selected well pads, infrastructure, roads, and utility corridors should, where possible, be sited along field edges, thus avoiding bisection of fields (Eshleman & Elmore., 2013).

Development and construction of shale gas sites have shown to increase TSS in local water bodies and gas well sites have been shown to produce sediment loads comparable to traditional construction sites, but regulation on erosion and sediment control with regard to shale gas sites are lacking (Olmstead et al., 2013). Non-oil and gas construction sites in Pennsylvania larger than 1 acre must install erosion and sediment control infrastructure (Olmstead et al., 2013). However, shale gas sites are not required to file erosion and sediment control plans unless larger than 5 acres (Olmstead et al., 2013). In general, most shale gas sites are not large enough to activate this requirement, although many operators do install stormwater control infrastructure for Marcellus Shale developments (Olmstead et al., 2013). To reduce the amount of TSS in local water bodies it is possible striker regulations need to be enforced. Baranzelli et al. (2015) concludes that oil and gas production methods require a more effective regulatory framework which establish clear restrictions which relate to all the main areas of concern with regards to shale gas extraction. They indicate a set of proper regulatory tools should be employed, including strict licensing on regulations and project based evaluations (Baranzelli et al., 2015).

With the development of shale gas sites some soil compaction is inevitable; one can only hope to restrict the size of the impact. Again this can potentially be mitigated by careful placement of well pads, infrastructure, roads, and utility corridors, where possible these should be sited along field edges, thus restricting the amount of land impacted (Eshleman & Elmore., 2013).

4.3.4 Aesthetic value

As mentioned previously in more recent times multi-well drilling is becoming more common as it is more efficient and cost effective. Multi-well pads also significantly reduce the visual impact of shale gas sites, as they occupy a smaller footprint (DECC, 2012).

5 TRANSPORT

5.1 Introduction

Aside from the impacts that can directly be associated with the spatial footprint of a well pad site, 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.

Broadly these impacts fall into the following categories:

- **Direct road and traffic management concerns, including:**
  - Additional disruption, congestion and delay to other road users
  - Safety issues regarding the use of vehicles on inappropriate roads (i.e. heavy traffic on rural roads, or in sub-urban areas)
  - Damage to pavement surfaces, or outright structural damage to roads or bridges
  - Extra burden on vehicular regulatory and law enforcement authorities
  - Movement of proppant additive materials to well sites, or potentially hazardous waste material from well sites to processing facilities.
- **Pollution concerns, including:**
  - Greenhouse Gas Emissions (GHG) – Primarily of Carbon Dioxide (CO_2), with minor components (<1% of overall CO_2e) of Methane (CH_4) and Nitrous Oxide (N_2O).
  - Local Air Quality (LAQ) Emissions of Regulated Pollutants – including Oxides of Nitrogen (NOx – especially Nitrogen Dioxide (NO2), Particulate Matter (PM), Carbon Monoxide (CO), various hydrocarbon species (HC)/volatile organic compounds (VOCs), Sulphur Dioxide (SO_2), Benzene and metals (Arsenic, Cadmium and Nickel).
  - Unregulated pollutants – including 1,3-Butadiene and Ammonia (NH_3).
  - Noise and Vibration – noise is a direct contributor to annoyance, sleep disturbance and has been linked to learning difficulties in children, and various cardiovascular effects. Vibration may be of import to sensitive sites (e.g. schools, hospitals and other medical facilities)
  - Contaminated water runoff from roads, either from normal operation of the vehicles itself, or from unsanctioned waste disposal activities
  - Impacts of the above to agriculture or biodiversity
  - Exacerbating impacts of congestion, leading to disproportionate increases in the above
- **Additional concerns, including:**
  - Changes to the employment opportunities, culture or heritage of a region – possibly associated with an influx of a large number of temporary workers (NYSDEC, 2015a).

- Crime and security issues – again possibly associated with large numbers of temporary workers (NYSDEC, 2015a).
- Community severance
- Visual intrusion

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).

