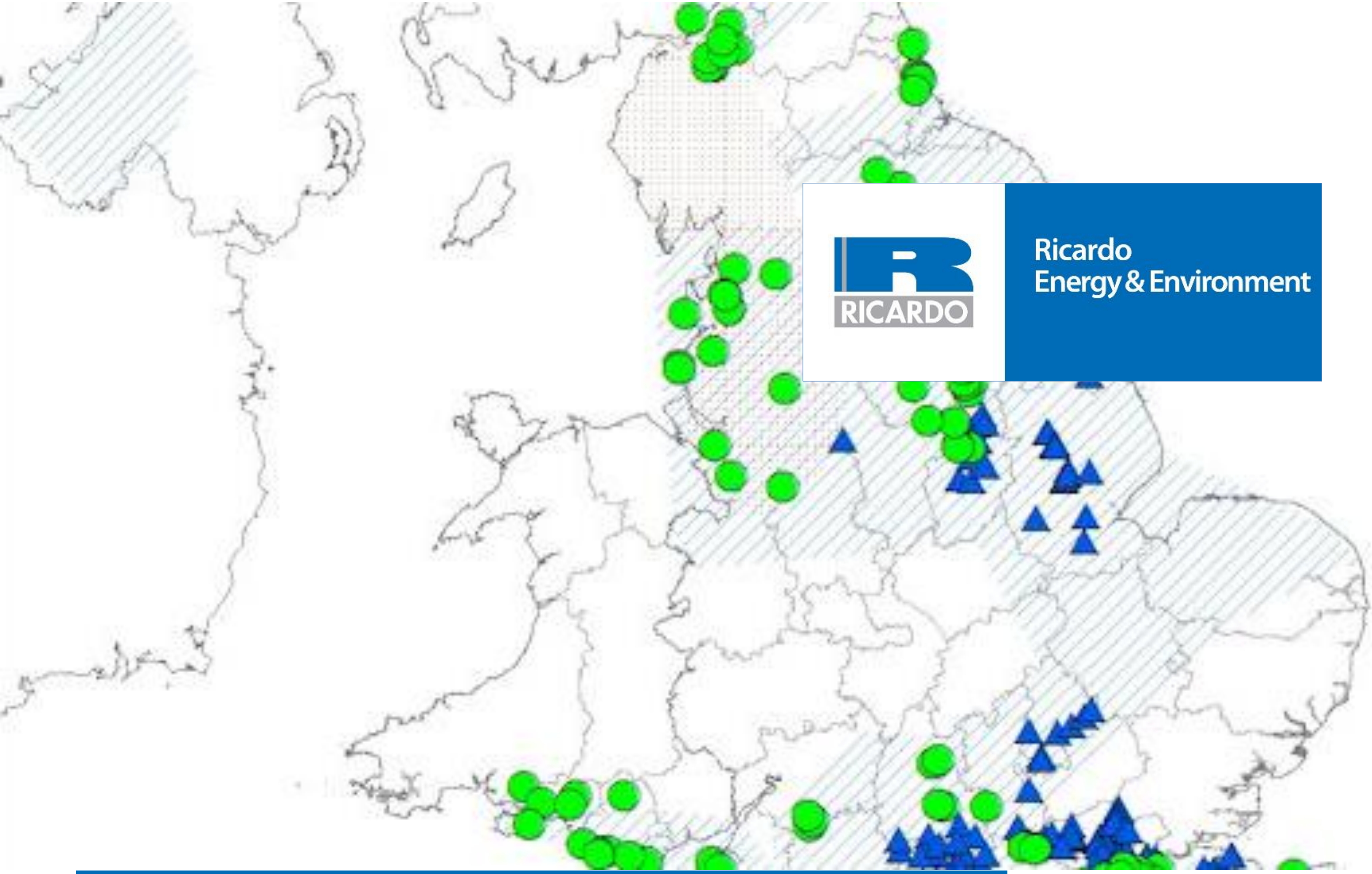

Onshore Oil and Gas monitoring: assessing the statistical significance of changes

Annex A: Supporting Information

Client: Environment Agency

Client Reference: Stats 4 Monitoring

ED 62964 | Issue 5 | Date 10 May 2018

Customer:

Environment Agency

Customer reference:

Stats 4 Monitoring

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Date:
10 May 2018

Ricardo Energy & Environment reference:

Ref: ED62964 | Annex A | Issue 4

Cover map: British Geological Survey methane groundwater monitoring network

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Appendices

1 Establishment of principles

1.1 Processes and pathways for pollutants

1.1.1 Air quality

1.1.1.1 Sources of emission

Onshore oil and gas facilities have numerous sources of emissions to air, which vary depending on the nature of the operation and the phase of the development. During the early phase of development (i.e. well construction and drilling) key emission sources include drilling rigs and pumps used for hydraulic fracturing; whilst during well completion, emissions often involve venting and/or flaring of natural gas. As the development moves into the production phase, key pollutant sources include pumps, which bring the gas to the surface, and compressors. Other key sources include amine units, dehydration units, fugitive emissions resulting from leaks in pipes and associated equipment, and vehicle movements, including heavy goods vehicles (HGVs) transporting water and proppant to and from the site. Compressor stations, located downstream of the wellhead, are also sources of combustion and fugitive emissions (GWPC & All Consulting, 2009).

The primary pollutants of concern are associated with fugitive and combustion emissions, and include:

- Oxides of nitrogen (NOx) – arising from the combustion of fossil fuels (e.g. vehicles, compressor engines and flares).
- Volatile organic compounds (VOCs) – resulting from the dehydration of natural gas.
- Particulate matter (PM_{10} (<10 microns) & $PM_{2.5}$ (<2.5 microns)) - arising from site preparation, construction, vehicle movements and combustion sources.
- Carbon monoxide (CO) – arising due to incomplete combustion of carbon-based fuels in engines and during flaring.
- Sulphur dioxide (SO_2) – arising due to the combustion of sulphur based fuels.
- Ozone (O_3) – forms as a result of emissions of NOx and VOCs.
- Methane (CH_4) – fugitive emission from gas processing equipment, particularly where being operated under high pressure.

Figure 1 provides a conceptual model of emissions arising from an OOG facility. Ozone has not been included, as it is not a direct emission from any of the components of the site but forms as a secondary photochemical pollutant over regional distances as a result of these emissions. With the exception of the flares, sulphur dioxide has been excluded as it is assumed all fuels will be low-sulphur to comply with the Sulphur Content of Liquid Fuels Regulations (2014) and Gas Safety (Management) Regulations (1996). Vehicle emissions have also been omitted from the diagram as these can be expected to occur throughout the operation, although at higher intensity during drilling and hydraulic fracturing operations, and they do not lie within the control of the Environment Agency.

Emissions are listed as being either ‘conduited’ (i.e. a discrete, measurable source, such as an emissions stack), fugitive or both of these. It should also be noted that the model reflects ‘normal operation’, although excessive fugitive emissions and/or flaring should not be considered acceptable under normal operating conditions.

Presenting the conceptual model in this format allows the user to consider key questions such as;

- Should the principal substances for detecting change, be those that appear at all stages in the process i.e. substances that occur most frequently in Figure 1 (i.e. VOCs and CH_4)?
- For detecting change, do substances that emit sporadically (e.g. H_2S) and don’t have routine emission limits need a different statistical approach to those that emit regularly and have limits?

Answers to these questions will be considered with reference to this conceptual model in the notes on survey design.

Table 1 summarises the likely source-pathway-receptor characteristics of these emission sources.

Figure 1: Conceptual model of emissions to air from an onshore oil and gas facility

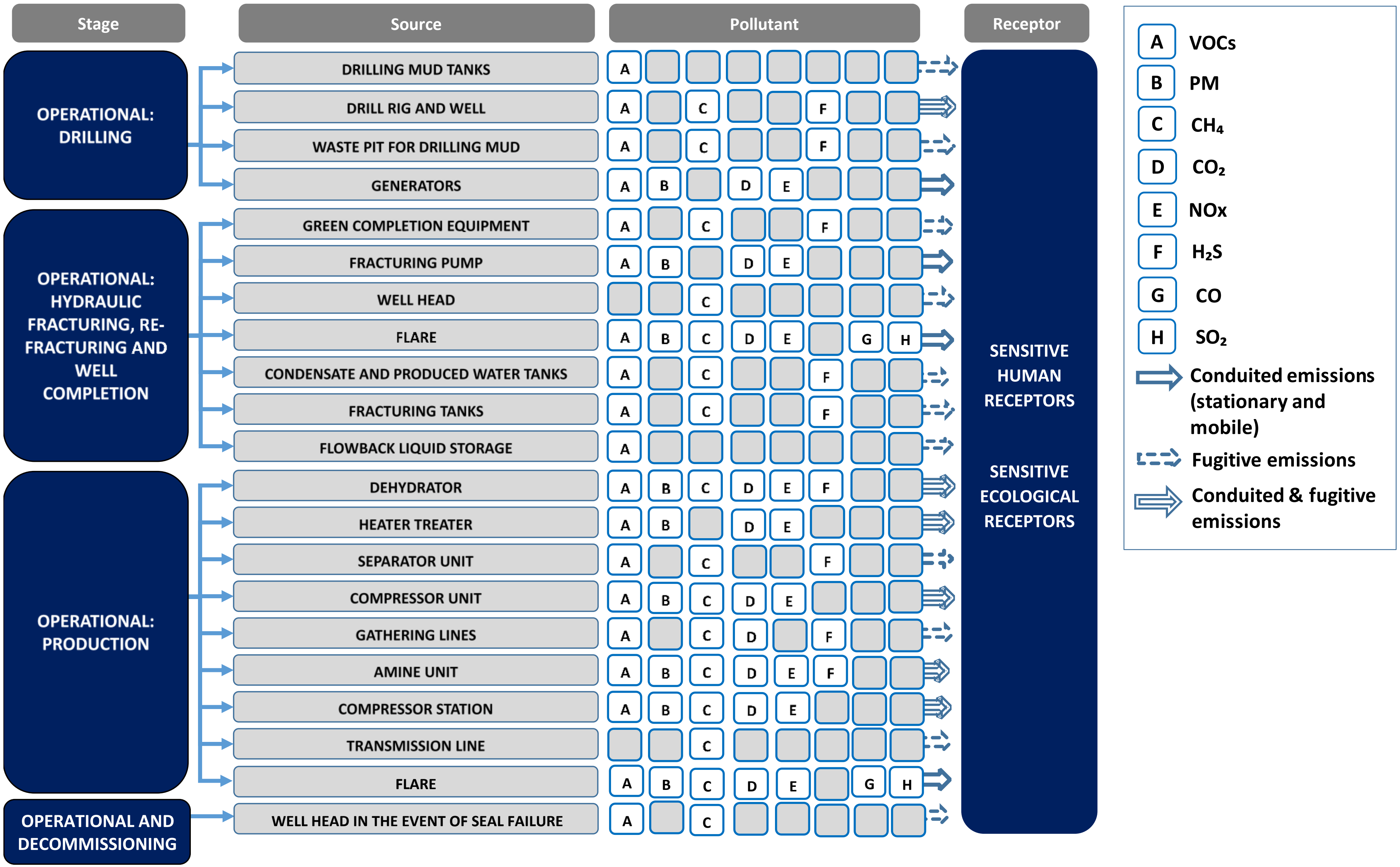


Table 1: Potential source-pathway-receptor characteristics of emissions to air during OOG development

Development stage	Sources	Pathways	Receptors	Potential impacts
Drilling	Drilling mud tanks	Ongoing fugitive emissions to air at ~1 to 2m above ground level.	Sensitive human receptors (e.g. houses, schools, hospitals etc.) Sensitive ecological receptors (e.g. Sites of Special Scientific Interest, Special Protection Areas, Special Areas of Conservation etc.)	Pollutants associated with emissions from OOG facilities have the potential to cause a range of health effects and ecological impacts. The extent to which these impacts occur will depend on the sensitivity of the receptors, the quantity released and the durations of exposure. The following provides a brief summary of some of the potential effects of these pollutants on human health and ecological systems, when concentrations in ambient air exceed designated air quality standards and guidelines (SEPA, undated) [Note: these are generic descriptions, and therefore do not necessary reflect the impacts of OOG facilities]. **Oxides of nitrogen** Human health – Respiratory problems, particularly in
	Drilling rig and well	During drilling; (i) Fugitive emissions to air from well head; (ii) contained emissions to air from drilling rig emission point (assumed to be in a raised position).		
	Waste pit for drilling mud	Ongoing fugitive emissions to air from surface of the waste pit.		
	Generators	Contained emissions to air at ~1 to 2m above ground level during drilling, from generator exhausts.		
Hydraulic fracturing, re-fracturing and well completion	Green completion equipment	Fugitive emissions to air at ~1 to 2m above the ground during completion.		
	Fracturing pump	Contained emissions to air from fracturing pump exhausts at ~1 to 3m above the ground during hydraulic fracturing.		

Development stage	Sources	Pathways	Receptors	Potential impacts
	Well head	Ongoing fugitive emissions to air at ~1 to 2m above the ground.		sensitive individuals (e.g. asthmatics). Ecological sites – Damage plant life. Contributes to the formation of acid rain. **Particulates (PM_{10} and $PM_{2.5}$)** Human health – Exacerbate respiratory and cardiovascular conditions. Smaller particles pose the greatest threat as they're carried deeper into the lungs. Ecological sites – Damage to plants, materials and buildings. **Carbon monoxide** Human health – Inhalation at high concentrations can be fatal. Long-term exposure at low concentrations can cause neurological damage and harm unborn infants. Ecological sites – Reacts with other pollutants to form ground level ozone.
	Flare	Contained emissions to air during completion resulting from the combustion of natural gas at the height of the flare stack (likely to be ~ 2 to 6m above the ground).		
	Condensate and produced water tanks	Ongoing fugitive emissions to air at ~1 to 2m above the ground.		
	Fracturing tanks	Ongoing fugitive emissions to air at ~1 to 2m above the ground.		
	Flow-back liquid storage	Ongoing fugitive emissions to air from storage tank at ~1 to 2m above the ground.		
Production	Dehydrator	Fugitive and contained emissions at ~1 to 2m above ground level during dehydrator use.		

Development stage	Sources	Pathways	Receptors	Potential impacts
	Heater treater	Fugitive and contained emissions at ~1 to 2m above ground level during heater treater use.		**O_3 and VOCs** Human health - O_3 forms as a result of the oxidation of VOCs in the presence of NOx and sunlight. O_3 is an irritant to the lungs and can increase symptoms of those suffering from lung diseases (e.g. asthma). There are numerous species of VOC, each having different effects on human health and the environment.
	Separator unit	Fugitive emissions at ~1 to 2m above ground level during separator unit use.		
	Compressor unit	Ongoing fugitive and contained emissions at ~1 to 2m above ground level.		
	Gathering lines	Ongoing fugitive emissions at ground level.		
	Amine unit	Fugitive and contained emissions at ~1 to 2m above ground level during amine unit use.		
	Compressor station	Ongoing fugitive and contained emissions at ~1 to 2m above ground level.		
	Transmission line	Ongoing fugitive emissions at ground level.		

Development stage	Sources	Pathways	Receptors	Potential impacts
	Flare	Contained emissions to air resulting from the combustion of natural gas at the height of the flare stack (likely to be ~2 to 6m above the ground).		
Decommissioning	Well head in the event of seal failure	Uncontrolled fugitive emissions to air at ~1 to 2m above ground level.		
All stages	Vehicle movements, including HGVs and site vehicles	Periodic emissions to air close to ground level from vehicle exhausts along access routes to the development and onsite. Vehicles also result in the generation of dust and particulates due to movement along unmade/dirt roads.		

Notes: Potential impacts source: AQIS (2017)

1.1.1.2 Timescales

Timescales required to carry out construction of the well-pad, drilling, well completion and operation of the site depends on several factors, including the topography of the site, the number of wells and the experience of the developer. Furthermore, the length of operation will depend on the nature of the shale being fractured, the level of extraction, the rate at which the fracturing fluid is injected and the intervals between stages. All of these variations affect the nature and scale of emissions to air.

The Tyndall Centre for Climate Change (2011) estimated timescales for a six-well multi-well pad, at a hydraulic fracturing site, see Table 2.

Onshore oil and gas facilities are also subject to significant diurnal operational variations, which depend on the nature of the site, any planning/regulatory controls, and the operator's working methods.

Table 2: Estimated development timescales of hydraulic fracturing sites in the Marcellus Shale region (Source: TCCC, 2011)

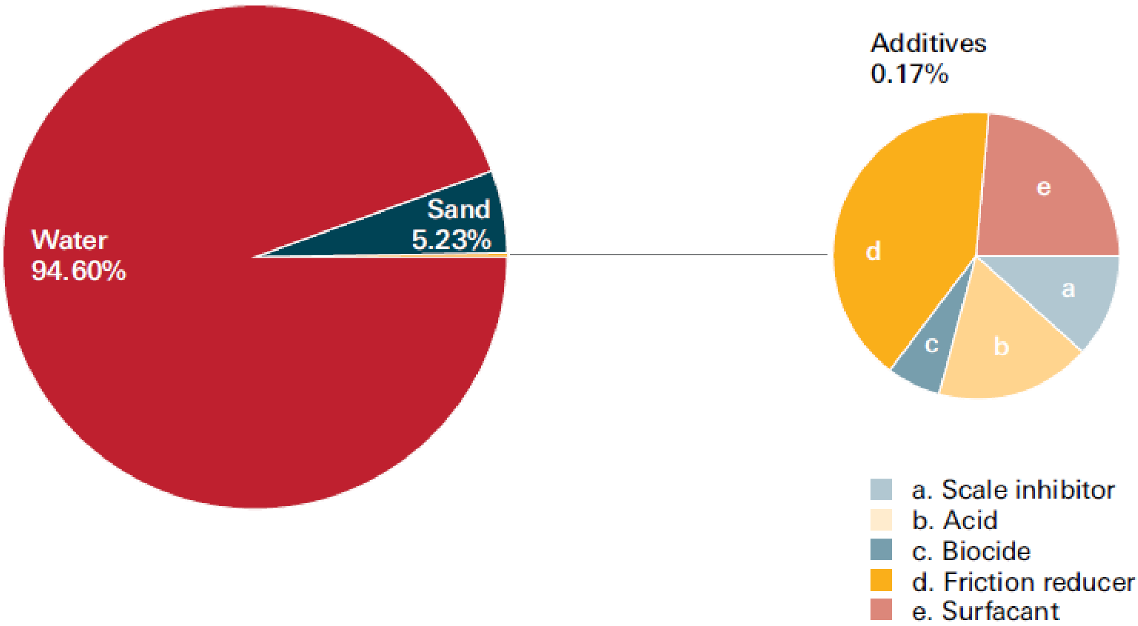
Operation	Duration
Access road and well pad construction	Up to 4 weeks per well pad
Vertical drilling with smaller rig	Up to 2 weeks per well; one to two wells at a time
Preparation for horizontal drilling with larger rig	5 to 30 days per well
Horizontal drilling	Up to 2 weeks per well; one to two wells at a time
Preparation for hydraulic fracturing	30 to 60 days per well, or per well pad if all wells treated during one mobilisation
Hydraulic fracturing procedure	2 to 5 days per well, including approximately 40 to 100 hours of actual pumping
Fluid return (flow-back) and treatment	2 to 8 weeks per well, may occur concurrently for several wells
Waste disposal	Up to 6 weeks per well pad
Well clean-up and testing	0.5 to 30 days per well
Overall duration of activities for all operations (prior to production) for a six well multi-well pad	500 to 1,500 days

Given differences in the duration and substances at risk at the different stages of site preparation and operation, an adaptive monitoring approach may be appropriate (i.e. different substances measured with different frequencies at different stages throughout lifetime of the well). This should be considered alongside the statistical approach undertaken in assessing change. It is recommended that baseline measurements are recorded on all substances of interest at regular intervals (i.e. equally spaced weekly, fortnightly or monthly). Use of adaptive monitoring approaches are considered in the notes on survey design.

1.1.2 Groundwater quality

Hydraulic fracturing involves the injection of fluid under pressure with the aim of releasing that pressure by fracturing the rock formation and thereby releasing gas embedded in the formation. The hydraulic fracturing fluid contains a base fluid which is mainly water (but could be other base fluids), and a proppant such as sand to hold open the fractures (Meiners *et al.*, 2013) so that gas can migrate. In addition, chemical additives are added to the fracturing fluid which perform various functions such as limiting bacteria growth, reducing friction and inhibiting corrosion (EPA, 2016a). Figure 3 shows the typical breakdown of hydraulic fracturing fluid components.

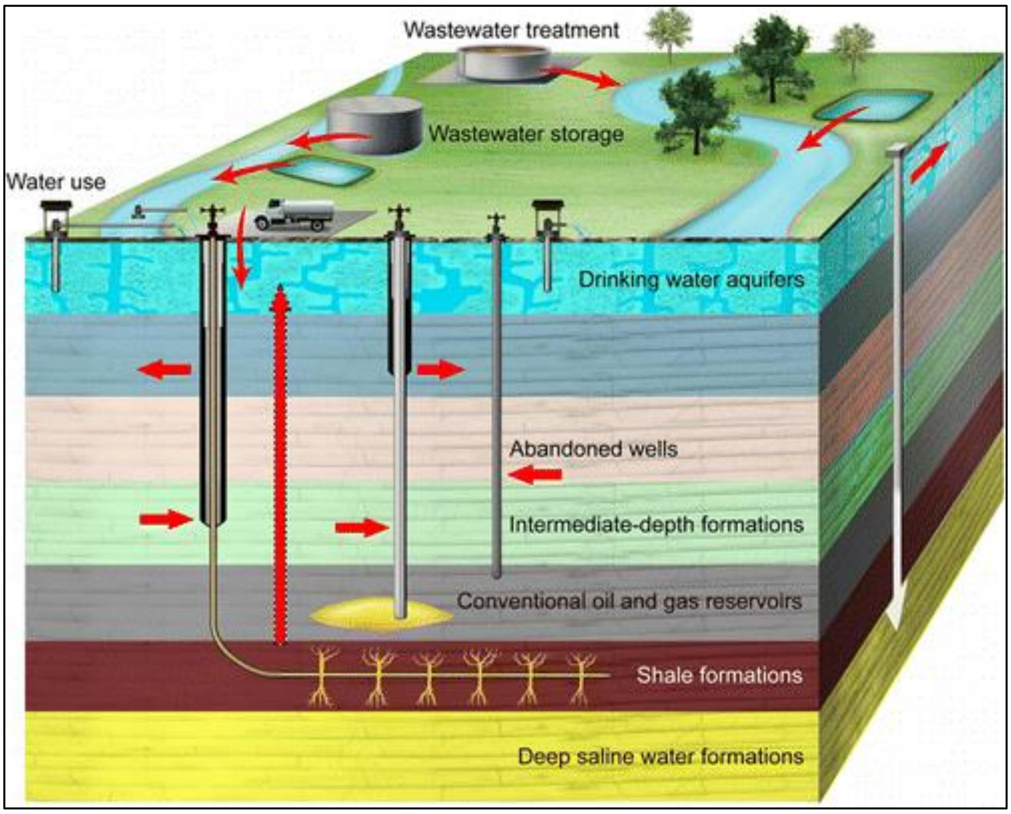
Figure 3: Typical composition of hydraulic fracturing fluid by volume (source: BGS, reproduced from The Royal Society and The Royal Academy of Engineering, 2012)



The sources, pathways and receptors for potential impacts on groundwater from onshore oil and gas are illustrated in

Figure 4 and Figure 5, and are described in Table 3. The sources could potentially affect groundwater and its receptors if not appropriately mitigated or managed. Potential impacts include contamination from surface spills or leaks, shallow aquifer contamination from leaking (annulus leaking) or abandoned wells, or leaks of saline water from deep formation waters to shallow aquifers. This illustration of the potential pathways provides background information on practical elements that need to be considered in statistical design of monitoring programmes, such as the location of monitoring wells and the depth of samples. Groundwater monitoring wells are generally located so that they provide protection to groundwater receptors. Wells that are located so that they represent the main pathways are known as sentry wells or warning wells that are used to detect contamination prior to it reaching a receptor (Council of Canadian Academies, 2014). Where there is a compliance target, these are known as a compliance point in the UK (DEFRA and EA, 2016). A well-developed conceptual model and an understanding of pathways and groundwater flow rates are necessary for designing appropriate monitoring programmes.

Figure 4: Schematic conceptual model of a generic onshore oil and gas site showing potential pathways of groundwater pollution (source: Vengosh et al. 2014)



Note: Groundwater receptors include any groundwater that has the potential to be a resource in the future. This may include springs that originate from deep formations or brackish groundwater in intermediate-depth formations. This is considered on a case by case basis.

Figure 5: Conceptual model of potential groundwater contamination from an onshore oil and gas facility

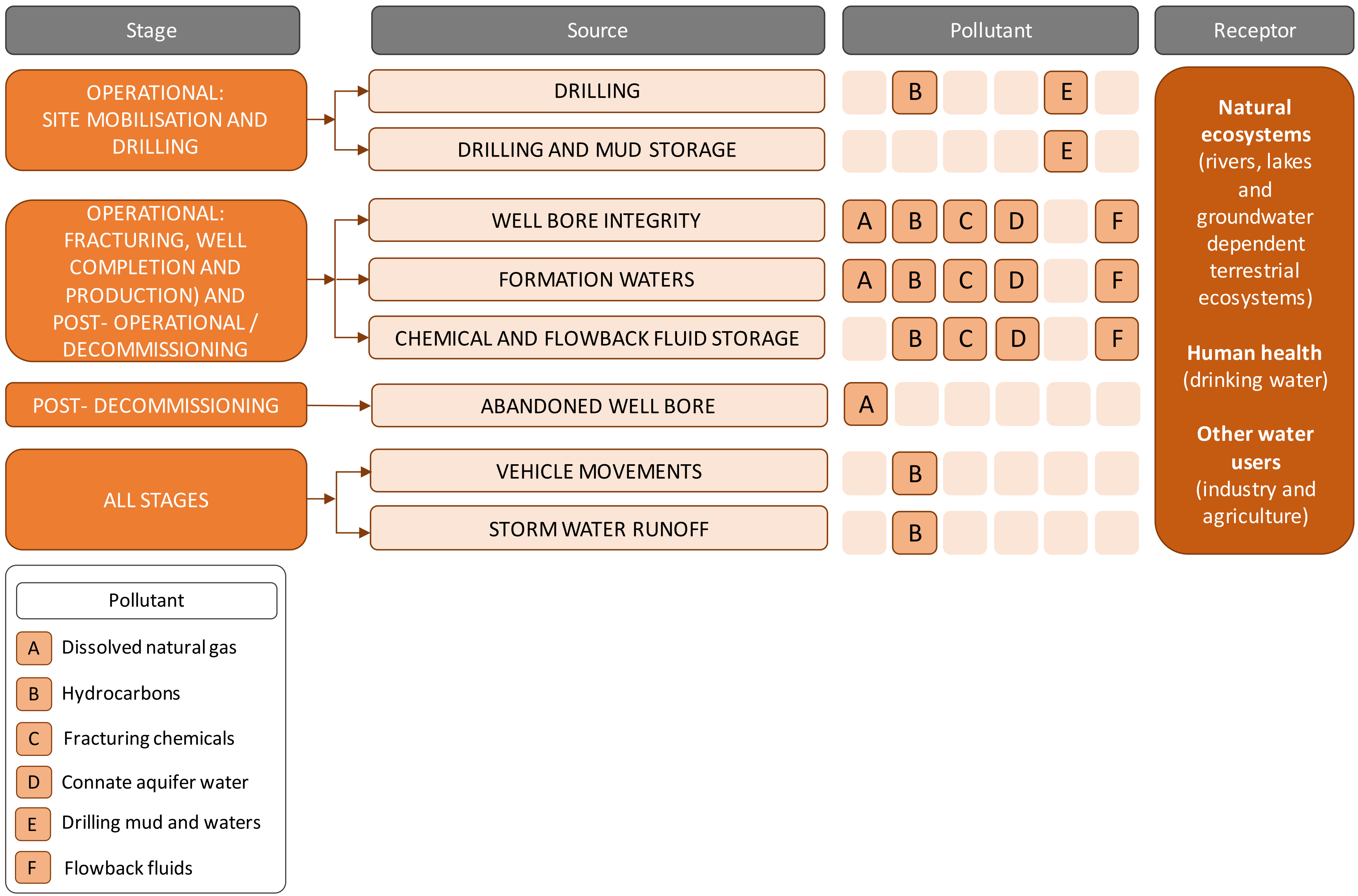


Table 3: Potential source-pathway-receptor characteristics of emissions to groundwater during OOG development

Development stage	Sources	Pathways	Potential impacts*	Receptors
Site mobilisation and drilling	Drilling	Release of pollutants into the well bore during the drilling process and subsequently the groundwater.	Potential release of chemicals crude oil, diesel oil Increased turbidity of groundwater due to drilling vibrations.	1) Potential impacts on human health in the event of exposure to drinking water (groundwater or surface water) that has been contaminated 2) Potential impacts on natural ecosystems including rivers, lakes and groundwater dependent terrestrial ecosystems where groundwater contributes base flow 3) Potential impacts on other water users such as industry or livestock from exposure to contaminated groundwater.
	Drilling mud storage	Contamination of the well pad followed by infiltration into groundwater and surface waters		
Hydraulic fracturing, re-fracturing and well completion, Production and Decommissioning	Well bore and well integrity[1]	Contaminants can migrate and impact shallow receptors in three ways: 1) via natural pathways; 2) via induced pathways; and 3) via artificial pathways (e.g. poor well design or poor well construction practice or over-pressurised drilling (i.e. well blowouts) (EPA, 2016a). It is also noted that pollutants could migrate and impact deeper aquifers that have the potential to be a groundwater resource in the future.	Natural gas constituents (e.g. methane). Chemicals within hydraulic fracturing fluids with the potential to cause contamination. Flowback fluid and production water chemicals such as chloride, heavy metals and Naturally Occurring Radioactive Material (NORM)	
	Formation waters			

[1] "*Well integrity' refers to preventing shale gas from leaking out of the well by isolating it from other subsurface formations*" (API, 2009; Royal Society and The Royal Academy of Engineering, 2012)

Development stage	Sources	Pathways	Potential impacts*	Receptors
	Chemical mixing tanks and flow-back liquid storage	Accidental releases from storage tanks, or spills when transferring the fluids from storage into a tanker, followed by infiltration into groundwater and surface waters.	Chemicals within hydraulic fracturing fluids Flowback fluid and production water chemicals such as chloride, heavy metals and NORM	
Post-Closure	Well bore - abandoned	Contaminants can migrate via poorly constructed or damaged wells or poorly decommissioned wells	Stray gas (i.e. methane)	
All stages	Vehicle movements, including HGVs and site vehicles Storm water runoff	Contamination of the well pad from spill, leaks and runoff, followed by infiltration into groundwater and surface waters	Hydrocarbon and other chemicals used onsite	

Potential pollutants from OOG that may contaminant groundwater and its receptors and therefore need to be incorporated into the groundwater monitoring programmes can be summarised as follows (Vengosh et al., 2014; EPA, 2016a):

- Stray gas: Dissolved natural gas components including methane and stable isotopes for fingerprinting naturally occurring methane from stray gas. These will change through the cycle of exploration, pre-production, production and decommissioning.
- Flowback fluid and produced waters from well leaks or storage on the surface with chemicals such as chloride, sodium, bromide, heavy metals and NORM. The concentration and potential range of chemicals is site specific.
- Displacement of connate waters into other aquifers (or small volumes of water from shale formations), e.g. saline movement, which requires consideration of determinands such as sodium, chloride and other major cations and anions and other pollutants such as heavy metals.
- Chemicals within hydraulic fracturing fluids. Additives make up 0.1-0.5% of hydraulic fracturing fluids (API, 2010; AMEC, 2014). The number of different additives registered for use in the US for hydraulic fracturing fluids is quite high with the USEPA (2015a) reporting 692 unique ingredients reported for base fluids, proppants and additives in hydraulic fracturing fluids.
- Drilling muds or fluids. UK Onshore Shale Gas Well Guidelines for the Exploration and Appraisal Phase, UK Onshore Oil and Gas (UKOOG, 2015a) recommends that OOG operators use water or water based fluids (WBF). WBFs are primarily composed of water or brine with barite and clay, but sometimes include chemical additives.
- Hydrocarbon contamination from surface spills and leaks.

1.2 Regulatory context

Table 4 summarises current regulatory context associated with air and groundwater quality for OOG developments in the United Kingdom, including links to corresponding European Union legislation where relevant.

Table 4: Regulations and recommendations governing air and groundwater quality for onshore oil and gas in the United Kingdom

EU legislation / recommendation	UK legislation	Aims / objectives / scope	Relevance to onshore oil and gas developments
Onshore oil and gas			
Commission Recommendation on minimum principles for the exploration and production of hydrocarbons (such as shale gas) using high-volume hydraulic fracturing (2014/70/EU)	The principles were expected to be made effective by the EU Member States within six months of their publication on 22 January 2014. England and Wales already had the Environmental Permitting (England and Wales) Regulations 2010 (SI2010/675) which has the ability to cover the Commission's recommendation requirements as Schedule 5 Part 1 of the regulations allows the environmental regulator to grant an application for an environmental permit subject to such conditions as it sees fit.[2]	The Recommendation is intended to complement existing EU legislation, covering issues such as planning, underground risk assessment, well integrity, baseline reporting and operational monitoring, capture of methane emissions, and disclosure of chemicals used in each well.	The recommendations related to air and groundwater monitoring include: **Baseline** *the operator determines the environmental status (baseline) of the installation site and its surrounding surface and underground area potentially affected by the activities;* *the baseline is appropriately described and reported to the competent authority before operations begin* *A baseline should be determined for:* *(a) quality and flow characteristics of surface and ground water;* *(b) water quality at drinking water abstraction points;* *(c) air quality;*

[2] UK response to this Recommendation in 2015: Environmental Aspects on Unconventional Fossil Fuels http://ec.europa.eu/environment/integration/energy/unconventional_en.htm

EU legislation / recommendation	UK legislation	Aims / objectives / scope	Relevance to onshore oil and gas developments
			Operational Monitoring *Member States should ensure that the operator regularly monitors the installation and the surrounding surface and underground area potentially affected by the operations during the exploration and production phase and in particular before, during and after high-volume hydraulic fracturing*. *The baseline study required should be used as a reference for subsequent monitoring.* *In addition to environmental parameters determined in the baseline study, Member States should ensure that the operator monitors the following operational parameters:* *(a) the precise composition of the fracturing fluid used for each well;* *(b) the volume of water used for the fracturing of each well;* *(c) the pressure applied during high-volume fracturing;* *(d) the fluids that emerge at the surface following high- volume hydraulic fracturing: return rate, volumes, characteristics, quantities reused and/or treated for each well;*

EU legislation / recommendation	UK legislation	Aims / objectives / scope	Relevance to onshore oil and gas developments
			(e) air emissions of methane, other volatile organic compounds and other gases that are likely to have harmful effects on human health and/or the environment. **Post- Closure Monitoring** *Member States should ensure that a survey is carried out after each installation's closure to compare the environmental status of the installation site and its surrounding surface and underground area potentially affected by the activities with the status prior to the start of operations as defined in the baseline study.*
-	Petroleum Act 1998 (as amended by the Infrastructure Act 2015)	The act amended the existing legislative framework for lateral drilling techniques and hydraulic fracturing in England and Wales.	It states that a hydraulic fracturing consent will not be issued unless certain conditions are met. The conditions relating to air and groundwater quality include: *(a) Assessment of environmental impacts* *(b) Independent well inspections* *(c) Monitoring of methane in groundwater* *(d) Monitoring of methane emissions* The level of methane in groundwater has to be monitored for a period of 12 months before hydraulic fracturing begins.

