Monitoring at shale gas sites: developing environmental quality baselines

Chief Scientist's Group research report

December 2021

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Professor Doug Wilson
Chief Scientist

Executive summary

The development of England's onshore oil and gas resources is at an important stage. After several years with little activity on the ground, permission has been granted for exploratory drilling and hydraulic fracturing at 2 sites in England; one in Lancashire (Preston New Road) and one in North Yorkshire (Kirby Misperton). Hydraulic fracturing began at Preston New Road in October 2018. A final hydraulic fracturing consent for the Kirby Misperton site has not yet been granted. Further applications for planning permission and environmental permits for hydraulic fracturing exploration may be received by decision-making authorities, including the Environment Agency, in the near future.

Understanding the environmental conditions in which hydraulic fracturing activities take place is an important part of managing the risks of these activities. This project built on previous studies to investigate baseline environmental conditions at the Preston New Road and Kirby Misperton sites, covering air quality, surface water quality, and the quality of water below the ground surface. The aims of the project were to:

- develop examples of characterising baseline air, surface water and groundwater quality at Preston New Road and Kirby Misperton
- investigate whether site operations have resulted in any observable changes in environmental quality at these sites
- review and refine previous guidelines for baseline monitoring methods for use at hydraulic fracturing sites

A previous Environment Agency report 'Onshore oil and gas monitoring: assessing the statistical significance of change' provided a set of flowcharts and decision trees to allow operators to design baseline surveys. It also provided guidelines on interpreting measurement data to determine whether it was adequate to investigate baseline air quality. For surveys continuing once operations began at the sites, the report provided guidelines for investigating whether operations at the hydraulic fracturing sites had resulted in any detectable changes.

The guidelines have been applied to environmental measurements at both the Preston New Road and Kirby Misperton sites. The baseline surveys at the 2 sites had been designed before the report on assessing the statistical significance of change was published. Nevertheless, the measurements obtained from these surveys provided a robust basis to characterise baseline air quality, surface water quality and groundwater quality in these areas. The data sets were made up of measurements carried out by the British Geological Survey (BGS), the Environment Agency and the operator. They cover a number of phases of activity, including:

- before any onshore oil and gas activity associated with the facility began (phase 1)
- site preparation, including moving earth, levelling/concreting the site, bringing plant to the site (phase 2)
- drilling and associated activities such as waste disposal (phase 3)
- hydraulic fracturing (phase 4)
- flowback of water from the well and extraction of gas (phase 5)

Hydraulic fracturing, flowback and drilling phases are only relevant to Preston New Road as hydraulic fracturing has not taken place at Kirby Misperton (and the well was drilled as part of previous onshore oil and gas activity at the site). Air quality data was available at Preston New Road for all 5 phases, and for water quality, for phases 1 to 3. But, at Kirby Misperton, data was only available for phases 1 and 2. Because these are among the first shale gas sites in the UK, a substantial amount of monitoring has been carried out. This will not be the case for all future sites. Applying methods to investigate this data was limited by the lack of data available, and the report evaluated some, but not all, of the data gathered.

Applying the guidelines allowed the substances measured during the baseline surveys to be prioritised, and measurements of these substances to be presented numerically and graphically.

For air quality data at Preston New Road, the guidelines were used to investigate whether measured levels of released substances had changed significantly between certain combinations of the phases listed above. There was limited data available to make 'like for like' comparisons between monitoring locations and phases. This meant that it was not possible to investigate whether there were systematic changes in measured levels of substances between the period before any activities took place (phase 1) and when operations began at the site (phases 3 to 5).

Based on the analysis of real-world data from these 2 sites, a number of recommendations were made to improve the guidelines, and to provide further detail in some important areas.

General recommendations

1. A simple breakdown into 2 phases comprising 'baseline' and 'operational' phases may not be adequate to reflect real-world complexities. The guidelines should be amended to provide for a range of activity periods, which could then be assessed individually, provided sufficient data are available in each period.

Air quality recommendations

2. Conceptual models should be used, together with other techniques (for example, data analysis and dispersion modelling) to account for the potential influence of distant sources on baseline air quality.
3. There should be a stage in the air quality survey design decision tree covering selecting pollutants. This would lead users to focus on priority substances for air quality.
4. One of the stages in the original guidelines was to carry out a test for adequacy. It was found that this step did not provide useful insights for air quality data analysis. It is therefore proposed to remove testing for adequacy from the recommended procedure for air quality data. However, identifying, and potentially removing outliers, is still recommended during quality assurance/quality control (QA/QC).
5. The guidelines should highlight that techniques to investigate the sources of measured levels of air pollutants should be used, but these may not be effective in situations where local sources are intermittent or irregular.
6. The guidelines should recommend using advanced air quality monitoring data analysis tools for routinely presenting baseline data provided that sufficient data is available. A wider range of tools could be used if measured levels of air pollutants give cause for concern.

Water quality recommendations

7. Conceptual models should be developed to ensure that groundwater and surface water flow are taken into account when designing baseline surveys.
8. In many cases, using a logarithmic scale on summary graphs allows measurement data to be inspected more easily.
9. Operators and regulators should identify and agree the substances of most interest before investing in detailed monitoring. Even if additional substances are measured, data analysis and interpretation should focus on the prioritised substances using a systematic approach, rather than assuming every measured substance is equally important. A methodology for doing this has been set out in the main text (Section 4.6.
10. When interpreting baseline data, it is important to bear in mind issues that could arise from external factors such as a change in laboratory methods.
11. There would be a benefit in developing a simplified approach to assess adequacy for non-expert users.

12. It is recommended that a methodology for grouping parameters should be provided within the statistical guidelines. Examples are set out in the main text (e.g. Section 2.7.4), and could include groupings for setting the baseline of upgradient and downgradient sites, shallow and deep groundwaters.
13. A requirement for summary statistics alongside qualitative (visual) analysis of individual and grouped data sites should be provided within the statistical guidelines.
14. A further stage should be added to the guidelines to calculate the percentage of limit of detection (LOD) values, and to specify how to extract useful information from values below the limit of detection. An approach for dealing with determinands that have a large proportion of values less than the LOD has been set out in Section 4.7.

Implementation issues

15. One year of baseline air quality data is likely to be enough to characterise baseline conditions and factors affecting measured concentrations, although this would not be able to account for changes from one year to the next. Shorter monitoring periods could be used in some circumstances, for example, where there are relatively few other sources of pollution. One year of measurements should also be the starting point for designing site-specific baseline water quality surveys.
16. The recommended methods would allow survey designs to be adapted as more information becomes available, for example, by changing the range of substances measured, changing survey durations or by changing the location or frequency of measurements, either for a single installation or to develop knowledge and understanding for the industry in general.
17. If the recommended approaches to designing baseline surveys and data interpretation in this and other reports are followed, monitoring programmes that provide adequate data for assessing baseline conditions and operational impacts can be designed. The analysis has emphasised the potential for data quality to influence the conclusions drawn from a monitoring study. Where there are gaps in data and/or the frequency of collection is reduced, the ability of the survey to accurately characterise the baseline conditions will be hindered. This demonstrates the importance of designing a monitoring survey that reflects the risks of a site and its activities, and the sensitivities of the surrounding area, and which adapts to changes as the development progresses. Furthermore, the study has illustrated how the location of monitoring stations will affect the nature of the data collected. If data are available from different locations, this may be used to infer impacts resulting from an emission source.
18. There are 2 areas where it is recommended that further analysis is carried out; firstly, to ensure the minimum requirements for data capture and quality are met, and, secondly, that the number and siting of monitoring locations are established, so that changes in baseline air and water quality, as a result of shale gas operations, are accurately identified.

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1 Introduction

1.1 Background

1.1.1 Onshore oil and gas in the UK

The development of England's onshore oil and gas resources is at an important stage. After several years with little activity on the ground, permission has been granted for exploratory drilling and hydraulic fracturing at 2 sites in England; one in Lancashire (Preston New Road) and one in North Yorkshire (Kirby Misperton). Hydraulic fracturing began at Preston New Road in October 2018.

It is anticipated that the number of applications for planning permission and environmental permits for hydraulic fracturing facilities in the UK may increase in future years.

1.1.2 Regulatory framework

The regulatory framework for managing unconventional oil and gas development was set out in guidance produced by the then Department for Energy and Climate Change (DECC)[1]. However, DECC has since been subsumed by the Department for Business, Energy and Industrial Strategy (BEIS). Guidance on the development of shale gas facilities in the UK can be found on the BEIS website[2].

The Environment Agency published sector guidance for the onshore oil and gas industry in August 2016[3]. This guidance covers the following activities:

- well pad construction
- drilling exploratory wells
- flow testing and well stimulation, including hydraulic fracturing
- storing and handling crude oil
- treatment of waste gases, including flaring
- handling, storage and disposal of produced waters and flowback fluid
- managing extractive wastes
- extraction of coal mine methane

The Environment Agency is also a statutory consultee for the planning and Environmental Impact Assessment (EIA) process.

Alongside these statutory obligations, a number of requirements in relation to baseline monitoring are contained in the Infrastructure Act 2015. These commitments are underlined by the European Commission Regulation on 'minimum principles for the exploration and production of hydrocarbons (such as shale gas) using high-volume hydraulic fracturing' (2014/70/EU). This also places obligations on member states in relation to baseline studies, requiring a baseline to be determined for:

a) quality and flow characteristics of surface and ground water
b) water quality at drinking water abstraction points
c) air quality
d) soil condition
e) presence of methane and other volatile organic compounds in water
f) seismicity
g) land use
h) biodiversity
i) status of infrastructure and buildings

j) existing wells and abandoned structures

This report focuses on requirements relating to air quality (c) and water quality (a) and (e).

1.2 Earlier work

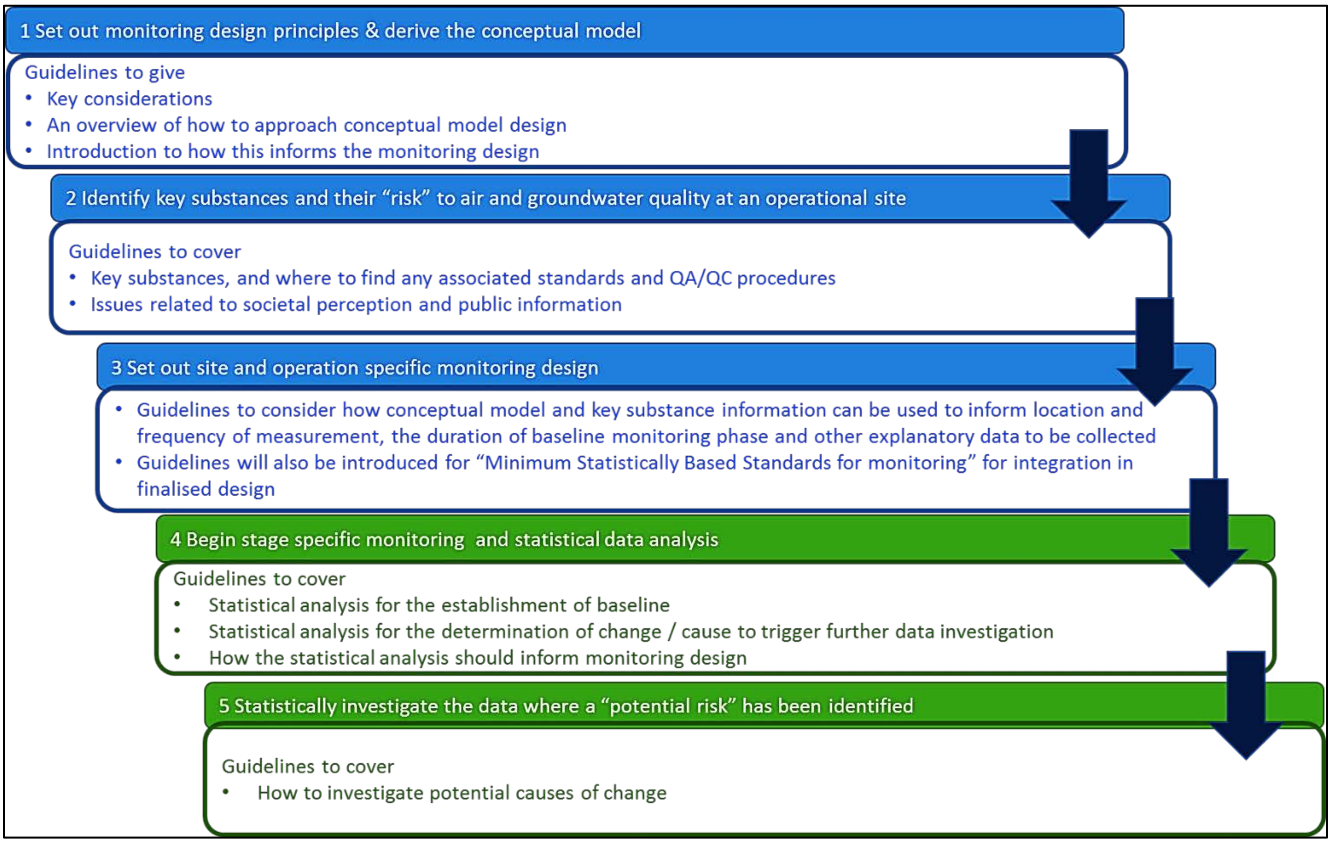
The main reference point for this current work is the Environment Agency project 'Onshore oil and gas monitoring: assessing the statistical significance of change' (project reference SC160020)[4]. That project set out a methodology for determining baselines for air quality and groundwater quality and the assessment of change, with application to hydraulic fracturing facilities. There was however limited testing of that methodology developed, and it was recommended that further work be completed to test its practicality and 'fitness-for-purpose' on data measured in the real world. References to 'guidelines' in this report refer to project reference SC160020, except where stated otherwise.

The aim of that earlier study was to provide guidelines in 3 main areas:

- monitoring design
- establishing baselines
- detecting and attributing change – methods to investigate the cause of a change once it had been detected

A 5-stage approach, as shown in Figure 1.1:, was developed. At every stage, there is an obligation to inform, communicate and explain. The approach was designed to make sure that any significant changes are detected and reported, even if there is no adverse effect.

Figure 1-1: Overview of staged process of survey design and statistical analysis from report SC160020



Note: Steps in blue were related to guidelines associated with survey design

Steps in green were related to guidelines associated with statistical analysis

Stage 1 involved setting out the principles governing the design of the monitoring programme applicable to both air and groundwater quality, and the development of the conceptual model. It is not always practical to consider the monitoring and analysis of air and groundwater quality together in a single approach and so later sections considered these aspects separately. This allowed enough detail to be provided for both, while allowing a different approach, where appropriate.

Stage 2 considered the main pollutants of concern, and provided guidelines on how to identify the principal substances at an operational onshore oil and gas (OOG) site in terms of their potential risk to air and groundwater quality.

Stage 3 described how the proposed monitoring design can be refined to make it specific to the particular site and operations for air quality and groundwater quality.

Stage 4 explained how to analyse the baseline data pertaining to air and groundwater quality, and then how to detect any change from baseline conditions.

Stage 5 considered how to investigate and attribute potential causes of a statistically significant change.

The output for stages 3 to 5 was presented in a series of flow charts and decision trees, with associated notes that provided explanations and comments on appropriate methods for each topic.

Case studies were provided to show the application of the guidelines, in which different segments of the approach were tested with some example data sets from other industrial sectors.

The limitations of this project included:

- no testing as an end to end example of establishing baselines and detecting change
- some elements were loosely defined
- there was no specific definition of the term 'baseline'

The focus of the project on assessing the statistical significance of change (SC160020) was to help operators and regulators design surveys that would be effective in characterising baseline air quality and detecting change away from baseline conditions. The starting point for any definition of a baseline period is the period before any activities have begun at the site. The current project is designed to clarify the different periods involved in a typical onshore oil and gas operation, to explore the possible definitions of baseline and operational periods, to evaluate and further develop the guidelines, and in particular, to provide additional detail in statistical analysis and presentation of baseline monitoring data. As a result, one of the main outputs of this project is revised and updated flowcharts and decision trees for establishing baselines (see chapter 4).

1.3 Other projects and reports

A number of baseline monitoring outputs have been developed by the British Geological Survey (BGS), including the Environmental Baseline Monitoring Project: Phase II – final report 1 OR17-049 and Environmental Baseline Monitoring Project: Phase III Progress Report 1, 2, 3 (2017 - 2018)[5,6]. These projects present a reference base of baseline conditions, analysis and reporting around the Kirby Misperton site. However, these projects do not provide a formal methodology for setting baselines. Similarly, the Environment Agency has carried out monitoring of ambient air quality at locations close to both the Kirby Misperton and Preston New Road sites. These data sets were analysed as part of the present project.

Data collected by BGS and the Environment Agency is of higher spatial and temporal resolution, and covers a larger area than may be expected in normal operation. But, it does provide an indication of some of the challenges in establishing a reliable baseline in practice, where there may potentially be fewer monitoring locations, with lower frequency measurements over a shorter time frame (for example, quarterly or 6 monthly values over 2 years).

Ricardo has also recently completed a project on behalf of the Environment Agency to develop a proposed framework for the design of adaptive monitoring regimes for pollutant concentrations in ambient air at shale gas sites (project reference SC170014 'Ambient air monitoring at shale gas sites: Framework for the design of adaptive monitoring regimes')[7]. The focus of this project was to design a regulatory framework that can be used by operators and regulators of onshore oil and gas installations to define an appropriate scope for an air quality monitoring survey. The aim of this framework is to allow a monitoring programme to be defined that is consistent between installations, and reasonable in terms of the air quality risks posed by shale gas sites. This includes having 'adaptive' monitoring programmes that can be adjusted in light of ongoing monitoring results.

1.4 Project aims and scope

The project aims were defined as follows, to:

- develop examples of environmental baselines for substances in air, surface water and groundwater at Kirby Misperton and Preston New Road
- compare the developed baselines for air, surface water and groundwater with the monitoring results obtained during any hydraulic fracturing operations to identify whether or not there have been changes in environmental quality due to site operations
- provide recommendations on the best practice methods for developing baselines that can be applied at other shale gas sites
- identify any strategic issues arising from the baseline work

The project scope was specified on the basis of 8 tasks:

1. Plan for developing baselines
2. Acquiring data acquisition
3. Developing baselines
4. Changes during baseline monitoring
5. Assessment of operational period monitoring data (operational phase data available for Preston New Road only)
6. Best practice recommendations
7. Support for policy implications
8. Reporting

Although the project is restricted to shale gas sites, the concepts and approaches discussed in this report may also apply to other types of facilities.

1.5 Report structure

The report is structured as follows.

- This chapter provides the project context and a review of the guidelines as previously published.
- Chapter 2 describes how these guidelines were applied to air and water quality data from the Kirby Misperton site.
- Chapter 3 describes how these guidelines were applied to air and water quality data from the Preston New Road site.
- Chapter 4 sets out suggested revisions and clarifications to the existing guidelines, resulting from applying the guidelines to these new data sets.
- Chapter 5 describes applying the guidelines to the assessment of variations between baseline and operational periods at the Preston New Road site.
- Best practice recommendations are summarised in chapter 6.

2 Environmental baselines for Kirby Misperton

The purpose of this section is to apply the guidelines set out in 'Onshore oil and gas monitoring: assessing the statistical significance of change'[4], in order to develop environmental baselines at Kirby Misperton. Examples of analysis are shown for Kirby Misperton, covering both air and water data. This assessment provides an opportunity to critique the guidelines, while simultaneously assessing the baselines for air and water. Through this assessment, lessons were learned and revisions to the guidelines were recommended (chapter 4).

2.1 Overview

The Kirby Misperton site is an existing operational onshore oil and gas sector installation operated by Third Energy. The Environment Agency issued environmental permits for exploratory hydraulic fracturing at the Kirby Misperton 8 (KM8) well site in April 2016. These permits set out legally binding conditions for site operations, including groundwater, surface water and air emissions from permitted activities.

The permits also include pre-operational conditions, monitoring and reporting requirements. Pre-operational condition 2 required the Environment Agency's approval of a written Hydraulic Fracture Plan, setting out how the operator will control and monitor the fracturing process. Pre-operational condition 3 required approval of an Emissions Monitoring Plan. Approvals for these plans were confirmed by the Environment Agency in October 2017.

Figure 2.1 shows where the shale gas site sits in the wider area. The well site is situated in a rural location surrounded by farm land. The village of Kirby Misperton is approximately 500 m to the north-east. Figure 2.2 shows the location of the monitoring sites. The Environment Agency monitoring site is upwind of the well head and the BGS monitoring site is downwind on the eastern edge of the Kirby Misperton site.

Figure 2-1: Kirby Misperton site plan

Figure 2-2: Kirby Misperton hydraulic fracturing site, including monitoring locations

2.2 Air quality aspects

In 2015, an Air Quality Impact Assessment (AQIA)[8] was submitted in support of the permit to operate the shale gas site at Kirby Misperton. The report concluded the following:

- "Process contributions from engine releases to ground level concentrations of nitrogen dioxide and PM_{10} are expected to exceed short-term air quality standards at the site boundary based on model predictions."
- "At the nearest locations of permanent human habitation process contributions to ground level concentrations of carbon monoxide, sulphur dioxide, volatile organic compounds and PM_{10} are not considered to be likely to have any significant impact on air quality."
- "Process contributions of nitrogen dioxide are more significant, although it is concluded that these are unlikely to pose a substantial threat to the continued attainment of air quality standards."
- "The maximum process contribution to ground level concentrations of methane, ethane, propane and higher hydrocarbons (expressed as benzene) was predicted to be equivalent to no more than 8% of the estimated long-term environmental benchmark at the site boundary, falling to below 1% of these levels at the nearest residential locations."

The results indicate that the monitoring strategy should be designed to identify short-term peaks in pollutant concentrations, in particular NO_2, at the boundary of the site. At the time of writing the AQIA, the timescales for operation were uncertain. However, the operator modelling included the following estimates for activity durations as shown in Table 2.1.

Table 2.1: Estimated operational phases set out in the 2015 AQIA

Phase	Activity	Duration
Workover	Well logging	2 operations each of around 5 hours
	Setting upper completions	2 operations each of around 4 hours
	Operating frack sleeves	9 operations each of around 24 hours
	Site vehicle movements	186 HGV movements in the phase with a scheduled maximum of 25 movements/day 6 LGV/passenger car movements/day
Hydraulic fracture stimulation and well test	Performing fracture	5 operations each of around 5 hours
	Well clean up (between zone fractures)	4 operations each of between one and 3 days
	Setting bridge plugs	5 operations each of around 24 hours
	Final well clean up	4 operations each of between one and 3 days
	Lifting the well	One operation of around 24 hours
	Flowback well	One operation of around 24 hours
	Site vehicle movements	434 HGV movements in the phase with a scheduled maximum of 49 movements/day 10 LGV/passenger car movements/day
Production test	Production test	One HGV movement every 2 to 3 days 4 LGV/passenger car movements/day
Production	Production	4 LGV/passenger car movements/day
Restoration	Restoration	1,240 HGV movements over the 6-week phase with an average of 36 movements/day 6 LGV/passenger car movements/day 4 earth movers each operated for a maximum of 6 hours per day over the 6-week phase

2.3 Water quality aspects

Extensive surface and groundwater quality monitoring was carried out around the KM8 well pad to identify any water pollution caused by activities at the site. In order to better understand the risks to water quality from the KM8 well and its operation, a brief overview of the geology, surface water and groundwater receptors and main risks to water quality is provided below.

The KM8 well was drilled in 2013 to a total depth of 3,068 m below ground level to access the remaining gas trapped beneath the Permian unconformity in the Kirby Misperton field. The well site itself is covered with 300 mm of stone hardcore, under which lies an impermeable geotextile membrane that prevents vertical migration of fluids between the ground surface and the groundwater beneath. Surface water run-off from the well site is diverted into an on-site storage facility to be disposed of by tanker.

The superficial deposits directly beneath the site are predominantly clay and sand, which means that a shallow groundwater system is expected, with low volumes of groundwater contributing to small, locally important water supplies. The bedrock stratigraphy and how this relates to the KM8 site conceptual hydrogeological model[9] is listed below:

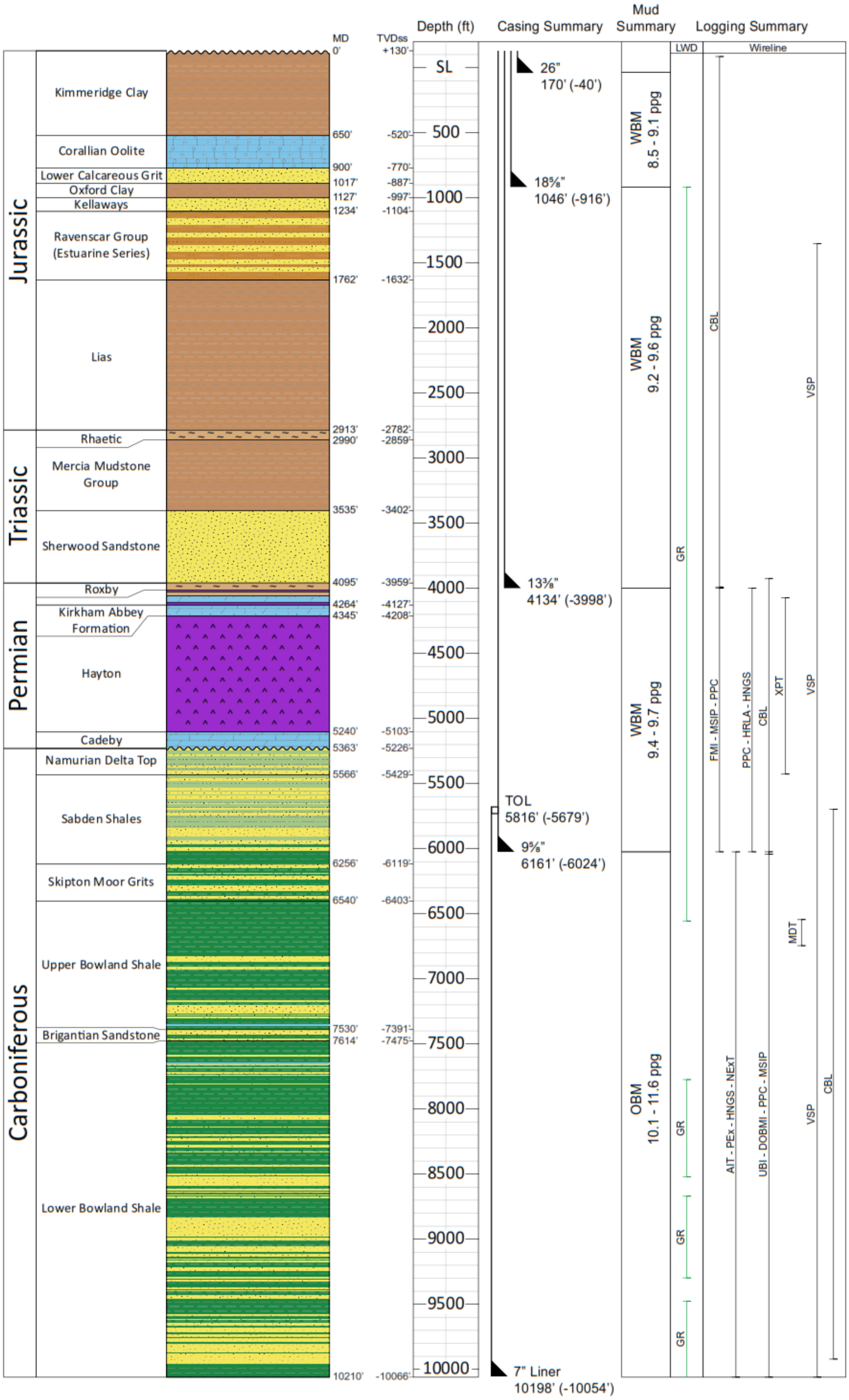
- **Ancholme Group:** This group is composed of mudstones, bituminous mudstones with thin limestones. Although classified as unproductive strata, the weathered upper layers may have groundwater potential. These strata separate the surface shallow groundwater from those of the deeper Corallian aquifer. Within the conceptual hydrogeological model, these strata are classed as layer 1 (useful hydraulic conductivity and storage, drinking water and water for other uses).

- **Corallian Group:** This group is composed of sandstones, calcareous sandstones and limestones. The Corallian Group is a regionally important principal aquifer which is likely of poor quality below the well site (saline waters). Around Scarborough, the aquifer is used as a drinking water supply but is not in hydrological connectivity with the Corallian Group beneath the well site due to faulting. Within the conceptual hydrogeological model, these strata are classed as layer 1 (useful hydraulic conductivity and storage, drinking water and water for other uses).
- **Oxford Clay Formation:** This lithology is a marine-derived mudstone. It is unproductive. Within the conceptual hydrogeological model, this lithology is classed as layer 2 (very low hydraulic conductivity and storage, unproductive strata). Layer 2 also includes other strata within the Jurassic, for example Dogger Formation and the Lias Group.
- **Triassic, Permian and Carboniferous strata:** These cover a wide range of lithologies such as sandstones, mudstones, limestones and evaporites. They are highly likely to be unproductive from a groundwater viewpoint and contain highly saline formation waters. Within the hydrogeological conceptual model, the Triassic strata (Sherwood Sandstone Group) are classed as layer 3 (useful hydraulic conductivity and storage, highly saline formation waters, no resource value and no active recharge), while the Permian (Zechstein group) and Carboniferous (Millstone Grit Group and Bowland Shale) are classed as layer 4 (limited hydraulic conductivity and storage, highly saline formation waters, no resource value and no active recharge).

There is a general geological dip towards the south-east, which is the likely direction for groundwater flow.

The KM8 borehole log shows the geological succession (Figure 2.3).

Figure 2-3: Borehole log of the KM8 borehole[9]



Within the strata beneath the site there are a large number of lithologies that form impermeable seals, including the Mercia Mudstone, Lias Group and Hayton Anhydrite (evaporite). These impermeable strata are likely to act as hydraulic barriers to the vertical movement of water (and contaminants) between adjacent strata. Of these, the Hayton Anhydrite is the most significant, being located within the Permian strata and between the Bowland Shales (the source rocks which may be hydraulically fractured) and the aquifers within the Jurassic and Quaternary superficial materials. This limits the potential risk of contamination of the aquifers close to the surface from hydraulic fracturing activities at the site.

There are no groundwater dependent terrestrial ecosystems adjacent to the site or within the groundwater area of interest. There is no mapped source protection zone (SPZ) within 2 km as indicated by the Environment Agency SPZ GIS mapping. The nearest SPZ is the Scarborough SPZ, which is approximately 6 km to the east of the site. No important groundwater receptors have therefore been identified.

There are 2 groundwater supplies within 2 km of the wellsite, and 4 beyond 2 km[9]. The groundwater supplies are mostly located at farms, and likely abstract water from the superficial material and weathered Ancholme Group. While any drinking water well has a default source protection zone of 50 m radius, smaller abstractions are not routinely mapped.

Seven surface water features exist within 2 km of the well site. These include:

- 4 ponds and lakes
- 3 watercourses: Sugar Hill Drain and its ditch system adjacent to the site, Costa Beck (1.5 km from the site) and Ackland Beck (1.7 km from the site)

The morphology of the land surface around the site, specifically surface flow directions to the south-west, indicates that there is potential for polluted surface run-off from the site to reach the adjacent drainage ditch at Sugar Hill Drain to the east, where surface water monitoring is carried out.

There are no surface water abstractions in close proximity to the KM8 wellsite. All water is supplied through the local drinking water network. Within 2 km, there is a single Environment Agency abstraction licence located at Flamingo Land, which abstracts from Costa Beck and is associated with agricultural use.

Considering the hydrogeology, surface morphology and the main surface water and groundwater receptors at risk of pollution, a source-pathway-receptor (SPR) model for the well development, hydraulic fracturing and operational phases was developed within the KM8 site environmental statement[9]. The SPR identified the following potential pollution risks to surface and groundwaters:

- spillage and discharge to surface water or infiltration through base of well site
- loss of well integrity leading to leakage
- migration of hydraulic fracturing fluids along natural faults and/or induced fractures

In order to monitor the potential impacts on surface water and groundwater quality from site pollution, a number of water quality monitoring locations were established by Third Energy and BGS. These are shown in Figure 2.4 and the data derived from these sites is used in the subsequent analysis.

Figure 2-4: Map showing surface and groundwater quality monitoring locations on the well pad and in the vicinity of Kirby Misperton site

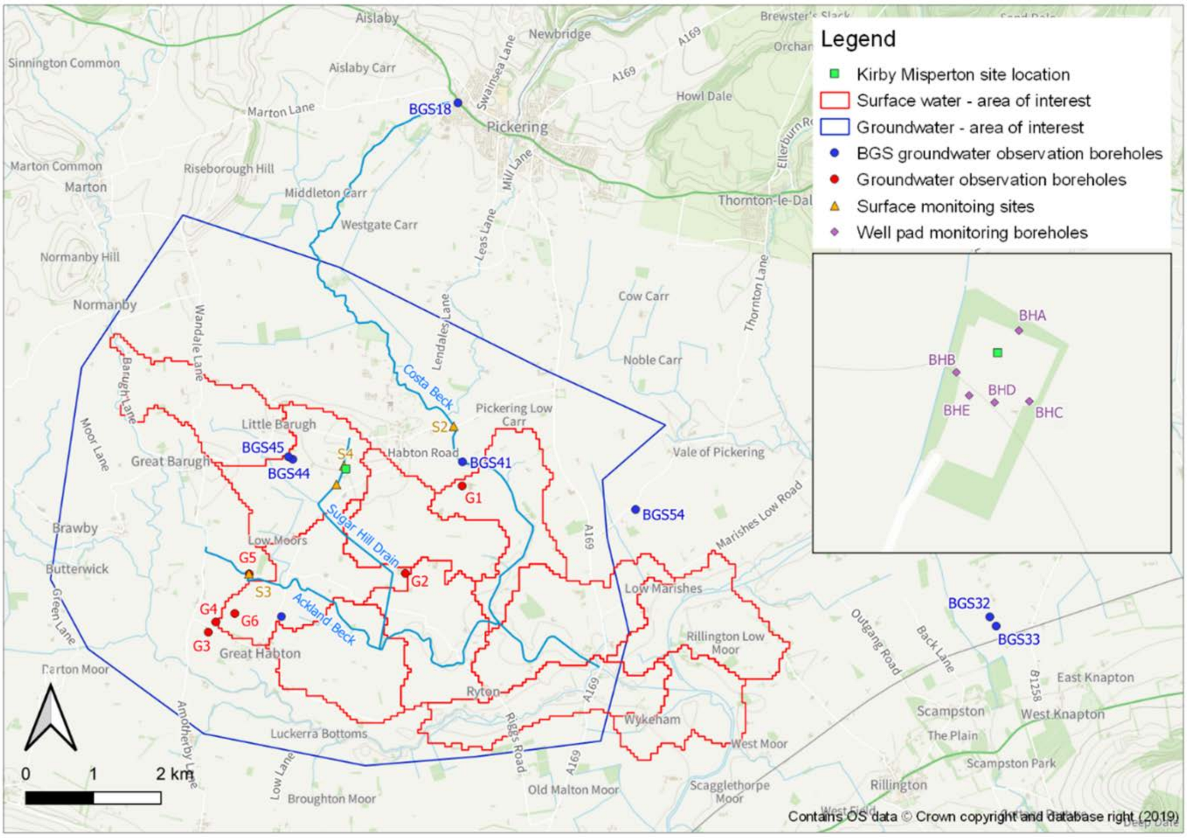


Figure 2.4 also indicates the surface water and groundwater areas of interest for the study. For the purposes of the study, these were defined as the potential areas where impacts from the site operation may occur. They can therefore be used to acquire additional data, such as Environment Agency routine water quality monitoring data, and general wider understanding of the site.

The areas of interest are defined based on analysis of the features that control water movement between sources and receptors. In the case of surface water for KM8, the area of interest was defined using a digital elevation model to understand the surface flow directions and contributing catchments to the watercourses surrounding the KM8 site. The groundwater area of interest was derived from interpreting geological and hydrogeological information, specifically the groundwater flow direction, the underlying geology and its structural orientation, the hydrogeological potential of the strata and considering faulting.

2.4 Site timeline

To understand the possible impacts on surface water and groundwater water quality from operational phases at the KM8 site, a timeline of the main activities at the site was produced using information provided by the operator and third parties. This timeline is displayed in Table 2.2.

Table 2.2: Timeline of main activities at the Kirby Misperton site

Date	Activity
2013	KM8 well drilled in existing Kirby Misperton gas field.
February 2015	Operator water quality monitoring began.
January 2016	BGS air quality monitoring began.

Date	Activity
January 2016	BGS baseline groundwater data monitoring began.
September 2016	Operator water quality monitoring ended.
April 2017	Operator water quality monitoring restarted.
June 2017	Operator water quality monitoring ended.
June 2017	BGS greenhouse gas monitoring ended.
23 August 2017	Environment Agency air quality monitoring began.
September 2017	Operator water quality monitoring restarted (ongoing).
25 September 2017	Noise barrier installed.
16 October 2017	Vehicle movements, crane and generator activity at the site started around this date.
31 December 2017	BGS air quality monitoring ended.
8 March 2018	Noise barrier removed.
11 March 2018	Vehicle movements, crane and generators no longer active at the site.
April 2018	BGS volatile organic compound (VOC) monitoring ended.
11 August 2018	Increase in activity at existing site due to maintenance outage period.

2.5 Baseline air quality data

Two air quality monitoring data sets collected at the Kirby Misperton site have been used in this study:

- continuous and periodic air quality monitoring data from measurements carried out by the Environment Agency
- continuous and periodic air quality monitoring data from measurements carried out by BGS

It should be noted that the site operator also carried out its own air quality monitoring. However, this data set was not used in this assessment because the monitoring data collected by the Environment Agency and BGS is a more comprehensive research data set, and therefore offered a greater opportunity to carry out a more detailed review of the proposed statistical analysis methodologies. Operator-collected data will be the norm in the future, and so is likely to be less comprehensive than the data sets used in this study. The report on adaptive air quality monitoring (Environment Agency, 2019) could be used to provide a framework for operators to consider options for the design of future monitoring programmes.

The Environment Agency and BGS monitoring locations are shown in Figure 2.2. BGS was already carrying out air quality monitoring to the east of the KM8 well. Consequently, the Environment Agency monitoring station was positioned close to the well but in a different direction, so as to provide upwind-downwind measurements, and thereby maximise the value of measurements.

Data availability for these 2 data sets are set out in Table 2.3.

Table 2.3: Air quality monitoring data availability at Kirby Misperton site

Data collector	Pollutant	Time-period	Averaging time
BGS	AQ (PM total, PM_{10}, PM_4, $PM_{2.5}$, PM_1MC, particle count, NO, NO_2, NOx)	Jan 2016 to Dec 2017	One-min

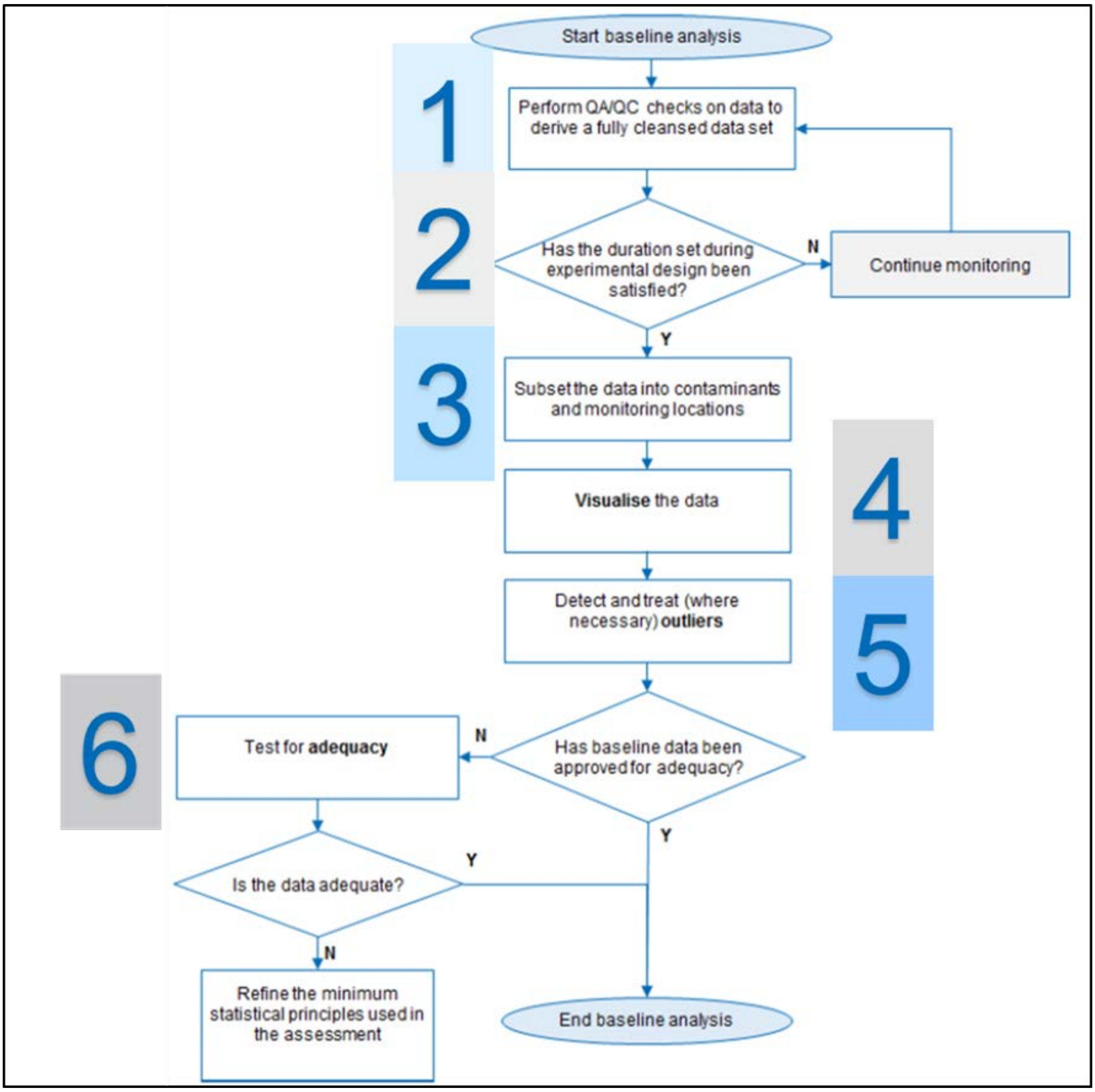
Data collector	Pollutant	Time-period	Averaging time
BGS	Greenhouse gases (CO_2, CH_4)	Jan 2016 to Jun 2017	One-min
BGS	VOC (ethane, ethene, propane, propene, isobutane, n-butane, acetylene, isopentane, n-pentane, isoprene, benzene, toluene)	Jan 2016 to Apr 2018	Weekly grab sample
Environment Agency	AQ (PM_{10}, $PM_{2.5}$, NOx, NO, NO_2, H_2S) & CH_4	Aug 2017 to Oct 2018	5-min
Environment Agency	VOC (BTEX)	Aug 2017 to Oct 2018	30-min

2.6 Air quality example: nitrogen dioxide and methane measured at BGS monitoring station, Kirby Misperton

In the guidelines developed in the project on assessing the statistical significance of change[4], establishing baselines was considered not as a distinct, separate step, but informed by and integrated within the monitoring design phase and reviewed within the operational phases. The guidelines that explicitly referenced establishing baselines were represented in a diagram in the original text (Diagram 2 – ‘Decision tree for statistical analysis of data for establishing a baseline at OOG sites’). This has been replicated and aligned with a series of stages (labelled 1 to 6) in Figure 2.5.

Stages 1 to 3 are not pollutant-specific, and apply to both nitrogen dioxide and methane. Stages 4 to 6 are then described for nitrogen dioxide and methane.

Figure 2-5: Data analysis procedure



2.6.1 Stage 1: Quality assurance/quality control (QA/QC) checks

The first stage is to perform QA/QC checks on the data set. This step removes data that is deemed invalid due to equipment malfunction. Examining the data provided, it became clear that the data had already been through the QA/QC process. In the BGS data set this is made evident by providing data quality flags. The concentration data that was highlighted as being of insufficient quality were removed.

2.6.2 Stage 2: Monitoring duration and on-site activities

The second stage is to define main activities and significant phases within the baseline data set, so the duration of monitoring during the baseline phase can be checked. Using activity data that was available, it was possible to determine when activity began on site. The quality of site activity data was not of sufficient temporal resolution, and did not provide enough detail on site activities to allow further useful insight into the type of activity that was performed on site. Activities at the site in relation to shale gas exploration began on 25 September 2017. As a result, this date was used as a cut off for the baseline period. Further analysis of baseline survey duration is provided in section 2.6.9.

2.6.3 Stage 3: Subset the data into contaminants and monitoring locations

At this stage, all pollutants listed in Table 2.3 were considered to decide whether they should be excluded from further analysis. A subset of pollutants was selected as there were a number of pollutants for which data was provided. Other substances that were excluded from analysis because of the lack of established air quality standards and guidelines were PM_{Total}, PM_4, PM_1, and particulate count.

2.6.4 Stage 4: Visualise the data

This example section considers nitrogen dioxide and methane as examples of the analytical approach, using the BGS data set. Further information on the other pollutants is provided in Appendix 1.

2.6.4.1 Nitrogen dioxide

The BGS data set for NO_2 considered in this application example was provided at one-minute intervals. The guidelines for temporal averaging covered data from one hour upwards. No consideration was given to data collected at sub-hourly intervals. Data was therefore initially averaged to one hour (Figure 2.6 and Figure 2.7). With a large number of peaks in hourly mean concentrations, and large amounts of noise in the hourly data, a daily averaging period was also applied (Figure 2.8).

The outliers in the box-whisker plot Figure 2.7 highlight the variability of the data at an hourly averaging period. Comparing Figure 2.7 and Figure 2.8 shows that hourly averaged data has many more outliers than daily averaged data. Any erroneous data has already been removed from these data sets during the QA/QC processes, and therefore these outliers represent valid measurements that demonstrate the variability within the data. The periods with the highest average concentrations were found to have a greater number of outliers.

There was an apparent uplift in NO_2 levels at the end of September 2017 (Figure 2.7), which commences around the time that on-site activity began. A similar uplift was observed in October 2016. The final baseline does not include the uplift that occurred from late September, as it comes after activity began on site (25 September 2017). It should be noted that, as NO will convert to NO_2 at a distance, it is important to consider NOx as well as NO_2.

Figure 2-6: Time series plot of hourly averaged NO_2 data collected by BGS at Kirby Misperton

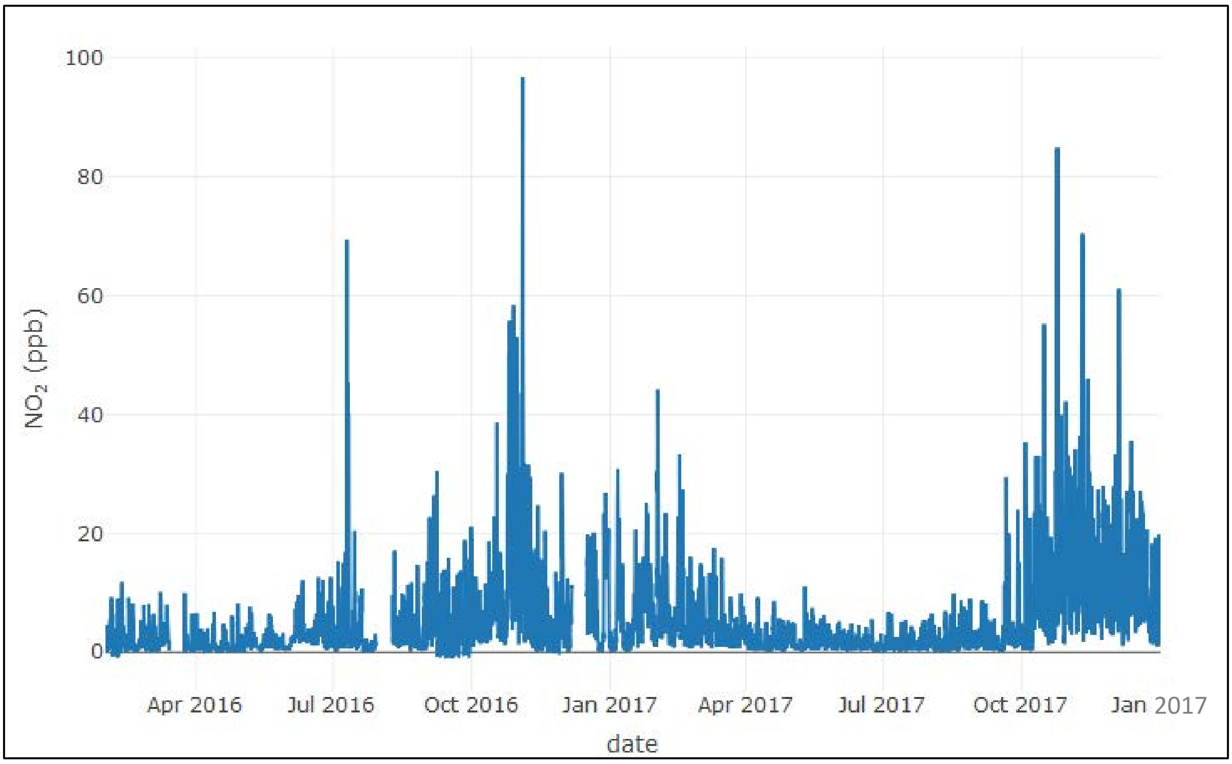
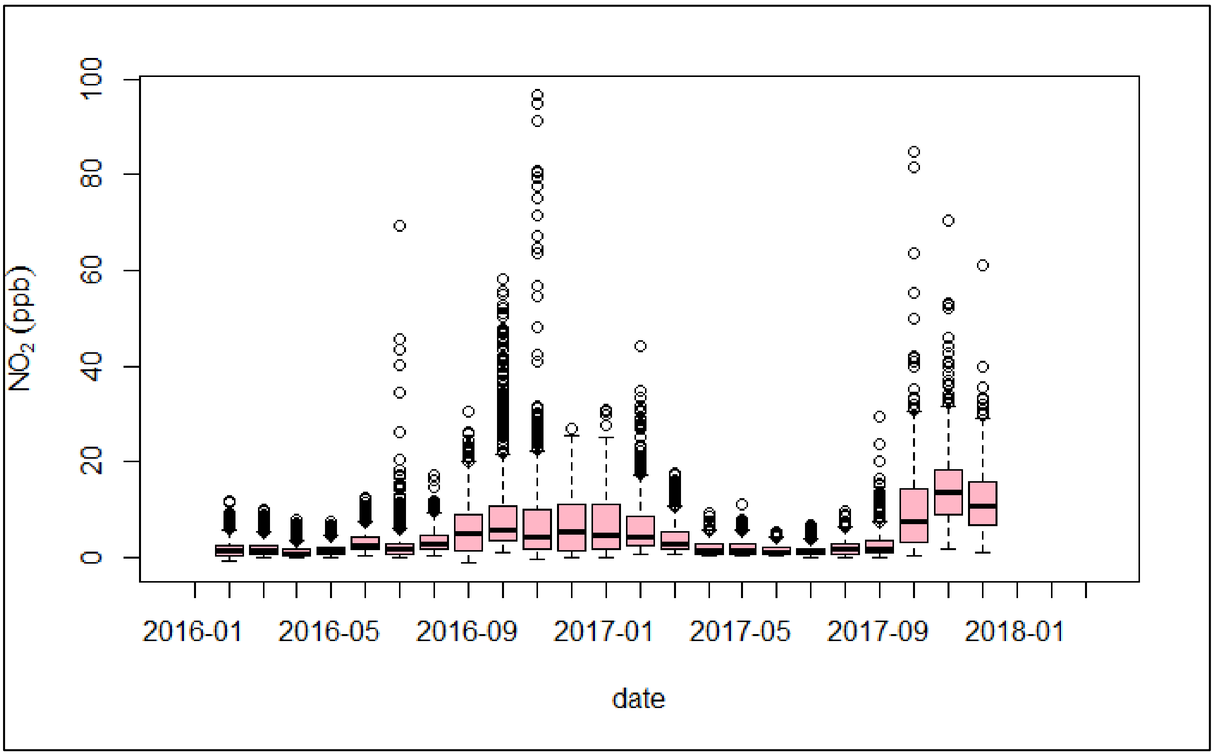
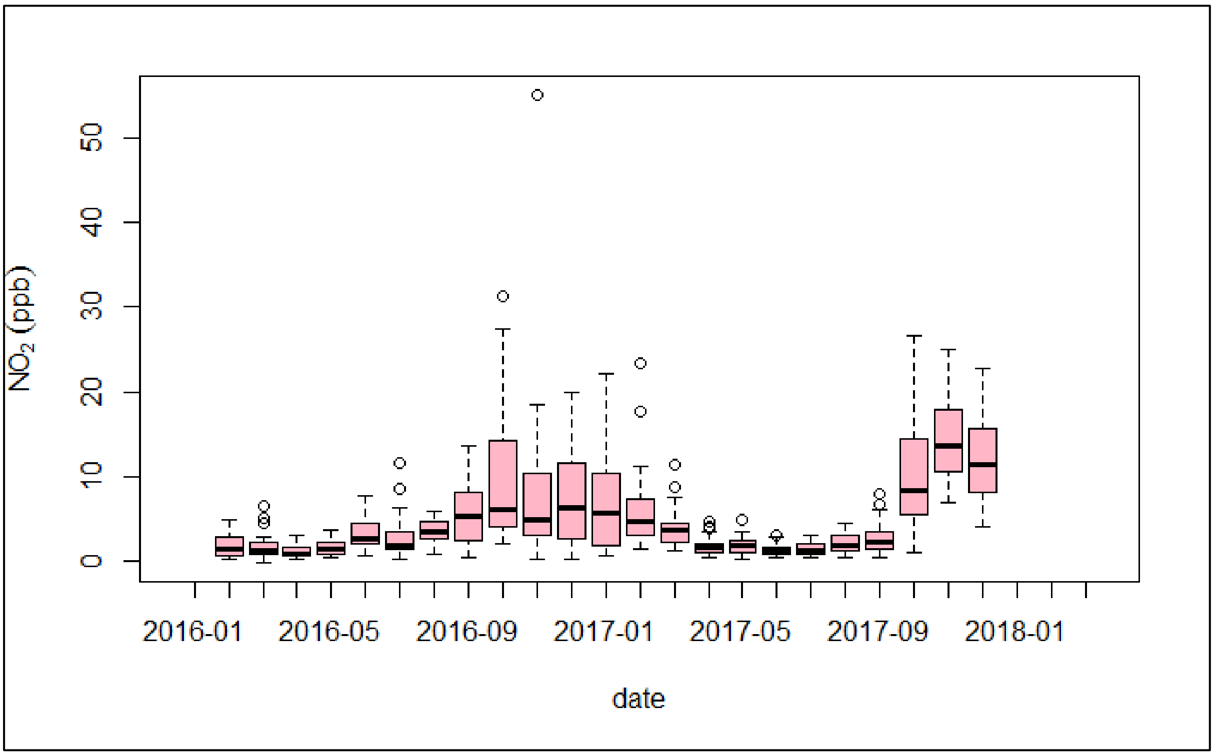


Figure 2-7: Box plot of hourly NO_2 data by month-year collected by BGS at Kirby Misperton



Note: Whisker markings set at 1.5× interquartile range

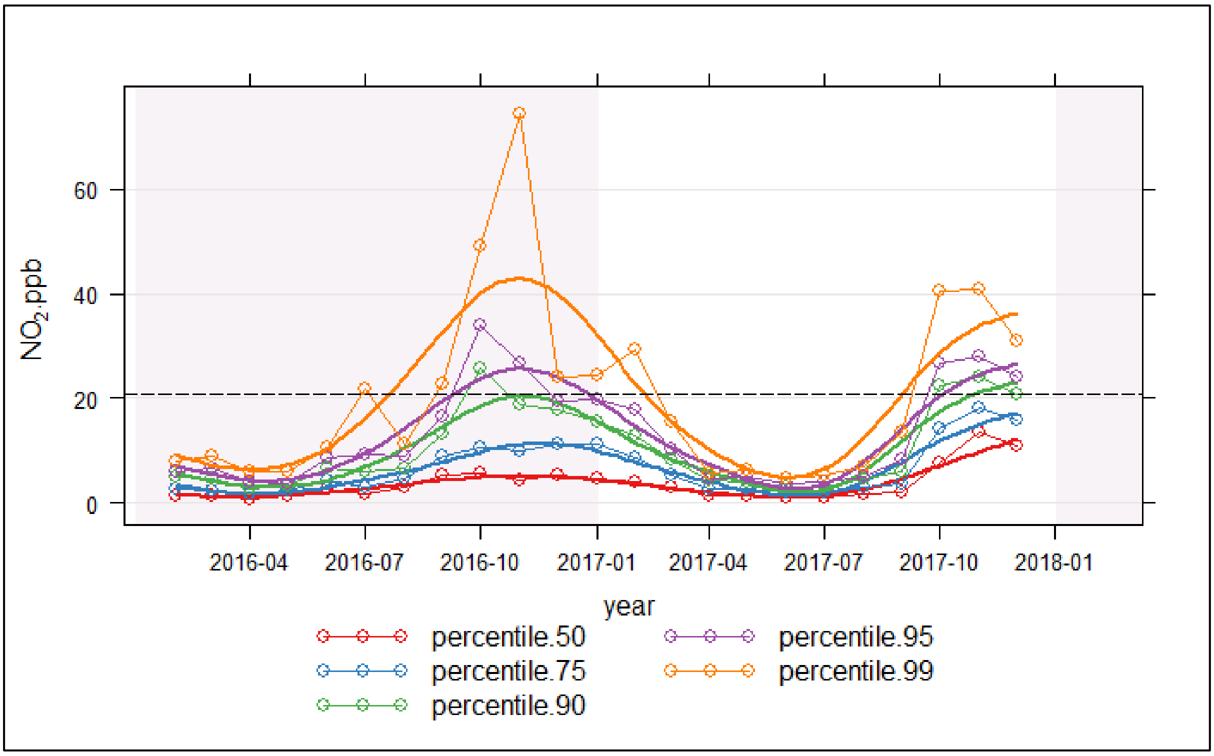
Figure 2-8: Box plot of daily NO_2 data by month-year collected by BGS at Kirby Misperton



Note: Whisker markings set at 1.5× interquartile range

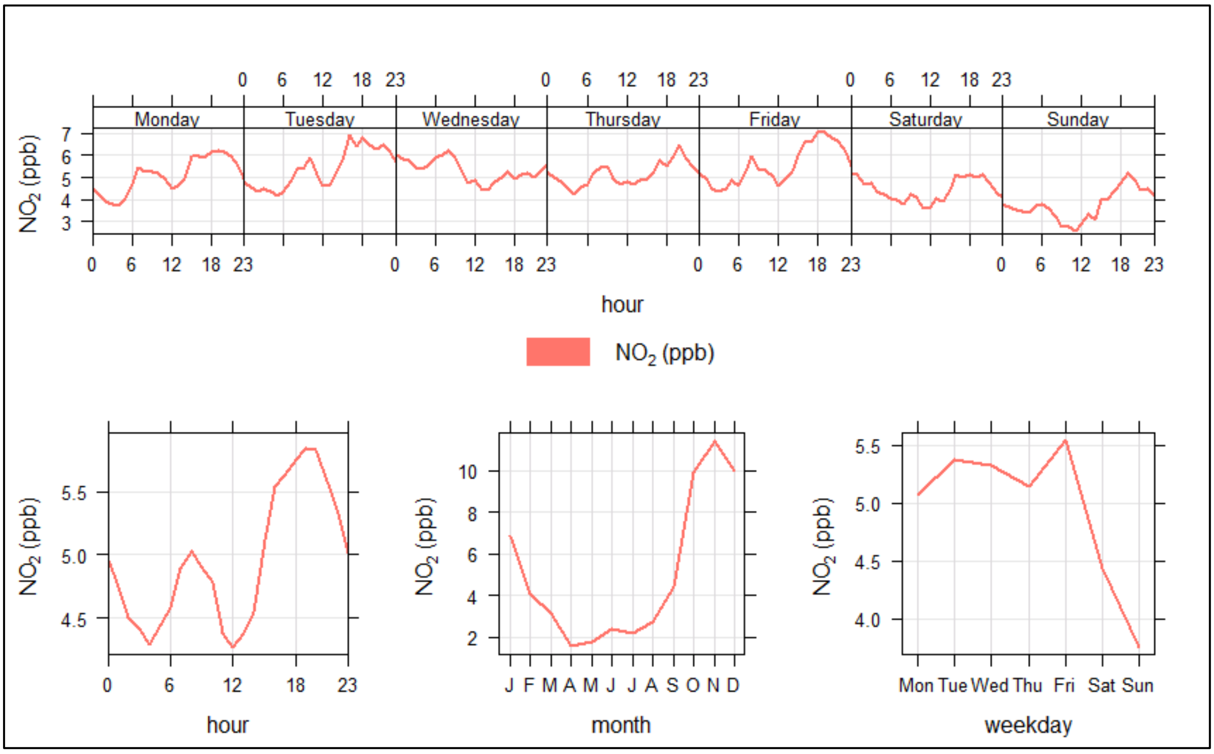
To better understand the trends at this 'data visualisation stage', some functions in the OpenAir package of tools for air quality analysis[10] were used. Applying the SmoothTrend function for calculating time series trends to percentiles, and time variation plots, were found to be particularly useful in understanding temporal trends within the data (Figure 2.9 and Figure 2.10). These plots show that NO_2 has a number of different temporal profiles on a daily, weekly and monthly basis (weekday versus weekend differences, commute hour differences, and winter highs, summer lows).

Figure 2-9: Smoothed trend of monthly averaged NO_2 data collected by BGS at Kirby Misperton (see accompanying text for interpretation)



Note: Shading is used to distinguish calendar years

Figure 2-10: Time variation plot to show different temporal variations of mean NO_2 data collected by BGS at Kirby Misperton

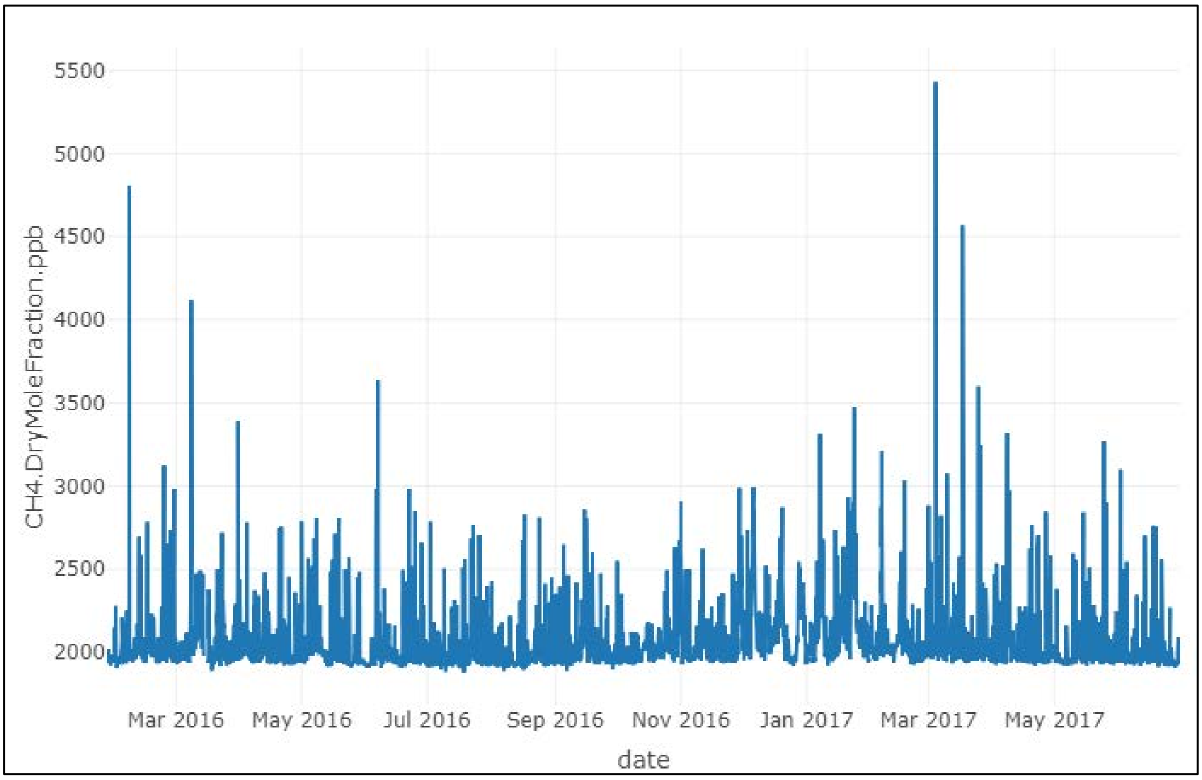


2.6.4.2 Methane

Data were averaged to one hour (Figure 2.11).