5.1.1 Scale of the Issue

In order to understand the scale of potential issues, the amount of traffic generated by a well or well pad represents a fundamental building block in assessing the magnitude of impacts. As well as the overall demand for transport, the temporal profile of that demand needs to be considered, in order to understand the *intensity* of shale gas-related traffic at a given point in time. Broadly, the construction and operation of a well pad site may be broken into the following steps (AEA, 2012):

1. Well pad site identification and preparation;
2. Well design, drilling, casing and cementing;
3. Technical hydraulic fracturing;
4. Well completion and water flow-back;
5. Well production;
6. Well abandonment.

AMEC (2013) presents a similar, but slightly more detailed list of stages to AEA, as part of the Strategic Environmental Assessment (SEA) examining issues surrounding the licensing of onshore oil and gas exploration in the UK. Stages, and sub-stages considered include:

1. Non-Intrusive Exploration:
   a. Site identification, selection, characterisation;
   b. Seismic surveys;
   c. Securing operational permits.
2. Exploration Drilling:
   a. Pad preparation, road connections, baseline monitoring;
   b. Well design and construction;
   c. Trial hydraulic fracturing;
   d. Well testing and flaring.
3. Production development:

a. Pad preparation, baseline monitoring;
b. Facility design and construction;
c. Well design and construction;
d. Hydraulic fracturing;
e. Well testing and flaring;
f. Pipeline connections (water in/out, gas out);
g. Possible re-fracturing.

4. Production/operation/maintenance:
   a. Gas production;
   b. Disposal of wastes;
   c. Power generation, chemical use, reservoir monitoring.
5. Decommissioning:
   a. Well plugging;
   b. Site equipment removal;
   c. Environmental and well integrity monitoring.
6. Site Restoration and relinquishment:
   a. Survey and inspection;
   b. Site restoration and reclamation.

AMEC (2013) notes that exploratory wells (Stage 2) may move through the subsequent stages as part of either long-term production testing, or site redevelopment to full production capabilities, both being subject to new consents and planning permission in the UK).

All stages will have an associated transport demand – though the general consensus in all literature examined is that the vast majority (70%+) of road traffic associated with shale gas operations arises during the movement of water and sand proppant to the site for injection to wells as part of the fracturing process, followed by movement of ‘flow-back’ or ‘recovered’ fluids away from the site, prior to full gas production (i.e. Stages 3 and 4 from the AEA document, or 2c and 3d from AMEC).

5.1.2 Water demand: Drilling and fracturing

The volume of water (and proppants) required to fracture a well, and the amount of flow-back, or produced water after fracturing, ultimately depends on the underlying geology of the site – e.g. on the depth and thickness of shale deposits. Literature is therefore variable as to water demands, and therefore estimates of the tanker traffic required are also variable.

Initial drilling of wells, prior to any fracturing procedure, has an associated demand for coolant water. Goodwin et al. (2012) report initial drilling as requiring on average 77000 gallons (US) (290m^3) for a vertical well and 130000 gallons (US) (492m^3) for a horizontal well, based on data from 445 wells in Wattenberg Field, Colorado. Jiang et al. (2013) cite values of 300 – 380m^3 of drilling water required, with a median of 320m^2 for Marcellus shale wells.

The need for large volumes of water for the fracturing process drives the major demand for surface transport to hydraulic fracturing sites. The amount of water required is highly dependent on the type of well (vertical or horizontal, as noted above) and the underlying geology of the drill site – though depth is a key determining factor (Gény, 2010).

The US EPA (2010) suggests that ’50000 to 350000 gallons (US)’ (190 – 1325m^3) of water are required for one well in a coal-bed formation, but for shale gas that value increases to ‘2 million to 5 million gallons (US)’ (7570 – 18930m^3) per well. Abdalla and Drohan (2010) cite values of ‘4 million to 8 million gallons (US)’ (15140 – 34000m^3) for Marcellus shale wells, required in the period of a single week, whilst Jiang et al. (2013) cite a range from 6700 to 33000 m^3, with a mean of 20000 m^3 for Marcellus shale wells. Jiang et al. (2013) also report using a normal distribution with mean 15000 m^3 and overall range from 3500 to 26000 m^3 to model freshwater (i.e. non-recycled water) demand for each well.