EU legislation / recommendation	UK legislation	Aims / objectives / scope	Relevance to onshore oil and gas developments
EIA Directive (2014/52/EU)	The Town and Country Planning (Environmental Impact Assessment) Regulations 2011 (Due for amendment by May 2017)	Specifies the range of development for which an EIA will be required, and lays out the scope and requirements of an EIA.	Most onshore oil and gas development will require an EIA. The industry trade association has undertaken to carry out an EIA for all developments. Where an EIA is not a mandatory requirement or provided voluntarily, it would be open to a local authority to require an EIA. An EIA is required to characterise baseline environmental conditions, including groundwater and air quality. The EIA also identifies potential adverse effects associated with the development, establishes avoidance and mitigation measures, and includes ongoing management and monitoring requirements.
Water			
Water Framework Directive (2000/60/EC)	Water Environment (Water Framework Directive) Regulations 2003 and the subsequent amendments in 2015 and 2016.	Establishes a legal framework to protect and restore fresh water to ensure sustainable use. Aims to prevent deterioration in water quality, achieve good chemical status and ecological status / potential and limit the discharge of priority substances. It also establishes an approach for water management based on river basins and natural geographical and hydrological units.	Onshore oil and gas developments will be required to protect the Water Framework Directive (WFD) status of sensitive receptors. Objectives to be set for the protection of surface waters and groundwater and specific receptors. To prevent or limit the input of pollutants into groundwater and to prevent the deterioration of the status of groundwater and to reverse any significant and sustained upward trend in the concentration of any pollutant. The threshold values have regard to the impact on and relationship with associated surface waters and directly dependent terrestrial ecosystems and wetlands

EU legislation / recommendation	UK legislation	Aims / objectives / scope	Relevance to onshore oil and gas developments
		The measures required to achieve ‘good’ status are laid out in River Basin Management Plans (RBMPs). Hazardous substances are defined under the directive as “*substances or groups of substances that are toxic, persistent and liable to bio-accumulate, and other substances or groups of substances which give rise to an equivalent level of concern.*” JAGDAG (2017) in the UK have developed a methodology for identifying hazardous substances.	
Groundwater Directive (2006/118/EC)	The Groundwater (Water Framework Directive) (England) Direction 2016. Additional controls relating to the release of pollutants to the subsurface are defined by the Environmental Permitting (England and Wales) Regulations 2016, whereby the environmental regulator must exercise its relevant functions so as to take all necessary measures to prevent the input of any hazardous substance to groundwater, and to limit the	A daughter directive of the WFD. For groundwater, the WFD requires the achievement of 'good status' in all groundwater water bodies. To achieve ‘good’ groundwater status, quantitative and chemical status must both must be 'good'. Relates to groundwater quality protection, specifically to the prevention of the release of hazardous substances, and reduction of the effect of pollutants in aquifers.	OOG developments will be required to protect the Water Framework Directive (WFD) status and provides groundwater quality thresholds. Additionally, any Naturally Occurring Radioactive Material (NORM) waste will have to adhere to the rules laid down in the Environmental Permitting (England and Wales) Regulations 2010 which will further reduce risk, although it should be noted that regulations with respect to hydraulic fracturing are currently developing and may change in the future.

EU legislation / recommendation	UK legislation	Aims / objectives / scope	Relevance to onshore oil and gas developments
	input of non-hazardous pollutants to groundwater so as to ensure that such inputs do not cause pollution of groundwater.		
Drinking Water Directive (DWD) (98/83/EC)	The Water Supply Regulations 2016 implements the directive by (revoking the Water Supply (Water Quality) Regulations 2010). It transposes requirements of the directive on the quality of water intended for human consumption. The remainder of the directive is implemented by the Private Water Supplies Regulations 2016.	Aims to protect human health from adverse effects of any contamination of water intended for human consumption. The directive applies to all distribution systems serving more than 50 people or supplying more than 10 m^3/d. A total of 48 microbiological, chemical and indicator parameters must be monitored and tested regularly. The standards set generally follow the World Health Organisation (WHO) guidelines. There are also parameters that don't relate to human health such as odour and taste.	Provides water quality standards for groundwater aquifers used as drinking water sources that could be affected by OOG developments. These are receptor based water quality standards for human health, including Drinking Water Standards (DWS) which are maximum acceptable concentrations in consumer supplies after treatment. Note that they are only one type of standard and lower ones may be required as part of the prevent and limit objectives under the WFD and GWDD.
Priority Substances Directive (2013/39/EU)	The Water Environment (Water Framework Directive) (England and Wales) (Amendment) Regulations 2015, amending the 2003 regulations. They transpose aspects of Directive 2013/39/EU and of the Council amending Directives 2000/60/EC and	This directive amends the first list of priority substances in Directive 2000/60/EC and Directive on Environmental Quality Standards (2008/105/EC). The directive lays down Environmental Quality Standards	Good surface water chemical status in relation to the priority substances and the associated EQSs listed in the original Directive of 2008 must be achieved. The regulations refer to the table of priority substances in Part A of Annex I to the EQS Directive. UKTAG guidance on substances

EU legislation / recommendation	UK legislation	Aims / objectives / scope	Relevance to onshore oil and gas developments
	2008/105/EC as regards priority substances in the field of water policy.	(EQS) for 45 priority substances which is an increase from 33 in the 2008 directive. The directive calls for the establishment of a new watch list of substances for which Union-wide monitoring data are to be gathered for the purpose of supporting future prioritisation exercises.	and allowable limits in various water bodies has been published. By 22nd December 2018 a monitoring programme for the additional 12 priority substances 34 to 45 for each river basin district must be in place. Provides receptor based environmental quality standards to protect the ecology of the aquatic environment for rivers, lakes, transitional and coastal water bodies. They can be used to derive standards in aquifers where groundwater baseflow contributes to these surface water bodies. Note that they are only one type of standard and lower ones may be required as part of the prevent and limit objectives under the WFD and GWDD.
Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) Directive (EC 1907/2006)	The REACH Enforcement Regulations 2008 (SI 2008 No.2852) UK REACH (Competent Authority is Health and Safety Executive).	The regulation replaces and amends a number of previous EU regulations and directives. It covers the entire EU (becoming law in the UK on 1st June 2007) and requires all companies who manufacture in or import into the EU,1t per annum or greater of chemical substances to register these substances with the European Chemicals Agency (ECHA). This has been phased in over 11 years with the final 1t	Operators of OOG projects are considered as “downstream users” of the chemical substances used, which means that they would not be subject to the main registration obligations. However, if the threshold is exceeded then chemicals must be registered and exposure scenarios for chemicals used should cover OOG uses and indicate how potential impacts on human health and the environment can be averted (ECHA, 2015).

EU legislation / recommendation	UK legislation	Aims / objectives / scope	Relevance to onshore oil and gas developments
		threshold being reached on 31 May 2018.	
Air quality			
Ambient Air Quality Directive (2008/50/EC)	Air Quality Standards Regulations 2010. Incorporates the 4th Air Quality Daughter Directive (2004/107/EC), which sets targets for concentrations of certain toxic heavy metals and polycyclic aromatic hydrocarbons.	Sets legally binding limits for concentrations of major air pollutants in outdoor air, including particulate matter and nitrogen dioxide. In England, the Secretary of State for Environment, Food and Rural Affairs is responsible for the limit values being met, whilst the Department for Environment, Food and Rural Affairs acts to co-ordinate air quality plans and assessment for the UK as a whole. The national administrations in Scotland, Wales and Northern Ireland have devolved responsibilities for meeting air quality limit values.	Operators will be required to demonstrate that emissions from their facilities will not make any significant contribution to an exceedance of these legally binding limit values.
	Environment Act 1995	Requires the UK Government and devolved administrations to produce a national air quality strategy, which provides air quality objectives for the UK. Part IV of the Act (and Part II of the Environment (Northern	Operators will be expected to show consideration for the presence of existing air quality issues within the vicinity of the proposed development site, including the locations of any designated AQMAs and their potential impact on delivering improvements in air quality resulting from

EU legislation / recommendation	UK legislation	Aims / objectives / scope	Relevance to onshore oil and gas developments
		Ireland) Order 2002) states that local authorities are required to review air quality in their local area and, if improvements are required, to designate Air Quality Management Areas (AQMAs). If an AQMA is designated, the local authority must produce an air quality action plan, which outlines the pollution reduction methods to be put in place.	measures set out in a local authority Air Quality Action Plans.
Strategic Environmental Assessment Directive (2001/42/EC)	Environmental Assessment of Plans and Programmes Regulations (2004)	Requires EU Member States to provide an SEA of any governmental programmes that may have a significant environmental impact.	In December 2013 the Department of Energy and Climate Change published an SEA for 'Further Onshore Oil and Gas Licensing' (DECC, 2013), which stated that negative impacts on localised air quality could be expected due to on-site machinery, flaring and vehicle movements; in particular during the 'exploration drilling' phase.
Industrial Emissions Directive (2010/75/EU)	Environmental Permitting Regulations (2016)	The IED is the main EU instrument regulating pollutant emissions from industrial installations, which aims to achieve 'a high level of protection of human health and the environment taken as a whole by reducing harmful industrial emissions across the EU, in particular through better	An onshore oil and gas installation may come under the permitting requirements for waste disposal, and/or radioactive substances. Waste disposal may apply to the use of flaring to dispose of gas, or potentially to the residue of fracturing fluids which remain in the target formation.

EU legislation / recommendation	UK legislation	Aims / objectives / scope	Relevance to onshore oil and gas developments
		application of Best Available Techniques (BAT)'.	
Directive on Emissions from Non-Road Mobile Machinery (Regulation (EU) 2016/1628, previously Directive 97/68/EC)	Non-Road Mobile Machinery (Emission of Gaseous and Particulate Pollutants) Regulations 1999 (1999/1053)	2016/1628 came into force on 1st January 2017 (EU, 2017). Specifies limits on emissions of NOx, CO, hydrocarbons and PM from a broad range of engine installations in line with equivalent standards in the US.	This Directive will influence the quality of the engines used through the design limits applied.

1.3 Air quality monitoring techniques

Monitoring of pollutant concentrations in ambient air is carried out in numerous ways, ranging from hand-held monitors and simple diffusion tubes, to complex analysis of absorption spectra. Potential approaches to air quality monitoring at OOG sites in the United Kingdom are discussed below.

1.3.1 Continuous and discrete sampling

The need to carry out either continuous or short-term, discrete sampling is largely determined by the likely short-term variability of the pollutant being assessed. Where variability in concentrations is likely to be significant, discrete samples are unlikely to be representative, and so continuous monitoring is likely to be required (EA, 2011). Continuous sampling can involve both the use of real-time analysers, and subsequent laboratory analysis.

The duration and repetition of short-term sampling will be linked to the averaging period against which measurements will be reported. Where the pollutant will be assessed against a particular standard, measurements must reflect the averaging period for that standard.

1.3.2 Averaging periods

Averaging periods for air quality monitoring are often determined by the aims and objectives of the study (e.g. assessment against EU Directive Limit Values). Where the averaging periods are not prescribed, they must be chosen on the basis of the nature of the pollutant (e.g. likely variability in concentrations, associated health impacts), and the receptor of concern (e.g. the length of time over which an impact will occur). Table 5 lists recommended averaging times for selected applications recommended by the EA.

The selected averaging time will affect the measurement technique, as some methods are only able to sample within a finite range of averaging times. Typically, the choice is between an indirect, less expensive manual method (e.g. diffusion tube), and a continuous method which provides a large quantity of high-resolution data.

Table 5: Suggested averaging times (Source: EA, 2011)

Order of minimum averaging period	Type of survey
10 seconds	Odour assessment; mobile sensors; acute respiratory effects; studies of puffs.
3 minutes	Useful for studying odours and acute health effects if faster response not available.
1 hour	Time average concentrations; dispersion studies; diurnal changes; discrete source studies; damage to plants
24 hours	Chronic health effects; area source studies; effects of weather systems; effects on different days of the week
1 month	Seasonal and annual variation; long-term effects from global source

1.3.3 Directional sampling

Methods of sampling can either be ‘omnidirectional’ or ‘directional’ (EA, 2011). The former involves sampling of air from all directions under all wind directions, which requires correlation with continuous meteorological data. The latter involves sampling of air when the wind is blowing from a specific direction and in some cases when it is above a certain speed. This is more commonly applied where background concentrations are low and there is a specific source being assessed.

A single sampler, downwind of a development, will provide an indication of the pollution levels arising from an upwind source. To provide more detailed analysis, a directional sampler can be fitted with two wind-vane operated receptors, with one collecting a sample when wind is blowing from the direction of the target source and the other collecting a sample at all other directions.

Directional samplers typically have a sampling arc of between 30 and 70 degrees, centred on the target source. However, if there are other sources within that arc, the contribution from the target source may be supplemented by contributions from other sources, so that the target source contribution is difficult to distinguish e.g. it may be overestimated. A solution to this is to set up more than one sampler around the target source, so that the contributions from the target source, other sources and background sources can be distinguished. Direction-resolving monitoring equipment can also be used to distinguish sources e.g. based on three or more wind sectors.

1.3.4 Fixed point and open path sampling

Ambient sampling can follow either the ‘fixed-point’ or ‘open-path’ method. Fixed-point sampling is the most common form, and consists of a network of sites at fixed locations, with each providing either time-averaged concentrations or spot-concentration values from a fixed point in space. As a result, fixed-point sampling is largely dependent on the selection process for the locations of the sites.

The open-path method allows measurements to be made directly in the atmosphere without obtaining samples. Rather than concentrations being measured at a specific point, the average concentration of a pollutant is calculated over an extended measurement path, with certain methods allowing the concentration to be spatially resolved. The advantage of this method is that it allows the determination of pollutant concentrations as they cross site boundaries, and along roadways etc. However, difficulties can arise in the interpretation of integrated path data.

1.3.5 Factors influencing monitoring survey design

1.3.5.1 Practical considerations

Design of a monitoring campaign for the assessment of ambient air pollution around OOG facilities will be influenced by several factors, including site-specific risks, the presence of nearby sensitive receptor sites and the nature of local meteorological conditions (UKOOGb, 2016).

In the UK, guidance published by the oil and gas production industry (UKOOGb, 2016) refers operators to the Environment Agency’s Technical Guidance Note on the monitoring of ambient air (M8). This provides general recommendations on the establishment of a monitoring campaign, which is appropriate for OOG sites, although does not specifically refer to the onshore oil and gas industry (EA, 2011). It suggests that an operator must take account of the following issues when designing a monitoring survey:

- **Background** – Background monitoring locations are typically representative of the wider region and located away from major pollutant sources. OOG sites are likely to be located in rural locations, away from major sources of pollution (however this is by no means guaranteed). The Environment Agency will require operators to develop a monitoring plan, which will require background monitors to be established at the proposed OOG site before construction takes place. It is likely to be appropriate to use the same location(s) for ongoing monitoring during operation.
- **Sensitive receptor sites** – It is common for monitoring equipment to be located at the receptor most likely to be impacted by emissions from the site. Identification of all sensitive receptor sites, including human and ecological, in close proximity to the development site is a crucial element of the monitoring campaign. As discussed, OOG sites are likely to be in rural, and potentially remote, locations. Therefore, it may not be practical to locate monitoring stations at residential properties if they are not in close proximity to the OOG installation. Furthermore, due to the number of heavy vehicles that are likely to travel to and from OOG sites, estimated

to be ~190 per week for a period of approximately two years during development of a pad with 15 wells (Broomfield et al., 2016), additional monitoring may need to be undertaken at sensitive receptors located along the main access routes to the site.

- **Multiple monitoring locations** – It may be advantageous to establish more than one monitoring station. By locating monitoring equipment at selected bearings from the site, and combining the measurements with meteorological data, triangulation of nearby sources of pollution can be enabled. Alternatively, by locating monitors on the same bearing, but at different distances, it is possible to determine the rate of drop-off in pollutant concentrations away from the site. This approach is relevant to the operational phase of a development. If it is intended to apply such an approach during operation, this would inform the design of a baseline monitoring survey. The ability to triangulate the source of pollutant contributions in an area with several sources may be particularly appropriate for regions where several OOG sites are likely to become operational.
- **Local meteorology and topography** – The way in which emissions disperse from a site is largely determined by wind speed and direction. It is therefore critical for operators to incorporate meteorological data which is representative of the conditions at the site. It may be possible to source this information from existing meteorological stations, such as those operated by the Met Office (http://www.metoffice.gov.uk), or site-specific meteorological measurements may also be carried out. This data will enable the identification of the locations which are likely to experience the greatest impact as a result of emissions dispersing from the site. Prevailing winds in the UK are predominantly south-westerly, but can be affected by local topography and water-land boundaries, and of course vary hour by hour and sometimes more frequently. As well as the influence of meteorology, emissions from the site will be affected by several factors, including the locations of the emission points, the characteristics of the emission (i.e. velocity, diameter, temperature etc.). Therefore, met data is regularly used in atmospheric dispersion modelling assessments to determine the most appropriate location of monitoring points. Once operation begins, continuous meteorological data can be combined with monitored pollutant concentrations to enable more detailed analysis of the dispersion of pollutants from the site.
- **Distance from source** – This must take into consideration the degree of dispersion from the site, which is influenced by the height of release, local meteorological conditions, atmospheric mixing, the type of pollutant and other factors. It is important to locate the monitoring station as close to the point of maximum impact as possible.
- **Upwind-downwind comparisons** – A common practice for the determination of pollutant contributions from a particular source is the placement of monitoring stations up and downwind of a source. This data is then combined with local meteorological conditions, in order to subtract the upwind concentration from the downwind concentration. If this is the intention, it is advisable to use the same locations for baseline monitoring surveys.
- **Interfering sources** – Where it is not possible to isolate a target source from other nearby sources of pollution it may be necessary to carry out directional sampling or to collect local meteorological data, in order to distinguish between interfering sources of pollution. This may become more apparent in areas where more than one well-site is developed, or with other existing sources of industrial pollution.
- **Sampling height** – The usual height for assessing the impact of emissions on humans is between 1 and 2 metres, however it is important that this is appropriate for the process being assessed (e.g. emissions from ground level can vary considerably with a small change in height from the ground). It may be necessary to carry out monitoring above these heights where differentiation between releases at ground level and at height are required. OOG sites have emission points both at height (e.g. flare, drilling rig) and at ground level (e.g. condensate and produced water tanks). Taking measurements at a range of heights can be a useful diagnostic tool to enable the source of a measured concentration to be identified.

- **Accessibility, obstruction and services** – Monitoring should be carried out in an accessible area, free from obstructions such as trees, buildings or walls, with adequate access to services (i.e. electricity, internet access).

In summary, the positioning of a monitoring station will be determined by the characteristics of the development site and the local area. Where monitors or samplers are positioned off-site, they will be placed at one or more of the following (EA, 2014):

- **The site boundary or 'fence-line'** – where net emission fluxes from the site may be estimated through the use of measured concentration transects at the permit boundary of the site, in support of relevant regulation and national reporting.
- **Residential properties, residential areas** and other sensitive locations – providing localised measurements at high sensitivity receptors.
- **Locations of maximum off-site impact** – the distance of which will depend on the nature and height of the release; for example methane emissions at ground level may travel further if they undergo plume rise (e.g. due to being discharged upwards under high pressure). The location of maximum offsite impact will likely be determined from atmospheric dispersion modelling.
- **Background locations** – in order to determine ambient concentrations due to other sources.
- **Local air cavities** – where pollutants associated with on-site processes may accumulate.

Existing guidance on the establishment of monitoring campaigns for OOG facilities in the UK is limited. This assertion is supported by research undertaken by the Unconventional Gas Exploration and Extraction (UGEE) Joint Research Programme in 2016, which looked into the characterisation of baseline air quality around OOG sites. The study found little evidence of established methods for the design of baseline studies of this type around the world (EPA, 2016a).

Exceptions to this were found to be in North America, where there are a small number of guidance documents and research papers. One example is published by the Government of New Brunswick (2013), which provides some guidelines for the establishment of ambient monitoring programmes around shale gas facilities. This indicates that the characteristics of a monitoring programme will be dependent on the presence of nearby industrial activities and/or other oil and gas operators, and the intensity of proposed and/or existing operations. Depending on these criteria, a comprehensive baseline monitoring campaign would be expected to include the following elements:

- A calculation of the total emissions within a given area.
- A modelling assessment showing the potential impact on ambient air quality at ground level, including the potential for the formation of ozone.
- Both the collection of grab samples and the installation of continuous monitoring stations.
- Odour monitoring, including a means to record and respond to odour events.

On the basis of their review, the UGEE programme provided a series of recommendations for the establishment of baseline air quality around OOG facilities, many of which are applicable to an ongoing monitoring campaign. They suggest that a successful monitoring campaign will involve the following characteristics (EPA, 2016a):

- Appropriate number and siting of monitors and weather stations. Where a site has no existing pollution sources nearby; a single, appropriately situated monitor may be suitable, however more than one monitoring location may be required in other circumstances. For example, in areas with more than one OOG site, there is no guarantee that background concentrations recorded at one will be representative of another. It is therefore recommended that a monitoring station be set-up at each well pad, or in a location representative of a cluster of well-pads. If the location of future well-pads is known in advance, a monitoring station could be strategically placed to represent all future wells. In order to monitor the effects of increased HGV movements on nearby roads, it may also be necessary to establish additional monitoring locations away from the site (e.g. at the roadside of the main access road).

- Monitoring of pollutants which reflect the risk posed by onsite emissions. Target pollutants should be established through a rigorous baseline study before operations commence. This allows the determination of baseline data applicable to the site in areas where an established network may not exist.
- Measurement techniques and methods which have regulatory approval.
- Averaging periods and pollutant measurement durations which enable comparison with applicable standards and legislation (see Table 6).
- The simultaneous collection of meteorological data. If an existing nearby, representative meteorological station cannot be identified, one should be installed onsite, in order to provide simultaneous measurements of wind speed and direction.
- Accurate and precise methods of measurement.
- A method which produces suitable data capture (temporal completeness).
- An approach that is consistent from site to site, and representative of international best practice.

1.3.5.2 Frequency and timing

The EPA (2016a) recommendations for the timing, frequency and locations of baseline monitoring systems for OOG facilities is provided in Table 6. It is anticipated that the structure of these monitoring strategies will be continued during the production phase, to provide monitoring of ambient pollutant concentrations throughout all phases of the development.

Table 6: Recommended monitoring criteria for emissions from OOG facilities (source: EPA, 2016a)

Pollutant	Proposed monitoring
NOx	*Site monitoring* • Monitoring should enable the characterisation of short-term peaks and long-term concentrations. • In order to enable comparison with air quality objectives, monitoring should be conducted for a minimum of one year, to allow the calculation of an annual average, and enable the determination of hourly averages. *Roadside concentrations* • Modelled background concentrations of NOx and NO_2 can be used for the determination of traffic related impacts, as per the Design Manual for Roads and Bridges (DMRB). • However, in order to provide a more accurate representative of roadside concentrations, it is recommended additional monitoring be carried out at a roadside location on one of the main access routes to the site. Ideally this will be carried out over a period of six months, covering both winter and summer months, however for practical reasons it can be carried out over shorter period – no less than one month.
SO_2	• Carried out for a period of no less than one month (however may not be necessary if flaring will not be routinely carried out).

Pollutant	Proposed monitoring
CO	• No supplementary baseline monitoring is required, due to a lack of evidence to suggest significant CO emissions associated with OOG activities, and consistently low background CO levels across the UK. • Data from the Automatic Urban and Rural Network (AURN) should be sufficient for the determination of a baseline.
Ozone	• No supplementary baseline monitoring is required, as O_3 is a secondary photochemical pollutant that is not directly released by OOG processes. • Data from the AURN should be sufficient for the determination of a baseline.
Particulate matter (PM_{10} and $PM_{2.5}$)	*Site monitoring* • Onsite monitoring should be carried out for a minimum of one year and should enable the determination of daily and annual averages. *Roadside concentrations* • Concentrations of particulates should be determined at roadside locations along the main access routes to the site. This can be done either through the establishment of an additional monitoring location or through the use of modelled background concentrations.
Benzene and non-methane volatile organic compounds (NMVOCs)	• Monitoring should be carried out at the well-pad to provide hourly concentrations over a period of at least 1 year. • A monitoring programme should be put in place which assesses concentrations of NMVOCs through the use of gas chromatography mass spectrometry (GC-MS). • Formaldehyde concentrations are not easily determined by GC-MS, so alternative means of estimating the background concentrations of formaldehyde should also be considered.
Polycyclic aromatic hydrocarbons (PAHs), assessed as benzo[a]pyrene (BaP)	• Measurements of BaP should be carried out within the curtilage of the proposed well-pad for at least one year (no temporal resolution is specified).
Radon	• Regular measurements over a one-year period within the curtilage of the proposed well pad. • Measurements should also be carried out within local residential premises for a period of at least three months.
Methane	• Measured for a period of no less than one month in order to characterise background concentrations.

These monitoring recommendations are broadly appropriate to the requirements for ambient air quality monitoring in the UK, however in some cases, the recommendations need to be adapted for the specific regulatory circumstances in the UK.

Performance requirements for continuous monitoring will be determined by:

(a) Air quality standards and guidelines set for the protection of human health and the natural environment

(b) The likely increases in ambient concentrations which can be expected to arise due to the operation of onshore oil and gas installations.

Values from the literature to support the discussion of the importance of these considerations is included below.

It should also be recognised that the monitoring guidelines correlate to the legislatory requirements, but may not reflect the time period necessary for a robust application of statistics for formal change detection methods and could lead to misinterpretation in non-formal methods. The literature review uncovered little data for OOG situations to inform these recommendations (Section 1.3.7). Potential requirements for refinement will therefore be made when considering the case studies.

Detail of the likely concentrations of key pollutants in ambient air resulting from OOG facilities as extracted from the literature is given in the Appendix and reproduced in summary form in Table 7 below. It includes the maximum and minimum values for each pollutant observed where available.

The data in Table 7 provides the total environmental concentration for a selection of pollutants around operational OOG facilities. Although background ambient concentrations for these locations are not available, it is reasonable to assume that background air quality levels in rural regions in the USA would be comparable with those in the United Kingdom. Therefore, it is possible to combine this data with background concentrations recorded in the United Kingdom, in order to make some initial estimates of the likely increase in ambient concentrations as a result of contributions from OOG sites. This is important, as the expected change in concentration will dictate the monitoring design and statistical process recommended.

Table 7: Ambient air quality monitoring campaigns at shale gas sites conducted by State Authorities in the USA – summary of recorded data (source: Macey et al., 2014)

Pollutant	Concentration		Unit	Notes	Study authority
	Max.	Min.			
VOCs - Total	5,321	6	ppb	Monitored at drilling site.	Max. - Arkansas Department of Environmental Quality Min. - Colorado Department of Public Health and Environment
VOCs - Benzene	180	2.2	µg/m^3	-	Colorado Department of Public Health and Environment / Geary County Health Department
VOCs - Toluene	540	1.5	µg/m^3	-	
NMVOCs	8,761	273	ppb	Monitoring at eight sites.	Colorado Department of Public Health and Environment
Methane	2,535	1,780	ppb	-	Colorado Department of Public Health and Environment
NO	NO/NO_2 concentrations found to *"rarely exceed detection limits"*.				Arkansas Department of Environmental Quality
NO_2					

Pollutant	Concentration		Unit	Notes	Study authority
	Max.	Min.			
$PM_{2.5}$	16.7	7.3	µg/m³	Monitoring at 8 sites.	Colorado Department of Public Health and Environment

1.3.6 Air quality monitoring survey design

Air quality surveys for OOG developments in the United Kingdom must be able to achieve the following objectives:

(a) To detect airborne concentrations at levels below 20% of the air quality criteria, in order to enable robust conclusions to be drawn regarding the potential health or environmental consequences of the total measured concentrations

(b) To detect variations from baseline at around 20% of the levels typically recorded in the vicinity of onshore oil and gas activities, to enable robust conclusions to be drawn regarding the contribution of such activities to measured concentrations during operational phases

The following aspects should also be taken into account when designing air quality surveys for OOG developments in the United Kingdom:

1. Variations in the nature and quantity of substances emitted during the operational lifetime.
2. The potential contribution of unplanned releases: a comprehensive environmental monitoring analysis should enable the contribution of any such unplanned releases to airborne pollutant levels to be identified.
3. Measurement at different locations around an OOG facility and/or at a range of heights may enable the contribution of different sources to be distinguished.
4. A default minimum for baseline monitoring is suggested for 1 calendar year in accordance with existing recommended literature values.
5. A screening approach will enable the range of substances measured to be minimised, in order to avoid excessive survey costs. For example, it may be possible to correlate levels of nitrogen dioxide, sulphur dioxide and/or PM_{10} / $PM_{2.5}$. Similarly, it may be possible to correlate levels of methane and individual VOCs. This would enable a reduced set of measurements to be made, with the potential for extending the range of measurements if a potential issue is identified. Additionally, a proportionate and adaptive campaign should be considered where locations are remote and there are no local receptors. This could include monitoring different contaminants in different phases and at different frequencies (e.g. scaling back intensity of monitoring as applicable).
6. As well as baseline and change detection requirements, the monitoring design should also consider what information is required should a change be detected for investigation. Advanced analytical tools are now available which enable the findings of continuous monitoring survey to be interrogated in detail. One example which applied conditional analysis to strengthen the source signal is that of Malby et al. (2013) and consisted of the the following basic stages:
    a. Visualisation: Plan selection of signals from target source.
    b. Conditional selection: Choose data from conditions with strong & frequent impacts from target source.
    c. Non-target source subtraction: Identify and deduct impact contributions from non-target sources.
    d. Trend evaluation: Assess rate and significance of changes in target-source impacts over time.

This approach is covered in more detail in Section 2.1.

In view of this, it is recommended that the following sequence of issues is considered when designing an air quality measurement programme:

- Substances.
- Duration (by phase of monitoring).
- Sampling duration.
- Use of screening/surrogate approaches.

In collating and reviewing ambient air quality data, operators should adhere to the QA/QC requirements set out in Local Air Quality Management (LAQM) Technical Guidance (TG16).

1.3.7 Assessing change

In most of the case studies in the literature, there is no baseline condition for analysis, so methods are restricted to defining what impact an activity is having, and/or if a detrimental impact is being detected with (or without) reference to a background site.

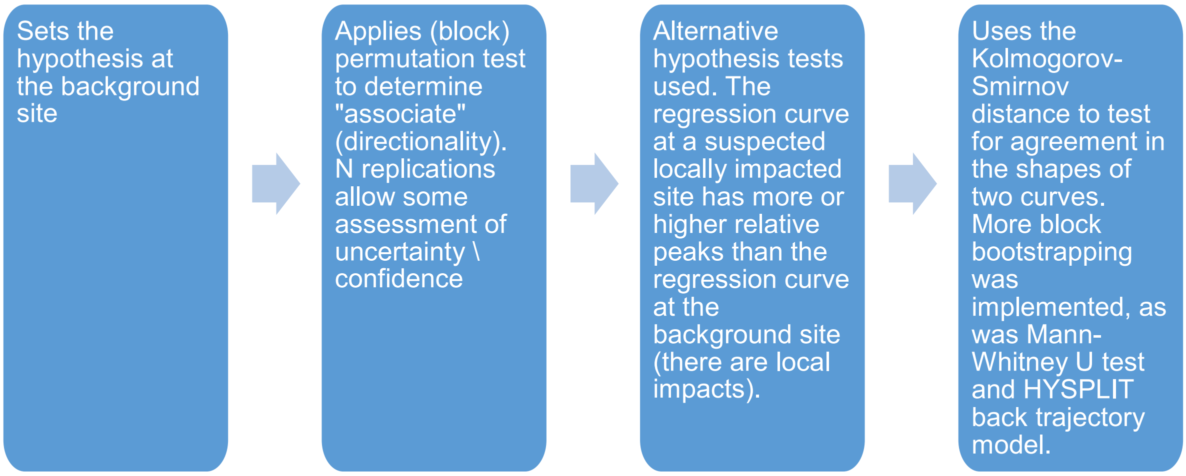
1.3.7.1 Comparing background sites to non-background sites

Cheng et al. (2015) used a Mann-Whitney U test to compare median concentrations at (a) several sites that have oil and gas activities with (b) locations that do not have such activities but have a background monitoring site. It gave strong evidence that the median concentration of NOx at the background site was higher than that at the sites where there were OOG activities. This would support the notion that simply comparing the absolute value of concentrations at two sites does not reveal clear and complete information about the impact from local sources.

Cheng et al. (2015) considered there to be several potential options for detecting a signal of impact which had been applied outside of the oil and gas sector and which could be considered for use within the sector. These included applications by Somerville et al. (1994, 1996), Donnelly et al., 2011, Henry et al. (2002, 2005) and Yu et al., 2004 for source apportionment methods and receptor modelling and techniques such as ‘wind sector analysis & parametric regression to determine systematic directionality’ and ‘source identification/ location and apportionment with nonparametric regression techniques (NPR) (e.g. kernel regression) with and without statistical testing of systematic directionality’. Discussion of the wider suite of methods used in air quality monitoring is covered in Section 2.1. A description of the statistical terms used is also provided for reference in Appendix D.

Cheng et al. (2015) considered that new statistical methods and a new framework tool were required to identify the existence of local impacts of OOG exploration and production activities on local air quality. In the case study for which they wished to define local impacts, baselining at sites pre-development had not occurred; NOx concentrations were not significantly different between developed and undeveloped sites and were generally much lower than the National Ambient Air Quality Standard, and there were only three to four species of VOCs more than 65% of the time. They asserted that a new method / framework was required to “*deal with pollutant concentrations below National Ambient Air Quality Standards where usual criteria and methods for data analysis were not sufficient*”. The statistical test developed focused on identifying and verifying the impact of local OOG exploration and production activities with respect to NOx, SO_2 and ethane, with concurrent characterization of background directionality and incorporating a measure of uncertainty. Stages included are summarised in Figure 6.

Figure 6: Summary of the nonparametric regression and statistical test applied by Cheng et al. (2015), to identify the impact of OOG development on local air quality



Using the foundations of kernel regression approach and bootstrap sampling, authors were able to construct a statistical framework of hypothesis tests to give quantitative probability evidence of the air quality impact from local OOG sources, to differentiate from regional effects. They concluded that the developed hypothesis-testing framework was able to provide statistical inference regarding the existence of local OOG operations and emissions after removal of the regional effect. The results indicated that when background variation (i.e. the regional effect) is non-negligible, this statistical approach works well for short-term (e.g. month-long) monitoring data without emission and baseline concentration information.

The approach considered by Cheng et al. (2015), did not look at detecting a baseline or a change from baseline, but at identifying whether suggested local emissions sources could be detected through a comparison with a local baseline. Where different pollutants show the same directional signal, this could lend support to a hypothesis that they originate from the same source. The adopted approach may also prove useful in application to OOG in the UK as it applies to low concentrations, which is likely to be the case for OOG facilities located in rural regions and is applicable where the number of OOG facilities is anticipated to grow. Other potential uses could be in reaffirming or investigating any observed change point detection. It is not anticipated that this method will be the method of choice, but that it will be one of a suite of options, applicable to a particular air or groundwater change assessment scenario.

1.3.7.2 Where baseline data is available

In the limited circumstance that baseline data is available, Ahmadi and John (2015) recommend the need to consider temporal and spatial separation of pollution trends to evaluate the impact of shale gas activities.

Ahmadi and John (2015) considered the impact of shale gas activities on ozone pollution in North Texas. Here, there is a long time series of data collection, and the scale of operation is large. They considered the contribution of one single gas well to be trivial when that well was operating properly, but that the cumulative impact of thousands of wells on ozone level could be significant and most apparent when background ozone is low. This has some relevance to the consideration of attributing source effects, as this would indicate that the source may need to be considered as multi-site with additive impact. Consideration may also therefore need to be given to the scale at which some contaminants are monitored. This concept of both site and regional monitoring is consistent with the recommendations for groundwater baseline monitoring from EPA (2016a) and EA (2016). Numerical modelling of ozone formation and dispersion, indicates the possibility of the significant contribution of shale gas activities in the near-field and on regional ozone levels (Carter and Seinfeld, 2012; Edwards et al., 2013; Kemball-Cook et al., 2010; Mansfield and Hall, 2013; Olaguer, 2012).