There was an apparent uplift in methane levels during March to April 2017 (Figure 2.11). This does not coincide with any known incidents or changes in activity at the site, and no shale gas activities were taking place at the time. However, the Kirby Misperton site is an active gas production site. Fluctuations in fugitive methane emissions from ongoing activities at the site are conceivable, and could account for the higher levels of methane observed at the site at this time.

Figure 2-11: Time series plot of hourly averaged methane data collected by BGS at Kirby Misperton

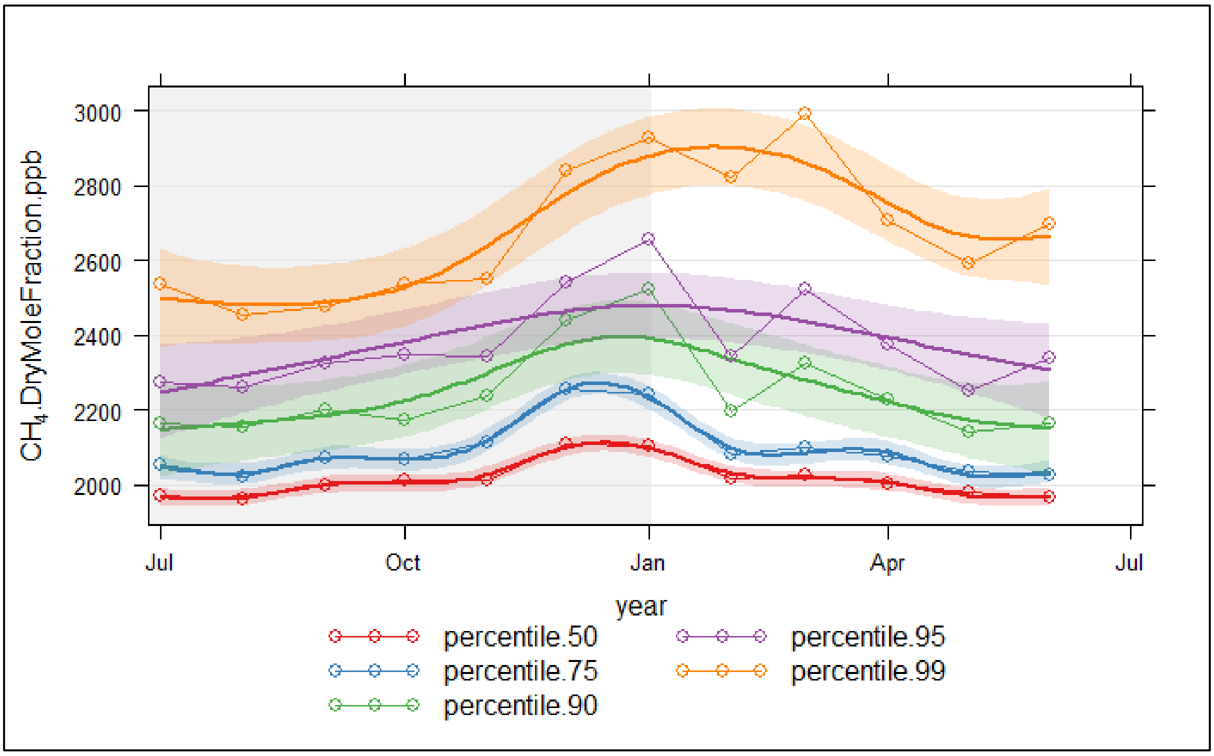


To better understand the trends, at this 'data visualisation stage', some functions in the OpenAir package of tools for air quality analysis were used. Applying the SmoothTrend function for calculating time series trends to percentiles, and time variation plots, were found to be particularly useful in understanding temporal trends within the data (Figure 2.12 and Figure 2.13). These plots show that methane has a number of different temporal profiles on a daily, weekly and monthly basis, although differences are relatively small.

- Methane levels are higher overnight than during the day. This is likely to be related to reduced dispersion at night-time due to lower wind speeds and atmospheric turbulence, as well as potentially linked to lower photochemical activity, resulting in less removal of methane from the atmosphere.
- Methane levels are higher during the winter months than during the summer. This may again be linked to reduced dispersion during the winter, as well as relatively low photochemical activity during winter months. A smaller increase in methane levels in March can also be observed in both these figures.

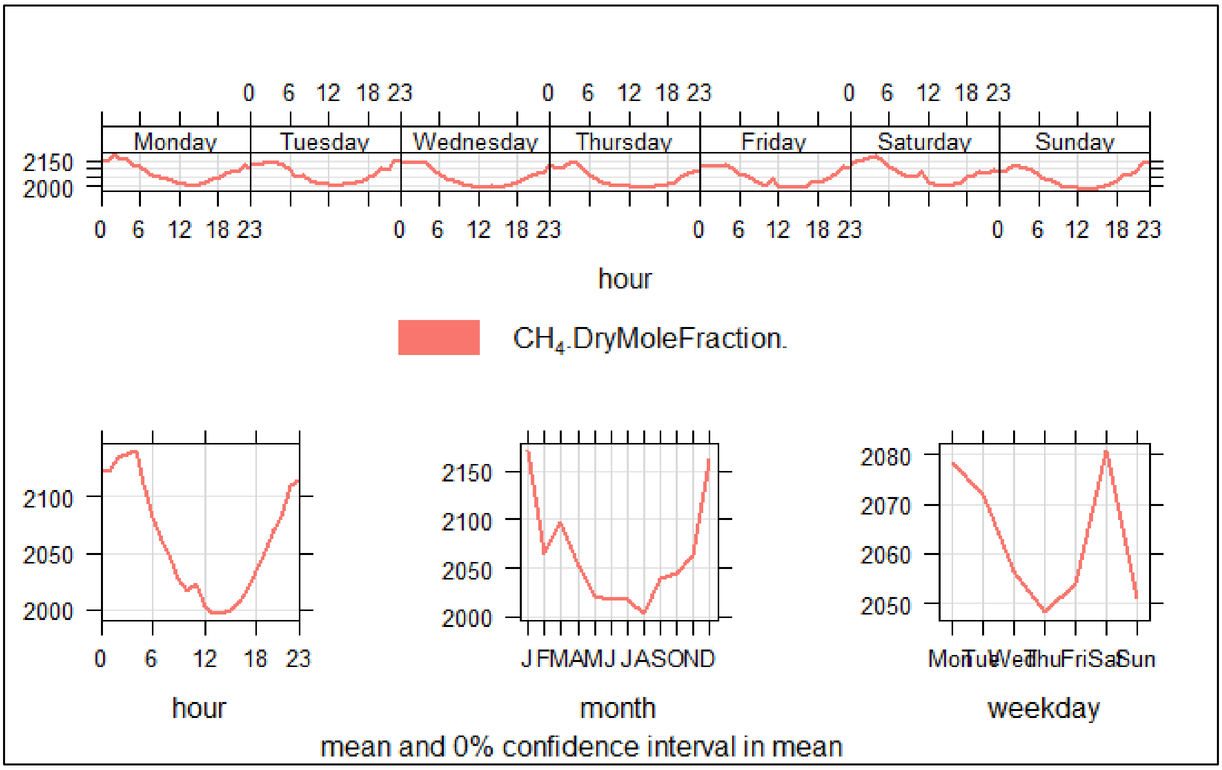
Figure 2-12: Smoothed trend of monthly averaged CH_4 data collected by BGS at Kirby Misperton

A1.45



Note: Shading is used to distinguish calendar years

Figure 2-13: Time variation plot to show different temporal variations of mean CH_4 data collected by BGS at Kirby Misperton (ppb)



2.6.5 Stage 5: Detect and treat outliers

The next step in the guidelines was to detect and treat outliers. The original concept for this approach is to investigate whether outliers may be invalid data that should be removed from the analysis. However, for air quality data, removing invalid data is carried out at stage 1 (QA/QC checks). Outliers are commonly encountered in air quality monitoring data sets, and do not normally indicate invalid data.

Outliers are identified at stage 4 (Visualise the data). Stage 5 is investigating the outliers detected in stage 4 (highlighted in Figure 2.7 and Figure 2.8). Examining the commonalities that outliers have can indicate local sources. Outliers could occur on a single day due to a short-lived local emission event. Outliers could occur during specific wind conditions highlighting a local source.

2.6.6 Stage 6: Test for adequacy

The final stage identified on Figure 2.5 was to carry out a test for adequacy. This was more relevant to water quality data, where temporal resolutions are generally low and was suggested as a way of assessing confidence in baselines for future use. Testing for adequacy with air quality data began with testing the distribution of the data. The results of distribution testing showed that the data did not belong to any known distribution.

2.6.6.1 Nitrogen dioxide

The distribution appeared visually to be close to a log-normal distribution (Figure 2.14), but under statistical testing failed to match a log-normal distribution (Table 2.4).

Figure 2-14: Histogram for hourly averaged NO_2 data collected by BGS at Kirby Misperton

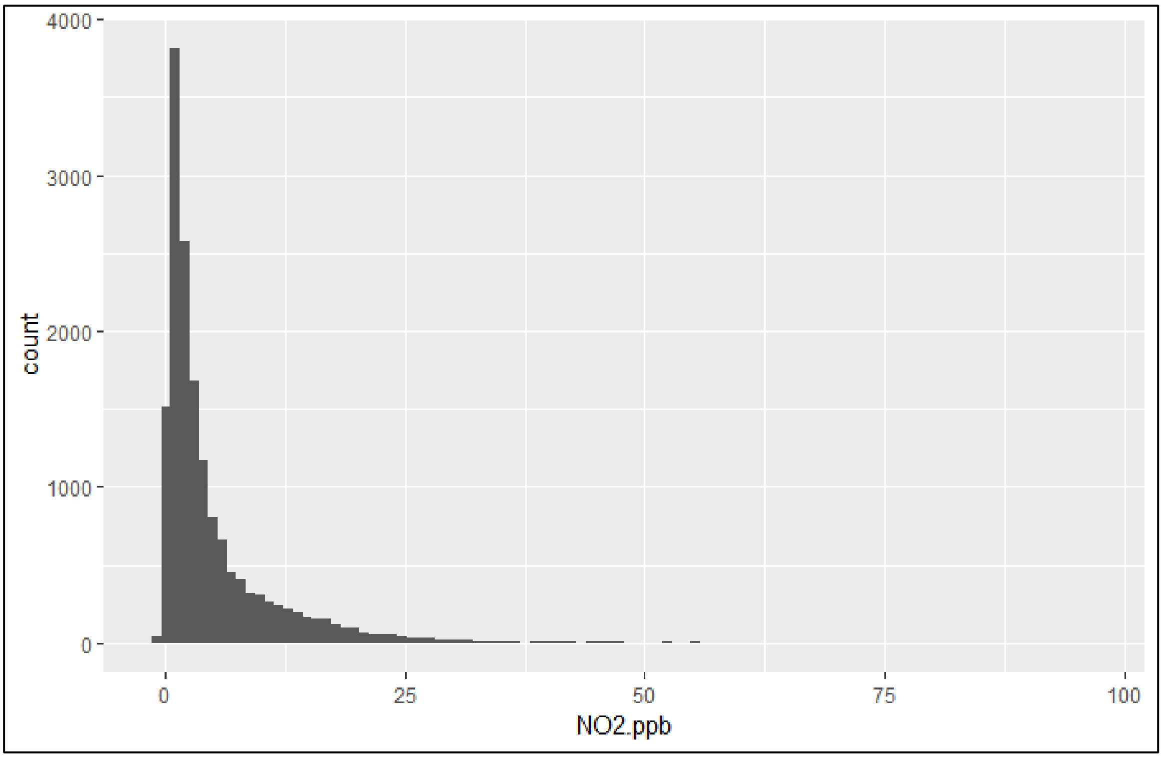


Table 2.4: Distribution testing for hourly averaged NO_2 data collected by BGS at Kirby Misperton

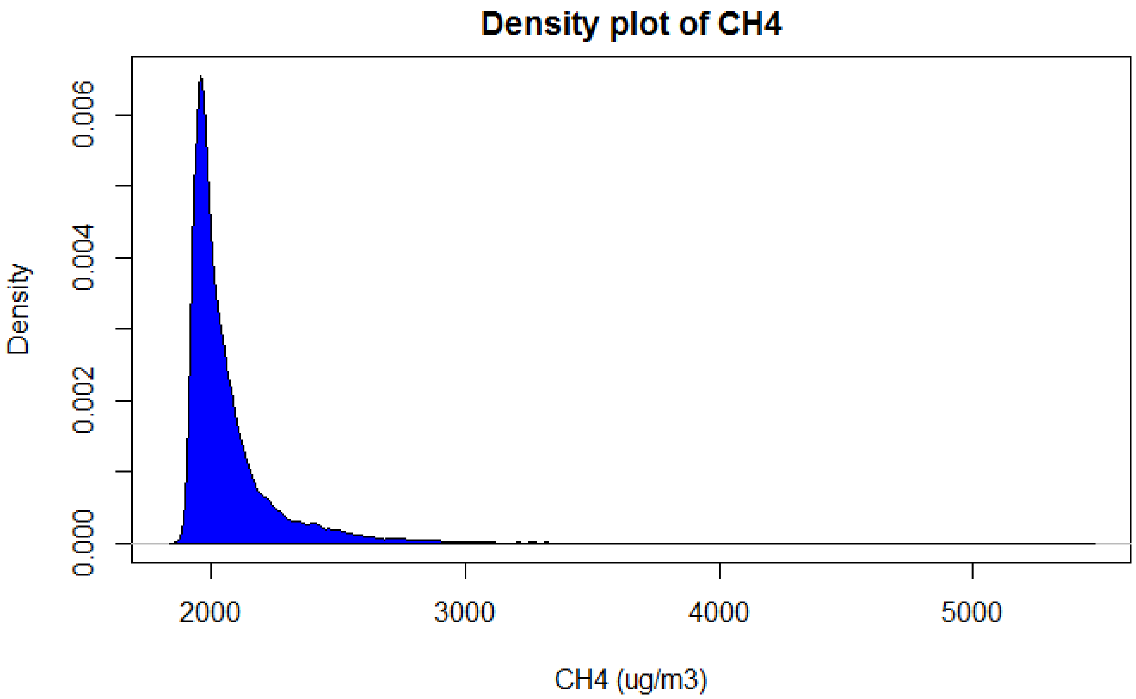
Pollutant	Normal	Logis	Lognorm	Gamma	Weibull
NO_2	0.22	0.21	0.22	0.22	0.41

The d-values returned from the Kokmogorov-Smirnov statistic test are shown in Table 2.4. The hypothesis for each distribution is rejected at the chosen significance level (alpha) if the d-value is greater than the significance level. For instance, if a d-value of 0.08 is returned, at a significance of 0.05 the distribution would be rejected, however the distribution would be accepted at a significance of 0.1. Table 2.4 shows that at a significance value of 0.05, all distributions would be rejected. Indeed, even at a much less demanding significance value of 0.2, all distributions would be rejected.

2.6.6.2 Methane

The distribution of CH_4 also appeared visually to be close to a log-normal distribution (Figure 2.14), but did not match a log-normal distribution when tested.

Figure 2-15: Density plot for hourly averaged CH_4 data collected by BGS at Kirby Misperton



2.6.6.3 Conclusion

Following investigation on real-world data sets, it was found that testing for adequacy did not provide useful insights or tools for data analysis. It is therefore proposed to remove testing for adequacy from the recommended procedure for air quality data.

2.6.7 Stage 6 (Alternative): Using diagnostic data analysis tools

This section and section 2.6.8 set out alternatives to stage 6 testing for adequacy, which can be applied to air quality data.

Diagnostic data analysis tools have recently become widely available. These can be applied to measured data sets to gain an insight into the likely characteristics of sources that affect the measured levels of air pollutants. A range of tools for extracting insight and information from air quality monitoring data are freely available using the OpenAir package[10].

These tools have previously been used for signal strengthening, that is, to identify and exclude signals that can be reliably identified as being due to other sources. An exploration of signal strengthening was attempted for the Kirby Misperton site. However, due to the rural nature of this site, it was not possible to strengthen the signal using tools available from the OpenAir package, as the local emission sources were not regular. Emissions in this location would only occur for a few days at a time rather than constantly. In other scenarios where relevant sources of emissions are more regular, for example, close to a major road, industrial sources or an urban site, it is recommended that signal strengthening should be considered.

2.6.7.1 Nitrogen dioxide

Using OpenAir tools or similar resources provides a useful insight into measured levels of NO_2 at Kirby Misperton. The polar plot for annual mean concentrations (Figure 2.16 below and Figure A.1.9 in Appendix 1) indicates that the measured concentrations of NO_2 are most strongly influenced by sources located to the south of the site, which affect the site under moderate to high wind speeds. This suggests the influence of sources located some distance from the site, such as traffic on the A64 or potentially power stations located in the Aire Valley to the south of the site. However, the highest concentrations of nitrogen dioxide occur under much lower wind speeds, in particular with winds from the south-west, as shown in Figure 2.17, which shows the concentration of the 99th percentile of different wind conditions. Comparison with Figure 2.2 indicates that the highest peak concentrations may result from more local sources such as operations at the existing onshore oil and gas site.

Figure 2-16: Polar plot of the mean concentration for hourly averaged NO_2 data collected by BGS at Kirby Misperton

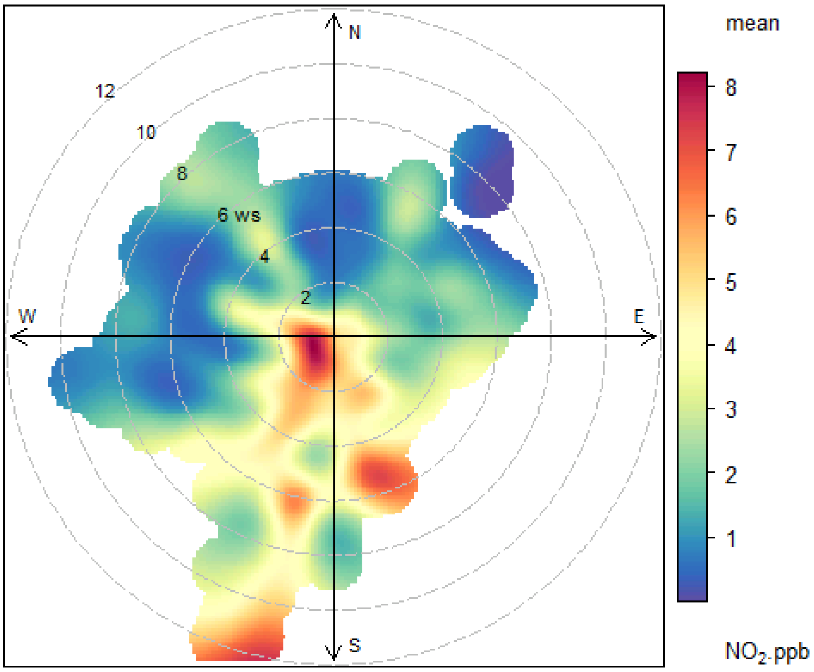
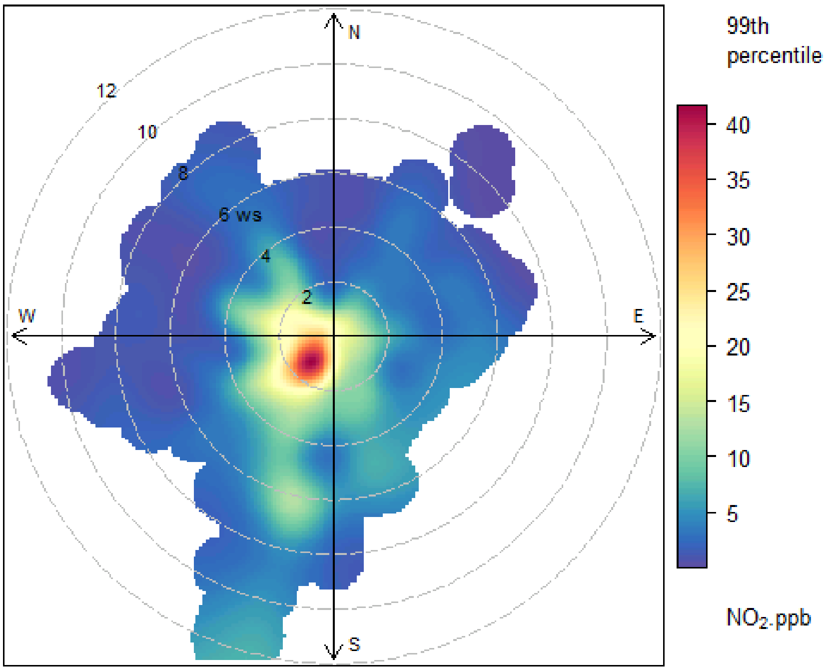
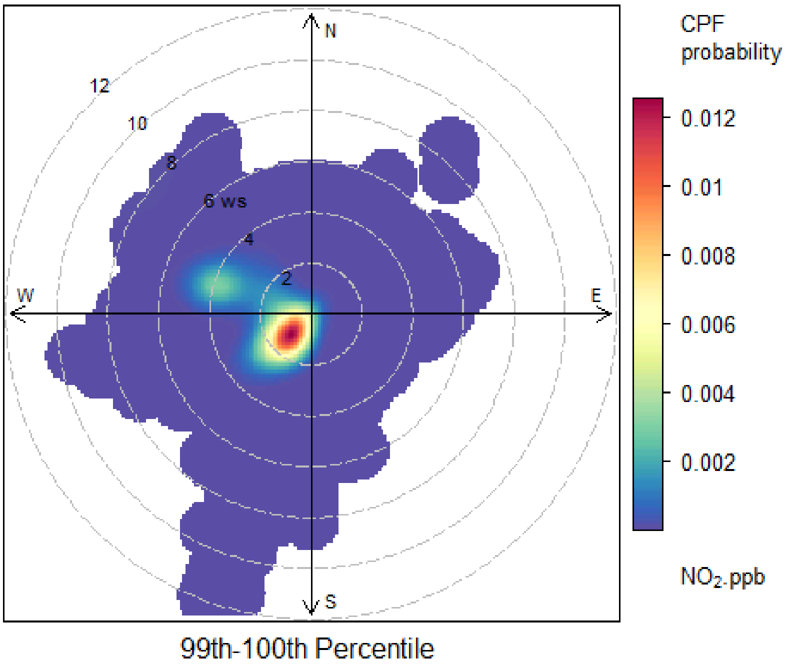


Figure 2-17: Polar plot of the 99th percentile concentration for hourly averaged NO_2 data collected by BGS at Kirby Misperton



Conditional probability plots show the probability that a concentration between 2 percentile values will occur for that wind condition. These plots are useful to understand how common high concentration events are, and therefore the frequency of high emission events. Figure 2.18 shows that the top 1% of concentrations are likely to come from the south-west with low wind speeds. There is also another source that has the highest 1% of concentrations west-north-west, with wind speeds of around 4 m/s. These plots can be used for comparison during the operational phase to highlight any new sources that contribute to the highest concentrations recorded at the site.

Figure 2-18: Polar plot of the conditional probability falling between the 99th and 100th percentile for different wind speeds and wind directions for hourly averaged NO_2 data collected by BGS at Kirby Misperton



2.6.7.2 Methane

The polar plot for annual mean CH_4 concentrations (Figure 2.19 below) shows low variability in methane levels above the natural background level. The highest levels of CH_4 occur under very low wind speed conditions, which may indicate a nearby low-level source. This would be consistent with a relatively small-scale source of methane such as the ongoing gas extraction activities at the KM site.

The 99th percentile polar plot indicates that the highest levels of methane are also linked to a nearby source. This plot further suggests that there may be another source located to the west of the KM site, which makes a smaller, but still detectable, contribution to methane levels under moderate wind speed conditions.

Figure 2-19: Polar plot of the mean concentration for hourly averaged CH_4 data collected by BGS at Kirby Misperton (ppb)

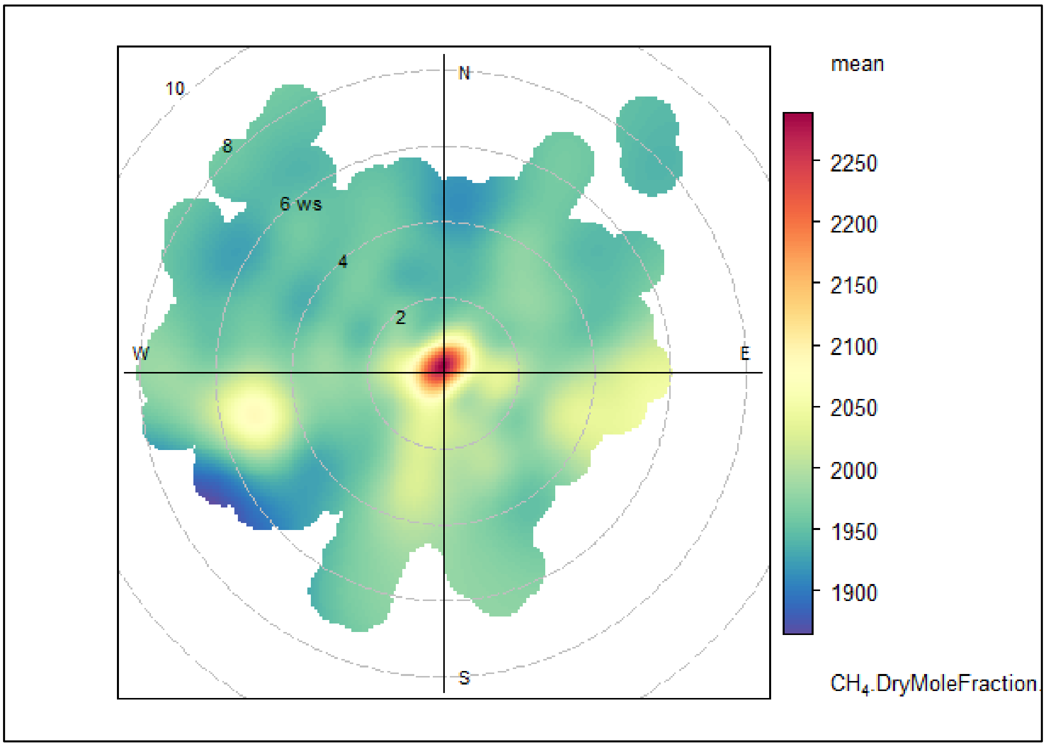
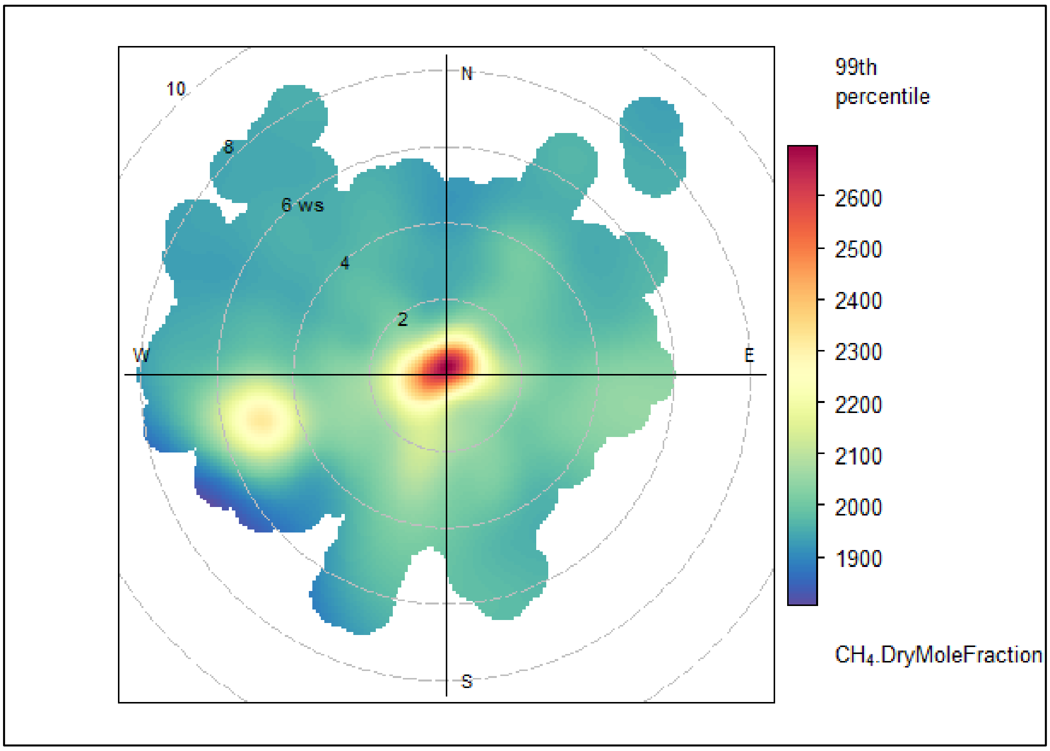


Figure 2-20: Polar plot of the 99th percentile concentration for hourly averaged CH_4 data collected by BGS at Kirby Misperton (ppb)



Conditional probability plots show the probability that a concentration between 2 percentile values will occur for that wind condition. These plots are useful to understand how common high concentration events are, and therefore the frequency of high emission events.

Figure 2-21. Polar plot of the conditional probability falling between the 99th and 100th percentile for different wind speeds and wind directions for hourly averaged CH_4 data collected by BGS at Kirby Misperton

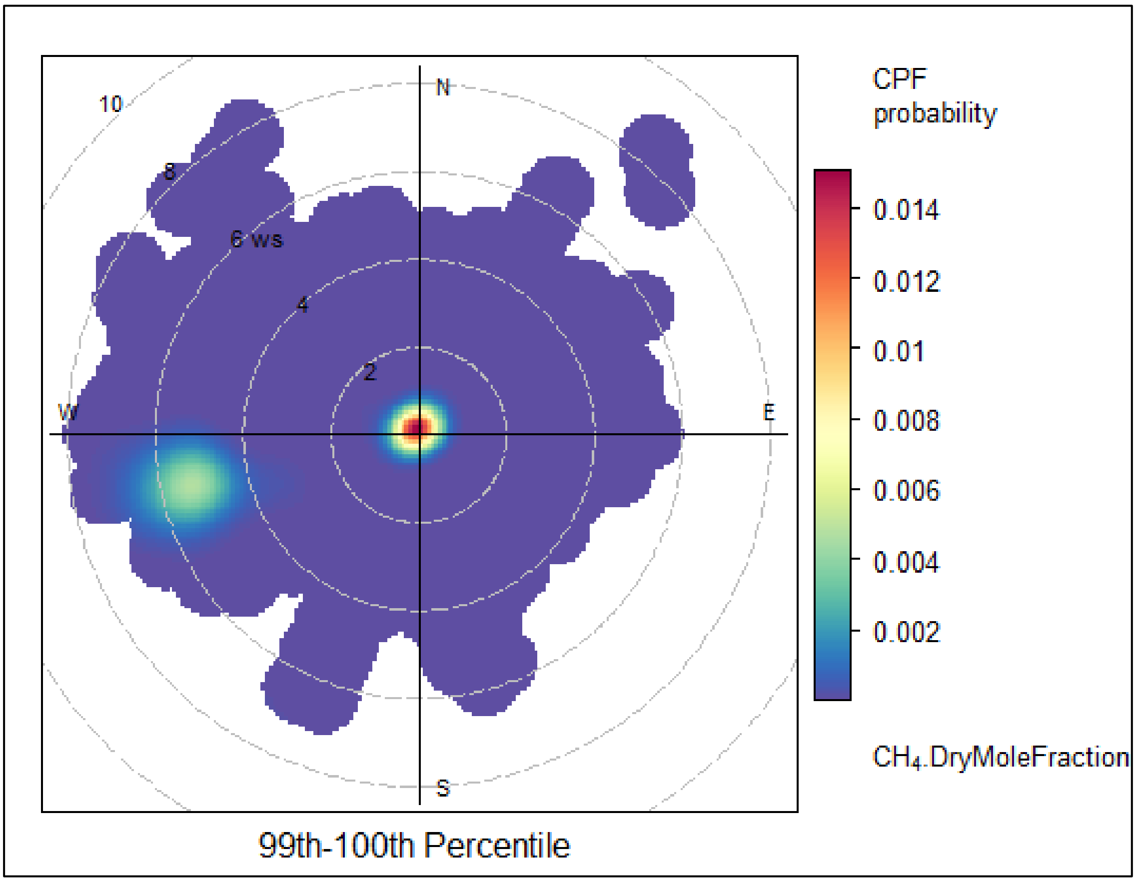


Figure 2.21 again highlights the near-field source of higher levels of methane, together with another less significant source located to the west of the KM site. Land uses in this direction are predominantly rural, with no obvious sources of methane. Potential sources might include landfill sites, composting/anaerobic digestion facilities or other onshore oil and gas activities. Intensive livestock activities could potentially result in methane emissions if, for example, animal manures are left to decompose anaerobically. If required, further investigation could be carried out to discover if potential sources of methane can be identified to the west of the KM site.

2.6.7.3 Conclusion

The study has shown that there are certain distinct, but sporadic dispersion and air quality impact features that occur in each data set. These features could be 'mapped' and described as 'baseline features', which could be referred to during later monitoring in order to:

- rule out existing features such as evidence of changes
- spot any new features that are products of change

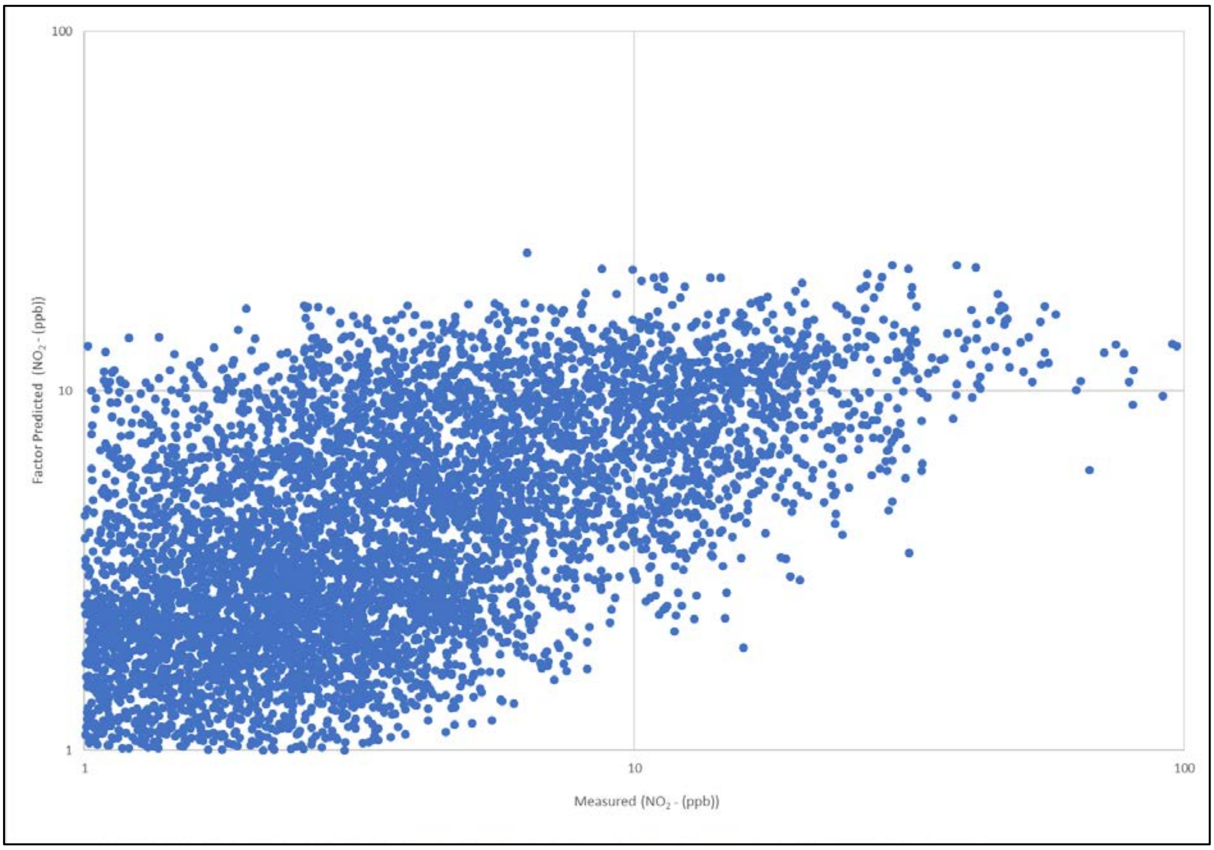
2.6.8 Stage 6 (Alternative): Factorisation approach

A second alternative approach to adequacy testing and diagnostic data analysis was suggested in Environment Agency (2019b). This report proposed using a 'factorisation approach'. This approach was designed to identify consistent variations in past concentrations that depended on measurable factors such as wind speed. Concentrations are normalised to remove these variations, leaving only variations due to other sources that remain to be investigated. The observation of significant variations in measured levels could be used as a trigger for further investigation of activities at the site.

A factorisation approach was trialled on the Kirby Misperton site using hourly averaged BGS data. A factor was assigned based upon both meteorological conditions (wind speed and wind direction) and on temporal factors (day of week, hour, month). These factors were generated by dividing the category average by the overall average. For example, NO_2 concentration on Monday divided by NO_2 concentration across all days. This methodology generated 5 individual factors (wind speed, wind direction, hour, day of week and month), which, when multiplied by the average, would provide a predicted value.

A test of this methodology can be seen in the logarithmic graph (Figure 2.22). The factorisation methodology does not provide a very robust method for predicting concentrations under given temporal and meteorological conditions. Ambient concentrations are determined mainly by emissions and meteorology. These factors were an attempt to categorise meteorology (wind speed and wind direction) and emissions (hour, day of week, month), but, in a rural setting, the emissions cannot be categorised using temporal profiles. Consequently, it was found that the lack of regular local emission sources contributed to the unsatisfactory performance of the factorisation approach in practice. If such a system were to be used in practice, it would trigger a large number of false readings, which would actually be due to the effects of other factors that result in unpredictability in measured levels of airborne pollutants. This would mean further investigation would be needed at the site.

Figure 2-22: Scatter-plot examining the potential to use factorisation as a method of predicting concentrations. Figure has a logarithmic scale and uses hourly averaged data for NO_2 at Kirby Misperton using BGS collected data



2.6.9 Test for baseline duration

Comparisons of different baseline survey lengths were also carried out. The first comparison was over the length of the baseline. The assessment uses 25 September 2017 as the date that activity began on site. The complete data column includes data before and after this date over the entire length of the data available (January 2016 to December 2017). From Table 2.5, it can be seen that there are differences when looking at different lengths of time for a baseline and, therefore if a length of time other than one year was chosen, a different result would be found. This is due to the seasonal aspect of ambient concentrations.

Table 2.5: Comparison of different lengths of baseline for NO_2 concentrations in (ppb) at Kirby Misperton for the BGS data

Metric	Complete data	All data before 25 Sept 2017	1 year before 25 Sept 2017	6 months before 25 Sept 2017	3 months before 25 Sept 2017
Median	2.81	2.08	2.36	1.42	1.39
Mean	4.95	3.80	4.46	1.95	1.95
Upper quartile	6.19	4.31	4.98	2.62	2.52

The full extent of the differences that could occur with just a 6-month baseline can be seen in Table 2.6. The differences can be highlighted when comparing March to September 2017 with September 2016 to March 2017. The former 6-month period has a median and mean of 1.67 and 1.91 respectively, whereas the later 6-month period has a median and a mean of 4.87 and 7.23 respectively.

Table 2.6: Comparison of different 6-month baselines for NO_2 (ppb)

Metric	Mar 2017 - Sep 2017	Feb 2017 - Aug 2017	Jan 2017 - Jul 2017	Dec 2016 - Jun 2017	Nov 2016 - May 2017	Oct 2016 - Apr 2017	Sep 2016 - Mar 2017	Aug 2016 - Feb 2017	Jul 2016 - Jan 2017	Jun 2016 - Dec 2016	May 2016 - Nov 2016	Apr 2016 - Oct 2016	Mar 2016 - Sep 2016
Median	1.67	1.76	2.11	2.43	2.98	4.30	4.87	5.44	4.54	4.49	3.85	2.77	2.14
Mean	1.91	2.19	3.26	4.14	4.73	6.55	7.23	7.29	6.60	6.13	5.48	3.62	2.80
Upper quartile	2.43	2.74	3.86	4.77	6.01	8.51	9.91	10.24	8.29	7.02	6.21	4.67	3.67

Even when one-year baselines are considered, there can still be some differences, which are highlighted in Table 2.7. The differences here are much smaller than the 6-month comparison. These differences highlight inter-year differences in either emissions or meteorology.

Table 2.7: Comparison of different one year baselines for NO_2 (ppb)

Metric	Sep2016-Sep2017	Aug2016-Aug2017	Jul2016-Jul2017	Jun2016-Jun2017	May2016-May2017	Apr2016-Apr2017	Mar2016-Mar2017
Median	2.36	2.48	2.61	2.80	2.95	2.91	2.73
Mean	4.46	4.69	4.84	5.02	5.12	5.10	5.01
Upper quartile	4.98	5.53	5.82	6.03	6.20	6.20	6.14

It is therefore concluded that a baseline of one year should be taken up to the date when site preparation begins. An example of baseline results obtained from a full year dataset can be found in Appendix 1, with data analysed for one year between 25 September 2016 and 25 September 2017.

2.6.10 Recommendations for baseline data summary

To fully understand the baseline data, it is important to understand both longer timescale trends and shorter events. This will help with making comparisons during the operation phase. A comparison of the baseline data set as described in 2.6.11 would allow for improvements in understanding of the causes of changes in baseline data (referred to as 'change attribution'). Local sources need to be considered together with meteorological data, as air quality data is strongly influenced by meteorology. The original guidelines acknowledged that wind plots and frequency plots could provide valuable information on local sources. A number of different polar plots using different metrics can provide valuable insight into local sources.

The typical distribution of air quality data, with a small number of relatively high values, means that reporting a range of percentile values typically provides a more useful description of data than mean concentration values. Considering percentile concentration plots may be particularly useful for detecting changes in baseline conditions early, especially in circumstances where the changes are quite marked. Considering higher percentiles may be particularly effective in highlighting the contribution of local sources.

It is recommended that a number of different metrics should be used to fully analyse the data. Weighted mean concentrations, conditional probability functions, percentile plots and averages can all be used to provide a robust description of baseline conditions.

- Percentile plots and averages – show the percentile or average concentration for different wind speed and direction conditions. These plots are useful for quickly understanding the factors likely to contribute to long-term mean concentrations, and the factors that contribute to the unusual events that result in the highest short-term exposures. Consequently, it is recommended that polar plots for average and higher percentile concentrations are used for routine data reporting.
- Weighted mean concentrations – show how different wind speed and directions contribute to overall concentrations. Low frequency events have less influence on the overall concentrations than high frequency events. These can be useful for diagnostic analysis, but are not recommended for routine data reporting.
- Conditional probability functions – show the likelihood of a concentration between 2 percentiles to come from certain wind speed wind directions. This can highlight wind conditions that lead to the highest concentrations. These can be useful for diagnostic analysis, but are not recommended for routine data reporting.

2.6.11 Conclusions

It was concluded that a summary of baseline conditions should include:

- summary statistics
- wind sector analysis using polar plots for average and higher percentile concentrations (for example, 75th percentile, 90th percentile, 95th percentile and 99th percentile)
- distribution
- time series

This information for NO_2 and CH_4 (together with the other pollutants) is provided in Appendix 1 section A1.1.

2.6.11.1 Nitrogen dioxide

- Table A1.1 sets out summary statistics
- Figure A1.1 provides a density plot for hourly mean nitrogen dioxide concentrations
- Figure A1.2 provides a one year time series for hourly mean nitrogen dioxide concentrations
- Figure A1.3 provides a one year time series plot for different percentile values
- Figure A1.4 provides a time variation plot for hourly mean nitrogen dioxide concentrations

- Figures A1.5 to A1.8 provide conditional probability plots of hourly mean nitrogen dioxide concentrations
- Figures A1.9 to A1.16 provide polar plots of hourly mean nitrogen dioxide concentrations
- Figure A1.17 provides a density plot for hourly mean nitrogen dioxide concentrations, showing the periods before and after site activities began

2.6.11.2 Methane

- Table A1.5 sets out summary statistics
- Figure A1.35 provides a density plot for hourly mean methane concentrations
- Figure A1.36 provides a one year time series for hourly mean methane concentrations
- Figure A1.37 provides a one year time series plot for different percentile values
- Figure A1.38 provides a time variation plot for hourly mean methane concentrations
- Figures A1.39 to A1.42 provide conditional probability plots of hourly mean methane concentrations
- Figures A1.43 to A1.50 provide polar plots of hourly mean methane concentrations

2.6.11.3 Overall conclusions

Suggested revisions to the guidelines in the report on assessing the statistical significance of change (Report ref. SC160020) in light of the analysis of data for Kirby Misperton are set out in section 4.

The surveys at Kirby Misperton were not designed in accordance with the guidelines set out in Report Ref. SC160020. However, the surveys were informed by experience of air quality monitoring, and a conceptual model of likely emissions to air from the onshore oil and gas installation at this site.

It is concluded that the one-minute data and subsequent averages collected by BGS at Kirby Misperton provided a satisfactory representation of baseline air quality at the site, bearing in mind the presence of existing onshore oil and gas activity at this location.

Some of the recommended analytical techniques did not give useful information for Kirby Misperton. In particular, the test for adequacy and distribution test was not found to be useful. This reflects inherent issues with air quality monitoring data. It also reflects the nature of the local environment near the Kirby Misperton site, with few consistently emitting sources of emissions to air. This has been taken into account in the recommended updates to the guidelines.

Instead of these techniques, it is recommended that time series plots, percentile plots and conditional probability/polar plots are used to investigate the data in more detail, and to understand the main factors that affect the measured levels of air pollution. These may include local or regional sources of pollution, alongside factors relating to meteorological conditions such as wind speed and wind direction. Daily changes and seasonal factors should also be considered.

2.7 Groundwater and surface water quality

The following water quality data sets were available for Kirby Misperton:

- 11 groundwater boreholes, all operated by Third Energy, from which a total of 16,672 measurements across 125 determinands were reported
- 4 surface water sampling locations, again all operated by Third Energy, from which a total of 4,454 measurements across 120 determinands were reported

The monitoring locations are shown in Figure 2.4.

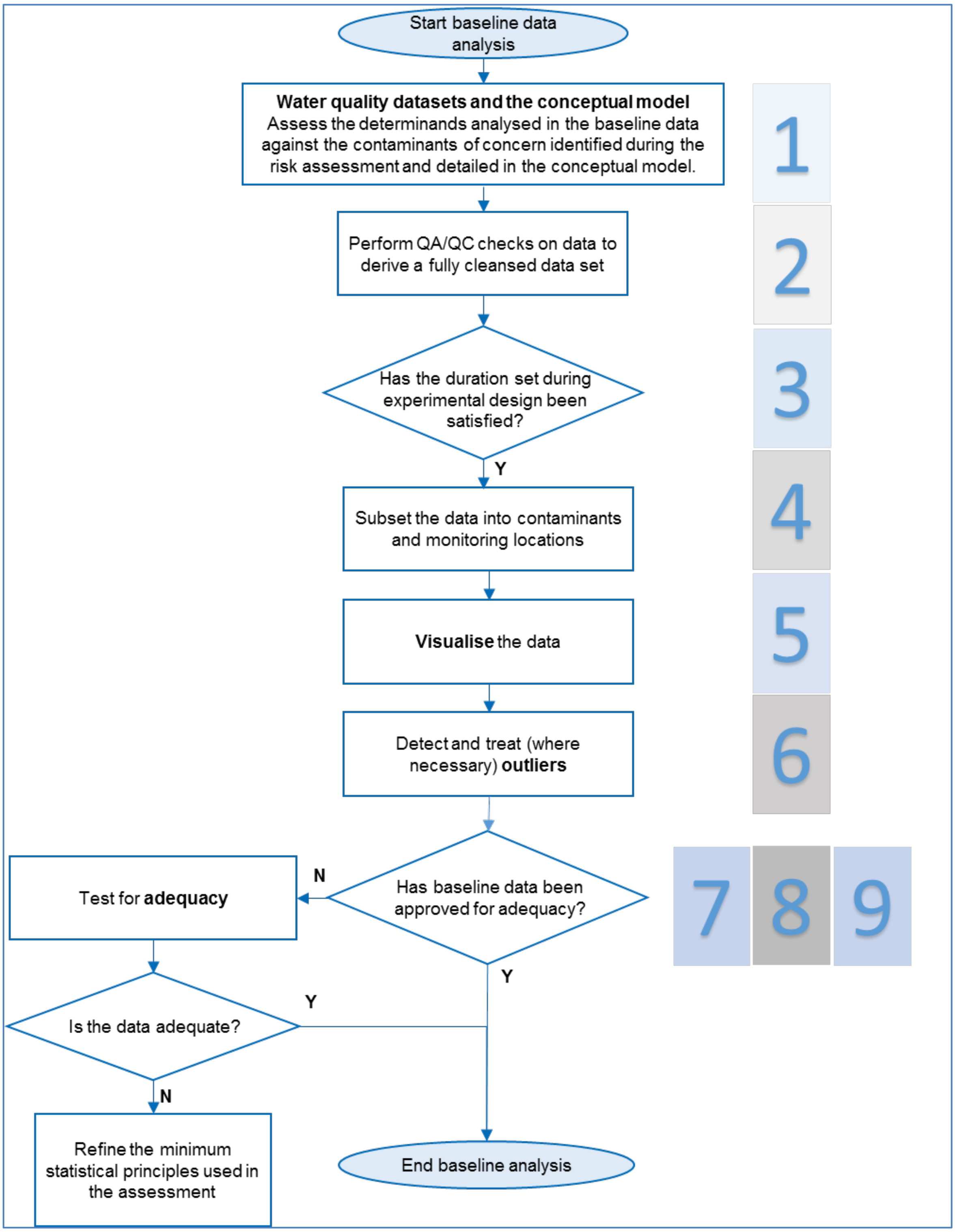
As with air quality, this section represents an example of applying the guidelines to establish a baseline for water quality at Kirby Misperton. Figure 2.23 brings together the relevant parts from the guidelines, including a modified decision tree, aligned to a series of overarching named steps (labelled 1 to 9).

From an initial assessment of the Kirby Misperton data, it was noted that some modifications on the initial design were necessary. These included a need to:

- account for identifying what parameters among large and varied suites of monitored values are of priority interest in assessing baseline characteristics. In the guidelines, it was assumed that parameters would reflect those identified in the conceptual model plus some others that represented low background variability in the natural environment. These are the most likely candidates for proving informative in identifying change (from OOG activities or otherwise). However, data received reflected a much larger quantity of determinands measured than anticipated
- account for changes in source data (for example, laboratories conducting analysis)
- more explicitly consider appropriate grouping categories or determine grouped baseline(s). This was deemed necessary due to the number of individual sites. Appropriate groupings were judged to include those with similar site attributes (for example, site type (groundwater on-site/ off-site or surface water) and depth of borehole)
- add a stage to calculate the percentage of limit of detection values, and include explicit guidance on how to determine 'baseline' if most, or all, values were below a measurement limit
- modify how the conceptual model is integrated into the process of establishing baselines. In the guidelines produced under Report Ref. SC160020, the conceptual model was used to determine which parameters to monitor rather than which parameters to analyse. The need to explicitly consider how to determine which parameters to prioritise in establishing a baseline is noted above. But, there may also be additional data from the conceptual modelling stage that should be retained within the modified decision tree to give context when interpreting the data. An example would be in estimated travel times and how this relates to the duration of monitoring. It should be noted that the conceptual model will also be subject to unknowns and uncertainties

In addition, a need to include summary statistics and recommended outputs of 'baseline' was identified for this project.

Figure 2-23: Decision tree for statistical analysis of data for establishing a baseline at OOG sites



The numbered stages associated with Figure 2.23 are summarised as:

1. Determine the appropriate parameters and data sets for analysis.
2. Perform quality assurance on the original data.
3. Define the main OOG preparation and operational activities and significant phases temporally within the selected 'baseline' data sets.

4. Subset the data into individual contaminants and monitoring locations and assign 'grouping parameters'.
5. Visualise the data.
6. Where identified as necessary, remove outliers.
7. Perform relevant tests on distributions.
8. Test different observation periods, including simulated observations, as necessary to determine confidence in the results.
9. Produce time series graphs and summary statistics.

A description of each of these stages as applied to the data from the 6 observation boreholes around the Kirby Misperton site, 5 observation boreholes on-site, and 4 surface water sites is provided in the subsections that follow.

2.7.1 Stage 1 – Determine appropriate parameters and data sets for analysis

At the Kirby Misperton site, only a subset of the BGS groundwater monitoring data was available at the time of the assessment. Therefore, a decision was taken to use only the Third Energy groundwater monitoring data in this project. An overview of the available groundwater and surface water data available at the time of the analysis is provided in Table 2.8 and the location of these monitoring sites is presented in Figure 2.4.

Table 2.8: Groundwater and surface water data overview

Data set	Data source	Water quality data type			Data set range	Notes
		Groundwater	On-site borehole	Surface water		
Kirby Misperton water quality data	Third Energy/ Envireau Water (contracted to Third Energy)	x	x	x	11 Feb 2015 to 14 Sept 2016 and 25 Apr 2017 to 19 Sept 2018	Sites sampled varies in each round. Only on-site boreholes collected in every sampling round in second period.
Environment Agency surface water quality data	Environment Agency open Water Information Management System (WIMS)			x	10 Jan 2000 to 18 Mar 2018	Taken from snapshot of longer period data.
BGS baseline groundwater data	BGS baseline project - Vale of Pickering / Fylde	x			01 Jan 2016 to 31 Oct 2018	Not all sites the same data range. Data was only a subset of all boreholes.

Stage 1 is deemed necessary to identify priority contaminants to take forward for analysis, where there are large numbers of determinands measured for different purposes. Selection criteria should consider the relevance of these contaminants to hydraulic fracturing activities as well as how useful they are in identifying future changes. This effectively acts as a data filtering stage. In addition to this, the analysis should also consider where there may be supplementary data to support establishing the baseline (for example, as per the identified Open WIMS data in Table 2.8).

Identifying priority contaminants

The guidelines identified that water quality data considerations should include:

- stray gas (dissolved natural gas, including methane)

- chemicals in hydraulic fracturing fluids, drilling muds and fluids, flowback fluid and produced waters from well leaks or storage on the surface (for example, chloride, sodium, bromide, heavy metals and Naturally Occurring Radioactive Material, NORM)
- hydrocarbons (indicative of contamination from leaks and surface spills)

To further refine this list to some specific contaminants, consideration was given to available information on fracturing fluids and flowback fluids. While a series of principal determinands could be identified from the fracturing fluid information at Kirby Misperton, no flowback fluid data was available. Data obtained from flowback fluid analysis at a recent nearby drilling and hydraulic fracturing operation at Preese Hall, Lancashire, identified a range of other determinands which are of interest in identifying change due to hydraulic fracturing activities. A 'reference measure of variability' (RMoV) was also calculated across all determinands. The RMoV was defined as the difference between the upper quartile and lower quartile relative to the median of the observations for each determinand. Determinands with the lowest non-zero[1] RMoV were deemed to be most useful in detecting change from a statistical perspective (expanding on the 'statistical considerations' that were part of the original monitoring design guidelines produced under Report Ref. SC160020[4] (Figure 2:16)).

The final list of prioritised determinands for analysis is provided in Table 2.9, with further detail of the methodology developed in section 4.6. At this stage, this list does not differentiate between the form of the analyte (for example, dissolved or total iron, or ammoniacal nitrogen as N, or NH-4).

Table 2.9: Substances identified for priority analysis at Kirby Misperton

Determinand group	Determinand	Surface water	Groundwater
Nutrients	Ammoniacal nitrogen	X	x
Major ions	Boron	X	
	Iron	X	x
	Magnesium	X	x
	Potassium		x
	Calcium	X	x
	Chloride	X	x
	Sulphate	x	x
	Total alkalinity		x
Trace elements	Arsenic		x
	Bromide	x	
	Copper	x	x
	Strontium		x
Natural gas	Dissolved methane		x
Organic chemicals	GRO (>C4-C12)	x	
Other	Acrylamide	x	x
	Electrical conductivity	x	x
	Total dissolved solids	x	

2.7.2 Stage 2 - Perform quality assurance on the original data

In stage 1, the data was analysed to identify parameters that may be of most interest in assessing baselines for the 11 Third Energy groundwater monitoring boreholes and 4 surface water sites. Stages

[1] Where the RMoV is zero, this indicates that upper quartile and lower quartile are equal and the majority of values are at or below the LOD.

2 to 9 were then carried out on the prioritised substances. The outputs from applying these stages to these priority contaminants are detailed in Appendix 2. A specific example in this and the following sections is made of electrical conductivity (EC). EC is a determinand that is useful in detecting pollution events because it:

- can be used as a proxy parameter for flowback fluid[11,12]
- is related to the concentration of charged particles in the water, and can indicate changes in the composition of groundwater[13,14]

Selecting EC does not suggest any priority or importance above any of the other determinands identified in Table 2.9, rather it uses EC as an example to illustrate the overall approach to setting a baseline using measured data. Plots for all other priority determinands in groundwater and surface water are given in Appendix 2.

Supplementary information identified that there were 2 stages of water quality data collection and subsequent analysis by 2 laboratories during the sampling period from February 2015 to June 2017. Between 11 February 2015 and 17 February 2016, data was analysed by laboratory 1, while data collected between 22 March 2016 and 15 September 2016 was analysed by laboratory 2. Data collected from April 2017 to September 2018 was all analysed by laboratory 2. Appropriate flags were added to the data to identify data analysed by laboratory 1 and laboratory 2.

The names given to the determinands measured by the 2 laboratories were marginally different, with, in some cases, method references given and, in other cases, not. Assumptions were made about how to combine this data as part of the filtering in stage 1, but original data references were maintained (see for example the treatment of dissolved iron in Appendix 2).

Where a different method was used, the standard deviations of paired percentage differences through time were calculated. Where values differed by more than 2 standard deviations (sd) from the mean, these values were also flagged as suspicious. In the case of EC, measurements were recorded, both in the lab and in situ. In situ observations were generally less than the lab measurements. Values that exceeded the limit of 2 sd are summarised in Table 2.10.

Table 2.10: Values of EC considered 'suspicious' based on relative difference between lab and in situ methods

Sample date	Site reference	Variable name	Measured value (µS/cm)
23 March 2015	G2	Electrical conductivity @25C (in situ)	86
04 March 2015	G3	Electrical conductivity @25C (in situ)	211
23 March 2015	G3	Electrical conductivity @25C (in situ)	170
23 March 2015	G3	Electrical conductivity @25C (lab)	1580
04 March 2015	G5	Electrical conductivity @25C (in situ)	172
04 March 2015	G5	Electrical conductivity @25C (lab)	820
23 March 2015	S1	Electrical conductivity @25C (in situ)	138
23 March 2015	S1	Electrical conductivity @25C (lab)	817
04 March 2015	S2	Electrical conductivity @25C (in situ)	150
04 March 2015	S2	Electrical conductivity @25C (lab)	608
23 March 2015	S2	Electrical conductivity @25C (in situ)	77

Sample date	Site reference	Variable name	Measured value (µS/cm)
04 March 2015	S3	Electrical conductivity @25C (in situ)	183
04 March 2015	S3	Electrical conductivity @25C (lab)	1240

The data provider did not give any detail about the quality assurance and quality control of the data. However, values that were noted to be above calibration limits were colour coded and flagged in the raw data from laboratory 1, which allowed these values to be interrogated further. This lab also provided duplicate measurement data and lab analysis of blanks.

No observations were noted as being above the calibration limits for EC.

Where duplicate values were taken, and the 'relative percentage difference' (RPD) measure was found to be greater than 20%, these were also flagged for further cleansing and analysis, with the assumption that this difference may be indicative of laboratory instrument drift[2]. The maximum RPD observed on the EC data was 15%, and 3 others had an RPD of ~5%. 17 of the 23 duplicate observations had an RPD of <3%.

2.7.3 Stage 3 - Define the main activities and significant phases temporally within the selected 'baseline' data sets

This is an important step as it identifies the timeline of activities at a site, which allows the baseline periods to be identified with confidence. It also allows an understanding of whether the experimental design for the duration of the required monitoring has been met. For Kirby Misperton, a number of activities and data collection periods were identified as being suitable for setting baselines. Table 2.11 shows the main events and baseline periods between December 2014 and October 2018.

Table 2.11: Timeline of main activities at the Kirby Misperton site

Date	Activity	Baseline phase
February 2015	Operator water quality monitoring began	Phase 1 (P1)
January 2016	BGS baseline groundwater data monitoring began	
September 2016	Operator water quality monitoring ended	
April 2017	Operator water quality monitoring restarted	Phase 1 (P1)
June 2017	Operator water quality monitoring ended	
September 2017	Operator water quality monitoring restarted	Phase 2 (P2)
25 September 2017	Noise barrier installed	

[2] This was applied on expert advice, given that detail of all methods and associated reference acceptable RPDs was not available

Date	Activity	Baseline phase
16 October 2017	Vehicle movements, crane and generator activity at the site started around this date	
8 March 2018	Noise barrier removed	
11 March 2018	Vehicle movements, crane and generators no longer active at the site	
11 August 2018	Increase in activity at existing site due to maintenance outage period	

In the case of the monitoring data, 2 baseline phases were identified; P1, a period before any significant on-site activity, and P2, a baseline period where no actual hydraulic fracturing activity was taking place, however on-site activity such as vehicular movements and noise barrier removal was more intensified, and could have impacted the baseline conditions. As such, P2 was flagged and analysed with caution when considered to represent baseline conditions.

2.7.4 Stage 4 - Subset the data into individual contaminants and assign 'grouping parameters'

There were 2 components of stage 4; (i) subsetting the data into individual contaminants and (ii) creating appropriate groupings of this data for further subsetting and follow-on analysis.

A subset of the Kirby Misperton data was taken for all priority contaminants of interest (Table 2.9). For EC, this included both lab and in situ EC measurements, at the 4 surface water and 11 borehole locations.