King (2012) provides the following table (Table 5.1) of average water demand, for both drilling and fracturing (NB: Values have been converted from US Gallons, rounded to nearest 10 m^3):

Table 5.1: Average water demands per Shale Well for Drilling and Fracturing (Source: King, 2012).

Unconventional development	**Average freshwater volume for drilling, m^3**	**Average freshwater volume for Fracturing, m^3**	**Saltwater volume for Fracturing, m^3**
Barnett	950	17410	-
Eagle Ford	470	18930	-
Haynesville	2,270	18930	-
Marcellus	320	21200	Increasing use
Niobrara	1140	11360	-
Horn River (EnCana and Apache)	950	-	Up to 45420

Unfortunately, for European operations, shale depths, especially in Eastern Europe may be up to 1.5x deeper than those found in the US and may require additional demands for water (Gény, 2010), though Gény also notes that the cost of water is typically ‘10x higher’ in Europe than in the US, driving a greater need to reduce use, and re-cycle wherever possible. More encouragingly data from the Preese Hall site suggested lower requirement of 8400 m^3 for a single test well, implying a total of 84000 m^3 for a 10-well pad (Broderick et al., 2011). The UK Department for Energy and Climate Change (DECC) suggest values for a fracturing operation of 10000 to 30000 m^3 per well, and comment that operating a well for a decade has the same water demand as ‘a golf course for a month, or a 1000 MW coal-fired power station for 12 hours (DECC, 2014). For their modelling activities Broderick et al. (2011) suggest that each stage of a fracking operation for a single well will require between 1100 and 2200 m^3 of water, leading to a total demand of 9000 to 29000 m^3 per well, or 54000 to 174000 m^3 for a six-well pad. These values were then used to provide carbon emissions estimates for a typical UK well. The European Parliament report '*Impacts of shale gas and shale oil extraction on the environment and on human health'* (EP DGIP, 2011) also summarises water-demand data from the states, based on site and region, as per King (2012). See Table 5.2:

Table 5.2: Water Demand of Various Wells for Shale Gas Production [Source: EP DGIP, 2011].

Site/Region	**Total Water per Well, (inc. drilling)**	**Fracturing water per well**	**Data source and year**
Barnett Shale	17000 m^3		Chesapeake Energy 2011
Barnett Shale	14000 m^3		Chesapeake Energy 2011
Barnett Shale	No data	4500 m^3 – 13250 m^3	Duncan 2010
Barnett Shale	22500 m^3		Burnett 2009
Horn River Basin (Canada)	40000 m^3		
Marcellus Shale	15000 m^3		Arthur *et al.* 2010
Marcellus Shale	1500 m^3 – 45000 m^3	1135 m^3 – 34000 m^3	NYCDEP 2009
Utica Shale, Québec	13000 m^3	12000 m^3	Questerre Energy 2010

Note: Regarding 'per well' values, as there may be a number of wells in operation on a particular pad, care must be taken to scale demand for (and waste produced by) fracturing fluids appropriately. The profile of on-site water demand, and hence the intensity of water deliveries by truck, may be buffered somewhat by the presence of on-site water storage facilities (see section 5.3).

5.1.3 Other material, fluid and chemical demands

For a variety of reasons various substances are added to the water in a fracturing operation. Primarily 'proppants' are added to assist in keeping fractures open once they are formed. Generally proppants are formed from various sands or man-made ceramics. Other additives may include: friction reducers and surfactants, clay stabilisers, corrosion inhibitors, scale inhibitors, crosslinking agents (to increase viscosity and improve proppant transport), breakers (to reduce viscosity), acids and bactericides (Broderick et al., 2011). Generally fracturing fluid may consist of greater than 90% water, 9.5% proppant and 0.5% other chemical additives by volume. Data from previous, current and proposed sites in the UK operated by Cuadrilla (Cuadrilla 2014a; 2014b) suggest fracking fluids with greater than 99.95% water and proppant, and 0.05% chemical additives by volume. Generally fracturing additive requirements in exploratory wells in the UK have been lower than typically used in the US (Broderick et al., 2011).