Ahmadi and John (2015) applied a Kolmogorov Zurbenko (KZ) filtering method (a type of trend analysis) to data from Dallas–Fort Worth (DFW) to determine the impact of shale gas activities on ozone pollution in North Texas. DFW has urban areas sprawled over 12 counties, 10 out of which have been failing to comply with the National Ambient Air Quality Standards (NAAQS) for ozone set by the US Environmental Protection Agency (EPA) (Ahmadi and John, 2015). DFW is partially located on the Barnett Shale (one of the most productive and fastest growing shale gas fields in the US), with shale gas activities developed only in the western half of the area due to the geological boundaries of the shale formation. This allows for a clear spatial segregation and allowed a comparison between the shale gas region (SGR) and non-shale gas region (NSGR). In addition, the area had been equipped with the air monitoring system by Texas Commission on Environmental Quality (TCEQ) operational over the three decades; allowing for the evaluation of the long-term impacts on the ozone time series. As well as there being an east west split of developed and non-developed areas, the authors also consider the intensification of drilling activities in 2007 to represent a 'before' and 'after' case study.

Ahmadi and John (2015) applied a KZ-filter to each time series of ozone to separate them into three components; a long-term trend component, seasonal component and short-term or stochastic component. The sum of the long trend and seasonal component, can be denoted as the baseline component (Milanchus et al., 1998; Rao et al., 1996, 1997). The approach used has potential for informing/supporting change detection conclusions. The data may also provide good insight into expected variability of measurement. However, the approach as applied, is considered to have had too many confounding factors to be conclusive e.g. such as NOx interactions (spatially variable with traffic), temperature lag treatment, distance from source and impingement of windblown sources, local factors and averaging.

1.4 Groundwater quality monitoring

This section provides an overview of the factors influencing groundwater quality monitoring programme design and groundwater quality monitoring techniques. The overview is provided to give context to the statistical techniques that may be applied (see Section 4) and to highlight any limitations in the groundwater quality data that may be considered background noise. This builds on existing groundwater monitoring of guidance including the Environment Agency (2016) "*Groundwater risk assessment for your environmental permit*" and statistical assessment of groundwater monitoring data such as the Environment Agency (2003) "*Guidance on monitoring of landfill leachate, groundwater and surface water*".

1.4.1 Factors influencing monitoring survey design

One of the key factors that should influence monitoring design is the objective that an operator is trying to satisfy; "The location, area, depth and media to be sampled must be linked to the selected working objective(s) and ultimately to the statistical tool(s) selected to interrogate the data." (EA, 2002). We can consider this as four generic basic key questions; where, what, how often, and for how long?

The key objective for this project is:

> *'to ensure that there is robust evidence from a site on which OOG operations are to occur to establish the 'baseline' condition and to ensure that information captured pre-development is suitable for characterising change and attributing the potential causes of change should the need arise'.*

There are at present only selected studies/guidelines that use these concepts within the literature, and specify what data may be required to meet these objectives. Examples include the EA guidance on the monitoring of landfill leachate, surface waters and groundwaters (EA, 2003), and EC guidance on groundwater monitoring for baseline setting and trend detection (EC, 2009).

EA (2003) stipulates that for new landfill sites, 'initial characterisation monitoring' needs to be completed prior to commencement of infill in order to draft assessment and compliance conditions into the site permit or operational plan. In the context of this report, this 'initial characterisation monitoring' is akin to 'baseline establishment'. At older operational or closed sites, where historic monitoring data are absent or inadequate, EA (2003) acknowledge that initial characterisation monitoring may need to be initiated at a later stage, using monitoring locations representative of conditions unaffected by the landfill. For the purposes of this report, we would refer to this monitoring as 'background site monitoring' to distinguish the two approaches to the setting of reference conditions.

EC (2004) established the following key principles for the development and design of monitoring networks and their operation:

- The amount of groundwater monitoring that is required will be proportional to the difficulty in judging:
  - The status of a body or group of bodies.
  - The presence of adverse pollution trends.
  - The implications of errors in such judgments.
- The design and operation of groundwater monitoring programmes should be informed by:
  - The objectives applying to the body.
  - The characteristics of the groundwater body, or group of bodies.
  - The existing level of understanding (i.e. the confidence in the conceptual model/understanding) of the particular groundwater system.
  - The type, extent and range of the pressures on the body, or group of bodies.
  - The confidence in the assessment of risk from pressures on the body, or group of bodies.
  - The level of confidence required in the assessment of risk.

These are all relevant to the OOG sector, and an adaptive and proportionate approach that takes into account uncertainties and risks is relevant.

In this section, values from the literature are reviewed to explicitly address the four questions of where, what, how often, and for how long[3]. However, prior to this, it is first necessary to consider the conceptual site model, which is essential to determine both the appropriate source-pathway-receptor terms, as well as the resultant potential risks to water resources. As a result, this is often used as the primary method to determine monitoring locations and frequency in the monitoring of groundwaters.

1.4.1.1 Scales of monitoring and conceptual models

The Irish EPA research programme highlighted that there are different scales of monitoring onshore oil and gas, including regional scale as well as the site specific scale, due to the potential for cumulative effects from several sites within a region (EPA, 2016b; Lavoie, 2014). This is consistent with the current approach in England and Wales, whereby the British Geological Survey (BGS, 2016a) are surveying the baseline methane concentrations in groundwater at a regional scale, which can be used as a reference point for any future changes in methane concentrations in groundwater. As described in Section 3.2, for England and Wales, OOG activities are permitted under the Environmental Permitting Regulations 2016.

Operators are required to carry out a groundwater risk assessment to assess what activities could directly or indirectly pollute groundwater and its receptors (Defra and EA, 2016). This risk assessment should be informed by the site conceptual model. The development of a site conceptual model is an iterative process whereby it becomes better defined at each stage of the risk assessment process. Defra and EA (2016) state that the main aim of the site conceptual model is to "*describe important hydraulic, hydro-chemical and biological processes that are at work in the soil, the unsaturated zone and the groundwater itself*" and should "*describe potential environmental impacts associated with the site, and any uncertainties in how the activity will interact with the hydrogeological setting*". Linkages between sources, pathways and receptors need to be adequately understood and described.

[3] NB "What" is dealt with in the next section rather than under the proceeding subsections

Where there are uncertainties in the site conceptual model, further characterisation of the groundwater and subsurface environment may be required by undertaking additional site investigations (Defra and EA, 2016). This characterisation phase provides the context needed to design the monitoring required for the protection of groundwater. The Council of Canadian Academies (2014) defines the characterisation phase as "*investigating the current nature and complexities of the groundwater system to understand migration pathways, identify receptors, and develop conceptual models that represent the entire system."* The EPA study (2016a) highlighted that the characterisation phase is not as straightforward for OOG operations as it is for the other industrial operations as there is less known about deeper groundwater conditions and the potential pathways to receptors near the surface (EPA, 2016a). Understanding the fracturing in the geological structures and the potential for them to be preferential pathways to receptors becomes very important (EPA, 2016a; Council of Canadian Academies, 2014).

It is standard practice that the site conceptual model is used to inform the groundwater monitoring required (e.g. Defra and EA, 2016; UKOOGb, 2015; EPA, 2016a; Council of Canadian Academies, 2014). The Environment Agency (2003) guidance on monitoring of groundwater for landfills emphasises that a risk based approach to the proper design of groundwater monitoring programmes is essential to focus the effort on actual risks. There is existing guidance available on developing conceptual models such as EA (2014b) and European Commission (2010).

1.4.1.2 Monitoring locations

Background groundwater quality up-gradient of the OOG site and operation, as well as groundwater down-gradient of the site and operations should be considered. The number of boreholes required will depend on the complexity of the hydrogeology at the site, the location of the receptors and the risk from the potential sources of pollution from the site itself. In the context of OOG operations, the site is often considered to be the well pad boundary. However, particularly in the case where there are horizontal wells, adequate spatial coverage is required because the sources of pollution may extend some distance from the well pad itself to sensitive receptors (EPA, 2016a).

It is the groundwater pathways to receptors that are considered highest risk that need to be monitored (DEFRA and EA, 2016; EA, 2003). For example, this could involve installing a monitoring borehole between a valuable drinking water abstraction borehole and the potential source of pollution. This will give an advanced warning of the development of any contaminant plume prior to it reaching the receptor.

Defra and EA (2016) and EA (2003) guidance states that there should be a minimum of three groundwater monitoring boreholes in order to determine the groundwater gradient at the specific site. It is standard practice to have more than this if the geology and hydrogeology are more complex (e.g. more strata) or for higher risk sites, or if there are several receptors (Defra and EA, 2016; EA, 2003). It may also be necessary to monitor nearby public and private drinking water supplies if they are potential receptors. This has been done for OOG studies elsewhere, e.g. USEPA (2015) and Council of Canadian Academies (2014).

Given the nature of OOG projects and the fact that horizontal wells extend beyond the site boundary, it may be necessary to have monitoring locations beyond the site boundary to provide adequate protection to sensitive receptors. For example, the Kirby Misperton A Wellsite in North Yorkshire is permitted by the EA, with five boreholes on the well pad itself and six offsite, one of which is 'deep', as well as three surface water monitoring locations.

In retrospective studies of incidents that have occurred at different sites by the USEPA, there has been a range in the number of sampling locations which depended on the extent of the issues and number of private wells. For example:

- Killdeer North Dakota: two supply wells, three domestic wells, one municipal well, nine monitoring wells and one state well (USEPA, 2015b).

- Northeastern Pennsylvania: there was an iterative approach with 33 domestic wells and two springs in the first round; 22 domestic wells, one spring, a stream, and a pond in the second round; and 21 domestic wells and one spring in the third round (USEPA, 2015c).
- St Lawrence Lowlands (Quebec): 81 private wells, 34 municipal wells and 15 ‘observation’ wells over a study area of 15,435 km^2, equivalent to the approximate exploration area of Utica Shale Gas in the region (Moritz et al, 2015). In this example, conventional oil and natural gas activity was previously established prior to shale gas development and could account for some in situ wells.

Mortitz et al (2015) also noted that natural faults were likely to be a preferential migration pathway for methane. As a result, they recommended that energy companies should respect a ‘safe distance’ from major natural faults in the bedrock when planning the localisation of hydraulic fracturing activities, to minimise the risk of contaminating the surrounding water. The same is true for monitoring points, as mixing these sources is likely to add more variability in the underlying data, which can mask any true signal of change that could arise from drilling operations.

In lessons from groundwater monitoring of non-OOG operations, the Contaminated Land Applications in the Real Environment (CLAIRE) “Principles and practice for the collection of representative groundwater samples, Technical Bulletin” (2008) highlights that a consideration of how aquifer hydrogeology and well hydraulics can influence sample quality should be part of the decision making process for the collection of representative groundwater samples. They note that the formation hydrogeology affects the design, installation and 3-D placement of monitoring wells, relative to known or suspected contaminant source zones in an aquifer (Nielsen and Nielsen, 2006; Nielsen and Schalla, 2006) and that for this reason, it is necessary to have an accurate 3-D understanding of the groundwater flow regime at a site. This should be based on an initial conceptual site model (CSM) which considers potential geological and structural controls on groundwater flow (e.g. spatial variation in high- and low-flow zones due to sedimentary architecture and fracture network geometry) and temporal variations in vertical and horizontal flow direction arising from pumping (e.g. existing abstraction or remediation boreholes) or recharge, amongst other factors. This information enables monitoring wells to be installed in locations which target either uncontaminated or contaminated groundwater, and to develop a monitoring well network that links preferential flow paths in the aquifer to deduce the spatial and temporal distribution of contaminants, plume geometry and processes controlling contaminant fate and transport at the appropriate scale (Wealthall et al., 2002; Thornton et al., 2006).CLAIRE (2008) conclude that without this knowledge, non-representative data can be generated on the distribution of contaminated zones and peak contaminant concentrations, potentially leading to erroneous interpretation of remediation performance and costly management decisions, regardless of how well the sample is subsequently collected and analysed (Wilson et al., 2004).

There are also a number of practical factors that need to be considered when determining the location of groundwater monitoring points, such as the health and safety implications of the drilling site, the drilling costs and land access issues (EA, 2006). These may limit the ability to locate monitoring boreholes in the most ideal locations that would provide robust groundwater monitoring data.

Whilst it is accepted that the conceptual model should be the primary method in determining appropriate monitoring on a site by site basis, some supplementary guidance that can be used as secondary sources of information\corroboration of the conceptual model is available. For example, for the establishment of baseline, Schedule 3, Paragraph 3(1) of the Landfill Regulations requires sampling to “be carried out in at least three locations before filling operations in order to establish reference values for future sampling”. For all sites at which groundwater monitoring is specified, there should be at least one measuring point in the groundwater inflow region (up-gradient of the landfill) and two in the outflow region (i.e. down-gradient) (EA, 2004a).

Under the Water Framework Directive, a greater degree of spatial representation was set. An optimal network was defined as one in which the average minimum distance between any location in the area to the closest sampling site expressed as a percentage of the average minimum distance was 100%, with only values that have a value of 80% of more accepted as non-biased. It would not seem that a statistically homogenous approach is required within this project, as the guidelines for OOG are centred on a risk-based approach for the protection of sensitive receptors. No further discussion of the approach is therefore made here, except to reference that there are options for a more statistical approach to stratified sampling that would not seem appropriate for the context of OOG development at the present time. Guidance on the "Analysis of Pressures and Impacts" for WFD (EC, 2003) indicates that space and time scales for assessment should be related to the space and timescale of load exertion and that compromises must be made to minimise the burden of data collection. The guidance recommends aligning the spatial scale to the targets of pressure, their size and the susceptibility of impact. Pressure location can be analysed as precise information or as density information (EC, 2003). In the first case, the relevant component of the waterbody is identified. In the latter, the area on which the pressure is exerted must be identified and small enough to make it possible to link the pressure to its target. The guidance cites an example of a confined groundwater in which the important data is the emissions on the recharge area, not over the total extent of the water body.

1.4.1.3 Monitoring timing, frequency and duration

The EA (2016) guidance for the OOG sector specified that as a minimum monitoring should include:

- Baseline monitoring.
- Monitoring through the operational lifecycle of the site.
- Decommissioning and post abandonment monitoring (to allow surrender of the permit).

Baseline monitoring will help to assess the pre-existing conditions against which changes can be identified and tracked. Baseline monitoring is therefore required at the local site specific level, as well as at the regional scale (EPA, 2016a; EA, 2016). The presence of pre-existing groundwater contamination issues and the lack of comprehensive baseline monitoring data has made it difficult in some cases to determine the impacts from OOG activities (Brantley et al. 2014).

The Petroleum Act 1998 (as amended by the Infrastructure Act 2015) requires that for high volume hydraulic fracturing baseline monitoring is required for a period of at least 12 months for methane in groundwater (EA, 2016). The EA (2016) guidance further states that the baseline data should be 3 sets of data at minimum to determine the natural variation. However, it is emphasised that the hydrological conditions at a particular site should determine the duration and frequency of baseline monitoring (EA, 2016).

The frequency of groundwater monitoring is not specified in the guidance as it depends on the pollutant travel times, hydrogeology of the site and the overall risk to receptors (Defra and EA, 2016). The EA's (2016) latest guidance for the onshore oil and gas sector highlight that the monitoring should reflect the different activities at the site. Higher frequencies may be required for higher risk activities such as well stimulation. The EA permit such as Kirby Misperton in North Yorkshire or Preston New Road require different frequencies for boreholes at different locations as well as different frequencies depending on the operational activities. For example, sampling and analysis is required weekly during fracking operations and monthly thereafter. This frequency would be considered quite high for groundwater sampling when compared to other monitoring programmes that can be quarterly, biannually or annually. At a regional scale BGS have undertaken their groundwater and surface water monitoring at quarterly intervals (BGS 2016b). There has also been a national methane baseline survey undertaken by BGS and supported by the EA that has been ongoing since 2012 (BGS, 2016a).

In the guidance for the monitoring of landfills for leachate, surface waters and groundwaters (EA, 2003), it is acknowledged that the frequency and range of monitoring data collected needs to be 'sufficient to be able to characterise seasonal and other non-landfill influences', but that one of the major complication with landfill data is that it often originates from a large number of monitoring points, each being sampled at most four times a year (EA, 2002). The statistical guidance notes on the interpretation of landfill monitoring data assert that to increase the power of any subsequent statistical analysis, whilst operating within a limited monitoring budget, it would be better as a general rule to advise operators to focus on a smaller number of monitoring points whilst increasing the measurement frequency. Where this is not possible, it will often be productive to carry out a joint assessment of data for comparable boreholes - an action that is especially relevant at the data screening stage (EA, 2002).

In cases where the travel time to receptor exceeds two years, EA (2003) recommends monitoring at least quarterly during the initial baseline establishment phase, quarterly for routine indicators (reduced to six monthly or annually if stable conditions are proved or for low risk sites except where groundwater flow velocities are high) and six-monthly for ongoing characterisation (reduced to annually if stable conditions are proved for low risk sites). Where there is intergranular or fissured flow, or there is large variability in measurements, which is close to or exceeds the "tolerable uncertainty"[4], higher monitoring frequencies might be justifiable; for example, for a travel time to receptor of more than 12 to 24 months, at least quarterly, or when travel time is six to 12 months, monthly. Where travel time is less than six months, the recommendation was that the frequency of monitoring should be set based on the risks.

The question of establishing a minimum number of samples needed to ensure the initial characterisation of monitoring data (baseline setting) are statistically valid for purpose was considered by the authors of this guidance. They concluded that a universally applicable guideline could not be set[5], with the number of samples needed ultimately depending on the baseline variability of the measurement and tolerable uncertainty required. To standardise approaches for landfill monitoring, the following guidance was given (Environment Agency, 2003):

- For most landfills, initial characterisation monitoring should be undertaken for at least one year prior to landfill development, but wherever possible for a longer period.
- For sites that can be demonstrated to pose low risks to receptors, initial characterisation monitoring should start at least three months prior to deposit of wastes and may be completed following commencement of waste input, subject to agreement with the EA.
- The monitoring frequency used during the initial characterisation monitoring period should be sufficient to characterise seasonal variation. Normally, quarterly or more frequent (e.g. monthly) sampling is required.
- In the absence of information to support alternative strategies, at least 16 sets of data should be obtained per uniform water body. Less stringent requirements would only be acceptable where data are demonstrated to be statistically valid for their intended purpose.
- Where water characteristics are uniform in a water body, samples could reasonably be obtained from a combination of several monitoring points. For example:
  - Four monitoring points could be monitored quarterly to obtain 16 samples within a one-year period.
  - Three monitoring points could be monitored every two months to obtain 18 samples within a one-year period.
- For situations in which local variations in water characteristics are present, initial characterisation monitoring needs to be carefully planned for each monitoring point to establish baseline conditions adequately (i.e. at least three groundwater boreholes per uniform water body are required).

Under the minimum requirements for WFD groundwater monitoring, it is stipulated that there should be at least one measurement per year during the operational phase, with the exact sampling frequency set by the natural conditions and dynamics of the groundwater body (EC, 2009). For formations in which the natural temporal variability of groundwater level is high or in which the response to pressures is rapid, more frequent monitoring will be required than will be the case for bodies of groundwater that are relatively unresponsive to short-term variations in precipitation or pressures (EC. 2004). This is translated into sampling frequencies in the UK in Table 2.

[4] Tolerable uncertainty is defined within the source text as a measurement of the degree of uncertainty that is acceptable without compromising the purpose of the measurement and would be set by the operator.

[5] Blakey et al. (1997), and Sara and Gibbons in Nielson (1991). Considered that 16-20 samples may be needed but had some reservations.

Table 2: Sampling frequency for groundwater hydrogeology in the UK.

Hydrogeology		Surveillance[1]	Operational[2]
Slow	Unconfined	Three years	Six monthly
	Confined	Six years	Annual
Fast	Unconfined	Annual	Quarterly
	Confined	Three years	Six monthly

Note: 1. Surveillance monitoring: parameters indicative of all the biological, hydro-morphological and general as well as specific physico-chemical quality elements must be monitored.
2. Operational monitoring: parameters used should be those indicative of the biological and hydro-morphological quality elements most sensitive to the pressures to which the body is subject, as well as all priority substances discharged and other substances discharged in significant quantities.

WFD guidance for trend detection expands upon this, recommending that trend analysis is performed with;

- At least eight measurements for annual measurements.
- At least 10 measurements for half-yearly measurements.
- At least 15 measurements for quarterly measurements.
- A minimum duration of at least five years across all frequencies.

Where monitoring is designed to pick up seasonal or annual variations, the timing of monitoring should also be standardised from year to year (EC, 2004) and care should be taken where two or more values in a row are missing (EC, 2009).

Other guidance notes for trend detection (EC, 2004) advise that;

- The frequency and depth should be tuned to physical and chemical characteristics of the natural system, groundwater flow conditions, recharge rates and reactive processes.
- The frequency and sampling should be tuned to support the scale with shorter screen lengths implying higher frequencies required.
- The chosen frequencies, depths and sampling supports should be justified.
- The 'evaluation' period should be a maximum of 12 years, with less than 10 years not recommended.

Whilst a five year monitoring campaign prior to OOG operations starting may be excessive, it should be acknowledged that this would allow characterisation of any year-to-year (short term) fluctuations to be characterised within the baseline assessment. It is also worth noting that, the guidance on impact and pathway assessment for the WFD, suggests that although most data sources provide yearly data, this does not provide information on significant pressures over a shorter timescale. It is asserted within the guidance that to correctly address all impacts, within-year data is required indicating the annual pattern, and that this should at least comprise the mean value, the peak value and its duration. They assert that the optimum frequency is monthly assessment (EC, 2003).

The Guidance for Trend Detection under the Water Framework Directive (EC, 2009), is that benchmark data on existing groundwater quality are needed for those contaminants that could pose a risk of deterioration, against which deterioration (future trends) may be assessed. Where sufficient groundwater monitoring data are already available for defining baseline levels, it is recommended that the starting point should be based on these data, otherwise the assessment should wait until sufficient data are available. This notion sets a precedent for determining if the data is adequate for the statistical analysis, and a possible feedback loop between the monitoring and the monitoring design.

EC, (2009) also notes that for trend assessment, the length of time series that should be considered depends on how the groundwater body reacts to changes in practices at the land surface (conceptual understanding), on the power of the trend test method in detecting trends, and on the quality of the data. It is noted that poor quality data and data with high Limits of Quantification (LOQs) may affect the analysis, although it is acknowledged that this may be more of an issue with longer time series, with higher LOQs observed in less recent observations. These effects are unlikely to be directly relevant to the trend assessment for OOG activities.

EC (2009) indicates that the minimum length of time series to be used in terms of the number of regularised measurements and the minimum number of considered years, depends on the monitoring frequency, the statistical method, the starting point for trend reversal and on the power of the method. Care should be taken to ensure that the length of the time series used is consistent with the conceptual model of the groundwater body (e.g. rates and residence times).

Guidance is also given on the maximum length of time series to be used for trend assessment, recognising that for long time series, trend results could be biased by changes in earlier years (EC, 2009). This may require consideration by the OOG industry in future, but is not considered further here.

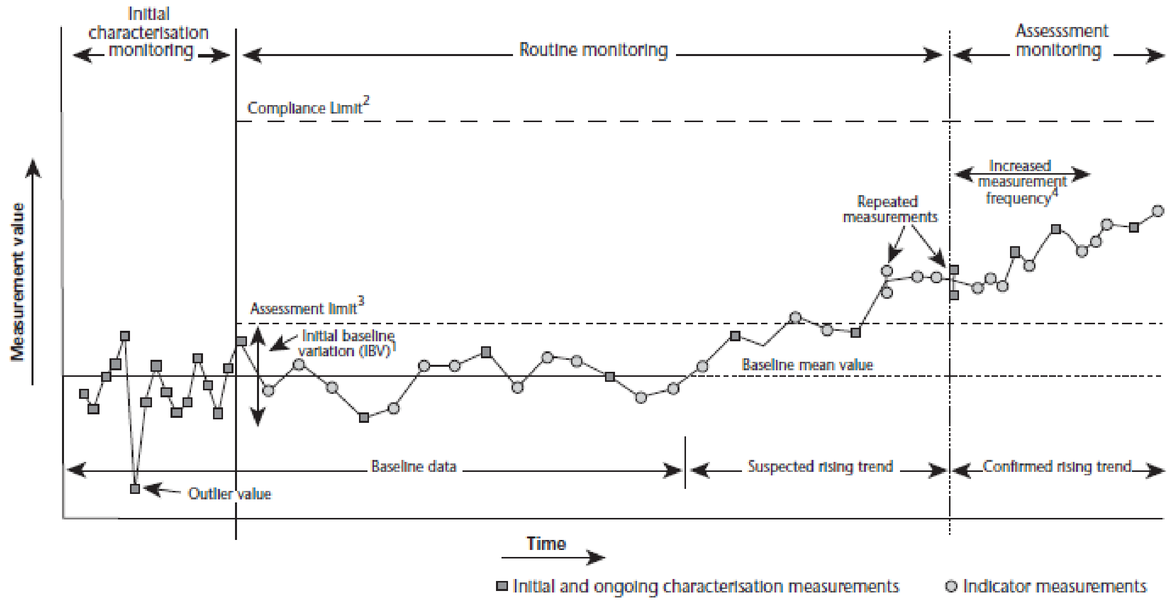
1.4.1.4 Adaptive Monitoring

EA (2003) provides guidelines on adaptive groundwater monitoring programmes. That guidance groups monitoring programmes into five categories:

- Initial characterisation monitoring.
- Routine monitoring.
- Pollution characterisation monitoring.
- Assessment monitoring.
- Completion monitoring.

While developed for landfills, the principles of groundwater monitoring design and implementation outlined in EA (2003) should be considered when designing similar programmes for the OOG industry.

Figure 7: Illustration of statistical concepts in relation to monitoring programmes



Source: EA, 2003.

Notes: 1. Initial baseline variation (IBV) would typically be defined using a statistical measure of variation such as range or standard deviation.
2. Compliance Limit is a regulatory standard.
3. Assessment limit is for early warning purposes. It may be a fixed limit (as illustrated), a time varying limit, or may be defined as an unacceptable rate of change unrelated to a specific limit.
4. Breach of the Assessment Limit leads to implementation of planned contingency action, in this case assessment monitoring. Increased monitoring frequency could be accompanied by an increased range of indicator measurements.

1.4.2 Groundwater quality parameters

1.4.2.1 Groundwater quality assessment criteria

The European Water Framework Directive (WFD) (Directive 2000/60/EC), transposed by the Water Environment (Water Framework Directive) Regulations 2003 (and amendments) requires member states to manage water in an integrated ecosystem-based approach (holistic approach). The WFD considers that all waters and their dependent ecosystems are inter-linked and inter-dependent. The key objectives of the WFD is to establish good status in all waters and to prevent deterioration of the status. The two key objectives for groundwater quality under the WFD can be summarised as follows:

- To prevent or limit the input of pollutants into groundwater and to prevent the deterioration of the status of groundwater and
- To reverse any significant and sustained upward trend in the concentration of any pollutant.

In order to help determine which substances should be prevented from entering groundwater and which ones should be limited, JAGDAG (2017) have developed a methodology for determining hazardous substances. The methodology makes determinations of substances in relation to the protection of groundwater and takes account of the risks posed to people and the environment via groundwater.

Limits of detection (LOD) or a Minimum Reporting Value (MRV), if applicable) are often used to assess whether a hazardous substance has been prevented from entering groundwater (EA, 2014).

The Groundwater Daughter Directive (GWDD) (Directive 2006/118/EC) transposed by the River Basin Management Typology and Groundwater Quality Status Regulations 2010, further describes how the chemical status of groundwater bodies is defined using threshold values, which indicate environmental risk and trigger the requirement for further investigation. Many of the threshold values relate to a trigger level for the protection of a groundwater receptor such as rivers, groundwater dependent ecosystems or drinking water supplies. Under the WFD, pollution is defined as the direct or indirect introduction of substances into land or water as a result of human activity that may cause harm to human health, aquatic ecosystems or terrestrial ecosystems dependent on the aquatic ecosystem. Therefore, standards are derived from standards appropriate to particular receptors for the assessment of groundwater quality compliance, including:

- Drinking Water Standards (DWS) which are maximum acceptable concentrations in consumer supplies after treatment
- Surface Water Environmental Quality standards (EQS) which are set to protect the ecology in rivers, lakes, estuaries and coastal waters

An understanding of the potential pathways to these receptors will inform the selection of locations of groundwater monitoring wells so that they provide protection to groundwater receptors. This is also known as a compliance point in the UK (DEFRA and EA, 2016) and requires a well-developed conceptual model, and understanding of the pathways and the groundwater flow rates and location of potential receptors. The compliance point is defined as "the point along the groundwater flow pathway where the defined target concentration (compliance limit or value) must not be exceeded*, as this would represent an unacceptable risk of harm to the receptor. The compliance point may be the receptor itself or a specified point along the source–pathway–receptor linkage (for example, within an aquifer nearer to the contamination source). Alternatively, it may represent pore water in the soil zone.*" (DEFRA and EA, 2016).

A compliance limit is the target concentration that shouldn't be exceeded at the compliance point, which can be theoretical (i.e. based on modelling) or based on physical monitoring (DEFRA and EA, 2016). The compliance point can also be the receptor itself, such as a river (DEFRA and EA, 2016). Natural background groundwater quality is taken into account when compliance limits are set.

1.4.2.2 Groundwater quality parameters relevant to OOG

There is a lot of published literature about the parameters that should be monitored in groundwater to determine if there is any impact from onshore oil and gas and these include reviews by the USEPA (2015a, 2015b) the Irish EPA (2016c) as well as ongoing work by the British Geological Survey (2016). The list of parameters can be quite extensive to cover and have been described by the USEPA (2015b) as a "broad spectrum of compounds and indicators that are potentially linked to hydraulic fracturing activities and/or that aid in providing a conceptual framework for evaluating potential impacts". The selection of parameters to analyse in groundwater samples links to the conceptual model and sources of pollution discussed in Section 3.1.2. The number of parameters can be quite extensive. For example, 225 parameters were analysed in each groundwater sample in a North-eastern Pennsylvania study (USEPA 2015b). The sparseness of sample data for the parameters of concern in the past has made it difficult in some cases to determine the impacts from OOG activities (Brantley et al. 2014).

The list of parameters that are monitored or recommended in these studies is summarised in Table 8. This is not considered an exhaustive list of parameters but provides an overview of the types of indicators commonly used and the special considerations for monitoring and assessment of results.

Table 8: Parameters commonly analysed for in groundwater samples for onshore oil and gas projects (adapted from: USEPA (2015a, 2015b), EPA (2016c) and BGS (2016a))

Group	Specific Parameters	Reason for Monitoring	Comments
Dissolved gasses	Dissolved methane, ethane, propane, CO_2	• Methane can be an indicator of leakage or migration of natural gas • Biogenic shale gas consists mostly of methane and thermogenic shale gas consists of methane and	• Gases such as methane are not monitored routinely in groundwaters because there are currently no drinking water standards or EQSs. Dissolved methane in drinking water is a risk because it's an asphyxiant, and an explosion and fire hazard in confined spaces

Group	Specific Parameters	Reason for Monitoring	Comments
		other gases and it is from the geological formation of fossil fuel (Royal Society and the Royal Academy of Engineering, 2012)	(Révész et al 2010). However, it is monitored in the UK where there is a perceived risk such as at landfill sites where there is the potential for gas migration. • Specialised sampling equipment is also required so that the sample does not contact the air (BGS, 2016a; EPA, 2016b; Darling and Gooddy, 2006). • Methane is present naturally in groundwater and has been detected in the UK at concentrations that average <10 µg/l (Darling and Goody, 2006). • Methane concentrations in groundwater are unlikely to be affected by seasonal variations (UKOOGb, 2015) • The topography can influence dissolved methane concentrations in groundwater (Darling and Gooddy, 2006; McIntosh et. al 2014), however this has been contested by others such as Jackson et al. (2013)
Stable isotopes	e.g. δ13C and δ2H	• Isotope analyses of methane can provide additional evidence of its origin.	• Biogenic methane has low values of the isotopes δ13C and δ2H whereas thermogenic methane has higher δ13C and δ2H values (Révész et al 2010). • Research into using isotope analysis of dissolved gasses is still ongoing (Royal Society and the Royal Academy of Engineering, 2012)
Naturally occurring radioactive material (NORM)	radium-226, radium-228, gross alpha activity, and gross beta activity	• Can indicate flowback fluid contamination of groundwater from well leaks or storage ponds on the surface	• Radium is the main radioisotope of concern in flowback waters, and measurements of both radium-226 and radium-228 can be

Group	Specific Parameters	Reason for Monitoring	Comments
			used to identify the source (Vengosh et al., 2014).
Major ions and trace elements	e.g. major cations (Ca, Mg, Na, K), major anions (Cl, SO4), and trace elements (As, Se, Sr, Ba).	• Can indicate the contamination of groundwater with saline waters (flowback or productions waters)	• Deep brine geochemistry can be compared to shallow groundwater geochemistry
Organic chemicals	e.g. Polyaromatic hydrocarbon (PAH), volatile organic compounds (VOCs)	• Can be an indicator of leaks or spills	
Fracturing fluid additives	Site specific	• Can be an indicator of well leaks or spills on the surface	• The composition of hydraulic fracturing fluids, and the types and numbers of additives, vary significantly because of site-specific factors such as geology, well design and operator preferences (Meiners et al,. 2013).
Other chemicals used onsite	Site specific	• Can be an indicator of leaks or spills	

Some parameters can be recorded in the field at the time of sample collection such as temperature, pH, electrical conductance (EC), dissolved oxygen (DO), and oxidation-reduction potential (ORP). BGS (2016b) are monitoring some of these continuously in groundwater in the Lancashire area as part of their regional baseline monitoring programme. The parameters include temperature, pH, specific electrical conductance as well as barometric pressure and total dissolved gas in hPa and the offset water depth.

In determining which parameters to select from what could be a large range of potential contaminants, the EA (2003) suggest that a broad range of measurements is required because, in most cases, detailed characterisation of the water will not have been undertaken historically, and the detailed nature of future impacts could therefore not be fully predicted. It is further recommended that there are two broad classifications of measurements, i.e. indicator measurements and ongoing characterisation measurements. The former should consist of measurements specified for compliance purposes, which should be monitored more frequently and could include the contaminants recommended for monitoring under Schedule 3, Paragraph 4(4) of the Landfill Regulations (pH, TOC, phenols, heavy metals, fluoride, arsenic and oil/hydrocarbons). Ongoing characterisation measurements should be repeats of those measurements specified during initial characterisation, but which require measurement less frequently than the indicator measurements.

1.4.3 Typical United Kingdom baseline concentrations

BGS have been undertaking a national methane baseline survey in groundwater since 2012 (BGS, 2016a). Much of the sampling has been focused in the Lancashire and Cheshire region. The results of the methane concentrations in groundwater within each region are summarised in Table 9. The maximum concentration was 14.2 mg/l within the Cumbria region.

Table 9: Summary of the methane baseline results up to January 2015 (BGS, 2016c)

Area	Concentration (mg/l)			Number of samples
	Minimum	Median	Maximum	
Central/southern Scotland	<0.0001	0.0036	1.68	31
Lancashire and Cheshire	0.0002	0.0025	0.091	15
Midlands and Yorkshire	<0.00005	0.0008	1.32	63
Southern England	<0.00005	0.0012	3.67	200
South Wales	0.008	0.034	0.0906	12
Cumbria and Northumberland	<0.0002	0.00065	1.434	16
Cumbria (Environment Agency data)	<0.1	<0.5	14.2	836
Lancashire and Cheshire (Environment Agency data)	<0.01	<0.5	132	2,842

1.4.4 Groundwater sampling and limitations in monitoring techniques

Monitoring of pollutant concentrations in groundwater is carried out by collecting groundwater samples from monitoring boreholes using submersible pumps, from drinking water supply wells that have permanent pumps installed and from springs.

Groundwater quality monitoring results have the potential to be influenced by monitoring techniques and the design and installation of the wells. Defra and EA (2016) highlight that uncertainties need to be considered as they will define how a result is assessed. They require that the details on the quality of the data that is generated is reported as well as information on whether conservative assumptions for data are valid.