Appropriate data grouping parameters for analysis in establishing baselines of surface water and groundwater data might include:

- type of water body (surface water and groundwater)
- on-site or off-site location
- the presence of a bedrock or superficial aquifer
- depth of borehole
- area of potential interest and control categories

The operator data did not include upgradient observations and therefore this category did not apply at Kirby Misperton. At this stage, the groupings represented only potential categories of data analysis. For EC, the lab and in situ EC measurements were therefore subsetted to:

- on-site, off-site and surface water measurements
- on-site boreholes by depth
- on-site boreholes that intersected the (i) Corallian Group and (ii) the Kimmeridge Clay
- off-site boreholes by depth

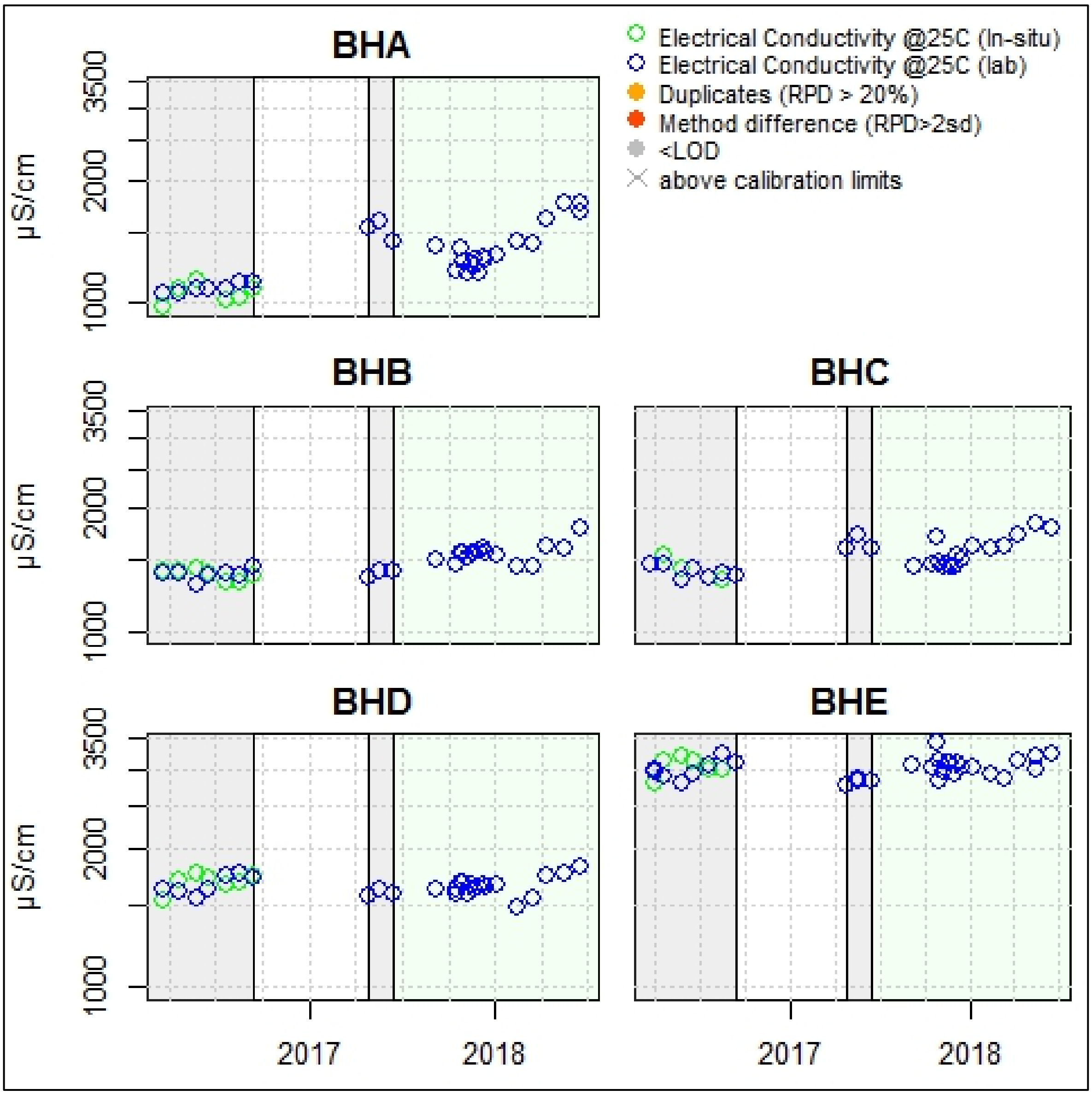
2.7.5 Stage 5 – Display the data

Following the guidelines, the data was displayed as a series of time series and box plots. Time series plots can be used to identify changes through time, while the box plots can be used to inform the temporal resolution for outlier detection, and any seasonality in the data.

Time series plots of EC measured in the on-site boreholes, off-site boreholes and surface water are presented in Figure 2.24 to Figure 2.26 respectively. In these plots, the shaded areas represent the baseline periods (section 2.7.3). The P1 baseline phase is represented by the grey shaded box, while the P2 baseline period is represented by the green shaded box. Solid black lines represent the start and end of a measurement phase. Values less than the limit of detection (LOD) and values flagged under the QA/QC analysis, are highlighted within all visualisations. For EC, no values were less than the limit of detection, and no values were greater than the calibration limit of the instrumentation. There were however, some method effect differences where duplicate measurements differed by more than 2 standard deviations (highlighted in dark orange in the plots).

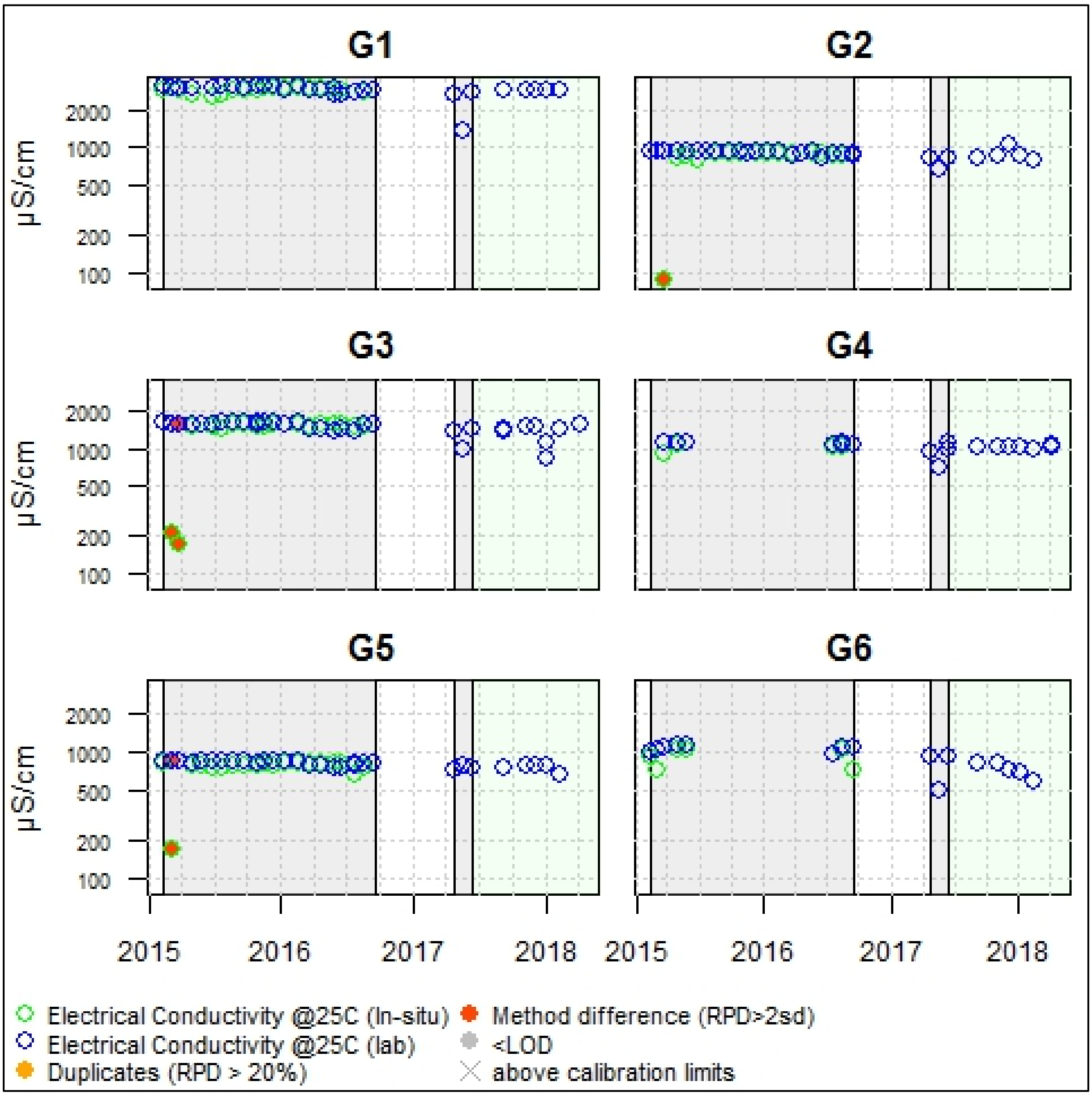
In the original guidelines, it was suggested that panel plots be used and all panels have the same x and y ranges. Though this was useful to visualise any basic trends, and highlighted differences between boreholes/surface waters, this approach resulted in a large range in the plot scales. As a result, small changes were not easily apparent on the plots. The y-axis was therefore converted to a logarithmic scale for visualisation purposes. To help clarify specific dates, vertical dashed lines indicate quarterly time periods (January 1, April 1, July 1 and October 1).

Figure 2-24: Time series plots of EC for on-site boreholes (BH-A to BH-E)



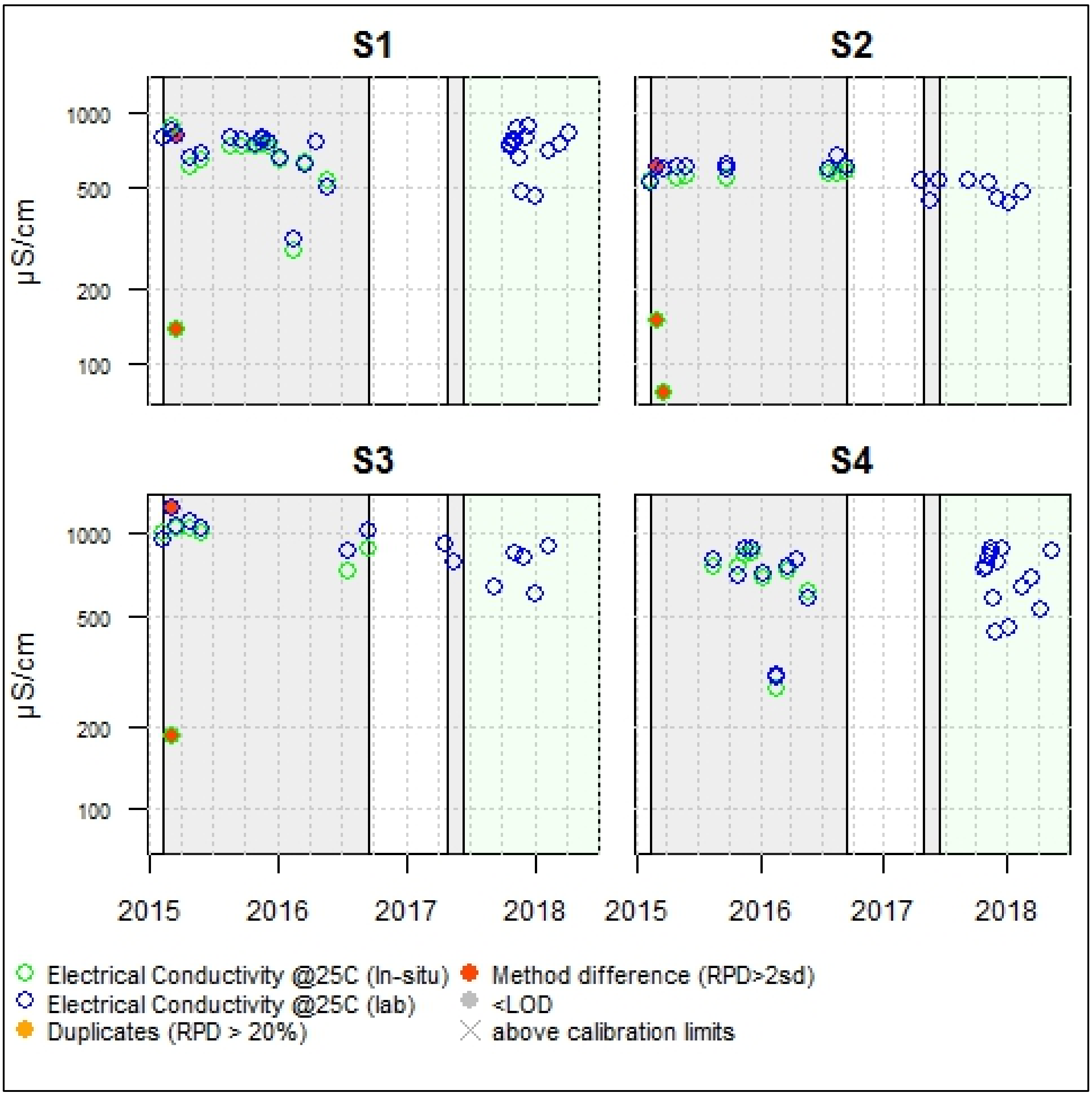
Note: The P1 baseline phase is represented by the grey shaded box, while the P2 baseline period is represented by the green shaded box. Solid lines show the start and end of data in these phases.

Figure 2-25: Time series plots of EC for off-site boreholes (G1 to G6)



Note: The P1 baseline phase is represented by the grey shaded box, while the P2 baseline period is represented by the green shaded box. Solid lines show the start and end of data in these phases.

Figure 2-26: Time series plots of EC for surface water monitoring sites



Note: The P1 baseline phase is represented by the grey shaded box while the P2 baseline period is represented by the green shaded box. Solid lines show the start and end of data in these phases.

The main purpose of the visualisation stage is to visually interpret where there may be changes in behaviour, erroneous values and trends. It is not intended, at this stage, to investigate these observations, but rather to highlight where they may be of interest for future reference. Observations are as follows:

- **General**
  - Lower values observed using in situ methods than laboratory methods. Some (comparatively) very low values using in situ methods observed at the start of the time series (values of <200 µs cm-1 observed during 2015). These were also flagged as 'suspicious' in stage 2, and shaded accordingly (see section 2.7.2). These could be calibration errors and there is enough evidence to suggest these data points should be removed from the data set.
- **On-site boreholes**
  - Data indicates a potential rising trend in EC.

- Plots seem to indicate potential differences in magnitude of EC measured at borehole BH-E when compared to the other 4 boreholes.

- **Off-site boreholes**
    - Low values in EC on 18 May 2017 across multiple boreholes.
    - Low values in EC in borehole G3 only on 1 May 2018.
    - Apparent difference in magnitudes of EC at borehole G1 when compared to the other 5 boreholes.
- **Surface water sites**
    - Low values in EC on 17 February 2016 across multiple sites.
    - More variability in EC than for groundwater.

Differences in magnitude within and between on-site boreholes (BH), off-site boreholes and surface water sites are noted in several places in this analysis. As an additional element to the guidelines, the changes through time, having accounted for the offsets in magnitude were therefore also visualised using a time series of normalised values at on-site borehole, offsite borehole and surface water grouped level.

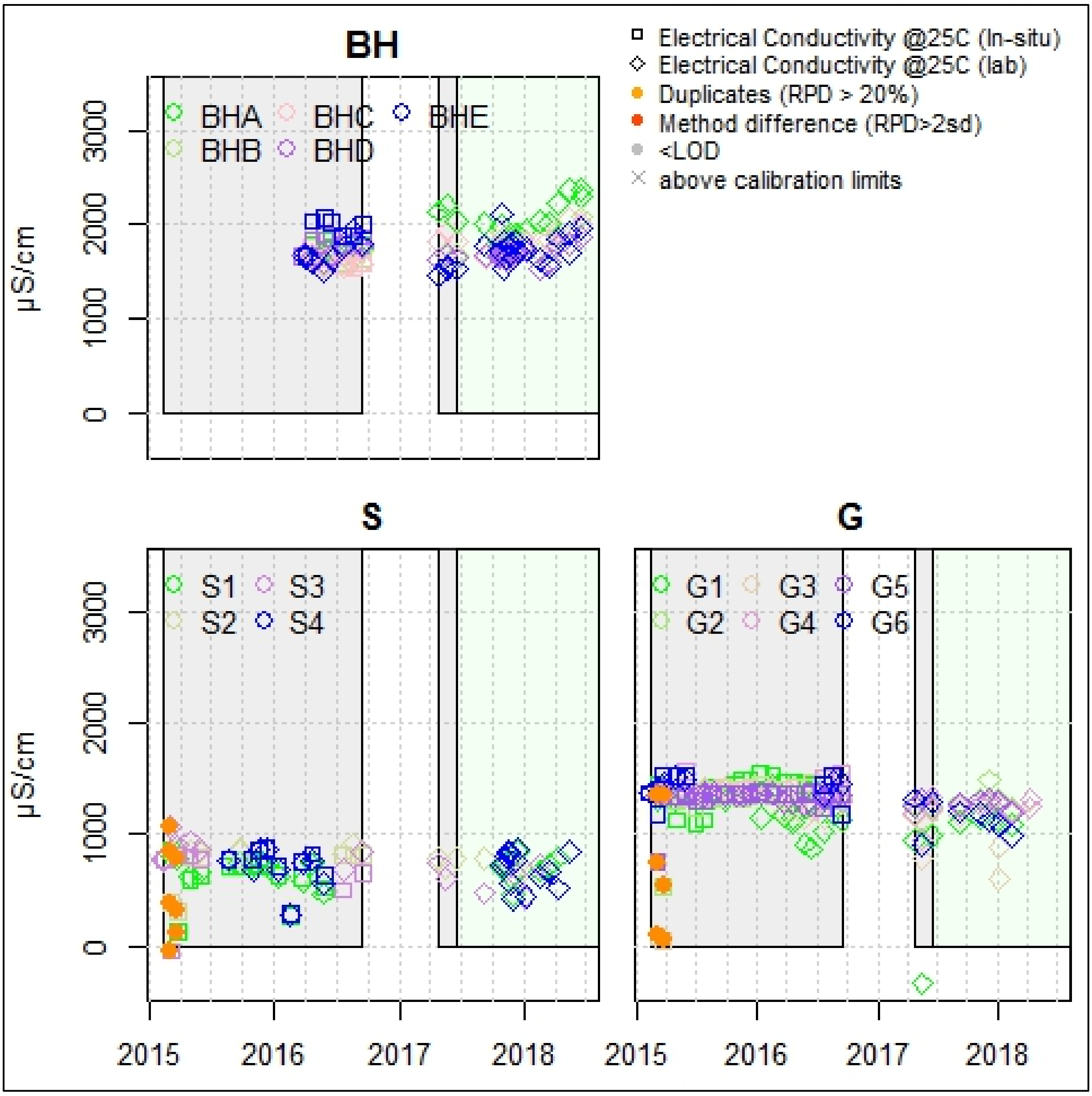
Normalised values were evaluated using Equation 1.

$$y^*(t) = y(t) - y(t_0) + \overline{y(t_0)}$$ **Equation 1**

Where; $y^*(t)$ is the normalised value of the observation (determinand) at a group level at time point t; $y(t_0)$ represents the first valid quality assured[3] observation measured and $\overline{y(t_0)}$ is the mean of all of $y(t_0)$ observations in the group. The resulting plot for EC is provided in Figure 2.27.

[3] 'Valid quality assured' observation in this case excludes values marked as having a relative percentage difference between methods of more than 2 standard deviations of the mean.

Figure 2-27: Normalised time series plots of EC from on-site boreholes (BH-A to BH-E), off-site boreholes (G1 to G6) and surface water sites (S1 to S4)



Note: The P1 baseline phase is represented by the grey shaded box, while the P2 baseline period is represented by the green shaded box. Solid lines show the start and end of data in these phases.

Observations from the grouped time series are as follows:

- **General**
  - o There appears to be some consistency in the temporal changes at a grouped level.
- **On-site boreholes**
  - o Values of EC have a higher mean concentration at the start than the off-site boreholes (on-site boreholes have a value of c.1,750 µs cm^{-1} whereas for off-site, the mean is 1,500 µs cm^{-1}).
  - o BH-A appears to show a convincing rising trend in EC through time. This becomes evident in PH2.
  - o Boreholes BH-B to BH-E, have a similar range in observed values through time where normalised to a similar start value) (approximately 500 µs cm^{-1})

- **Off-site boreholes**
    - Greater variation in measured values at G1 compared to the other off-site boreholes.
    - With the exception of the suspicious values from the sensor measurements at the start of the analysis and the low values observed in May 2017 identified in the individual borehole analysis, values of EC in boreholes G2 to G4 demonstrate relatively little variation through time compared with both off-site boreholes and surface water sites (a range of around 250 μs cm^{-1}).
- **Surface water sites:**
    - Values of EC have a lower start mean concentration than the groundwater measurements (~750 μs cm^{-1}).

The recommended resolution for box plot visualisation from the guidelines for bi-monthly and monthly measurements was for seasonal, annual and combination season and year analysis, with outlier detection to be performed at a seasonal level.

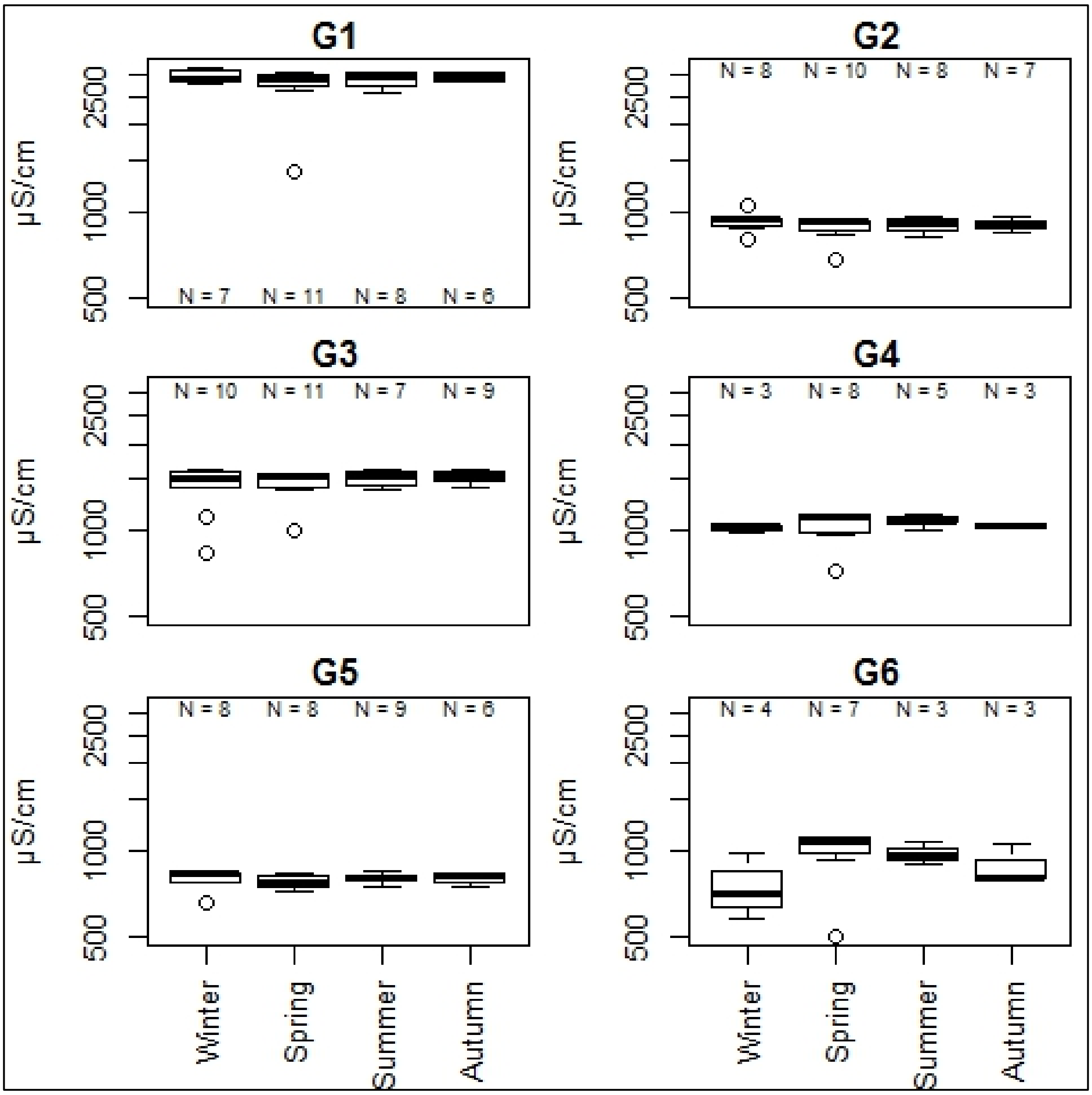
The counts of the observations that go into these combinations are shown in Table 2.12. It is apparent from this analysis that the frequency of measurement is highly variable. In some season/year combinations no measurements are taken, whereas others have less than one measurement per month, and others multiple measurements every month. On this basis, any interpretation of the distribution of data at seasonal or higher resolution would be inappropriate. Nevertheless, outliers of the box plot stats at this resolution will still be considered as indicative.

Table 2.12: Counts of EC observations (lab method) by site ID, year and season

Monitoring Ref	Winter				Spring				Summer				Autumn		
	2015	2016	2017	2018	2015	2016	2017	2018	2015	2016	2017	2018	2015	2016	2017
BH-A				4		3	2	3		1		2		1	9
BH-B				4		3	3	3		1		1		1	8
BH-C				4		3	2	3		1		1		1	8
BH-D				4		3	2	3		1		1		1	9
BH-E				4		4	3	4		1		1		1	9
G1	1	3		3	3	6	2		3	1	3		3	1	2
G2	1	4		3	5	3	2		3	2	3		3	2	2
G3	1	3		6	5	3	2	1	4	1	4		4	1	4
G4				3	4		2	2		1				1	2
G5	1	4		3	3	3	2		3	1	3		3	1	2
G6	1			3	5		2			1				1	2
S1					3	3		2					4		8
S2					4		2						2	1	2
S3					3		2							1	2
S4						3		4					2		7

For demonstration, box plots of EC measured in the off-site groundwater sites are presented in Figure 2.28. The off-site groundwater boreholes were selected for this demonstration, as on visual analysis, generally these boreholes did not appear affected by any underlying trend, and counts per season were relatively uniform. The box plots follow the standard layout for such plots. Specifically, the central line in a box represents the median, the lower and upper bounding lines of a box represent the lower (25th) and upper (75th) quartiles, the whiskers represent 1.5 times the interquartile range (the upper quartile value minus the lower quartile value), while the dots above and below a whisker represent outliers to the data.

Figure 2-28: Box plots for lab derived EC measured in the off-site groundwater monitoring boreholes



As with the time series analysis, some brief comments are made:

- 23 statistical outliers were identified and these were mainly lower than the average values. This represents around 5% of the EC observations; not considered to be an excessive number

- o the low values in EC measured in May 2017 in borehole G3 were among the identified outliers
- o as observed in the time series plots, there are potential differences in the magnitude of EC at borehole G1 when compared to the other 5 boreholes
- o there is inconsistent seasonal variation across the boreholes. This may be a result of low and non-uniform counts of measurements and potential outliers

2.7.6 Stage 6 - Where identified as necessary, remove outliers

Stage 6 carries out an analysis of outliers. The rationale of the method is that outliers should be examined and only removed where they are judged to be erroneous. Removing all outliers is not recommended since many are actual real measurements.

Within the lab EC data set, 36 outliers were identified at a seasonal level during baseline phases P1 and P2 using the default methodology from the guidelines. Comparing the outliers with the time series data allowed consideration each data point to be considered. The outliers were:

- low EC values measured on 18 May 2017 across multiple boreholes. Comparison with available supplementary data (groundwater levels and rainfall) indicated that following a dry April, there had been rain events in preceding days, which may have led to dilution
- low EC values measured in borehole G3 on 1 May 2018
- low EC values measured on 17 February 2016 across multiple sites

All EC values identified as outliers were considered to be plausible measurements, were deemed to be non-erroneous and were kept within the data sets.

2.7.7 Stage 7 - Perform relevant tests on distributions

As part of the guidelines, the final stage in the 'establishing baselines' phase was to determine whether there was enough data to establish baselines with confidence using a test for adequacy (Stage 8). Comparisons of the baseline with operational data were then dealt with during operational analysis.

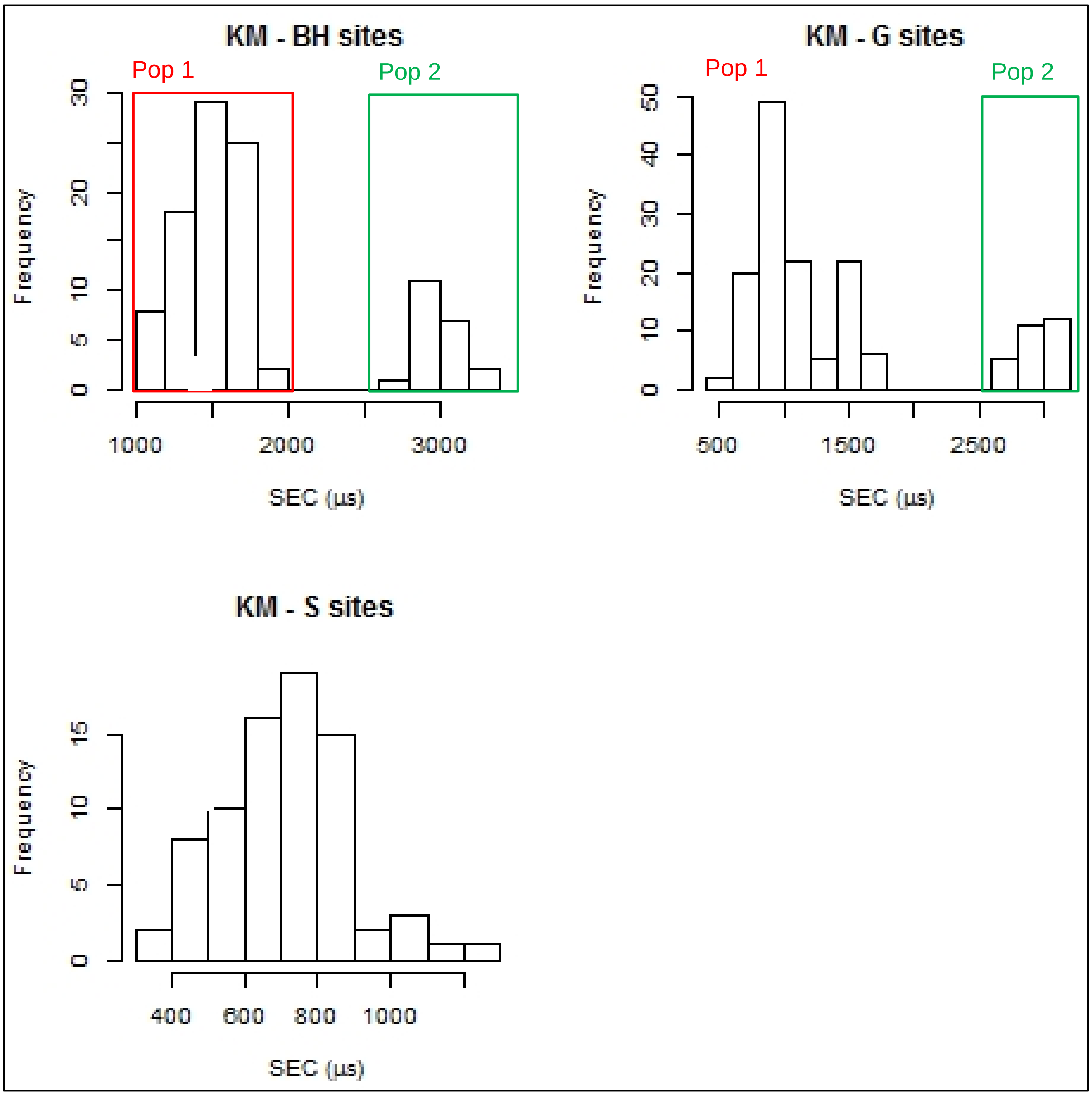
It was noted within the guidelines that the working assumption is that the data are expected to be normally distributed. This assumption is tested to see if it is justified using (i) visual assessment, (ii) quantile-quantile plots (Q-Q plots), (iii) normality tests, and (iv) where this is not justified, the suitability of different distributions is tested.

The step of visually identifying a likely appropriate distribution for the data (for example, normal, log-normal, exponential) was supported in the guidelines by a selection flowchart. It was suggested in the guidelines that the analysis was carried out on a determinand and site basis. However, when the methodology for EC was applied, it appeared that there were too few observations for this to be meaningful for water quality. It is anticipated that this is also likely to be the case for measured data for other shale gas sites. Therefore, it is proposed that the guidelines should be revised to recommend that this stage of the assessment is carried out on a grouped basis, where clearer distribution patterns were identifiable in the case study data.

As a first stage (visualisation), the EC data for Kirby Misperton was plotted as histograms (Figure 2.29) for the on-site boreholes (BH), off-site boreholes (G) and surface water sample sites (S). The histograms showed that:

- EC for the on-site boreholes and off-site boreholes show 2 populations (Pop 1 and Pop 2 on Figure 2.29), and therefore a regrouping should be considered
- EC for the surface water sites follow an approximately normal distribution (with some skew), centred around 750 µS/cm

Figure 2-29: EC distributions for data measured at Kirby Misperton



For the on-site boreholes, the population 2 values are for borehole E; population 1 values are for the remaining on-site boreholes (A, B, C and D) (Figure 2.29). The KM8 Environmental Statement indicates that there is a difference in the depths to which these boreholes are drilled[9]. BH-A, BH-B, BH-C are drilled to a depth of 10 m and end in the superficial deposits and weathered Kimmeridge Clay formation. BH-D is deeper at 50 m, ending in the unweathered Kimmeridge Clay formation. However, BH-E is drilled to 220 m, significantly deeper than the other 4 on-site boreholes. Its target lithology is in the Corallian Group. Therefore, BH-E is significantly deeper and in a different lithological and hydrogeological regime than the other on-site boreholes, which most likely accounts for the observed difference in measured data and population.

For the off-site boreholes (G), the population 2 values are mainly associated with site G1. G3 also showed some higher measurements, suggesting it had a different response to the other off-site boreholes. To try and understand any geological reasons for this difference, geological data was analysed in a cross-section. The cross-section stratigraphy indicates that G1 is likely located within a sequence of thicker superficial deposits, which directly overlies unweathered Kimmeridge Clay formation. Boreholes G2, G4, G5 and G6 are located on a sequence of thinner superficial deposits, which overlie weathered Kimmeridge Clay that transitions to unweathered Kimmeridge Clay formation.

Borehole G3 is located on a similar sequence, however the superficial deposits and weathered Kimmeridge Clay are indicated to be very thin at this location, and the borehole is mostly drilled within the unweathered Kimmeridge Clay formation. This difference in strata may act to control the difference in hydrogeological response and the rate at which flows and contaminants are transferred vertically from the surface and laterally through the strata. This could account for the observed differences in measurements at G1 and G3 when compared to the other off-site boreholes.

The histograms therefore indicated that it was pertinent to analyse the data as 6 individual groups:

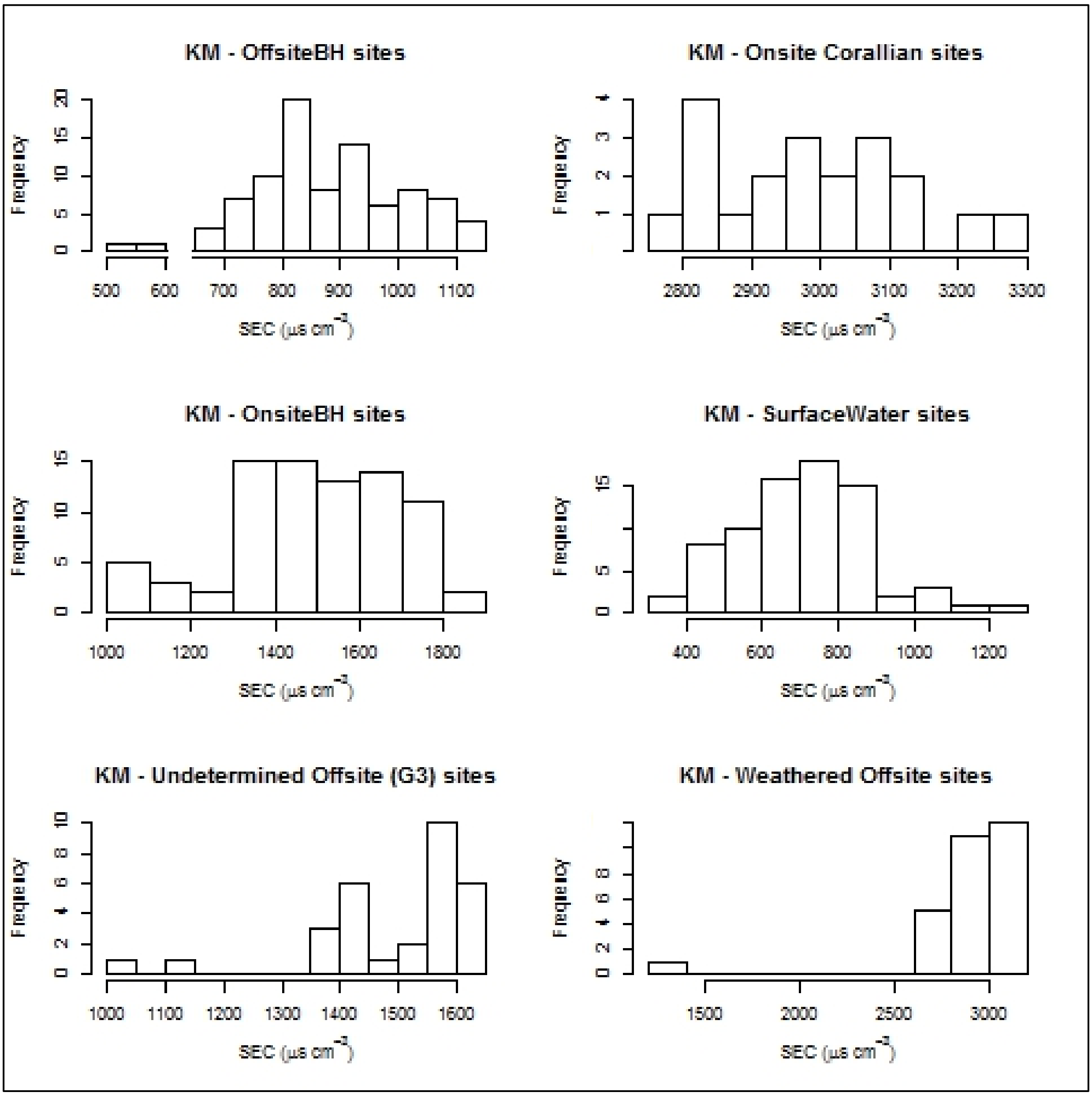
1. on-site boreholes (BH-A, BH-B, BH-C and BH-D)
2. on-site boreholes (BH-E)
3. off-site boreholes (G2, G4, G5 and G6)
4. off-site boreholes (G1 only)
5. off-site boreholes (G3 only)
6. surface water – all sites

These 6 groupings were then assessed as per the guidelines.

2.7.7.1 Visualisation

Histograms of the distributions of the re-defined groups are shown in Figure 2.30. Off-site, on-site and surface water sites, at a visual level, show potential to be considered to be normally distributed. G1, G3 and on-site Corallian site boreholes (BH-E) had too few observations to determine if a normal distribution may be appropriate.

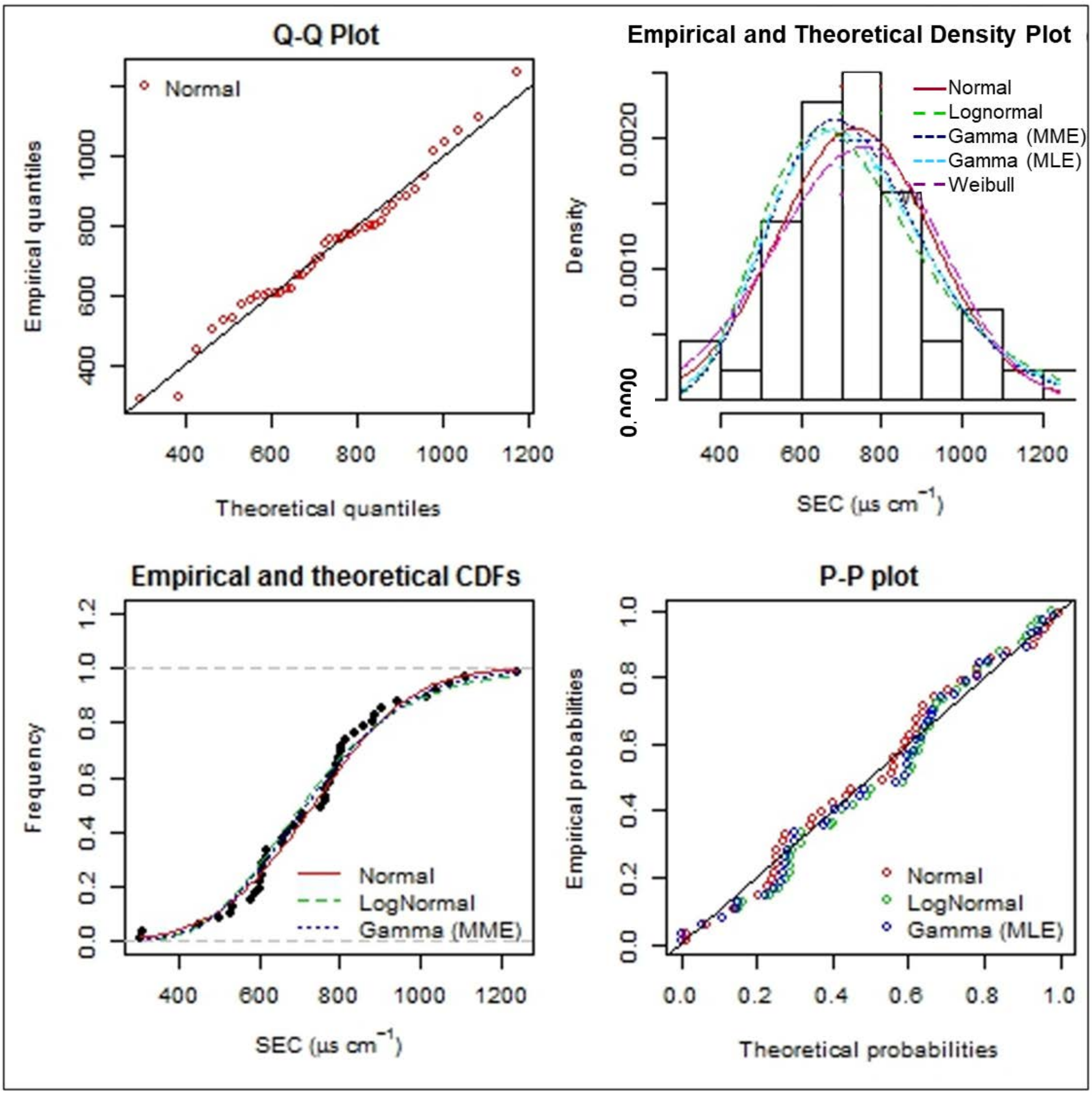
Figure 2-30: EC distributions for data measured at Kirby Misperton (re-grouped data)



2.7.7.2 Q-Q plots

In addition to the visualisation of histogram, comparing the quantiles of normal distributions alongside other distributions can be used to assess suitable distributions. An example is shown for the P1 observations for the surface water sites.

Figure 2-31: Empirical and theoretical distribution comparisons for Kirby Misperton surface water sites (P1 data)



2.7.7.3 Normality tests

Before an assessment of whether a more complex description of the data is required, and to confirm the conclusions formed from the visual assessments, distributions are first assessed in terms of whether a normal distribution of the data or logged data can be satisfied. The hypothesis test consists of a null hypothesis and an alternative hypothesis:

- null hypothesis (H0): There is no difference between the distribution of the data/logged data and a normal distribution
- alternative hypothesis (H1): There is a difference between the distribution of the data/logged data and a normal distribution

For large sample sizes (30 observations or more), an Anderson-Darling test may be considered the most appropriate statistical test for normality. For smaller sample sizes (less than 30 observations), a Shapiro-Wilk test may be considered more appropriate. Future sites may have less data than the sites studied as part of this project. Applying these tests to the data for P1 of the surface water sites results in an (Anderson-Darling) p-value of 0.4. This indicates that there is not enough statistical evidence (at the 5% significance level) to reject a hypothesis of no difference between data and normal distribution (in other words, we could assume a normal distribution may be appropriate to describe the surface water data).

A summary of the test results for the EC sites is shown in Table 2.13.

Table 2.13: Results of normality tests for EC grouped data at Kirby Misperton

Group	Anderson-Darling p-value	
	Unlogged (as received) data	Logged data
On-site boreholes (BH) Kimmeridge Clay	0.023	<0.001
On-site boreholes (BH) Corallian Group	0.81	0.85
Off-site boreholes, excluding boreholes G1 and G3 (low connectedness)	0.22	0.22
Off-site boreholes, G1 only (weathered/highly connected)	<0.0001	<0.0001
Off-site boreholes, G3 only	<0.001	<0.0001
Surface water – all sites	0.36	0.038

2.7.7.4 Distribution tests

As part of the visualisation and Q-Q plots, the appropriateness of the normal distribution versus alternative distributions were highlighted. There was no requirement to look further at alternative distributions for the Kirby Misperton data. A summary of the most appropriate distributions is shown in Table 2.14.

Table 2.14: Results of statistical distribution tests for EC grouped data at Kirby Misperton

Group	Appropriate distribution
On-site boreholes (BH) Kimmeridge Clay	Normal*
On-site boreholes (BH) Corallian Group	Normal**
Off-site boreholes, excluding boreholes G1 and G3 (low connectedness)	Normal**
Off-site boreholes, G1 only (weathered / highly connected)	NA***
Off-site boreholes, G3 only	NA***
Surface water – all sites	Normal

*Rejected at the 5% significance level, but not at the 2.5% level. Other distributions do not (visually) indicate an obvious improvement to the fit. **No substantive difference between the normal and lognormal values. Preference applied to utilise unlogged values *** NA indicates that no suitable distribution identified/required. For borehole G3, more observations are necessary.

2.7.8 Stage 8 - Test different observation periods (including simulated observations as necessary) to determine confidence in the results

As part of the guidelines, the final stage in the 'establishing baselines' phase was to use a test for adequacy to determine whether there was enough data to establish baselines with confidence. Comparing the baseline with operational data was then dealt with during operational analysis. In the approach here, the consideration is therefore a penultimate stage.

The distribution for the on-site Corallian Group (BH-E) and off-site boreholes G1 and G3 were not tested due to the low number of observations.

As part of this analysis, indicator values were calculated. 'Indicator values' relate to what change (increase or reduction) in parameter concentration/value would be required to indicate that a statistically significant deviation from the baseline had occurred with 80% probability.

For determinands expected to show an increase in value where impacted by OOG operations, indicator levels can be applied to assess the likelihood of change in qualitative terms. Where a mean value of sample observation goes above a predetermined value calculated from baseline ($\overline{x}_0 + \delta$), and assuming the same standard deviation, s_0 (homogeneity of variance) and number of observations (assessment on a rolling period), this could be considered 'likely' to be indicative of change using the verbal scale of outcomes shown in Table 2-15. The choice of 80% probability that exceedance of the indicator value constitutes a significant change from the monitored background is somewhat subjective, but has a firm base in the Intergovernmental Panel on Climate Change[15] recommendations. These use a standard verbal scale for the attachment of probabilistic information to uncertain outcomes, as set out in Table 2-15.

Table 2-15: Verbal scale for the attachment of probabilistic information to uncertain outcomes as outlined by the Intergovernmental Panel on Climate Change[15]

Verbal description	Certainty range (%)
Exceptionally unlikely	0% to 1%
Very unlikely	1% to 10%
Unlikely	10% to 33%
About as likely as not	33% to 66%
Likely	66% to 90%
Very likely	90% to 99%
Virtually certain	99% to 100%

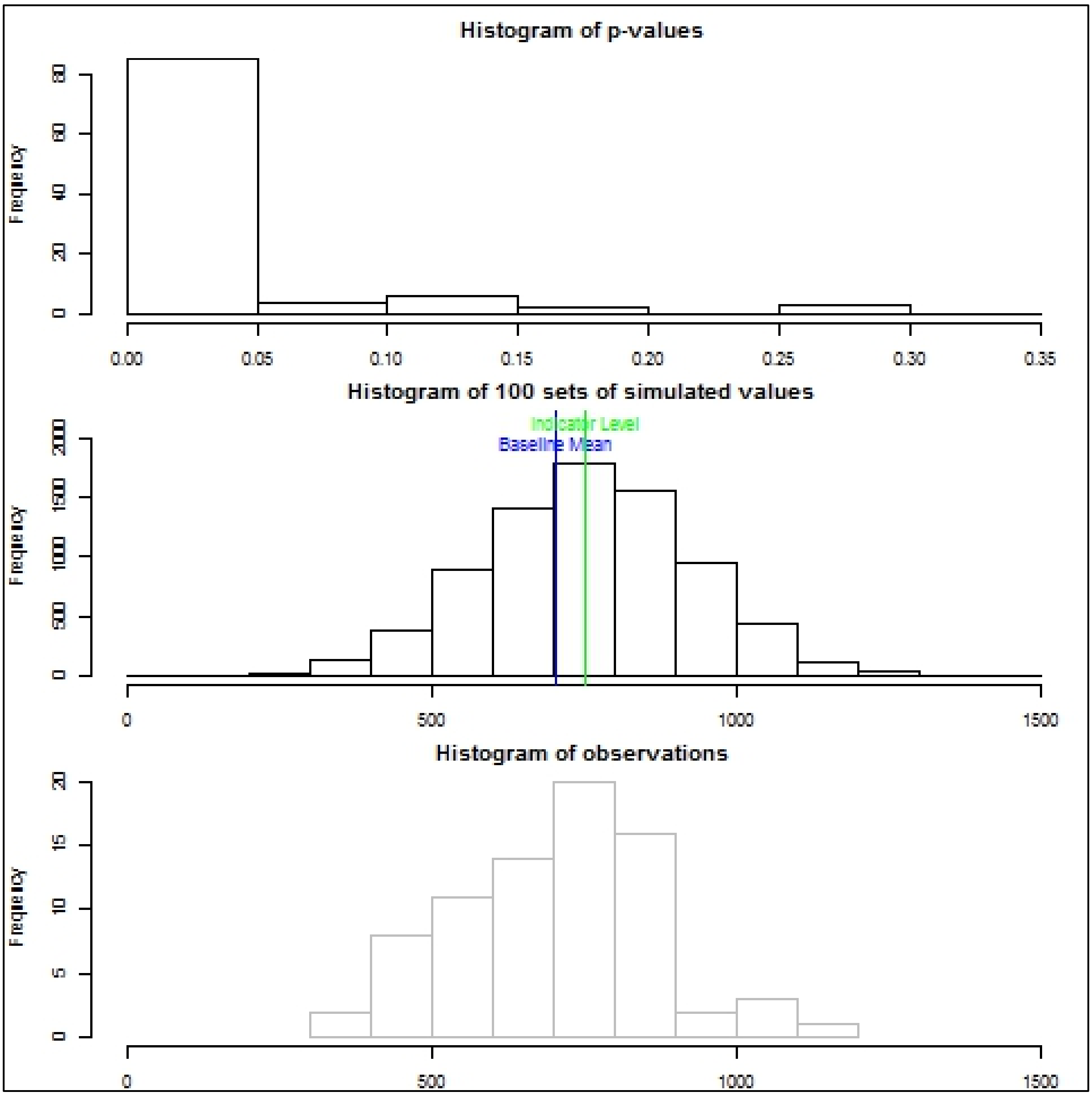
The 80% value is also consistent with the confidence level used in assessing whether trends in groundwater pollutant concentrations are statistically significant for the Water Framework Directive (UKTAG, 2012) [16]. It is also noted that 80% is approximately in the middle of the 'likely' category (66 to 90%).

Applying indicator levels is based on the theory that if enough repeat samples were to be taken with these new characteristics (from a normal distribution, $\overline{x}_1 = \overline{x}_0 + \delta$, $s_1 = s_0$), the null hypothesis (that the means are equal) would be rejected 80% of the time.

An example with the surface water measurements for EC as shown in Figure 2-32. The 3 panels show (i) the distribution of calculated p-values from 100 simulations ($\overline{x}_1 = \overline{x}_0 + \delta$, $s_1 = s_0$, $n_1 = n_0$), where the p-value is calculated on the null hypothesis that δ is equal to 0, and the alternative hypothesis is that δ is positive. It should be observed that the frequency of p-value in the 0-0.05 range is around 80% as expected from the set power; (ii) the distribution of all simulated values of a new (indicator level) distribution with mean displaced by δ, with the mean of the baseline ($\overline{x}_0$) and indicator level ($\overline{x}_0$+ δ) shown; and (iii) the histogram of observed baseline values. The indicator value ($\overline{x}_0$+ δ) was evaluated using a one-sided, two-sample power.t.test, with power set equal to 0.8 in the computing language R (see also power test entry in the glossary).

It should be noted that this is an indication of what to look at during the operations phase, but should not be overinterpreted. Additional formal statistical tests (as detailed in the previous project) would still need to be applied to statistically show a change.

Figure 2-32: Histograms of simulated value results



Indicator values calculated are summarised in

Table 2.16.

Table 2.16: Indicator values for Kirby Misperton grouped EC data (µS cm^{-1})

Site ID	Mean, x_0 (baseline)	Standard deviation, s_0 (baseline)	Effect size, δ	Number of observations, n_0 (baseline)	Indicator level
G1	2,873	323	153	29	3,026
G6	889	189	123	16	1,012
BH-E	3,011	151	76	26	3,087
On-site boreholes (excluding BH-E)	1,495	185	45	104	1,540
Off-site boreholes (excluding G1 and G6)	1,057	305	76	101	1,133
Surface water sites	704	170	49	77	753

2.7.9 Stage 9 - Produce time series graphs and summary statistics

In the guidelines, analysis was considered on a continuum, and there was no explicit advice given on how baseline conditions could be represented. Instead, outputs from the establishing baselines phase (cleaned and grouped data) was passed forward into the operational phase for the assessment of change. Under this project, therefore, it is recommended that a new stage is included in the updated guidelines.

This stage is intended to represent a 'data pack of outputs' that together represent a baseline characterisation. It is suggested that this data pack includes the data time series and box plots with outliers, suspicious values and values greater or less than an LOQ/LOD flagged (or removed) at an individual site and grouped level. The data pack should also include site and grouped site summary statistics of mean, standard deviation, median, median absolute deviation (MAD) and skew, together with the outputs of the adequacy testing, including indicator values.

Time series and box plot outputs for EC have been shown in previous steps. Evaluated site statistics for surface water site (S1) are shown in Table 2.17 to give an example of how it was implemented.

Table 2.17: EC summary statistics for Kirby Misperton surface water site S1

Statistic	Electrical conductivity
Count (n)	28
Mean	706 µS/cm
Standard deviation	141 µS/cm
Median	759 µS/cm
MAD	93 µS/cm
Skew	-1.16 µS/cm

Data packs in Appendix 2 show the baseline representation from Kirby Misperton priority interest determinands identified in section 2.7.1. These consist of:

- individual site time series

- grouped time series data normalised mean across the group
- grouped data box plots
- individual site statistics
- grouped data statistics

2.7.10 Critical review of baseline data

Groundwater data was taken from 6 observation boreholes around the Kirby Misperton site (Figure 2.4.). One issue identified was the assumption in the conceptual model framework in Environment Agency 2019a that it would be possible to locate groundwater monitoring boreholes upgradient and downgradient relative to the onshore oil and gas installation. It was found that the 6 off-site observation boreholes (G boreholes) are not optimally located. The Kirby Misperton site is situated in a locally elevated position and, given the southerly groundwater flow direction, the 6 observation boreholes are located down hydraulic gradient of the groundwater flow direction from the site.

The positioning of the observation boreholes around any site is an important consideration and should be discussed with appropriate parties before any site conceptual model or monitoring infrastructure is developed. It is important for their siting to be able to characterise the upgradient groundwater quality, which can then be compared with the groundwater quality downgradient of any relevant hydraulic fracturing activity to identify any changes in groundwater quality. The guidelines covered this recommendation in monitoring.

While baselines could not be set upgradient and downgradient at Kirby Misperton, they could be established for boreholes grouped by depth or aquifer type. This recommendation for grouping data is included in the revised guidelines for setting baselines considered later in this report.

The analysis of Kirby Misperton data highlighted the benefits of extending the guidelines on selecting appropriate groupings. An obvious grouping is for upgradient and downgradient, and is a concept used in guidelines for setting baselines using landfill data. As this was not possible in this practical example of application, revised guidelines for setting baselines (within the scope of recommendation for this project) should consider the situation where this information is not available. For Kirby Misperton, the approach adopted was to consider groupings based on the depth of borehole and aquifer type.

2.7.11 Conclusions

The collected data at Kirby Misperton have been presented to understand baseline groundwater and surface water conditions. An important issue relates to the lack of up groundwater-gradient boreholes, either off-site or on-site. This may present issues when attempting to evaluate the effect of the site on groundwater quality during any future operational phase. Designing such monitoring programmes should include a robust conceptual model (for example, as set out in Environment Agency 2019a) to ensure that the most appropriate monitoring regime is established.

This section has considered EC as an example determinand to demonstrate the process of establishing a baseline. The recommended standard data packs for what are considered other priority determinands at Kirby Misperton are provided in Appendix 2. They include acrylamide, total dissolved solids, ammoniacal nitrogen, Gasoline Range Organics (GRO) (>C4-C12), a selection of major ions (arsenic, boron, copper, iron, magnesium, potassium, strontium, bromide, calcium, chloride, sulphate and total alkalinity) and dissolved methane.

3 Applying guidelines to baseline data: Preston New Road

The purpose of this section is to test the guidelines that were set out in the project on assessing the statistical significance of change (Environment Agency 2019a). An example of the analysis is shown at Preston New Road for air and water data. This assessment provides an opportunity to critique the guidelines, while simultaneously assessing the baselines at both sites. Through this assessment, lessons were learned and revisions to the guidelines were recommended.

3.1 Overview

The Preston New Road (PNR) site is a new onshore oil and gas installation operated by Cuadrilla. The Environment Agency issued an environmental permit for exploratory drilling and hydraulic fracturing at the Preston New Road site in January 2015. This permit set out legally binding conditions for these operations, covering groundwater, surface water, releases to both air and water emissions, safe storage of waste, noise from mining waste and groundwater activities.

The permit also included pre-operational conditions, monitoring and reporting requirements. Pre-operational condition 2 required the Environment Agency's approval of a written Environmental Management and Monitoring Plan.

Figure 3.1 shows that Preston New Road is in a rural location, with the town of Little Plumpton about 500 m to the east. Figure 3.2 shows a main arterial road to the south. The British Geological Survey (BGS) monitoring location is close to the town of Little Plumpton. The Cuadrilla monitoring location is on the boundary line of the shale gas site, but monitoring data during the operational phase was not released in time for analysis. The Environment Agency air quality monitoring site is not on the Cuadrilla site. Its location has not been disclosed but is in an upwind direction.

Figure 3-1: Preston New Road site plan

Figure 3-2: Approximate site location and position of BGS continuous monitoring station

3.2 Air quality aspects

The monitoring plan[17] described the baseline air quality monitoring survey carried out at the site by an independent consultant. The baseline monitoring survey comprised grab sample short-term monitoring of methane, passive diffusion tube monitoring of nitrogen dioxide (NO_2), hydrogen sulphide (H_2S) and BTEX (including benzene), and depositional and directional monitoring for particulate matter (PM_{10}) and dust. The plan proposed a more comprehensive operational monitoring strategy.

This plan was approved by the Environment Agency in May 2018. Pre-operational condition 3 required the Environment Agency's approval of a written Hydraulic Fracture Plan, setting out how the operator will control and monitor the fracturing process, including monitoring the ambient receiving environment, of which local air quality is a part. The Hydraulic Fracture plan for the first well at the PNR site was approved by the Environment Agency in July 2018. Other plans cover waste disposal, well integrity, seismicity, flaring and shut-down.

Preston New Road site is located in a rural location surrounded by farm land. The nearest building is approximately 300 m to the south, which is on the southern side of the A583. The village of Little Plumpton is approximately 500 m to the south-east.

3.3 Water quality aspects

The boreholes and surface water monitoring locations near the Preston New Road site are shown in Figure 3.3. To better understand the risks to water quality from the Preston New Road site operation, a brief overview of the geology, surface water and groundwater receptors and the main risks to water quality are provided below.

The Preston New Road well was drilled to a depth of ~3,500 m to the target rocks of the Bowland Shales and Hodder Mudstones.

The superficial deposits directly underlying the site are characterised by 3 layers; the Upper Boulder Clay, Middle Sands and Lower Boulder Clay. These are defined as secondary A aquifers, with only the Middle Sands likely to have notable groundwater potential (these falling under the West Lancashire Quaternary Sands and Gravels aquifer) and supplying good quality groundwater to local sources[18].

Beneath the superficial deposits, the bedrock geology beneath the site (and its hydrogeological potential) can be characterised as:

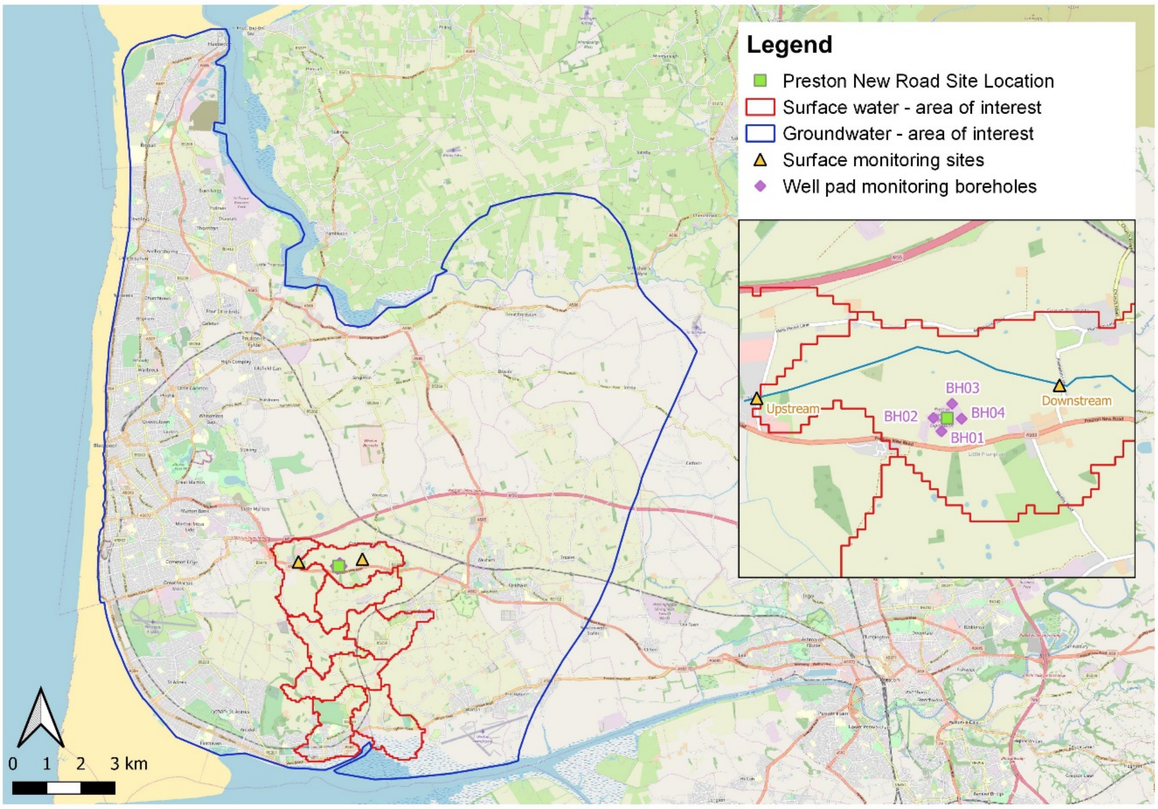
- **Mercia Mudstone Group:** Triassic rocks comprising nearly wholly of grey, red and brown mudstones with interbedded siltstones with some layers of halite. These rocks are generally of low permeability with no aquifer potential in the area.
- **Sherwood Sandstone Group:** A thick Triassic red to red-brown sandstone sequence. It is a principal aquifer in many parts of the north of England. However, beneath the Preston New Road site it is not a drinking water aquifer as it contains saline groundwater (53,000 to 91,000 mg/l chloride).
- **Manchester Marls:** These Permian rocks are a calcareous mudstone and siltstone, which are locally sandy or coarser in places. The Manchester Marls forms an impermeable barrier to upward flow within the sequence. They contain no groundwater.
- **Collyhurst Sandstone:** These rocks are a fine to very coarse sandstone and conglomerate with occasional mudstones and are of Permian age. While the formation is a principal aquifer at outcrop, beneath the site it is not a source of water due to the natural presence of hydrocarbons and the salinity of groundwater in the rock.
- **Millstone Grit Group, Bowland Shales and Hodder Mudstone:** These are a mixture of feldspathic coarse sandstones, with interbedded siltstones and mudstones (Millstone Grit Group) and dark and black interbedded fissile mudstones (Bowland Shales and Hodder

Mudstone), all of Carboniferous age. These rocks are very deep and hold no drinking water quality groundwater.

Data indicates that there is a westward groundwater flow in superficial deposits, with possible local interactions between sands and gravels and wetlands and watercourses.