If a base requirement of 20000 m^3 of water and 5% by volume proppant is assumed, this equates to a transportation need for delivery of 1000 m^3 of sand, or 1700 tonnes of sand (assuming dry sand with density 1700 kg/m^3). Unfortunately, many of the additive chemicals are hazardous or toxic – requiring separate, carefully controlled delivery to site. NY DEC (2009) states that most transportation and on-site storage of chemicals is done in 1 – 1.5m^3 high density polyethylene (HDPE) steel caged containers.

5.1.4 Flow-back material

The US Environmental Protection Agency (US EPA, 2010) suggests that the rate recovery of injected fluids from hydraulic fracturing is variable – ranging between 15 and 80%. NYCDEP (2009) suggests use of a 'worst case' option of 100% in the calculation of tanker demand, whilst NYSDEC (2011; 2015a) reports 9 to 35% for Marcellus shale wells in Pennsylvania. Cuadrilla report values of 20 to 40% for returned waters (Cuadrilla, 2014b). The variability in reported flow-back water percentages makes modelling transport demands problematic, potentially almost doubling overall traffic in the 'worst case' scenario.

Using the US EPA (2010) values above, Broderick et al. (2011) give flow-back per well as being between 1300 and 23000 m^3 of fluid (or 7900 to 138000m^3 for a six-well pad). For further calculations a rate of 50% was assumed.

As with initial water demand, the actual intensity and duration of surface transport profiles associated with flow-back material will therefore depend heavily not only on the amount of waste produced, but also on the available storage of that waste (if any) on site. Broderick *et al.* cite one operator as suggesting that a typical waste-water pit for flow-back fluid form a single well as having a volume of 2,900 m^3 (with dimensions approximately 10m x 10m x 3m deep), hence for a multi-well pad, with larger water demands, further on-site storage would be necessary. Alternately, rather than being stored in on-site lined pits, on-site tanks may be used.

The availability of on-site storage would also influence the operational profile of wells at the site, given that ability to operate wells simultaneously may be curtailed by available waste storage capacity.

The overall demand profile is also potentially non-linear, given the bulk of flow back occurs immediately following the fracturing operation, implying that more tankers may be needed to transport water away from site in the days directly after fracturing. Broderick et al. state that approximately 60% of flow-back waste is produced within the first four days after fracturing, with reducing amounts of flow-back continuing for each day, over an approximate two-week period. NYSDEC (2011; 2015a) also gives the '60% over the first four days' value and suggests a total recovery period of 2 to 8 weeks.

Hydraulic fracturing fluids are typically mixed and blended on-site during operations to achieve better overall control, flexibility and suitability of the fluids to the operation on-hand. The nature of the additive chemicals used, plus the increased salinity of the flow-back waste with contact to minerals, mean that storage and disposal of wastes is problematic. The same tankers used in the delivery of water to site are not the same vehicles removing waste from site, NYCDEP (2009) notes that a 3 million gallon (11360 m^3) fracking operation, using 9000 gallon (34 m^3) tankers, and assuming 100% flow-back, produces over 600 tanker trips.

Additionally, waste flow-back fluid may be re-cycled on- or off-site. Re-cycling involves the separation and removal dissolved solid materials from the fluid, before re-mixing and further use in fracturing operations. Eventually, the accumulating fraction of solid material and salinity renders the water as non-viable for recycling. However, the presence or absence of re-cycling facilities may mitigate or alter the demand profiles for water transportation.

The waste problem is further compounded if waste has come into contact with naturally occurring radioactive materials (NORMs), as it may not be feasible to use conventional wastewater treatment plants to process or recycle waste, necessitating further specialist vehicles, and transportation to possibly more distant and remote treatment sites.

5.1.5 Additional produced water

In addition to the immediate disposal of flow-back fracking fluids, there is also the need to handle longer-term ‘produced water’ from wells, both before full gas production can occur, and possibly constantly throughout the production life of the well. Produced water is water that occurs naturally in the gas-bearing strata. Sumi (2008) reports that the volumes of produced water can be considerable (sample data from two US operators suggested initial median rates of 6.2 m^3 and 8.4 m^3 of produced water for every 28 m^3 of gas extracted – though these values may also include flow-back fluids), and that the periods over which produced water removal is required can be lengthy: from 6-18 months till peak gas production, then periodically through the operational life of the site.