1.4.4.1 Borehole construction and development

There can be issues around the construction of boreholes for monitoring. If they are not properly constructed and commissioned they can lead to poor quality groundwater samples or samples that are not representative of the intended groundwater zone (e.g. EPA, 2010; CLAIRE, 2008; Nielsen and Nielsen, 2006; British Columbia Ministry of Environment, 2016). CLAIRE (2008) define a representative groundwater sample as one where "*the chemical and microbiological properties of the groundwater sample reflect those in the aquifer adjacent to the sampling point*."

Guidance on the proper design and installation of groundwater monitoring boreholes is covered in existing British standards (EA, 2006):

- BS5667 Water Quality – Sampling. Part 22: Guidance on the design and installation of groundwater monitoring points.
- BS5930 Code of practice for site investigations.

- BS10175 Investigation of potentially contaminated sites - code of practice.

In addition, boreholes should be logged by a qualified geo-environmental specialist. They should record the subsoil, rock units, water strikes and groundwater levels as well as borehole construction, in order to have an adequate understanding of what collected water samples with be representative of (UKOOG, 2015; USEPA, 2010; EPA, 2016a; CLAIRE, 2008). Guidance indicates that well screens should be as short as possible, i.e. less than 3m (BS5667-22, 2010; USEPA, 2010) but it will depend on the flow horizons for a particular borehole.

The Council of Canadian Academies (2014) have highlighted that the use of domestic wells or older boreholes for monitoring purposes may not be reliable as there could be leakage or surface water intrusion due to the deterioration of seals around the casings and they may have been inadequately installed to provide representative groundwater samples.

1.4.4.2 Sampling techniques

There are a few different accepted groundwater sampling techniques for obtaining representative groundwater samples. These include purge and sample and low flow sampling (CLAIRE, 2008; BS5667-22, 2010). It is important for the field parameters (pH, electrical conductivity and dissolved oxygen) to be stabilised prior to sample collection in order to ensure a representative groundwater sample. The appropriate method selected will depend on the construction of the borehole, the hydrogeology (e.g. low yield boreholes) and the parameters that need to be analysed (CLAIRE, 2008; BS5667-22, 2010). There are also many different types of pumps that can be used for collecting groundwater samples.

Degassing of groundwater samples occurs when a sample is brought to the surface and exposed to the atmosphere and the loss of gasses will underestimate their concentration in the groundwater (CLAIRE, 2008). This can also lead to changes in the concentrations of other contaminants such as dissolved metals by causing chemical precipitation (CLAIRE, 2008). Sampling groundwater at springs also needs special consideration, as the methane results would not be representative of groundwater conditions as it will have undergone some degree of degassing.

This is a particular issue for sampling dissolved gasses and their stable isotopes. It can be quite difficult to obtain a groundwater sample that has not been exposed to air. This will depend on the setup of the pumping apparatus and tubing, and the borehole construction itself. Methods for collecting methane and stable isotope sampling are described in EPA (2016b). The EPA (2016b) study highlighted that the method chosen should be validated by collecting duplicate samples in the field for analysis.

A lack of quality control procedures can lead to publishing erroneous data which can have significant consequences (USGS, 2011). Confidence in the results is required in order to make decisions and assess change. Therefore, quality control procedures need to be designed into the monitoring programme from the beginning and used to qualify groundwater quality data as necessary. Guidance on QA/QC samples that should be performed during groundwater sampling are described in “Guidance on quality assurance and quality control of environmental water sampling and handling” (BS5667-22 (2010) Part 14 - Water quality sampling).

Consistency checks on the data can also be carried out such as calculating the ionic balance, examining ratios of total dissolved solids and electrical conductivity or comparing laboratory and field data results (EA, 2014). Quality control procedures are also required to account for errors and bias in the laboratory analysis (CLAIRE, 2008).

1.4.5 Assessing change

In most of the literature examples, there is no baseline condition for analysis, so methods are restricted in defining what impact an activity is having and/or if operations are causing a detrimental impact. Moritz et al. (2015) conducted an assessment of baseline concentrations and sources of methane in Quebec prior to shale gas development[6], but there has yet to be a follow-up post development analysis. In this study, the baseline was assessed over a 10 month period (August 2012 to May 2013) following a period of inactivity in exploration since 2010. Groundwater was sampled from 81 private wells, 34 municipal wells and 15 'observation' wells; and analysed for methane, ethane and propane concentrations as well as the $\delta^{13}C$ signature of methane. Methane was detected in 80% of the wells with an average concentration of 3.8 ± 8.8 mg/l, and a range of <0.0006 to 45.9 mg/l. Most of the gas measured in the samples was biogenic in origin, however thermogenic sources also contributed to some extent to the groundwater pool of light hydrocarbons in the area. The range in baseline concentrations (i.e. pre-activity) observed shows some of the limitations of investigation triggered by threshold values, as well as the large variability in background concentrations. Eighteen wells in the study area exceeded thresholds for drinking water alert in Quebec of 7mg/l and at four wells, methane concentrations were higher than 28mg/l (approximately equivalent to the solubility of methane in water at 1atm and 15°C). The authors asserted that these high concentrations could indicate methane spontaneously degassing and could be attributed to facilitated migration of gases through natural faults in the bedrock.

Humez et al (2016) used the same data set for the analysis of a number of other water quality parameters (Ca, Na, K, Cl, F, SO_4, pH, alkalinity, total dissolved solids (TDS) and free gases) over a longer time series (2006-2014). It is worthwhile to note that this then included the exploration phase data that had been excluded from Moritz et al (2015). Ideally, analysis would be performed on this exploration phase data to establish any impact of this phase, and, should there be no impact, this could then be incorporated to provide an extended data set for baselining from which to detect change. Humez et al. (2016) did not make a distinction between these phases, but considered that there were a variety of approaches that could be taken to groundwater monitoring for baseline, ranging in complexity (reproduced in Table 10).

Where studies do look for deterioration, they are usually based on pre-existing operations and look at differences between basic statistical summaries (e.g. mean, median, standard deviation and range; as used by Moritz et al., 2015) or trend analysis (e.g. Mann Kendall).

Exceptions to this include the use of reference 'background' sites by Osborn et al. (2011), who considered the statistical significance of the difference between natural gas concentrations (and their carbon isotopes) in groundwater between boreholes in gas production areas and non-production areas (at a regional scale). This analysis was not however supplemented by pre- and post- development, and the statistical method used in the testing of significance of difference between 'active' and 'non-active' drilling areas was also not elucidated. The importance of baseline data was recognised by these authors, who suggested that systematic and independent data on groundwater quality, including dissolved-gas concentrations and isotopic compositions, should be collected before drilling operations begin in a region, with data made available for public analysis to improve environmental safety, scientific knowledge, and public confidence (Osborn et al., 2011). The authors also considered long-term monitoring of groundwater and surface methane emissions during and after extraction to be important in ensuring the sustainable future of shale-gas extraction.

Humez et al (2016) similarly concluded that establishing effective sampling strategies and accurate and reproducible analytical methods for obtaining data on the occurrence and sources of methane in shallow groundwater was 'of utmost importance for assessing future anthropogenic impacts from unconventional oil and natural gas development.'. Similar to Osborn et al. (2011), these authors considered that both chemical and isotopic techniques should be used.

[6] Province had a long history (>100years) of conventional oil and natural gas activity, with the drilling of more than 400 000 wells (Humez et al, 2016)

Table 10: Analysis of the sampling and monitoring approaches used in the baselining study for methane in groundwater prior to unconventional oil and gas activities in Quebec by Humez et al (2016)

Approach	Information obtained/added value	Complexity/costs
Dissolved methane concentration analysis	Baseline/contamination level of methane, comparison to legal thresholds	
Dissolved and free methane concentration analysis	Check of inconsistencies related to degassing, oxidation, leakage etc. (upon sampling, transport, analysis)	
Dissolved/free gas analysis for methane, other alkanes, CO_2, other gases	Correction of air contamination, detection of oxidative processes, dryness parameter → indicator of origin and transport pathways (e.g. diffusive vs. advective transport)	
C–isotope analyses of dissolved/free methane	Indicator of CH_4–source (biogenic vs. thermogenic), mixing of different sources (including stray gas)	
C–isotope analyses of dissolved/free CO_2, alkanes	Detection of sources/formation mechanisms and secondary processes, e.g. oxidation (e.g. Chung et al., 1988)	
C and H–isotope analyses of CH_4 and H_2O	Further discrimination of reactive mechanisms within the main gas types: identification of biogeochemical processes, e.g. CO_2 reduction, acetate fermentation…	
Statistical data analysis (chemical and isotopic larger data sets)	• Geostatistical analysis (not applied in study of Humez et al, 2016): spatial variability of baseline, identification of anomalies, contamination pathways… • Triplicate sampling: assessment of realistic combined sampling analytical uncertainties • Periodic sampling on same well: assessment of baseline variations / contamination events • Continuous sampling for varying operating conditions: assessment of the impact of sampling conditions, e.g. pumping rates • Descriptive statistics: significance of differences between data subsets (e.g. lithological, depth–dependences), significance of multi–parameter correlations	

Notes: 1. The width of the blue bar indicates the complexity and costs of the respective approaches.

The most common types of analysis found in the literature search did not consider change or deterioration, but instead attributed difference between sites to be a result of the impacts of OOG activities. These studies have looked for explanatory variables (e.g. in geophysical environment or topography, or distance to natural faults) using methods such as PCA or multiple regression (Jackson et al 2013, Warner et al 2012 and Moritz et al 2015), or have looked at statistical differences between concentrations for different combinations of variables (e.g. at different proximities to site, or, at different depths/heights above valley bottom) using tests such as Pearsons / Spearmans ranks to determine correlations, and hypothesis tests such as Mann Whitney or its k-sample extension Kruskall-Wallis (e.g. Fontenot et al. 2013, Jackson et al. 2013). They often only consider single determinands and not multiple indicators, for example looking at whether the migration of methane gas coincides with the migration of other groundwater contaminants (Burton et al., 2016).

2 Principles for statistical assessments of air and groundwater quality data

In applying statistical techniques to air and groundwater quality for OOG activities, these are commonly in the application of threshold values. In air quality statistical analysis, analysis also tends to involve the multivariate analysis of wind speed and direction, often using Wind Sector Analysis.

A review of the literature indicates that existing guidance does not appear to be substantive enough for the purposes of defining baselines in unconventional OOG monitoring. Several of the directives reference baselines, but few consider either how the baseline may be identified or detail behind what should be done with it when it is. For example, the recommendation on minimum principles for the exploration and production of hydrocarbons (such as shale gas) using high-volume hydraulic fracturing (2014/70/EU) defines what the baseline should incorporate, but does not specify how the baseline should be defined in terms of time scales of measurement. Furthermore, it specifies that baseline is required for reference for subsequent phases, but not how it should be used in the reference or comparison, i.e. in looking for change.

Prior to considering appropriate baseline recommendations, we therefore look at how baseline and methods of detecting change are approached in the air and groundwater quality disciplines outside of onshore oil and gas, and also in other sectors.

Using the variability of the observations in which recommended approaches have been defined, and comparing these with values observed in current studies for the oil and gas industry, we will issue a set of default suggestions on monitoring length and frequency for the establishment of baselines.

Before considering the approaches used in the wider air quality and groundwater quality sectors, we first define some classifications for the different analytical techniques in terms of how they may be applied. For the purposes of application to the determination of baseline and the detection of change, we classify the approaches into four broad categories;

- Statistical techniques which in combination with others can be used to show difference/change
- Signal detection / strengthening techniques which in combination with other approaches can be used to apportion the cause of change\maximise the potential of detecting change
- Statistical difference or change techniques
- Uncertainty techniques

More information about different methods associated with these techniques (and examples of their application) is given in Appendix D. Here, we give examples associated with the different approaches where they are judged to support potential approaches that could be applied to the assessment of change for OOG.

2.1 Air quality

In the UK, local authorities are required to assess if ambient air quality complies with UK and EU standards (Malby et al., 2013), which is conventionally performed though the calculation of simple bulk statistics, including annual means and percentiles, compared with corresponding standards. Comparison of observed values to thresholds, does not however, allow identification of change or necessarily attribution that an activity has led to an above threshold value. To focus the analysis, we concentrate on ‘baseline’ assessment and ‘detection of change’.

2.1.1 Setting the baseline

In the analysis by Barratt et al. (2007), carbon monoxide (CO) 'baseline' concentrations (from which change was to be inferred) were measured at a roadside over an approximate 20 month period (~595 observations). These values were measured as daily mean CO concentrations from 15 minute capture values of the Governments Automatic Urban and Rural Network (AURN) QA\QC ratified data. This baseline data, was used directly in change detection using the CUSUM procedure[7], following adjustment for background trends[8] using a linear fitted relationship to running annual mean concentrations[9] from other background sites. Whilst it is important to consider the potential for underlying trends in baseline, it should be recognised that the method of adjustment and indeed the requirement for adjustment is related to the choice of method adopted for detecting changes. Barratt et al. (2007) used a reference mean that was assumed static, and as a consequence, adjustment to baseline values for underlying trends was necessary for this application of the CUSUM method.

Where using parametric methods of assessing change, it may also be necessary to normalise the data. A frequently used method is in taking logs and / or using averages over discrete time periods. Whilst Barratt et al. (2007), did not statistically test for normality (i.e. using Kolmogorov Smirnov), the authors did consider the effects of applying both logs and weekly averages to assess any effect on the conclusions reached.

2.1.2 Detecting change

Barratt et al. (2007) and Carslaw et al. (2006) adopted a CUSUM technique (a method of change detection; see glossary) to identify step-changes in ambient air quality concentrations due to local traffic management interventions. While there are many other methods that originate from the change detection method family (see Appendix D), the CUSUM method is the one that is the most frequently used (largely due to its simplicity). Barratt et al. (2007) represents an early adoptee of change detection as a formalised statistical approach, concluding that whilst further development was required to prove its utility, further investigation should be considered. This investigation could consider one of the many other refinements of the method, as highlighted in Section 4.2.2 and referred to in Appendix D.

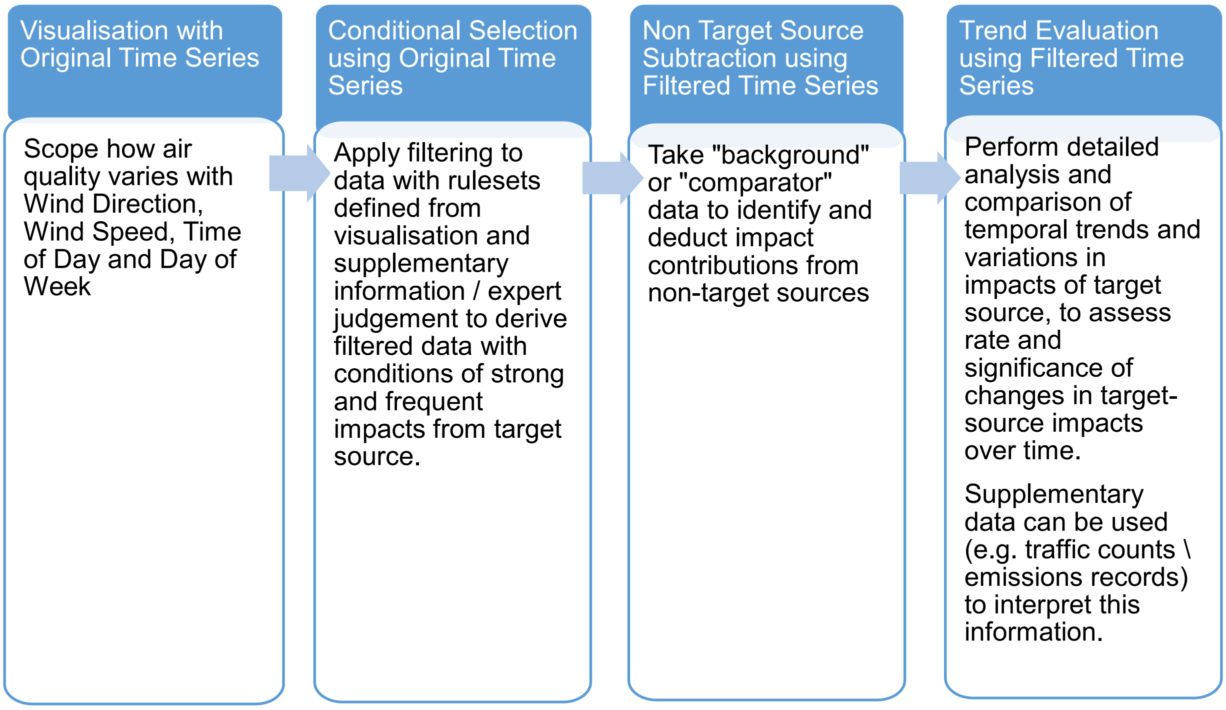
Malby et al. (2013) chose not to adopt formal change detection techniques, following the recommendation by Barrett et al. (2007) that these methods be used only where changes in pollution levels are large relative to other influences, such as seasonal emission variations and meteorological influences. Malby et al. (2013) presented their techniques for detecting if the contribution of a source to air pollution concentrations changed, using an example of a road traffic source and NO_2/NOx data over a data collection period of approximately 10 years. This analysis we consider to be classified as a 'signal detection\strengthening technique, which in combination with others can be used to apportion the cause of change and/or to maximise the potential of detecting change'. Malby et al. (2013) used subsets of ambient monitoring data that had been 'conditionally' selected to reveal more subtle changes. This is represented in Figure 8. Malby et al. (2013) suggest that the primary aim of conditional analysis should be to increase the signal-to-noise ratio in the ambient record, in order to distinguish and track the impact of emissions from a target source over time.

[7] This method falls into the classification of Statistical Difference or Change Techniques under the category Change Detection Techniques

[8] Classifications; background techniques under the classification "Statistical Techniques, which in combination with others can be used to show Difference / Change"

[9] Classifications; trend detection techniques under the classification "Statistical Techniques, which in combination with others can be used to show Difference / Change"

Figure 8: Summary of "Conditional Analysis" Approach adopted by Malby et al (2013)



Malby et al. (2013) assert that the emission performance of an individual air-pollution source can be inferred from an ambient record by isolating its signal of impacts. However, they also note that there are a number of complexities, which mean that this analysis is often not performed. Individual signals can be modified (e.g. through atmospheric dispersion), obscured (e.g. through the mixing of signals from other local sources and longer range background pollution) or complicated by confounding factors (e.g. through the frequency of specific dispersion conditions that deliver raised impacts). These complexities can also be applied to baseline monitoring and the detection of change within the OOG industry.

The conditional selection/analysis approach adopted by Malby et al. (2013) used wind-direction ranges centred on the target source and prevailing wind, with temporal windows of emission and dispersion. The ranges used and factors selected were acknowledged to be subjective. Applying conditional selection criteria\rulesets filtered the full time series to intermittent (irregular) time series for selected conditions, for which signal strength could be further improved by reducing superimposed background 'noise' from other local and more distant sources. It was proposed that this source signal 'clarification', could be performed using either concurrent measurement from site upwind of the suspected source (a 'background site'), or using 'comparator data' from the periods of time which were not thought to have impacts from target source. The use of background sites by Malby et al. (2013), which independently corroborated rates of increase in NO_2 attributed to traffic on the M4, lent powerful evidence-based support to the arguments made.

Carslaw et al. (2007) used background sites to assign a background signal plus predicted site difference to infer that where trends existed in NO_2, these could be assigned to changes in traffic emissions. The use of an alternative site to provide difference data from expected baseline conditions is a concept that may add value to an approach selected for OOG.

Other techniques have been applied to detect emissions performance, but these are not deemed relevant for review here as they do not apply to the approach of baselining and the detection of change from background.

2.2 Groundwater quality

2.2.1 Setting the baseline

An assessment of 'baseline' conditions of groundwaters in England and Wales, was established by the EA/BGS in their 'Baseline Reporting Series'. In 2004, a series of 23 reports were put together for the 'baseline' quality of groundwater across England and Wales. These baselines were intended to represent the scientific basis for defining natural variations in groundwater quality, and whether or not anthropogenic pollution was taking place. The Baseline Reports Series assessed the controls on water quality responsible for causing natural variations in groundwater, and provided a comparator for assessing the likely outcomes and timescales for restoration across all 'important aquifers' in England and Wales.

The definition of 'baseline' used within these reports was however, "*the range in concentration (within a specified system) of a given element, species or chemical substance present in solution which is derived from natural geological, biological, or atmospheric sources*". This definition of baseline differs from the definition being used within this report. That is to say that here, the baseline is defined by the pre-development status of a borehole and/or local aquifer, which may or may not contain some pre-existing anthropogenic component to water quality. Whilst it is recognised that the data held in these reports provides useful reference data and information, borehole-to-borehole variability alongside sometimes large local variations within an aquifer, should preclude automatic adoption of these baseline standards as being directly representative of the pre-development condition and the establishment of a baseline from which to assess evidence of change.

EC (2003) notes that in situations with no observed data, one possible means to evaluate status (or in this case 'background concentrations') would be to use a similar analogous site for which data are available and to assume that the assessment made from the observed data can be applied validly for both sites. The document also references a major caveat to this however, in that major point source discharges, or other anthropogenic modifications that take effect at a particular location (e.g. abstraction or impoundment) will almost certainly preclude the use of analogues, as the particular characteristics of the point source impact will be highly dependent on the location (EC, 2003). This is a similar approach as that referenced within EA (2003) for initial condition referencing in existing sites, which did not have measurements prior to site operations. As previously discussed (Section 1.4.1), key considerations in establishing an "adequate" baseline for change detection include questions of 'what', 'where', 'how often' and for 'how long'? As this section is focused on the statistical analysis of the data once it has been collected, we present statistical applications that have been applied in the literature for handling of baseline data.

Application of principal component analysis to characterise the mechanisms affecting groundwater quality pre- and post-activity has been applied in the fields of monitoring the impacts of geological carbon sequestration (for example Iranmanesh et al., 2014). The monitoring, verification and accounting (MVA) program for the large scale carbon capture and storage Decatur project uses shallow groundwater monitoring to establish baseline conditions, and to verify project activities are protective of human health and the environment and meet conditions of permitting.

Iranmanesh et al. (2014) used principal component analysis (PCA) to determine changes in attribution by conducting analysis pre- and post-CO_2 injection. The authors concluded that the results of the PCA on both data sets, indicated that water-rock interactions were the primary mechanism governing groundwater quality during both periods, and hence that CO_2 injection activities did not impact the quality of the shallow groundwater in the project area (Iranmanesh et al., 2014). A 'comprehensive baseline data set of groundwater quality' was considered by Iranmanesh et al. (2014) to comprise samples collected on a monthly basis over a 12-month period.

2.2.2 Detecting change

No examples of formal change detection techniques were found in application to groundwater.

EC (2003) recognises that most impacts cannot be measured and assessed directly, and usually are derived from observations of changes in state and the likelihood of these changes being caused by known pressures. The most important points that make it possible to establish sound (therefore recognised as true) relationships are the correct time and space scales of data collection of both pressures and states.

Under the WFD, there is no requirement for the assessment of change, but water quality should not be shown to be deteriorating. Numerous documents detail methods to be employed in trend assessment (e.g. EC, 2002; EC, 2003; EC, 2009). EC (2009) requires that the assessment be based on a recognised statistical method such as regression analysis (Annex IV A(2)(c)) and that the method chosen should also be able to test the statistical significance of a measured trend. In order to distinguish between natural variation and trends with an adequate level of confidence and precision, the trend test methodology should also be able to perform a test on seasonality where appropriate, e.g. where significant concentration variations occur within a year. The advice indicates that in almost all cases, a linear regression will suffice.

2.3 Lessons from other sectors

The need to detect if a change has taken place is a common question in environmental studies and beyond. A variety of statistical tests and variations on these tests exist, with nomenclature and the latest thinking often being sector-specific. It is proposed that 'change-point analysis' is considered as a tool for this project alongside 'boot-strapping methods' to assess levels of confidence in the magnitude of change. There are different methods that exist for single and multiple changes within the data from the formal change detection methods which we classify as separate to change difference methods that are often hypothesis tests which compare before and after, or site to site, rather than an ongoing, statistical effect.

2.3.1 Change-point analysis

A change point is a point in time at which the parameters of the underlying distribution or the parameters of the model used to describe the time series abruptly change (e.g. mean, variance, trend). Change-point methods have been used for a variety of different applications in the environment such as in the detection of regime changes in temperature and in precipitation, to detect regime shifts, to detect shifts in aerosol and cloud data, and to study past changes in the land uptake of carbon, as well as across different disciplines in the detection of artificial shifts (Beaulieu et al., 2012). Change-point detection in variance has been applied mostly in finance in order to study volatility in stock market prices.

One of the major problems with standard change-point detection techniques is that it is difficult to obtain the distribution of the statistic under the null hypothesis of no change. Different approaches can be applied to approximate this distribution, such as the Bonferroni inequality, the asymptotic theory and Monte Carlo methods. Another issue is the decision rule for determining change (Beaulieu et al., 2012). Another major drawback with currently used change-point methods is the assumption that the residuals are independent (i.e. no autocorrelation / time dependence). This is of relevance where metrics display seasonality. One potential method variation of change-point detection is therefore in using an informational approach (i.e. an approach based on the use of an information criterion).

Further adaptations exist for change point methods to account for non-normal distribution of the data, e.g. non-parametric approaches based on ranks, such as the change-point method developed by Pettitt (1979) and applied in Ocean Sciences (Ebbesmeyer et al., 1991 and Francis and Hare, 1994).

There are several approaches that have been presented in the statistical literature to discriminate between these models, such as the likelihood-ratio test, Bayesian approach, cumulative sums tests (as adopted by Carslaw et al., 2007), wavelets and the informational approach.

Of the change detection techniques, few have been applied to air and water quality. Barratt et al. (2007) considered their application of the CUSUM technique to be the first in application to detecting change in air pollution levels. However, the method has existed since 1954, first developed for use in industrial process control to detect deviations in production parameters from pre-determined values. They have since been used extensively in industrial process control as well as in a variety of other industries. In its original application to quality control, the method was applied to the data set until the process was identified as out of control, at which point the process would be halted, re-adjusted and re-started. The use of a single pre-determined value from which to identify a step change to environmental time series data is liable to require a 'large' change and to incur a lag time in detection, due to the fact that the monitoring has to show a sustained change above seasonality and background noise.

Barratt et al (2007) took this to be a limitation of the methodology, but it is important to note that there are several adaptations to the method that address this (see range of methods for formal change detection covered in 0). In their application, Barratt et al. (2007) concluded that while the method was able to detect a change, seasonality and other factors precluded precise characterisation of the timing of the change. As a consequence, they recommended that in application to environmental time series data, predicted change from the activity of concern should be large relative to other influences.

3 Case studies

3.1 Case study 1: Establishing an air quality baseline at a proposed Onshore Oil and Gas site

3.1.1 Introduction

The following case study provides an example of the process for establishing baseline air quality at a proposed Onshore Oil and Gas (OOG) facility, in line with the recommendations set out in this report. This example is based on air quality monitoring data collected by the Environment Agency in 2016 at a proposed exploration site located in the north of England.

The site is situated in a rural setting, surrounded by agricultural land, with several small villages located within a 2km radius. It is considered to be representative of the type of location in which an OOG facility may be developed in the United Kingdom (UK).

3.1.2 Conceptual model, establishment of monitoring location and QA/QC

This stage is represented by Figure 4.1 in the main report, "*Diagram 1: Flowchart for the monitoring design for establishing a pre-development baseline for OOG activities*", and the first step of the Figure 5.3 in the main report, "*Diagram 2: Decision tree for statistical analysis of data for baseline establishment at OOG sites*" for quality assurance and quality control (QA/QC) in preparation of the data for further analysis. It is assumed that as good practice, the stages of defining the model, assessing appropriate location, frequency and duration of monitoring, refinement and validation, have all occurred, and we here consider some retrospective information.

Figure 9 provides a simple conceptual model for an OOG test site, including the boundary of the site, the locations of nearby sensitive receptors and the siting of a single, downwind monitoring station. In this example, specific sources of emissions have not been included, however a more detailed conceptual model would be expected to include local emissions sources that may impact upon air quality, including those at the development site, and any nearby sources which may result in a cumulative effect on air quality. It should also be noted that the monitoring station in this example would be suitable for detecting changes in ambient air resulting from emissions from sources at ground level, however, it may not be suitable for emissions from raised stacks, due to its proximity to the boundary of the site.

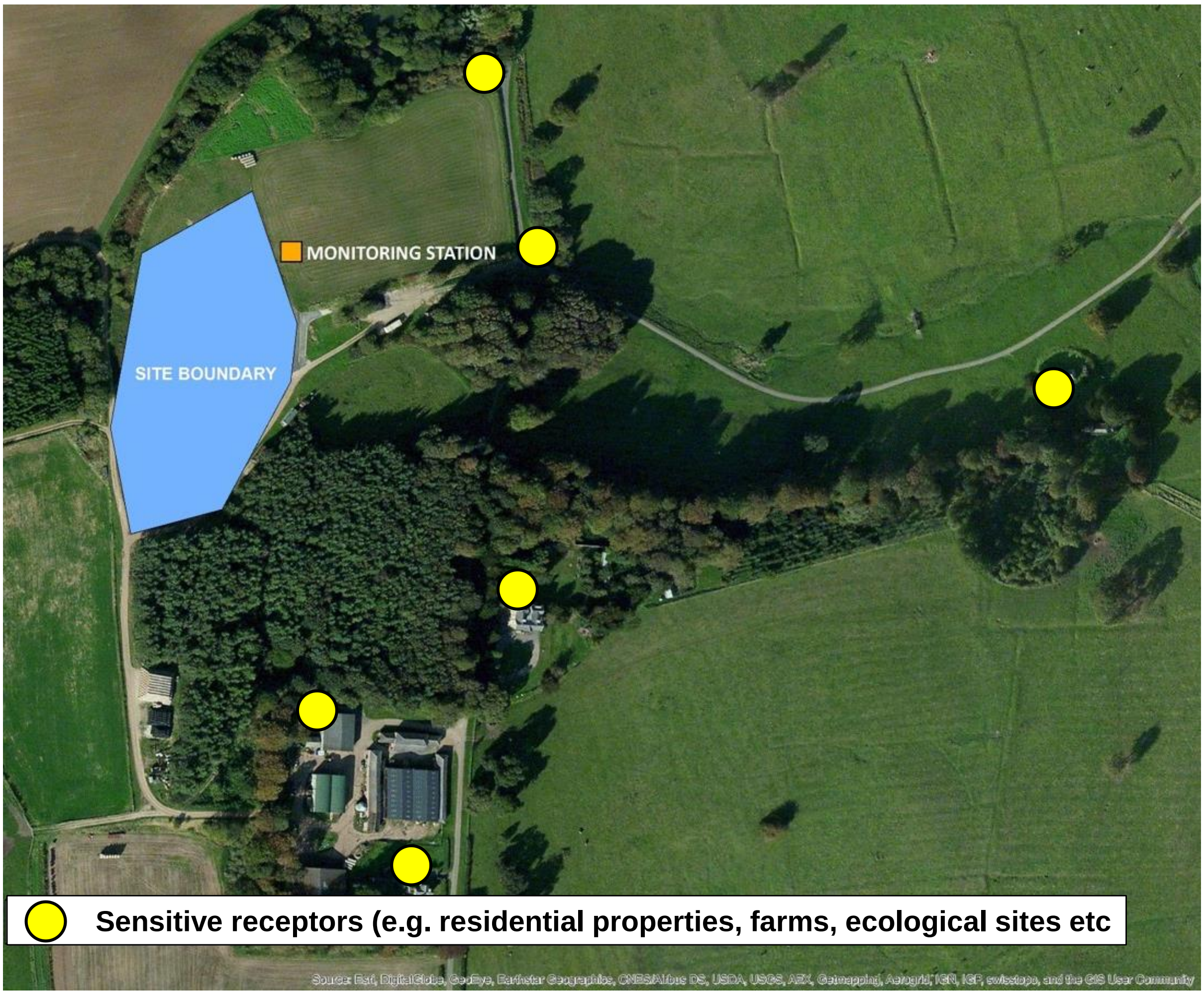
Figure 9 also includes a wind rose of wind speed and direction, recorded at a nearby, representative meteorological station, and an illustration of the local terrain, covering an area of 1.6km^2, centred on the well-pad. These have been included to demonstrate how the positioning of the monitoring station would be influenced by local weather conditions, most significantly prevailing winds, and local topography. Other considerations may include the presence of any obstacles and access to utilities. It is recommended that site information is reviewed both prior to and following site selection as it provides context in interpreting the values observed.

The location of a monitoring station would be expected to be determined on the basis of the results of an atmospheric dispersion modelling assessment. However, in the absence of this data, the information in Figure 9 has been provided as an indication of the factors that would influence how a monitoring campaign is set up. In this example, one monitoring station has been established in the prevailing downwind direction from the station, in order to collect air quality monitoring data prior to the operation of the site. Although the establishment of a single monitoring station may be adequate to establish baseline air quality levels, operators should not be discouraged from employing a second, upwind monitoring station in order to provide a comparison of ambient pollutant concentrations in airflows just before and just after they receive emissions contributed by site operations. There is insufficient evidence at the current time to establish if this secondary site should become a statutory requirement, but there is certainly value added in having this evidence stream.

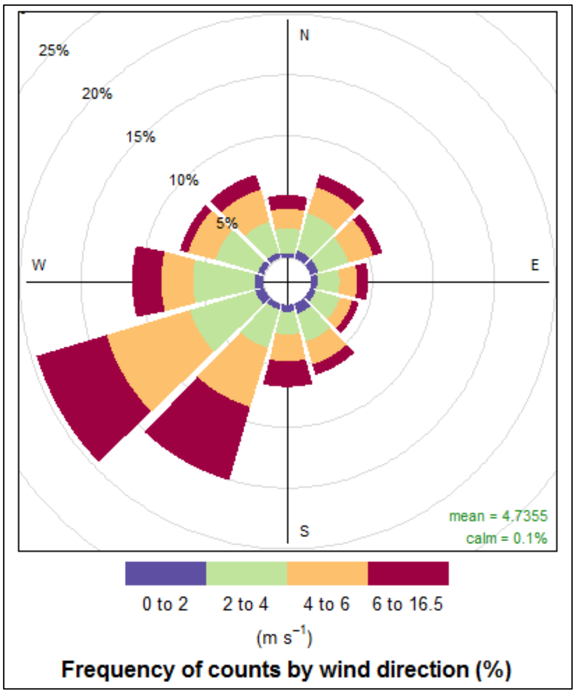
Standard QA/QC procedures, in accordance with the Environment Agency's M8 Guidance, would also be a requirement for sampling and collection of air quality monitoring data. Detail of the measurement methods were not made available for this case study and it is beyond the scope of this document to cover QA/QC processes. It was however noted that negative values existed in the measurements of $PM_{2.5}$ and PM_{10}. A limit of detection (LoD) value consistent with the typical 1 hour LoD for real-time monitoring using a tapered element oscillating microbalance (TEOM) quoted in the Environment Agency M8 guidance[10], was therefore introduced for these parameters. Values of $PM_{2.5}$ and PM_{10} less than 0.06 $\mu g/m^3$ were hence flagged as below the LoD. Subtle differences in the actual limit of detection should not bias the integrity of conclusions reached within this analysis.

[10] p.32, EA, 2011

Figure 9: Simple conceptual model of an OOG test facility



Illustrative wind rose



3.1.3 Monitoring duration

The default minimum standard monitoring periods and frequency suggested for each of the parameters measured is show in Table 3. The duration of the measurement period, frequency of assessment and total number of observations for analysis has also be appended for reference.