Faulting is an important control in the geology on the Fylde peninsula, exerting particular control on hydrogeology. The Woodsfold Fault (general north-south trending fault) is important, as it acts as an impermeable barrier on the western boundary of the Fylde (represented as the straight boundary to the eastern edge of the groundwater area of interest, Figure 3.3). It separates the potable groundwater east of the fault with the highly saline groundwater to the west of the fault (and beneath the Preston New Road site)[18].

Figure 3-3: Map showing water quality monitoring locations in the vicinity of Preston New Road site



As noted above, groundwater present in the bedrock aquifers beneath the site is highly saline and of poor quality and therefore offers no resource value. The Mercia Mudstone Group acts as an impermeable barrier to prevent water and contaminants moving vertically between adjacent strata. This limits the potential implications of contamination of the aquifers close to the surface from hydraulic fracturing activities at the site. The most important groundwater receptors were concluded to be the Middle Sands superficial aquifer and the Sherwood Sandstone Group aquifer. However, due to the impermeable Mercia Mudstone Group, neither were considered to interact significantly with each other[18].

There are several groundwater abstractions adjacent to the site and data indicates that these mostly abstract water for non-drinking water uses (spray irrigation) from the blown sand deposits. These abstractions include Lytham Green Golf Club (~4.5 km to the south), Royal Lytham and St Anne's Golf Club (~5.5 km to the south-west) and St Anne's Old Links Golf Course (~6 km to the west). Data indicates that only one abstraction is likely to abstract water from the Middle Sands superficial aquifer, located ~5 km to the north-west. This is used to supply water to a fishery, which may require high quality uncontaminated water. The nearest drinking water abstraction from the Sherwood Sandstone is located east of the Woodsfold Fault, ~9km from the site and operated by United Utilities. As discussed above, this fault is shown to isolate this abstraction from saline aquifer beneath the site.

The main surface water receptors close to the site have been identified as adjacent small watercourses[18]:

- Carr Bridge Brook: ~0.25 km north of site
- Main Drain: ~1.2 km to west of site (of which Carr Bridge Brook is a tributary) and which eventually flows into the River Ribble estuary
- Wrea Brook: ~1.5 km to the south of the site

In addition to these watercourses, there are numerous small marl ponds and drains in agricultural land around the site, and these are receptors by way of direct surface water flow and indirect groundwater flow.

The infiltration of surface waters into the superficial aquifer (Middle Sands) is likely to be limited by low permeability Boulder Clays, which are up to 6 m thick. This makes surface water and groundwater interactions unlikely.

Considering the hydrogeology, surface morphology and the main surface water and groundwater receptors at risk of pollution, a source-pathway-receptor (SPR) linkage for the well development, hydraulic fracturing and operational phases was developed within the Preston New Road site environmental statement[18]. The SPR identified the following main risks specific to surface and groundwater:

- contaminant release during installation of surface and buried arrays = low risk
- contaminant release due to defects in well membrane = low risk
- contamination in overflow or discharge from the well pad drainage system = low risk
- spill from vehicle in transit = low risk
- release of hydraulic fracturing fluid or flowback fluid and poor quality formation water due to loss of well integrity = very low risk
- loss of well integrity caused by hydraulic fracturing = very low risk
- loss of well integrity due to natural seismicity = very low risk
- loss of well integrity due to long term well degradation = low risk
- induced fractures extend beyond the target zone = very low risk
- residual fracturing fluid contaminants migrate to receptors = no plausible pathway

Figure 3.3 indicates the location of monitoring sites and the identified areas of interest for the study.

3.4 Site timeline

A timeline of activities at Preston New Road, as provided by the operator and third parties, is set out in Table 3.1. Air quality monitoring activities are not included in this table, but the following Table 3.2 covers monitoring activities and shows how they were scheduled in comparison with the shale gas development activities.

Table 3.1: Timeline of the main activities at the Preston New Road site

Phase	Date range	Detailed activity	Date
Before activities began	1 December 2014 to 4 January 2017	Operator Surface Water Quality monitoring began	1 December 2014
		Operator Surface Water Quality monitoring ended	22 May 2015
		Operator Groundwater Quality monitoring began	1 July 2016

Phase	Date range	Detailed activity	Date
		Permission for exploratory drilling granted	1 October 2016
		Operator Surface Water Quality monitoring restarted	14 December 2016
Site preparation	5 January 2017 to 17 August 2017	Site construction started	5 January 2017
		On-site traffic activity	26 January 2017
		Drilling begins	1 June 2017
		Cuadrilla applied for permit variation	6 July 2017
		Drilling rig arrives at the site	27 July 2017
Drilling 1	17 August 2017 to 1 March 2018	Drilling begins and first well spudded	17 August 2017
		Environmental permit variation approved	12 December 2017
		Cuadrilla applied for permit variation to allow discharge of surface water to Carr Bridge Brook	14 December 2017
		Well 1 drilling complete	1 March 2018
Drilling 2	1 April 2018 to 14 October 2018	Well 2 drilling started	1 April 2018
		Environmental permit variation approved	2 May 2018
		Well 2 drilling complete	17 July 2018
Hydraulic fracturing	15 October 2018 to 14 December 2018	Hydraulic fracturing began	15 October 2018
		Hydraulic fracturing ended	14 December 2018
Extraction	2 November 2018 onwards	First shale gas extraction and flaring began	2 November 2018

3.5 Baseline air quality data

For this assessment, 2 data sets have been analysed at Preston New Road:

- continuous and periodic air quality monitoring data from measurements carried out by the Environment Agency
- continuous and periodic air quality monitoring data from measurements carried out by BGS

The operator, Cuadrilla, has obtained its own baseline monitoring data, but states that "in consultation with the Environment Agency, it [the BGS baseline data set] will be used as the primary data source for the baseline period." In view of the extensive and detailed information available from the BGS data set, this independent data set was analysed to evaluate baseline air quality conditions. The operational period at the site was from 17 August 2017, including drilling and hydraulic fracturing activities.

A summary of the monitoring data collected by BGS and the Environment Agency at Preston New Road, along with a timeline of activities relating to the main emission sources, is provided in Table 3.2.

Table 3.2: Activity data at Preston New Road site and baseline data collected by BGS and the Environment Agency

Year	Month	Activity	Monitoring data collected by BGS			Monitoring data collected by the Environment Agency	
			Particulates (TSP, PM_{10}, PM_4, $PM_{2.5}$, PM_1) Oxides of nitrogen (NO, NO_2, NOx)	CO_2, CH_4	NMVOCs*	Particulates (PM_{10}, $PM_{2.5}$) Oxides of nitrogen (NOx, NO, NO_2) H_2S CH_4	NMVOCs (BTEX)
			One-min	One-min	Weekly grab sample	5-min	30-min
2016	January		√	√			
	February		√	√			
	March		√	√			
	April		√	√			
	May		√	√			
	June		√	√			
	July		√	√			
	August		√	√			
	September		√	√			
	October	Planning permission for exploratory drilling granted.	√	√			
	November		√	√	√		
	December		√	√	√		
2017	January	Site construction begins. On-site traffic activity.	√	√	√		
	February		√	√	√		
	March		√	√	√		
	April		√	√	√		

Year	Month	Activity	Monitoring data collected by BGS			Monitoring data collected by the Environment Agency	
			Particulates (TSP, PM_{10}, PM_4, $PM_{2.5}$, PM_1) Oxides of nitrogen (NO, NO_2, NOx)	CO_2, CH_4	NMVOCs*	Particulates (PM_{10}, $PM_{2.5}$) Oxides of nitrogen (NOx, NO, NO_2) H_2S CH_4	NMVOCs (BTEX)
			One-min	One-min	Weekly grab sample	5-min	30-min
	May		✓	✓	✓		
	June		✓	✓	✓		
	July	Drilling rig arrives.	✓		✓		
	August	Drilling begins and first well spudded.	✓		✓	✓	✓
	September		✓		✓	✓	✓
	October		✓		✓	✓	✓
	November		✓			✓	✓
	December		✓			✓	✓
2018	January		✓			✓	✓
	February		✓			✓	✓
	March	Well 1 drilling complete.	✓			✓	✓
	April	Well 2 drilling starts.	✓			✓	✓
	May		✓			✓	✓
	June		✓			✓	✓
	July	Second shale gas well completed. Consent granted on UK's first horizontal shale gas well.	✓			✓	✓
	August		✓			✓	✓
	September	Consent granted for second horizontal shale gas well.	✓			✓	✓

Year	Month	Activity	Monitoring data collected by BGS			Monitoring data collected by the Environment Agency	
			Particulates (TSP, PM_{10}, PM_4, $PM_{2.5}$, PM_1) Oxides of nitrogen (NO, NO_2, NOx)	CO_2, CH_4	NMVOCs*	Particulates (PM_{10}, $PM_{2.5}$) Oxides of nitrogen (NOx, NO, NO_2) H_2S CH_4	NMVOCs (BTEX)
			One-min	One-min	Weekly grab sample	5-min	30-min
		Oil and Gas Authority gives final approval for hydraulic fracturing at first horizontal shale gas well.					
	October	Hydraulic fracturing begins.				√	√
	November	First shale gas extract and flare.				√	√
	December					√	√

* Ethane, ethene, propane, propene, isobutane, n-butane, acetylene, isopentane, n-pentane, isoprene, benzene, toluene.

3.6 Air quality example: PM_{10} measured at BGS monitoring station, Preston New Road

To further test the guidelines[4], data analysis was completed for Preston New Road. The overall data analysis procedure is summarised in Figure 2.5. Testing another pollutant and another site will strengthen conclusions and recommendations that can be made relating to the guidance. An example of the analysis is provided below for PM_{10}.

3.6.1 Stage 1: QA/QC checks

The first stage is to perform QA/QC on the data set. This step removes data that is deemed invalid due to equipment malfunction. Examining the data provided, it became clear that it had already been through the QA/QC process. In the BGS data set, this is made evident by data quality flags being provided. The concentration data that was highlighted as being of insufficient quality were removed.

3.6.2 Stage 2: Monitoring duration

The second stage is to define main activities and significant phases within the baseline data set, so the duration of monitoring during the baseline phase can be checked. Using activity data that was available, it was possible to determine when activity began on site. This has been highlighted in Table 3.1. The BGS air quality data was provided during 3 phases at the site: before site preparation, during site preparation and during drilling of well 1. The Environment Agency data set is not available for the time before or during site preparation, but is available during drilling and hydraulic fracturing and therefore is analysed in chapter 5.

Further analysis of baseline survey duration is provided in section 2.6.9.

3.6.3 Stage 3: Subset the data into contaminants and monitoring locations

This example section considers only PM_{10},, but further information on the other pollutants is provided in Appendix 3. Data were provided for a number of pollutants, but the analysis of all pollutants would be unnecessary, due to the lack of associated standards for some pollutants, and because some pollutants were not part of the guidelines on primary pollutants of concern. As a result, at this stage, a subset of pollutants were selected for analysis. The pollutants that were excluded from analysis were PM_{Total}, PM_4, PM_1, and particulate count.

3.6.4 Stage 4: Visualise the data

The BGS air quality data was provided at one-minute intervals (apart from VOC data, which was collected weekly, but is not relevant to this example). Hourly averages were taken as no pollutants of note require less than one hour averaging time. This made the data more manageable. Visualisation of the hourly averaged data (Figure 3.4 and Figure 3.5) provided some clarification of trends in the data, but daily averaged data (Figure 3.6) provided more clarity and insight into the trends within the data.

Figure 3-4: Time series plot of hourly averaged PM_{10} data collected by BGS at Preston New Road

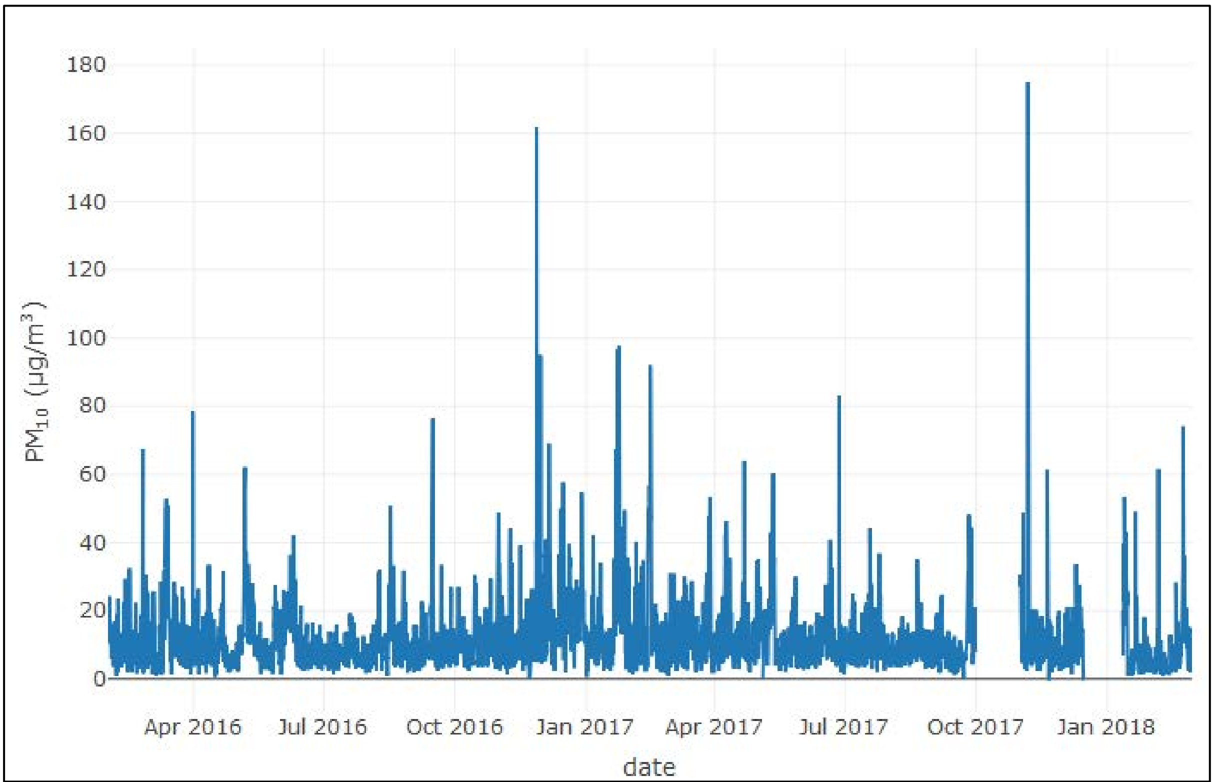
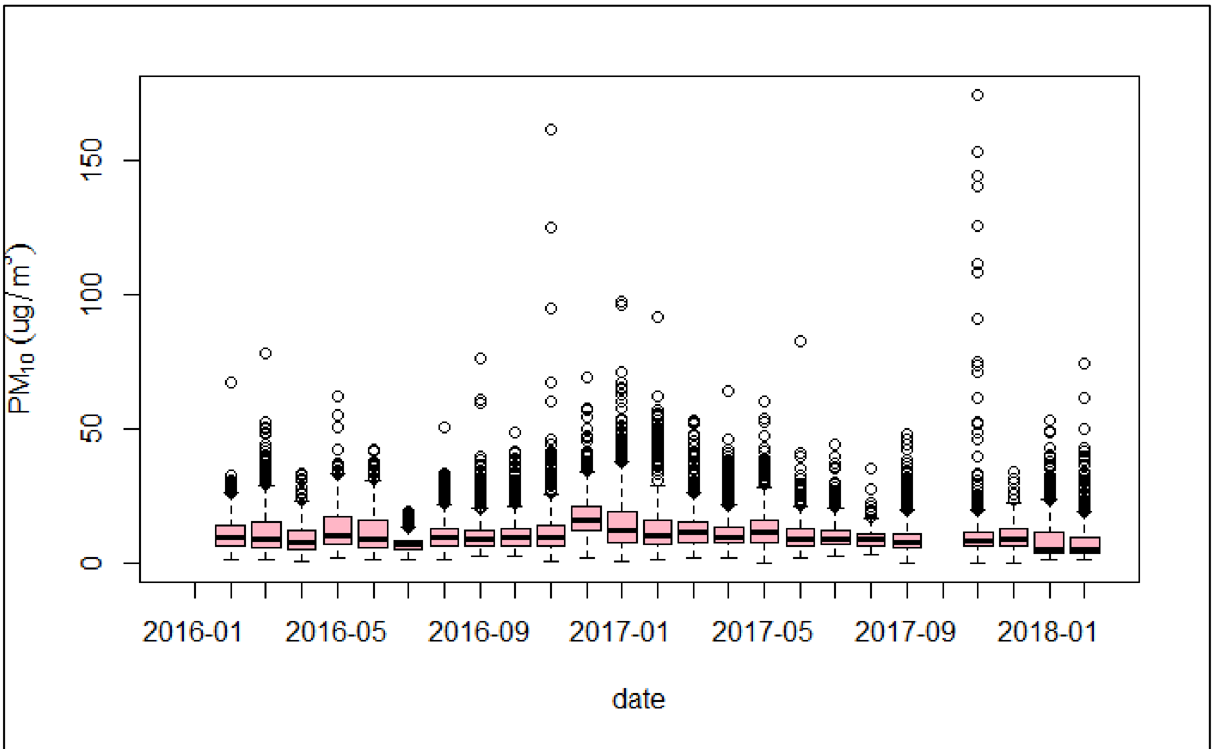
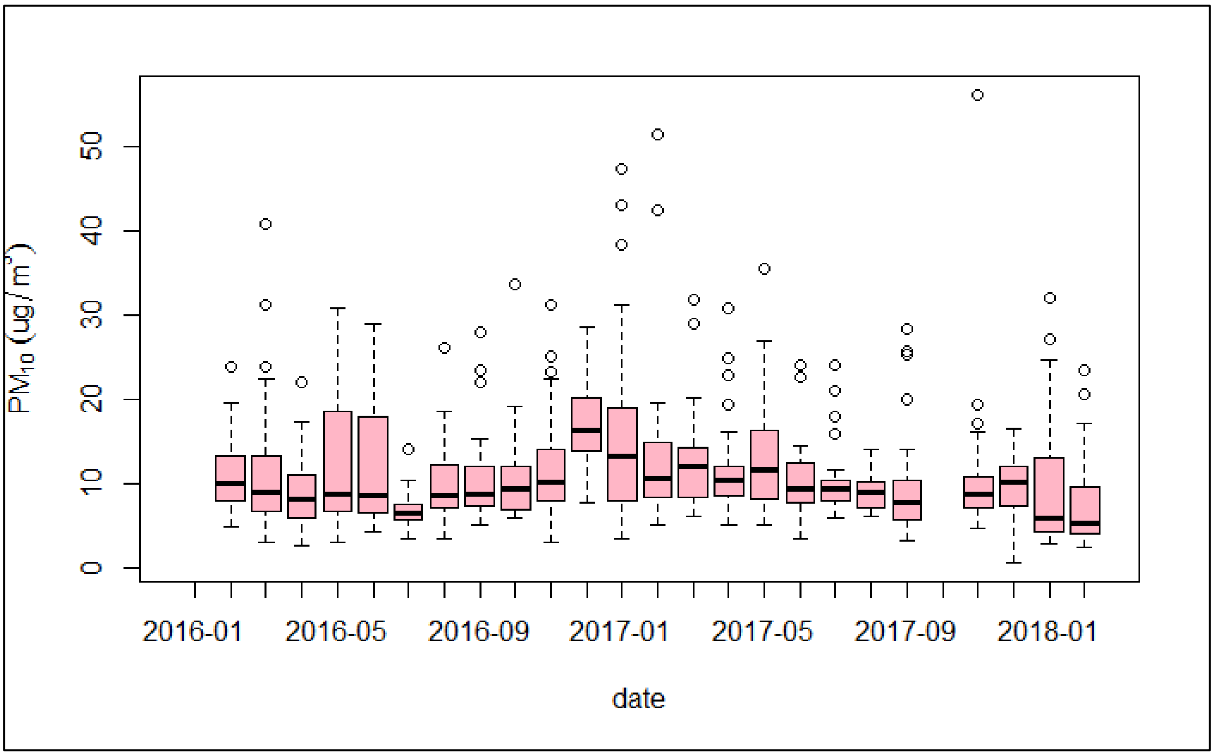


Figure 3-5: Box plot of hourly PM_{10} data by month-year collected by BGS at Preston New Road



Note: Whisker markings set at 1.5× interquartile range

Figure 3-6: Box plot of daily PM_{10} data by month-year collected by BGS at Preston New Road



Note: Whisker markings set at 1.5× interquartile range

To better understand the trends in the data, some functions in the OpenAir package of tools for air quality analysis were used. Applying the SmoothTrend function for calculating time series trends to percentiles, and TimeVariation plots, were found to be particularly useful in understanding temporal trends within the data (Figure 3.7 and Figure 3.8). These plots show that PM_{10} has a number of different temporal profiles on a daily, weekly and monthly basis, although this does highlight some potential peculiarities in the data.

Figure 3-7: Smoothed trend of monthly averaged PM_{10} data by collected by BGS at Preston New Road

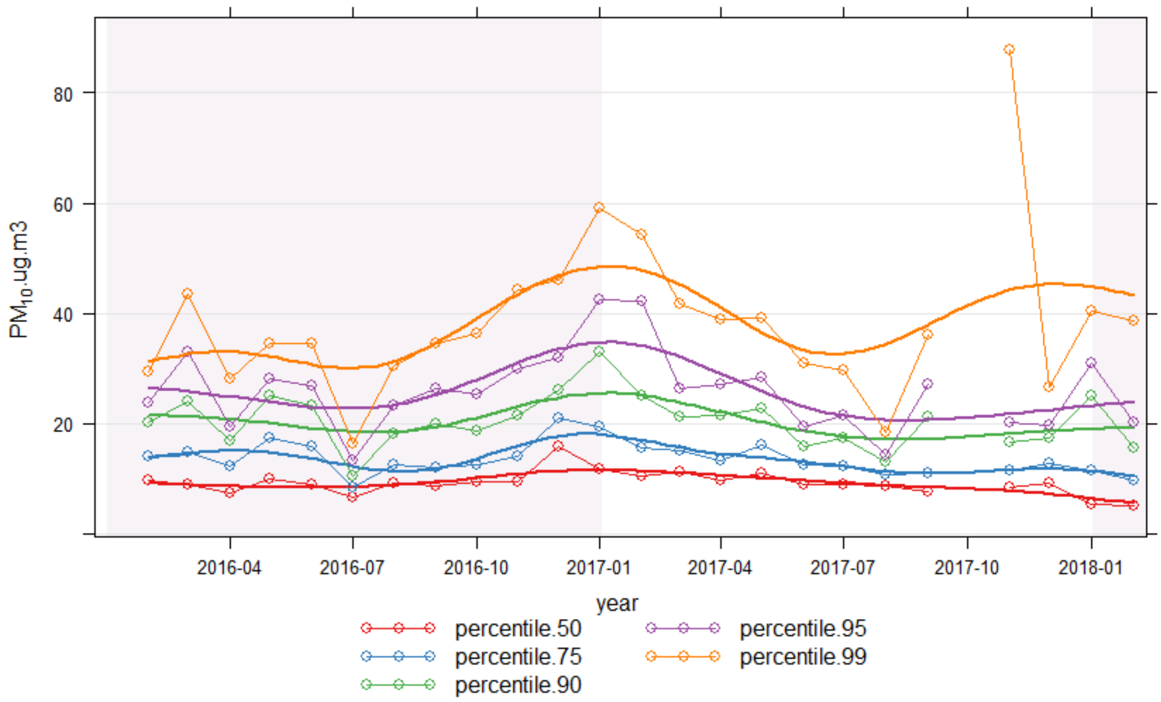
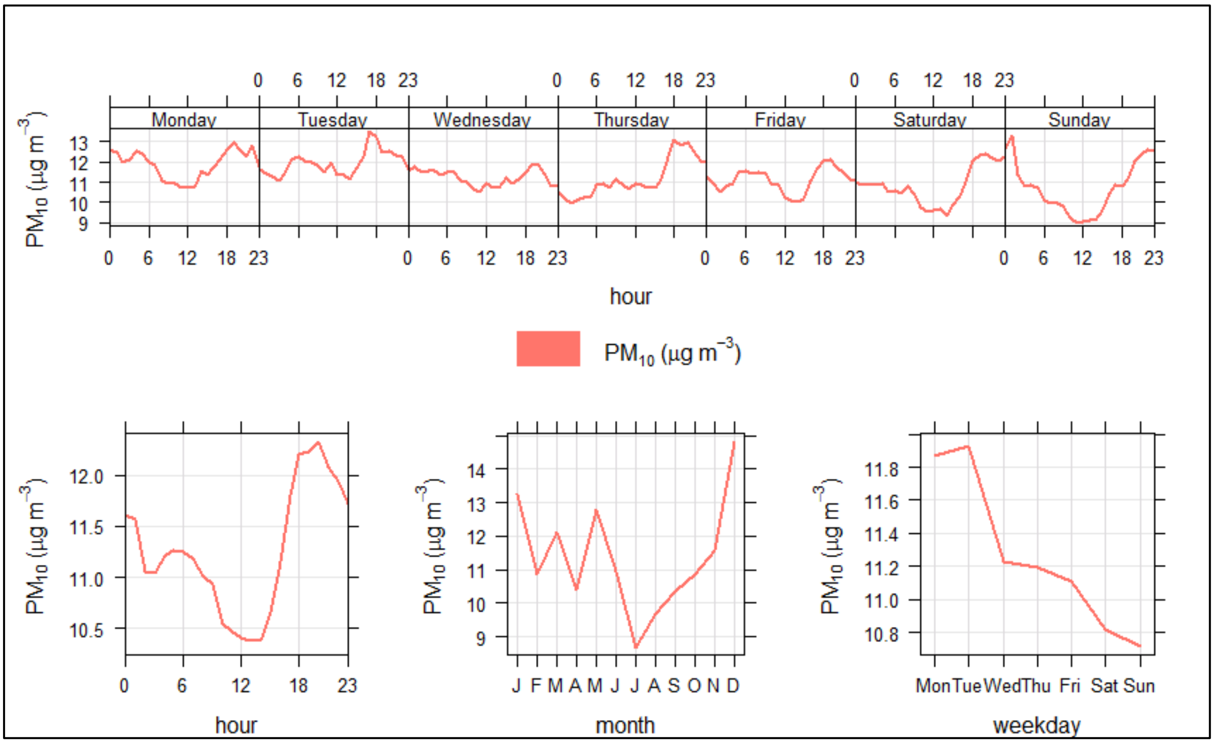


Figure 3-8: Time variation plot to show different temporal variations of mean PM_{10} data collected by BGS at Preston New Road



3.6.5 Stage 5: Detect and treat outliers

The next step in the guidelines was to detect and treat outliers. The original concept for this approach is to investigate whether outliers may be invalid data that should be removed from the analysis. However, for air quality data, invalid data is removed at stage 1 (QA/QC checks). Outliers are commonly encountered in air quality monitoring data sets, and do not normally indicate invalid data. Outliers that are not from invalid data should be included in the baseline.

Outliers are identified at stage 4 (Visualise the data). Stage 5 is investigating the outliers detected in stage 4 (as highlighted in Figure 3.5 and Figure 3.6). Examining the commonalities that outliers have can be illuminating of local sources. Outliers could occur on a single day due to a short-lived local emission event. Outliers could occur during specific wind conditions, highlighting a local source.

3.6.6 Stage 6: Test for adequacy

The final stage, identified in Figure 2.5, was to carry out a test for adequacy. This was more relevant to water quality data, where temporal resolutions are generally low, and was suggested as a way of assessing confidence in baselines for future use.

Following investigation on real-world data sets as described in section 2.6.6, it was found that testing for adequacy did not provide useful insights or tools for data analysis. It is therefore proposed to remove testing for adequacy from the recommended procedure for air quality data.

3.6.7 Stage 6 (Alternative): Using diagnostic data analysis tools

A range of tools for extracting insight and information from air quality monitoring data are freely available using the OpenAir package[10]. As described for Kirby Misperton, signal strengthening was investigated, but not found to be applicable to the Preston New Road site because of the rural nature of the monitoring station. In other scenarios where relevant sources of emissions are more regular (for example, close to a more heavily trafficked road, industrial sources or an urban site), it is recommended that signal strengthening should be considered.

The use of OpenAir tools or similar resources does provide useful insight into measured levels of PM_{10} at Preston New Road. The polar plot for annual mean concentrations (Figure 3.9) indicates that the annual mean measured concentrations of PM_{10} are most strongly influenced by a source to the south-east, which makes a significant contribution under moderate wind speeds. This suggests the influence of sources located some distance from the site, such as PM_{10} emissions from road traffic and other sources in the Preston area and using the M6.

The highest concentrations of PM_{10} occur under these south-easterly winds, but with a more significant contribution under lower wind speeds, as shown in Figure 3.10. Polar plot of the 99th percentile concentration for different wind speed wind directions hourly averaged PM_{10} data collected by BGS at Preston New Road with all available data after QA/QC is shown in Figure 3.12. This indicates that the highest peak concentrations, while not presenting any concerns with regard to potential exceedances of air quality standards, may result from more local sources such as traffic on the nearby A583 Preston New Road slowing to pass through the village of Little Plumpton.

Figure 3-9: Polar plot of the mean concentration for hourly averaged PM_{10} data collected by BGS at Preston New Road

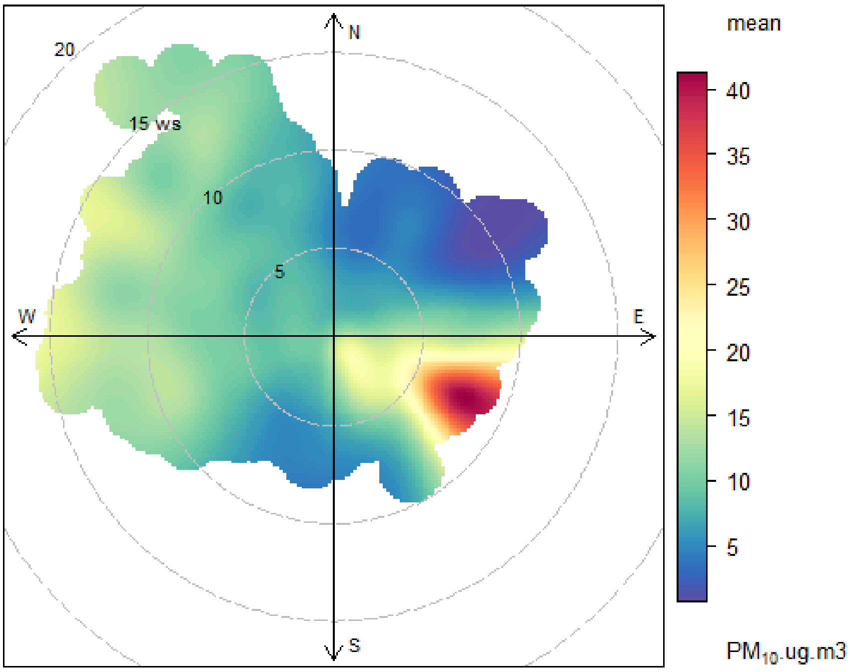
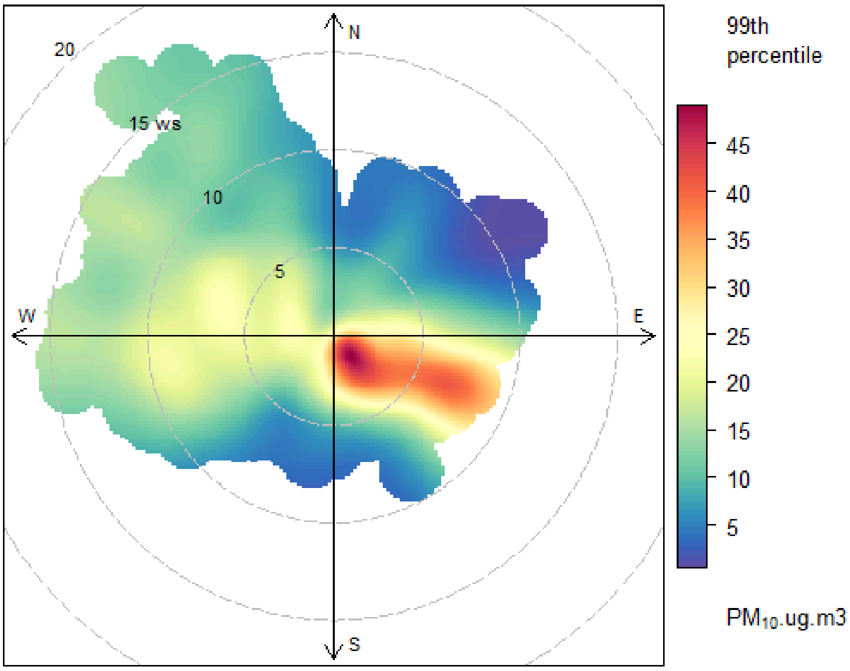


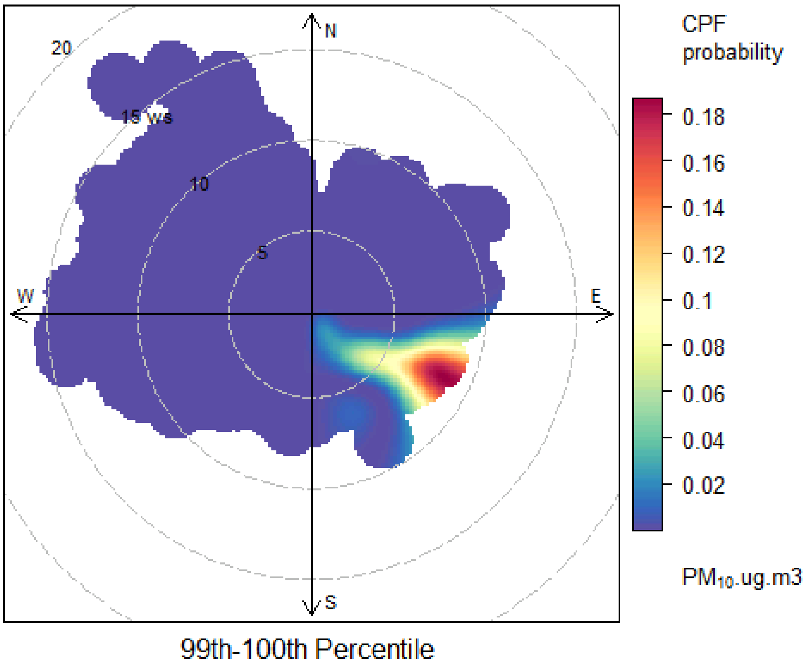
Figure 3-10: Polar plot of the 99th percentile concentration for hourly averaged PM_{10} data collected by BGS at Preston New Road



Conditional probability plots show the probability that a concentration between 2 percentile values will occur for that wind condition. These plots are useful to understand how common high concentration events are, and therefore the frequency of high emission events. Figure 3.11 shows that all the top 1% of concentrations are likely to come from the east-south-east, with wind speeds between 5 and 10 m.s-

[1]. These plots can be used for comparison during the operational phase to highlight any new sources that contribute to the highest concentrations recorded at the site.

Figure 3-11: Polar plot of the conditional probability falling between the 99th and 100th percentile for hourly averaged PM_{10} data collected by BGS at Preston New Road



3.6.8 Conclusions

The analysis of PM_{10} levels at Preston New Road confirms the findings set out in sections 2.6.10 and 2.6.11. Using polar plots for routine reporting and preliminary evaluation of measured concentrations is recommended. A recommended final summary of baseline conditions would include:

- summary statistics
- wind sector analysis using polar plots for average and higher percentile concentrations (for example, 75th percentile, 90th percentile, 95th percentile and 99th percentile)
- distribution
- time series

This information for PM_{10} (alongside the other pollutants) is provided in Appendix 3 section A3.2.

- Table A3.2 sets out summary statistics.
- Figure A3.18 provides a density plot for hourly mean PM_{10} concentrations.
- Figure A3.19 provides a one year time series for hourly mean PM_{10} concentrations.
- Figure A3.20 provides a one year time series plot for different percentile values.
- Figure A3.21 provides a time variation plot for hourly mean PM_{10} concentrations.
- Figures A3.22 to A3.25 provide conditional probability plots of hourly mean PM_{10} concentrations.
- Figures A3.26 to A3.33 provide polar plots of hourly mean PM_{10} concentrations.

The data was analysed for one year before drilling began. The dates of the baseline therefore run between 17 August 2016 and 17 August 2017.

Suggested revisions to the guidelines from Environment Agency 2019a in light of the analysis of data for Preston New Road are set out in section 4.5.

The surveys at Preston New Road were not designed in accordance with the guidelines. However, the BGS survey was informed by experience of air quality monitoring, and a conceptual model of likely emissions to air from the onshore oil and gas installation at this site.

It is concluded that the research data collected at the BGS station at Preston New Road provided a satisfactory representation of baseline air quality at the site.

3.7 Baseline groundwater and surface water quality data

The following water quality data sets were available for Preston New Road:

- measurements of 61 individual parameters (with a total of 300 measurements each) were available for 8 groundwater boreholes
- measurements for a total of 191 individual parameters (with a total of 79 measurements each) were available for 6 surface water sampling locations situated upstream and downstream of the site

The operator provided groundwater data to the Environment Agency. The Environment Agency carried out surface water sampling and analysis. The boreholes and surface water monitoring locations are shown in Figure 3.3.

A more limited example of applying the methodology to prepare the baseline data for subsequent analysis is presented below, following stages 1 to 5 set out in the modified decision tree (Figure 2.23). The full presentation of baseline groundwater and surface water data for Preston New Road is provided in Appendix 4.

3.7.1 Stage 1 – determine appropriate parameters and data sets for analysis

The determinands identified for consideration at Preston New Road are set out in Table 3.3. These parameters were defined using the methodology outlined in section 4.6.

Table 3.3: Substances identified for priority analysis at Preston New Road

Determinand group	Determinand	Surface water	Groundwater
Nutrients	Ammoniacal nitrogen	X (as N)	X (as NH4)
	Total organic nitrogen	x	
Major ions	Calcium		x
	Chloride	x	x
	Iron	x	x
	Magnesium		x
	Potassium	x	x
	Sodium	x	x
	Sulphate	x	
	Total alkalinity		x
Trace elements	Chromium	x	
	Cobalt	x	
	Copper	x	x
	Mercury	x	
Natural gas	Dissolved methane	x	x
	Dissolved carbon dioxide		x
Stable isotopes	Carbon (δ13C-CO_2)		x
Other	Acrylamide	x	x

Determinand group	Determinand	Surface water	Groundwater
	Total dissolved solids		x

3.7.2 Stage 2 - Perform quality assurance on the original data

In stage 1, data was analysed in its raw format to identify parameters that may be of priority interest in assessing baselines. Stages 2 onwards were then carried out on the prioritised substances. The outputs from applying these stages to these priority contaminants are detailed in Appendix 4. A specific example in this and the sections that follow is made of ammoniacal nitrogen. Ammoniacal nitrogen is a determinand that was deemed potentially useful for detecting pollution events because it:

- may[4] be useful as a proxy parameter for flowback fluid
- demonstrated relatively low background variability (comparative to other variables) over the baseline establishment period

The data provider carried out quality assurance and quality control of the data. Borehole data provided to the report authors contained no information on the limits of detection/limits of quantification. Data 'below the detectable limit', which we assume to be synonymous with the 'limits of detection', were flagged in the supplied surface water quality data, which allowed rulesets to be applied to these data during later analysis. For groundwater, the limits of detection were assumed for the prioritised determinands, using insights from the data and standards from the literature.

Table 3.4: Assumed limits of detection applied to borehole data

Determinand group	Determinand	Minimum measured value	Assumed limit of detection	Measurement unit
Nutrients	Ammoniacal nitrogen as NH4	0.03	0.03	mg/l
Major ions	Calcium (dissolved)	98.2	*	mg/l
	Chloride	10	*	mg/l
	Iron (total dissolved)	20	20	µg/l
	Magnesium (dissolved)	31.4	*	mg/l
	Potassium (dissolved)	1.4	*	mg/l
	Sodium (dissolved)	24.1	*	mg/l
	Total alkalinity (as CaCO3)	250	1	mg/l
Trace elements	Copper (dissolved)	7	7	µg/l
Natural gas	Dissolved methane	0.01	*	mg/l
	Dissolved carbon dioxide	9.8	*	mg/l
Stable isotopes	Carbon (δ13C-CO_2)	-63.9	*	ppm ‰. VPDB
Other	Acrylamide	50	50	µg/l
	Total dissolved solids	384	*	mg/l
	Salinity	0.1	0.1	%

Note: Asterisks denote 'Not applied; less than all recorded values'

No information was provided on duplicate measurements, values above calibration limits or values regarded as suspicious.

[4] Very high concentrations in nitrogen were seen in 'nitrogen' in the flowback fluids in Preese Hall, but speciation was not recorded.

3.7.3 Stage 3 - Define the main activities and significant phases temporally within the selected 'baseline' data sets

Table 3.5 identifies the main events and baseline periods between December 2014 and October 2018.

Table 3.5: Timeline of the main activities at the Preston New Road site

Phase	Date range	Data period
Before activities began	Up to 4 January 2017	Baseline phase 1 (P1)
Site preparation	5 January 2017 to 17 August 2017	Baseline phase 2 (P2)
Drilling	17 August 2017 to 14 October 2018 (activity 17 August 2017 to 17 July 2018)	Baseline phase 3 (P3)
Hydraulic fracturing	15 October 2018 to 2 November 2018	Operational phase 1
Well testing	2 November 2018 onwards	Operational phase 2

3.7.4 Stage 4 - Subset the data into individual contaminants and assign 'grouping parameters'

Data grouping for Preston New Road was carried out by assigning surface water measurements to 'upstream' and 'downstream' measurements, and borehole measurements to shallow and deep targeted response zones at each borehole. Groundwater measurements were not grouped.

Measured levels of ammoniacal nitrogen are presented in this section for illustrative purposes. Selecting this determinand does not imply any priority or importance, and any of the other determinands from the data sets could be of equal importance.

For ammoniacal nitrogen, measurements were as NH_4 at the 4 operator borehole locations (all on-site) for shallow and deep response zones, and as N at the 2 surface water sites (upstream and downstream of the well pad).

Appropriate data grouping parameters for further analysis in establishing baselines of surface water and groundwater data for the provided data was judged to be:

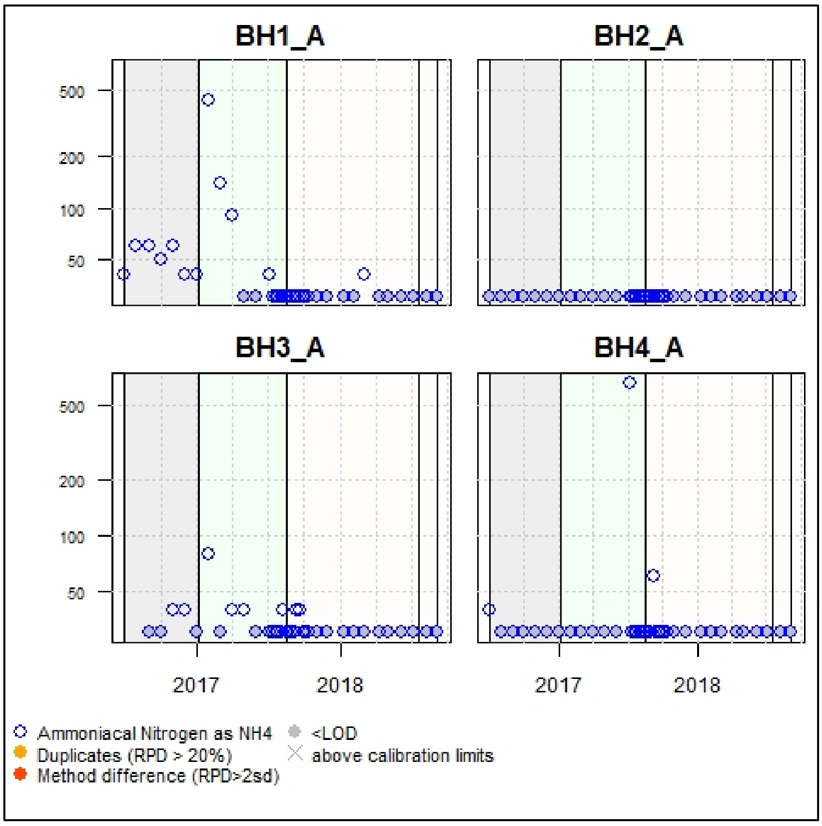
- water body type (surface water and groundwater)
- target response zone (shallow or deep)

3.7.5 Stage 5 - Display the data

Following the guidelines, the data was visualised as a series of time series and box plots. Time series plots can be used to identify changes through time, while the box plots can be used to inform the temporal resolution for outlier detection, and any seasonality in the data.

Time series plots for ammoniacal nitrogen measured in groundwater shallow and deep response zones and surface water are presented in Figure 3.12 to Figure 3-14 respectively. As with the analysis for Kirby Misperton, in these plots, the shaded areas represent the baseline periods outlined in Table 3.5. The P1 baseline phase is represented by the grey shaded box, while the P2 baseline period is represented by the green shaded box. The P3 baseline period is represented by the pink shaded box. Solid black lines represent the start and end of a measurement phase. In the case of P3, an additional solid line marks the end of physical drilling activity. Values less than the limit of detection (LOD) and values flagged under the QA/QC analysis are highlighted within all visualisations. No values in the PNR data were reported as being greater than the calibration limit of the instrumentation, and there was no duplication of methods or measurements.

Figure 3-12: Time series plots for ammoniacal nitrogen as NH_4 measurements in groundwater at Preston New Road for shallow response zones



Note: The P1, P2, P3 baseline phases are represented by the grey, green and pink shaded boxes respectively. Solid lines mark the start and end of data in these phases. In the case of P3, an additional solid line marks the end of physical drilling activity. Units are in nanograms.

Figure 3-13: Time series plots for ammoniacal nitrogen as NH_4 measurements in groundwater at Preston New Road for deep response zones

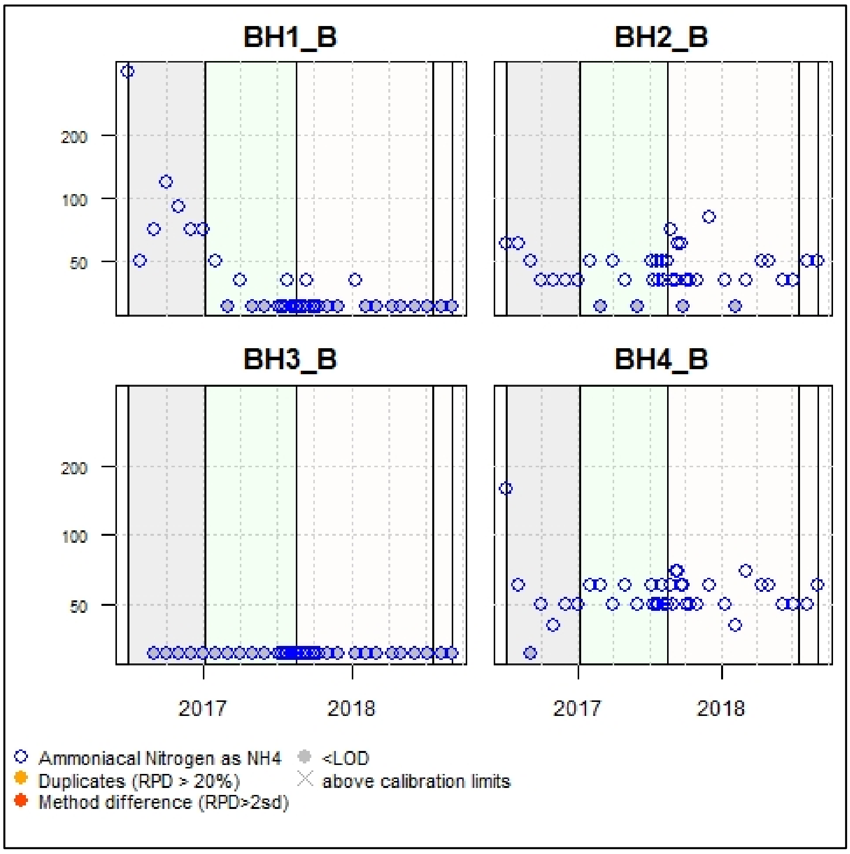
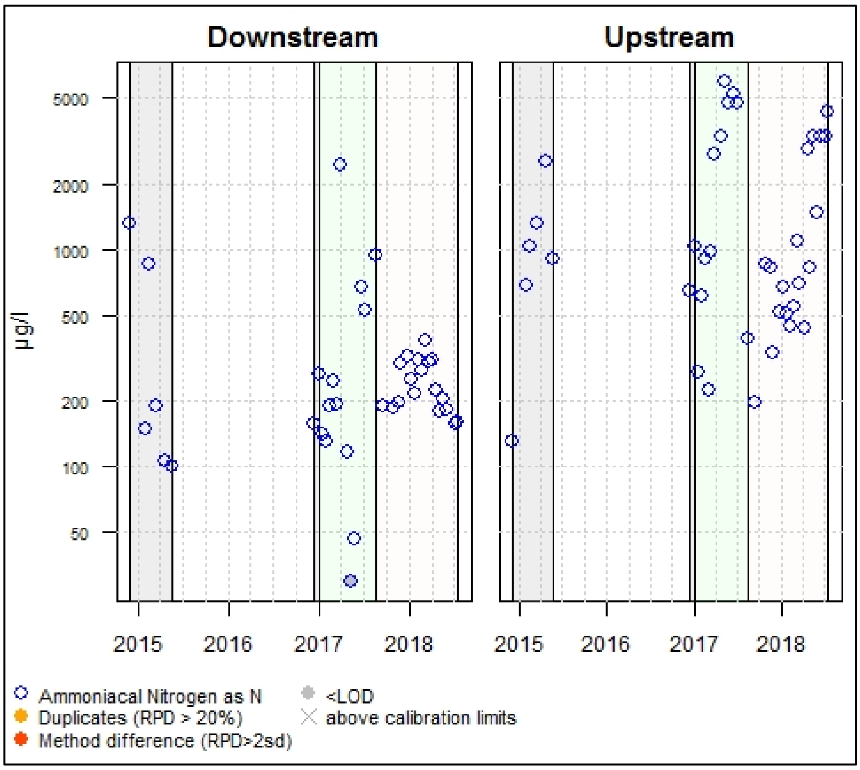


Figure 3-14: Time series plots for ammoniacal nitrogen as N measurements in surface waters at Preston New Road for surface waters



A logarithmic scale was used for the y-axis for visualisation purposes. It was noted previously that the main purpose of this stage is to visually interpret where there may be changes in behaviour, erroneous values or trends. It is not intended at this stage to investigate these observations, but rather to highlight where they may be of interest for future reference. Observations are as follows:

- **General**
    - As anticipated, values of ammoniacal nitrogen are much lower in groundwaters compared to surface waters (even accounting for the difference in measurement unit NH_4 vs N).
    - There did not appear to be any obvious extreme values in the observations.
- **Boreholes**
    - A higher percentage of values were less than the limit of detection during P1 than during the other phases across most boreholes.
    - The deep reference response zone for BH-2 and BH-4 (BH1-B and BH4-B) had higher concentrations of ammoniacal nitrogen as NH_4 than their surface water counterparts.
- **Surface water sites**
    - There appears to be no significant difference between the phases nor between upstream and downstream locations for ammonium nitrogen as N.

In the Kirby Misperton analysis, normalised time series plots of the grouped variables were created. This appeared of limited value for this variable (that is, there are no apparent similar behaviours exhibited over different magnitudes) and is not replicated here.

The recommended resolution for box plot visualisation from the guidelines produced as part of the preceding project for bi-monthly and monthly measurements was for seasonal, annual and combination season and year analysis, with outlier detection to be performed at a seasonal level.

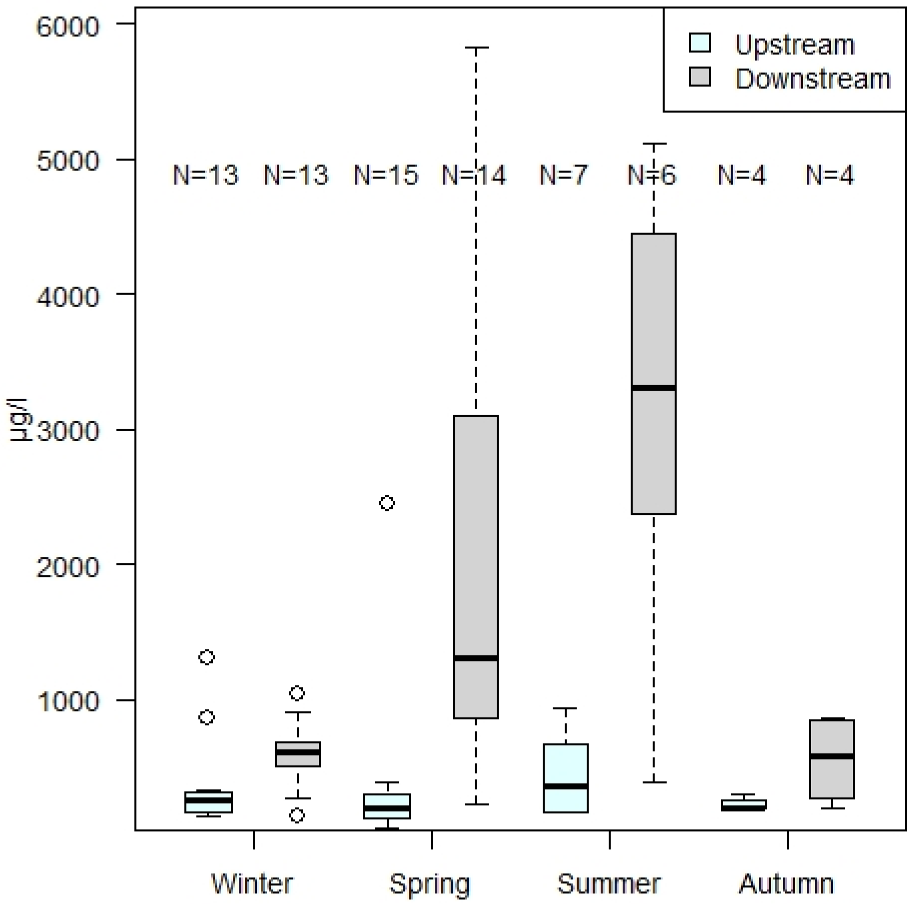
The counts of the observations that go into these combinations are shown in Table 3-6. It is apparent from this analysis that the frequency of measurement is variable between some sites and years. In some season/year combinations, no measurements are taken, whereas others have up to weekly measurements. On this basis, any interpretation of the distribution of data at seasonal or higher resolution would be inappropriate. Nevertheless, outliers of the box plot stats at this resolution will still be considered as indicative.

Table 3-6: Counts of ammoniacal nitrogen observations by site ID, year and season

Monitoring Ref	Winter				Spring				Summer				Autumn			
	2015	2016	2017	2018	2015	2016	2017	2018	2015	2016	2017	2018	2015	2016	2017	2018
BH1-A			3	2			3	3		2	10	3		3	8	1
BH2-A			3	2			3	3		2	10	3		3	8	1
BH3-A			3	2			3	3			10	3		3	8	1
BH4-A			3	2			3	3		2	10	3		3	8	1
BH1-B			3	2			3	3		2	10	3		3	8	1
BH2-B			3	2			3	3		2	10	3		3	8	1
BH3-B			3	2			3	3			10	3		3	8	1
BH4-B			3	2			3	3		2	10	3		3	8	1
Upstream	3		5	5	3		6	6			3	4			4	
Downstream	3		5	5	3		5	6			3	3			4	

For demonstration, box plots of ammoniacal nitrogen as N measurements from the surface water sites are presented in Figure 3-15. On visual analysis of this data, it did not appear affected by any underlying trend. The box plots follow the standard layout for such plots. Specifically, the central line in a box represents the median, the lower and upper bounding lines of a box represent the lower (25th) and upper (75th) quartiles, the whiskers represent 1.5 times the interquartile range (the upper quartile value minus the lower quartile value), while the dots above and below a whisker represent statistical outliers to the data.

Figure 3-15: Box plots for ammoniacal nitrogen as N measured at surface water sites



As with the time series analysis, some brief comments are made. The main elements are:

- 5 statistical outliers were identified. These values are associated with the winter and spring measurements and are within the range observed across the year, and so would not be considered erroneous
- as observed in the time series plots, measurements of ammoniacal nitrogen are generally higher downstream compared to upstream of the site

The seasonal variation is difficult to interpret given the difference in observation counts between winter and spring, and summer and autumn.

3.7.6 Conclusions

This partial presentation of baseline water quality monitoring data for Preston New Road provides a further demonstration of the presentation of summary data for an onshore oil and gas installation. All data were collected during the pre-operational period (P1) and the site preparation period (P2 to P3). There were no apparent changes in measured baseline levels between these periods. In particular, there were no apparent increases in baseline concentrations of selected substances during drilling at the Preston New Road site (Period P3).

Following completion of the remaining data preparation and review stages 6 to 9, it would be possible to investigate these qualitative observations further using tools for detecting change.

It was concluded that the collected data at Preston New Road can be used for developing an assessment of baseline groundwater and surface water conditions. Recommendations for standard data presentation packs are provided in section 4.7.9.

The measured data for the main determinands is provided in Appendix 4.

4 Suggested revisions and clarifications to guidelines

Based on applying the guidelines from Environment Agency 2019a for statistical assessment of baseline air quality to real-world data, the following suggestions for improving these guidelines are made. Some propose a change in the guidelines, but the majority of suggestions recommend providing further detail on applying the existing guidelines.

4.1 Definition of baseline period

It is important to consider a number of different phases of activity when analysing baseline and operational phase data.

In principle, the phases of activity at an individual hydraulic fracturing site are likely to include one or more of the following:

1. before any onshore oil and gas (OOG) activity begins
2. site preparation, including moving earth /levelling/concreting site, bringing plant to site
3. drilling and associated activities such as waste disposal
4. hydraulic fracturing
5. flowback and ongoing production
6. site closure
7. managed abandonment

The present project covers the first 5 of these stages. Stages 1 and 2 represent baseline activities, stages 3, 4 and 5 represent operational phases, and stages 6 and 7 represent the site closure phase.

The 3 types of measurement considered in this project respond over different timescales. Any pollutants discharged to groundwater could take a significant time to reach groundwater monitoring boreholes. In contrast, pollutants discharged to surface water or to the atmosphere, which pass a sampling/measurement point, would be expected to transfer rapidly, and effectively instantaneously, the measurement location. It is therefore appropriate to consider these periods in different ways when considering air quality, surface water and groundwater quality monitoring data.

Table 4.1: Onshore oil and gas installation phases

Activity phase	Treatment for:		
	Air quality data	Surface water quality data	Groundwater quality data
1. Before OOG activity begins	AQ phase 1: Before activity begins	WQ phase 1: Before activity begins	GW phase A: Baseline
2. Site preparation	AQ phase 2: Site preparation	WQ phase 2: Site preparation	
3. Drilling	AQ phase 3: Drilling	WQ preparatory phase 3: Drilling	
4. Hydraulic fracturing	AQ phase 4: Hydraulic fracturing	WQ phase 4: Hydraulic fracturing	GW phase B: Operational
5. Flowback and extraction	AQ phase 5: Flowback/extraction	WQ phase 5: Flowback/extraction	

The responses of surface water and groundwater to pollution events are significantly different. Surface waters are rapidly responding and any potential impacts from site activities, such as drilling, processing, hydrocarbon or flowback fluid spillages could quickly impact on a watercourse. Similarly, these impacts may be rapidly improved due to flow in a watercourse. Compared with groundwaters, contributing influences on quality (for example, an upstream sewage treatment works) are relatively easy to identify and factor into an assessment of upstream and downstream monitoring locations. The differences in phase consideration between surface waters and groundwaters, proposed in Table 4-1, reflect the likely difference in response times and larger effects of dilution between these 2 types of water body. As an example, fine sediment pollution that could occur during construction of bunds or hydrocarbon pollution from vehicles in surface waters is unlikely to be as apparent in groundwaters and therefore not isolated as a distinctly different phase.

4.2 Historical groundwater contamination

For groundwater, movement of water through either the voids between particles (intergranular flow) or through fractures (fracture flow) can be several orders of magnitude slower than that in surface waters (although groundwater movement by fracture flow can be very rapid when compared to intergranular flow). It may also take time for any contaminants to be transported to the groundwater. Therefore, the effects of any spillage or contamination may take much longer to be observed in groundwater than in surface waters. The response of groundwater is further complicated by the properties of the aquifer and the interaction with wider geological features. This means that baseline selection at individual sites where an aquifer is present is usually highly site specific. Unlike rivers, identifying flow direction of groundwater can be difficult. These flow directions can sometimes change seasonally as groundwater levels change, especially in the case of superficial aquifers. There is also the conceptual consideration of establishing a baseline in an aquifer since most aquifers have been variously impacted by human activity for decades or indeed much longer. This includes diffuse nutrient pollution or abstraction for drinking water supplies. Indeed, very few aquifers actually represent truly natural and unmodified conditions. Such information should be considered on a site by site basis.

In some cases, especially where surface waters have a baseflow component, for example groundwater contributing to river flow which is supplied by an aquifer, there is the possibility that hydraulic fracturing activities that directly impact groundwater could indirectly impact linked surface waters. In such cases, this should be taken into account when designing and interpreting baseline surface water quality surveys.

4.3 Development of conceptual model

There are no significant changes to the recommendation that a conceptual model should be developed or to the guidelines on key issues for consideration[4].

Although the conceptual model relates to monitoring survey design, existing conceptual models were reviewed as part of the study since they provided important information on selecting monitoring sites and also information on specific important features when interpreting baseline data, for example the subsurface geological structure or the influence of wider pollution sources on air quality around a site. Furthermore, at Kirby Misperton, off-site operator groundwater monitoring boreholes were all found to be located downgradient from the site, which is not optimal for baseline data analysis. This reiterates the importance of using a conceptual model as part of the design process for developing a baseline groundwater survey, and for interpreting baseline data.

4.4 Survey design in relation to the report on adaptive monitoring for air quality

In strict terms, recommendations in relation to survey design lie outside the scope of this project, as these recommendations are not directly linked to interpreting baseline data (although survey design is, of course, critical to the scope and quality of data available for interpretation). However, the guidelines on air quality monitoring were reviewed in light of the completion of the shale gas Ambient Monitoring Framework report[7].

The report on adaptive monitoring provided recommendations for conducting an ambient monitoring campaign at shale gas sites in England, following the completion of an air quality impact assessment of a conceptual shale site. The framework aimed to provide a dynamic approach to ambient air quality monitoring at shale sites, and recommended 3 levels of surveillance:

- **Routine surveillance** – provides a starting point (or base case) for most sites, and includes typical monitoring requirements for specified pollutants that should be applied as a default in all cases (unless reduced and/or enhanced surveillance is indicated).

- **Reduced surveillance** – appropriate for pollutants and sites that are identified to be low risk, low concentration and low impact.

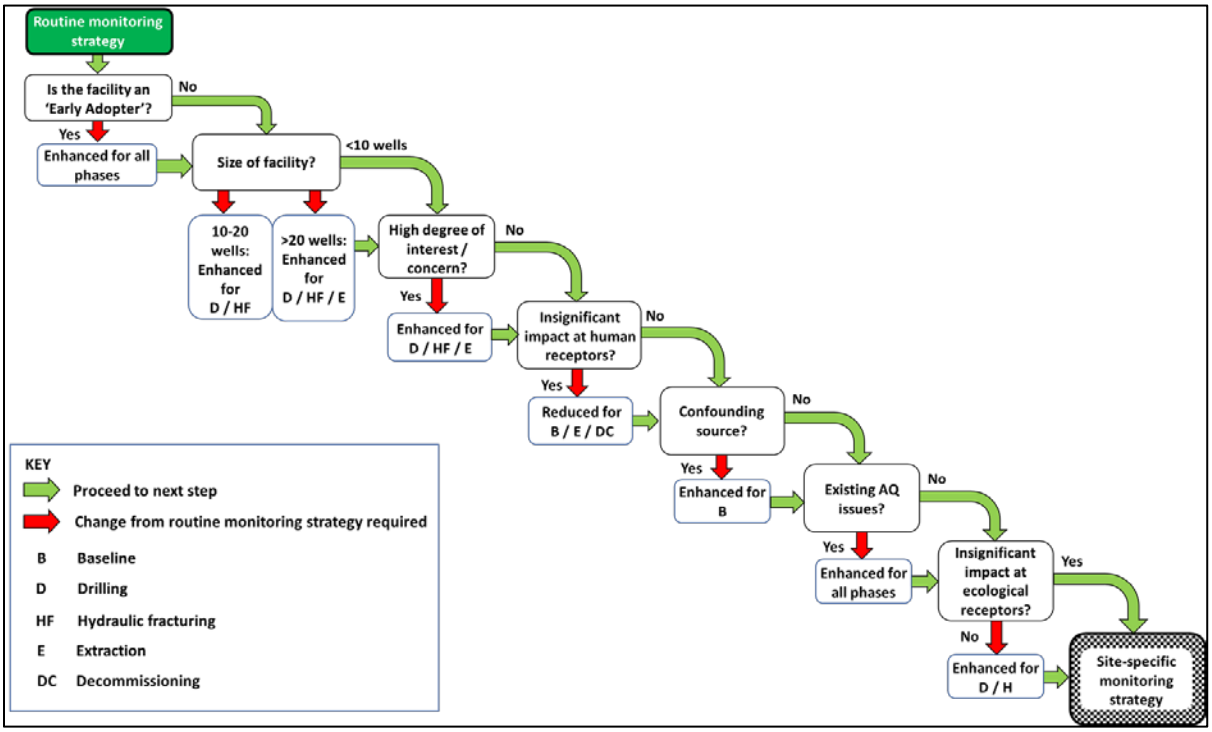
- **Enhanced surveillance** – extends the routine surveillance if needed, by applying a targeted higher level or duration of monitoring for one or more pollutants.