The volume of traffic associated with produced water removal will depend both on the amount of water produced on the site’s capacity to store the water in tanks or evaporate from/store the water in lined ponds. As with the initial flow-back fluids, produced water will likely be highly saline and contaminated. Somewhat contrary to the figures suggested by Sumi, NYSDEC (2011; 2015) (requoted in EP DGIP, 2011) give a suggested requirement of 2 to 3 tanker trips per year to handle produced water removal – which would produce almost negligible environmental impact.

5.1.6 Re-fracturing

During the 5-20 year operational lifespan of a drilling site, it may be viable to 're-fracture' the well a number of times in order to release further gas resources (Abdalla and Drohan, 2010) and increase the economic productivity of a particular site. However, Roussel and Sharma (2011) report that re-fracturing may be viable for only 15% of pads, based on analysis of data from Colorado, whilst NYCDEC (2011) states that Barnett shale wells 'generally would benefit from re-fracturing within 5 years of completion, but the time between fracture stimulations can be less than one year or greater than 10 years', whilst 'Marcellus shale operators … have stated their expectation that re-fracturing is a rare event'. Broderick et al. (2011) assumed a single re-fracturing of 50% of wells in a UK-wide shale gas scenario.

If feasible, each re-fracturing operation will incur the need for similar, if not greater levels of water demand (and hence transportation demand) as the initial fracturing operation. Sumi (2008) quotes Halliburton as reportedly requiring '25% more job volume' in a re-fracturing, when compared to the previous fracturing. The precise number of times re-fracturing may occur is also reportedly variable. For example, Ineson (2010) reported that, as of 2006, some Barnett Shale wells had been re-fractured over 10 times, with the majority re-fractured at least twice.

Aside from the uncertainty regarding the feasibility of re-fracturing and the number of re-fracturing events, it may be assumed that there would be a surface transport demand at least as great as the initial fracturing demand, for each re-fracturing operation, assuming that no additional pipeline infrastructure had been constructed in the intervening time.

5.1.7 Well plugging and decommissioning

At the end of operational life (or in the event of an unsuccessful operation) wells are plugged and abandoned. Well casings and ancillary equipment are removed, and sites may be further re-landscaped to 'make good'.

NYCDEP (2009) (re-quoted in Broderick et al., 2009) suggests that at least 15 m^3 of cement must be placed in the top of wellbores 'to prevent any release or escape of hydrocarbons or waste water'.

5.1.8 Total truck demand

Many reports investigated in the literature (e.g. Broderick et al., 2009; EP DGIP, 2011) cite elements of NYCDEP (2009) when calculating the resource demands, and commensurate overall truck movements associated with fracturing operations. Broderick et al. (2011) provide the following summary table (Table 5.3), based on NYCDEP (2009) data, as used in their calculation of greenhouse gas emissions from a six-well pad:

Table 5.3: Truck Visits over the lifetime of a six-well pad [Source: Broderick et al. (2011), based on NYCDEP (2009)].

Purpose	Per well Low	High	Per pad Low	High
Drill pad and road construction			10	45
Drilling rig			30	30
Drill fluid and materials	25	50	150	300
Drilling equipment (casing, drill pipe etc.)	25	50	150	300
Rig completion			15	15
Completion fluid and materials	10	20	60	120
Completion equipment (pipes, wellheads)	5	5	30	30
Hydraulic fracture equipment (pumps and tanks)			150	200
Hydraulic fracture water	400	600	2,400	3,600
Hydraulic fracture sand proppant	20	25	120	150
Flow-back water removal	200	300	1,200	1,800
Total (Bracketed number for 'per well' includes values associated with pad construction)	685 (890)	1050 (1340)	4,315	6,590
...of which associated directly with fracturing process			*3,870* *90%*	*5,750* *87%*

A separate table in Broderick *et al.* provides resource requirements per well based on a combination of Cuadrilla data (Regeneris Consulting, 2011) and NYCDEP data (2009). This information is presented in Table 5.4.