Table 3: Minimum Standards for Monitoring Duration

Parameter	NOx	NO_2	$PM_{2.5}$	PM_{10}	BTEX	Methane
Minimum Monitoring Duration	12 months	12 months	12 months	12 months	12 months	12 months
Minimum Monitoring Frequency	Hourly	Hourly	Hourly	Hourly	Hourly	Hourly
Required Assessment Frequency (for AQ standards)	Hourly average	Hourly average	Daily and annual	Daily and annual	NA	NA
Duration of valid[11] measurements at site	133 days ~4 months	133 days ~4 months	209 days ~7 months	209 days ~7 months	133 days ~4 months	133 days ~4 months
Temporal resolution of measurements at site	5mins	5mins	5mins	Hourly	30mins	5mins
Temporal resolution of assessment at site (mean average)	Hourly	Hourly	Hourly	Hourly	Hourly	Hourly
Number of valid	51,578	51,578	55,922	57,877	5,832-5,839	5,839

[11] There was a gap in the validated records such that the measurement period was not continuous. The duration period excludes the gap over which there were no valid measurements made.

measurements[12]						
Number of data points used in the assessment	4,324	4,324	4,720	4,866	134	134

Note: BTEX - Benzene, Toluene, Ethyl-benzene, and M&P-Xylenes

In this example, monitoring data was collected for a period of between four and seven months, and therefore does not provide data covering the required 12 months. For the purposes of this assessment, we will assume that the default minimum period has been reached, and will consider whether the duration was adequate in Section 1.1.7.

3.1.4 Subset the data into separate contaminants and monitoring locations

In this case study, there was only a single monitoring location. In the analysis that follows each of the individual contaminants was plotted and assessed. It is often helpful to plot contaminants side by side over consistent timescales as this can highlight where there are consistencies or inconsistencies between contaminants.

3.1.5 Data visualisation

The monitoring station used in this example collected continuous data on particulates (PM_{10} and $PM_{2.5}$), oxides of nitrogen (NOx), nitrogen dioxide (NO_2), methane (CH_4), and VOCs, including benzene, toluene, ethylbenzene and M&P-xylenes between February and September 2016.

Visualisation is provided in Figures 10 to 18. This includes time-series plots of the data (as hourly concentrations) and monthly box plots for each pollutant, showing the distribution of the observations and the intra-annual variability observed. If there had been more than one year of data, a second boxplot would also be constructed. The report also recommends creating annual box plots of recorded data but this was not possible due to the limited duration of the monitoring campaign.

Concentrations of particulates, NO_2 and benzene have been plotted against their applicable long-term air quality standards. Concentrations of toluene, ethylbenzene and M&P-xylene were found to be significantly lower than the applicable Environmental Assessment Levels (EAL)[13], and have therefore been plotted without this comparison. There are no air quality standards for the protection of human health, or EALs, for CH_4 or NOx.

A higher and lower outlier value has also been calculated for each dataset and are shown where applicable on the charts. These are discussed in more detail in Section 1.1.6.

In brief, the visualisations show:

- Increased variability in the observations in July to September for PM_{10}, that is not observed in other contaminants. There is no strong apparent seasonality, apart from this possible exception.
- Values that breach thresholds on individual days for all pollutants except NO_2 and benzene. Although, it should be noted that the contexts by which the standards are assessed are not shown (e.g. as number of allowable exceedances within a timeframe, or use of annualised average).
- Two-week window in July where no observations were collected. This needs to be taken into consideration in averaging and analysis.
- Some loss of data for time periods in other contaminants.

[12] Value excludes any later removal of outliers.

[13] https://www.gov.uk/guidance/air-emissions-risk-assessment-for-your-environmental-permit

Figure 10: Hourly PM_{10} concentrations, plotted against the long-term air quality standard and box-plot of monthly PM_{10} concentrations recorded between March and September 2016

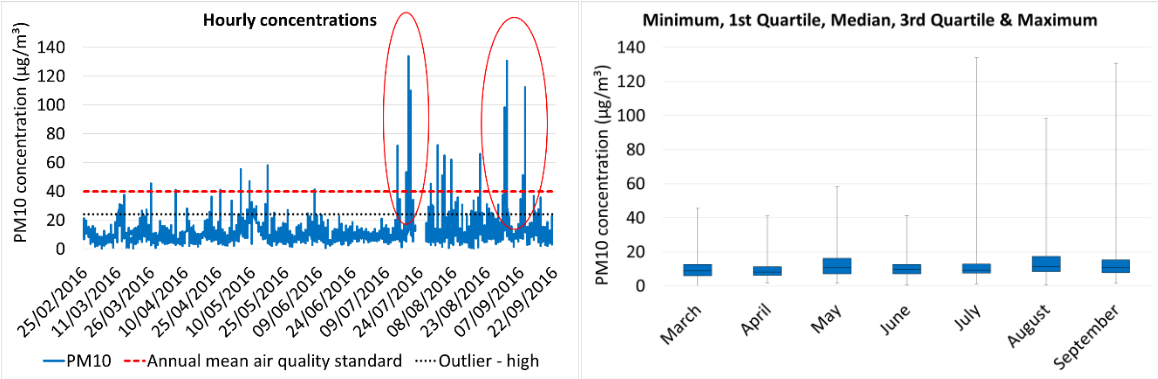


Figure 11: Hourly $PM_{2.5}$ concentrations, plotted against the long-term air quality standard and monthly box-plot of $PM_{2.5}$ concentrations recorded between March and September 2016

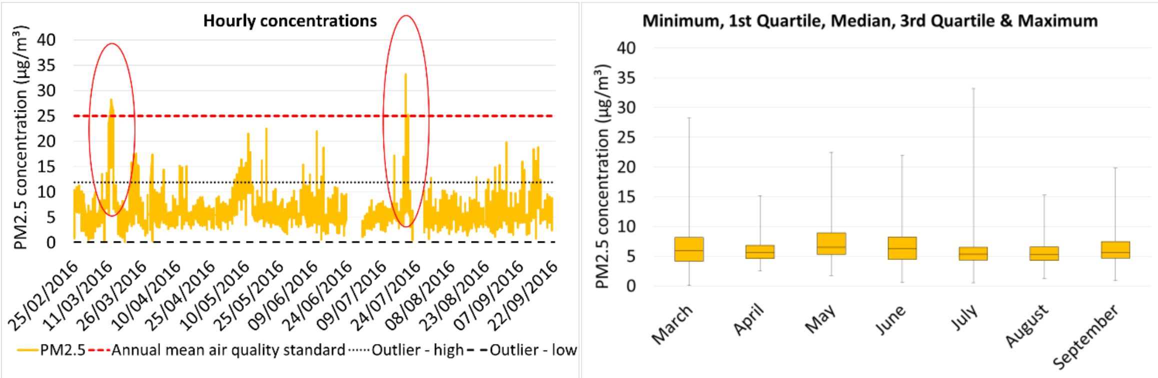


Figure 12: Hourly NO_x concentrations, plotted against the long-term air quality standard and monthly box-plot of NO_x concentrations recorded between March and September 2016

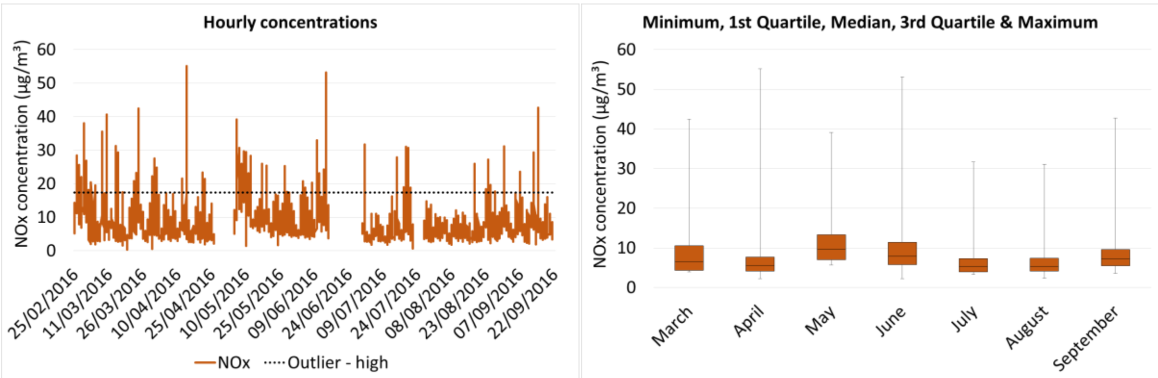


Figure 13: Hourly NO_2 concentrations, plotted against the long-term air quality standard and monthly box-plot of NO_2 concentrations recorded between March and September 2016

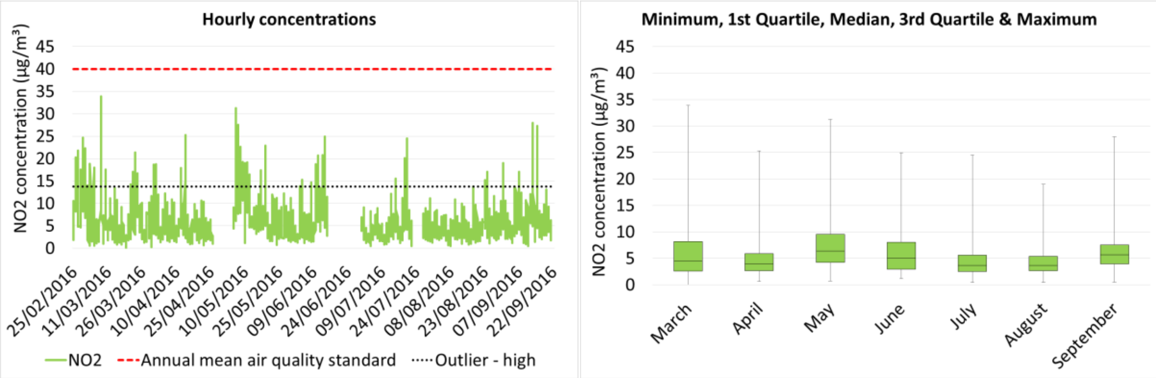


Figure 14: Hourly CH_4 concentrations and monthly box-plot of CH_4 concentrations recorded between March and September 2016

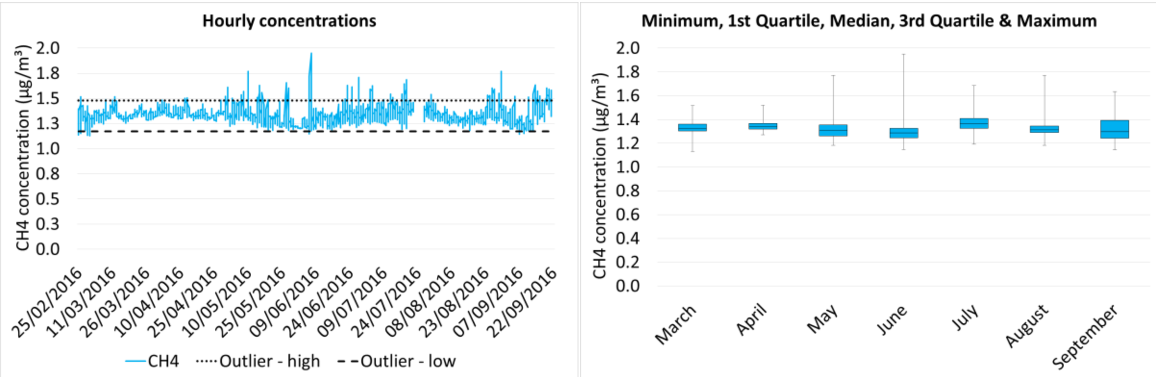


Figure 15: Hourly benzene concentrations, plotted against the long-term air quality standard and monthly box-plot of benzene concentrations recorded between May and September 2016

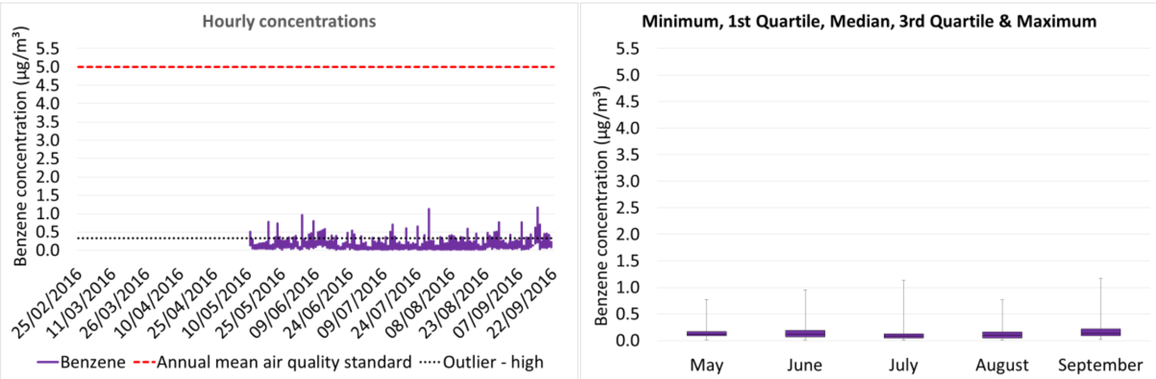


Figure 16: Hourly toluene concentrations and monthly box-plot of toluene concentrations recorded between May and September 2016

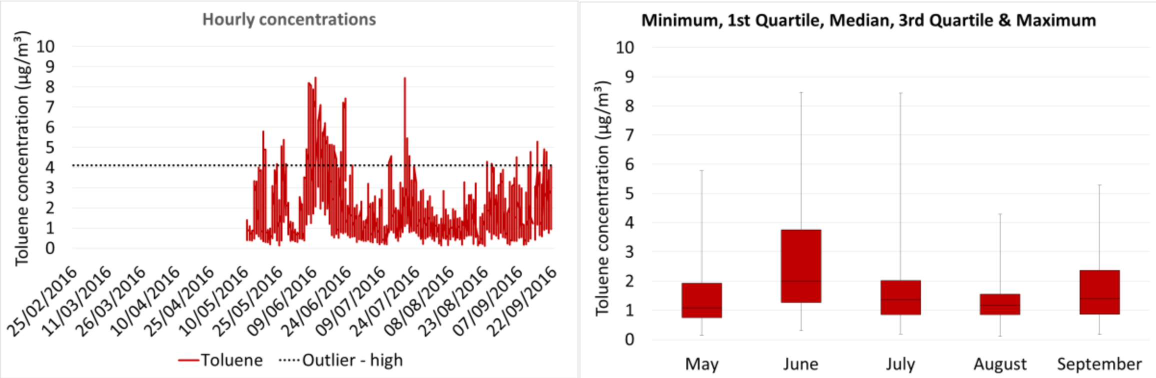


Figure 17: Hourly ethylbenzene concentrations and monthly box-plot of ethylbenzene concentrations recorded between May and September 2016

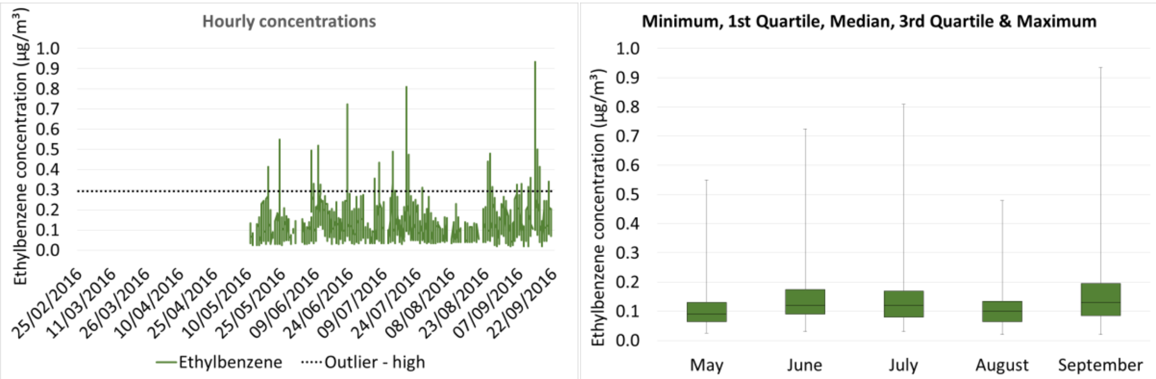
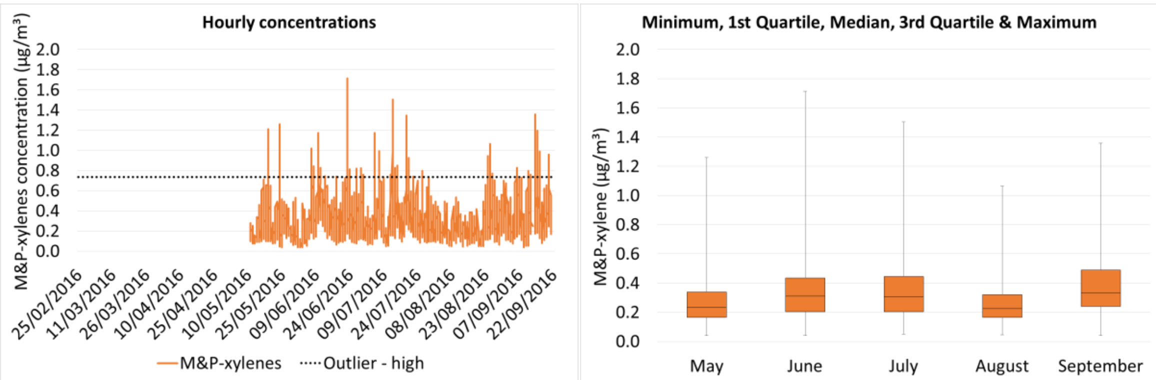


Figure 18: Hourly M&P-xylene concentrations and monthly box-plot of M&P-xylene concentrations recorded between May and September 2016



3.1.6 Detection and treatment of outliers

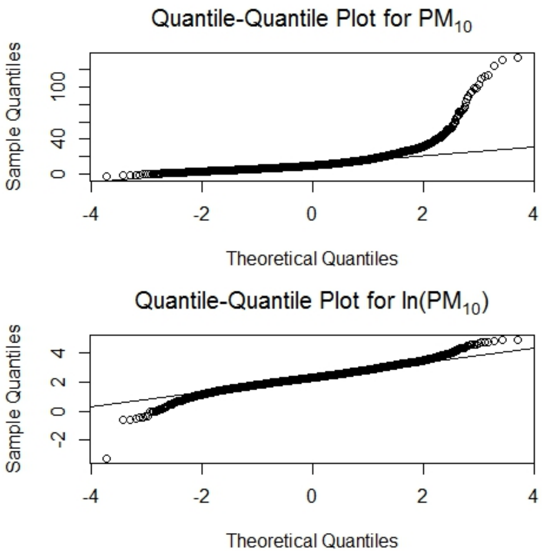
Potential outliers were calculated using the default methodology as lying outside the thresholds set by the lower quartile minus 1.5 times the interquartile range and the upper quartiles plus 1.5 times the interquartile range, calculated by the combination of month and year. A number of outliers identified within the dataset were circled in red in Figures 10 to 18. In most cases, statistical outliers will be accepted as genuine high or low values, but following good practice, we advocate that they are investigated. Investigation indicated that there were no examples of “obvious” true anomalies in the data set.

3.1.7 Testing for adequacy

Visual analysis of the data highlighted a potential change in the variability in PM_{10} (greater count and peak of maximum concentrations) during the summer months. There are a number of factors that may result in short-term increases in ambient PM_{10}, including changes in weather conditions and activities resulting in the emission of particulate within the vicinity of the monitoring station. However, for baseline assessment, this data would need to be characterised as part of an annualised cycle from which to detect further change (i.e. should there be a detected change, monitoring periods should be at least 12 months to be considered 'adequate').

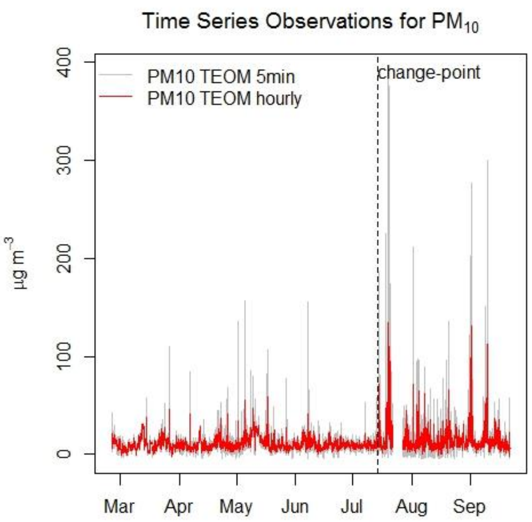
To test the assertion of adequacy for change detection, the data was first tested for normality and then assessed for change using an appropriate change detection technique. The quantile-quantile (QQ) plots for normality are shown in Figure 19. The top plot shows the untransformed data. The bottom plot shows log transformed data. Normality tests show that both logged and unlogged data could be accepted as normal. However, plotting the data clearly shows that taking logs leads to a better approximation of the normal distribution, as indicated by the symmetry around the solid line shown on the charts.

Figure 19: QQ plots used for visual corroboration in the acceptance of normality



Testing for change on means on the log transformed data was conducted using the cusum technique. It was found that there was a significant change around 14 July in the data set, as shown by the dotted line in Figure 20. This appears consistent with visual assessment of the data, and may be due to localised activities or a change in wind direction/speed in July.

Figure 20: Testing for Adequacy of the baseline data; change point assessment



For completeness, Figure 20 also shows the raw five-minute observations. These are included to show that the choice of resolution does not affect our conclusions, i.e. the same change in behaviour is seen in both the raw five-minute observations and the hourly-averaged dataset.

In this example, monitoring data was collected for a period of approximately seven months, and therefore does not provide data covering the required 12 months. Monitoring would be required to continue at the site in order to proceed beyond this stage of the change detection flow chart.

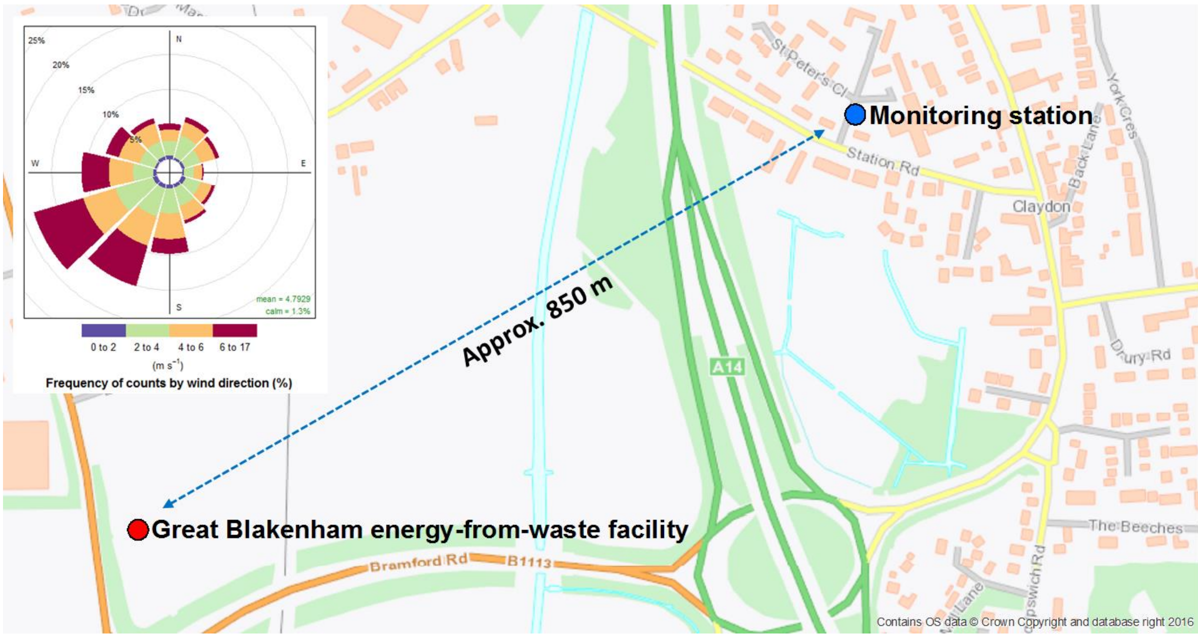
3.2 Case study 2: Analysis of monitored air quality data at the Great Blakenham energy-from-waste facility

3.2.1 Introduction

The following case study provides an illustration of some of statistical analysis of operational data, and considers some of the steps to be taken in order to complete a more comprehensive investigation of air quality impacts.

This example uses data recorded at an ambient air quality monitoring station located on St Peter's Close in Great Blakenham, Suffolk. The station was established in 2014 in anticipation of the opening of the nearby Suffolk energy-from-waste (EfW) facility. Figure 21 illustrates the location of the monitoring station and the EfW facility, and provides a wind rose of meteorological data recorded at the Wattisham meteorological station in 2015, which is situated approximately 9.5km west of the EfW facility.

Figure 21: Location of Great Blakenham EfW facility and St Peter's Close monitoring station



The EfW plant began operating in December 2014, providing capacity to treat up to 296,000 tonnes of household and business waste per year. Emissions from the facility are released to the atmosphere via two stacks at a height of 81m. The location of the monitoring station was selected on the basis that it will provide an indication of the level of impact of emissions to air from the EfW facility on sensitive receptors (e.g., houses and schools), within the village of Great Blakenham. As shown in the image above, the monitoring station is situated approximately 0.85km north-east of the EfW site. Between these two points lies an A-road and the cross-country train line linking Ipswich with Stowmarket.

The steps taken in the analysis of the data performed in Case Study 1 were replicated for baseline and operational data (data not shown). To provide context without replicating the detail of the first case study, time-series data is provided in Figures 22 and 23 below.

The monitoring station records data on ambient concentrations of NOx, NO_2, SO_2 and PM_{10} between January 2014 and December 2015, providing approximately 12 months of pre- and post-operational concentration data. Graphs comparing the hourly concentrations of these four pollutants recorded during 2014 and 2015 are provided below. Concentrations of NO_2 and PM_{10} have been compared against the applicable annual mean air quality standard. There are no applicable annual mean air quality standards for the protection of human health for NOx and SO_2.

Figure 22: Hourly concentrations of NOx, NO_2 and SO_2 recorded at the St Peter's Close monitoring station in 2014 and 2015

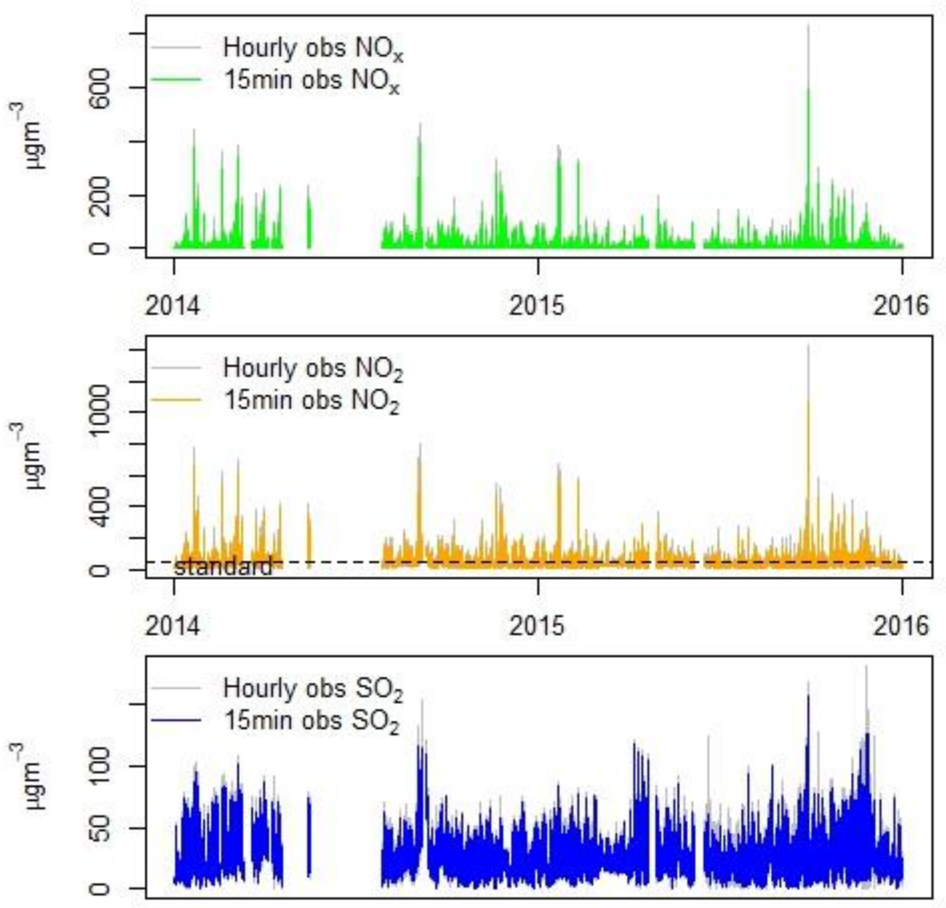
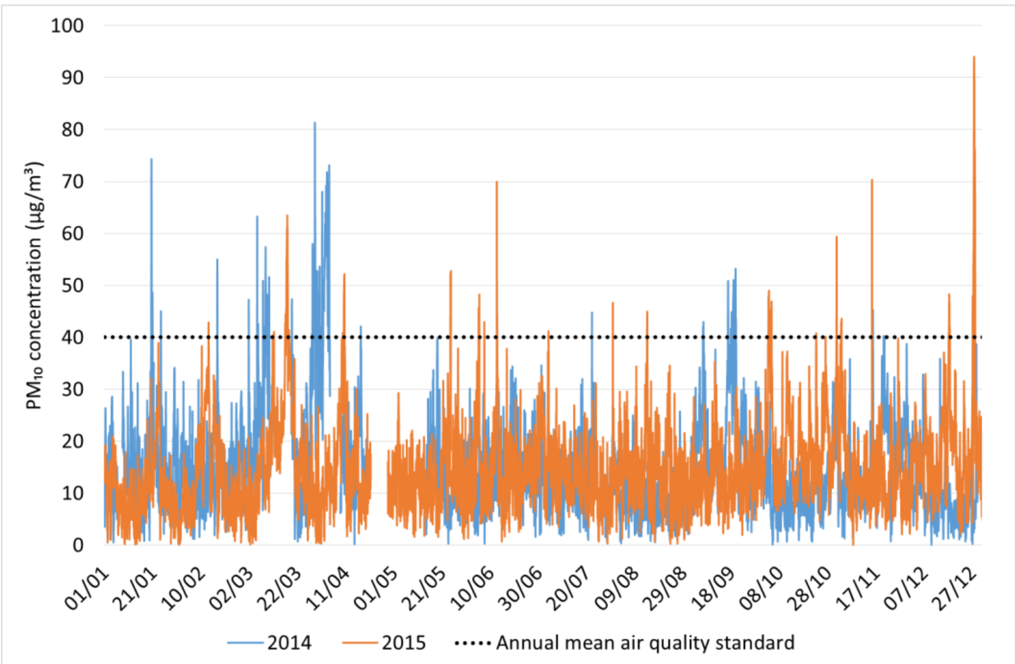


Figure 23: Hourly concentrations of PM_{10} recorded at the St Peter's Close monitoring station in 2014 and 2015



3.2.2 Conceptual model

A conceptual model was used to identify additional sources and pathways for further investigation. No other sources of emissions were identified in the locality from the conceptual model.

3.2.3 Wind sector analysis

In order to investigate the effect that emissions from the EfW facility are having on levels of ambient air at the St Peter's Close monitoring station, polar plots of pollutant concentrations prior to (01/01/2014 – 01/12/2014) and following (02/12/2014 – 31/12/2015) operation of the EfW plant have been created, as shown in Figures 24 and 25.

The polar plots visually indicate that marginally higher concentrations of NOx and NO_2 occurred during winds from a south-westerly direction, of approximately 10-15m/s, following the operation of the EfW facility. Whereas, concentrations of SO_2 appear to show a reduction in concentrations associated with winds over 10m/s from a south-westerly direction between 2014 and 2015, which would suggest a change in contributions of SO_2 from this direction, however further assessment of local sources would be required to confirm this. For PM_{10}, higher concentrations were more strongly associated with easterly winds in both 2014 and 2015, which is to be expected, as concentrations of particulates are more likely to be influenced by localised sources, such nearby traffic movements.

The change in concentration of oxides of nitrogen associated with higher wind speeds, from the direction of the EfW facility, is an indication that the operation of the facility has resulted in a change in baseline air quality, albeit minor within the context of national air quality standards.