The framework recommends users provide the following information on the characteristics of the site:

- Is the facility an ‘early adopter’?
- What size is the facility?
- Does the operator have a history of regulatory problems?
- Will the facility be situated close to sensitive receptors?
- Is the facility located close to a confounding source?
- Does local ambient air quality data indicate existing air quality issues?
- Is the facility located close to protected ecological sites?

The framework uses these site characteristics to guide the decision-making process for developing a monitoring strategy, as illustrated in the following monitoring strategy decision tree.

Figure 4-1: Monitoring strategy decision tree recommended in the report on adaptive monitoring



Once the applicable surveillance level is identified, operators would be required to apply recommended monitoring approaches, which reflect the potential risks posed by each pollutant to ambient air quality throughout the phases of a shale gas site, and the likely costs of implementation.

The review of the monitoring guidelines, and application of the statistical approach to monitoring data collected at Kirby Misperton and Preston New Road, completed under this project, has confirmed the importance of some of the recommendations put forward in the report on Unconventional Oil and Gas Ambient Monitoring Framework,[7] and highlighted some aspects of the proposed monitoring framework that may need revising. These are summarised below:

- **Monitoring durations** – The analysis of ambient air quality data indicates that, for most pollutants, monitoring for less than 6 months is not enough to gather a reliable and comprehensive data set. For the air pollutants most relevant to onshore oil and gas activities, including NO_2, PM_{10} and NMVOCs, it may be appropriate to require a baseline assessment of at least 12 months before any site activities begin. Furthermore, given the irregular nature of site activities at shale facilities, it may also be appropriate for monitoring durations to be completed for the length of each phase (that is, until the operator has confirmed these activities have stopped), rather than for a recommended minimum duration (for example, 3, 6, 9 months).
- **Monitoring frequencies** – The analysis of data collected at Kirby Misperton and Preston New Road has highlighted the value in collecting continuous data over passive or grab samples. Although continuous monitoring does carry an additional cost and technical burden, it provides far greater clarity on short-term fluctuations in ambient concentrations, and when combined with local meteorological data, would allow these changes to be more accurately characterised and differentiated from potential confounding sources. Recommendations for continuous monitoring approaches put forward in Environment Agency 2019b remain valid.
- **Monitoring locations and preliminary dispersion modelling** – Ambient monitoring data collected at 2 locations at Preston New Road illustrated a significant difference in pollutant concentrations recorded simultaneously. This highlights the fact that data collected at a single monitoring location will not provide the full picture for changes in ambient air quality. This is particularly the case where the source signals are varied in intensity, timing and location, such

as at shale gas facilities. It may therefore be appropriate to use 2 monitoring locations that straddle the site in alignment with the predominant wind direction. This analysis has also demonstrated the critical need to use dispersion modelling to identify monitoring locations that offer the greatest potential for identifying signals from shale gas facilities, as operations move from phase to phase.

4.5 Establishing a baseline – air quality

Based on experience of applying the guidelines set out in the report on assessing the statistical significance of change (Environment Agency 2019a), it is concluded that chapters 2, 3 and 4 of the report provide valuable guidelines on survey design. The following revisions are proposed for designing baseline air quality surveys and interpreting the data.

- A limited range of parameters is typically available for air quality monitoring surveys. Nevertheless, attention should be focused on the most relevant substances, and there should be a stage in the survey design decision tree covering selecting pollutants. This would lead users to focus on substances for which air quality standards and guidelines have been established, and/or substances that could potentially be emitted from onshore oil and gas installations and associated activities. This is discussed further in section 4.5.1.
- The report on the statistical significance of change was prepared on the basis that a well-defined ‘baseline’ period could be established. In practice, ‘baseline’ conditions may be harder to define (for example, at Kirby Misperton, a permitted onshore oil and gas activity has been in operation throughout the survey period). The guidelines could usefully be amended to provide for a range of activity periods, which could then be assessed individually, provided there is enough data available in each period. This will require clear and regular information from site operators about what activities they are carrying out and when.
- Following investigation on real-world data sets, it was found that testing for adequacy did not provide useful insights or tools for data analysis. It is therefore proposed to remove testing for adequacy from the recommended procedure for air quality data.
- Signal strengthening techniques should be investigated, but are unlikely to be effective in situations where local sources are intermittent or irregular. Advanced monitoring data analysis tools such as polar plots should be used for routine presentation of baseline data, and a wider range of tools can be used if measured levels of air pollutants during site preparation, drilling or operational phases give cause for concern.
- An alternative approach was suggested in a previous study of air quality measurements at an onshore oil and gas facility, which used a ‘factorisation approach’ (Environment Agency, 2019c). The analysis carried out in this report indicated that this approach would be unsuitable for ambient air quality data collected at hydraulic fracturing facilities. However, further testing of this approach, using a larger data set is recommended.
- Appropriate statistical descriptors and presentations of baseline air quality data should be used, as set out in section 4.5.2.

4.5.1 Identifying substances

Recommendations for identifying substances to be included in an ambient air quality monitoring campaign at shale gas sites in the UK are summarised in **Table** 4.2.

Table 4.2: Recommended monitoring methods for emissions from shale gas facilities during baseline period. From Environment Agency, 2019b[7]

Substance	Monitoring surveillance required	Proposed approach	Monitoring duration	Monitoring frequency	Monitoring method
NOx/NO_2	Reduced	Ambient monitoring	6 months	Cumulative - short-period	Passive samplers
	Routine	Ambient monitoring	6 months	Continuous - hourly	Chemiluminescence
	Enhanced	Ambient and roadside monitoring	One year ambient; 6 months roadside	Continuous - hourly	Chemiluminescence
SO_2	Reduced	No monitoring required; data from Automated Urban and Rural Network (AURN) sufficient for baseline			
	Routine	No monitoring required; data from AURN sufficient for baseline			
	Enhanced	Ambient monitoring	3 months	Continuous – hourly	UV fluorescence, Fourier Transform Infra-Red (FTIR) or electrochemical
CO	Reduced	No monitoring required; data from AURN sufficient for baseline			
	Routine	No monitoring required; data from AURN sufficient for baseline			
	Enhanced	Ambient monitoring	3 months	Continuous - hourly	UV fluorescence, FTIR or electrochemical
Ozone	Reduced	No monitoring required; data from AURN sufficient for baseline			
	Routine	No monitoring required; data from AURN sufficient for baseline			
	Enhanced	Ambient monitoring	6 months	Continuous – hourly	Electrochemical
Particulate matter (PM_{10} & $PM_{2.5}$)	Reduced	No monitoring required; data from AURN sufficient for baseline			
	Routine	Ambient monitoring	6 months	Continuous – hourly	Tapered Element Oscillating Microbalance (TEOM), Beta-Attenuation Monitor (BAM) or optical light scattering
	Enhanced	Ambient and roadside monitoring	One year ambient; 6 months roadside	Continuous - hourly	TEOM, BAM or optical light scattering
Benzene and non-methane volatile organic compounds (NMVOCs)	Reduced	No monitoring required; data from hydrocarbon network sufficient for baseline			
	Routine	Ambient monitoring	6 months	Cumulative - short-period	Passive samplers
	Enhanced	Ambient monitoring	One year	Continuous - hourly	Gas chromatography (GC) or GC mass spectroscopy

Substance	Monitoring surveillance required	Proposed approach	Monitoring duration	Monitoring frequency	Monitoring method
Polyaromatic hydrocarbons (PAHs), assessed as benzo-a-pyrene (BaP)	Reduced	No monitoring required; data from PAH network sufficient for baseline			
	Routine	Ambient monitoring	6 months	Cumulative - short-period	High/low volume samplers (minimum 2 samples per month)
	Enhanced	Ambient monitoring	One year	Cumulative - short-period	High/low volume samplers (minimum 2 samples per month)
CH_4	Reduced	Ambient monitoring	3 months	Continuous - hourly	Flame ionisation detector (FID) or FTIR
	Routine	Ambient monitoring	6 months	Continuous - hourly	FID or FTIR
	Enhanced	Ambient monitoring	One year	Continuous – hourly	FID or FTIR

It may be that some additional pollutants are monitored but their analysis is not recommended as part of this guidance. The value of collecting this monitoring data may have some scientific value, as well as potentially helping when identifying sources, as some pollutants may highlight specific sources when analysed together with other recommended pollutants. For example, in the above assessments additional PM fractions were available but chosen not to be analysed, however they may still have value.

4.5.2 Statistical descriptors

In this study, there was initially an attempt to complete statistical change analysis as part of the test for adequacy. Using statistical descriptors and statistical change analysis was included in the original guidelines to inform practitioners of the potential issues with low volume data (short duration and low frequency); an issue that is more likely to arise in relation to water quality data sets. For air quality, data is more likely to be of sufficient duration, and therefore this step was not considered a requirement for air quality.

Attributing a change in emissions for air quality data should be through using wind sector analysis and carried out together with, or in parallel to, mean, median and percentile statistics to provide a 'data pack of outputs' to represent 'baseline' conditions for a period of one year.

In view of this, it is recommended that a summary of baseline air quality conditions would include:

- confirmation of the dates of the baseline period, together with a commentary on why this period is considered to be an adequate reference period that represents local air quality before any perturbation by OOG activities
- summary statistics – for example, mean, 50th percentile, 75th percentile, 90th percentile, 95th percentile, 99th percentile. Additionally, for substances with established standards or guidelines, a comparison with the applicable air quality standard/guideline should be provided
- wind sector analysis using polar plots for average and higher percentile concentrations (for example, 75th percentile, 90th percentile, 95th percentile and 99th percentile)
- distribution plots
- time series plots

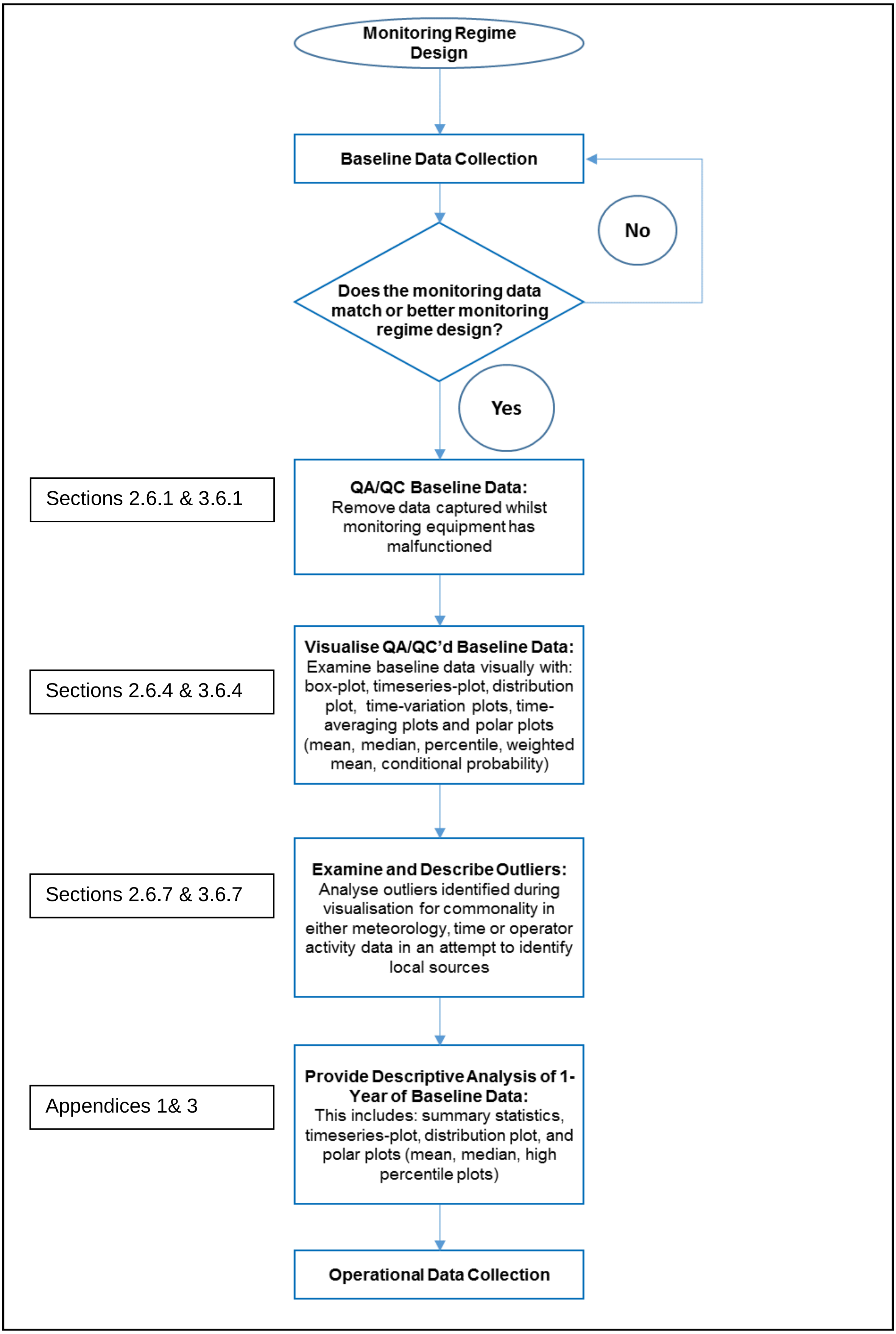
4.5.3 Update to previous guidelines

The analysis carried out in this study has allowed specific recommendations to be integrated into the guidelines on establishing baselines put forward in the report on assessing the statistical significance of change (Environment Agency 2019a). These recommendations include:

- defining a baseline period that appropriately reflects the conditions at the site before any activities associated with the shale gas development take place
- providing an explanation of the methods for detecting change that the baseline is designed to enable. For example, it should be explained that the baseline will allow directional and frequency analysis of elevated-concentration events, so any new patterns of event can be distinguished from pre-existing patterns
- developing a conceptual model, reflecting the emission sources, nature of the emissions, pollutants and receptors
- determining statistical descriptors for air quality data
- a monitoring survey designed to reflect an adaptive, risk-based approach
- preparing and maintaining an operator log, alongside the monitoring survey

These principles have been incorporated in an update to the flow diagram presented in the report on assessing the statistical significance of change, as presented in Figure 4.2.

Figure 4-2: Updated flow diagram for establishing air quality baseline



4.6 Establishing a baseline - water quality

The main findings from the assessment of water quality data were that the guidelines set out in the report on assessing the statistical significance of change (Environment Agency 2019a) could usefully be updated as follows:

- baseline surveys should account for identifying what parameters among large and varied suites of monitored values, are of priority interest in assessing baseline characteristics
- baseline surveys should explicitly account for the implications of changes in source data (for example, changes in laboratories)
- include a stage for deterministic assessment of values where the majority of values are less than the LOD/LOQ
- include a stage to group values and determine grouped baseline (for groundwater data only)
- incorporate additional data selection ('Identifying lines of evidence')
- provide an alternative to the approach on adequacy for non-expert users, including setting indicator values in assessing confidence in the expressions of baselines
- provide specific guidelines on presentation of statistical descriptors

Following a review of the relevant sections of the guidelines on establishing baselines and applying these to the data, 9 basic steps were identified. The two steps were to 'determine appropriate parameters/data sets for analysis (using conceptual model and stats guidelines)', covering substance data (step 1) and additional data (step 2). This is described more fully in the following subsections. Other steps 3 to 9 are more closely aligned with the previous guidelines under the establishing baselines flow diagram and are therefore not individually described.

4.6.1 Selecting substances

It is relatively straightforward to measure a wide range of substances. Generally, they will be selected based on their relevance to the site activity. However, this is not always the case. In the context of measuring the impact potential of a shale gas facility on water quality not all information may be relevant. Consequently, it is important to identify a targeted range of substances that can directly, or as a proxy, indicate pollution. Therefore, the available substances should be prioritised to avoid focusing on substances that are not relevant or do not indicate any impacts from pollution from shale gas activities.

The following process is proposed to determine which substances should be prioritised for subsequent analysis. There are 3 main steps to this process and these are outlined as follows:

1) List all measured substances available from a site monitoring programme.
2) Understand how each substance is related to 4 specific categories:
    a. **recommended parameter –** Is the substance listed or considered within any current relevant guidance on understanding and/or monitoring the impacts of OOG activities? For example, is it based on the guidance published by the regulator (for example, the Environment Agency) or an acknowledged expert body (for example, British Geological Survey)? This category represents an industry-specific substance of interest but may not be a site-specific substance of importance
    b. **permit parameter –** Is the substance explicitly listed for monitoring on an Environment Agency permit? This will be a site-specific parameter related to the activity being permitted, however it should be noted that this substance may not be specific to shale gas activities and may not be an industry specific substance of interest
    c. **site-specific –** Is the substance considered to be a concern or indicate a problem from a site-specific standpoint? It is likely that such a substance will have been identified from a conceptual model, supporting data and industry experience, expert interpretation or could be a specific component of a hydraulic fracturing fluid or

flowback fluid. This category will represent a substance that is of importance within the shale gas industry and also on a site-specific basis. Such a substance could therefore be considered high priority when compared with other substances. In this instance, a higher weighting could be applied to ensure that these substances are appropriately considered in this process

d. **low variability –** Does the substance show a low variability? This is calculated with reference to the upper quartile, lower quartile and median of the measured data for each substance. This ranking helps highlight substances that are relatively invariant in the natural environment but may show clear change in response to pollution from hydraulic fracturing activities

3) Where a substance falls under the recommended parameter, permit parameter or low variability category, the substance is assigned a score of 1 for that category. If the substance falls under the site-specific category, it is assigned a score of 1.5, representing a higher weighting due to the importance of the substance. If a substance does not fall under a category, no score is given.

After scoring all substances against each of the 4 categories, a priority score is calculated (with the site-specific category weighted) by adding the weighted scores.

Priority score = A + B + C + D

Where:

A = Recommended parameters

B = Permit parameter

C = Site-specific parameter

D = Low variability

An example of this approach is provided in Table 4.3.

Table 4.3: An example of prioritising substances using the proposed method

Group	Substance	Recommended parameter	Permit parameter	Site-specific substance	Low variability	Priority score
Dissolved gasses	Methane	1	1		1	3
	Ethane	1	1			2
	Butane		1			1
Major anions	Chloride	1			1	2
	Sulphate	1				1
	Carbonate					0
	Fluoride		1			1
Organic chemicals	PAH	1				1
Heavy metals	Iron		1	1.5		2.5
	Lead		1			1
	Copper		1	1.5		2.5
Other	ionic/non-ionic surfactants	1		1.5		2.5
	Alkalinity		1		1	2
	Electrical conductivity	1		1.5	1	3.5

4.6.2 Selecting additional data

Using additional data to help develop the area of interest around a site as well as support the analysis of measured data is recommended in accordance with normal practice for investigating influences on surface and groundwater quality. This additional data can take a number of forms. However, a range of relevant data are identified. These include:

surface water flows – to understand the frequency and magnitude of changes in discharges in a surface watercourse (although noting that this data is not always available for smaller watercourses, and consequently not relevant to the examples considered in this study)

topographical models – specifically geospatial interpretation of digital elevation models (DEMs) to understand surface flow vectors and surface water catchments

local meteorological data – this can include rainfall total, wind direction and temperature, and is useful in interpreting measurements, for example understanding linkages between rainfall and peaks in suspended solids in a surface watercourse

hydrogeological measurements – these include measurements in groundwater level and aquifer properties that can be used to identify groundwater flow direction, hydrological connectivity

geological information – this includes analysis of the vertical arrangement of strata, their composition and mineralogical properties and hydrogeology and structural geology (for example, faulting, folding, dips and strikes)

abstractions and discharges – surface and groundwater abstractions and discharges. These may indicate important receptors or contributors/drivers to water quality

These data sources should be considered on a per application basis and integrated into subsequent analyses as appropriate.

4.6.3 Presenting statistical descriptors

The recommended descriptors for each prioritised measurement are as follows:

1. individual site time series
2. grouped time series data normalised mean across the group
3. grouped data box plots
4. individual site statistics
5. grouped data statistics

Examples of individual site time series, box plots and summary statistics for conductivity at Kirby Misperton are provided in section 2.7 and for ammoniacal nitrogen at Preston New Road in section 3.7.

4.7 Guidance on establishing a baseline (water quality)

This section provides an update to the guidelines for water quality[4]. It is set out through a series of decision trees (Figure 4.3, Figure 4-4, and Figure 4-5) with accompanying guidance notes, mirroring the approach used previously.

Figure 4-3 details stages 1 to 4 of the process. The approach for establishing baselines for stage 5 onwards depends on the determinand of interest (that is, if the majority of values are large enough to exceed the limit of detection (LOD) and/or quantification (LOQ). For determinands where the majority of measurements exceed LOD/LOQ thresholds, the steps set out in Figure 4-4 (full quantitative assessment) should be followed or the process set out in Figure 4-5 (deterministic assessment) should be adopted. Guidance notes are numbered and link to the decision trees.

Figure 4-3: Decision tree for stages 1 to 4 of setting a baseline

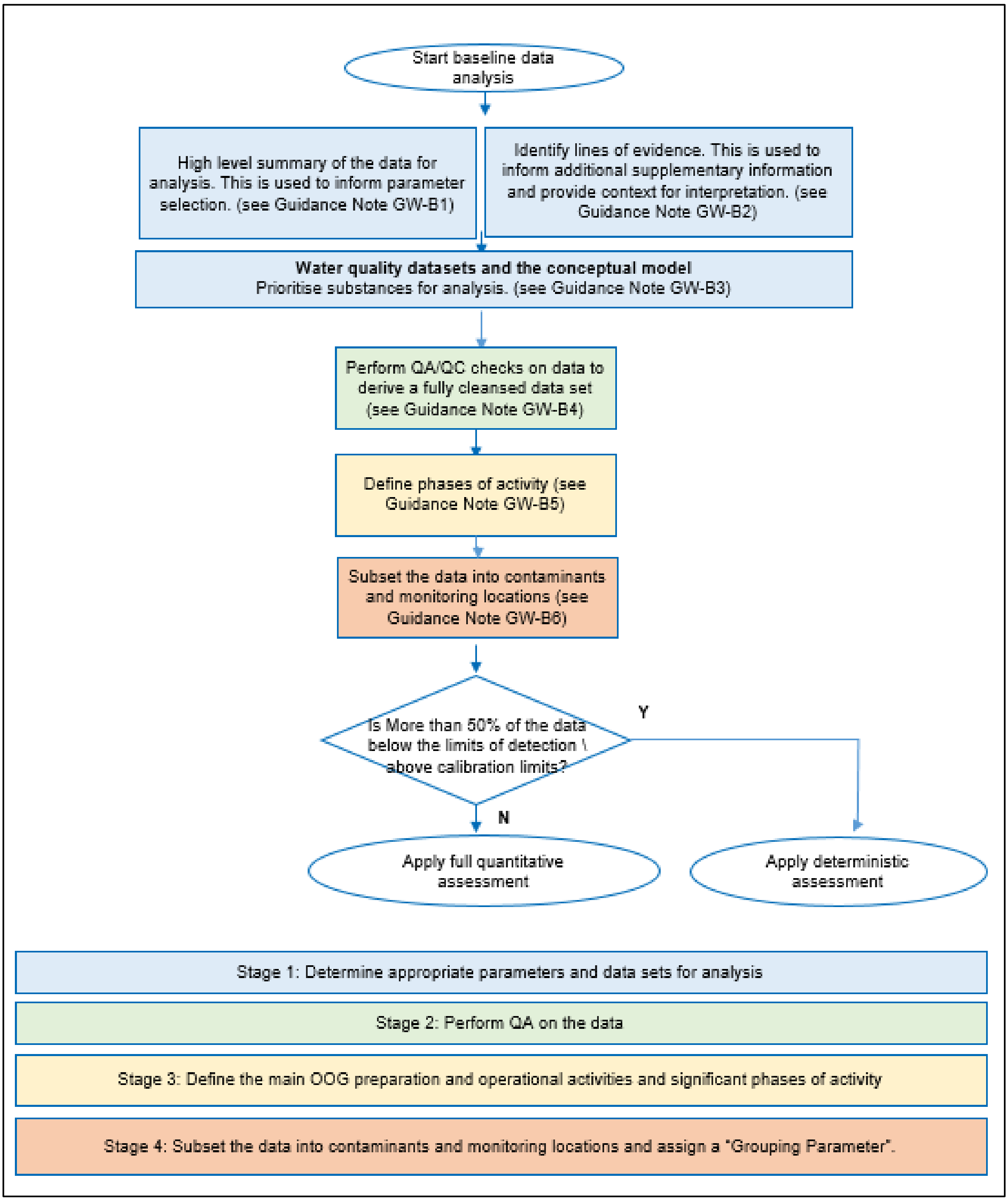


Figure 4-4: Decision tree for full quantitative assessment in setting a baseline

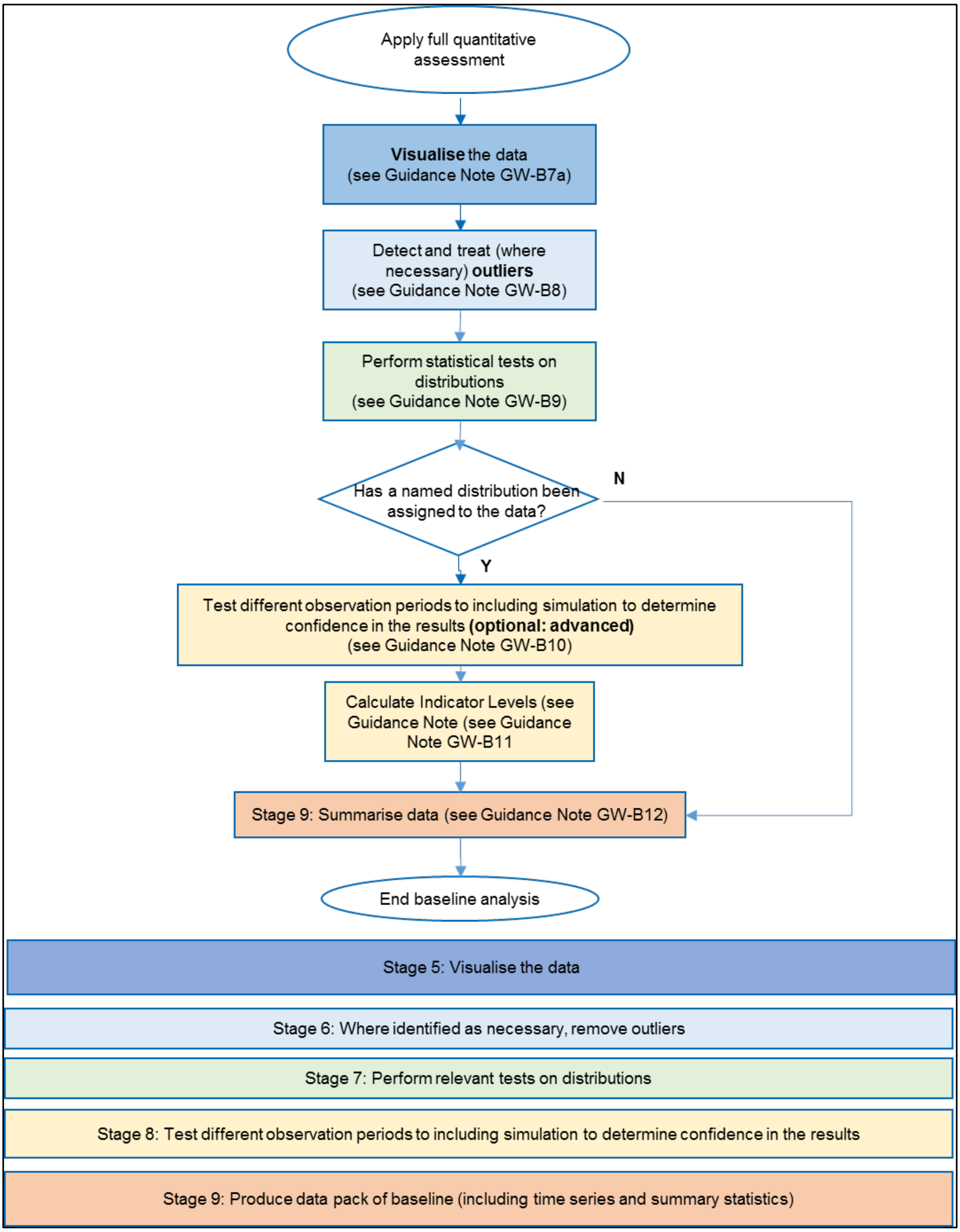
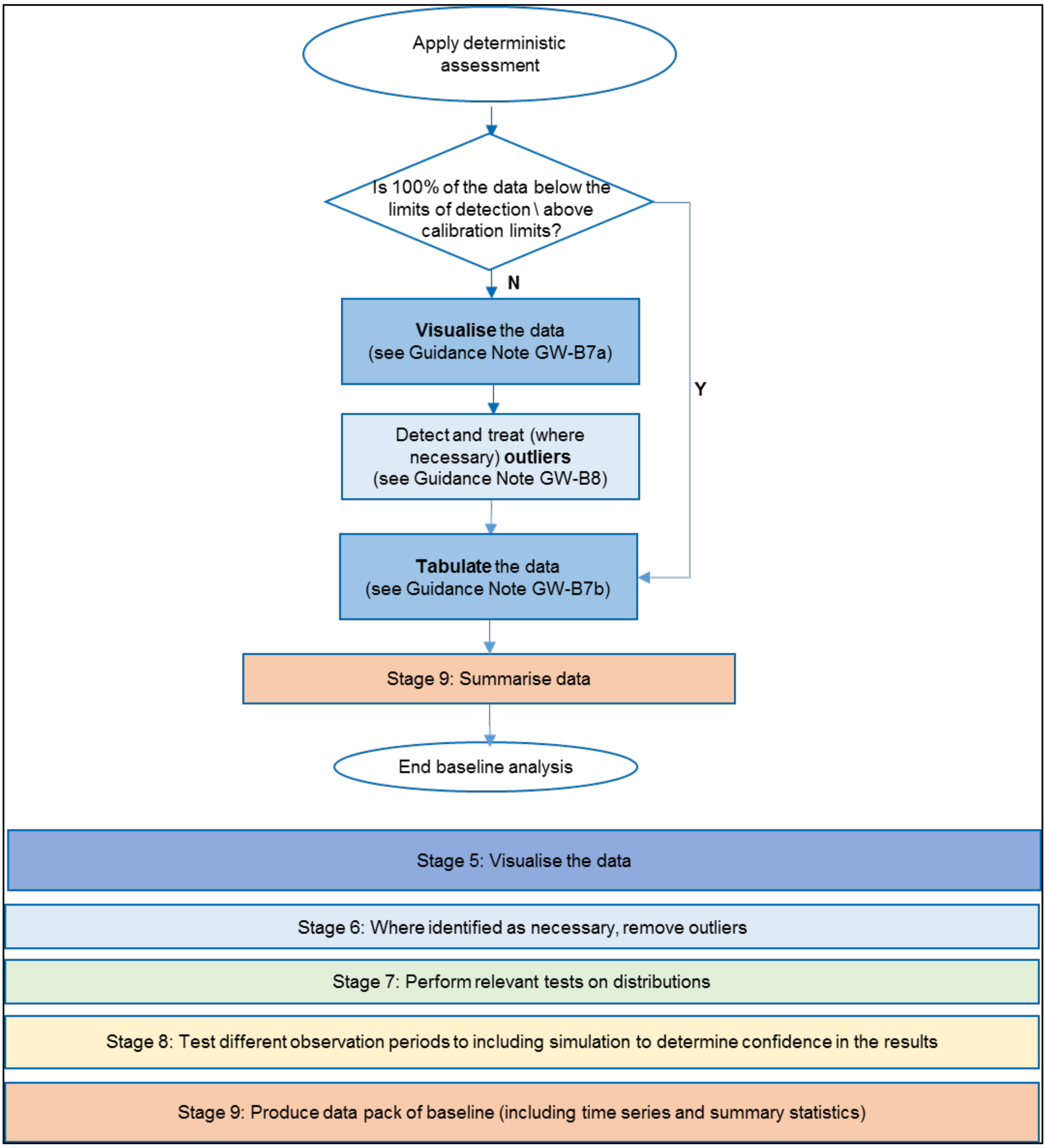


Figure 4-5: Decision tree for deterministic assessment in setting a baseline



4.7.1 Stage 1: Determine appropriate parameters and datasets for analysis

Guidance note GW-B1

High level summary of the data

The parameters monitored, proportion of values over and under the LOD/LOQ[5], durations of monitoring and 5 number summaries (minimum, lower quartile, median, upper quartile and maximum value of the data set) should all be evaluated as this will help select parameters for detailed analysis. A ‘reference measure of variability’ (RMoV) can be calculated from the 5 number summaries using the equation:

---

[5] NB No action is taken in the treatment of LODs / LOQs at this point

$$RMoV = \frac{Q_{75} - Q_{25}}{Q_{50}}$$ **Equation 2**

Where *RMoV* is a reference measure of variability, Q_{75} is the upper quartile of measured values, Q_{25} is the lower quartile of measured values and Q_{50} is the median of the measured values. No account needs to be taken of limits of detection/quantification in this calculation, as the RMoV is used only as a reference for selecting parameters of interest. Where the RMoV is equal to zero, this is indicative of the majority of all values being at or under the limit of detection/quantification.

Guidance note GW-B2

Identify lines of evidence

Identify (i) the contaminants of concern identified during the risk assessment and detailed in the conceptual model to help priority parameter assessment, and (ii) additional data sets that may be useful in interpreting the data. This step is used to inform both additional supplementary information and provide (geo)context for interpretation.

Considering contaminants of concern

Potential pollutants from shale gas sites that may contaminate groundwater and its receptors are considered in a variety of regulator and industry guidance. For example, existing UKTAG[19] and Environment Agency guidance[20] describes how to determine appropriate assessment criteria for groundwater quality parameters and how these should be used to determine risk to groundwater receptors. At a local level, selecting the main substances that, if found at elevated levels in the natural environment, could indicate impact from a shale gas site, will be informed by the risk assessment and the proposed operations at a particular site, as well as the conceptual site model. The risk assessment, conceptual site model, permit and any relevant regulator/industry guidance should all therefore be consulted within this step.

Identifying the area of interest

The area of interest for ground and surface water observations will depend on the hydrogeology of the site, receptor location and the risk from potential sources of pollution from the shale gas site, as well as the location of other operations in the area that may affect water quality at site. In the context of shale gas 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 towards sensitive receptors[12]. Identifying the area of interest in these circumstances would need to be considered together with pathways and potential exit points that would allow contaminants from these sources to pass.

Baseline monitoring will help to assess existing conditions against which changes can be identified and tracked. Baseline monitoring (and analysis) is therefore required at the local site-specific level, as well as at the regional scale[3,**Error! Bookmark not defined.**].

Regional monitoring carried out by the Environment Agency can be used as supplementary information in interpreting water quality and variability in monitoring parameters. Any available regional data identified within an area of interest could prove particularly useful, where these local data sets have long/longer duration. The appropriateness of using nearby regional monitoring boreholes to inform the baseline for a particular site needs to be considered on a case by case basis, though some general guidelines on establishing an area of interest are provided as follows:

Guidance note GW-B3

Rank priorities of parameters for establishing a baseline

The data sets for consideration may contain a large suite of parameters. These may include parameters of regulatory importance; parameters which may, if found in the natural environment, be indicative of an impact from shale gas operations; and additional parameters provided as a bulk suite of determinands from the lab.

To establish which parameters may be of most interest in establishing a baseline, this step therefore proposes a framework of using the outputs from the previous steps to rank parameters and provide a mechanism for establishing which parameters should establish baselines as a priority. Priority parameters may not necessarily reflect ONLY parameters that, if there were to be elevated levels, could indicate impact from shale gas activities, but also those that may provide a more easily identifiable change in baseline conditions, which could be indicative of another source.

4.7.2 Stage 2: Perform quality assurance on the data

Guidance note GW-B4

Laboratory procedures for QA/QC checks are well documented and are not detailed here. It may also be anticipated that QA/QC checks may already have been carried out. An exception is made in discussing the limit of detection/quantification. The Environment Agency recommends taking half of the limit of detection/quantification (LOD/Q) for values that are recorded as below detection/quantification thresholds. Consideration should be given to evaluating statistics, including and excluding these values/this assumption. It is recommended that flags are added to these values, rather than making any adjustment to the recorded/provided values at this stage.

The output of this stage should be a fully ‘cleansed’ data set. This indicates a data set that is ready to use, having had poor quality data removed or rectified. Outliers may or may not have been corrected (where they have not been corrected this is addressed in a later stage of the process).

4.7.3 Stage 3: Define the main shale gas preparation and operational activities and significant phases temporally within the selected ‘baseline’ data sets

Guidance note GW-B5

This is an important step as it identifies the timeline of activities at a site. Locating these temporally allows the baseline periods to be identified with confidence. In many cases, more than one baseline phase will be identified, a period before any significant on-site activity begins, and a site preparation period where no actual hydraulic fracturing activity was taking place. However, on-site activity such as vehicular movements, installing and removing noise barriers may be more intensified and could impact the baseline conditions.

4.7.4 Stage 4: Subset the data into individual contaminants and monitoring locations and assign a ‘grouping parameter’

Guidance note GW-B6

There were 2 parts to stage 4; (i) partitioning of contaminants at an individual site level, and (ii) partitioning of contaminants at a grouped location level. The first part is self-explanatory and involves subsetting data to an individual monitoring borehole/surface water station and determinand.

The data groupings by monitoring location (the second part of stage 4) should consider:

- type of water body (surface water and groundwater)
- on-site and off-site location
- presence of a bedrock or superficial aquifer
- depth of borehole
- area of potential interest and control categories

4.7.5 Stage 5: Display the data

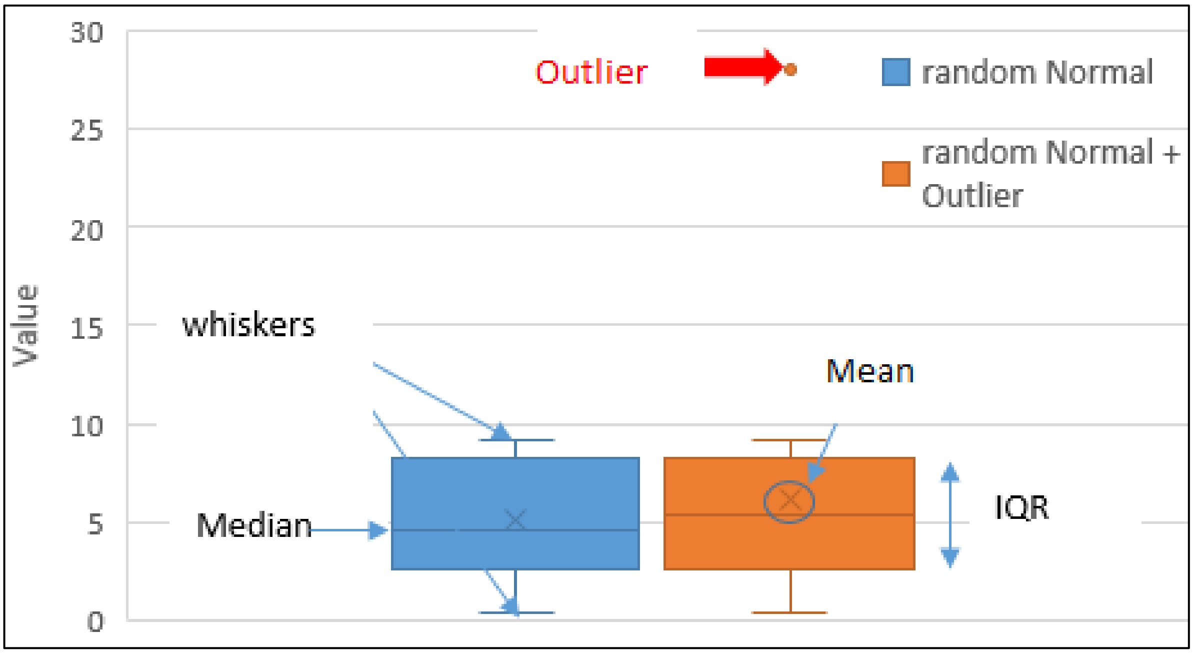
Guidance note GW-B7

It is proposed that a simple time series plot of the data is created in the first instance to highlight the changes through time. It is recommended that plots are drawn over the same time period to allow direct comparison between observations to see if there are visual correlations of high and low values. Where there are big differences, using logarithmic scales should be considered.

Where there appear to be differences in magnitude between sites, but temporal variation appears to be similar, grouped time series can also be created, normalised to a representative start value for the group (for example, mean value).

The box plot (box and whisker diagram) is a standardised way of displaying the distribution of data and helps compare multiple data sets. The box plot uses the median, the approximate quartiles, and the lowest and highest data points to convey the level, spread, and symmetry of a distribution of data values. It can also be easily refined to identify outlier data values, where outlier data values are defined as being beyond the whiskers. Some statistical software and other packages (such as Excel) now default to this view. General characteristics such as the symmetry of the distribution, the location of the central value, and the spread of the observations are immediately apparent and can be seen in the example below.

Figure 4-6: Example box plot



The approximate symmetry of the 2 box and whisker plots in this chart show that the data is approximately normal.

Using the box plot technique, data can be visualised and the distribution plotted by:

- month
- month and year
- season
- season and year
- year

There are no fixed rules on which of these plots should be used. Some suggestions of those that may be the most appropriate, based on the frequency of the data collection, are in Table 4.4. Where there are multiple observations per month (less than weekly), it is recommended that observations are plotted by month and, where observations are recorded monthly, box plots plotted seasonally. Where there is more than one year of observation, single year plots could also be used to provide a visual interpretation of the inter and intra month and year variation. Care should be taken however in selecting an appropriate resolution/overinterpreting box plot data, as where the frequency is variable and non-uniform through time, this could create bias.

Table 4.4: Recommended plot resolution for box plots

Frequency of observation	Plot type					
	Month	Season	Year	Month/ year	Season/ year	Full time period
Hourly	✓*		✓	(✓)		
Daily	✓*		✓	(✓)		
Weekly	✓*	✓	✓	(✓)	(✓)	
Fortnightly	✓	✓*	✓	(✓)	(✓)	
Monthly		✓*	✓		(✓)	
Bimonthly		✓*	✓		(✓)	
Quarterly			✓*			
Annually						✓*

Note: (✓) indicates where multiple years only
* indicates the recommended resolution of outlier analysis. This should be transferred to its bracketed counterpart where there are multiple years of data and there appears a significant difference between those years

Guidance note GW-B7b

Tabulate the data

Where values are all below the limit of detection/quantification, it is not necessarily informative to create a large volume of graphs (which all show a constant value/inappropriate levels of accuracy). It is therefore suggested that tabulated summaries are used. Summaries might include, for example, site type (on-site/off-site/surface water), monitoring location reference, the limit of detection/quantification (for as many different LODs/LOQs as have been attributed to the data), start of monitoring (for associated LO /LOQ), end of monitoring (for associated LOD/LOQ) and the count of observations.

Summary statistics of the baseline should be characterised from the LODs/LOQs taken at half value for the lowest resolution LOD/LOQ or half the value of a higher resolution if the omission of the lower resolution LOD/ LOQ measurements does not appreciably affect the number of observations measured (that is, if there are limits of <2.5 (n=20) and <1(n=2), then the LOD/LOQ of 2.5 should be used. Any future change in the LOD/LOQ, should incorporate a similar assumption for direct comparison with baseline (that is, all values of <2.5 µg/l (including values <1 µg/l) should be assumed to have a value of 1.25 µg/l in the calculation of summary statistics).

4.7.6 Stage 6: Where identified as necessary, remove outliers

Guidance note GW-B8: Outlier detection

An outlier can be defined as 'an observation which deviates so much from the other observations as to arouse suspicions that it was generated by a different mechanism'[21].

There are 2 main reasons why identifying potential outliers is important:

1. The outlier may be the result of sampling error and indicate erroneous data that should be removed from the analysis.
2. The outlier may indicate true anomalies in the data that are of scientific interest and therefore robust statistical techniques need to be considered to investigate these further.

A default of 1.5 multiplied by the inter-quartile range either side of the upper and lower quartile is suggested. This can be expressed as values that lie below the lower limit or above the upper limit of the outlier limits as defined below for the set of values *x*:

$$\text{outlier lower lim}(x) = Q25(x) - 1.5(Q75(x) - Q25(x))$$

$$\text{outlier upper lim}(x) = Q75(x) + 1.5(Q75(x) - Q25(x))$$

This is aligned to the default in many software packages and what is often shown on box plots. The statistical software language R[22] will autogenerate and report outliers based on the above equations without the need to explicitly calculate. Other options include a range approximating the 95% confidence interval or 99% confidence interval assuming a normal distribution (approximately 2 or 3 times the standard deviation respectively). These options will generally identify fewer observations for further analysis as potential outliers, **but implicitly assume that the data is normally distributed.** In the statistical guidance provided in the analysis of landfill monitoring data[23], it is suggested that the multiple outlier test is adopted, which adopts the assumption of normality, recursively applying the algorithm on values outside of the confidence interval. This routine was available to users using the Environment Agency's TDF (Test Data Facility) at the time of writing the 2002 report. We do not stipulate which outlier test is used under these guidelines and users may choose what they believe to be the most appropriate.

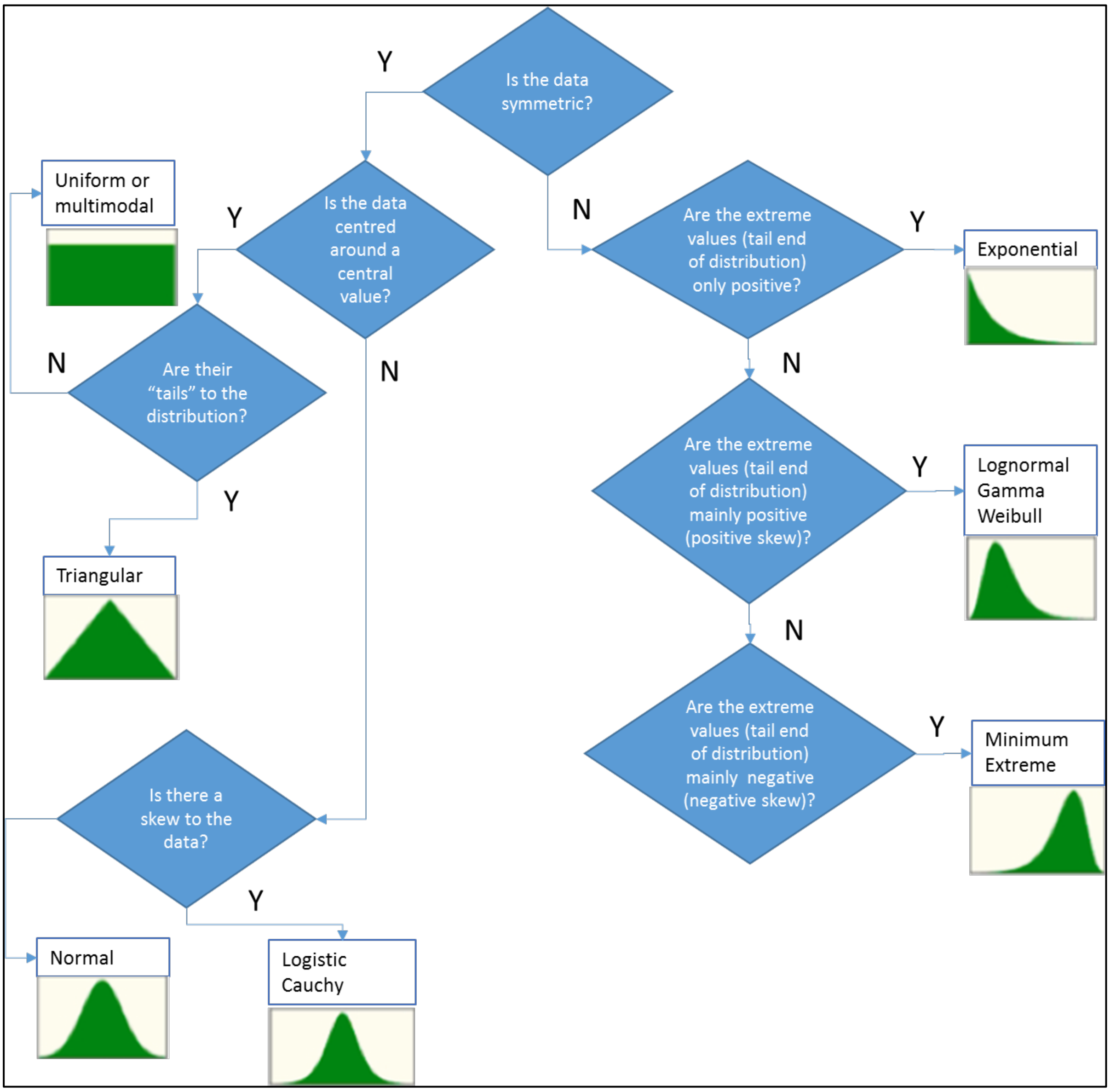
It should be acknowledged that outliers are not necessarily invalid data points; indeed, they may well be valid, and the most important, information rich, part of the data set. Under no circumstances should they be automatically removed from the data set. Outliers may deserve special consideration; they may be the relevant to the phenomenon being studied or the result of human errors.

4.7.7 Stage 7: Perform relevant tests on distributions

Guidance note GW-B9: Tests

A guide to selecting the appropriate distribution for testing against is shown below:

Figure 4-7: Distribution choices



The working assumption is that the data are expected to be normally distributed. The assumption should be tested to see if it is justified using (i) visual assessment, (ii) quantile-quantile plots (Q-Q plots), (iii) normality tests, and (iv) where this is not justified, the suitability of different distributions should be tested.

4.7.7.1 Visualisation

The step of visually identifying a likely appropriate distribution for the data (for example, normal, log-normal, exponential) can be assessed using histograms of the data supported by the above selection flowchart. This can be carried out on a determinand and site basis where there is enough data. If there are too few observations to be 'meaningful', assessment should be carried out on a grouped basis, where clearer distribution patterns may be identifiable. The term 'meaningful' is subjective and data dependent or data led. A small sample is commonly defined as having less than 30 observations, so while samples with less than 30 observations are acceptable, caution should perhaps be exercised at this level.

Groupings tested, could be those identified in stage 4, or modified as the data requires.

4.7.7.2 Q-Q plots

In addition to data visualisation using histograms, a comparison of the quantiles of normal distributions alongside other distributions can be used to assess suitable distributions.

4.7.7.3 Normality tests

Before an assessment of whether a more complex description of the data is required and to confirm the conclusions formed from the visual assessments, distributions are first assessed in terms of whether a normal distribution of the data or logged data can be satisfied. The hypothesis test consists of a null hypothesis and an alternative hypothesis:

- null hypothesis (H0): there is no difference between the distribution of the data/logged data and a normal distribution
- alternative hypothesis (H1): there is a difference between the distribution of the data/logged data and a normal distribution

For large sample sizes (30 observations or more), an Anderson-Darling test may be considered the most appropriate statistical test for normality, whereas for smaller sample sizes (less than 30 observations), a Shapiro Wilks test may be considered more appropriate.

4.7.7.4 *Distribution tests*

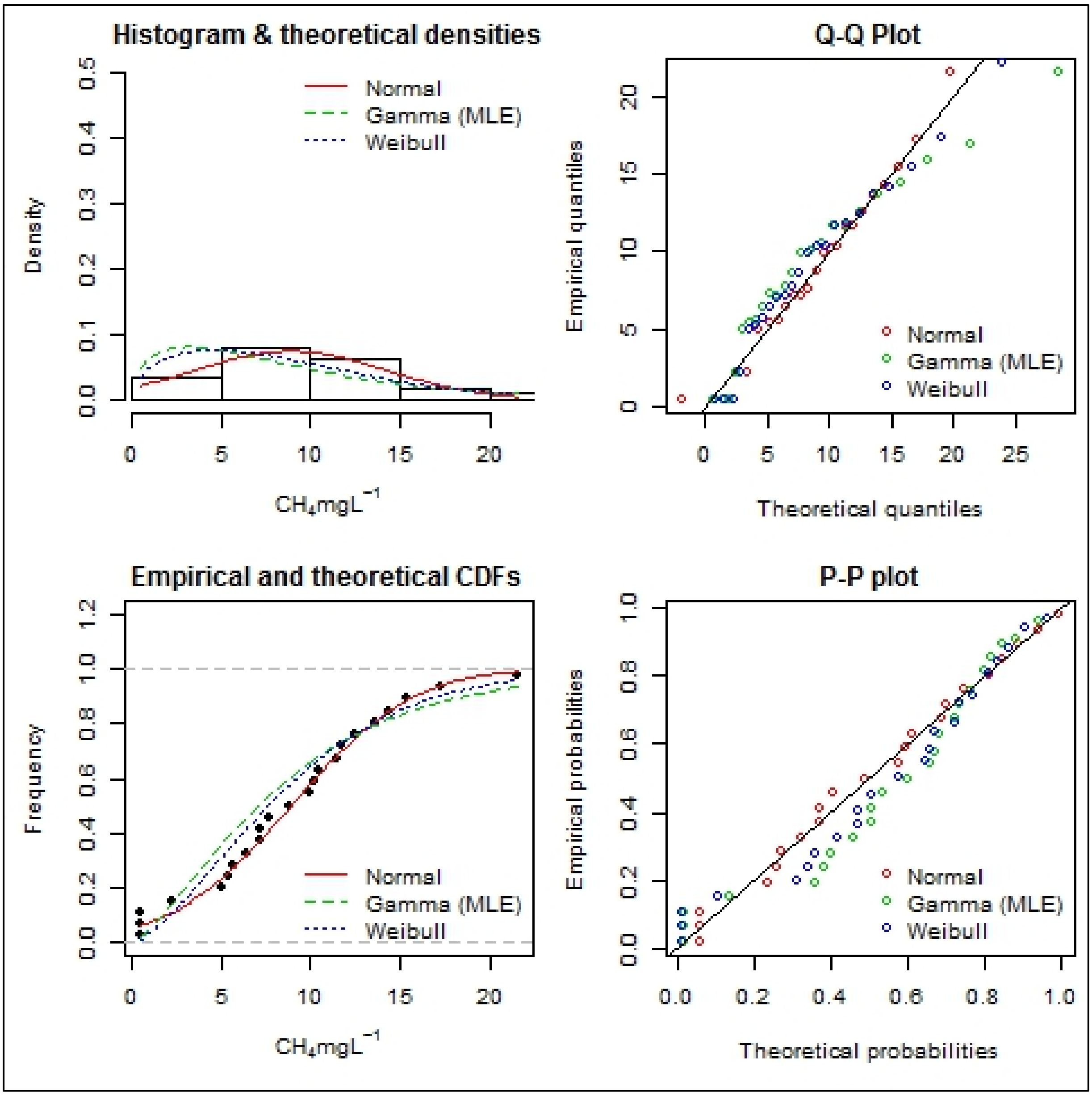
Distribution tests are optional. They should be considered and carried out in cases where additional confidence in the robustness of baseline is desired. This stage is a pre-requisite to stage 8.

The appropriateness of the normal distribution versus other distributions are considered during the process of visualisation and QQ plots. If normality tests cannot be accepted on raw or transformed data (for example, by taking logs), formal further testing may be required.

Five distributions were tested for suitability (the normal distribution, the lognormal distribution, a gamma distribution fitted by maximum likelihood estimation (gamma MLE), a gamma distribution fitted by matching moment estimation (gamma MME) and the Weibull distribution), and the 3 most plausible plotted in Figure 4.7 (using the functionality of the 'fitdistrplus' package in the statistical software language R[6])[22]. The reader should not concern themselves with the definition of these terms – they are simply used to represent a range of appropriate distributions for testing and to show proof of method.

[6] Useful functions include fitdist(<data>,<distribution name>); which allows the user to generate to fit a named distribution to the data set of interest; and; gofstat(list(<fitted distribution 1>,..< fitted distribution n>)) which allows the user to compare and contrast the fit statistics of the 1…n fitted distributions (e.g. normal, log normal, gamma and Weibull).

Figure 4-8: Visualisations associated with different theoretical distributions associated with some miscellaneous empirical measurements of dissolved methane



Statistics reported through the 'gofstat' function in R are shown in Table 4.5 and Table 4.6.

Table 4.5: Goodness of fit statistics for different theoretical distributions associated with some miscellaneous empirical measurements of dissolved methane

	Normal	LogNormal	Gamma (MME)	Gamma (MLE)	Weibull
Kolmogorov-Smirnov statistic	0.072	0.248	0.129	0.183	0.137
Cramer-von Mises statistic	0.018	0.326	0.077	0.169	0.097
Anderson-Darling statistic	0.180	2.019	1.681	1.105	0.855

Table 4.6: Goodness of fit criteria for different theoretical distributions associated with some miscellaneous empirical measurements of dissolved methane

	Normal	LogNormal	Gamma (MME)	Gamma (MLE)	Weibull
Akaike's information criterion	146.513	157.171	154.152	148.404	146.376
Bayesian information criterion	148.784	159.442	156.423	150.675	148.647

The statistics indicate that applying the theoretical normal distribution has the lowest probability of non-rejection of difference from the hypothesised distribution, using all 3 of the methods listed in Table 4.5. As an example, at the 95% confidence level, we would not reject a difference from the hypothesis that the data followed a normal distribution using the Cramer-von Mises statistic, but we would reject the hypothesis that the data followed a gamma distribution. Using the goodness of fit criterion, the minimum deviation was achieved through applying the normal and Weibull distributions.

4.7.8 Stage 8: Test different observation periods, including simulated observation periods, as necessary, to determine confidence in the results

Guidance note GW-B10: Adequacy tests (Optional - For increased confidence in the robustness of baseline)

This stage is recommended where greater confidence in the baseline assessment is desired. The stage should be carried out if possible, and where relevant, to test to see that the conclusions are not statistically different with different frequencies or duration of data.

Once an appropriate distribution has been selected and fitted to the sample data set, multiple simulations can be run with the data, using different frequencies and durations of analysis. These can then be used to determine the sensitivity of the output to the choice made in frequency or duration set at the monitoring design stage.

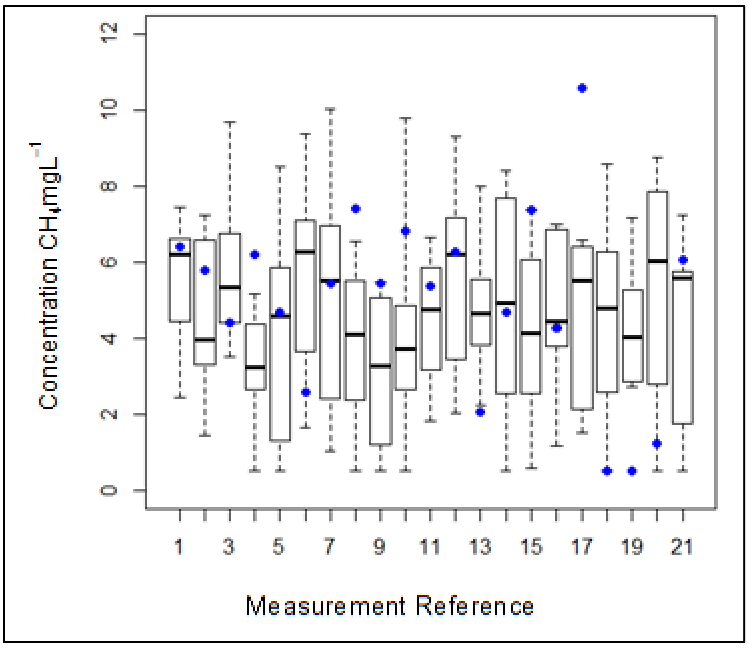
This type of analysis could also be used to test what a statistically robust survey frequency and duration would be where a highly intensive data set is available over a long enough time period, that is if the data can be assessed to determine adequacy for establishing a baseline.

Using the sample mean (mu) and standard deviation (sd), 100 time series of 21 observations from a normal distribution were generated in R. This may also be performed in Excel using the NormInv and Rand commands. A further 100 time series were then also generated using the sample mean and standard deviation from only the first 12 observations, to represent a scenario in which the data had been collected less frequently/over a shorter duration. With no seasonality, this scenario could be assumed to represent a single year of sampling measured monthly.

A box plot of the simulated results using this new scenario is shown in Figure 4.8. Here, the blue points represent the observed concentrations, and the box and whiskers show the range of simulated data. A cusum test performed on these simulated data sets resulted in no instances of change detected using only 12 observations. In simulations from the full sample of 21, one simulation only resulted in a change. It is reassuring that both give the same result in terms of accuracy. However, visual interpretation of Figure 4.8 provides both an explanation of the result, and context for the implications of the finding. The first half of the data set showed less variability than the last half, with the lowest and highest values measured in the latter half of the monitoring period. This resulted in measurement 17 representing a higher concentration than any data point simulated (at any time reference) in the reduced data scenario. The lower variability observed in the first 12 measurements gave the data set false precision, and, had the site gone operational with a baseline of this shorter length, there would be a greater likelihood of falsely detecting change in the operational data.

This analysis provides an example of the importance of having enough data; confidence in the baseline was overemphasised, with a change more likely to be falsely detected in the operational stage.

Figure 4-9: Box plots of simulated measurements using observations 1 to 12, site 1, case study 4



Note: Blue points represent all measured values

4.7.8.1.1 Stage 9: Produce data pack of baseline (including time series and summary statistics)

This stage is intended to represent a data pack of outputs that together represent a baseline characterisation. It is suggested that this data pack includes the data time series and box plots with outliers, suspicious values and values greater or less than an LOD flagged (or removed), at an individual site and grouped level. Site and grouped site summary statistics of mean, standard deviation, median, median absolute deviation (MAD) and skew should be provided, along with the outputs of the adequacy testing including indicator values.

Recommended data packs should consist of:

1. individual site time series
2. grouped time series data normalised mean across the group
3. grouped data box plots
4. individual site statistics
5. grouped data statistics

This should bring together the outputs from previous stages.

5 Applying the updated guidelines to operational data

This section describes applying revised guidelines for monitoring baselines and detecting change to ambient monitoring data collected during 'operational' phases at Preston New Road. The application of the guidelines focused on air quality data and was designed to trial using them in a 'real world' situation.

Ideally, air quality data would have been available at both the Environment Agency and BGS monitoring sites for the pre-activity baseline phase and all later phases, so comparisons could be made at each monitoring site between that baseline and each later phase. However, the available data were limited, so a comparison with the pre-activity baseline was only possible at one monitoring site and for one later phase. Moreover, the comparison of pre-activity baseline was with a pre-operational phase involving 'site preparation' rather than with an operational phase involving 'drilling', 'hydraulic fracturing' or 'extraction'. The scope for trialling the guidelines was therefore limited, which illustrates the kind of data availability issues that can arise in a 'real world' situation.

In order to trial the guidelines further, they were used to make additional comparisons involving a combination of 2 pre-operational phases and various individual and combined operational phases. The additional comparisons gave further examples of how the guidelines can be applied, but they were not strictly 'baseline' comparisons against the original pre-activity situation. The additional comparisons checked if changes in pollutant concentrations had occurred between the various phases and combinations of phases, and investigated if any changes were statistically significant.