Table 5: Resource requirements per well under Cuadrilla Development Scenarios [Sources: Broderick et al. (2011) quoting Regeneris Consulting (2011) and NYCDEP (2009)].

Parameter	Resource use per Well	
Well pad area	0.7 ha	
Water required for fracturing	8,399 m^3	
Fracking chemicals volume	3.7 m^3	
Well cuttings volume	138 m^3	
	Low estimate	High estimate
Flow-back fluid volume	1232 m^3	6627 m^3
Total duration of activities in pre-production phase	83 days	250 days
Total truck visits	719	1098

EP DGIP (2011) also cites NYCDEC (2009) as a primary data source, and provides a slightly different, but comparable table (Table 5.5) to Broderick *et al.* (Table 5.3). Table 5.5 assumes:

> "A single well pad. Total well length 1500m to 4000m, consisting of 900m to 2100m depth and 600m to 1800m of lateral length with a 6 inch diameter production casing and 8 inch diameter production borehole. Lateral is cased but not grouted" (EP DGIP, 2011).

Table 5.5: 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

Activity	Materials	Volume	Associated Truck movements	Implied truck capacity/rate
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.

A separate column has been added to Table 5, to provide estimate the capacities of the trucks used in the transportation of materials. These values assume that each truck movement is associated with a two-way trip, rather than a movement being associated with a single on-way trip, to or from site.

The NYSERDA (2010) and NYSDEC (2011; 2015a) documents go somewhat further than the other literature presented in this document that four scenarios are discussed [NB: the same scenarios are repeated in both documents, with information from NYSERDA (2010) forming parts of NYSDEC (2011) and (2015a)]:

1. An 'early development vertical well' scenario – with a single well, on a single pad with all water demands met by truck;
2. As above, but with a horizontal well;
3. As one, but a 'peak well' scenario, with water delivery transport demands significantly reduced through the use of pipelines to bring water to, and remove water from the site;
4. As three, but with a horizontal well.

NYSERDA (2010) / NYSDEC (2011; 2015a) also breaks the component traffic down into 'light' trucks and 'heavy' trucks. Data for all scenarios is presented in Table 4.6 (Vertical well data) and Table 4.7 (Horizontal well data). Columns have been added to the original tables to show the percentage reductions between early- and peak-development.

Table 5.6: Estimated One-way, Loaded trips per Vertical Well, in Early- and Peak-Development Scenarios [Source: All Consulting, 2010 cited in NYSDEC, 2011; Reprinted in NYSDEC 2015a**].**

Activity	**Early Well Pad Development**		**Peak Well Pad Development**		**Percentage reduction (Early well to Peak well)**	
	Light Trucks	Heavy Trucks	Light Trucks	Heavy Trucks	Light Trucks	Heavy Trucks
Drill Pad Construction	90	32	90	25	-	-22%
Rig Mobilisation	140	50	140	50	-	-
Drilling Rig Fluids		15		15		-
Non-Rig Equipment		10		10		-
Drilling (Rig crew etc.)	70	30	70	30	-	-
Completion chemicals	72	10	72	10	-	-
Completion Equipment		5		5		-
Hydraulic Fracturing Equipment (on-site tanks)		75		75		-
Hydraulic Fracturing Water Haulage		90		25		-72%
Hydraulic Fracturing Sand		5		5		-
Waste and produced water disposal		42		26		-38%
Final pad preparations	50	34	50	34	-	-
Miscellaneous	85	0	85	0	-	-

Activity	Early Well Pad Development		Peak Well Pad Development		Percentage reduction (Early well to Peak well)	
	Light Trucks	Heavy Trucks	Light Trucks	Heavy Trucks	Light Trucks	Heavy Trucks
TOTAL One-Way, Loaded Trips Per Well	**507**	**398**	**507**	**310**	**-**	-22%

Table 5.7: Estimated One-way, Loaded trips per Horizontal Well, in Early- and Peak-Development Scenarios [Source: All Consulting, 2010 cited in NYSDEC, 2011/ NYSDEC, 2015a].