Figure 24: Polar plots of NOx and NO_2 concentrations recorded at the St Peter's Close monitoring station prior to and following the operation of the EfW plant (µg/m³)

NOx **NO_2**

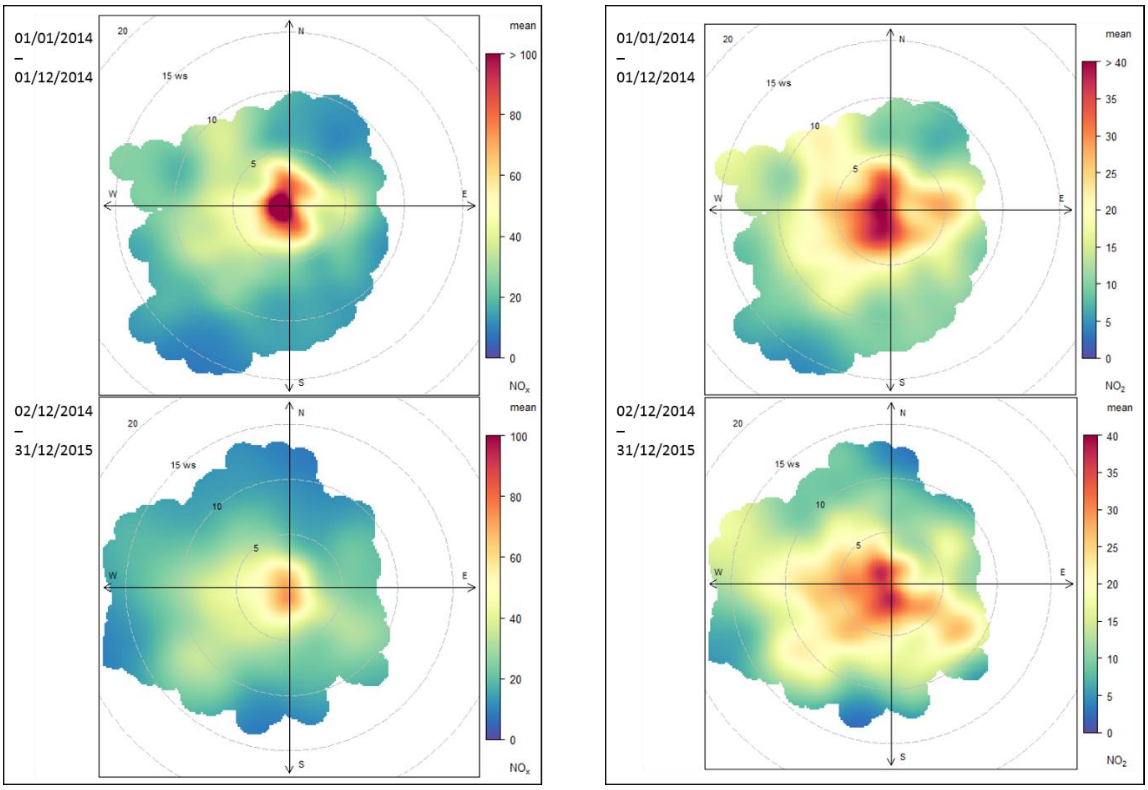
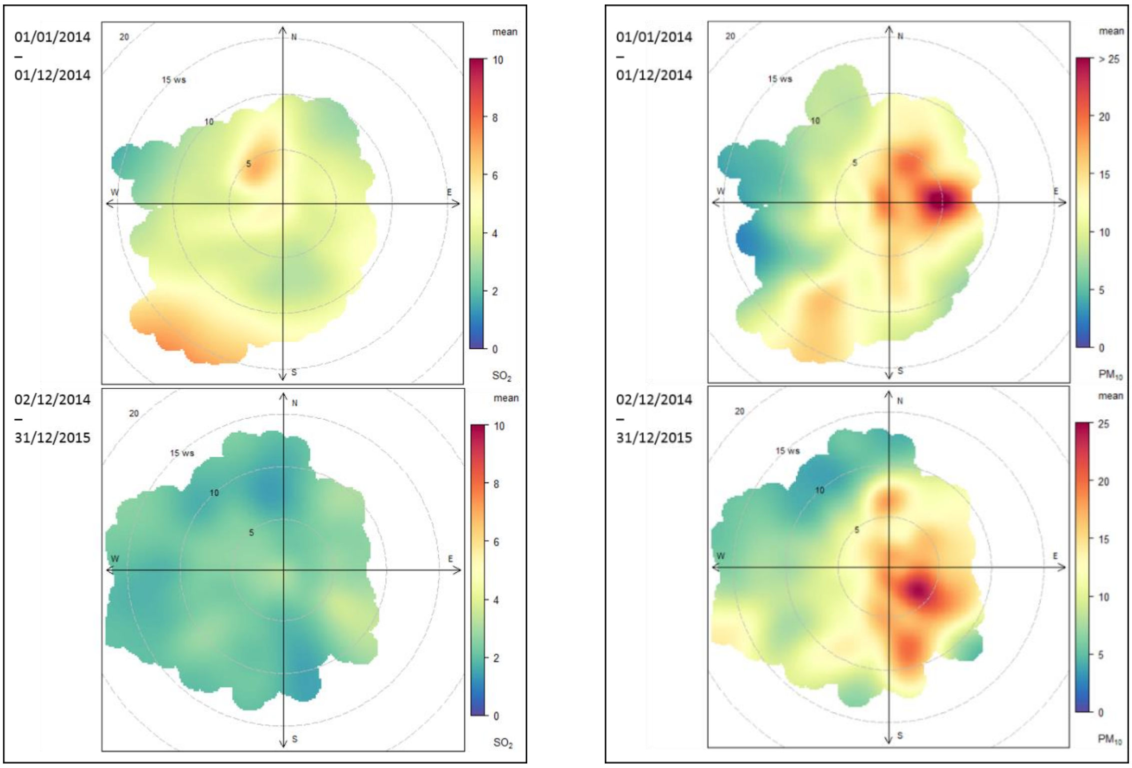


Figure 25: Polar plots of SO_2 and PM_{10} concentrations recorded at the St Peter's Close monitoring station prior to and following the operation of the EfW plant (µg/m³)

SO_2 | **PM_{10}**



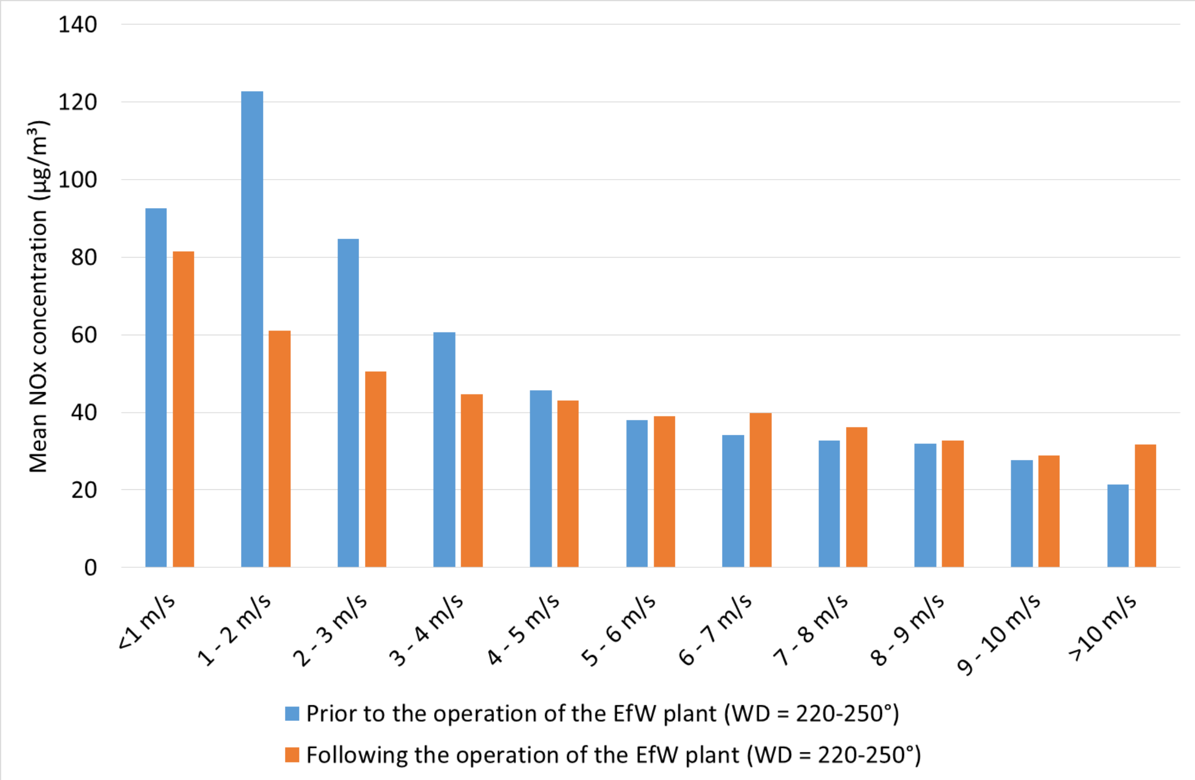
3.2.4 Identify rulesets and perform conditional analysis to increase signal strength

Only one ruleset for signal strengthening was identified. This was that only concentrations from wind directions of between 220 and 250° should be used as representative of the source, reflecting the direction of the EfW from the monitoring station.

Figure 26 shows that prior to the operation of the EfW facility, the monitoring station at St Peter's Close experienced the highest average concentrations of NOx (>80µg/m³), associated with winds from a south-westerly direction, during periods of low wind speed (≤3m/s). When compared with average concentrations recorded following the operation of the EfW plant, values recorded in 2014 were higher at all wind speeds ≤5m/s. However, at wind speeds >5m/s, concentrations following operation were consistently found to be higher than in 2014.

These results suggest the introduction of the new emission source has altered the concentrations of NOx in ambient air at the monitoring station in Great Blakenham, under meteorological conditions that correspond with the direction and distance of the EfW plant. However, it is important to note that concentrations arising from other directions were also found to show marginal increases, following the operation of the EfW facility (e.g. from a south-easterly direction), despite no known changes in emission sources from that direction having occurred during the assessment period. Therefore, on the basis of this analysis, it is not possible to confirm that changes in baseline air quality at the St Peter's Close monitoring station following the operation of the EfW can be attributed to emissions from this facility.

Figure 26: Comparison of mean NOx concentrations, prior to and following the operation of the EfW plant, during periods of wind direction 220 and 250°



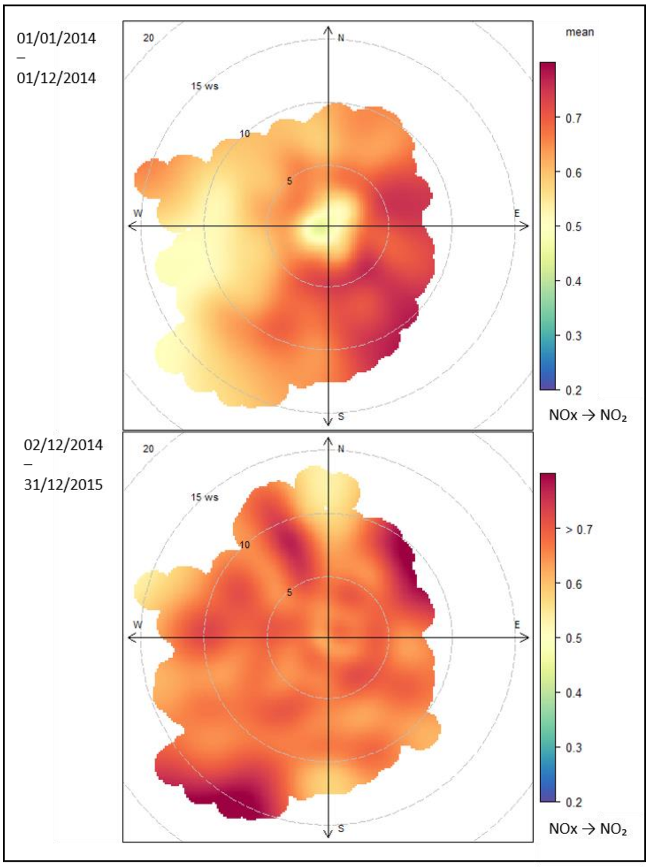
3.2.5 Supplementary analysis

Further analysis of the monitored data can be carried out by combining the NOx and NO_2 data, in order to calculate the conversion rate of gases at the monitoring station, as emissions from the EfW facility would be expected to have a relatively low conversion rate of NOx to NO_2. The following polar plots provide a comparison of this conversion between 2014 and 2015.

Figure 27 indicates that prior to the operation of the EfW facility there was a maximum conversion of NOx to NO_2 of just over 75% to the south east of the monitoring station, whereas once the facility became operational, the maximum conversion rate increased to over 80% with south westerly winds and wind speed >10m/s.

This rate of conversion from NOx to NO_2, within the distance between the stack and the monitoring station, is higher than what would be expected for emissions from an EfW facility, suggesting there may be other sources of NOx/NO_2 associated with winds from a south westerly direction. Therefore, it has not been possible to provide sufficient evidence to prove that the change in the baseline air quality at the St Peter's Close monitoring station is as a result if contributions from of the EfW plant. This is not unexpected, as emissions from this type of facility are regulated to ensure that they do not result in an unacceptable change to ambient levels of air quality. Furthermore, the monitoring station at St Peter's Close is more likely to be affected by local emission sources.

Figure 27: Polar plot of NOx to NO_2 conversion at the St Peter's Close monitoring station prior to and following the operation of the EfW plant (µg/m^3)



3.3 Case study 3: Air quality investigation of the source of nickel concentrations at monitoring stations in Sheffield

3.3.1 Introduction

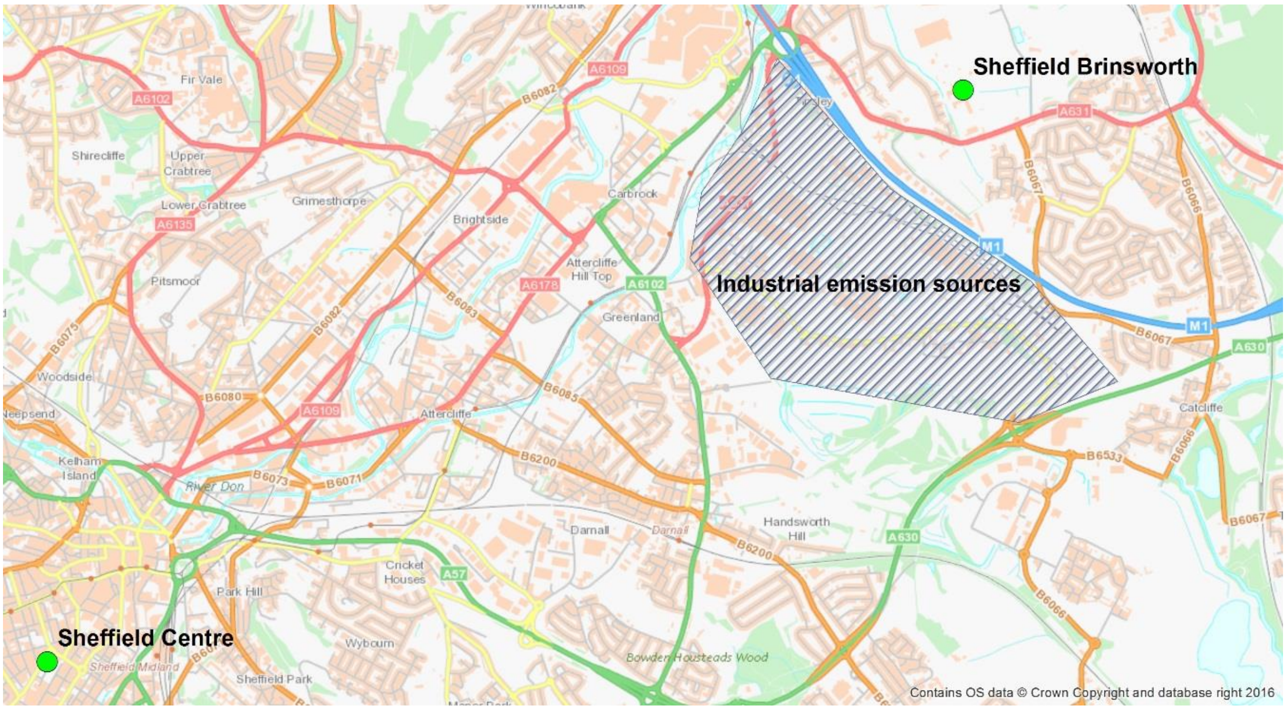
As demonstrated in Case Study 2, wind sector analysis (WSA) allows us to correlate measured concentrations for a specific location and time with meteorological data, including wind direction and speed. This correlation enables us to identify the likely direction from which pollutants have travelled towards a monitoring station. This can then be combined with information on local pollutant sources to determine potential sources.

The following provides an example of a study, undertaken by the National Physics Laboratory (NPL; Brown & Butterfield, 2012), where this form of analysis was used to identify the source of heightened concentrations of nickel (Ni) at monitoring locations in Sheffield. Due to persistent occurrences of high concentrations of nickel, in the PM_{10} phase of ambient air, recorded at one of Sheffield's Urban and Industrial Heavy Metals Monitoring Network stations, the Environment Agency commissioned NPL to carry out an investigation into the likely source of these emissions. The study was undertaken using data recorded at two monitoring stations:

1. Sheffield Brinsworth station (data recorded between 2004 and 2011) – this monitoring site is located in the prevailing downwind direction from several industrial processes and, prior to the NPL study, had recorded Ni concentrations in excess of the air quality target values, as specified in Directive 2004/107/EC.
2. Sheffield Centre station (data recorded between 2008 and 2011) – this monitoring site is situated in the prevailing upwind direction from the major industrial sources in Sheffield, and was reported as experiencing concentrations which were significantly lower than Sheffield Brinsworth.

The locations of the two monitoring stations are illustrated in Figure 28. An industrial area, including a large steelworks situated along the western edge of the M1 upwind of the Sheffield Brinsworth monitoring station, has also been highlighted.

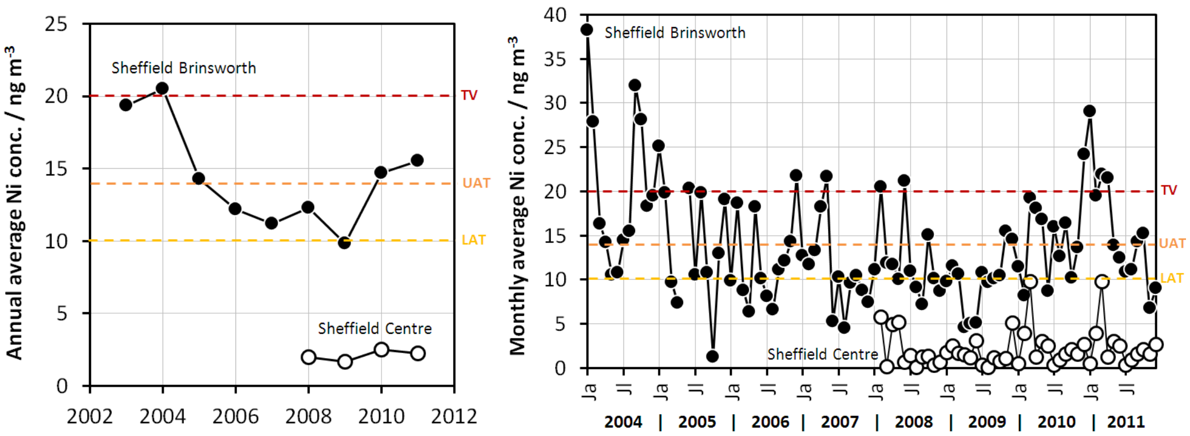
Figure 28: Locations of the Sheffield Centre and Sheffield Brinsworth monitoring stations



3.3.2 Data visualisation

The NPL study provided annual and monthly plots of Ni concentrations at the two monitoring stations, as shown in Figure 29. This data illustrates that long-term concentrations exceeded the Lower Assessment Threshold (LAT) for Ni at the Sheffield Brinsworth site in every year between 2003 and 2011. In addition, monthly concentrations were found to exceed the Threshold Value (TV) on several occasions during this period. In contrast, annual average Ni concentrations at Sheffield Centre persistently fell below the LAT. The monthly plot also illustrates the level of variability in Ni concentrations recorded at both monitoring stations. These results provided a strong indication that further analysis into the source of Ni at Sheffield Brinsworth was required.

Figure 29: Annual and monthly Ni concentrations at the Sheffield Brinsworth and Sheffield Centre monitoring stations between 2003 and 2011 (Source: Brown & Butterfield, 2012)



* TV – Threshold Value; UAT – Upper Assessment Threshold; LAT – Lower Assessment Threshold

3.3.3 Wind sector analysis

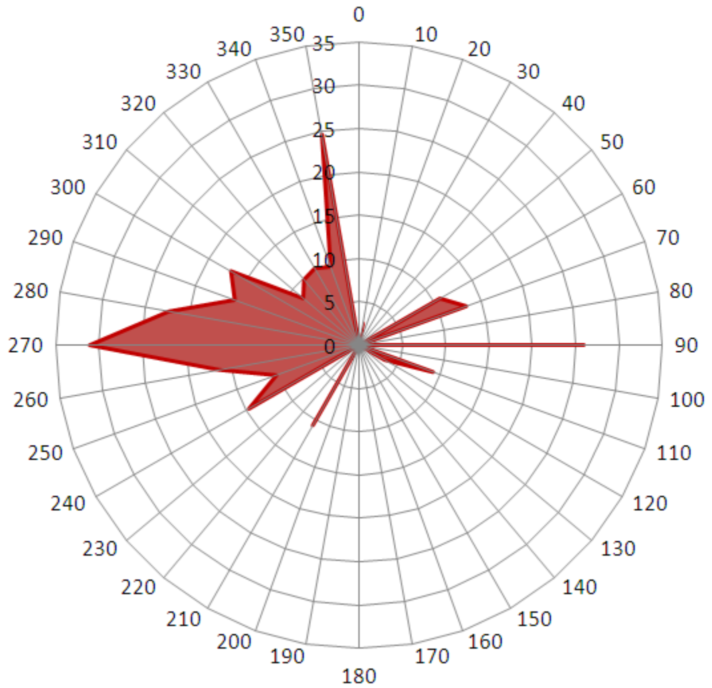
NPL combined weekly concentration data recorded at the Sheffield Brinsworth with wind data collected by a local meteorological station (Woodbourn Road Athletic Stadium) at a height of 10m and 35m. Within each weekly period, the average wind speed and vector averages of wind direction were calculated and assigned to 10° sectors. In order to adjust measured concentrations for wind speed, NPL then multiplied each weekly concentration by the corresponding wind speed and calculated the median value for each 10° sector, in order to prevent the results being skewed by outlying values.

The results indicated that the highest Ni concentrations at Sheffield Brinsworth had occurred during periods where the wind originated from a west and north-westerly direction, whereas the highest concentrations at Sheffield Centre occurred during winds from an east and south-easterly direction.

The NPL study acknowledges that although the calculation of vector average wind direction would be expected to provide a reliable indication of the average wind speed-weighted direction of pollutant concentrations, the study was restricted by Ni concentrations being recorded on a weekly basis, which is unlikely to represent the variability in wind directions throughout the week. Therefore, it was necessary to attribute concentrations to wind directions by considering the proportion of time that the wind came from an individual sector for a specific one-week monitoring period. This required a trade-off between precision and data availability. A figure of 50% wind from one sector was used to associate weekly measurements with a particular wind direction.

Figure 30 provides a pollution rose of average nickel concentrations recorded at Sheffield Brinsworth, as a function of wind direction, screened to include only weeks where at least one 50° sector accounted for at least 50% of the measured wind.

Figure 30: Wind sector analysis of Ni concentrations at Sheffield Brinsworth, where one 50° sector accounts for 50% of measured wind



3.3.4 Other sources and applied conditional analysis

No further sources were identified and conditional analysis was not performed for this data set. Given that wind speed and direction were approximated, applying additional assumptions to subset the data further would add to uncertainty.

3.3.5 Background data and filtering

Background site data was available however, this was not used for filtering. Rather, it was used for comparison.

3.3.6 Regression testing

NPL also carried out principal component analysis to investigate the correlations between other metal concentrations recorded at both monitoring stations. This found significant correlations between nickel and manganese, and between nickel and chromium, indicating the source of the emissions is linked. A lower correlation between nickel and iron suggests that there may be several processes contributing to levels of iron at Sheffield Brinsworth, some relating to Ni production, and others not. This analysis provides several key indicators of the industrial processes resulting in the greatest impact at Sheffield Brinsworth.

3.4 Case study 4: Establishing baseline groundwater quality data

3.4.1 Introduction

The following case study provides an example of the process for establishing baseline groundwater quality. The data utilised for this case study is from the Environment Agency's national groundwater monitoring network. This monitoring programme is designed to be representative of the national or regional groundwater situation, and the data is not appropriate for evaluating site-specific operational scenarios. The sites are selected to be representative of particular geological settings, land-uses and pollution pressures and therefore the results are generally evaluated on an aquifer basis or for a group of similar aquifers. Nevertheless, the data is useful for showing natural variations in groundwater quality using a long-term record of dissolved methane in groundwater.

Two sites have been selected from a total of 1,077 sites, because they had the most data on which to derive conclusions. They are hereafter referred to as Site 1 and Site 2.

3.4.2 Conceptual model, establishment of monitoring location and QA/QC

This stage is represented by Figure 4.1 in the main report, "*Diagram 1: Flowchart for the monitoring design for establishing a pre-development baseline for OOG activities*", and the first step of the Figure 5.3 in the main report, "*Diagram 2: Decision tree for statistical analysis of data for baseline establishment at OOG sites*" for quality assurance and quality control (QA/QC) in preparation of the data for further analysis. The data utilised within this case study is based on data from another monitoring programme and has hence not been defined in terms of the frequency and duration that measurements would need to be taken for OOG. We accept that QA/QC checks will have been carried out.

Both boreholes are located in the north-west of England. Site 1 is in a more urbanised area and Site 2 is surrounded by pasture land.

Site 1 is located on a hillside at an elevation on about 180mOD. Site 1 is within the Pennine Lower Coal Measures Formation and the South Wales Lower Coal Measures Formation. This is a formation with interbedded grey mudstone, siltstone and sandstone. It is a moderately productive aquifer with intergranular flow. The borehole itself is drilled to a depth of 120m in sandstone. The sandstone is overlain by nine metres of backfill. The borehole is grouted with a bentonite seal to 25m below ground level.

Site 2 is located at an elevation of about 110mOD, which is a topographic low compared with the surrounding area. Site 2 is located within the Millstone Grit aquifer. This formation is a fine to coarse grained sandstone interbedded with grey siltstones and mudstones. It is a moderately productive aquifer with intergranular flow. The borehole has been drilled to a depth of 63m and the bedrock is overlain by about 47m of gravel and boulder clay. It is grouted to 15m. The borehole was artesian when it was drilled in 1994.

3.4.3 Frequency and duration of the monitoring data

The duration of the measurement period, frequency of assessment and total number of observations for analysis at the two sites is summarised in Table 4.

In this example, monitoring data was collected for a period of a little over 12 years. This is longer than the minimum monitoring period recommended in the EPA guidance and leads to a greater number of monitoring points than the minimum required for WFD groundwater trend assessment. A larger number of data points / higher frequency of measurement will, however, lead to more certainty in the assessments.

Table 4: Monitoring duration and frequency of sampling for data used in Methane baseline assessment

Parameter	Methane Site 1	Methane Site 2
Required assessment frequency (for groundwater standards)	N/A	N/A
Duration of valid measurements at site	c.5,000d ~13yrs 7months	c.4,600d ~12yrs 7months
Temporal resolution of measurements at site	Variable - average six monthly	Variable - average five monthly
Temporal resolution of assessment at site	As measured	As measured
Number of valid measurements[14]	23	21
Number of data points used in the assessment[3]	As measured	As measured

3.4.4 Subset the data into separate contaminants and monitoring locations

In this case study, there was only a single contaminant, with single wells. However, two locations were selected. In the analysis that follows both sites are shown on same graphic.

3.4.5 Visualisation of the data

Analysis is provided in Figures 31 and 32. This includes time-series plots of the data and monthly and yearly box plots, showing the distribution of the observations and the inter and intra-annual variability observed.

In brief, the visualisations show;

- Greater variability in the observations in the Site 1 observations, as well as higher overall concentrations. The variability could be due to the unconfined nature of the aquifer at this location.
- January, February, July and August have the greatest consistency in measurement. No observations taken at any site in April, May, October or November.
- Most observations in a single year were taken in 2005.
- There does not appear strong evidence to suggest a seasonal change in methane. Removing the August measurements for Site 2, it may at first glance appear that summer measurements are lower than winter measurements, but the range is large and skewed by three

[14] Value excludes any later removal of outliers

measurements in close succession in a single year. Year on year plots (not shown) do not lead to the same visual conclusions.

Figure 31: Dissolved methane observations at two baseline monitoring wells 1998-2012, from the national groundwater monitoring network

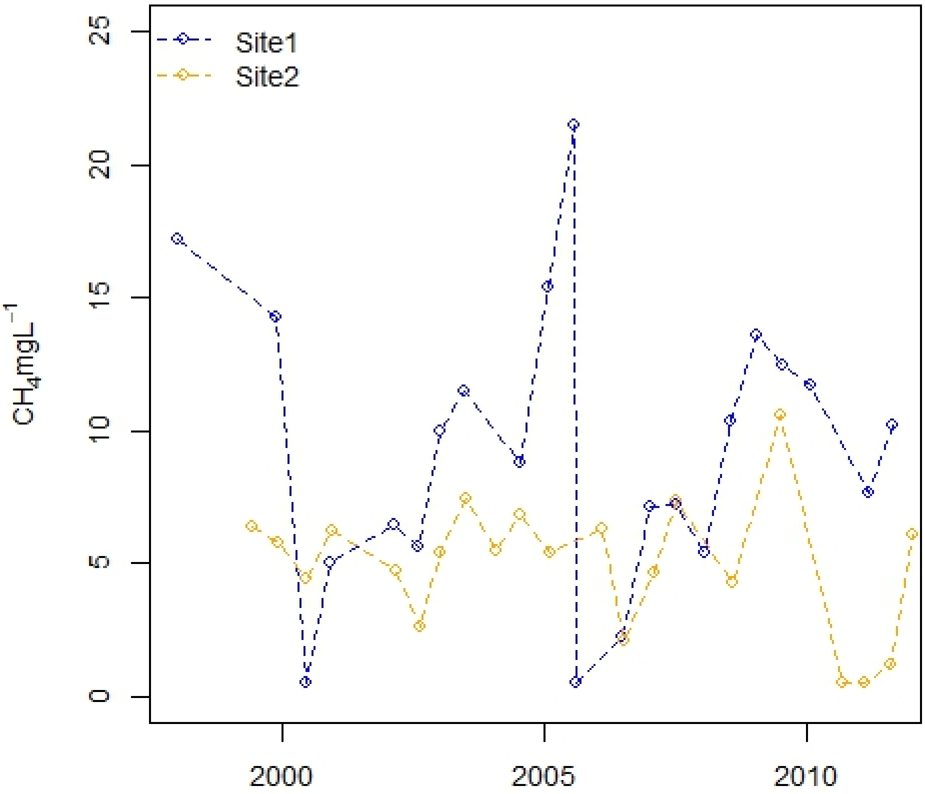
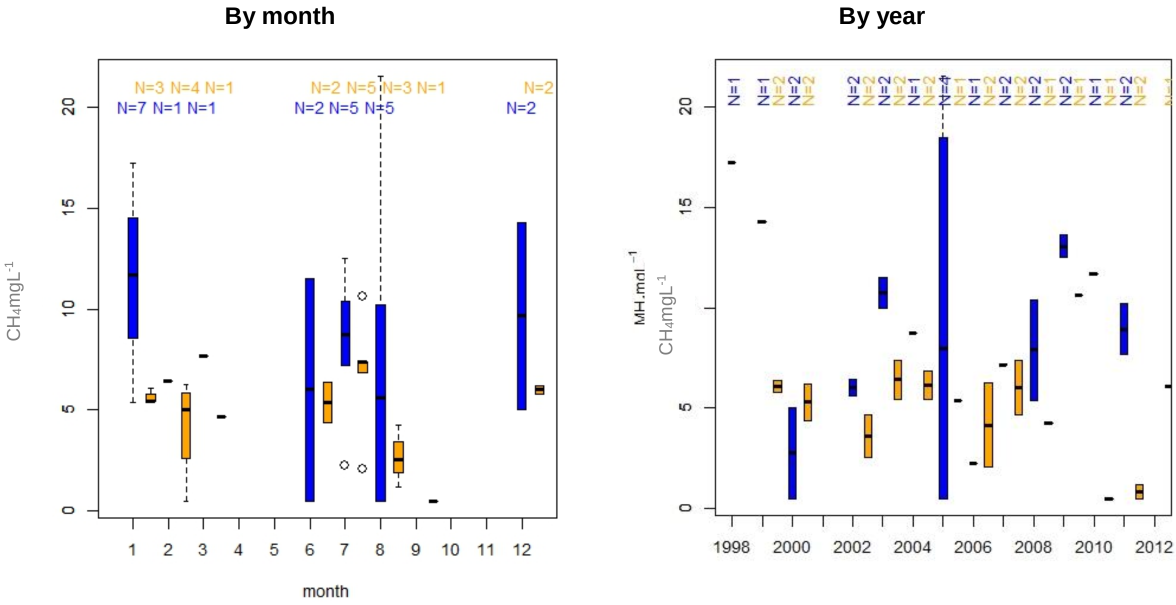


Figure 32: Boxplots of dissolved methane observations at baseline monitoring wells 1998-2012 at two sites from the national groundwater monitoring network



Note: Site 1 shown in blue and Site 2 shown in yellow.

3.4.6 Detection and treatment of outliers

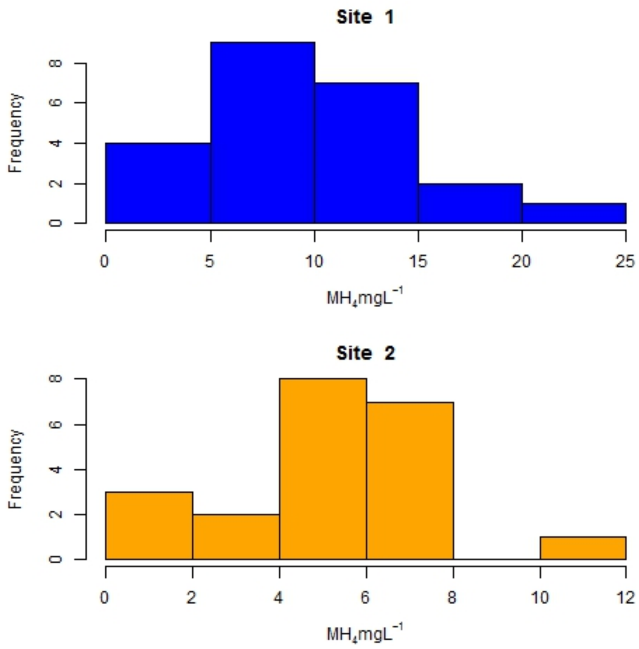
Potential outliers were calculated using the default methodology as lying outside the thresholds set by the lower quartile minus 1.5 times the interquartile range and the upper quartiles plus 1.5 times the interquartile range, calculated across the full time series (i.e. not on a by month or by year basis). No statistical outliers were identified for Site 1. For Site 2, four statistical outliers were identified (concentrations <0.5, 0.502, 1.22 and 10.6mg/l). These values represent the extremes of the time series shown in Figure 32, but there does not appear any evidence to suggest that these values are genuine anomalies. All values are therefore accepted for further analysis.

3.4.7 Testing for adequacy

It was noted in Section 3.4.3, that there are relatively few observations on which to assess the baseline (certainly in comparison with high resolution air quality data) and that more observations would lead to greater certainty. For the purposes of this assessment of adequacy, we are concerned with determining if the baseline data effectively characterises the pre-development status and we ask; is there underlying “change” (seasonal or stepwise) and is this fully captured and understood. In Case Study 1, it was shown that there was a change detected in the baseline data for PM_{10}, that could feasibly be part of a seasonal cycle, but that this was not fully characterised, and hence the data was not of adequate duration to monitor future change in this metric. In this example, we are concerned if the number of data points (frequency) are adequate for the purpose of future change detection. In order to establish the most appropriate statistical technique for assessment, it is first necessary to consider the assumption of normality.

Visual analysis of histograms of the data (Figure 33), indicates that an assumption of normality (or skewed normality) may be acceptable. As asserted in the visualisation section, we assume no seasonality. There were more than 20 observations in each data set (23 at Site 1 and 21 at Site 2).

Figure 33: Histograms of dissolved methane observations at the boreholes at the two sites used for baseline establishment



Analysis of the data for change indicates that one change point would be detected at observation 17, using the cumulative mean test only. This is the statistical outlier "large" observation seen in July 2009 in the Site 2 observations. In the baseline observations, this would be accepted as investigated in the outlier analysis phase and we would conclude that the data set is adequate.

In order to demonstrate operational testing of the decision flow chart, data collected at an operational OOG, will be considered under Case Study 5.

3.5 Case study 5: Analysis of operational groundwater quality data at an existing OOG site

3.5.1 Introduction

The following case study provides an example of the process for analysing change in groundwater quality at an existing conventional OOG facility during its operation. It is important to note that here, we do not have the benefit of having established baseline conditions. This means that we cannot be sure that the starting circumstance from which we assess change has not been changed already. However, it does give the opportunity to test how the approach may work in practice.

This example is based on groundwater quality monitoring data at an exploration site located in the south of England. The site is an onshore oil field that has been in operation since the late 1980s. The number of production wells increased in the late 2000s and so did the production of oil and gas. Given this change in the level of productivity, we will assume that the data prior to 2005 represents a 'baseline' of 'low activity', and that following 2005 represents an 'operational phase' of 'increased activity'. The production wells are drilled through to reservoir rock over 600m below ground level. For the purpose of this case study, the production wells are assumed to be vertical.

No account will be taken of any potential effects of exploration or drilling activities, as this data is solely from the operational phase of the site. However, it is important that these phases are documented and analysed appropriately following baseline establishment for new OOG sites.

3.5.2 Conceptual model and QA/QC

Figure 34 provides the plan view of the OOG site, including the boundary of the site, monitoring locations and the locations of nearby sensitive receptors, as well as an indication of the direction of groundwater flow. The groundwater receptors have the potential to be contaminated by operations on the surface at the site through infiltration, as well as by the production wells.