Table 5.1 shows the scope of the air quality data available for applying the guidelines. Specifically, it shows the names and dates of each phase and the periods of data available at each monitoring site during each phase. The dates of each phase are based on the timeline of activities in Table 3.1, and the durations of data at each site are based on the timeline of monitoring in Table 3.2.

Table 5.1 shows that there were 2 types of phase. The first type were 'pre-operational' phases that comprised a 'pre-activity baseline' phase (1) and a site preparation' phase (2). The second type were 'operational' phases that comprised a 'drilling' phase (3), a 'hydraulic fracturing' phase (4) and an 'extraction' phase (5).

Operational phase data are provided in the data pack at Appendix 5.

Table 5.1: Air quality monitoring data used for comparisons between phases

Phase					Monitoring data available		Comments
No.	Title	Type	Start	End	BGS	Environment Agency	
1	Pre-activity baseline	Pre-operational (inactive)	~1 December 2014	4 January 2017	January to December 2016	No data collected	~12 months of BGS pre-activity data available
2	Site preparation	Pre-operational (preparatory)	5 January 2017	17 August 2017	January to August 2017	No data collected	
3	Drilling	Operational	17 August 2017	17 July 2018	August 2017 to December 2017	August 2017 to July 2018	BGS data available for 4½ months only

Phase					Monitoring data available		Comments
No.	Title	Type	Start	End	BGS	Environment Agency	
n/a	Pause in activities		18 August 2018	14 October 2018	Not applicable	Not applicable	Pause data not used for comparisons
4	Hydraulic fracturing	Operational	15 October 2018	14 December 18	Data not available	Oct to Dec18	Extraction began before hydraulic fracturing ended, so phase dates overlap
5	Extraction	Operational	2 November 2018	~31 December 2018	Data not available	Nov to Dec18	

In order to determine and attribute changes in air quality, data should be compared on a 'like-for-like' basis, for example comparisons between phases should use data from the same site, and for the same pollutant and averaging time. Table 5.1 shows that some data were available for each of phases 1 to 5, but that the data came from different sites, for example phase 1 to 3 data came mostly from the BGS site, but phase 3 to 5 data came mostly from the Environment Agency site. Because the availability of data moved between the sites, the number of 'like-for-like' comparisons that could be made was limited. This illustrates the kind of practical constraints that can arise in 'real world' situations.

5.1 Comparison of air quality phase 1 with phase 2

A comparison of data before and during site preparation was carried out for NO_2 and PM_{10}. This is a strict 'baseline' comparison between the original pre-activity baseline phase (phase 1) and the site preparation phase (phase 2), which uses data from the same site (BGS) on a 'like-for-like' basis. However, it is not a comparison between the pre-activity baseline and an operational phase, because phase 2 is 'pre-operational' (**Table 5.1**).

NO_2 and PM_{10} were selected as these pollutants showed the greatest potential for demonstrating the guidelines. Table 5.2 summarises the mean and median values for each pollutant and phase.

Table 5.2: Mean and median of NO_2 and PM_{10} in phase 1 and phase 2

Pollutant	Metric	Phase 1: Pre-activity baseline	Phase 2: Site preparation
NO_2 (ppb)	Mean	4.31	3.31
NO_2 (ppb)	Median	2.24	1.92
PM_{10} ($\mu g.m^{-3}$)	Mean	11.68	12.03
PM_{10} ($\mu g.m^{-3}$)	Median	8.91	8.88

A statistical test was done for each pollutant to check if its population of concentrations in phase 1 differed from that in phase 2 (to a given level of confidence). Due to the non-normality of the pre-activity baseline data as discussed in chapter 2, a non-parametric test was required. The Mann-Whitney test was used, and Table 5.3 shows the results for each pollutant, which are expressed as 'p-values'.

Each p-value represents the level of confidence that random sampling variations could have caused the amount of difference found between the 2 populations compared. If a p-value is below 0.05, there is more than 95% confidence that random variations did not cause the amount of difference. The difference is then attributed to having significantly different populations, that is indicating a significant change in air quality between phases.

Table 5.3: Results of Mann-Whitney test for NO_2 and PM_{10} between phase 1 and phase 2

Pollutant	Test result (**p-value)**
NO_2	6.61×10^{-9}
PM_{10}	0.76

For PM_{10}, the p-value was 0.76, which is more than 0.05, so the PM_{10} concentrations measured during the site preparation phase (phase 2) were not statistically significantly different from those measured in the pre-activity baseline phase (phase 1). There was therefore no significant change in PM_{10} levels between the phases. However, for NO_2, the p-value was 6.61×10^{-9}, which is less than 0.05, so it is concluded that the NO_2 concentrations measured during phase 2 differed significantly from those in phase 1. **Table 5.2** shows that the difference was a reduction in concentrations, which means there was a significant decrease in NO_2 levels between the pre-activity baseline phase and the site preparation phase. This implies that any increases in NO_2 levels that might have occurred as a result of site preparation must have been outweighed by decreases in NO_2 due to other factors. For example, any increase in levels due to site preparation activity may have been outweighed by the effect of changes in meteorological conditions between phases 1 and 2, although a dispersion analysis would be needed to confirm this.

5.2 Comparison of air quality combined phases 1 and 2 with phase 3

This comparison uses data from the BGS site and is between a combination of the 2 pre-operational phases for pre-activity baseline and site preparation (phases 1 and 2) and the operational phase for drilling (phase 3) – see **Table 5.1**. It should be noted that this is not a strict comparison against the pre-activity baseline, because the combination of pre-operational phases includes preparatory activities. Also, the data from the BGS site do not cover the whole period of drilling at Preston New Road, but only the first 4½ months when air quality data were available.

The comparison was carried out for NO_2 and PM_{10}, and **Table 5.4** summarises the means and medians for each pollutant and phase. Mann-Whitney tests were used to check the significance of the difference in each pollutant between the 2 periods compared and the results are shown in **Table 5.5**. The concentration of NO_2 was significantly higher during the drilling phase (phase 3) than during the combined phases 1 and 2. This may reflect increased vehicle and plant activity at the site during the drilling phase, but may also be due to other causes, such as changes in meteorological conditions. By contrast, PM_{10} concentration was higher in the combined phases 1 and 2 than during the drilling phase (phase 3). This could have been because of preparatory activities, for example, vehicle movements or ground works, which emitted PM_{10} during the pre-operational phase, but which were absent during the drilling phase.

Table 5.4: Mean and median of NO_2 and PM_{10} in combined phase 1 and 2 and phase 3

Pollutant	Metric	Combined phase 1+ 2 (Pre-operational)	Phase 3 Drilling (Operational)
NO_2 (ppb)	Mean	4.73	9.06

NO_2 (ppb)	Median	2.54	6.76
PM_{10} (µg/m^3)	Mean	11.87	9.73
PM_{10} (µg/m^3)	Median	9.11	7.62

Table 5.5: Results of Mann-Whitney test for NO_2 and PM_{10} between combined phase 1 and 2 and phase 3

Pollutant	Test result (p-value)
NO_2	$< 2.2 \times 10^{-16}$
PM_{10}	$< 2.2 \times 10^{-16}$

5.3 Comparison of air quality phase 3 with combined phases 4 and 5

This comparison used data from the Environment Agency site, whose precise location was not disclosed but was up prevailing wind (south-west) of the Preston New Road and BGS sites. The data covered the drilling phase (phase 3), the hydraulic fracturing phase (phase 4) and the extraction phase (phase 5). Extraction began before hydraulic fracturing had finished (Table 3.1) so that, for comparison purposes, it was necessary to combine these phases. The combined phase (phases 4 and 5) was compared with the drilling phase (phase 3).

The pollutants considered were NO_2, PM_{10} and CH_4. Table 5.6 summarises the mean and median concentrations for each pollutant and period. Mann-Whitney tests were used to check the significance of the difference in each pollutant between phase 3 and phases 4 and 5 combined, with the results shown in Table 5.7.

Table 5.6: Mean and median of NO_2, PM_{10} and CH_4 in phase 3 and combined phase 4 and 5

Pollutant	Metric	Phase 3: Drilling	Combined phase 4 and 5: Hydraulic fracturing and extraction
NO_2 (ppb)	Mean	10.629	13.639
NO_2 (ppb)	Median	9.025	11.068
PM_{10} (µg.m^{-3})	Mean	13.464	12.404
PM_{10} (µg.m^{-3})	Median	12.374	11.392
CH_4 (mg.m^{-3})	Mean	1.366	1.381
CH_4 (mg.m^{-3})	Median	1.397	1.370

Table 5.7: Results of Mann-Whitney test for PM_{10}, NO_2, CH_4 between phase 3 and combined phase 4 and 5

Pollutant	Test result (p-value)
NO_2	$< 2.2 \times 10^{-16}$
PM_{10}	0.0002312
CH_4	$< 2.2 \times 10^{-16}$

Concentrations of NO_2 were significantly greater in the combined hydraulic fracturing and extraction phase than in the drilling phase. However, concentrations of PM_{10} were significantly lower in the combined hydraulic fracturing and extraction phase than in the drilling phase. Concentrations of CH_4 in the combined hydraulic fracturing and extraction phase differed significantly from those in the drilling phase, as shown by the low p-value. However, the overall direction of change is unclear because the mean increased between the drilling and combined phases 4 and 5, while the median decreased.

It should be noted that it may be easier to define a baseline in a situation with emissions that are continuous or that vary regularly, for example with time of day, directional sector, day of week. This is because it is then easier to define a repeating pattern to use as a reference for showing up any change. However, in a rural situation further from other potentially relevant sources such as KM8, the signals from different existing sources may be relatively sporadic in time and space, for example because of intermittent emissions from farming, construction or meteorologically-driven emissions. Therefore, it may be difficult to summarise them easily in a baseline distribution.

A fundamental consideration for setting baselines is that the measured baseline comprises a data archive that summarises the air quality that would be expected to occur in future if there were no changes. This data archive is useful as a reference point when considering whether or not a change has occurred, and for attributing any change to its cause(s). Different ways of defining baselines are alternative ways of interpreting this data archive. Similarly, different ways of assessing change are alternative ways of identifying if there has been a departure from the measured baseline concentrations.

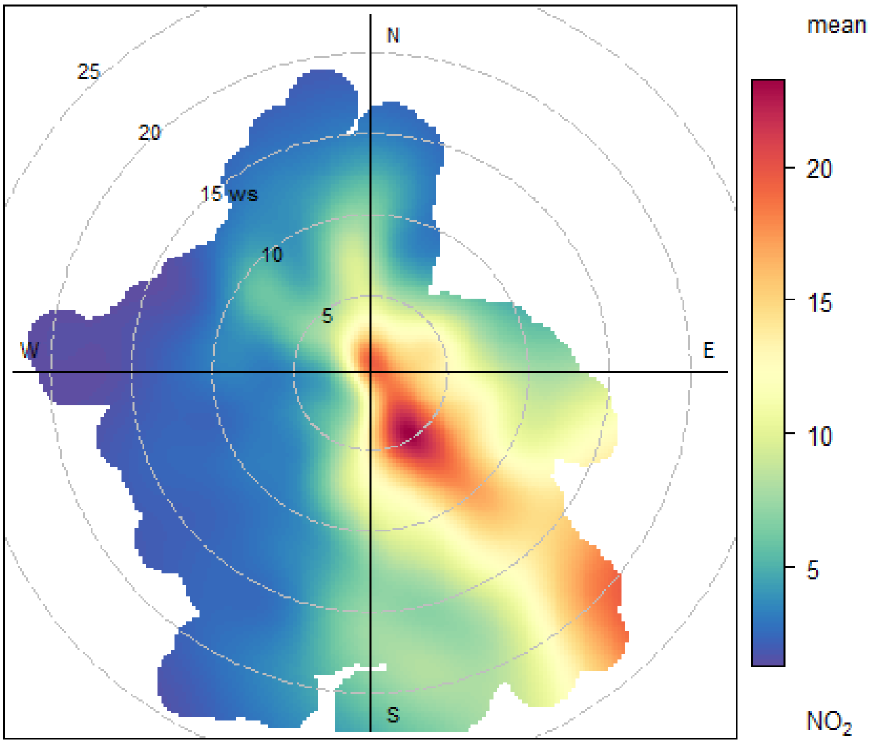
5.4 Investigating operational period data

The analysis above provides an example of data analysis to investigate whether operational period measurements are significantly different to baseline measurements. The measurements carried out by the Environment Agency during the operational period were also analysed to investigate whether any episodes of unusually high concentrations were observed, and whether any conclusions could be drawn regarding the potential sources of these episodes. For the interpretation of directional plots, it should be noted that the well pad was located to the north-east of the Environment Agency's monitoring site.

Drilling took place at the site between 17 August 2017 and 1 March 2018, and between 1 April 2018 and 14 October 2018. Hydraulic fracturing took place from 15 October 2018 to 14 December 2018. Figure A5.2 shows that levels of nitrogen dioxide were generally lower during the second period of drilling, but higher during the first period of drilling and during hydraulic fracturing. PM_{10} levels (Figure A5.18) showed the opposite pattern, with higher levels during the second period of drilling. There was no indication of higher levels of methane or benzene during hydraulic fracturing, with levels of these substances similar to the levels measured during the second drilling period, and lower than the levels measured during the first drilling period. Throughout the drilling and hydraulic fracturing periods, measured levels of methane were typically lower than those measured at the BGS installation during the baseline period.

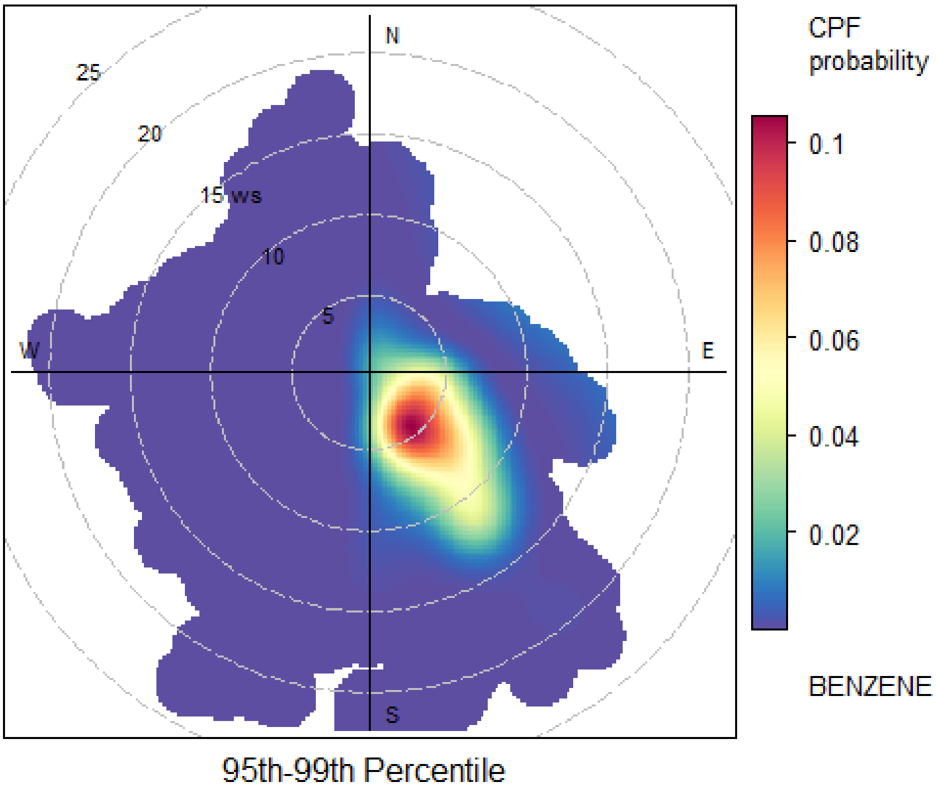
The polar plots for nitrogen dioxide (Figures A5.5 to A5.16 – see example below) indicate that the main source of nitrogen dioxide at the Environment Agency monitoring site during the operational phase is located to the south-east of the site. This could reflect local traffic sources, and/or may reflect the influence of emissions from the urban areas of Preston or Greater Manchester.

Figure 5-1: Polar plot of the mean concentration for different wind speed wind directions for operational phases (drilling and hydraulic fracturing) data for NO_2 (Preston New Road, Environment Agency site) (Copy of Figure A5.9)



Levels of methane and benzene were also influenced mainly by sources located to the south-east of the monitoring station, for both mean/median concentrations and higher percentile values. An example figure for benzene is provided below.

Figure 5-2: Conditional probability plot between the 95th and 99th percentiles for operational phases (drilling and hydraulic fracturing) data for benzene (Preston New Road, Environment Agency site) (Copy of Figure A5.55)



A more complex pattern of sources of PM_{10} was observed, with the main contribution coming from the west, but with higher percentile values (peak concentrations) being characterised by low wind speeds and a potentially significant contribution from the south-east.

The Environment Agency site was installed at a location upwind of the prevailing wind direction relative to the onshore oil and gas (OOG) site, with the well pad located to the north-east of the monitoring site, in order to provide a complementary view of the impact of the facility compared to the BGS station. Partly as a result of this, the wind came from the direction of the OOG relatively infrequently, and only with light wind speeds. Although the polar plots provide a limited data set to evaluate the potential impact of operational impacts from the OOG site, there is no indication of a significant contribution to measured levels of any of the pollutants being considered due to emissions from the Preston New Road site.

5.5 Recommended operator log

This study has highlighted the importance of collecting detailed information on the characteristics of shale gas sites, including the timings and nature of activities being carried out. This information is essential for the accurate analysis of environmental data, in particular ambient air quality data, which is especially sensitive to short-term changes in site activities.

It is recommended that the following information is collected in a site information log to be completed by site operators, with the specific aim of facilitating accurate and representative monitoring campaigns:

- phase – confirmation of the operational phase of the site
- date – confirmation of the day(s) of activity

- source type – confirmation of the nature of the source (for example, site vehicles, HGVs, non-road mobile machinery, flare)
- activity – a description of the activities being carried out
- weather conditions – a description of wind speed, wind direction, precipitation, air temperature and cloud cover, from on-site instrumentation or independent representative sources
- start and end times – confirmation of the approximate durations of activity
- additional notes – further information to support the characterisation of monitoring data

6 Conclusions and recommendations

6.1 Conclusions

The guidelines in the report on assessing the statistical significance of change (Environment Agency 2019a) provide a robust approach to data analysis and presentation. This methodology has been applied to 'real world' datasets obtained at 2 active onshore oil and gas installations. The data sets were obtained largely during the pre-operational and site preparation phases.

From this analysis, it was concluded that the guidelines would benefit from certain adaptations and clarifications. These are described in sections 4.5 and 4.6.

6.2 Considerations for application/interpretation

6.2.1 General

It will be important for operators and regulators to have access to suitable expertise to design robust air quality and water quality baseline monitoring programmes. Understanding and applying the guidelines from the report on assessing the statistical significance of change (Environment Agency 2019a), as amended in this report, requires understanding air quality and water quality monitoring techniques, and numerical analysis methods.

Together with the research reports on statistical significance of change and the design of air quality monitoring frameworks (Environment Agency 2019a and 2019b), this report should enable monitoring programmes to be designed that conform with reasonable requirements for baseline environmental surveys without operators or regulatory authorities having to carry out excessive duties. Future developments would not necessarily need extensive monitoring programmes, or the support of publicly funded site-specific monitoring activity, but could accommodate a suitable monitoring programme within the normal regulated site operational activities.

The sites being considered in this study benefitted from a considerable investment in monitoring carried out by the operator, the Environment Agency and the British Geological Survey. This resulted in an extensive monitoring database at each site, although, in practice, there were limitations with some of the data that meant the full range of analysis could not be completed. This level of investment in monitoring would not typically be available at future installations.

The evaluations set out in the report on assessing the statistical significance of change (Environment Agency 2019a) and this report may potentially allow survey designs to be adapted as more information becomes available, both at an individual site, and as knowledge increases in relation to onshore oil and gas more generally as the industry develops. For example, it may be possible and appropriate to change the range of substances measured, change survey durations, and/or change the location or frequency of measurements. A suitable framework for managing this process at an individual site is set out in the report on monitoring frameworks (Environment Agency 2019b).

6.2.2 Air quality

In relation to the duration of air quality monitoring, it was found that data obtained over shorter monitoring periods than one year gave different results to data obtained in a one year period. The starting point for baseline air quality surveys should therefore be a one year survey. However, methods developed by Defra provide a way of estimating longer period average data from shorter surveys.[24] These could potentially be applied to data measured over a shorter period, as low as 3 or 6 months, to estimate levels on an annualised basis (the approach is only valid for generating representative annual means). The report on monitoring frameworks[7] gives more detailed recommendations on appropriate survey duration.

In relation to airborne substances that should be monitored, again the report on monitoring frameworks provides detailed proposals for an approach to identifying appropriate substances. Typically, monitoring surveys should focus on the substances likely to be released from onshore oil and gas installations, and those for which air quality standards and guidelines are available. Based on the guidelines in the monitoring frameworks report, this is likely to include oxides of nitrogen, PM_{10} and $PM_{2.5}$, together with other substances, potentially including methane, volatile organic compounds, carbon monoxide, hydrogen sulphide and polycyclic aromatic hydrocarbons[7].

For baseline survey monitoring, measurements at different locations are typically variable and not directly comparable. However, a single monitoring station can give sufficient results to characterise baseline air quality when combined with currently available data analysis tools to investigate the factors influencing the measured concentrations. For operational phase monitoring, although not investigated in detail in this study, a range of options are available:

- Applying statistical tools for detecting change, to determine the significance of changes in measured levels from one project phase to another, particularly when moving from site preparation to hydraulic fracturing, and into production.
- Continuing to apply data analysis tools to investigate the sources of air pollution and how these may change between phases – for example, investigating whether there is evidence for new sources of pollution relating to traffic movements or on-site sources.
- Using a dispersion model of emissions from the site to evaluate operational phase measurements and determine whether any changes may have been due to site emissions or associated vehicle movements.
- Carrying out monitoring at 2 or more locations surrounding a site (for example, upwind and downwind of the prevailing wind direction) and investigating evidence for an incremental change in concentrations that could result from site operations.

6.2.3 Surface water and groundwater

Typically, a baseline surface water or groundwater monitoring survey covers a very wide range of substances, not all of which would be relevant for assessing baseline conditions and potential operational impacts at a shale gas installation. For this reason, the data analysis framework starts with stage 1: ‘determine appropriate parameters and data sets for analysis.’ Substances should be selected on a site-specific basis in light of the expected range of activities and potential contaminants. For example, it would be valuable for baseline surveys to include measurements of surfactants or other additives present in hydraulic fracturing fluids, which would represent a move away from standard data sets.

This study did not investigate alternative location numbers or study durations in respect of groundwater and surface water quality. A judgment of a suitable number of sampling locations would need to take account of the site-specific hydrogeology and surface water flow regimes, and it is not appropriate to provide generic suggestions in this report. The data sets in this study extended to over 2 years, and this was found to be adequate to characterise baseline water quality at the Kirby Misperton site. Furthermore, the analysis of observation periods (stage 8) showed that a shorter baseline survey period for electrical conductivity could have been used without materially affecting the validity of the baseline survey analysis and conclusions. While generalisations should be treated with caution, in most circumstances, a baseline survey period of one year is recommended as an initial working minimum.

6.3 Recommendations for future work

The findings of this project may have implications for the Environment Agency and would benefit from further analysis. Relevant issues may include:

- **Definition of baseline periods**
  There is no formal definition of what constitutes a baseline period. The starting point would be

the period before any activities start at a site, but this study has identified that real world complexities in the development of a facility may make this simple definition difficult to apply in practice. The study has identified that different considerations apply to what may be considered as a baseline period for air quality, surface water quality, and groundwater quality measurements. Air quality and surface water quality measurements may respond to new activities at a site over a very short timescale. In contrast, groundwater measurements would be expected to take a long period to respond to any change resulting from a new activity. For this reason, this study has suggested different definitions of baseline, preparation and operational periods:

  - air quality and surface water quality: pre-operation, site preparation, drilling, hydraulic fracturing, extraction/flowback
  - groundwater quality: before fracturing (pre-operation, site preparation; drilling), fracturing and operation (hydraulic fracturing; extraction/flowback)

- **Setting indicator levels**
  Including 'indicator levels' in the surface and groundwater guidelines were assessed as part of this study. For air quality, adopting a similar principle in the form of a 'factorisation approach' was explored. While using a factorisation approach was dropped from the recommended approach to establishing baselines in air quality, for water quality, the calculation of an indicator level was added as a component of the baseline establishment data packs for water. Indicator levels represent the change in parameter concentration/value that would be required to indicate that a statistically significant deviation from the baseline had occurred with a specified probability. It should be noted however that, as the name suggests, these are indicative of a change, and other formal methods would still need to be used in statistically detecting change. Care therefore must be taken in interpretation.
- **Responding proportionately to different levels of exceedance**
  During baseline periods, regulators may wish to investigate the causes of exceedances, but would not normally need to treat this as a regulatory issue.
  During operational periods, regulators are likely to seek investigation of the causes of exceedances of indicator levels with operators. The analysis of operational phase data in this study shows that a wide range of factors influences the levels measured during site preparation, drilling, hydraulic fracturing and flowback/extraction phases, and an exceedance would not necessarily be linked to any activity at the regulated site.
  This study has demonstrated the use of advanced tools for investigating air quality monitoring data to help in understanding the causes of measured levels of released substances. Further evaluation of the proposed methods to analyse the significance of changes in surface water and groundwater data that may be associated with operational activities is recommended.
- **Approaches to the regulation of the onshore oil and gas sector compared with other industry sectors**
  The report on assessing the statistical significance of change and this study provide new insights and methods for baseline survey design, and data presentation and analysis. These methods are potentially relevant to a wide range of other industry sectors, but have not been systematically applied to other sectors. It is recommended that the Environment Agency should consider developing similar guidelines for other sectors, potentially focusing on higher risk sectors for air quality and water quality impacts.
- **Limitations of baseline data compilations**
  This study does not provide any analysis of the likely validity period of baseline survey measurements. Any such advice would need to take account of factors, including trends in baseline levels of relevant substances. Baseline data for substances for which environmental levels are generally constant or in decline would have a longer validity period than data for which environmental levels are generally rising, or for which there is no relevant data. If there is an extended gap between baseline monitoring being carried out and on-site activities taking

place, this may result in baseline measurements being less valuable or invalid for determining baseline conditions.

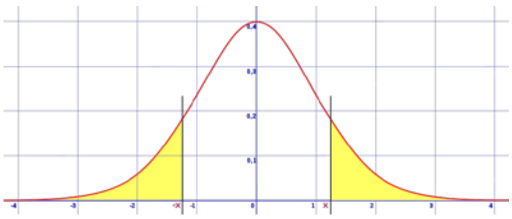
- **Usefulness of baselines compared to other methods of judging site emissions performance**
  Using upstream (or upwind) and downstream (or downwind) measurements to judge site emissions performance can be an effective way of assessing emissions performance, particularly for low-level sources of emissions to air (stack discharges or fugitive releases). Sufficient data is required to analyse individual upwind and downwind records, taking account of the detailed meteorological conditions. Upwind/downwind analysis is proving useful for tracking impacts/performance at other (non-OOG) sites such as anaerobic digestion facilities.
  In the case of groundwater quality, groundwater flows take place over long timescales, so a study using this approach could take a long time to carry out, and would be subject to uncertainties around the groundwater flow regime.
  Experience in the US confirms that baseline groundwater and surface water measurement data is essential for demonstrating site performance.
- **Reporting on measured baseline data**
  This study provides guidelines on the presentation and reporting of measured baseline data. The study shows that, for air quality, one year of data would be adequate for the case study sites. It is important for measurements to be taken at consistent location(s) using consistent techniques.
  For baseline reports, a quarterly management report to confirm satisfactory completion of the survey, together with a full report at the conclusion of the survey, would normally be sufficient. This study does not address operational surveys. Appropriate reporting frequencies may need to be identified on a case-by-case basis, potentially by considering the risks posed by the site, using a framework similar to that set out in Report Ref. SC170014.
  More generally, operators should explain how baseline surveys have been designed, and how evidence for change has been evaluated, in order to demonstrate that the monitoring survey design is fit for purpose for detecting any significant effect of the onshore oil and gas activity. This is particularly important in situations where a survey does not identify any significant or detectable changes from baseline conditions.
- **More detailed investigation of approaches for evaluating operational phase data to investigate evidence for detectable impacts from operational sites**

Glossary

Anderson-Darling test	Tests if a data sample comes from a population with a specific distribution; commonly a normal or exponential distribution. It is a refinement of the Kolmogorov-Smirnov (K-S) test, and gives more weight to the tails than the K-S test. It is an empirical distribution function test.
Cramer-von Mises test	Tests if a data sample comes from a population with a specific distribution; commonly a normal or exponential distribution. It is a refinement of the Kolmogorov-Smirnov (K-S) test, and gives more weight to the upper (or to the lower) tail of the distribution. It is an empirical distribution function test.
Cumulative distribution function (CDF)	The probability that the variable takes a value less than or equal to x.
Effect size	A measure of how important a difference is. Large effect sizes mean the difference is important; small effect sizes mean the difference is unimportant.
Empirical cumulative distribution function (also called empirical distribution function)	Like the cumulative distribution function (CDF), this is a probability model for data. While the CDF is a hypothetical model of a distribution, the empirical distribution function models empirical (observed) data; that is it is the probability distribution obtained from sampling a sample, instead of the population.
Empirical distribution function tests	Assume the population mean and standard deviation are not known, and are to be estimated from the data. Without this assumption, the probability values may differ.
Exponential distribution	Mainly used in reliability applications; often modelling data with a constant failure rate, or for modelling the time elapsed between events.
Indicator levels	Indicator levels relate to what change (increase or reduction) in parameter concentration/value would be required to indicate that a statistically significant deviation from the baseline had occurred with a specified probability (β). Indicator levels are established using a power t test, where the indicator level is represented by the mean (μ) plus or minus a delta value (δ).
Kolmogorov-Smirnov test	Tests if a data sample comes from a population with a specific distribution; commonly a normal or exponential distribution. It tends to be more sensitive near the centre of the distribution than at the tails. The refined tests, Anderson-Darling and Cramer-von Mises, are generally considered to be more powerful than the original Kolmogorov-Smirnov tests. It is an empirical distribution function test.

Kurtosis	A measure of whether the data are heavy-tailed or light-tailed relative to a normal distribution. Datasets with high kurtosis tend to have heavy tails or outliers.
Lilliefors test	Tests if a data sample comes from a population with a normal distribution. It is a refinement of the Kolmogorov-Smirnov (K-S) test, and corrects the K-S for small values at the tails of probability distributions. It is an empirical distribution function test.
Logistic distribution	Used for modelling growth. It is symmetrical, unimodal (has one peak) and is similar in shape to the normal distribution (although tends to have slightly fatter tails).
Mann–Whitney test	Compares 2 sample means that come from the same population, and tests whether 2 sample means are equal or not. Usually used when the data is ordinal or when the assumptions of the t-test are not met. It is a non-parametric test.
Median absolute deviation	The average distance between each data point and the mean. A robust measure of how spread out a data set is. The variance and standard deviation are also measures of spread, though they are more affected by extremely high or extremely low values, and non-normality.
Moment	Technically defined by a mathematical formula that happens to equal formulas for some measures in statistics. The first moment is the mean; the second is the variance; the third is the skewness; the fourth is the kurtosis; and the fifth is a measure of the relative importance of tails versus centre (mode, shoulders) in causing skew.
Non-parametric test	A test that does not assume anything about the underlying distribution as opposed to a parametric test, which makes assumptions about a population's parameters. Parametric tests tend to be more accurate and have greater statistical power, though the assumptions of parametric tests need to be met in order to use them.
Normal distribution	A probability distribution that is symmetric about the mean, showing that data near the mean are more frequent in occurrence than data far from the mean. Plotting it as graph, it appears as bell-shaped.
Null hypothesis	The commonly accepted fact; it is the opposite of the alternate hypothesis.
Outliers	Stragglers (extremely high or extremely low values) in a data set.

p–value	The probability of finding the observed, or more extreme, results when the null hypothesis is true.
P-P plot	Compares the empirical cumulative distribution function of a data set with a specified theoretical cumulative distribution function.
Probability density function	Gives the probability distribution for a continuous random variable, as opposed to the probability mass function, which gives the probability for a discrete random variable. Its graph is a curve above the horizontal axis that defines a total area, between the curve and axis, of 1. The percentage of this area included between any 2 values coincides with the probability that the outcome of an observation described by the PDF falls between those 2 values. Every random variable is associated with a PDF (for example, a bell curve describes a variable with a normal distribution).
Robust statistics	Resistant to outliers, that is if the data include very high or very low values, robust statistics will be good estimates for population parameters, while non-robust statistics will be poor estimators. For example, the arithmetic mean is very susceptible to outliers (non-robust), while the median is not affected by outliers (robust).
Reference measure of variance	An informal statistical descriptor, developed for the purposes of this project to encourage selection of determinands that show lower levels of baseline variability. The RMoV of a determinand is defined as the difference between the upper quartile and lower quartile as a percentage of the median of the observations.
Q-Q plot	Compares the quantiles of a data distribution with the quantiles of a standardised theoretical distribution from a specified family of distributions.
Shapiro-Wilk test	Tests if a random sample comes from a normal distribution. It is an empirical distribution function test.
Skewness	A measure of symmetry, or more precisely, the lack of symmetry. A distribution is symmetric if it looks the same to the left and right of the centre point. The distribution has positive skewness (or right-skewed) if the tail of high values is longer than the tail of low values. Positive skewness indicates the mean of the data values is greater than the median. The distribution has negative skewness (or left-skewed) if the tail of low values is longer than the tail of high values. Negative skewness indicates the mean of the data values is less than the median.
Statistical power	The likelihood of detecting an effect when there is an effect to be detected. If statistical power is high, the probability of concluding there is no effect when, in fact, there is one, goes down.

	It is affected mainly by the size of the effect, and the size of the sample used to detect it. Bigger effects are easier to detect than smaller effects, while larger samples offer greater test sensitivity than small samples.
Tails	As the name suggests, these are the appendages on the side of a distribution. The image below shows the tails of a normal distribution. 
Weibull distribution	A continuous probability distribution, commonly used to assess product reliability, analyse life data and model failure tests.

Appendices

Appendix 1	Kirby Misperton (KM) air quality (AQ) baseline data pack
Appendix 2	Kirby Misperton (KM) water quality (WQ) baseline data pack
Appendix 3	Preston New Road (PNR) air quality (AQ) baseline data pack
Appendix 4	Preston New Road (PNR) water quality (WQ) baseline data pack

Appendix 1 – Kirby Misperton air quality baseline data pack

This appendix contains the data presentation pack for measured concentrations of the prioritised substances at the BGS and Environment Agency monitoring stations at Kirby Misperton.

Graphical and tabulated data summaries should be accompanied by an initial table of basic site/monitoring information.

Table A1.1: BGS site information

Aspect	Description for BGS site			
Site location	NGR			
Dates for which data provided	1 June 2016 to 1 June 2017			
Data capture	NO_2	PM_{10}	CH_4	VOC
Site preparation	25 September 2017 to 11 March 2018			
Drilling	Not taken place			
Hydraulic fracturing	Not taken place			

Table A1.2: Environment Agency site information

Aspect	Description for Environment Agency site			
Site location	NGR			
Dates for which data provided	23 August 2017 to 22 August 2018			
Data capture	NO_2	PM_{10}	CH_4	VOC
Site preparation	25 September 2017 to 11 March 2018			
Drilling	Not taken place			
Hydraulic fracturing	Not taken place			

Section A1.1: Kirby Misperton site, BGS monitoring station - nitrogen dioxide

Section A1.2: Kirby Misperton site, BGS monitoring station - PM_{10}

Section A1.3: Kirby Misperton site, BGS monitoring station - CH_4

Section A1.4: Kirby Misperton site, BGS monitoring station - speciated VOCs

Section A1.5: Kirby Misperton site, Environment Agency monitoring station - nitrogen dioxide

Section A1.6: Kirby Misperton site, Environment Agency monitoring station - PM_{10}

Section A1.7: Kirby Misperton site, Environment Agency monitoring station - CH_4

A1.1 Kirby Misperton, BGS site - NO_2

Figure A1.1: Density plot for one year of hourly baseline data for NO_2 (Kirby Misperton, BGS site)

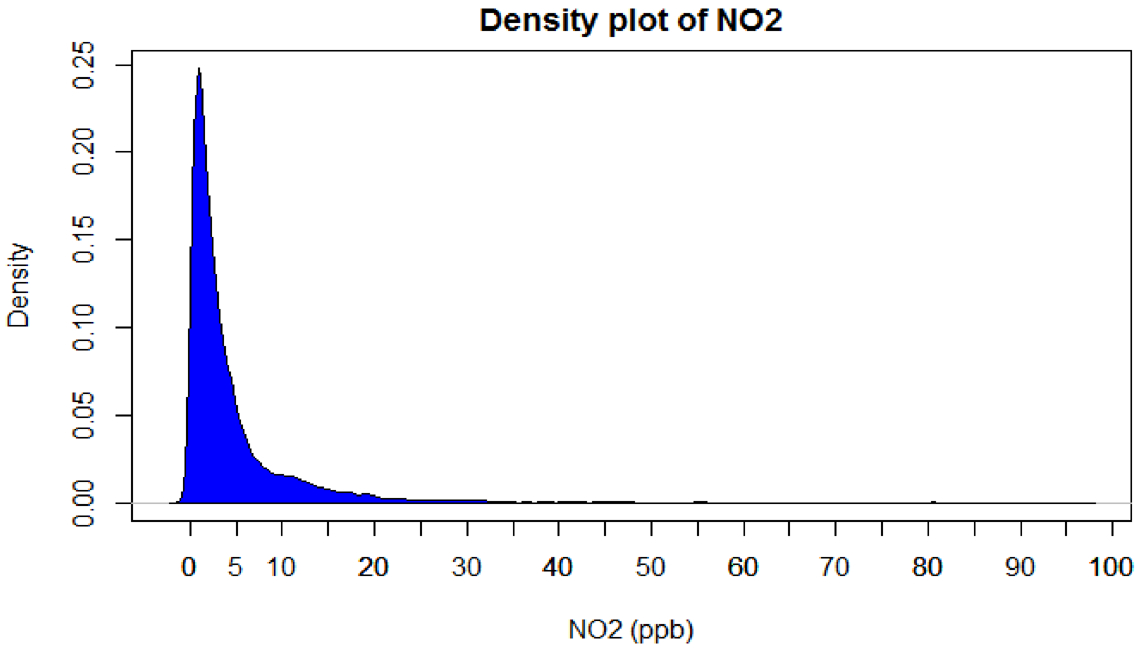


Figure A1.2: Time series for one year baseline data for NO_2 (Kirby Misperton, BGS site)

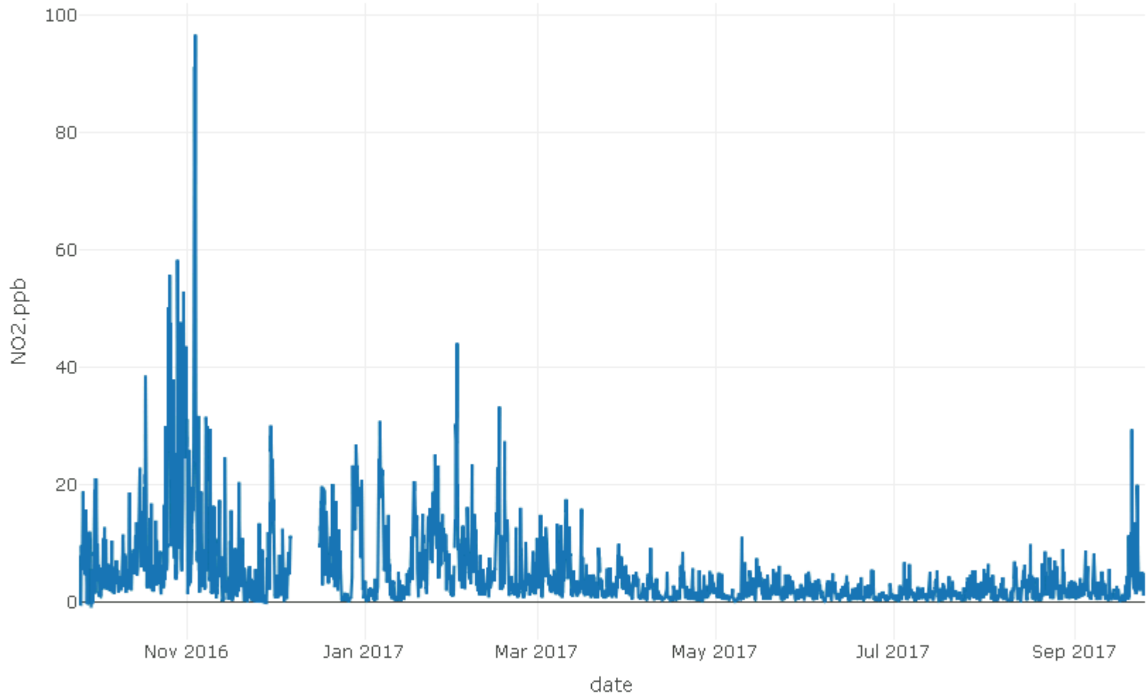


Figure A1.3: Time series plot of different percentiles for one year of hourly baseline data for NO_2 (Kirby Misperton, BGS site)

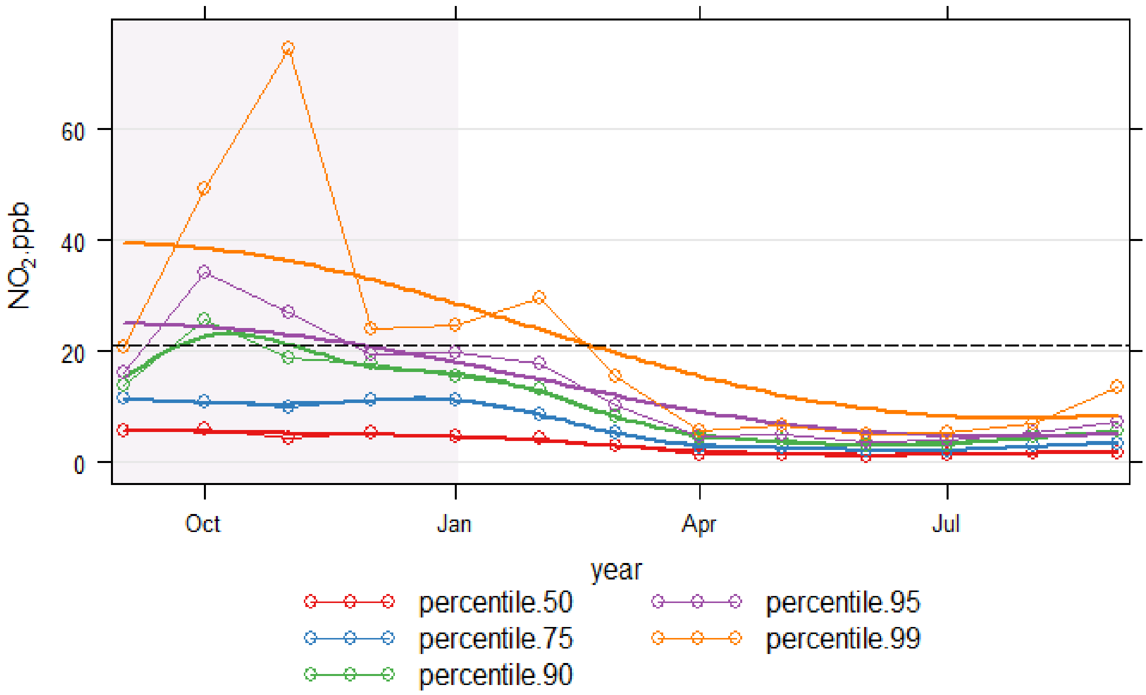


Figure A1.4: Time variation plot for one year of baseline data for NO_2 (Kirby Misperton, BGS site)

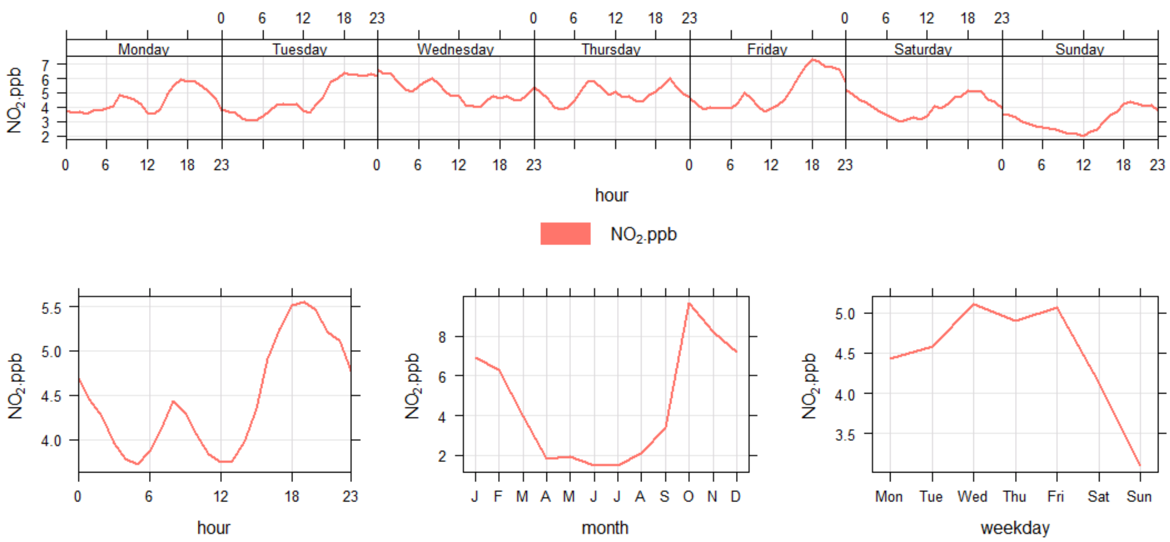


Table A1.3: Summary statistics for one year of baseline data for NO_2 (Kirby Misperton, BGS site)

Metric	NO_2.ppb
Mean	4.46

Metric	NO_2.ppb
50%	2.36
75%	4.98
90%	11.07
95%	15.77
99%	30.85
99.8%	54.71

Conditional probability plots

Conditional probability plots provide information on the likelihood that a wind speed and wind direction falls between the 2 percentiles. These plots allow for an understanding of where the highest concentrations are likely to come from.

Figure A1.5: Conditional probability plot between the 75th and 90th percentiles for one year of baseline data for NO_2 (Kirby Misperton, BGS site)

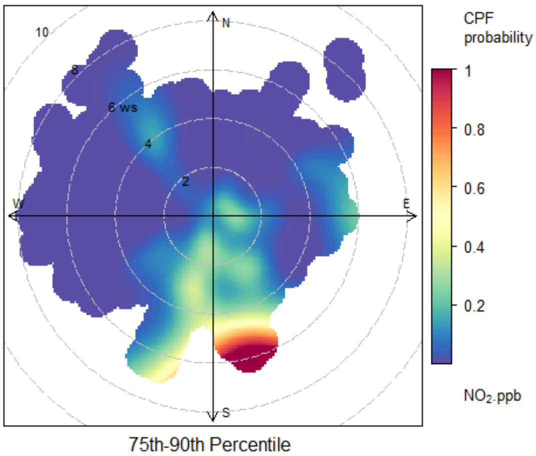


Figure A1.6: Conditional probability plot between the 90th and 95th percentiles for one year of baseline data for NO_2 (Kirby Misperton, BGS site)

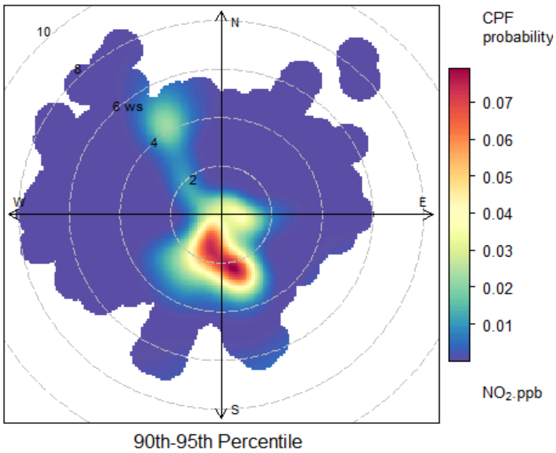


Figure A1.7: Conditional probability plot between the 95th and 99th percentiles for one year of baseline data for NO_2 (Kirby Misperton, BGS site)

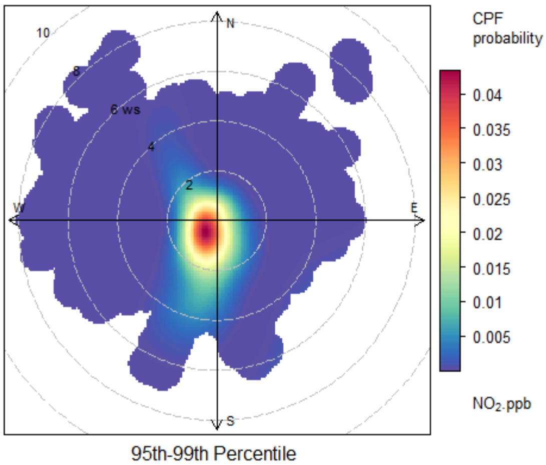


Figure A1.8: Conditional probability plot between the 99th and 100th percentiles for one year of baseline data for NO_2 (Kirby Misperton, BGS site)

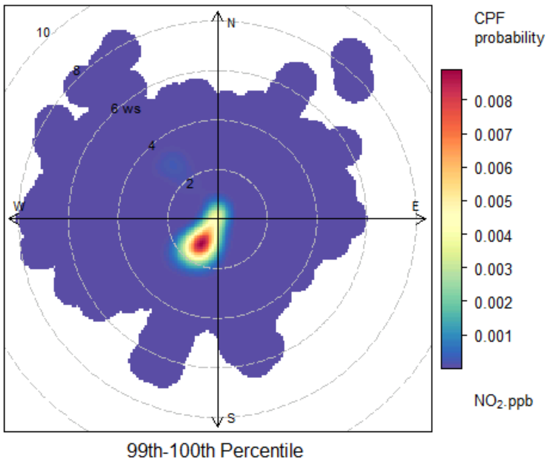


Figure A1.9: Polar plot of the mean NO_2 concentration (Kirby Misperton, BGS site)

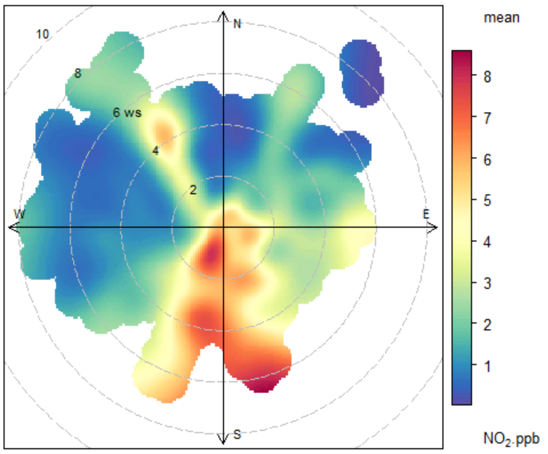


Figure A1.10: Polar plot of the median NO_2 concentration (Kirby Misperton, BGS site)

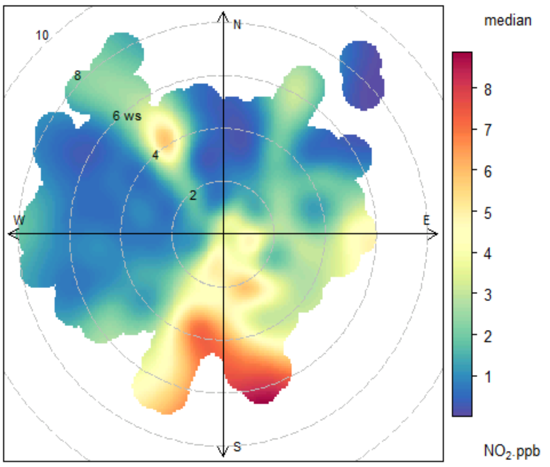


Figure A1.11: Polar plot of the weighted mean (mean/frequency) NO_2 concentration for one year of baseline data for NO_2 (Kirby Misperton, BGS site)

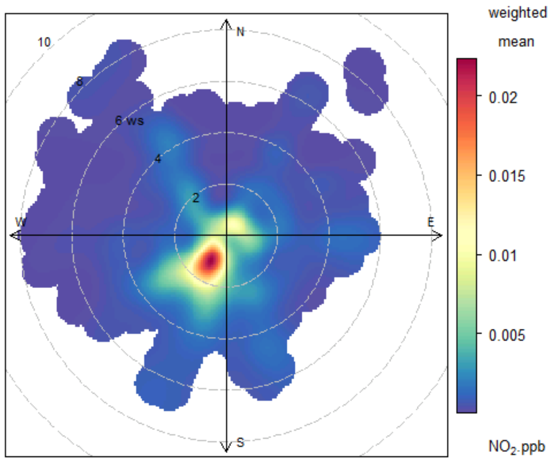


Figure A1.12: Polar frequency plot for NO_2 for one year of baseline data (Kirby Misperton, BGS site)

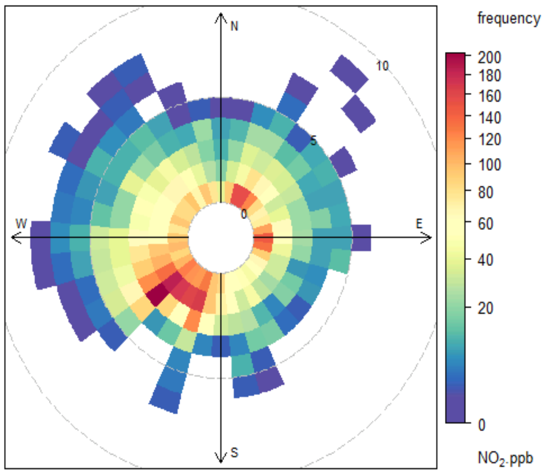


Figure A1.13: Polar plot of the 75th percentile NO_2 concentration (Kirby Misperton, BGS site)

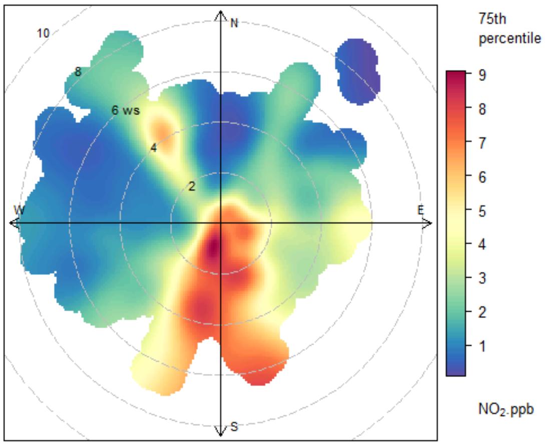


Figure A1.15: Polar plot of the 90th percentile NO_2 concentration (Kirby Misperton, BGS site)

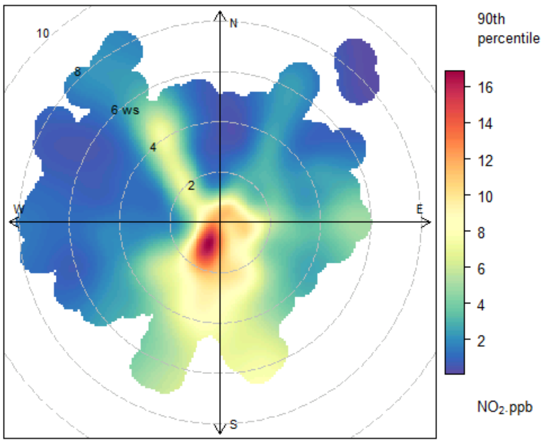


Figure A1.14: Polar plot of the 95th percentile NO_2 concentration (Kirby Misperton, BGS site)

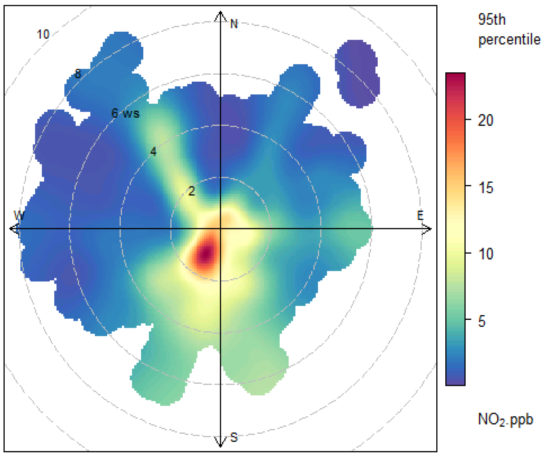


Figure A1.16: Polar plot of the 99th percentile NO_2 concentration for one year of baseline data for NO_2 (Kirby Misperton, BGS site)

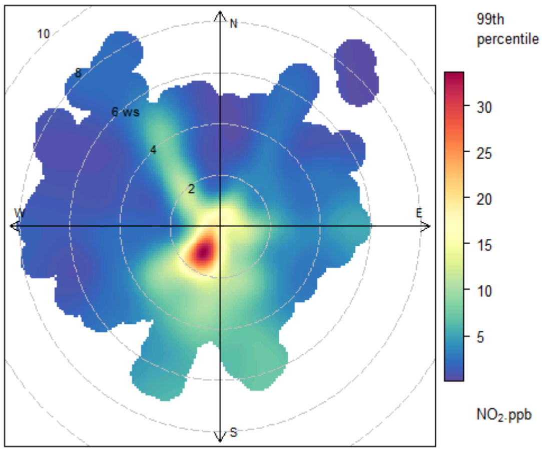
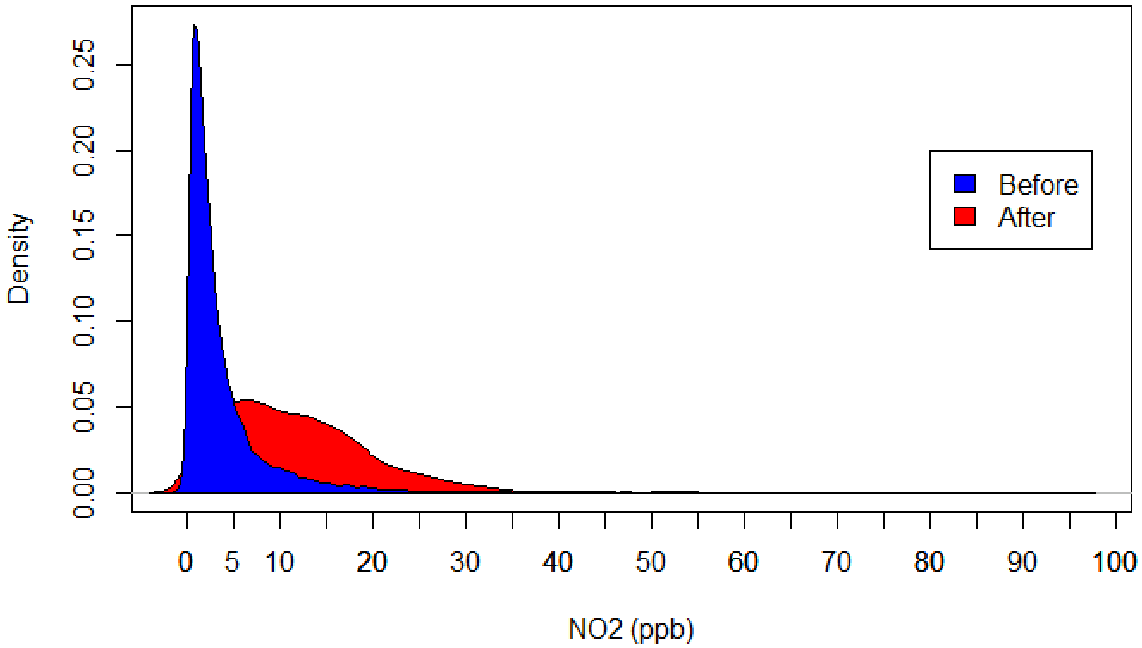


Figure A1.17: Density plot for baseline data for NO_2 (Kirby Misperton, BGS site) showing before and after site activities began



A1.2 Kirby Misperton, BGS site - PM_{10}

Figure A1.18: Density plot for one year of baseline data for PM_{10} (Kirby Misperton, BGS site)

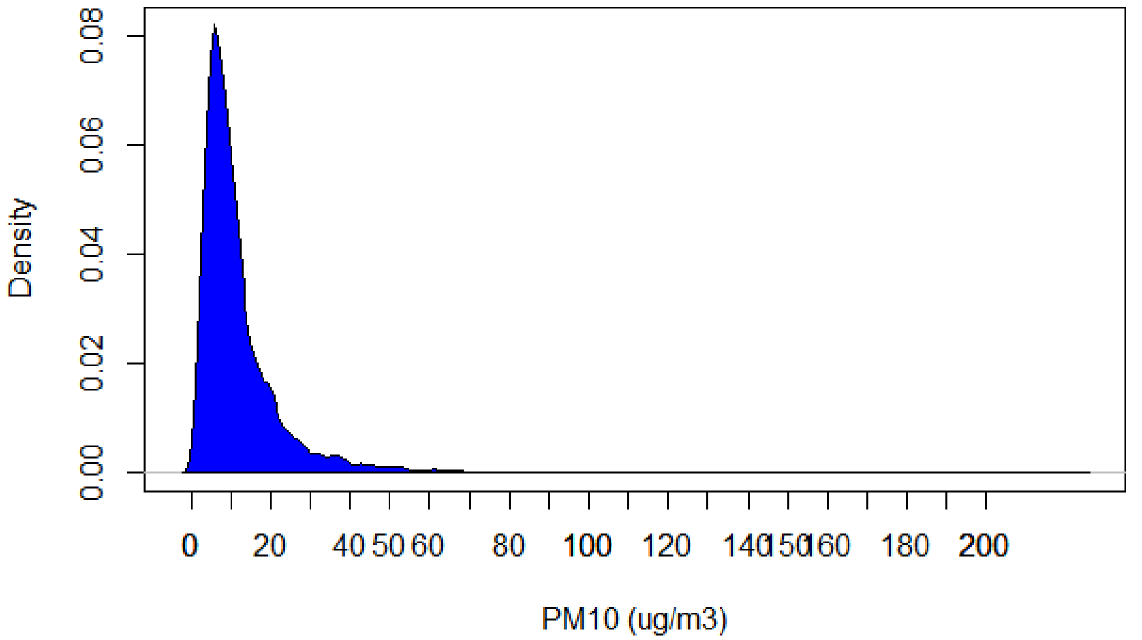


Figure A1.19: Time series for one year baseline data for PM_{10} (Kirby Misperton, BGS site)

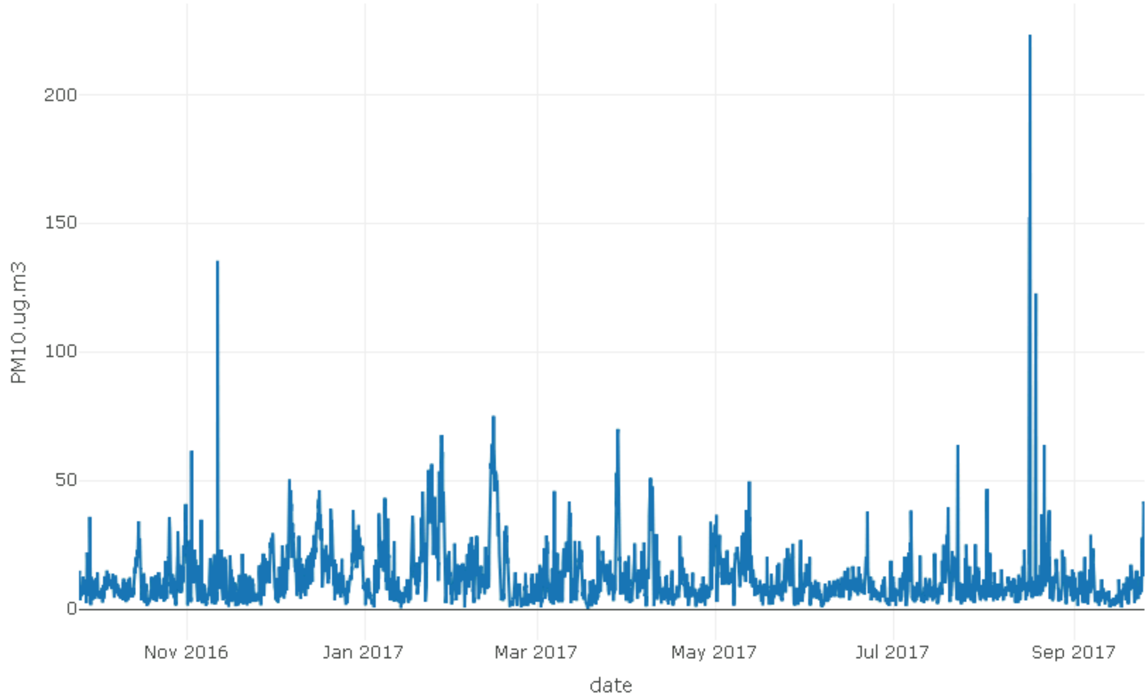


Figure A1.20: Time series plot of different percentiles for one year of baseline data for PM_{10} (Kirby Misperton, BGS site)