Activity	Early Well Pad Development		Peak Well Pad Development		Percentage reduction (Early well to Peak well)	
	Light Trucks	Heavy Trucks	Light Trucks	Heavy Trucks	Light Trucks	Heavy Trucks
Drill Pad Construction[1]	90	45	90	45	-	-
Rig Mobilisation	140	95	140	95	-	-
Drilling Rig Fluids		45		45		-
Non-Rig Equipment		45		45		-
Drilling (Rig crew etc.)[2]	140	50	140	50	-	-
Completion chemicals	326	20	326	20	-	-
Completion Equipment		5		5		-
Hydraulic Fracturing Equipment (on-site tanks)		175		175		-
Hydraulic Fracturing Water Haulage[3]		500		60		-88%
Hydraulic Fracturing Sand		23		23		-
Waste and produced water disposal		100		17		-83%
Final pad preparations	50	45	50	45	-	-
Miscellaneous	85	0	85	0	-	-

Activity	Early Well Pad Development		Peak Well Pad Development		Percentage reduction (Early well to Peak well)	
	Light Trucks	Heavy Trucks	Light Trucks	Heavy Trucks	Light Trucks	Heavy Trucks
TOTAL One-Way, Loaded Trips Per Well	**831**	**1,148**	**831**	**625**	**-**	-46%
Percentage difference compared to Vertical Well scenarios	**+63%**	**+188%**	**+63%**	**+102%**	**-**	**-**

[1]Assumes construction of a new well pad for each well, which could be considered an overestimate if the site is initially planned as a multi-well pad. [2]Assumes that separate vertical and directional drilling rigs are required. [3]Assumes 5 million gallons (US) (18,927m^3) of water per well is required, which implies that individual tankers are assumed to carry approximately 38m^3 of liquid.

ICF (2009) presents a section on 'Onsite Truck Usage' the following values are given per horizontal well, based on personal communication with a particular operator:

- Haulage of construction equipment: 25 truck loads
- Location buildings and equipment: 4 truck loads
- Construction materials and sand: 143 truck loads
- Hydraulic fracturing 158 truck loads
- Total prior to well completion 330 truck loads

The total truck loads given in ICF (2009) appear lower than the total values given in other literature, plus there is no indication as to the volumes of materials and water transported to and from the site.

5.1.9 Truck and tanker size, weight and loading assumptions

All truck trips in the original NYCDEP (2009) document were assumed to be by '18-wheeler semi- trucks or 9000 gallon (34 m^3) capacity tankers. AEA (2012) notes from NYCDEP (2009) that the maximum laden weight of tanker used in the state is 36 tonnes, as compared to the maximum laden weight of an EU/UK tanker of 40 tonnes (44 tonnes for vehicles moving materials from railheads). Therefore, AEA (2012) posits that there may be fewer overall vehicle movements than the US figures indicate, given the heavier possible loading, with the suggestion that values for heavy truck movements and trips be reduced to 83% (or equivalent to '20 to 30 movements a day') of the values suggested in Tables 6 and 7.

A fully-laden 44 tonne tanker may contain 37000 litres of fluid (BP, 2014), whilst AMEC (2013) assumed a tanker capacity of 30 m^3 (30,000 litres), whilst a rigid-body ‘dumper truck’ was assumed to be used to move materials on site. Such a vehicle with a capacity of 10 m^3 has a laden weight of 17 – 25 tonnes.

5.1.10 Compounding effects

The impact of a single well, or even multi-well pad may be of little significance. However, the siting of multiple pads in a confined geographic area, or an area with existing infrastructure constraints, may lead to periods of generated traffic having a disproportionate, non-linear effect on the surrounding network

5.1.11 Air pollution exceedence criteria

Whilst effects on annual average pollutant totals might be negligible, many of the EU Air Quality Standards also contain ‘exceedence’ criteria with effective limits over shorter durations. It is possible that short duration, but high intensity traffic associated with peaks in water demand, could trigger NO_2 and PM exceedences in localised areas, and would be of concern in populated locations.

5.2 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).

5.2.1 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).

5.2.2 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.

5.2.3 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

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