The site is situated in a rural setting, surrounded by agricultural land and there are no industrial facilities or significant urban areas located up-gradient. Potential receptors identified include:

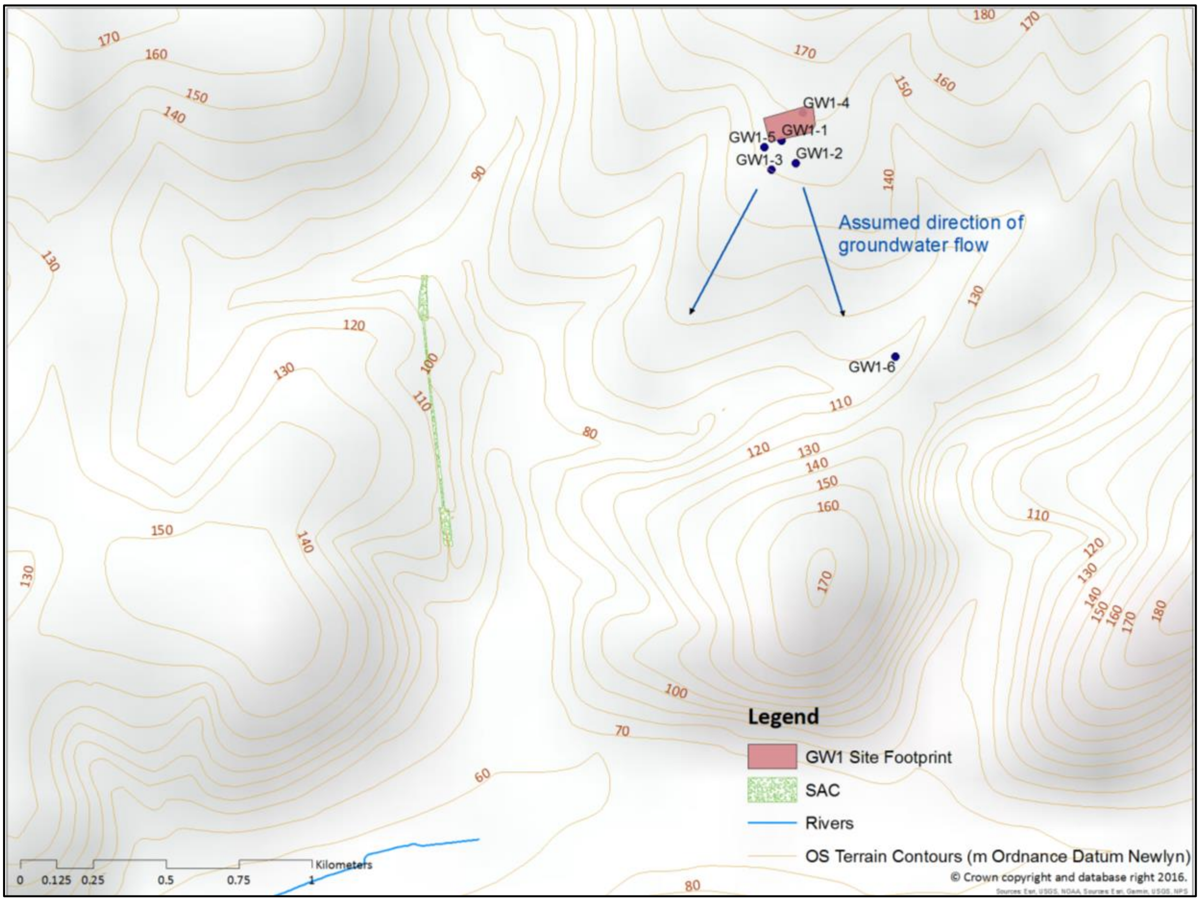
- The highly productive Chalk aquifer with fractured flow, which underlays the site, which is a drinking water resource.
- The river down-gradient of the site.

There is also a nature conservation site designated as a Special Area of Conservation (SAC) (in addition to a designation as a Site of Special Scientific Interest) approximately 1.5 km to the south-west. This site does not have sensitive wetland habitats dependent on groundwater quality and is separated by a valley from the site, and is therefore at low risk of contamination.

There is one borehole (GW1-4) located in the north-east area of the site within the site boundary. This borehole is located up-gradient of operational activity, but is still in close proximity. All other boreholes are located down-gradient of the operations.

Detail of the sampling methodology and laboratory analysis were not available for this case study, and it is beyond the scope of this document to review QA/QC procedures. The data is therefore assumed to be fit for purpose.

Figure 34: Overview plan of conventional OOG site indicating borehole locations and groundwater sensitive receptors



3.5.3 Frequency and duration of the monitoring data

Potential pollutants from OOG that may contaminate groundwater and its receptors include flowback fluid which includes consideration of chloride and consideration of Electrical Conductivity (EC) as a proxy parameter (Vengosh et al., 2014; EPA, 2016a). Electrical conductivity is related to the concentration of charged particles in the water and can indicate changes in the composition of groundwater (McNeely et al., 1979; Tutmez et al., 2006).

Chloride, extractable petroleum hydrocarbons (EPH >C10-C40) and electrical conductivity (EC) were therefore selected for analysis. Other contaminants from the dataset could equally be of interest and importance, but for demonstration purposes, only these three were selected, and were analysed at only two of the locations; the borehole up-gradient of the site (GW1-4) and the closest down-gradient borehole (GW1-1).

The duration of the measurement period, frequency of assessment and total number of observations for analysis for relevant contaminants is shown in Table 5.

In this example, monitoring data was collected for approximately 24 years and though there was some variability in collection frequency across the time-series, the frequency was generally greater than would be required for baseline assessment and change detection.

Table 5: Monitoring Duration and Frequency for assessment of "operational" data for change in Groundwater Case Study

Parameter	Chloride GW1-4	Chloride GW1-1	Conductivity GW1-4	Conductivity GW1-1	EPH (>C10-C40) GW1-4	EPH (>C10-C40) GW1-1
Required assessment frequency (for groundwater standards)	Monthly over 12 months	Monthly over 12 months	N/A	N/A	N/A	N/A
Duration of (valid) measurements at site	c.6,500d ~18yrs	c.8,700d ~24yrs	c.6,500d ~18yrs	c.8,700d ~24yrs	c. 3,000d ~ 8yrs	c.5,107 ~14yrs
Temporal resolution of measurements at site	Variable	Variable	Variable	Variable	Variable	Variable
Temporal resolution of assessment at site	As measured	As measured	As measured	As measured	As measured	As measured
Number of valid measurements[15]	348	8,707	340	8,707	251	1,490
Number of data points used in the assessment	As measured	As measured	As measured	As measured	As measured	As measured

3.5.4 Subset the data into separate contaminants and monitoring locations

In this case study, three contaminants were analysed from two boreholes, one up-gradient (GW1-4) and down-gradient (GW1-1) of the site.

[15] Value excludes any later removal of outliers

3.5.5 Data visualisation

Analysis set out in the operational analysis flowchart (Figure 5.10 in the Main Report, "*Diagram 3-GW: Decision tree for statistical analysis of data for determining change in groundwater quality for OOG activities*") is provided below. The analysis includes time-series plots of the data and monthly box plots for each pollutant, illustrating the distribution of measured values and relative variability between contaminants and sites, as well as within and between years.

The guidelines supplied under this project are not prescriptive in the rulesets applied to values measured as below the LoD. The LoD for chloride concentrations is 5mg/l and no values at any of the sites were observed to be below the LoD for chloride; therefore no values were removed from the datasets or the graphs. In addition, no values were below the LoD for EC. Concentrations of EPH (C10-C40) less than the limit of detection (LoD) were flagged in the dataset. LoDs were variable by sample and site. In the up-gradient site, the LoD was generally set at 10µg/l but was increased to 20µg/l for a selected subset of observations. Only 24 observations (of 251, approximately equivalent to 10%), and all measured between June and December 2000, did not have a flag on the data entries to indicate being below the limit of detection. These entries, were however all recorded at 10µg/l, and it seems plausible that these values too, may also have been below the LoD. These findings are consistent with expectations, as extractable petroleum hydrocarbons are not naturally occurring in the environment. In the down-gradient borehole, there were 679 (of 1,490, and equivalent to approximately 45%) observations of EPH (C10-C40) which had values that were not flagged as below the LoD. 187 of these had the value of 10µg/l.

In the absence of a defined ruleset for treatment, EPH concentrations below the LoD were removed from the analysis for baseline setting and assessing change, and also from the box-plots[16]. The values are not excluded from the time-series graphs, but are highlighted in red.

Assessment criteria were selected based on their relevance to the groundwater receptors, as described in the operational analysis flowchart (Figure 5.10 in the Main Report). The selected assessment criteria were added to the time series graphs where measured values breach or approach threshold values, to provide an indication of where groundwater quality may not be acceptable due to the risk to the nearby receptors.

Potential outliers were calculated using the default methodology as lying outside the thresholds set by the lower quartile minus 1.5 times the interquartile range and the upper quartiles plus 1.5 times the interquartile range, calculated by the combination of month and year. Approximately 10 statistical outliers in each of the data sets for the three contaminants were identified within the dataset from the up-gradient borehole, and 60 to 80 outliers per contaminant were identified in the down-gradient borehole dataset. Outliers are highlighted in amber in Figure 35, and are discussed in Section 3.5.6. It should however be noted these are not for automatic exclusion, just an opportunity to sense check on very high or very low observations.

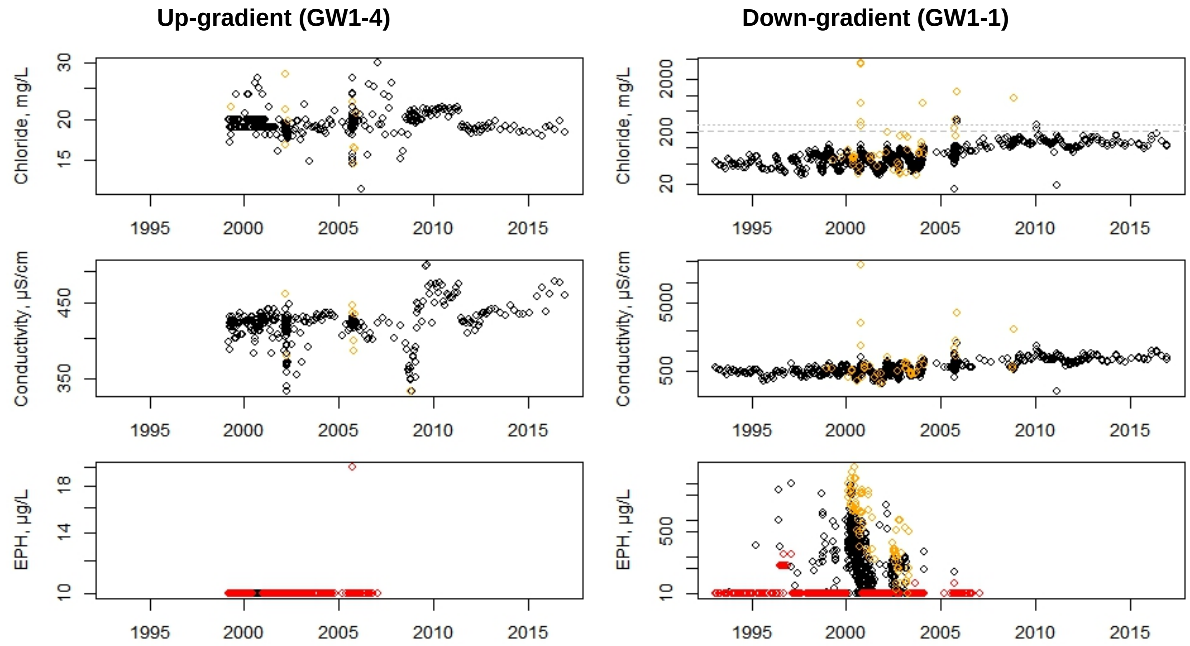
For ease of comparison across the different metrics and to show any consistent behaviours, plots are drawn on a panel using the same time series limits (Figure 35). In brief, the graphics show:

- The monitoring period for the up-gradient borehole is shorter than the one at the down-gradient borehole, starting around 1998 as opposed to 1993 at GW1-1.
- There is an apparent correlation between the temporal variability of conductivity and that of chloride, with statistitical outliers in one being matched in other.

[16] Though not a standard default, inclusion under a single value (such as half the limit of detection), could change the derived statistics to have a bias towards low values with increased variance. By excluding them from the analysis, the test for change and characterisation of baseline will be based on considering only values above the LoD, which if there is no change in behaviour would be a fair test. Where there is a change in behaviour identified, it would be considered best practice to check to ensure conclusions had not been skewed by the removal of very low values (see investigation guidelines (A4)).

- There are no breaches of threshold water quality parameters up-gradient of the site, but a number of breaches of both the groundwater threshold (dashed line) and drinking water standard (dotted line) for choride down-gradient of the site.
- There is a potential change in chloride and conductivity readings (e.g. up-gradient conductivity 2005) and an apparent trend (e.g. down-gradient). Any change in up-gradient values are indicative of underlying environmental change \ alternative source.

Figure 35: Time series plots of chloride, EC and EPH concentrations for boreholes at a conventional OOG facility



Note: Relevant standards are also shown; the groundwater threshold (dashed line) and drinking water quality standard (dotted line) for chloride

There are a large number of values less than the level of detection in the EPH dataset. The time series is also much shorter for this time series. Chloride concentrations at the borehole up-gradient of the facility (GW1-4) were relatively low between 1999 and 2015, and did not exceed the drinking water standard (250 mg/l, maximum acceptable concentration (MAC)) or the groundwater threshold value (188 mg/l). Chloride concentrations ranged from 12.2 to 30mg/l.

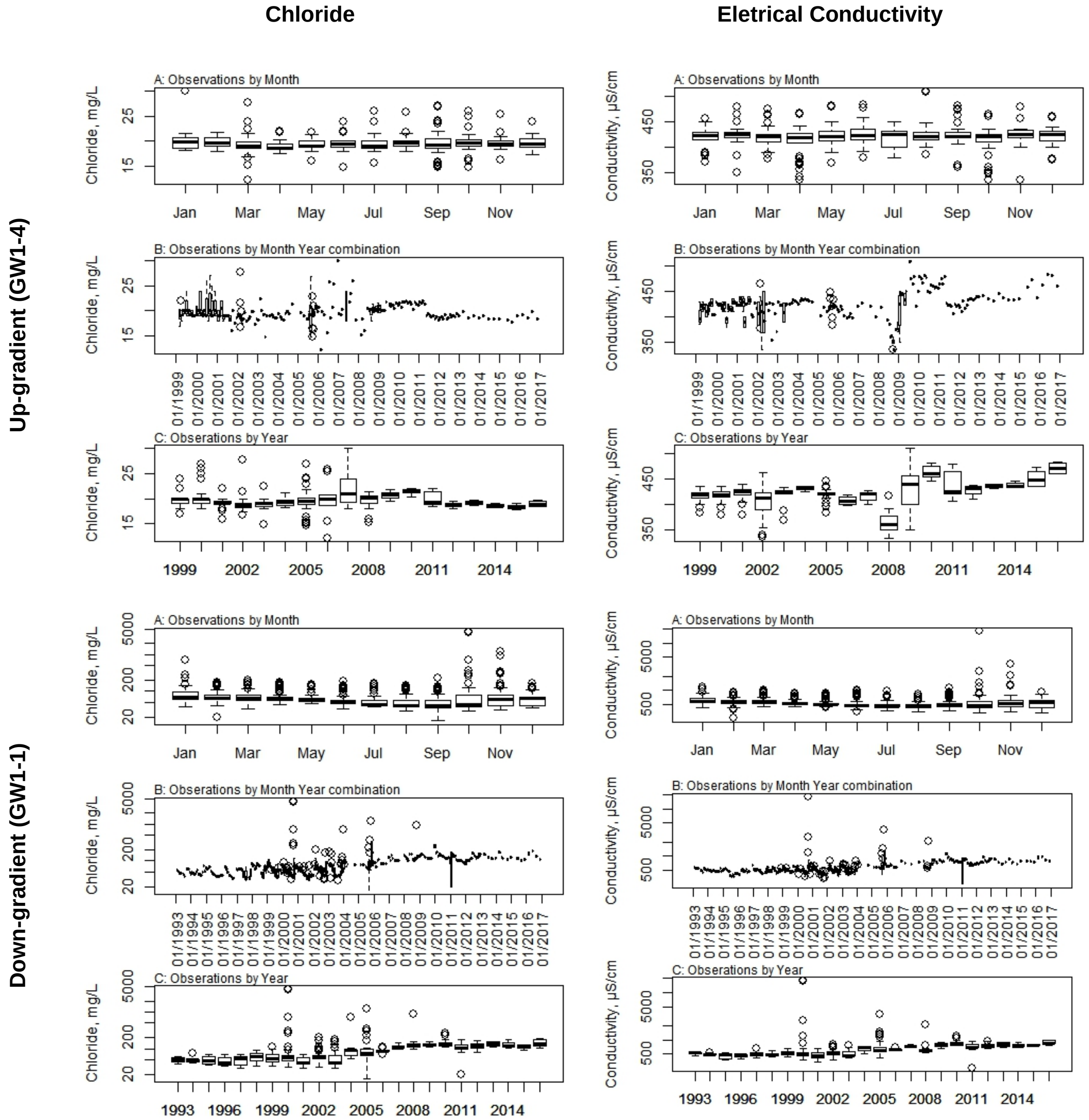
Chloride concentration data from the down-gradient borehole closest to the site (GW1-1) exceeded the drinking water standard 16 times throughout the monitoring record, with concentrations ranging from 15.7 to 4,200mg/l. For a period of five days during October 2000, chloride concentrations exceeded the drinking water standard of 250mg/l and peaked on 14/10/2000 at 4,200 mg/l, the highest concentration recorded. Another period of high chloride concentrations occurred between September to November 2005, with the highest concentration recorded on 04/11/2005 at 1,200 mg/l. The annual mean is less than the threshold. Visual analysis of the data for both background and downgradient, however, indicates some potential deterioration in chloride concentrations which could lead to future drinking water failures. This will be further investigated in later stages of the decision tree.

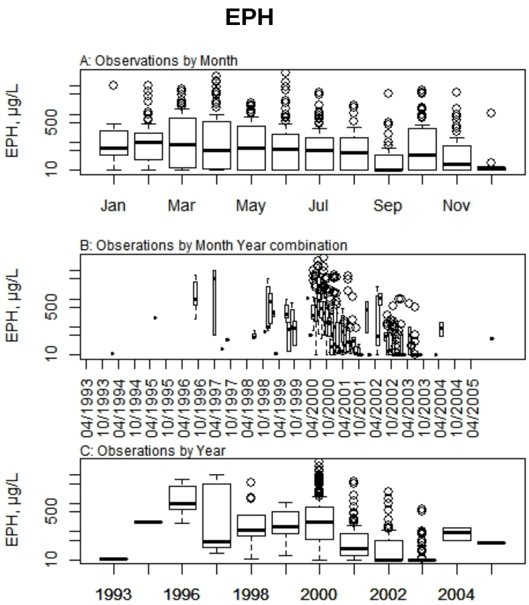
There are no standards for EPH but for the purpose of this case study we have assumed that it is hazardous substance and therefore should not be detected in groundwater above the LoD. As described in the previous section, it would seem reasonable to accept that there were no breaches of the LoD for EPH at the borehole up-gradient of the facility. For the downgradient borehole, however, EPH was measured at values higher than the LoD more than 40% of the time. Values ranged from 10.3µq/l to 28,200µq/l.

The report also indicates that boxplots of distributions should also be drawn over the time period, to visualise any apparent distribution changes. These are shown in Figure 36. In brief, the visualisations show:

- Looking only at monthly observations, there appears to be a seasonal signal, with higher concentrations of chloride and higher electrical conductivity in winter compared to summer.
- The greater width of bars in the “by Month Year” combinations of data for chloride and EC can be considered to be a result of greater frequency of observation at the start of the monitoring period, rather than a change in the underlying variability. This is most apparent at the up-gradient borehole where the frequency was greater at the start of the observation period than at the down-gradient site. The statistical technique applied in analysis should take into consideration this change in intensity.
- Apparent trends are seen at both boreholes in both chloride and EC.
- No conclusions can be drawn around the intra- or inter-year variability for EPH due to the inconsistency in measurement frequency.

Figure 36: Box plots of Chloride, Electrical Conductivity and EPH concentrations for boreholes at a conventional OOG facility





3.5.6 Analysis of outliers

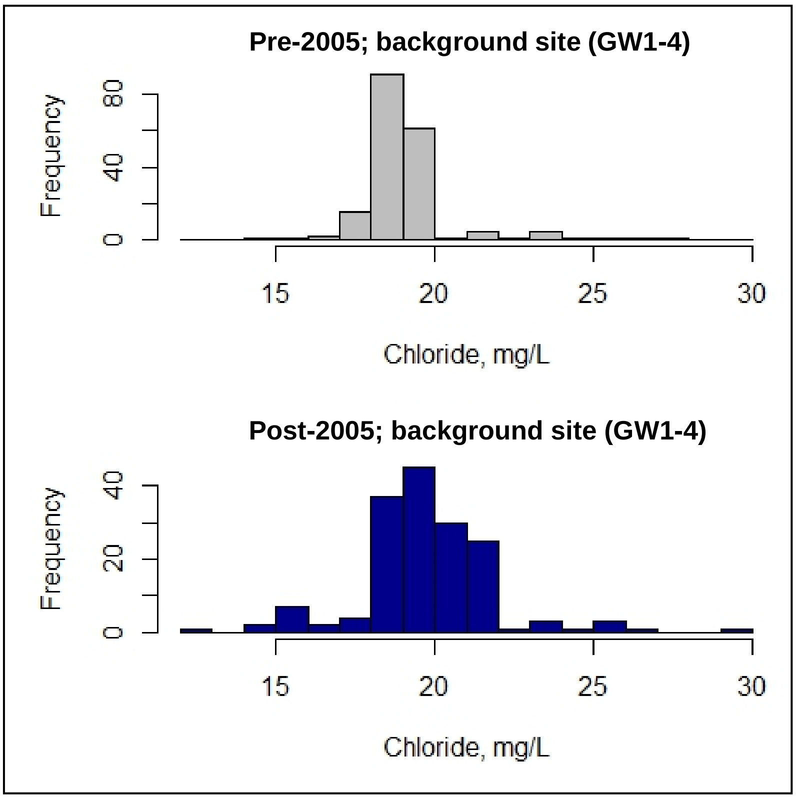
The above preliminary analysis has identified a number of potential outliers within the dataset, highlighted in Figure 35. The default assumption of by month and year combination, median +/-1.5 times the interquartile range was adopted and led to around 10 outliers being identified at the borehole up-gradient of the facility and around 60 outliers down-gradient of the facility. The larger number of statistical outliers at the down-gradient site is a result of higher peak concentrations.

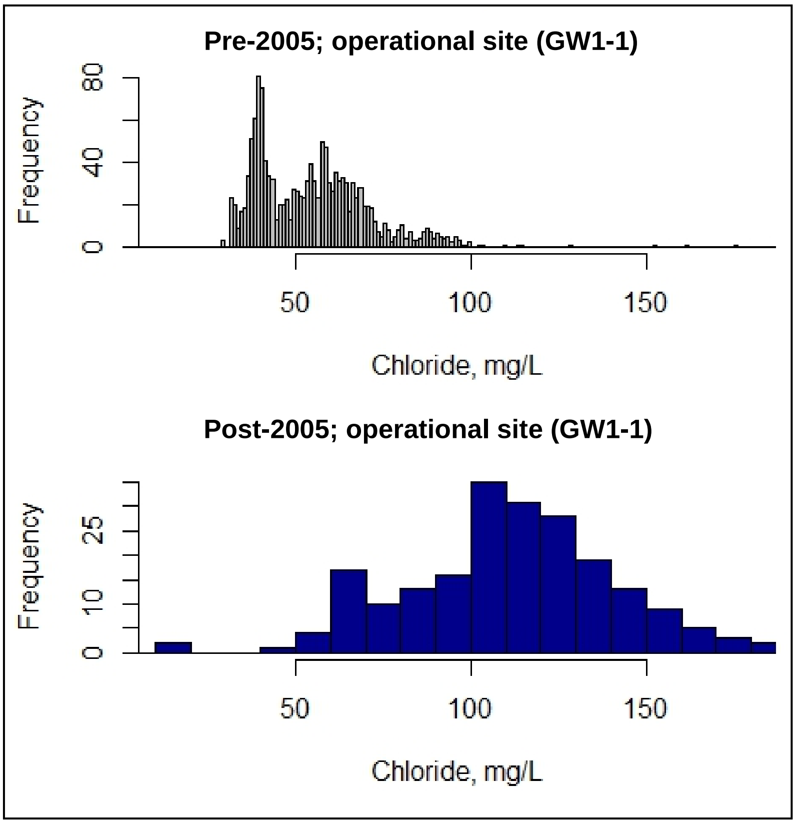
The purpose of identifying the statistical outliers is in identifying values that may require cross validation. It is not within the scope of this document to perform this more detailed assessment of corroborating individual values. However, noting that multiple contaminants showed peaks at the same time, then we consider there to be reasonable evidence to accept the values as genuine observations.

3.5.7 Test for Normality

The baseline and operational phases are tested for normality separately (Figure 37). In this case study the ‘baseline’ of ‘low activity’ is assumed to be pre-2005, with observations during and post 2005 representing an ‘operational phase’ of ‘increased activity’. Both phases are tested separately for normality. The frequency and change in intensity of the monitoring, does not make it appropriate to perform the statistical tests by month or by month\year combination. Therefore, statistics are performed at the “pre” and “post” level.

Figure 37: Histograms of the distributions of observations in chloride pre and post 2005 in the background site (GW1-4) and operational site (GW1-1)





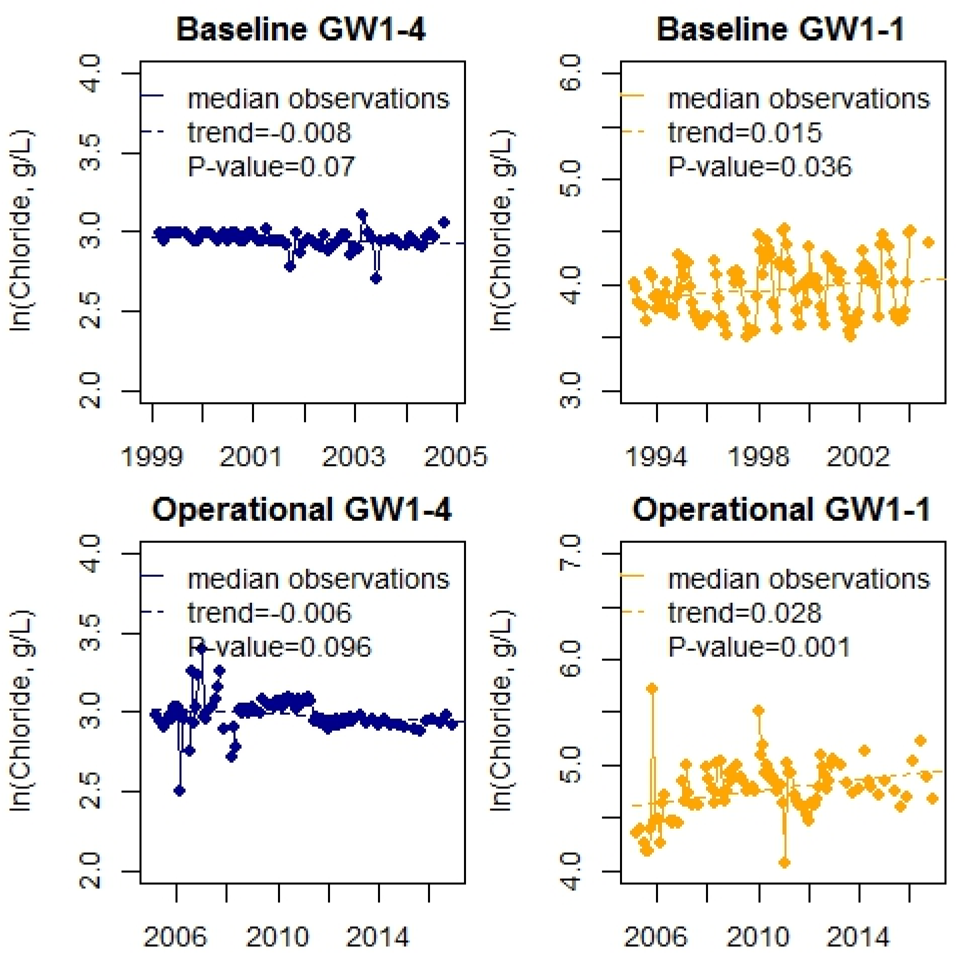
3.5.8 Trend Analysis

Trends were fitted to the data pre and post intensification. Following the guidelines, since the data has been shown to be normal after transforming logarithmically, it is acceptable to conduct a linear regression on the log-transformed outputs. The outputs of this analysis are shown in Figure 38. Each of the graphs show a linear fit to the data, calculated trend, and associated p-value.

It may be observed that for chloride concentrations in the borehole up-gradient of the facility (GW1-4, Figure 38), a negative trend is calculated for both pre-intensification (baseline) and post-intensification (operation). As the p-value associated with these slopes is greater than 0.05 however, we can conclude that there is no statistical evidence at the 95% confidence limit, to suggest a relationship between chloride concentrations and time; i.e. there is no statistically significant evidence of deterioration in the up-gradient borehole. In the down-gradient borehole, however, there is a statistically significant relationship at the 5% level of deterioration, and this trend, is increased in the "operational" (post intensification) phase.

As a result of these findings, attribution as to the causes of this apparent deterioration would be conducted.

Figure 38: Trends in chloride concentrations in baseline and operational scenarios



4 References

Ahmadi, M. and John, K. (2005). Statistical evaluation of the impact of shale gas activities on ozone pollution in North Texas. *Science of the Total Environment*, 536, pp 457-467

Air Quality in Scotland (2017). *Pollutants overview*. Available at: http://www.scottishairquality.co.uk/air-quality/pollutants#co [Accessed 06 January 2017].

AMEC (2014). Technical Support for Assessing the Need for a Risk Management Framework for Unconventional Gas Extraction. Report for European Commission DG Environment. http://ec.europa.eu/environment/integration/energy/pdf/risk_mgmt_fwk.pdf [Accessed 13 January 2017].

API (American Petroleum Institute) (2009). Hydraulic Fracturing Operations – Well Construction and Integrity Guidelines. API Guidance Document HF1, first edition. http://www.shalegas.energy.gov/resources/HF1.pdf [Accessed 13 January 2017].

Arkansas Department of Environmental Quality (2011). *Emissions Inventory & Ambient Air Monitoring of Natural Gas Production in the Fayetteville Shale* [online]. Available at: https://www.adeq.state.ar.us/air/ [Accessed 12 January 2017].

Barratt, B., Atkinson. R, Anderson, H.R., Beevers, S., Kelly, F., Mudway, I.,and Wilkinson, P. (2007). Investigation into the use of the CUSUM technique in identifying changes in mean air pollution levels following introduction of a traffic management scheme, *Atmospheric Environment,* 41, pp 1,784-1,791

Beaulieu, Chen, J. and Sarmiento, J.L. (2012) Change-point analysis as a tool to detect abrupt climate variations. Philosophical Transactions of the Royal Society A 370: 1228-1249

BGS. (2016a). Shale Gas: National methane baseline survey of UK groundwaters. Available at: http://www.bgs.ac.uk/research/groundwater/shaleGas/methaneBaseline/home.html [Accessed: 20 December 2016].

BGS. (2016b). Environmental baseline monitoring in Lancashire - Real-time data and data summaries – Groundwater Quality. Available at: http://www.bgs.ac.uk/research/groundwater/shaleGas/monitoring/lancsDataSummary.html? [Accessed: 20 December 2016].

BGS. (2016c). National methane baseline survey: results summary Summary results, January 2015. Available at: http://www.bgs.ac.uk/research/groundwater/shaleGas/methaneBaseline/results.html [Accessed: 13 January 2016].

Blakey N.C., Young C.P., Lewin K., Clark L., Turrell J., and Sims P. (1997). Guidelines for monitoring leachate and groundwaters at landfill sites. Report No. CWM 062/97C. Environment Agency, Bristol.

Brantley, S.L., Yoxtheimer, D., Arjmand, S., Grieve, P., Vidic, R., Pollak, J., Llewellyn, G.T., Abad, J., Simon, C. (2014). Water resource impacts during unconventional shale gas development: The Pennsylvania experience. *International Journal of Coal Geology*, 126, pp 140-156

British Columbia Ministry of Environment (2016). *Water and Air Baseline Monitoring Guidance Document for Mine Proponents and Operators*. British Columbia Ministry of Environment.

Broomfield, M., Buckland, T., Perera, N., Lewin, A., DeVenny, A. & Rollo, C. (2016). *Unconventional oil and gas development: Understanding and mitigating community impacts from transport*. Available at: http://www.gov.scot/Resource/0050/00509327.pdf [Accessed 06 January 2017].

Burton, T.G., Rifai, H.S., Hildenbrand, S.L., Carlton (Jr), D.D., Fontenot, B.E. and Schug, K.A. (2016). Elucidating hydraulic fracturing impacts on groundwater quality using a regional geospatial statistical modeling approach. *Science of the Total Environment,* 545-546, pp 114-126

Carlton, A.G., Little, E., Moeller, M., Odoyo, S., Shepson, P.B., 2014. The data gap: can a lack of monitors obscure loss of clean air act benefits in fracking areas? *Environmental Science & Technology*, 48, pp 893–894.

Carslaw, D.C., Ropkins, K., Bell, M.C. (2006). Change-point detection of gaseous and particulate traffic-related pollutants at a roadside location. *Environmental Science and Technology*, 40, pp 6,912–6,918.

Carslaw, D.C., Carslaw, N. (2007). Detecting and characterising small changes in urban nitrogen dioxide concentrations. *Atmospheric Environment*, 41, pp 4,723–4,733.

Carter, W.P., Seinfeld, J.H., 2012. Winter ozone formation and VOC incremental reactivities in the Upper Green River Basin of Wyoming. *Atmospheric Environment*, 50, pp 255–266

Cheng, H., Small, M.J. and Pekney, N.J. (2015). Application of nonparametric regression and statistical testing to identify the impact of oil and natural gas development on local air quality. *Atmospheric Environment*, 119, pp 381-392.

CLAIRE (2008). *Principles and Practice for the Collection of Representative Groundwater Samples.* Contaminated Land: Applications in Real Environments. Technical Bulletin TB3. Available at: http://www.claire.co.uk/component/phocadownload/category/17-technical-bulletins?download=47:technicalbulletin03 [Accessed 20 December 2016].

Council of Canadian Academies (2014). Environmental Impacts of Shale Gas Extraction in Canada. Ottawa (ON): The expert panel on harnessing science and technology to understand the environmental impacts of shale gas extraction, ISBN 978-1-926558-78-3.

Darling, W G, and Gooddy, D C. (2006). The hydrogeochemistry of methane: evidence from English groundwaters. *Chemical Geology*, 229 (4), pp 293–312.

DEFRA and EA (2016). Groundwater risk assessment for your environmental permit. Available at: https://www.gov.uk/guidance/groundwater-risk-assessment-for-your-environmental-permit [Accessed: 20 December 2016].

Department of Energy and Climate Change. (2013c). *Strategic Environmental Assessment for Further Onshore Oil and Gas Licensing*. London: Department of Energy and Climate Change. Available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/273997/DECC_SEA_Environmental_Report.pdf [Accessed 03 January 2016].

Ebbesmeyer,C.C., Cayan,D.R., Mclain,D.R., Nichols,F.N., Peterson,D.H. & Redmond,K.T. (1991) 1976 step in Pacific climate: Forty environmental changes between 1968-1975 and 1977-1984. pp. 115-126. In: J.L. Betancourt and V.L. Tharp (Eds.) Proceedings of the 7th Annual Pacific Climate (PACLIM) Workshop, April 1990. California Department of Water Resources. Interagency Ecological Study Program Technical Report 26.

ECHA (European Chemicals Agency) (2015). ECHA Clarifies how to Report Substances Used in Hydraulic Fracturing. ECHA/NI/15/08. Available online: http://echa.europa.eu/view-article/-/journal_content/title/echa-clarifies-how-to-report-substances-used-in-hydraulic-fracturing [Accessed 07 February 2017].

Edwards, P.M., Young, C.J., Aikin, K., deGouw, J., Dubé, W.P., Geiger, F., et al. (2013). Ozone photochemistry in an oil and natural gas extraction region during winter: simulations of a snow-free season in the Uintah Basin, Utah. *Atmospheric Chemistry and Physics*, 13, pp 8,955–8,971.

Environment Agency (2002). Techniques for the Interpretation of Landfill Monitoring Data Guidance notes, Final R&D Technical Report P1-471, Unpublished.

Environment Agency (2003). *Guidance on monitoring of landfill leachate, groundwater and surface water*. ISBN:1-84432-159-2. Available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/321602/LFTGN02.pdf [Accessed 20 December 2016].

Environment Agency (2006). Guidance on the design and installation of groundwater quality monitoring points, Science Report SC020093, ISBN: 1844325342.

Environment Agency (2011). *Technical Guidance Note (Monitoring) M8 – Monitoring Ambient Air*. Available at: https://www.gov.uk/government/publications/m8-monitoring-ambient-air [Accessed 28 December 2016].