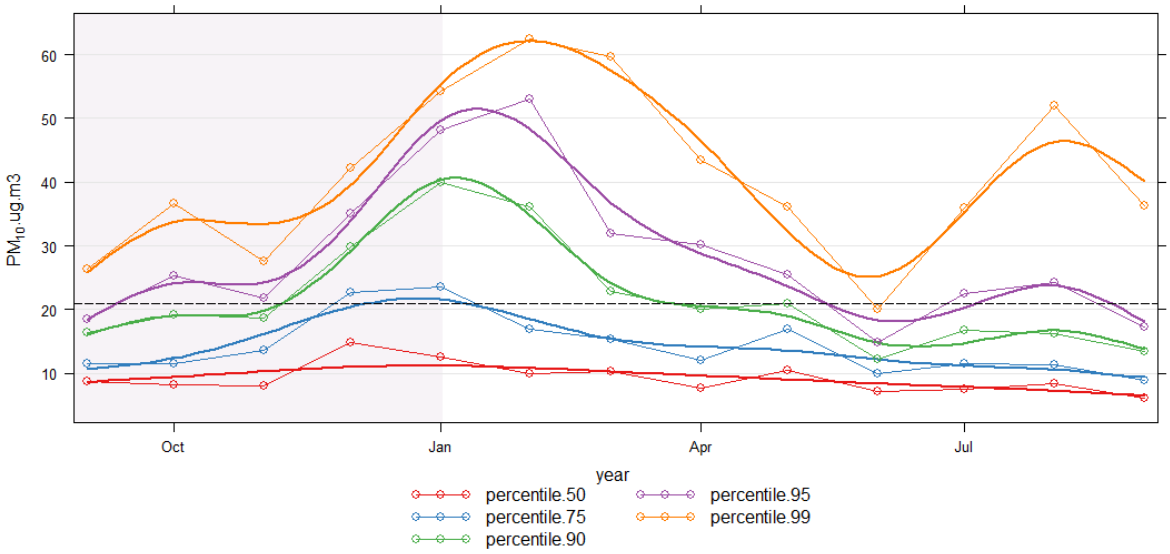


Figure A1.21: Time variation plot for one year of baseline data for PM_{10} (Kirby Misperton, BGS site)

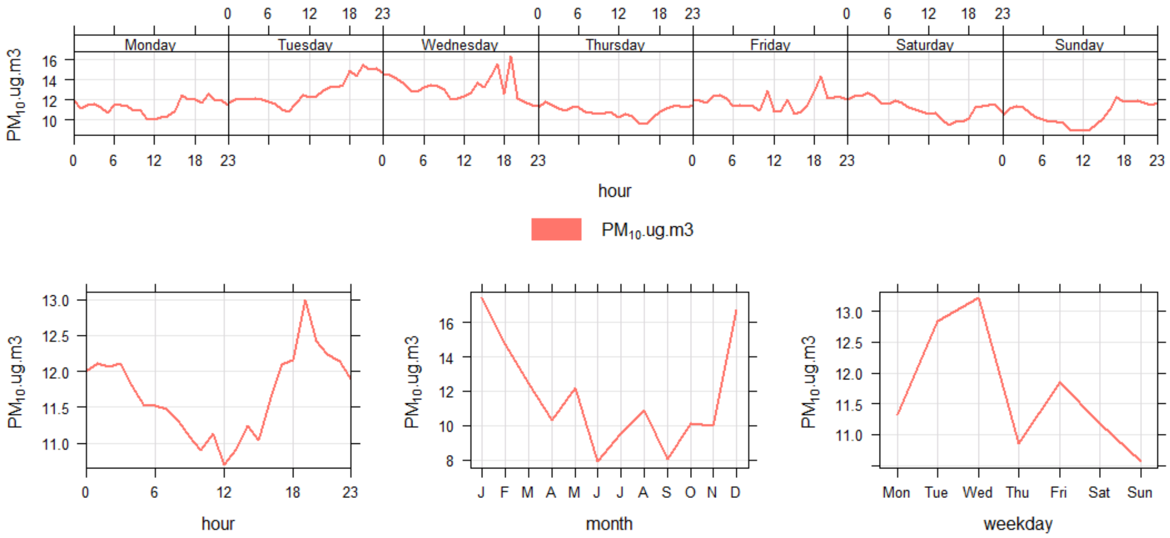


Table A1.4: Summary statistics for one year of baseline data for PM_{10} (Kirby Misperton, BGS site)

Metric	PM_{10} ug/m^3
Mean	11.69
50%	8.85
75%	14.00
90%	22.66
95%	31.12
99%	51.29

Figure A1.22: Conditional probability plot between the 75th and 90th percentiles for one year of baseline data for PM_{10} (Kirby Misperton, BGS site)

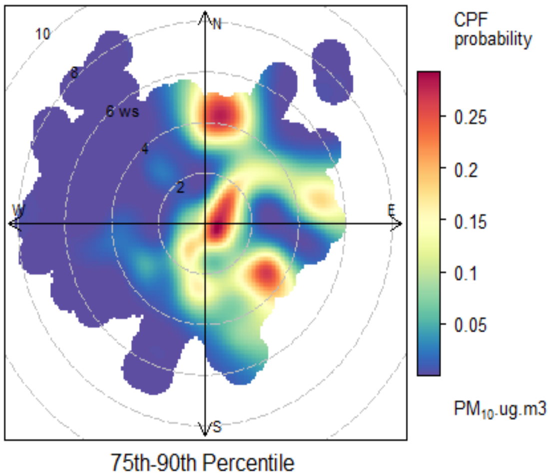


Figure A1.23: Conditional probability plot between the 90th and 95th percentiles for one year of baseline data for PM_{10} (Kirby Misperton, BGS site)

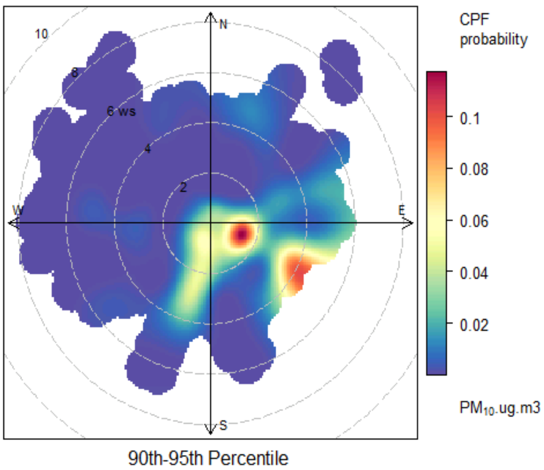


Figure A1.24: Conditional probability plot between the 95th and 99th percentiles for one year of baseline data for PM_{10} (Kirby Misperton, BGS site)

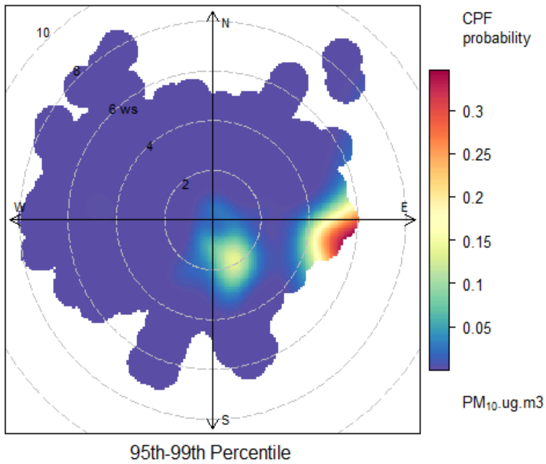


Figure A1.25: Conditional probability plot between the 99th and 100th percentiles for one year of baseline data for PM_{10} (Kirby Misperton, BGS site)

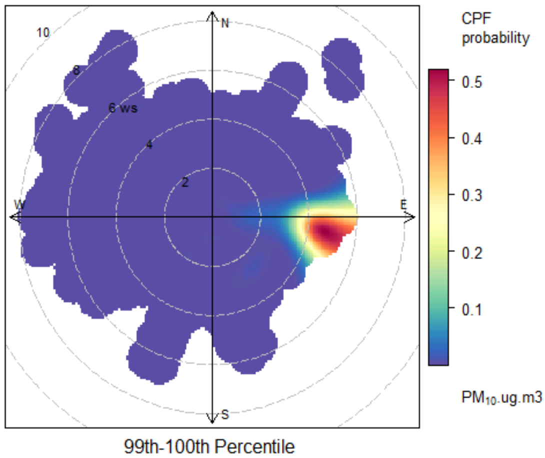


Figure A1.26: Polar plot of the mean concentration for one year of baseline data for PM_{10} (Kirby Misperton, BGS site)

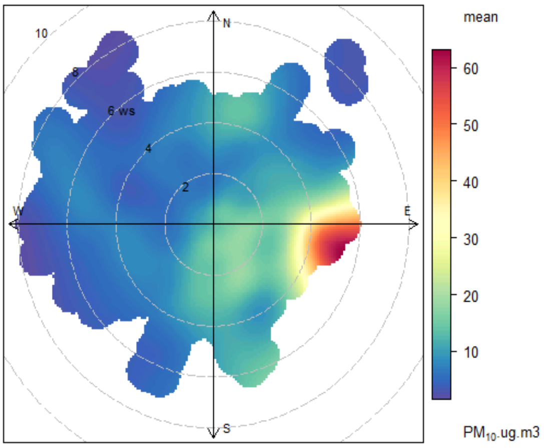


Figure A1.28: Polar plot of the weighted mean (mean/frequency) for one year of baseline data for PM_{10} (Kirby Misperton, BGS site)

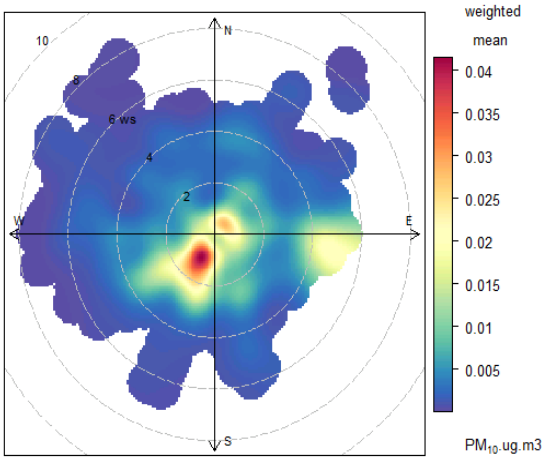


Figure A1.27: Polar plot of the median concentration for one year of baseline data for PM_{10} (Kirby Misperton, BGS site)

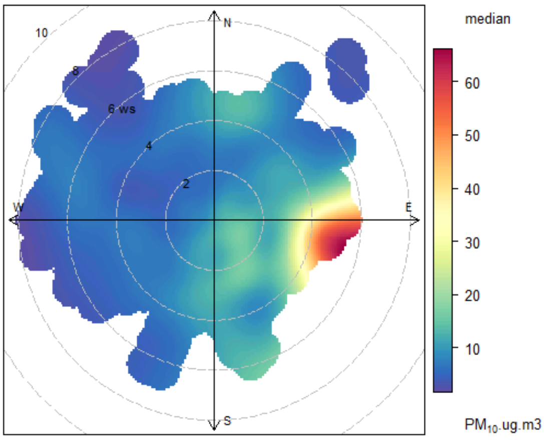


Figure A1.29: Polar frequency plot for one year of baseline data for PM_{10} (Kirby Misperton, BGS site)

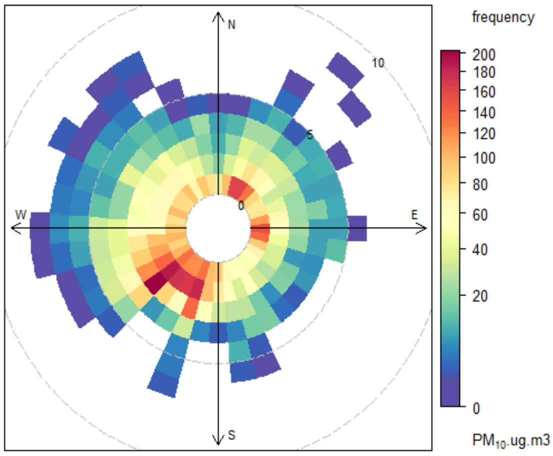


Figure A1.30: Polar plot of the 75th percentile concentration for one year of baseline data for PM_{10} (Kirby Misperton, BGS site)

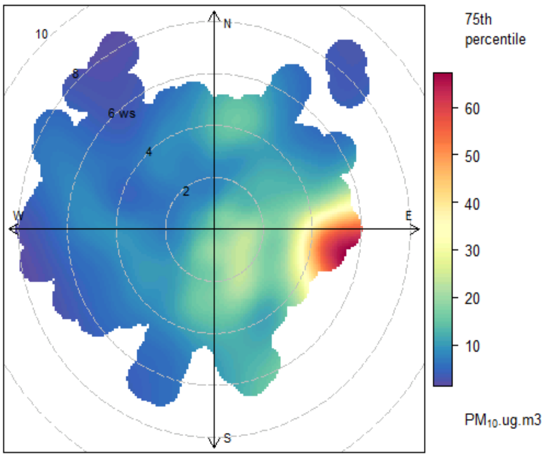


Figure A1.31: Polar plot of the 90th percentile concentration for one year of baseline data for PM_{10} (Kirby Misperton, BGS site)

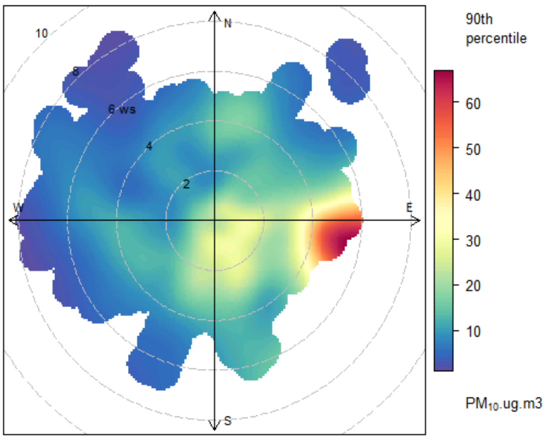


Figure A1.32: Polar plot of the 95th percentile concentration for one year of baseline data for PM_{10} (Kirby Misperton, BGS site)

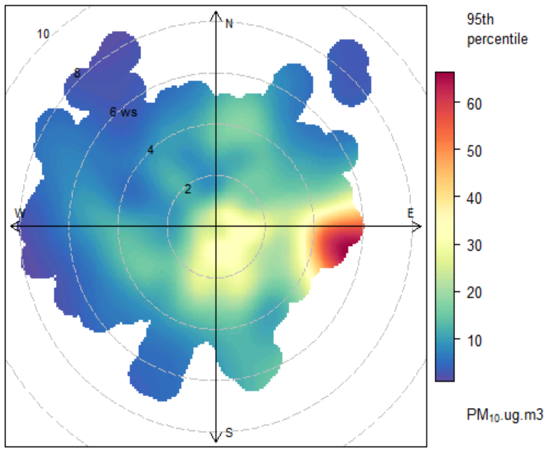


Figure A1.33: Polar plot of the 99th percentile concentration for one year of baseline data for PM_{10} (Kirby Misperton, BGS site)

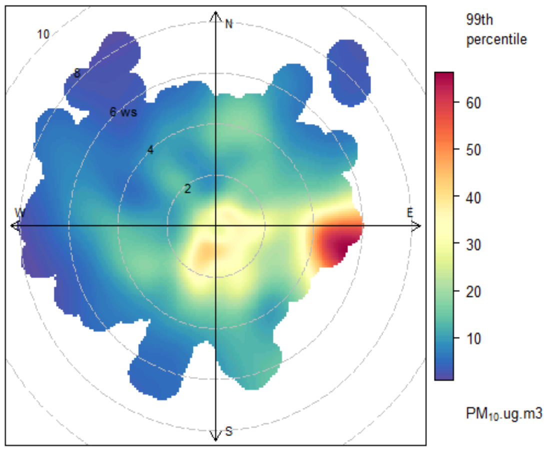
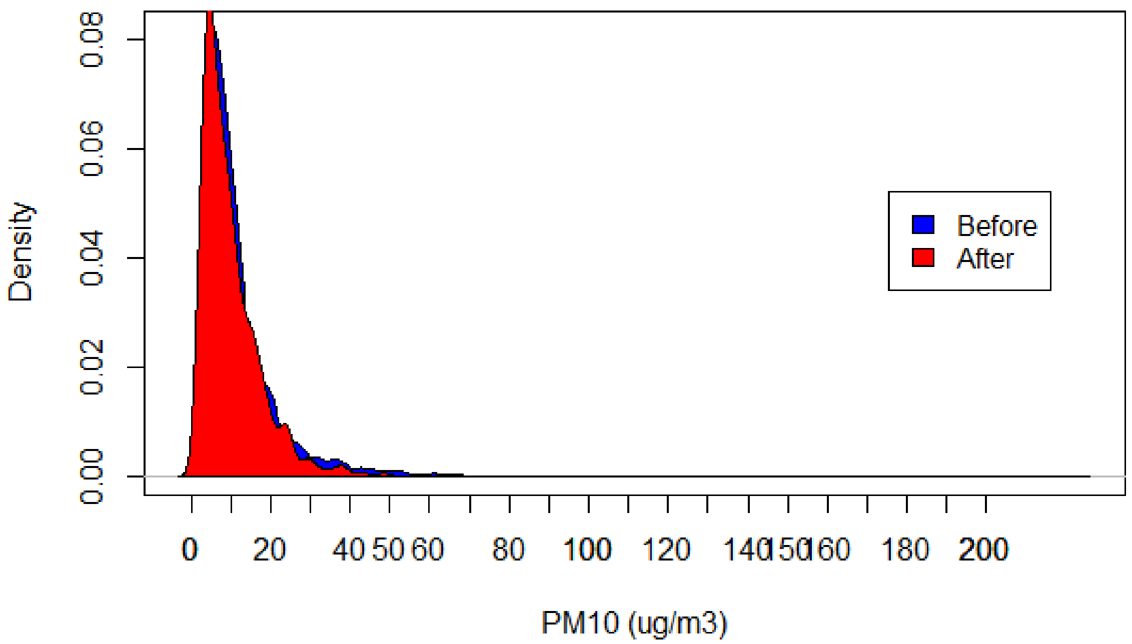


Figure A1.34: Density plot for one year of baseline data for PM_{10} (Kirby Misperton, BGS site) showing before and after site activities began



A1.3 Kirby Misperton, BGS site - CH_4

Figure A1.35: Density plot for one year of baseline data for CH_4 (Kirby Misperton, BGS site)

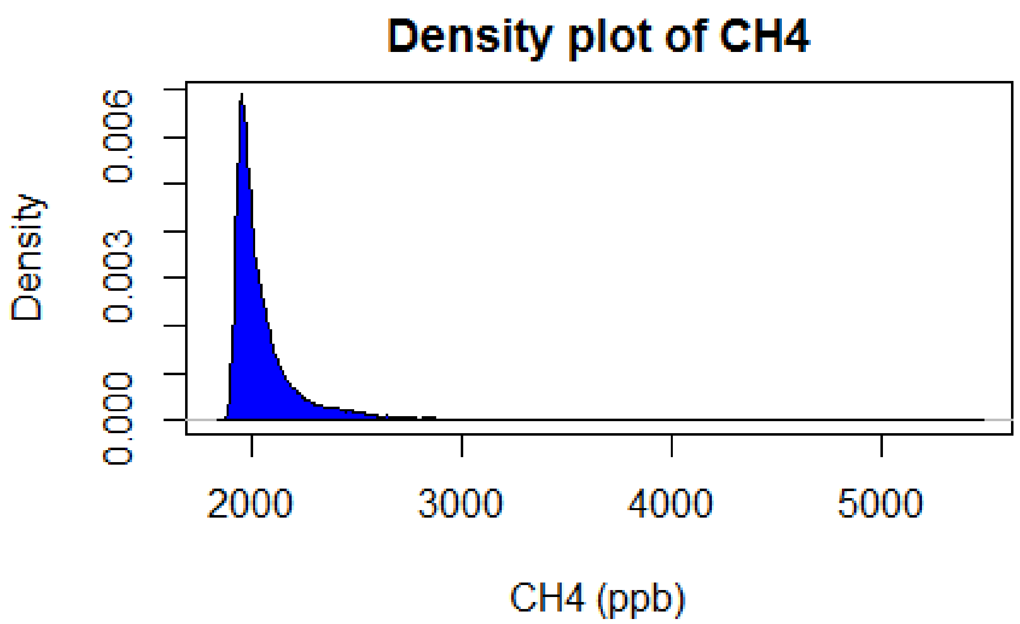


Figure A1.36: Time series for one year baseline data for CH_4 (Kirby Misperton, BGS site) (ppb)

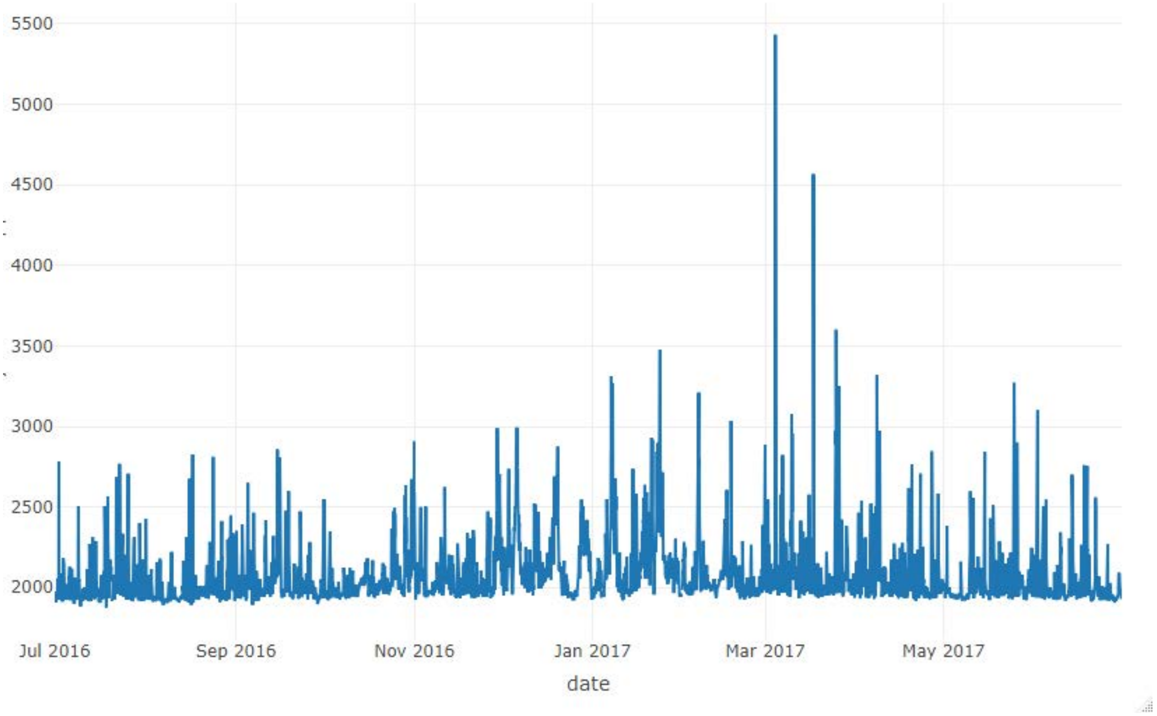


Figure A1.37: Time series plot of different percentiles for one year of baseline data for CH_4 (Kirby Misperton, BGS site) (ppb)

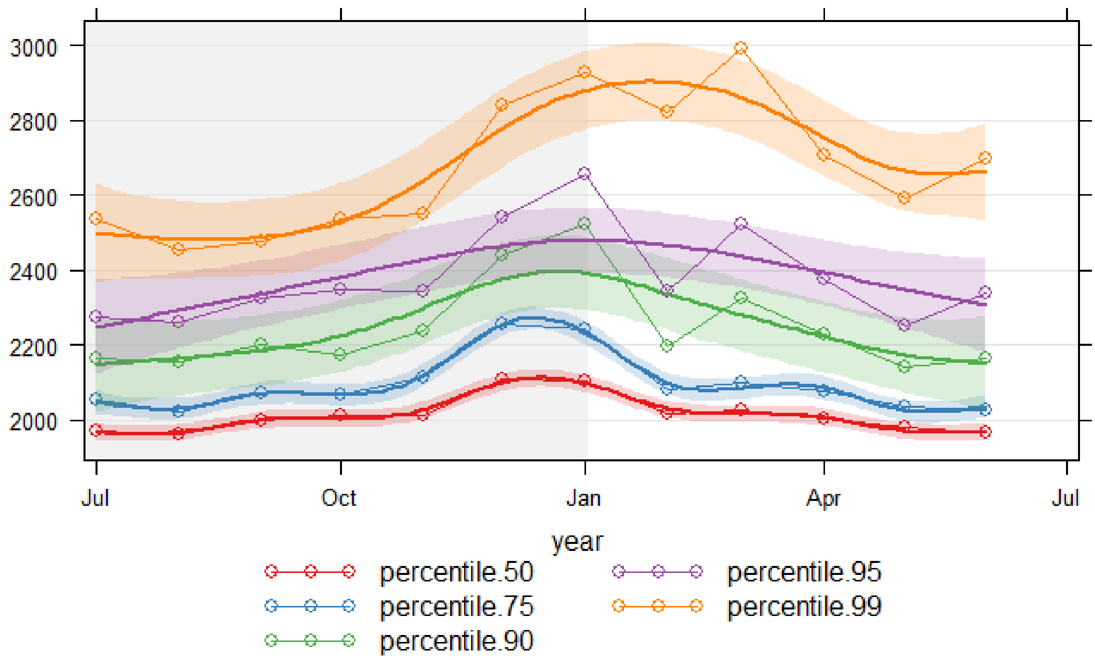


Figure A1.38: Time variation plot for one year of baseline data for CH_4 (Kirby Misperton, BGS site) (ppb)

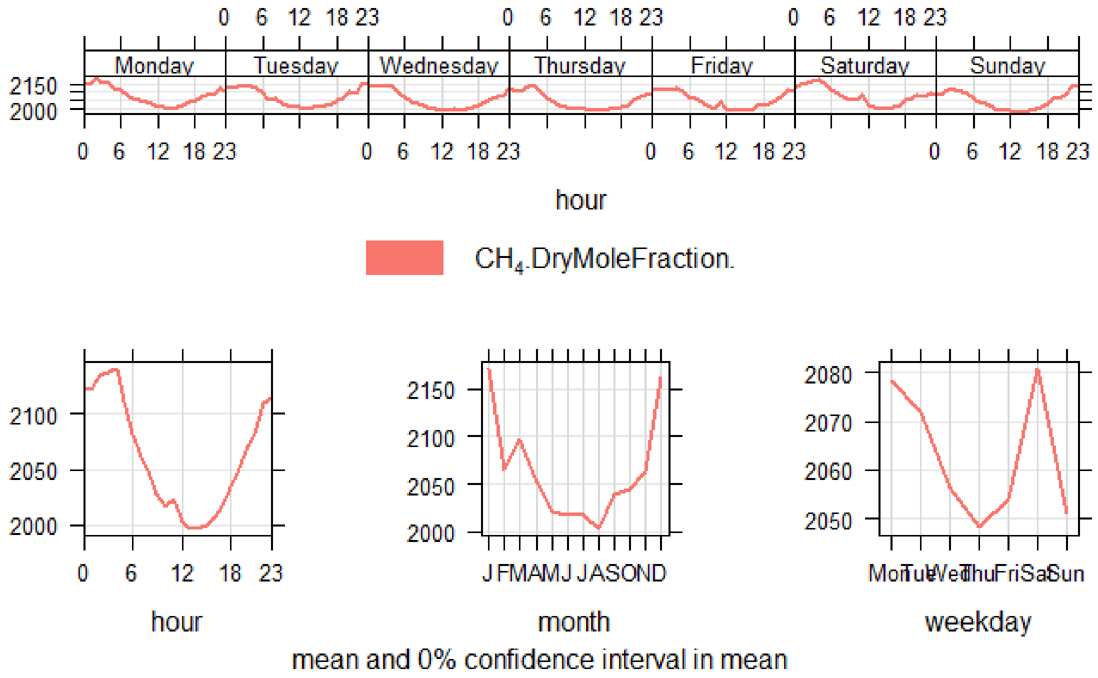


Table A1.5: Summary statistics for one year of baseline data for CH_4 (Kirby Misperton, BGS site)

Metric	CH_4 ppm
Mean	2.06
50%	2.01
75%	2.10
90%	2.26
95%	2.42
99%	2.76

Figure A1.39: Conditional probability plot between the 75th and 90th percentiles for one year of baseline data for CH_4 (Kirby Misperton, BGS site)

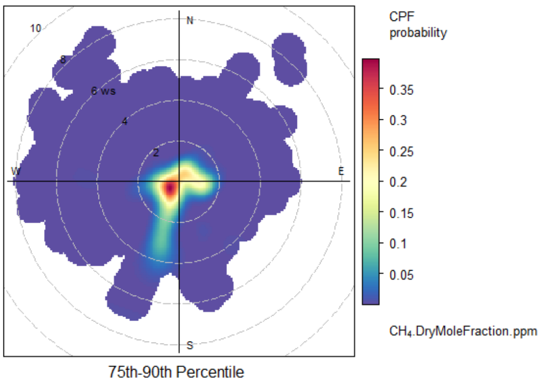


Figure A1.40: Conditional probability plot between the 90th and 95th percentiles for one year of baseline data for CH_4 (Kirby Misperton, BGS site)

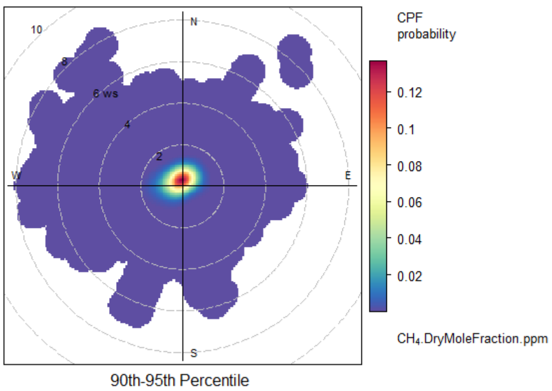


Figure A1.41: Conditional probability plot between the 95th and 99th percentiles for one year of baseline data for CH_4 (Kirby Misperton, BGS site)

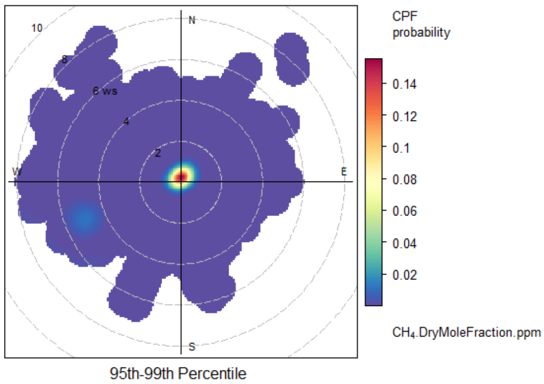


Figure A1.42: Conditional probability plot between the 99th and 100th percentiles for one year of baseline data for CH_4 (Kirby Misperton, BGS site)

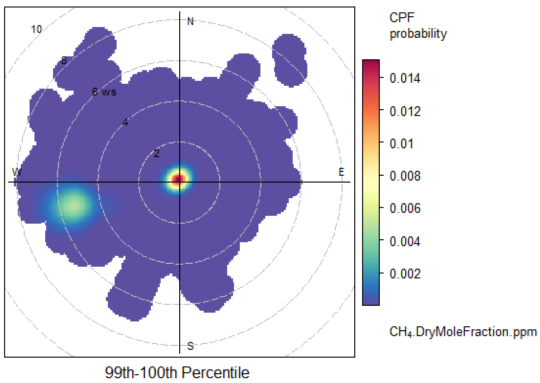


Figure A1.43: Polar plot of the mean concentration for one year of baseline data for CH_4 (Kirby Misperton, BGS site) (ppb)

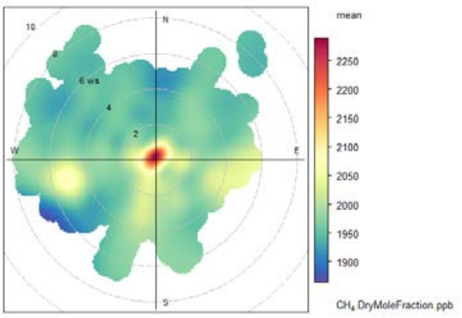


Figure A1.44: Polar plot of the median concentration for one year of baseline data for CH_4 (Kirby Misperton, BGS site) (ppb)

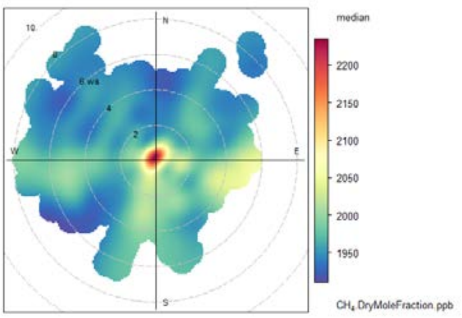


Figure A1.45: Polar plot of the weighted mean (mean/frequency) for one year of baseline data for CH_4 (Kirby Misperton, BGS site) (ppb)

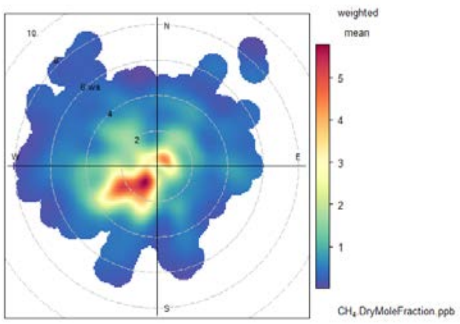


Figure A1.46: Polar frequency plot for one year of baseline data for CH_4 (Kirby Misperton, BGS site) (ppb)

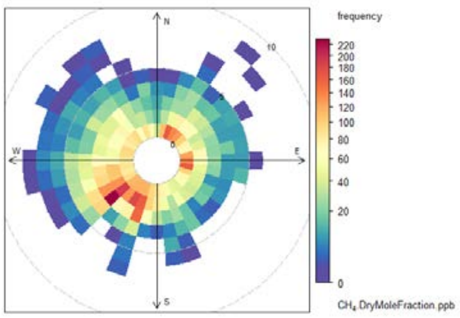


Figure A1.47: Polar plot of the 75th percentile concentration for one year of baseline data for CH_4 (Kirby Misperton, BGS site) (ppb)

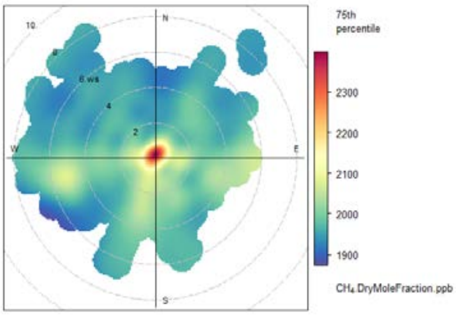


Figure A1.48: Polar plot of the 90th percentile concentration for one year of baseline data for CH_4 (Kirby Misperton, BGS site) (ppb)

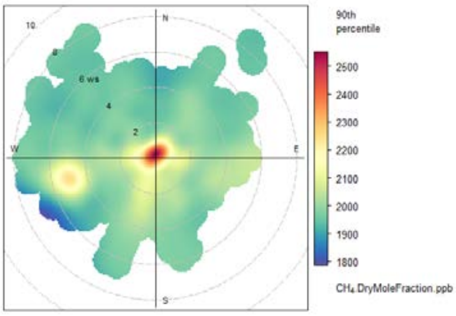


Figure A1.49: Polar plot of the 95th percentile concentration for one year of baseline data for CH_4 (Kirby Misperton, BGS site) (ppb)

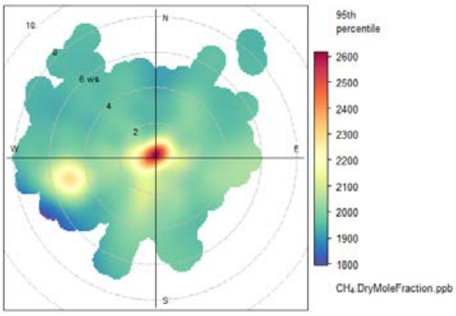
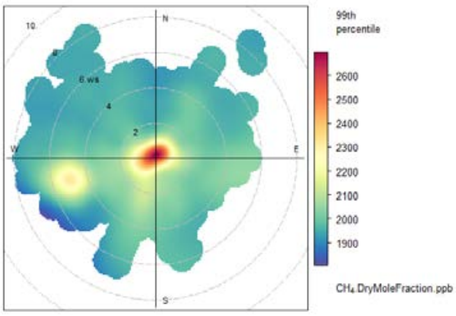


Figure A1.50: Polar plot of the 99th percentile concentration for one year of baseline data for CH_4 (Kirby Misperton, BGS site) (ppb)



A1.4 Kirby Misperton, BGS site - VOC

Table A1.6: VOC summary statistics before activity (31 January 2017 to 14 September 2017 from 32 measurements)

	ethane (ppb)	ethene (ppb)	propane (ppb)	propene (ppb)	iso-butane (ppb)	n-butane (ppb)	acetylene (ppb)	iso-pentane (ppb)	e (ppb)	isoprene (ppb)	benzene (ppb)	toluene (ppb)
Mean	2.05	0.57	0.86	0.11	0.22	0.40	0.24	0.22	0.17	0.02	0.10	0.10
Median	1.75	0.47	0.75	0.09	0.16	0.30	0.14	0.12	0.10	0.02	0.08	0.07
75%	2.49	0.68	1.10	0.13	0.30	0.56	0.31	0.29	0.18	0.03	0.11	0.12
90%	3.82	1.02	1.86	0.19	0.52	0.89	0.79	0.63	0.70	0.06	0.25	0.32
95%	4.42	1.17	2.21	0.22	0.61	1.03	1.01	0.78	0.95	0.08	0.31	0.41
99%	4.89	1.29	2.48	0.24	0.69	1.14	1.19	0.91	1.16	0.09	0.37	0.48

A1.5 Kirby Misperton, Environment Agency site - NO_2

Figure A1.51: Density plot for one year of baseline data for NO_2 (Kirby Misperton, Environment Agency site) (µg/m^3)

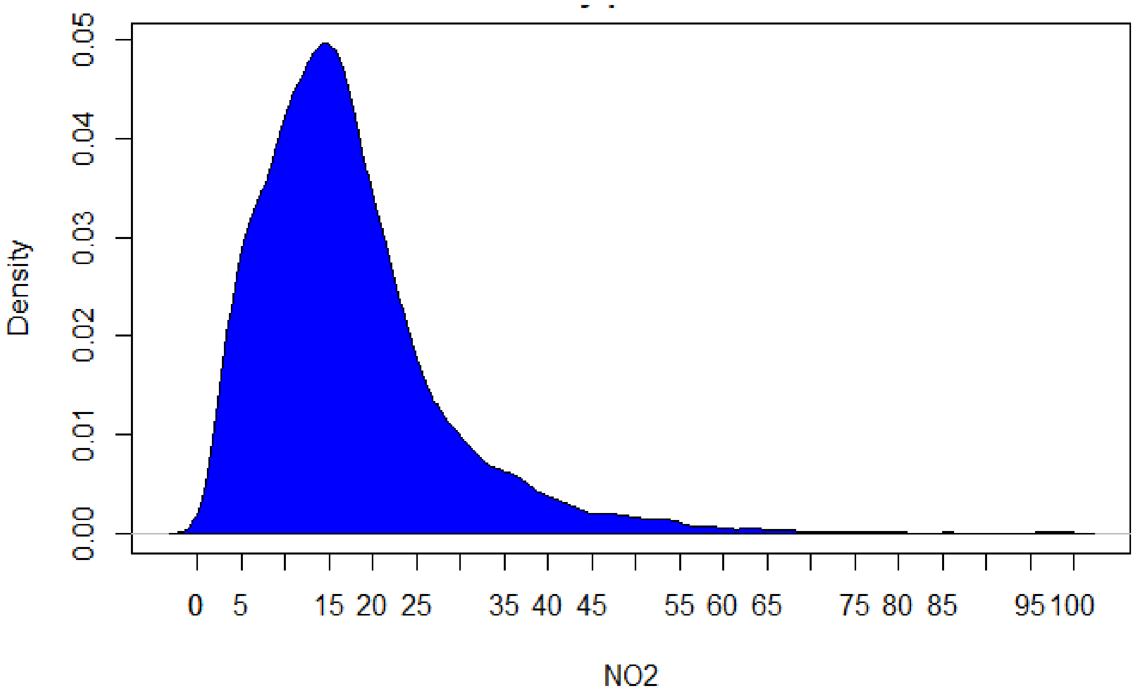


Figure A1.52: Time series for one year baseline data for NO_2 (Kirby Misperton, Environment Agency site) (µg/m^3)

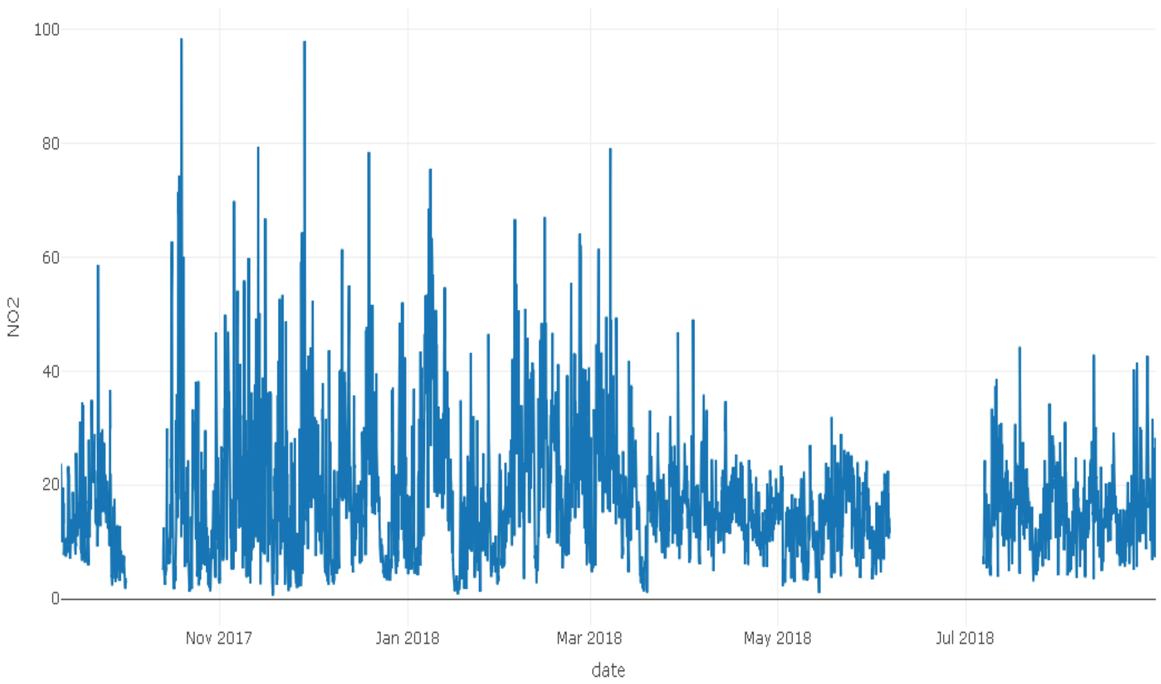


Figure A1.53: Time series plot of different percentiles for one year of baseline data for NO_2 (Kirby Misperton, Environment Agency site) (µg/m³)

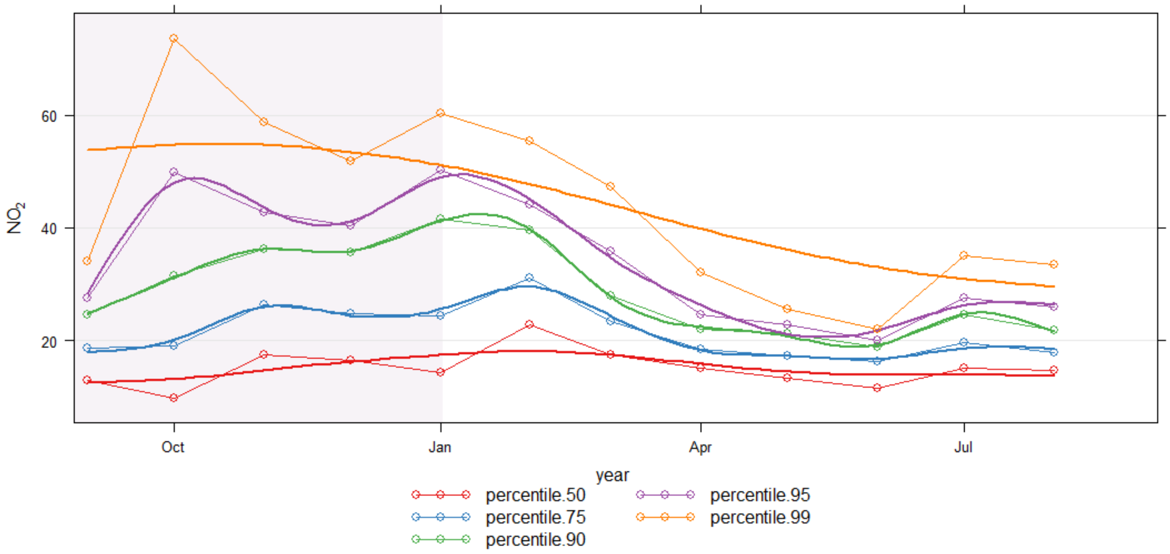


Figure A1.54: Time variation plot for one year of baseline data for NO_2 (Kirby Misperton, Environment Agency site) (µg/m³)

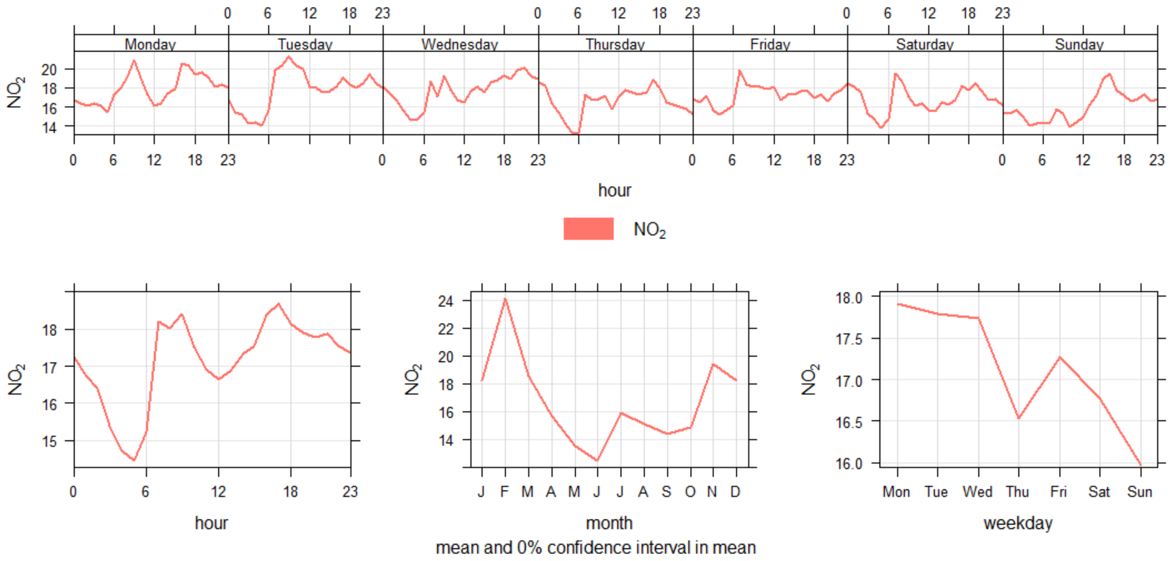


Table A1.7: Summary statistics for one year of baseline data for NO_2 (Kirby Misperton, Environment Agency site)

Metric	NO_2 (µg/m^3)
Mean	17.14
50%	15.30
75%	21.44
90%	30.15
95%	37.50
99%	53.65
99.8%	69.84

Figure A1.55: Conditional probability plot between the 75th and 90th percentiles for one year of baseline data for NO_2 (Kirby Misperton, Environment Agency site)

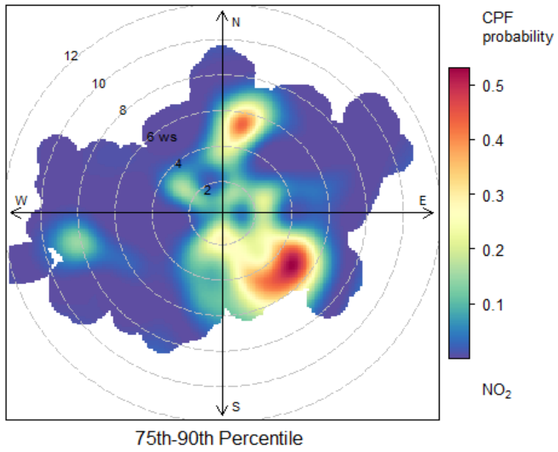


Figure A1.56: Conditional probability plot between the 90th and 95th percentiles for one year of baseline data for NO_2 (Kirby Misperton, Environment Agency site)

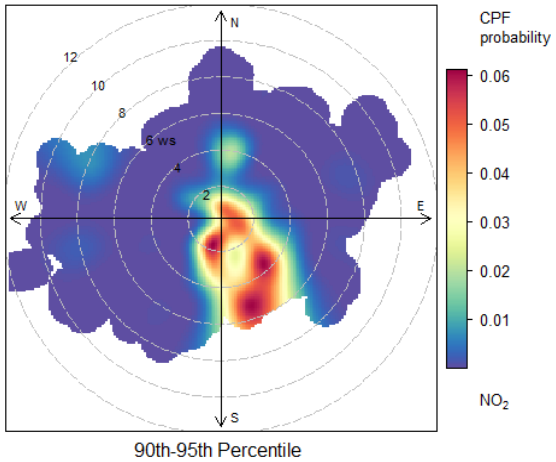


Figure A1.57: Conditional probability plot between the 95th and 99th percentiles for one year of baseline data for NO_2 (Kirby Misperton, Environment Agency site)

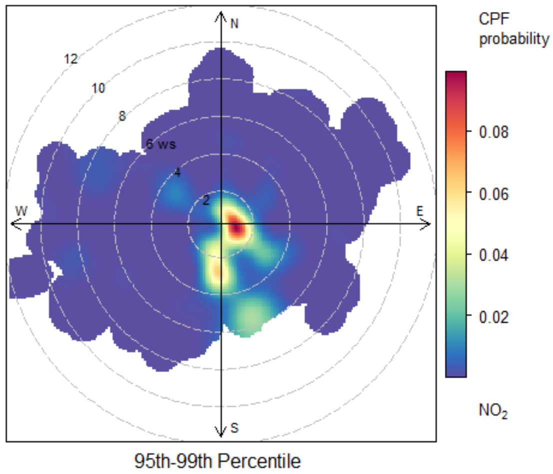


Figure A1.58: Conditional probability plot between the 99th and 100th percentiles for one year of baseline data for NO_2 (Kirby Misperton, Environment Agency site)

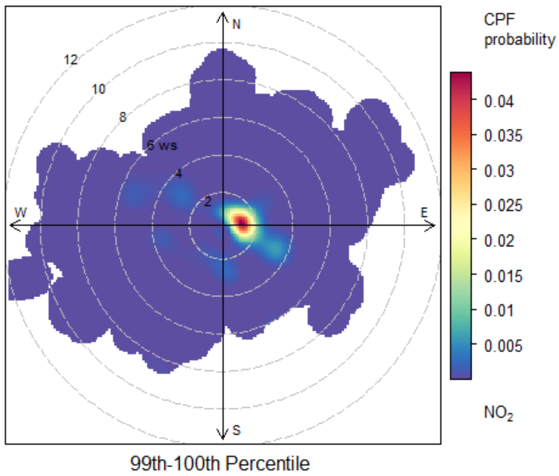


Figure A1.59: Polar plot of the mean concentration for one year of baseline data for NO_2 (Kirby Misperton, Environment Agency site) (µg/m^3)

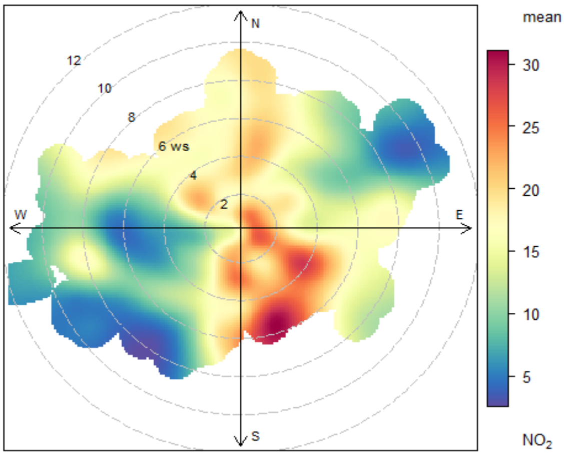


Figure A1.60: Polar plot of the median concentration for one year of baseline data for NO_2 (Kirby Misperton, Environment Agency site) (µg/m^3)

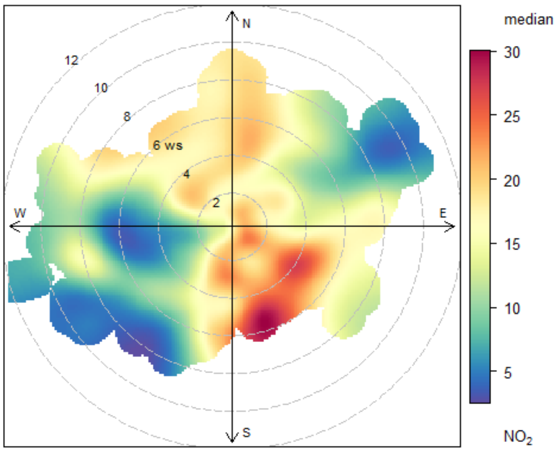


Figure A1.61: Polar plot of the 75th percentile concentration for one year of baseline data for NO_2 (Kirby Misperton, Environment Agency site) (µg/m^3)

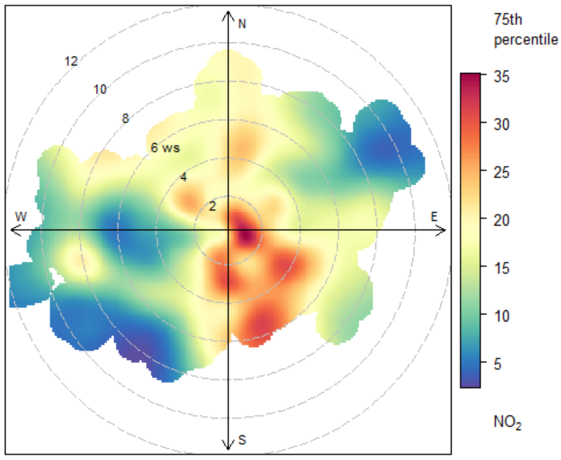


Figure A1.62: Polar plot of the 90th percentile concentration for one year of baseline data for NO_2 (Kirby Misperton, Environment Agency site) (µg/m^3)

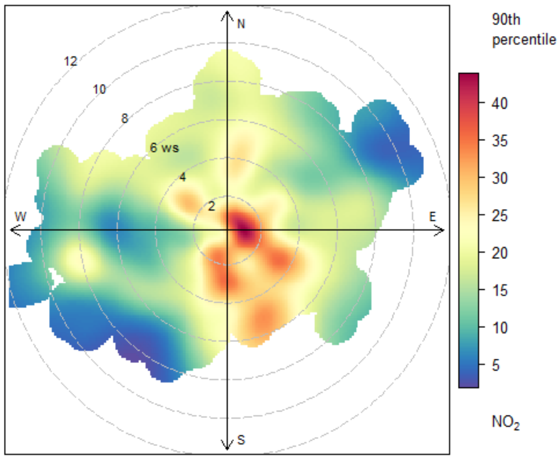


Figure A1.63: Polar plot of the 95th percentile concentration for one year of baseline data for NO_2 (Kirby Misperton, Environment Agency site) (µg/m^3)

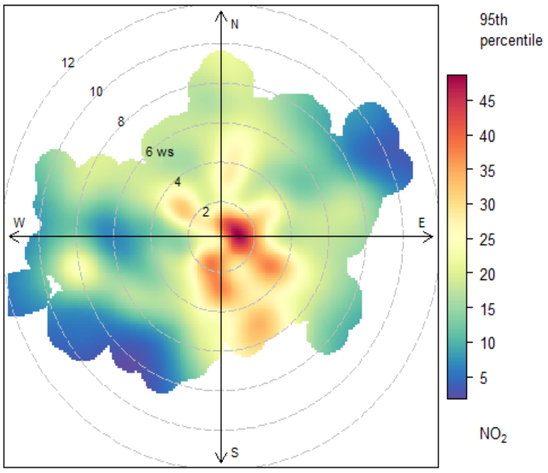


Figure A1.64: Polar plot of the 99th percentile concentration for one year of baseline data for NO_2 (Kirby Misperton, Environment Agency site) (µg/m^3)

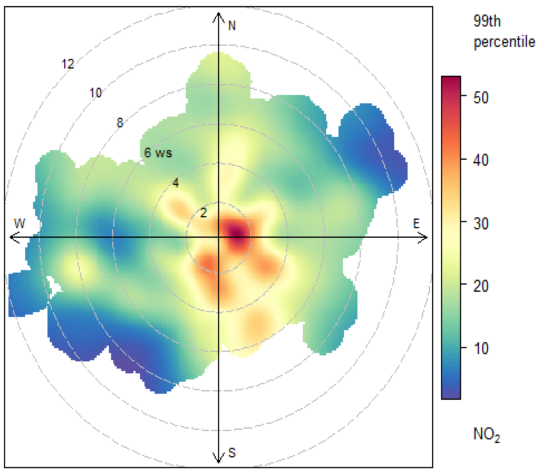


Figure A1.65: Polar plot of the weighted mean (mean/frequency) for one year of baseline data for NO_2 (Kirby Misperton, Environment Agency site) (µg/m^3)

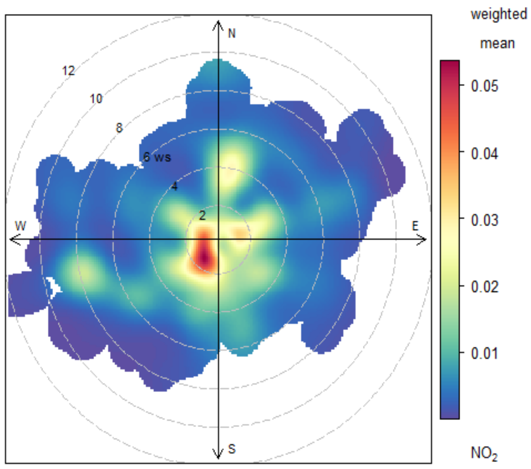


Figure A1.66: Polar frequency plot for one year of baseline data for NO_2 (Kirby Misperton, Environment Agency site)

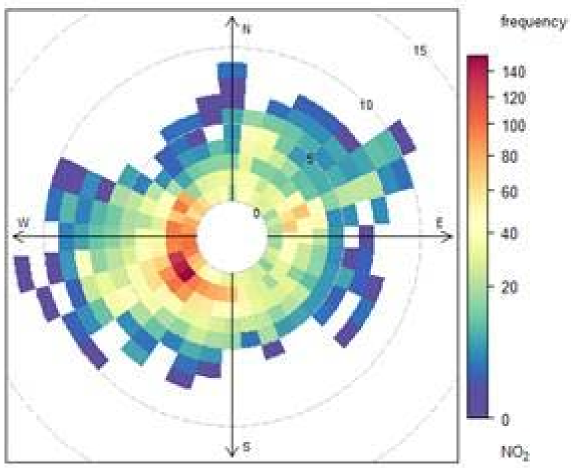
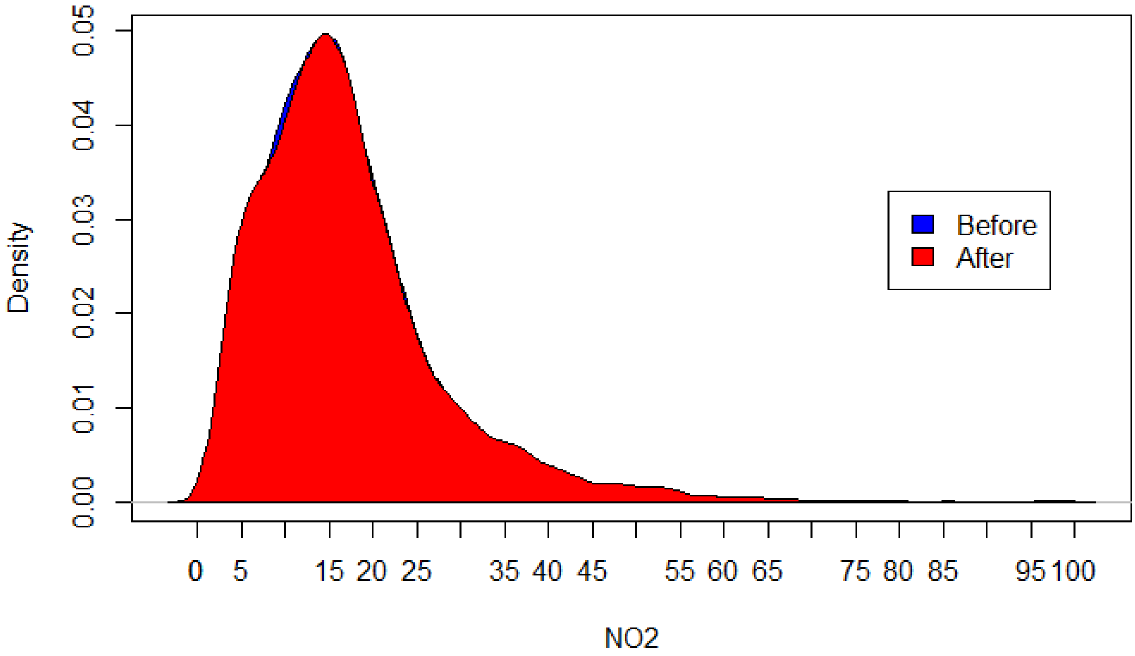


Figure A1.67: Density plot for one year of baseline data for NO_2 (Kirby Misperton, Environment Agency site) (µg/m^3) showing before and after site activities began



A1.6 Kirby Misperton, Environment Agency site - PM_{10}

Figure A1.68: Density plot for one year of baseline data for PM_{10} (Kirby Misperton, Environment Agency site) (µg/m³)