Environment Agency (2014). *Considerations for quantifying fugitive methane releases from shale gas operations*. Available at: https://www.gov.uk/government/publications/considerations-for-quantifying-fugitive-methane-releases-from-shale-gas-operations [Accessed 28 December 2016].

Environment Agency (2014). *How to comply with your environmental permit*. Additional guidance for: Groundwater risk assessment for treated effluent discharges to infiltration systems. Available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/489148/J5_user_manual.pdf [Accessed: 20 December 2016].

Environment Agency (2014b). *Hydrogeological risk assessment report template*. Available at: https://www.gov.uk/government/publications/hydrogeological-risk-assessment-report-template [Accessed: 20 December 2016].

Environment Agency (2016). *Onshore Oil & Gas Sector Guidance*. Version 1, 17 August 2016. Available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/545924/LIT_10495.pdf [Accessed 20 December 2016].

European Commission (2003). Common Implementation Strategy for the Water Framework Directive (2000/60/EC) Guidance Document No. 3, Analysis of Pressures and Impacts ISBN No. 92-894-5123-8

European Commission (2004). Common Implementation Strategy for the Water Framework Directive (2000/60/EC). Guidance Document No 7, Monitoring under the Water Framework Directive. ISBN 92-894-5127-0.

European Commission (2009). Common Implementation Strategy for the Water Framework Directive (2000/60/EC), Guidance Document No. 18, Guidance on Groundwater Status and Trend Assessment, ISBN 978-92-79-11374-1

European Commission (2010). Common Implementation Strategy for the Water Framework Directive (2000/60/EC) Technical Report - 2010 – 042, Guidance document No. 26 – Guidance on risk assessment and the use of conceptual models for groundwater. Available at: https://circabc.europa.eu/sd/a/8564a357-0e17-4619-bd76-a54a23fa7885/Guidance%20No%2026%20-%20GW%20risk%20assessment%20and%20conceptual%20models.pdf [Accessed 03 January 2017].

European Commission (2017). *Non-Road Mobile Machinery Emissions* [online]. Available at: https://ec.europa.eu/growth/sectors/automotive/environment-protection/non-road-mobile-machinery_en [Accessed 03 January 2017].

Environmental Protection Agency (2016a). Environmental Impacts of Unconventional Gas Exploration and Extraction (UGEE) Final Report 4: Impacts and Mitigation Measures (part 1 of 3). Available at: http://www.epa.ie/pubs/reports/research/ugeejointresearchprogramme/ [Accessed: 20 December2016].

Environmental Protection Agency (2016b). Environmental Impacts of Unconventional Gas Exploration and Extraction (UGEE). Final Report 1: Baseline Characterisation of Groundwater, Surface Water and Aquatic Ecosystems – Part 2. Available at: http://www.epa.ie/pubs/reports/research/ugeejointresearchprogramme/ [Accessed: 20 December 2016].
European Commission (2010). Common Implementation Strategy for the Water Framework Directive (2000/60/EC) Technical Report - 2010 – 042, Guidance document No. 26 – Guidance on risk assessment and the use of conceptual models for groundwater. Available at: https://circabc.europa.eu/sd/a/8564a357-0e17-4619-bd76-a54a23fa7885/Guidance%20No%2026%20-%20GW%20risk%20assessment%20and%20conceptual%20models.pdf [Accessed 03 January 2017].
Francis,R.C. & Hare,S.R. (1994) Decadal-scale regime shifts in the large marine ecosystems of the Northeast Pacific: a case for historical science. Fisheries Oceanography, **3,** 279-291.

Government of New Brunswick (2013). *Responsible Environmental Management of Oil and Natural Gas Activities in New Brunswick* [online]. Available at:

http://www2.gnb.ca/content/dam/gnb/Corporate/pdf/ShaleGas/en/RulesforIndustry.pdf [Accessed 04 January 2016].

Ground Water Protection Council & ALL Consulting (2009). *Modern Shale Gas Development in the United States: A Primer* [online]. Available at: https://energy.gov/sites/prod/files/2013/03/f0/ShaleGasPrimer_Online_4-2009.pdf [Accessed 29 December 2016].

Humez, P., Mayer, B., Ing, J., Nightingale, M., Becker, V., Kingston, A., Akbilgic, O., Taylor, S. (2016) Occurrence and origin of methane in groundwater in Alberta (Canada): Gas geochemical and isotopic approaches. *Science of the Total Environment,* 541: pp 1,253–1,268

ICF International (2009). *Technical Assistance for the Draft Supplemental Generic EIS: Oil, Gas and Solution Mining Regulatory Program – Well Permit Issuance for Horizontal Drilling and High-Volume Hydraulic Fracturing to Develop the Marcellus Shale and Other Low Permeability Gas Reservoirs (Agreement No. 9679)* [online]. Available at: http://www.mde.state.md.us/programs/Land/mining/marcellus/Documents/ICF_Technical_Assistance_Draft_Supplemental_Generic_EIS_Analysis_Potential_Impacts_to_Air.pdf [Accessed 03 January 2017].

Iranmanesh, A., Locke R.A. and Wimmera, T.B. (2014). Multivariate statistical evaluation of groundwater compliance data from the Illinois Basin – Decatur Project. *Energy Procedia*, 63, pp 3,182-3,194.

ISO (2010). Water quality - Sampling - Part 14: Guidance on quality assurance and quality control of environmental water sampling and handling. ISO 5667-14.

Lavoie, D., Rivard, C., Lefebvre, R., Sejourne, S., Theriault, R., Duchesne, M.J., Ahad, J.M.E, Wang, B., Benoit, N., Lamontagne, C. (2014). The Utica Shale and gas play in southern Quebec: Geological and hydrogeological syntheses and methodological approaches to groundwater risk evaluation, *International Journal of Coal Geology*, 126, pp 77-91

Jackson, R.B., Vengosh, A., Darrah, T.H., Warner, N.R., Down, A., Poreda, R.J., Osborn, S., Zhao, K., Karr, J.D. (2013). Increased stray gas abundance in a subset of drinking water wells near Marcellus shale gas extraction. *Proceedings of the National Academy of Sciences of the United States of America* 110 (28), pp 11,250–11,255.

JAGDAG (2017). Methodology for the determination of hazardous substances. Joint Agencies Groundwater Directive Advisory Group. Available at: http://www.wfduk.org/stakeholders/methodology-determination-hazardous-substances.[Accessed 07 February 2017].

Kemball-Cook, S., Bar-Ilan, A., Grant, J., Parker, L., Jung, J., Santamaria, W., et al. (2010). Ozone impacts of natural gas development in the Haynesville shale. *Environmental Science & Technology*, 44, pp 9,357–9,363.

Macey, G., Breech, R., Chernaik, M., Cox, C., Larson, D., Thomas, D. & Carpenter, D. (2014). Air concentrations of volatile compounds near oil and gas production: a community-based exploratory study. *Environmental Health*, pp 13:82.

Malby, A.R., Whyatt, J.D. and Timmis, R.J. (2013). Conditional extraction of air-pollutant source signals from air-quality monitoring. *Atmospheric Environment*, pp 74: 112-122

Mansfield, M., Hall, C., (2013). Statistical analysis of winter ozone events. *Air Quality, Atmosphere and Health,* 6, pp 687–699

McIntosh, J.C., Grasby, S.E., Hamilton, S.M., Osborn, S.G., 2014. Origin, distribution and hydrogeochemical controls on methane occurrences in shallow aquifers, southwestern Ontario, Canada. *Applied Geochemistry*. 50, pp 37-52.

McNeely, R.N., Neimanis, V.P., Dwyer, L. (1979) Water quality sourcebook, a guide to water quality parameters, InLand Waters Directorate, Water Quality Branch, Ottawa, Canada, 88pp

Meiners, H.G., Denneborg, M., Muller, F. et al., 2013. Environmental Impacts of Fracking Related to Exploration and Exploitation of Unconventional Natural Gas Deposits Risk Assessment, Recommendations for Action and Evaluation of Relevant Existing Legal Provisions and Administrative Structures. 82/2013. Available at: https://www.umweltbundesamt.de/sites/default/files/medien/378/publikationen/texte_83_2013_environmental_impacts_of_fracking.pdf [Accessed 12 January 2017].

Milanchus, M.L., Rao, S.T., Zurbenko, I.G., (1998). Evaluating the effectiveness of ozone management efforts in the presence of meteorological variability. *Journal of the Air & Waste Management Association*, 48, pp 201–215.

Moore, C.W., Zielinska, B., Petron, G., Jackson, R.B. (2014). Air impacts of increased natural gas acquisition, processing, and use: a critical review. *Environmental Science & Technology*, 48 (15), pp 8,349–8,359.

Moritz, A., Hélie, J.-F., Pinti, D.L., Laroque, M., Barnetche, D., Retaileau, S., Lefebvre, R., Gélinas, Y. (2015). Methane baseline concentrations and sources in shallow aquifers from the shale gas-prone region of the St. Lawrence Lowlands (Quebec, Canada). *Environmental Science and Technology*, 49 (7), pp 4,765–4,771.

Nielsen D.M. (1991). Practical handbook of groundwater monitoring. Lewis Publishers Inc, Bota Racon.

Nielsen, D.M. & Nielsen, G.L. (2006). Groundwater sampling. In Practical handbook of environmental site characterisation and ground-water monitoring, edited by Nielsen, D.M. CRC-Taylor & Francis, 2nd Edition, pp 959-1,112.

Nielsen, D.M. & Schalla, R. (2006). Design and installation of ground-water monitoring wells. In Practical handbook of environmental site characterisation and ground-water monitoring, edited by Nielsen, D.M. CRC-Taylor & Francis, 2nd Edition, 639-806.Olaguer, E.P. (2012). The potential near-source ozone impacts of upstream oil and gas industry emissions. *Journal of the Air & Waste Management Association*, 62, pp 966–977.

Osborn, S. G., Vengosh, A., Warner, N.R. and Jackson, R.B. (2011). Methane contamination of drinking water accompanying gas-well drilling and hydraulic fracturing. *Proceedings of the National Academy of Sciences,* 108(20) pp 8,172-8,176

Pekney, N., Veloski, G., Reeder, M., Tamilia, J., Diehl, J. & Hammack, R. (2014). *Measurement of Air Quality Impacts During Hydraulic Fracturing on a Marcellus Shale Well Pad in Greene County, Pennsylvania* [online]. Available at: http://www.searchanddiscovery.com/documents/2014/80357pekney/ndx_pekney.pdf [Accessed 12 January 2017].

Pettitt, A. N., (1979). A non-parametric approach to the change point problem. Journal of the Royal Statistical Society Series C, Applied Statistics 28, 126-135.Rao, S.T., Zurbenko, I., Porter, P., Ku, J., Henry, R. (1996). Dealing with the ozone nonattainment problem in the Eastern United States. *Journal of Environmental Management,* 1, pp 17–31.

Rao, S.T., Zurbenko, I., Neagu, R., Porter, P., Ku, J., Henry, R. (1997). Space and time scales in ambient ozone data. *Bulletin of the American Meteorological Society*, 78, pp 2,153–2,166.

Révész KM, Breen KJ, Baldassare AJ, Burruss RC (2010). Carbon and hydrogen isotopic evidence for the origin of combustible gases in water supply wells in north-central Pennsylvania. Applied Geochem 25, pp 1,845–1,859. Available at: http://www.mde.state.md.us/programs/Land/mining/marcellus/Documents/isotopic_evidence_article.pdf. [accessed 13 January 2017].

Royal Society and Royal Academy of Engineering. (2012). Shale gas extraction in the UK: a review of hydraulic fracturing. Available at: http://www.raeng.org.uk/publications/reports/shale-gas-extraction-in-the-uk [Accessed 12 January 2017].

SEPA (date unknown). Pollutant Fact Sheets [online]. Available at: http://apps.sepa.org.uk/spripa/Pages/SubstanceSearch.aspx [Accessed 12 February 2016].

Thornton, S.F., Bottrell, S.H., Roger Pickup, R.P., Michael Spence, M.J., & Keith Spence, K.H. (2006). Processes controlling the natural attenuation of fuel hydrocarbons and MTBE in the UK Chalk aquifer, Report RP3.

Tutmez, B., Haipoglu, Z., Kaymak, U. (2006) Modelling electrical conductivity of groundwater using an adaptive neuro-fuzzy inference system, Computers & Geosciences, 34(4): 421-433

Tyndall Centre for Climate Change Research (2011). *Shale gas: a provisional assessment of climate change and environmental impacts* [online]. Available at: http://www.tyndall.ac.uk/sites/default/files/coop_shale_gas_report_final_200111.pdf [Accessed 12 January 2017].

UKOOG (2015a). UK Onshore Shale Gas Well Guidelines: Exploration and Appraisal Phase. Issue 3 (March 2015). http://www.ukoog.org.uk/images/ukoog/pdfs/ShaleGasWellGuidelinesIssue3.pdf [accessed 13 January 2017].

UKOOG (2015b). Guidelines for the Establishment of Environmental Baselines for UK Onshore Oil and Gas. Available at: http://nlhfrp.ca/wp-content/uploads/2015/01/UK-Guidelines_for_the_Establishment_of_Environmental_Baselines_for_UK_Onshore_Oil_and_Gas_Issue_1_January_2015.pdf. [Accessed 29 December 2016].

USEPA (2010). Low Stress (Low Flow) Purging and Sampling Procedure for the Collection of Groundwater Samples from Monitoring Wells, EPASOP- GW 001. https://www.epa.gov/quality/low-stress-low-flow-purging-and-sampling-procedure-collection-groundwater-samples-monitoring [Accessed 29 December 2016].

USEPA (2015a). Assessment of the potential impacts of hydraulic fracturing for oil and gas on drinking water resources, External review draft, EPA/600/R-15/047a. Available at: https://cfpub.epa.gov/ncea/hfstudy/recordisplay.cfm?deid=244651 [Accessed 29 December 2016].

USEPA (2015b). EPA's Study of Hydraulic Fracturing and Its Potential Impact on Drinking Water Resources: Retrospective Case Study in Killdeer, North Dakota. Available at: https://www.epa.gov/hfstudy/retrospective-case-study-killdeer-north-dakota [Accessed 29 December 2016].

USEPA (2015c). EPA's Study of Hydraulic Fracturing and Its Potential Impact on Drinking Water Resources. Retrospective Case Study in Northeastern Pennsylvania. Available at: https://www.epa.gov/hfstudy/retrospective-case-study-northeastern-pennsylvania [Accessed 29 December 2016].

USGS (2011). Quality Assurance and Quality Control of Geochemical Data: A Primer for the Research Scientist. Available at: http://pubs.usgs.gov/of/2011/1187/pdf/ofr2011-1187.pdf [Accessed 29 December 2016].

Vengosh, A., Jackson, RB, Warner, N., Darrah, TH., and A. Kondash (2014). A Critical Review of the Risks to Water Resources from Unconventional Shale Gas Development and Hydraulic Fracturing in the United States. Environmental Science & Technology, 48, pp 8,334−8,348.

Warner, N.R., Jackson, R.B., Darrah, T.H., Osborn, S.G., Down, A., Zhao, K., White, A., Vengosh, A. (2012). Geochemical evidence for possible natural migration of Marcellus formation brine to shallow aquifers in Pennsylvania. Proceedings of the National Academy of Sciences of the United States of America, 109 (30), pp 11,961–11,966.

Wealthall, G.P., Thornton, S.F. & Lerner, D.N. (2002). Assessing the transport and fate of MTBE-amended petroleum hydrocarbons in the UK Chalk aquifer. In GQ2001: Natural and Enhanced Restoration of Groundwater Pollution, Sheffield, U.K., 16-21 June 2001. (eds, Thornton, S.F & Oswald, S.O.), IAHS Publ. No. 275, 205-212.

Wilson, R.D., Thornton, S.F. & Mackay, D.M. (2004). Challenges in monitoring the natural attenuation of spatially variable plumes. Biodegradation, 15, 359-369.

Appendix A Air quality criteria

Recorded ambient concentrations of air pollutants associated with OOG developments will need to be assessed against air quality standards and guidelines for each pollutant, as presented in the table below.

Appendix A: Standards / guidelines applicable to ambient concentrations of pollutants potentially emitted from OOG facilities

Standard / Guideline	Pollutant	Standard / Guideline	Period	Limit	Number of permissible exceedances
European Union air quality limit value	SO_2	European Union air quality limit value	1 hour	350µg/m^3	Not to be exceeded >24 times per calendar year
European Union air quality limit value	SO_2	European Union air quality limit value	24 hours	125µg/m^3	Not to be exceeded >3 times per calendar year
UK Air quality objective	SO_2	UK Air quality objective	15 minutes	266µg/m^3	Not to be exceeded >35 times per calendar year
European Union air quality limit value	SO_2	European Union air quality limit value	Calendar year & winter	20µg/m^3	Rural areas (critical value to protect vegetation)
European Union air quality limit value	NO_2	European Union air quality limit value	1 hour	200µg/m^3	Not to be exceeded >18 times per calendar year
European Union air quality limit value	NO_2	European Union air quality limit value	Calendar year	40µg/m^3	
European Union air quality limit value	NOx	European Union air quality limit value	Calendar year	30µg/m^3	Rural areas (critical value to protect vegetation)
European Union air quality limit value	PM_{10}	European Union air quality limit value	24 hours	50µg/m^3	Not to be exceeded >35 times per calendar year

Standard / Guideline	Pollutant	Standard / Guideline	Period	Limit	Number of permissible exceedances
European Union air quality limit value	PM_{10}	European Union air quality limit value	Calendar year	40µg/m^3	
UK Average Exposure Indicator	$PM_{2.5}$	UK Average Exposure Indicator	Calendar year	20µg/m^3	
European Union air quality limit value	Benzene	European Union air quality limit value	Calendar year	5µg/m^3	
Environment Agency Environmental Assessment Level (EAL)	Toluene	Environment Agency Environmental Assessment Level (EAL)	Calendar year	1,910µg/m^3	
Environment Agency EAL	Toluene	Environment Agency EAL	Maximum 1 hour mean	8,000µg/m^3	No exceedances
Environment Agency EAL	Ethyl-benzene	Environment Agency EAL	Calendar year	4,410µg/m^3	
Environment Agency EAL	Ethyl-benzene	Environment Agency EAL	Maximum 1 hour mean	55,200µg/m^3	No exceedances
Environment Agency EAL	Xylene	Environment Agency EAL	Calendar year	4,410µg/m^3	
Environment Agency EAL	Xylene	Environment Agency EAL	Maximum 1 hour mean	66,200µg/m^3	No exceedances
European Union air quality limit value	CO	European Union air quality limit value	Maximum rolling 8-hour mean	10mg/m^3	No exceedances
European Union air quality limit value	O_3	European Union air quality limit value	Maximum 8 hour mean	120µg/m^3	Not to be exceeded > 25 times per calendar year
European Union air quality limit value	PAHs (assessed as BaP)	European Union air quality limit value	Annual average	1ng/m^3	Total content in the PM_{10} fraction averaged over calendar year
None	Methane	None		Non hazardous	

Standard / Guideline	Pollutant	Standard / Guideline	Period	Limit	Number of permissible exceedances
None	Carbon dioxide	None		Non hazardous	

Appendix B Typical United Kingdom baseline air pollutant concentrations

Typical baseline concentrations of air pollutants associated with OOG developments measured at other sites in the United Kingdom are summarised in the table below.

Appendix B: Typical United Kingdom baseline concentrations of pollutants potentially emitted from OOG facilities

Pollutant	Setting	Typical UK baseline concentration (µg/m³)	Typical UK baseline standard deviation (µg/m³)	Comment
SO_2	Urban	3.83µg/m³	3.86µg/m³	Data recorded at London Eltham in 2016
	Rural	0.94µg/m³	0.58µg/m³	Data recorded at Harwell in 2015
NO_2	Urban	34.8µg/m³	51.0µg/m³	Data recorded at London Eltham in 2016
	Rural	5.16µg/m³	6.47µg/m³	Data recorded at High Muffles in 2016
PM_{10}	Urban	23.9µg/m³	14.8µg/m³	Data recorded at London Eltham in 2006 (Monitoring ended in 2007).
	Rural	7.27µg/m³	5.66µg/m³	Data recorded at Auchencorth Moss in 2016
$PM_{2.5}$	Urban	11.7µg/m³	9.76µg/m³	Data recorded at London Eltham in 2016
	Rural	2.55µg/m³	4.00µg/m³	Data recorded at Auchencorth Moss in 2016
Benzene	Urban	0.53µg/m³	0.44µg/m³	Data recorded at London Eltham in 2016
	Rural	0.16µg/m³	0.13µg/m³	Data recorded at Auchencorth Moss in 2016
Toluene	Urban	0.96µg/m³	1.14µg/m³	Data recorded at London Eltham in 2016
	Rural	0.11µg/m³	0.16µg/m³	Data recorded at Auchencorth Moss in 2016

Pollutant	Setting	Typical UK baseline concentration ($\mu g/m^3$)	Typical UK baseline standard deviation ($\mu g/m^3$)	Comment
Ethyl-benzene	Urban	$0.22\mu g/m^3$	$0.24\mu g/m^3$	Data recorded at London Eltham in 2016
	Rural	$0.065\mu g/m^3$	$0.18\mu g/m^3$	Data recorded at Auchencorth Moss in 2016
Xylene	Urban	$0.25\mu g/m^3$	$0.31\mu g/m^3$	Data recorded at London Eltham in 2016
	Rural	$0.09\mu g/m^3$	$0.32\mu g/m^3$	Data recorded at Auchencorth Moss in 2016
CO	Urban	$0.26mg/m^3$	$0.21mg/m^3$	Data recorded at London North Kensington
	Rural	-	-	-
O_3	Urban	$38.5\mu g/m^3$	$24.3\mu g/m^3$	Data recorded at London Eltham in 2016
	Rural	$55.2\mu g/m^3$	$15.8\mu g/m^3$	Data recorded at Auchencorth Moss in 2016
PAHs (assessed as BaP)	Urban	$0.15ng/m^3$	$0.083ng/m^3$	Data recorded at London Kent
	Rural	$0.035ng/m^3$	$0.0085ng/m^3$	Data recorded at Auchencorth Moss in 2015

Appendix C Contribution to airborne concentrations from onshore oil and gas activities

Data on the likely contributions from shale gas facilities in the United Kingdom is severely limited due to the early stage of development of this industry. However, monitoring campaigns have been undertaken by several State Authorities in the USA. The table overleaf summarises the outcomes of ambient air pollution monitoring campaigns at shale gas sites in the USA conducted up to 2014, as reported by Macey et al. (2014).

Summary of ambient air quality monitoring campaigns at shale gas sites conducted by State Authorities in the USA (source: Macey et al., 2014)

State Authority	Year	Target compounds	Sampling equipment	Sample sites	Duration	Representative findings
Arkansas Department of Environmental Quality	2011	VOCs (total), NO, NO_2	PID (fixed), PID (handheld)	• Four compressor stations • Six drilling sites • Three well sites (fracking) • One upwind	1 day (4 to 6 hours)	• VOCs "almost always below or near detection limits detection limits" • VOCs at drilling sites elevated (avg. 38 to 678ppb; max. 350 to 5,321ppb) • NO/NO_2 rarely exceed detection limits[17]
Colorado Department of Public Health and Environment	2012	NMVOCs (78), Methane	Canister	• One well pad (Erie)	3 weeks	• Detects: 42 of 78 compounds in >75% of samples • Benzene "well within EPA's acceptable cancer risk range" • Acute and chronic HQs "well below" 1
Colorado Department of Public Health and Environment	2009	NMVOCs (78), VOCs, $PM_{2.5}$	Canister, PID (handheld), Filter (handheld)	• Eight wells (four drilling, four completion)	1 day	• Total NMOC avg. 273 to 8,761ppb at eight sites • Total VOC avg. 6 to 3,023ppb at eight sites • $PM_{2.5}$ avg. 7.3 to 16.7µg/m^3 at eight sites

[17] Note: Monitors were set to only detect results >300 ppb.

State Authority	Year	Target compounds	Sampling equipment	Sample sites	Duration	Representative findings
Colorado Department of Public Health and Environment / Geary County Health Department	2007	VOCs (43), PM_{10}	Canister, Filter	• 14 sites • Seven sites	24 months	• Detects = 15 of 43 compounds • Benzene avg. 28.2µg/m^3, max. 180µg/m^3 (grab) • Toluene avg. 91.4µg/m^3, max. 540µg/m^3 (grab)
Colorado Department of Public Health and Environment	2003 - 2012	NMOCs, Carbonyls	Canister	• Five sites (2003) • Six sites (2006) • Three sites (2012)	2 months	• Methane avg. 2,535ppb (Platteille) vs. 1,780ppb (Denver) • Top NMOCs in Platteville = ethane, propane, butane • Benzene & toluene higher in Platteville
Colorado Department of Public Health and Environment	2002	VOCs (42), SO_2, NO, NO_2	Canister, Continuous	• Two well sites • One residential, • One active flare • Two up and down-valley • One background	1 month	• Detects: six of 42 VOCs • Benzene in six of 20 (2.2 to 6.5µg/m^3) • Toluene in 18 of 20 (1.5 to 17µg/m^3)
Ohio Environmental Protection Agency;	2014	VOCs (69), PM_{10}/$PM_{2.5}$, H_2S, CO	Canister, GC/MS, Filter	• One well site • One remote site	12 months	• Ongoing; data update provided in February 2014 • Detects include BTEX, alkanes (e.g., ethane, hexane), H_2S • Second site planned near processing plant

State Authority	Year	Target compounds	Sampling equipment	Sample sites	Duration	Representative findings
Pennsylvania Department of Environmental Protection	2010	VOCs (48), Alkanes, Leak detection	Canister, OP-FTIR, GC/MS, FLIR	• One compressor stations • One condensate tank • One wastewater impoundment • One background	5 weeks	• Detects include methane, ethane, propane, benzene (max. 758ppb) • No concentrations "that would likely trigger air-related health issues" • Fugitive gas stream emissions
Pennsylvania Department of Environmental Protection	2011	VOCs (48), Alkanes, Leak detection	Canister, OP-FTIR, GC/MS, FLIR	• Two compressor stations • One completed well • One well site, (fracking) • One well (tanks, separator) • One background	4 weeks	• Detects include BTEX (benzene max. 400ppb), methylbenzenes • No concentrations "that would likely trigger air-related health issues" • Fugitive emissions from condensate tanks, piping
Pennsylvania Department of Environmental Protection	2011b	VOCs (48), Alkanes	Canister, OP-FTIR, GC/MS	• Two compressor stations • One well site (flaring) • One well site (drilling) • One background	4 weeks	• Detects include benzene (max. 400 ppb), toluene, ethylbenzene • Natural gas constituent detects near compressor stations • Concentrations "do not indicate a potential for major air-related health issues"
Pennsylvania Department of Environmental Protection	2012	Criteria, VOCs/HAPs, Methane, H_2S	"Full suite"	• One gas processing • Two large compressor stations • One background	12 months	• Ongoing; report due in 2014

State Authority	Year	Target compounds	Sampling equipment	Sample sites	Duration	Representative findings
Wyoming Department of Environmental Quality	2013	VOCs/NMHCs, Ozone, Methane, NO, NO_2, $PM_{10}/PM_{2.5}$	Canister, UV Photometric, FID, Chemiluminescence, Beta Attenuation	• Seven permanent stations (e.g., Boulder, Juel spring, Moxa) • Three mesonet stations (Mesa, Paradise Warbonnet) • Two mobile trailer locations (Big Piney, Jonah Field)	Ongoing	• WDEQ mobile monitors placed at locations w/ oil & gas development • Mini-SODAR also placed adjacent to Boulder permanent station • "Relatively low concentrations" of VOCs found in canister samples • VOCs "consistently higher" at Paradise site (near oil & gas sources)

Appendix D Summary of statistical techniques

Technique	Summary
Change Detection / Change Point analysis	A change point is a point in time at which the parameters of the underlying distribution, or, the parameters of the model used to describe the time series, abruptly change (e.g. mean, variance, trend). The most popular method is the technique known as CUMSUM.
Conditional Analyses	Chow and Watson (2008, cited in Malby et al., 2013) recommended that a combination of conditional analysis and appropriately designed monitoring networks to deliver more and earlier insights for air quality management purposes. Malby et al (2013) assert that 'there is considerable potential for conditional techniques to contribute to source-performance assessments and to better air quality management decisions'. Furthermore, they state that 'conditional analysis methods are already useful for earlier detection of air-quality issues and for better targeting of abatement measures and policy priorities.' Known limitations of this method include that well sited background monitors are required to take account of the directions of target sources and prevailing winds in order to maximise data occupancy in background-to-target directions. Conditional selection can be based on subjective judgements. Confidence in these judgements can be maximised by approaching them in a structured and systematic way that can be justified and be corroborated independently. Conditional techniques are unlikely to be used in isolation, but generally in conjunction with other methods (e.g. dispersion modelling, source-emissions testing, emissions inventories) and surveys of the types, levels and timing of source activities.
Cumulative sum control chart (CUSUM)	CUSUM offers a simple and rapid method for identifying sustained changes in pollution levels Known limitations of this method are discussed by Barratt et al, (2007), who considered that in its basic form, the CUSUM method should only be used where changes in pollution levels are large relative to other influences, such as seasonal emission variations and meteorological influences. It is also important to note that in its basic form, it assumes independent normally distributed data whereas air pollution measurements tend to have a skewed distribution and a high degree of autocorrelation.
Kernel Regression	A number of studies have demonstrated the validity of Kernel Estimation in Sector Analysis (Henry et al., 2002, 2009; Yu et al., 2004; Donnelly et al., 2011). Nonparametric kernel regression is effective when performed on short-term data, which is one major advantage over WSA (Donnelly et al., 2011) and can be used in circumstances where there is no emission and baseline concentration information (Cheng et al. 2015) Known limitations of this method include the need to consider autocorrelation effects of time series data (Cheng et al., 2015).

Technique	Summary
Source apportionment (SA)	Due to the high spatiotemporal variability of OOG emissions, applying traditional source-oriented air quality models to source apportionment (SA) is difficult. The complexity of source apportionment in VOC emissions from OOG activities was highlighted by Cheng et al. (2015). They noted that emission sources could exhibit high spatiotemporal variability as a consequence of different operation strategies, different stages of the well lifetime, and variation in the composition of raw gas by reservoir and site.
Multivariate statistical techniques	Multivariate statistical techniques are an efficient way to display complex relationships among many objects (Kouping et al., 2007, cited in Iranmanesh et al., 2014). Multivariate statistical techniques can be an effective means of managing, interpreting, and representing data about groundwater constituents and geochemistry (Belkhiri et al., 2010, cited in Iranmanesh et al., 2014).
Parametric Regression Techniques and Wind Sector Analysis (WSA)	To help identify a directional signal in observed concentration data, wind sector analysis (WSA) and parametric regression have been used to fit concentration-wind direction relationships (Somerville et al., 1994, 1996). Wind directions with high pollutant concentrations can be identified and corresponding sources recognized. Following analysis, a statistical hypothesis test can be carried out to verify the presence of systematic directionality. Known limitations of this method include include that WSA requires long-term monitoring data to guarantee rigorous concentration estimates (Donnelly et al., 2011, cited in Cheng et al., 2015). In addition, parametric regression involves strong assumptions about the form of the model, thereby limiting its generality (Cheng et al., 2015).
Principal Components Analysis (PCA)	Principal Components Analysis (PCA) is a multivariate statistical technique frequently applied to environmental data. PCA looks for linear combinations of the variables that can be used to summarize data; a data dimension reduction technique. Principal components are the eigenvectors of a variance-covariance or a correlation matrix of the original data matrix. Using the correlation matrix, each variable is normalized to a unit variance. The first principal component, or factor, accounts for the greatest variability in the data, and there are potentially an infinite number of new factors with each accounting for less data variability than the previous. Advantages of this technique include that PCA does not lose significant information (Maitra and Yan J, 2008 cited in Iranmanesh et al., 2014)
Receptor Modelling	Receptor modelling in the oil and gas industry can be focused on mass balance and mathematical criteria. Since OOG operations involve multiple highly variable activities, however, the output factors of receptor models may mix OOG emissions with other sources and the impact of OOG operations becomes difficult to isolate. (Cheng et al., 2015)

Appendix E Statistical techniques for change detection

The table below summarises techniques used in the discussion of principals for statistical assessments, which in combination with others can be used to show Difference / Change

Statistical techniques	Methods	Comments
Correlation Techniques Answers question: is one thing related to another (e.g. proximity to site and methane concentrations in groundwater)	Pearson Rank Spearmans Rho	Implies is related to another but not the causal factor (e.g. height is related to intelligence in children, NOT Children are intelligent because they are tall)
Explanatory variable Techniques Answers question: How much of a relationship is explained by something else? (e.g. Methane concentrations in groundwater best described by proximity of wells AND distance to well)	Parametric Regression Techniques (e.g. ANOVA) Non Parametric Regression Techniques (e.g. Principle Components Analysis)	Implies what might explain an outcome (e.g. if height AND age AND Intelligence, regression techniques might find that AGE best describes Intelligence).
Trend Detection Techniques Singular relationship: things increasing/decreasing/or staying the same (e.g. Ozone has been statistically increasing in recent years) Not when they have changed	Parametric Techniques; Least Squares curve fit (e.g. Linear, Moving Average Models (ARMA/ARIMA)) Non Parametric Techniques (e.g. Kendalls-Tau, Kernell Regression)	Indicates how something varies through time (assuming a single relationship), e.g. Children get more intelligent as they get older.
Background Correction Techniques Used where no baseline	Matched Difference	Corrects for base level of intelligence for children are aged 11 to calculate rate of intelligence increase through secondary school.
Baseline Establishment Techniques Must be used for change detection	Basic statistics for use in Change detection	Indicates if the variance of intelligence increases from children as they start secondary school, with which to detect, significant changes at secondary school
Wind Sector Analysis Specific to Air Quality Techniques. Can be used to strengthen the signal by	See Text	Can be used to filter before Change Detection \ Difference analysis to enhance signal strength

Statistical techniques	Methods	Comments
removing much of the background variation		
Conditional Analysis Techniques	See Text. Method as applied by Malby et al. (2013	Can be used to isolate \ attribute signals to specific sources.

Technique	Example Methods	Comments	Pros/Cons in OOG application
Difference Detection Techniques (e.g. Paired Comparison Techniques) -I have 2 sites…are they different? -I have 2 time phases…before and after; are they different? (NOT HOW they are different?) (NOT WHEN did they change?)	Parametric Examples Non-Parametric Examples T-Test (mean) Mann-Whitney (distribution)	Can be combined with other techniques to show a difference, e.g. the rate of intelligence increase is DIFFERENT in children (aged <18) to Adults (18 and over) or the rate of intelligence increase is DIFFERENT in children aged 15 relative to age 11.	Pro: Probably more suitable to fugitives than Change detection Pro: Commonly known and used Con: Assumes that all change since “baseline” established will be a result of the operation, unless background sites available and assumptions made and applied
Change Detection Techniques -Establish trends -Are things different now to how they were? -WHEN did they change? -HOW have they changed?	Tests on Mean CUMSUM & Cumulative Deviation Test Pettitt Test (non parametric) Signal-to-noise ratios and Tipping Points Lanzante method STARS Tests on Variance Downton-Katz Rodionov Tests on Frequency Nikiforov method Vector auto-regressive method	Shows if and when a change / multiple changes happen (e.g. when the rate of intelligence changes) (e.g. children aged 13, 15 and adults aged 22).	Pro: Can autocorrect for background changes Pro: Coupled with Bayesian Analysis can give uncertainty bounds to the assessment. Con: May not be suitable for fugitives Con: Unclear at the moment if the background variability will be prohibitive for use of this technique across all parameters

Technique	Example Methods	Comments	Pros/Cons in OOG application
Bayesian Techniques -Can be coupled to Change Detection and provide uncertainty estimates of change points	Monte-Carlo Markov Chain	Can be combined with change detection to show that with 95% certainty there was a rate of intelligence increase in children aged between 12 and 14.	

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