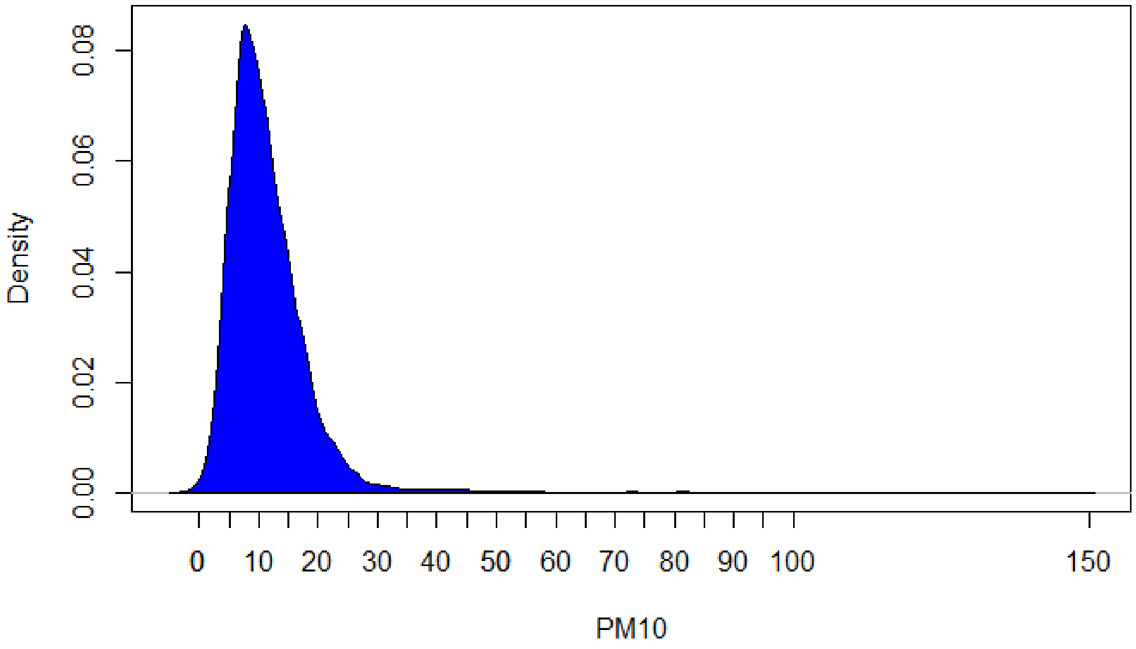


Figure A1.69: Time series for one year baseline data for PM_{10} (Kirby Misperton, Environment Agency site) (µg/m³)

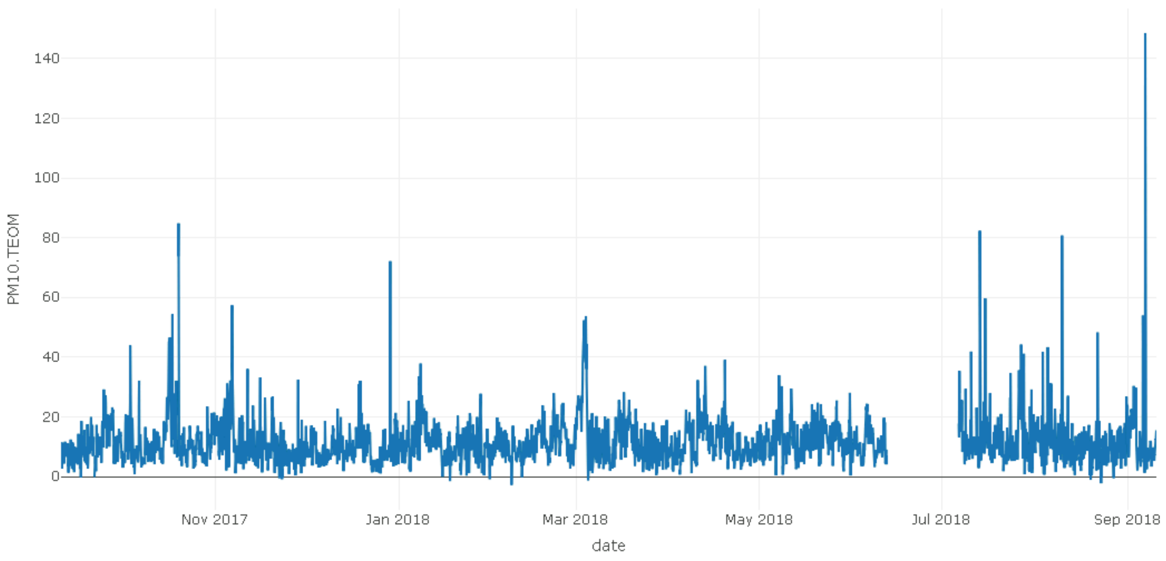


Figure A1.70: Time series plot of different percentiles for one year of baseline data for PM10 (Kirby Misperton, Environment Agency site) (μg/m³)

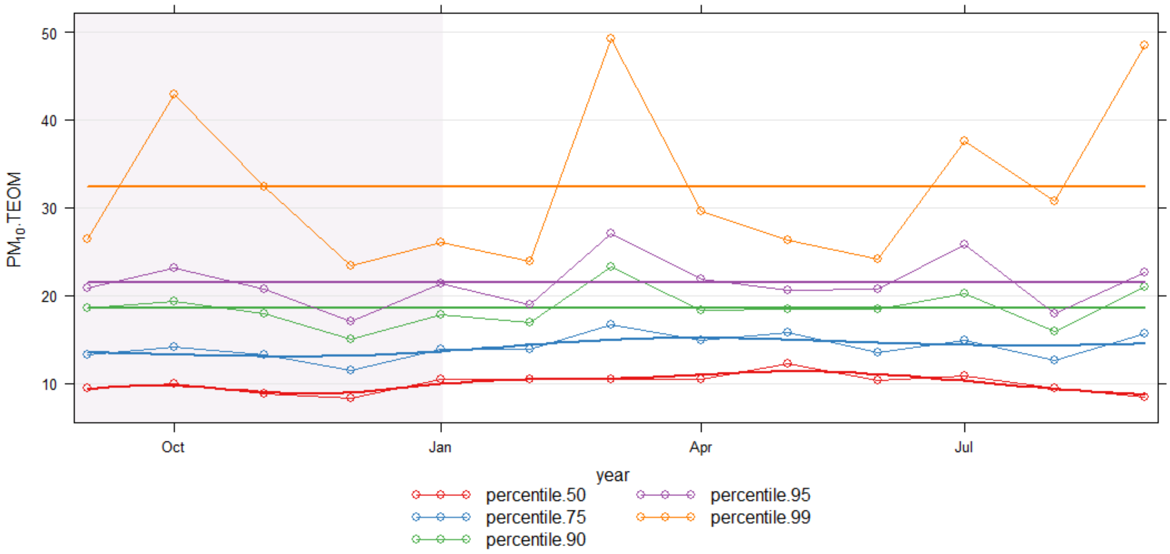


Table A1.8: Summary statistics for one year of baseline data for PM_{10} (Kirby Misperton, Environment Agency site)

Metric	PM_{10} (µg/m^3)
Mean	11.24
50%	10.06
75%	14.15
90%	18.416
95%	21.95
99%	33.32

Figure A1.71: Conditional probability plot between the 75th and 90th percentiles for one year of baseline data for PM_{10} (Kirby Misperton, Environment Agency site)

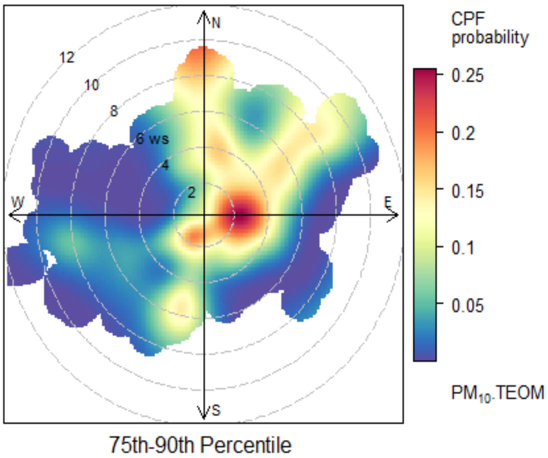


Figure A1.72: Conditional probability plot between the 90th and 95th percentiles for one year of baseline data for PM_{10} (Kirby Misperton, Environment Agency site)

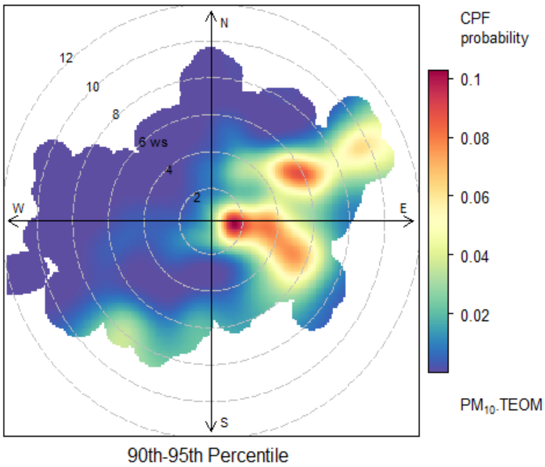


Figure A1.73: Conditional probability plot between the 95th and 99th percentiles for one year of baseline data for PM_{10} (Kirby Misperton, Environment Agency site)

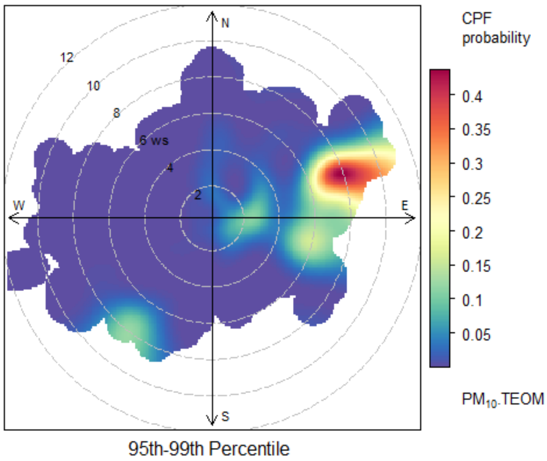


Figure A1.74: Conditional probability plot between the 99th and 100th percentiles for one year of baseline data for PM_{10} (Kirby Misperton, Environment Agency site)

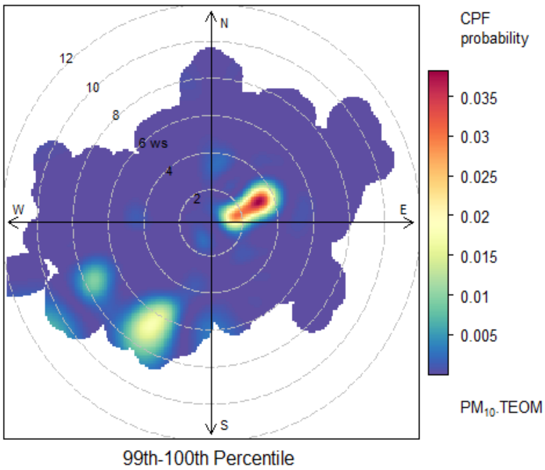


Figure A1.75: Polar plot of the mean concentration for one year of baseline data for PM_{10} (Kirby Misperton, Environment Agency site) (µg/m^3)

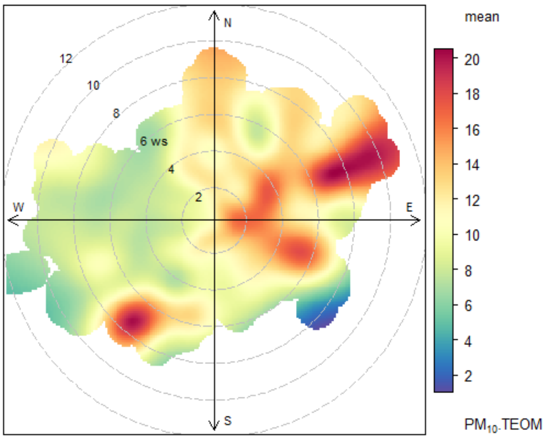


Figure A1.76: Polar plot of the median concentration for one year of baseline data for PM_{10} (Kirby Misperton, Environment Agency site) (µg/m^3)

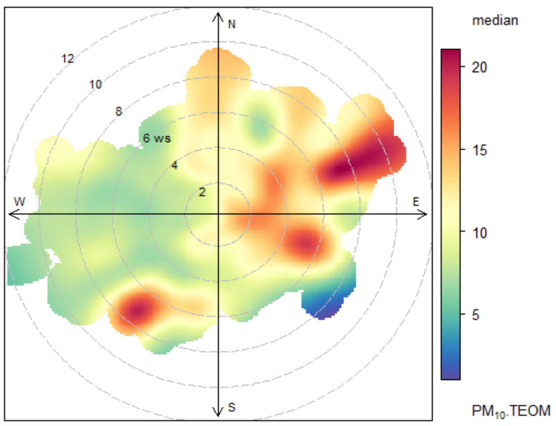


Figure A1.77: Polar plot of the 75th percentile concentration for one year of baseline data for PM_{10} (Kirby Misperton, Environment Agency site) (µg/m^3)

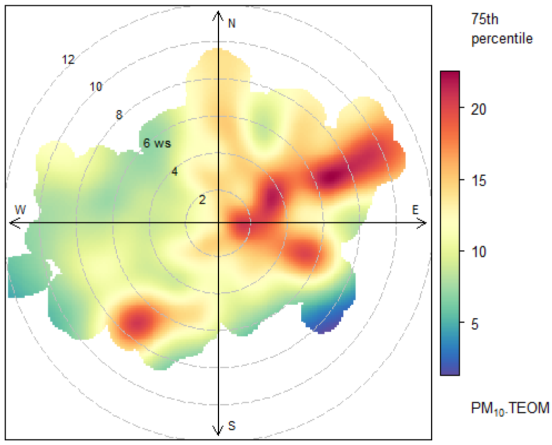


Figure A1.78: Polar plot of the 90th percentile concentration for one year of baseline data for PM_{10} (Kirby Misperton, Environment Agency site) (µg/m^3)

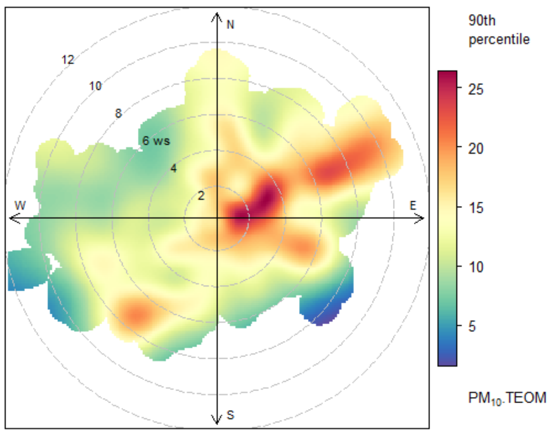


Figure A1.79: Polar plot of the 95th percentile concentration for one year of baseline data for PM_{10} (Kirby Misperton, Environment Agency site) (µg/m^3)

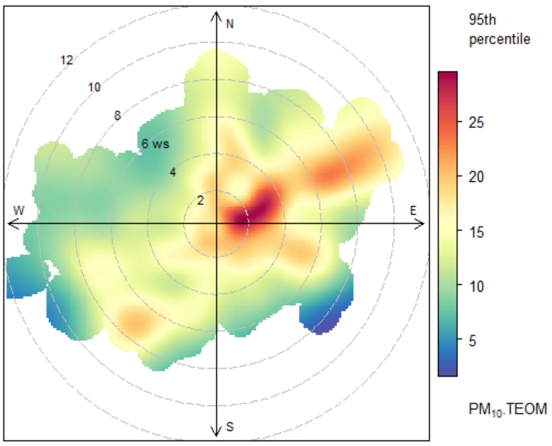


Figure A1.80: Polar plot of the 99th percentile concentration for one year of baseline data for PM_{10} (Kirby Misperton, Environment Agency site) (µg/m^3)

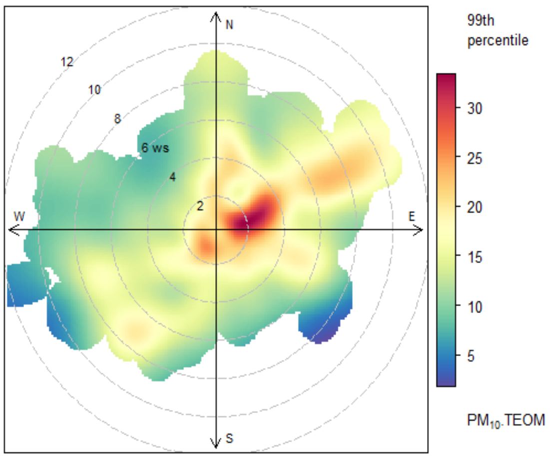


Figure A1.81: Polar plot of the weighted mean (mean/frequency) for one year of baseline data for PM_{10} (Kirby Misperton, Environment Agency site)

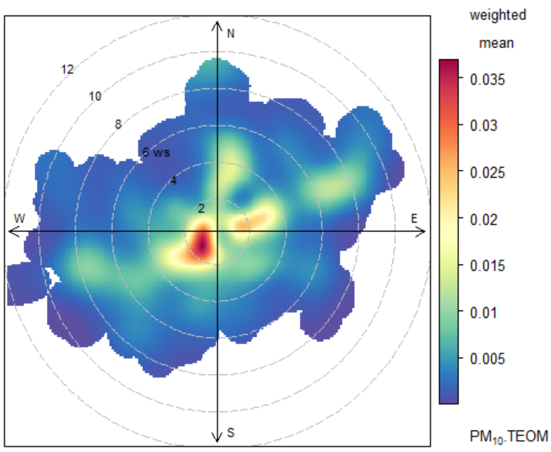


Figure A1.82: Polar frequency plot for one year of baseline data (Kirby Misperton, Environment Agency site)

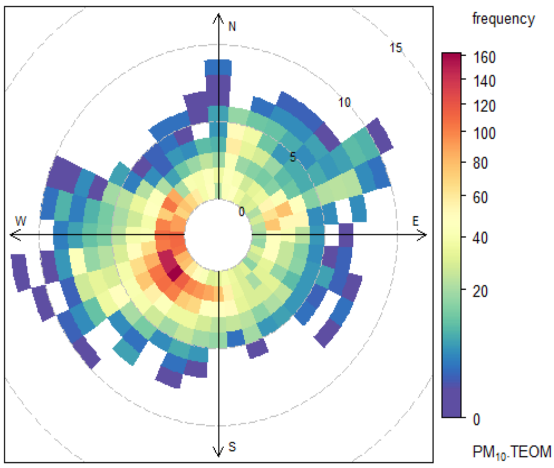
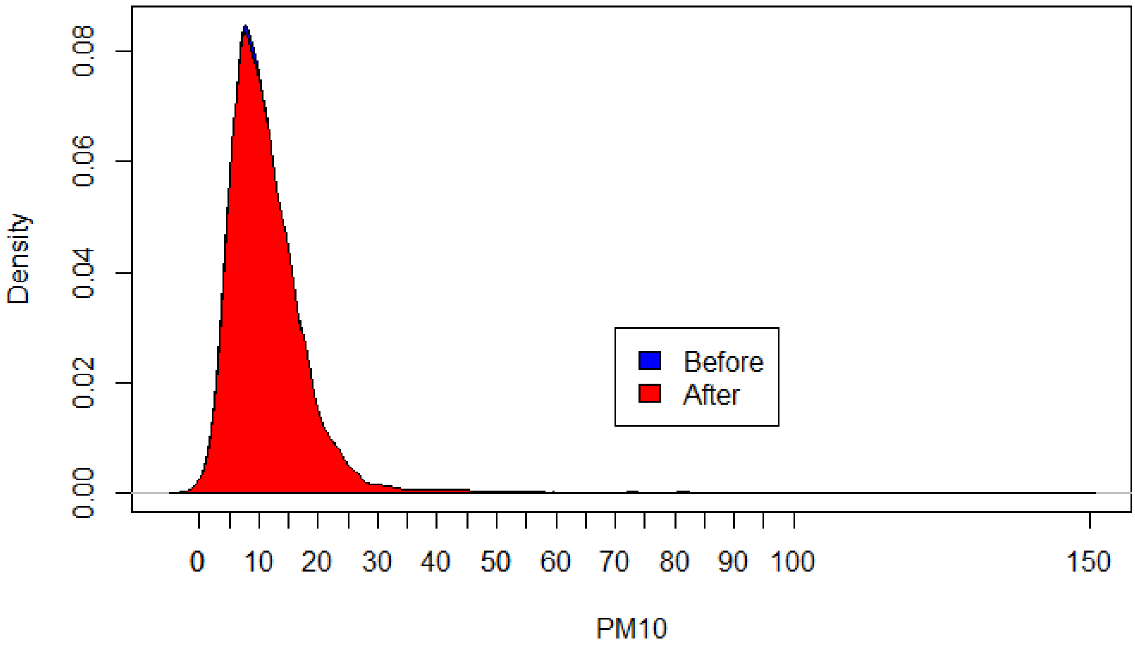


Figure A1.83: Density plot for one year of baseline data for PM_{10} (Kirby Misperton, Environment Agency site) (µg/m³)showing before and after site activities begin



A1.7 Kirby Misperton, Environment Agency site - CH_4

Figure A1.84: Density plot for one year of baseline data for CH_4 (Kirby Misperton, Environment Agency site)

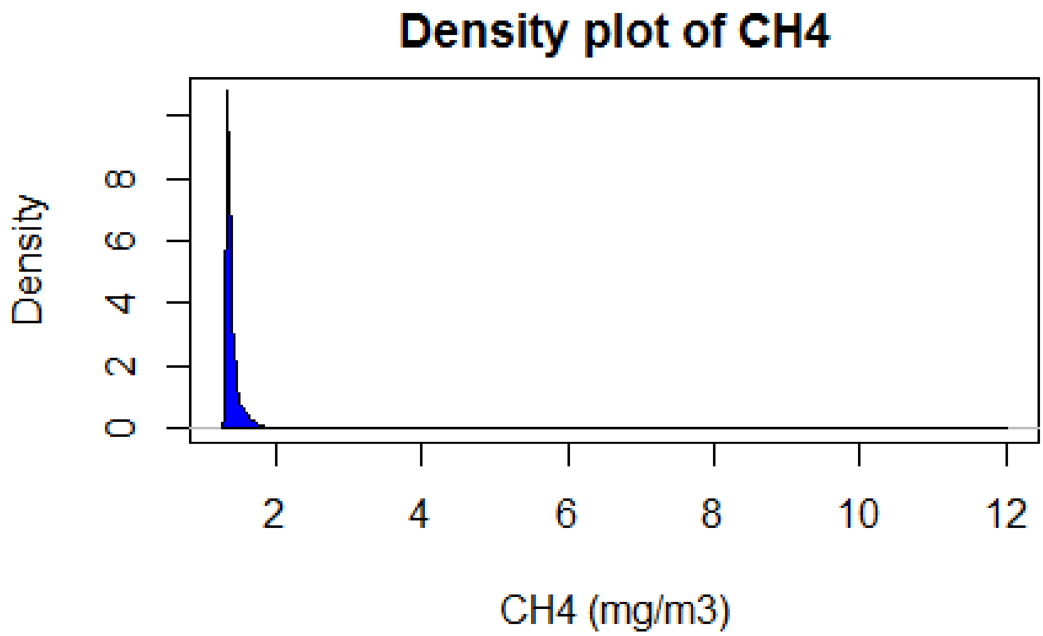


Figure A1.85: Time series for one year baseline data for CH_4 (Kirby Misperton, Environment Agency site) (mg/m^3)

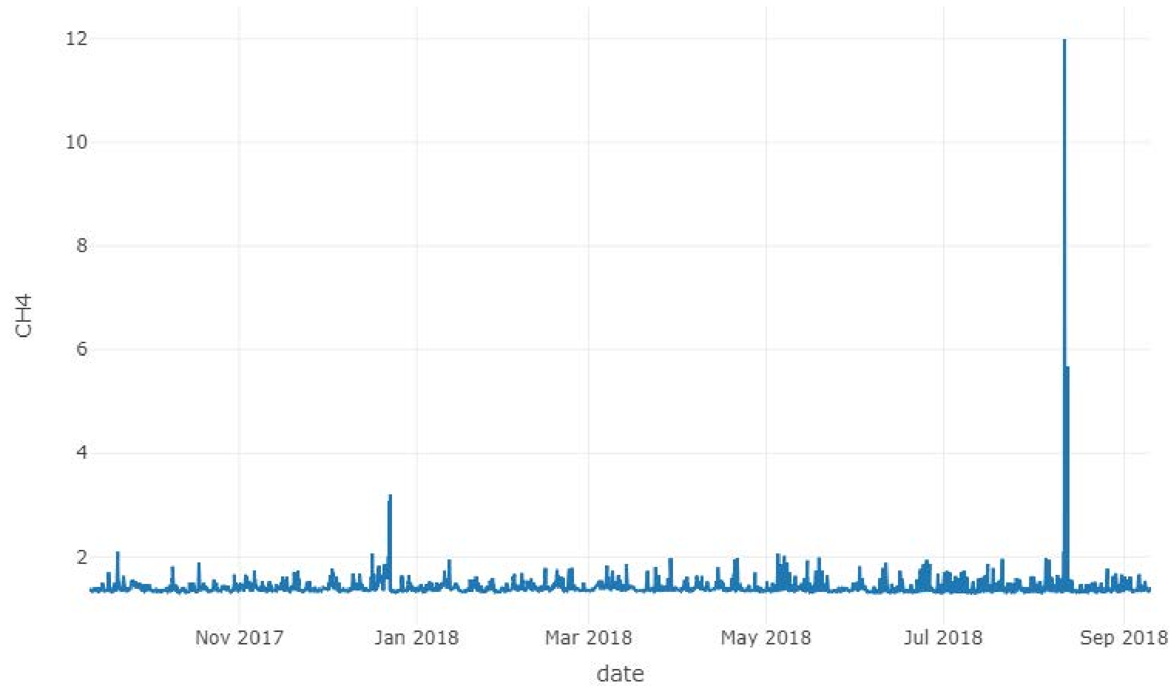


Figure A1.86: Time series plot of different percentiles for one year of baseline data for CH_4 (Kirby Misperton, Environment Agency site) (mg/m^3)

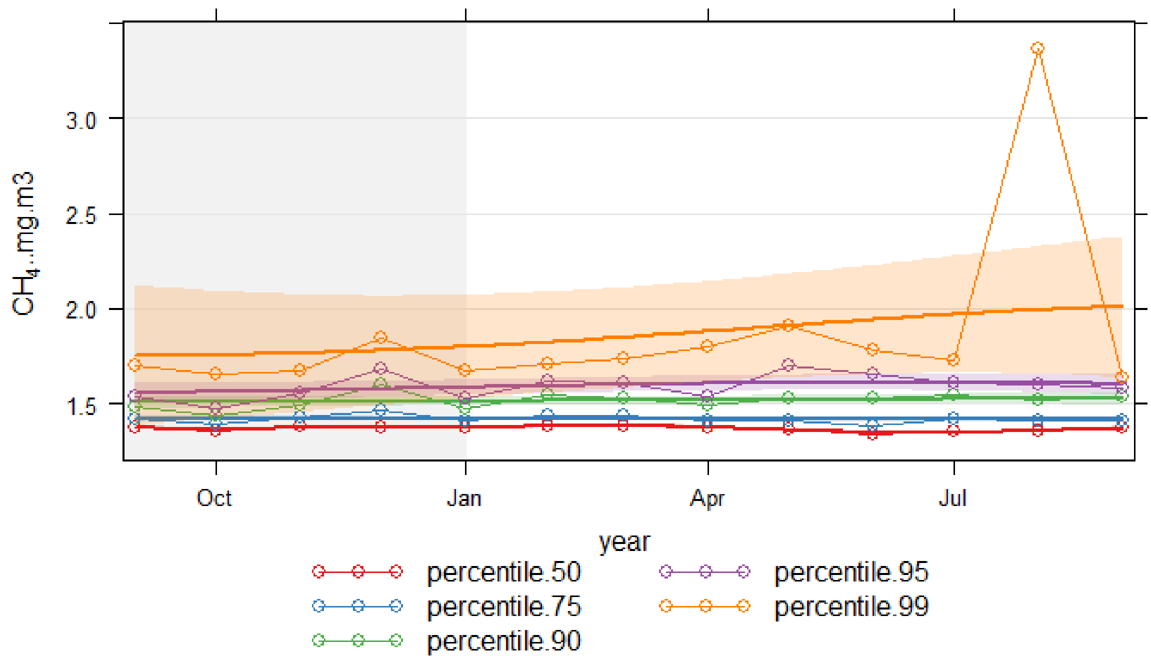


Table A1.9: Summary statistics for one year of baseline data for CH_4 (Kirby Misperton, Environment Agency site)

Metric	CH_4 (mg/m^3)
Mean	1.41
50%	1.37
75%	1.42
90%	1.52
95%	1.60
99%	1.79

Figure A1.87 Conditional probability plot between the 75th and 90th percentiles for one year of baseline data for CH_4 (Kirby Misperton, Environment Agency site)

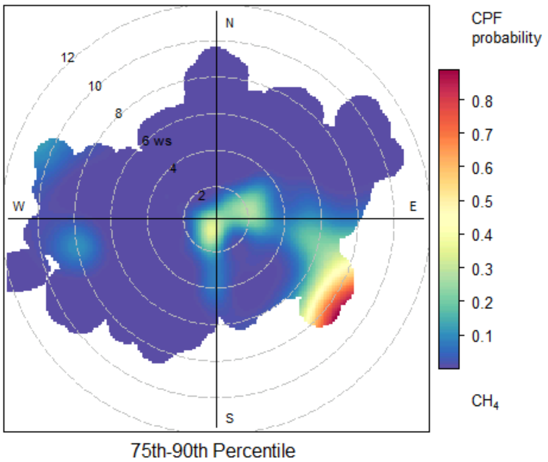


Figure A1.88: Conditional probability plot between the 90th and 95th percentiles for one year of baseline data for CH_4 (Kirby Misperton, Environment Agency site)

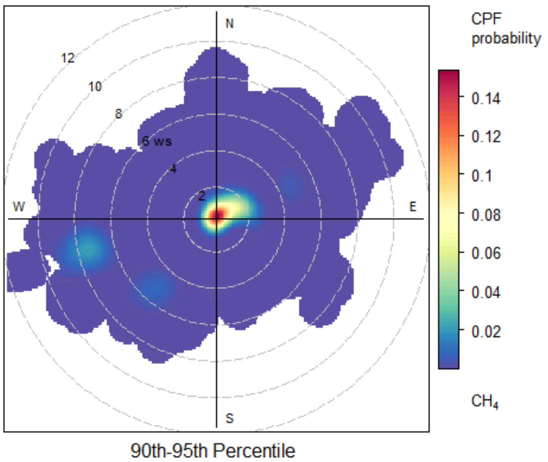


Figure A1.89: Conditional probability plot between the 95th and 99th percentiles for one year of baseline data for CH_4 (Kirby Misperton, Environment Agency site)

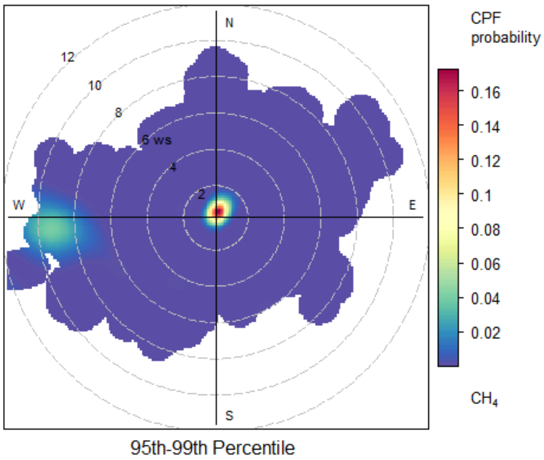


Figure A1.90: Conditional probability plot between the 99th and 100th percentiles for one year of baseline data for CH_4 (Kirby Misperton, Environment Agency site)

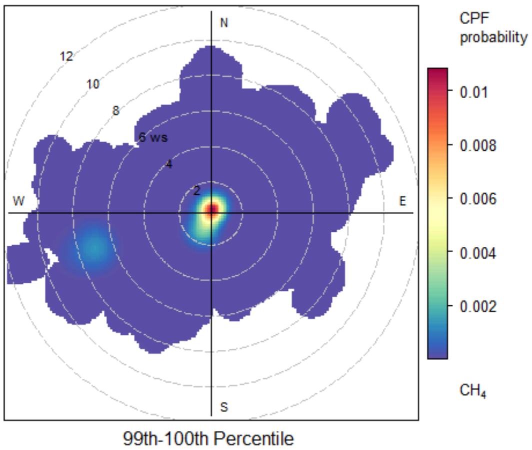


Figure A1.91: Polar plot of the mean concentration for one year of baseline data for CH_4 (Kirby Misperton, Environment Agency site)

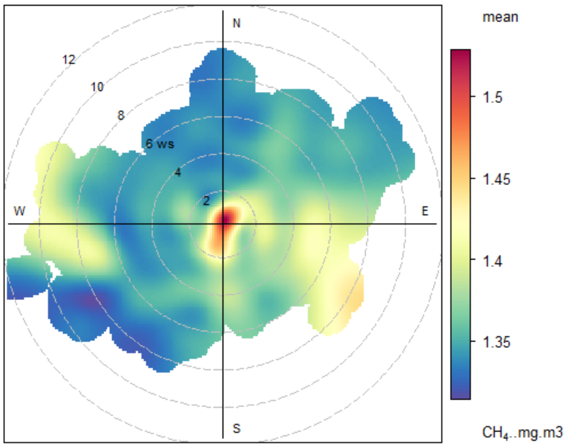


Figure A1.92: Polar plot of the median concentration for one year of baseline data for CH_4 (Kirby Misperton, Environment Agency site)

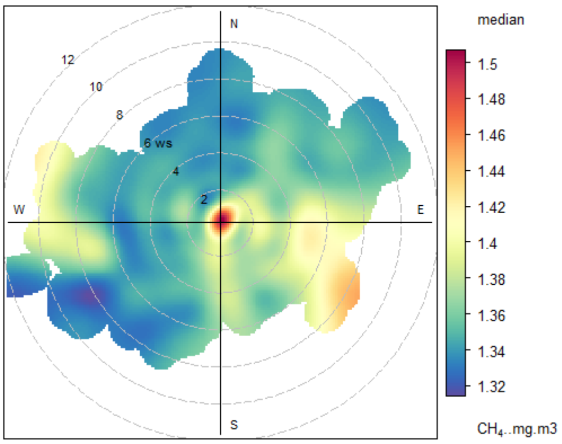


Figure A1.93: Polar plot of the 75th percentile concentration for one year of baseline data for CH_4 (Kirby Misperton, Environment Agency site)

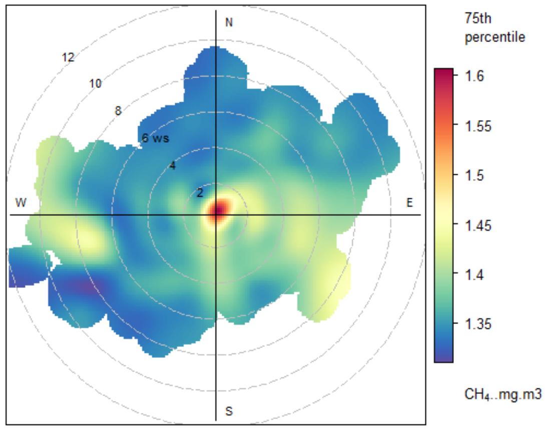


Figure A1.94: Polar plot of the 90th percentile concentration for one year of baseline data for CH_4 (Kirby Misperton, Environment Agency site)

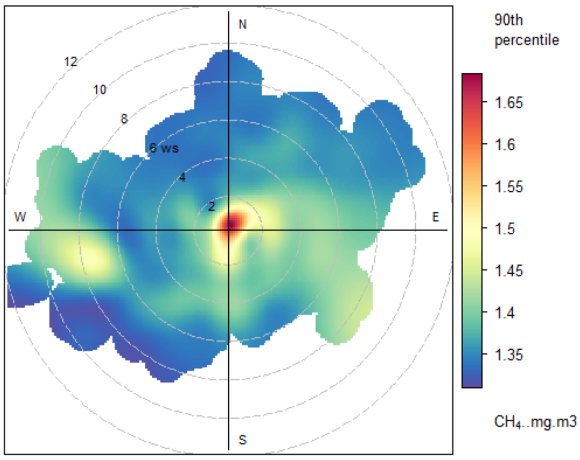


Figure A1.95: Polar plot of the 95th percentile concentration for one year of baseline data for CH_4 (Kirby Misperton, Environment Agency site)

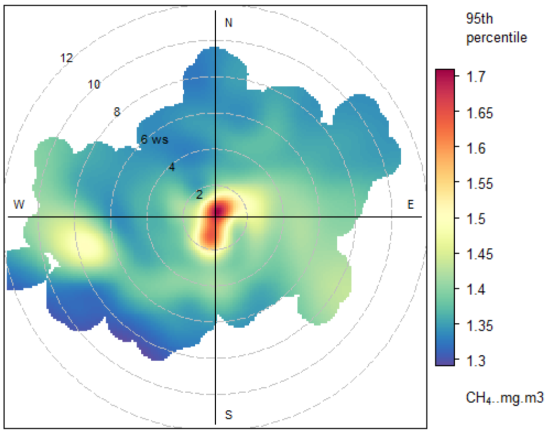


Figure A1.96: Polar plot of the 99th percentile concentration for one year of baseline data for CH_4 (Kirby Misperton, Environment Agency site)

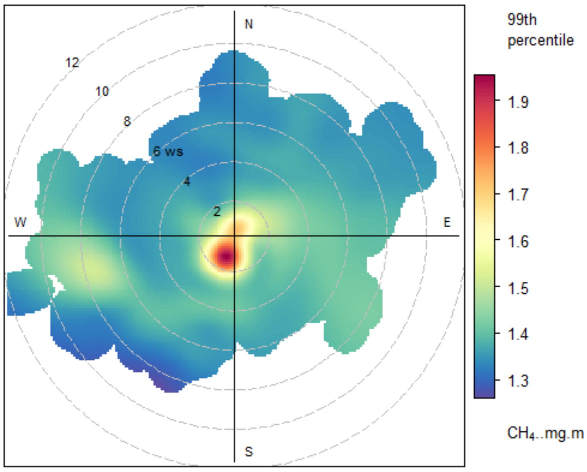


Figure A1.97: Polar plot of the weighted mean (mean/frequency) for one year of baseline data for CH_4 (Kirby Misperton, Environment Agency site)

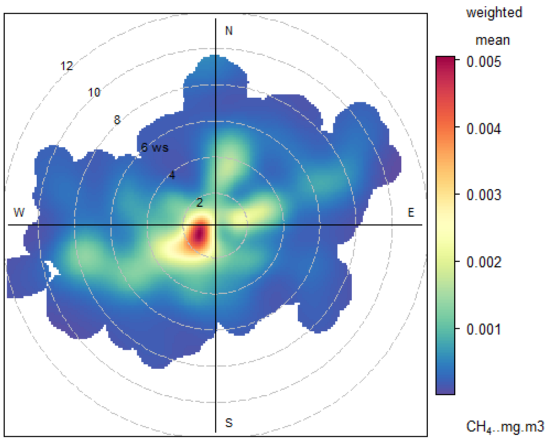


Figure A1.98: Polar frequency plot for one year of baseline data (Kirby Misperton, Environment Agency site)

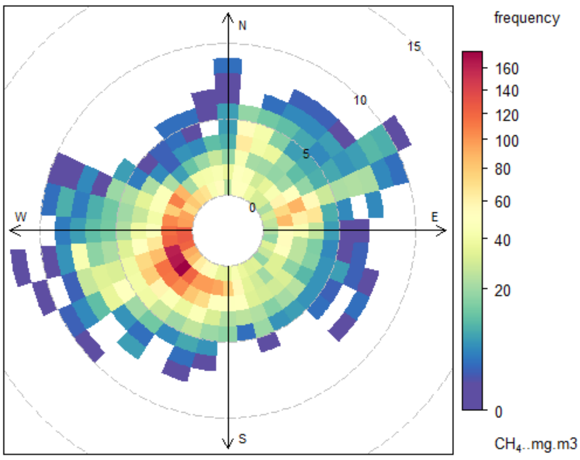
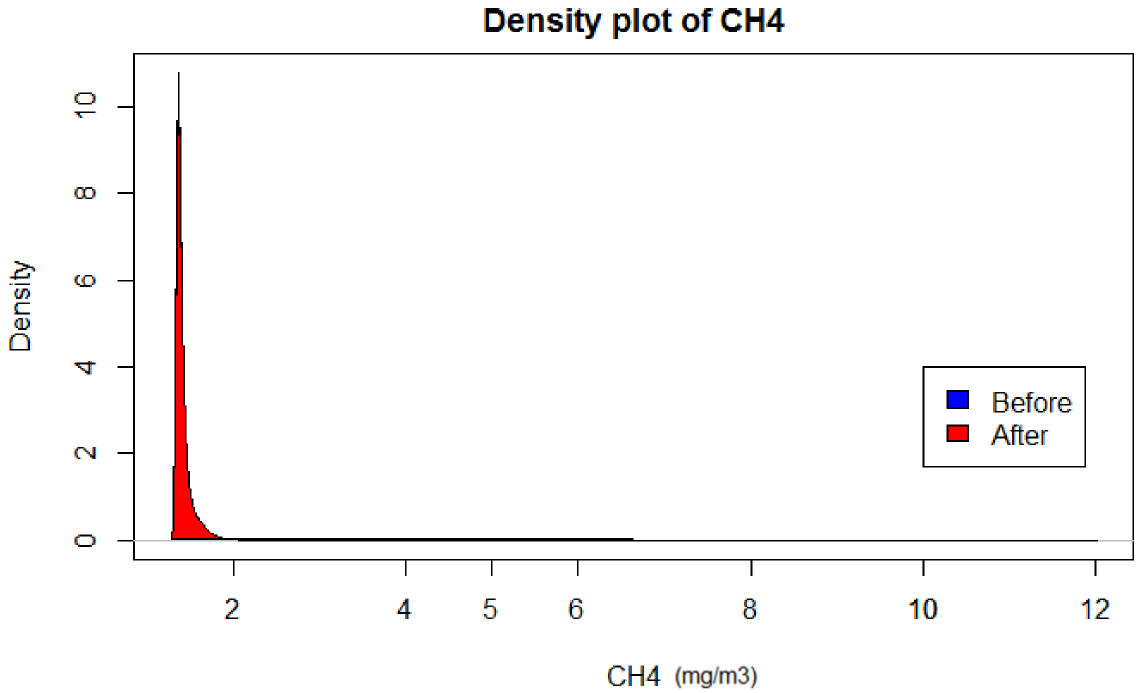


Figure A1.99: Density plot for one year of baseline data for CH_4 (Kirby Misperton, Environment Agency site) showing before and after site activities began



Appendix 2 – Kirby Misperton water quality baseline data pack

A2.1 Kirby Misperton operator measurements

The section outlines the ‘baseline data’ for the highest priority determinands from operator measurements at Kirby Misperton (determinands with a priority score of 2.5 or above). The methodology for identifying these priority determinands is outlined in section 2.7.1 and the finalised list of priority determinands has been replicated below for ease of reference.

Table A2.1: Priority determinands for KM Determinand group	Determinand	Surface water	Groundwater
Inorganic chemicals	Ammoniacal nitrogen	x	x
Major ions	Arsenic		x
	Boron	x	
	Copper	x	x
	Iron	x	x
	Magnesium	x	x
	Potassium		x
	Strontium		x
	Bromide	x	
	Calcium	x	x
	Chloride	x	x
	Sulphate	x	x
	Total alkalinity		x
Natural gas	Dissolved methane		x
Organic chemicals	GRO (>C4-C12)	X	
Other	Acrylamide	X	x
	Electrical conductivity	X	x
	Total dissolved solids	X	

Detailed information on the laboratory methodology used was unavailable, and so for QA/QC purposes, a basic rule of thumb has been adopted that flags values (within time series) with more than 20% relative difference in duplicate measurements. This was carried out as part of stage 2 of the overall baseline data analysis (see also section 2.7.2). As part of QA/QC checks, the percentage of values that were at or below the limit of detection (LOD) were identified (Table A2.2), as well as any values that were above any calibration limit identified as being suspicious (for example, high blank values). These are reported on in Table A2.3.

The proportion of values identified as suspicious was generally low, and did not give cause for concern on the suitability of the parameter for analysis. However, some determinands did have a high percentage of values at or below the LOD. In these cases, stage 9 (of Figure 2-23) might be deemed unsuitable. As an example, time series of a value constantly ‘less than the LOD’ would not be considered informative. In addition, future assessment of change for these determinands could not be considered on a quantitative scale as the exact quantity (and variability in measurement) is not known. As a result, in an extension to the methodology, determinands in this category were assessed and reported separately. The cut off as to whether a deterministic summary was necessary was determined by if 'the majority of values were over the LOD (>50%). The remainder of this section is split between parameters that would be deterministically assessed in detecting change and those that are assessed by the full method as outlined in the main text for Specific Electrical Conductivity (SEC).

Table A2.2: Priority determinands that have a majority of measured values at or below the limit of detection and are therefore considered to be taken forward for a deterministic assessment

Parameter	% values at or below the limit of detection
GRO (>C4-C12)	100
Acrylamide	100
Dissolved copper	96.71
Dissolved arsenic	73.25
Bromide	53.85

Table A2.3: Priority determinands with 'suspicious' values

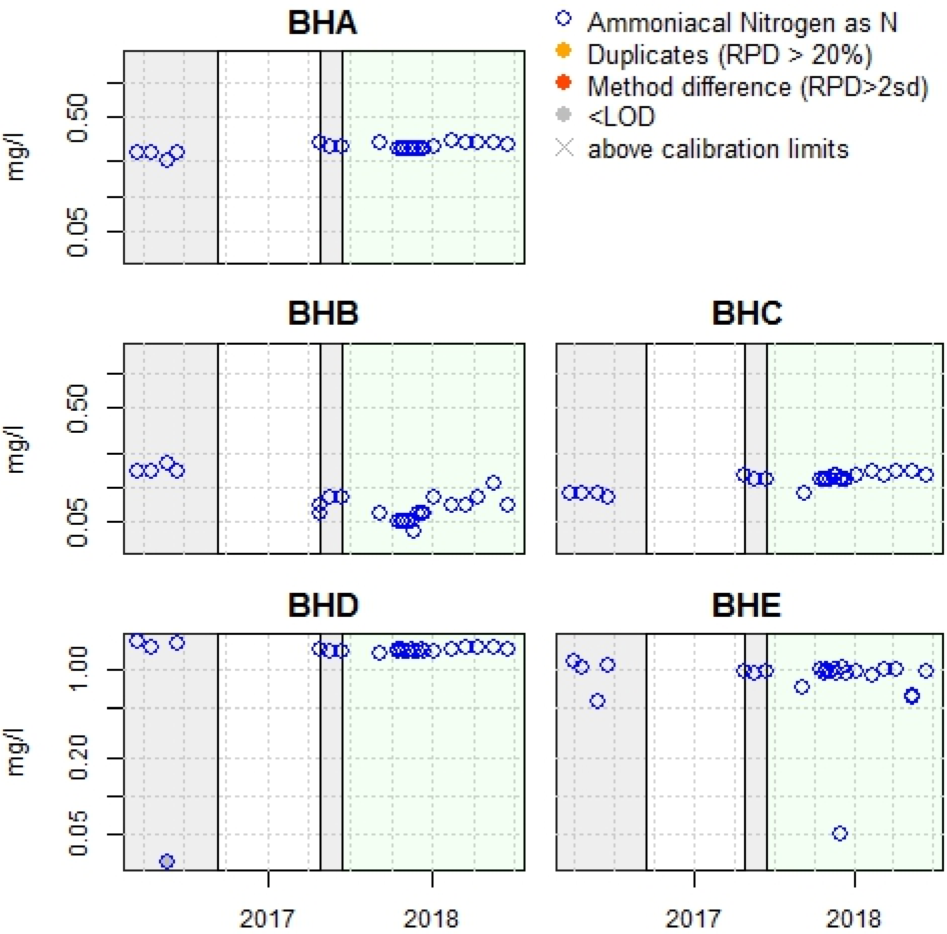
Parameter	Total count of observations	Count of duplicates taken	% of observations above the calibration limit	% of duplicate measurements with a relative percentage difference above 20%
Dissolved methane – bottle	388	22	10.82	13.64
Dissolved methane – cannister	13	0	100	0
Total iron	358	15	0	20
Total dissolved solids	418	25	0	4

A2.1.1. Determinands for full quantitative further analysis

Ammoniacal nitrogen

1. Individual site time series

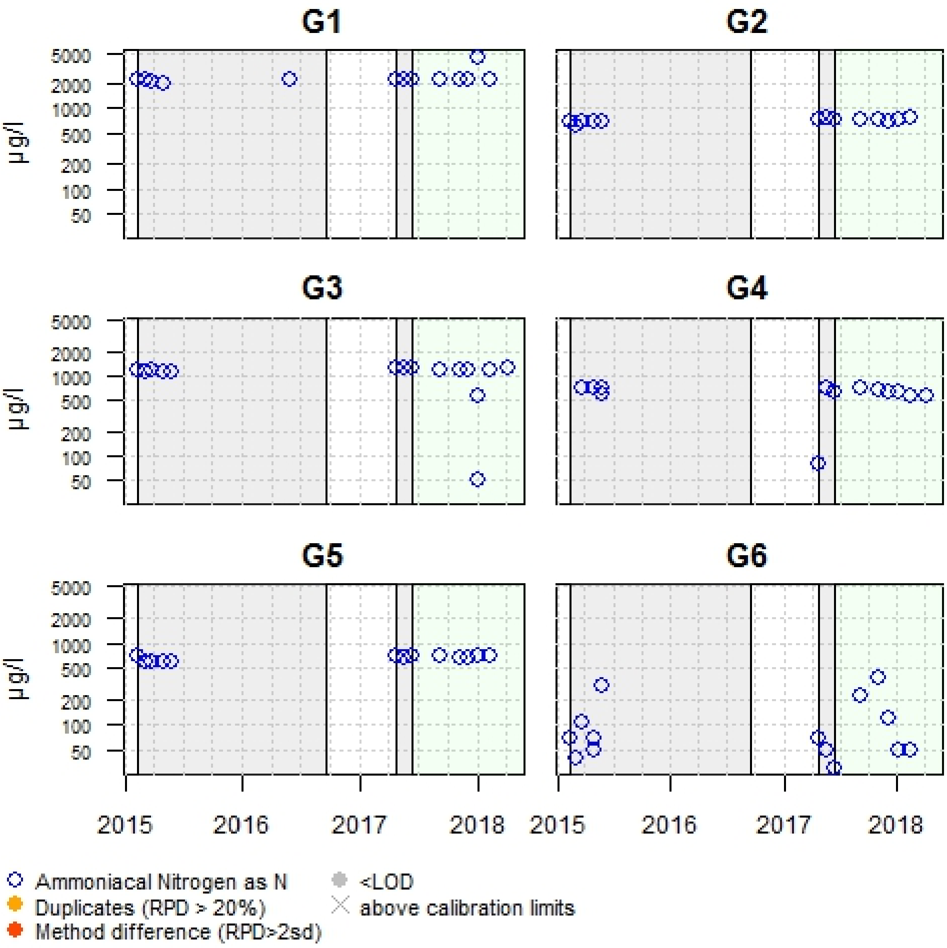
On-site boreholes



Observations and notes:

- Only ammoniacal nitrogen as N is shown (as opposed to ammoniacal N as NH4). It was not deemed necessary to analyse both, as it appeared that on at least some dates for some sites, one variable was derived from the other.
- Boreholes A to C have measurements of ammoniacal N of 0.05 to 0.5 mg/l.
- Boreholes A and C appear to have higher concentrations of ammoniacal N in the second phase compared with the first phase, though borehole B appears to demonstrate the opposite relationship.
- Boreholes D to E have measurements of ammoniacal N of 0.5 to 2 mg / L apart from 2 very low values (possible outliers).
- There were no duplicate observations and no values were recorded as less than the LOD.

Off-site boreholes

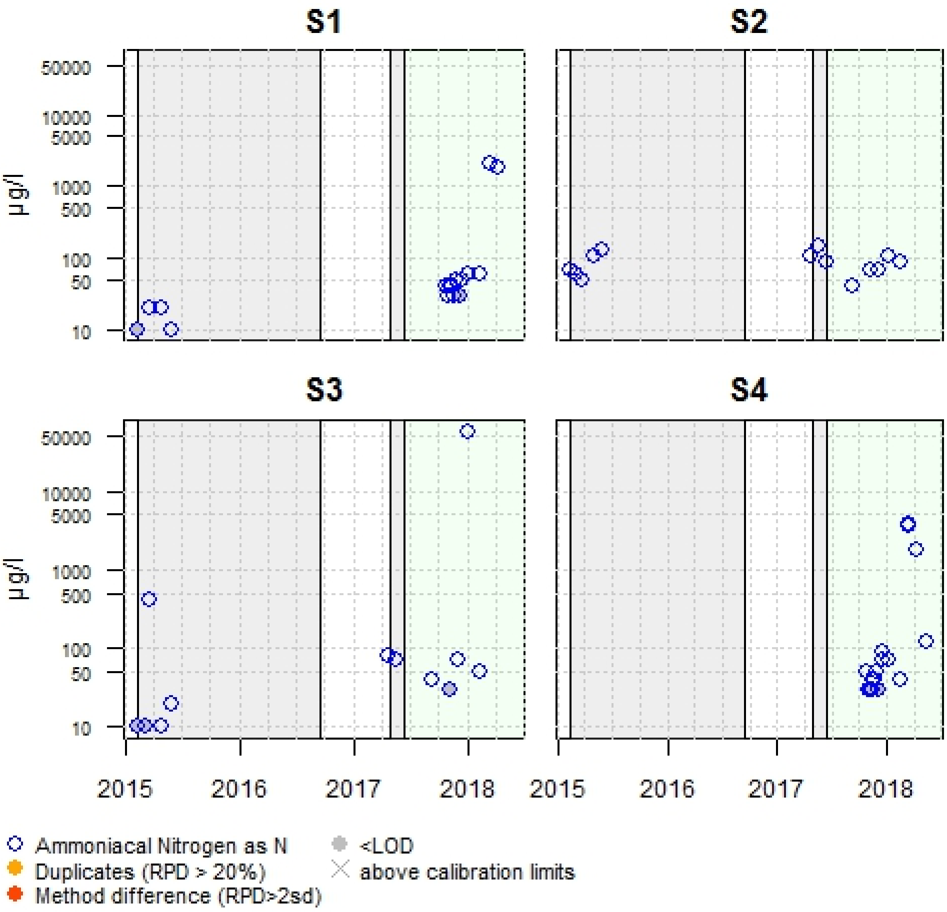


Observations and notes:

- Boreholes G2 to G5 demonstrate similar magnitudes that appear relatively constant through time.
- Boreholes G6 appear[7] to show greater variability and lower ammoniacal N concentrations than the other on-site boreholes, though this may in part be a consequence of using the logged scale.

[7] Care should be taken in this interpretation due to use of the logarithmic scale

Surface waters



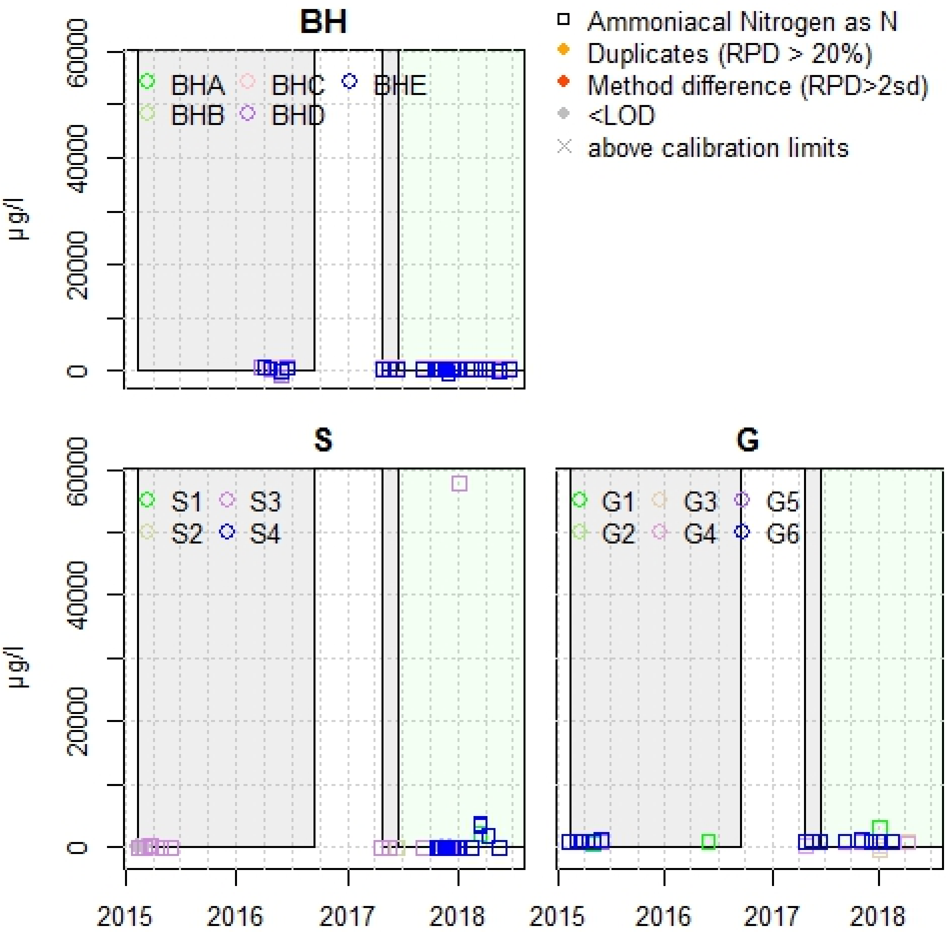
Observations and notes:

- Much higher variability observed than in groundwaters.
- No P1 observations in S4.

Conclusions: Individual site time series

- Care should be taken in interpreting the ammonium data, as it demonstrates higher variability in the natural environment than other parameters, and there are gaps in the record (for example, no 2016 observations for surface waters). Where this variable is used, it should not be analysed in isolation but together with other parameters and supporting evidence.

2. Grouped time series



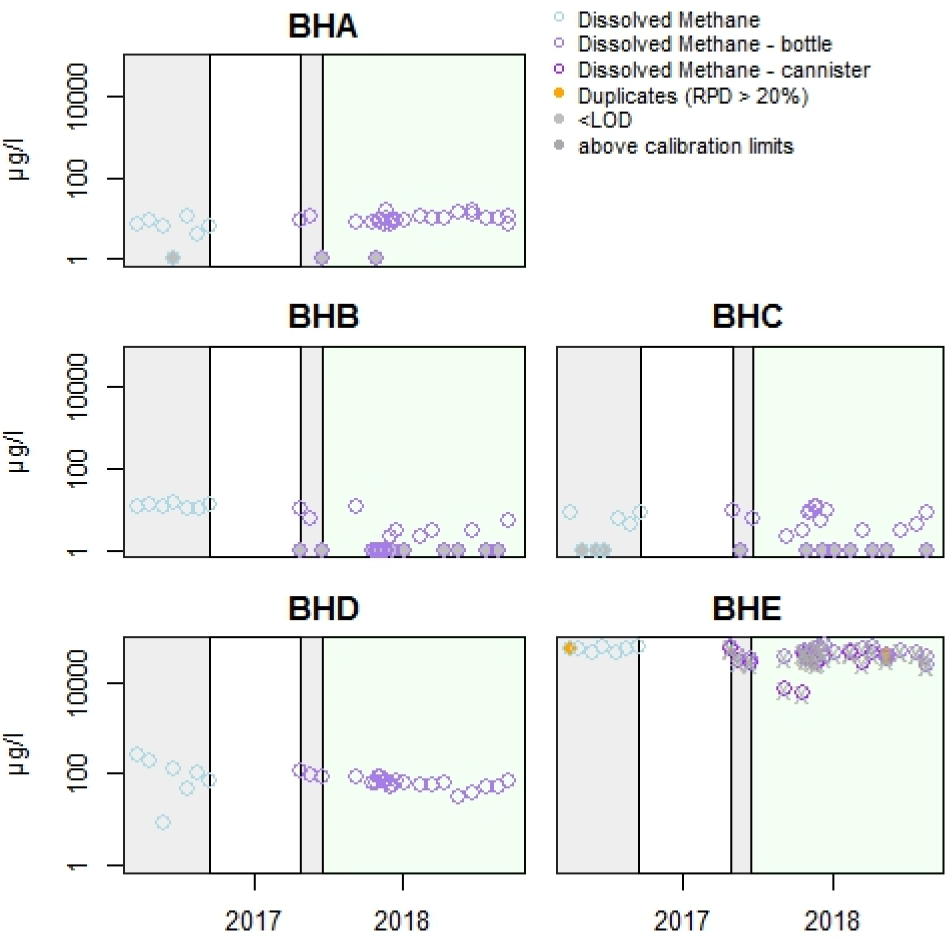
3. Grouped data box plots

This was deemed inappropriate for this variable.

Methane

1. Individual site time series

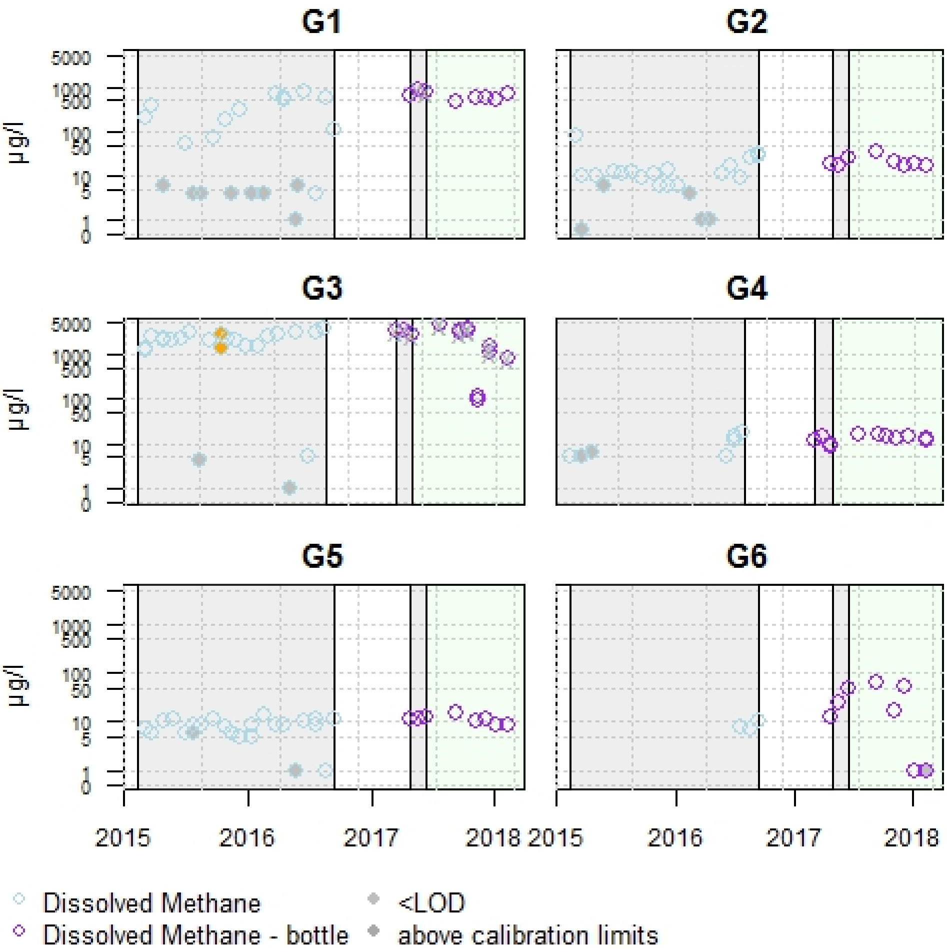
On-site boreholes



Observations and notes:

- Boreholes A to D have measurements of methane between <1(LOD) and 258 µg/l.
- Boreholes A to C have measurements of a similar order of magnitude.
- Borehole D appears to have consistently higher values than boreholes A, B, C and E.
- At Borehole E, the values post 2017 are over the calibration limit (indicated by the crosses on the measurements) and range to over 66,000 µg/l. Two methods of measurement were adopted at this site ('bottle' and 'cannister'), but both provided similar results. The pre-2017 values were measured by a different lab. This lab did not provide any indication of whether or not values were above the calibration limit. The British Geological Survey (BGS) conducted nearly 170 analyses of methane in GB groundwaters from aquifers across the UK from the 1980s to late 2000s. Almost all separate sites were sampled only once, and at various times over the past 3 decades. In this data set, 99% of samples show methane concentrations of less than 500 µg/l and the remaining 1% have concentrations between 500 and 1,680 µg/l[25]. Values seen here are well above the maximum threshold of that data set and, as such, the absolute values of these observations should be regarded with some suspicion.

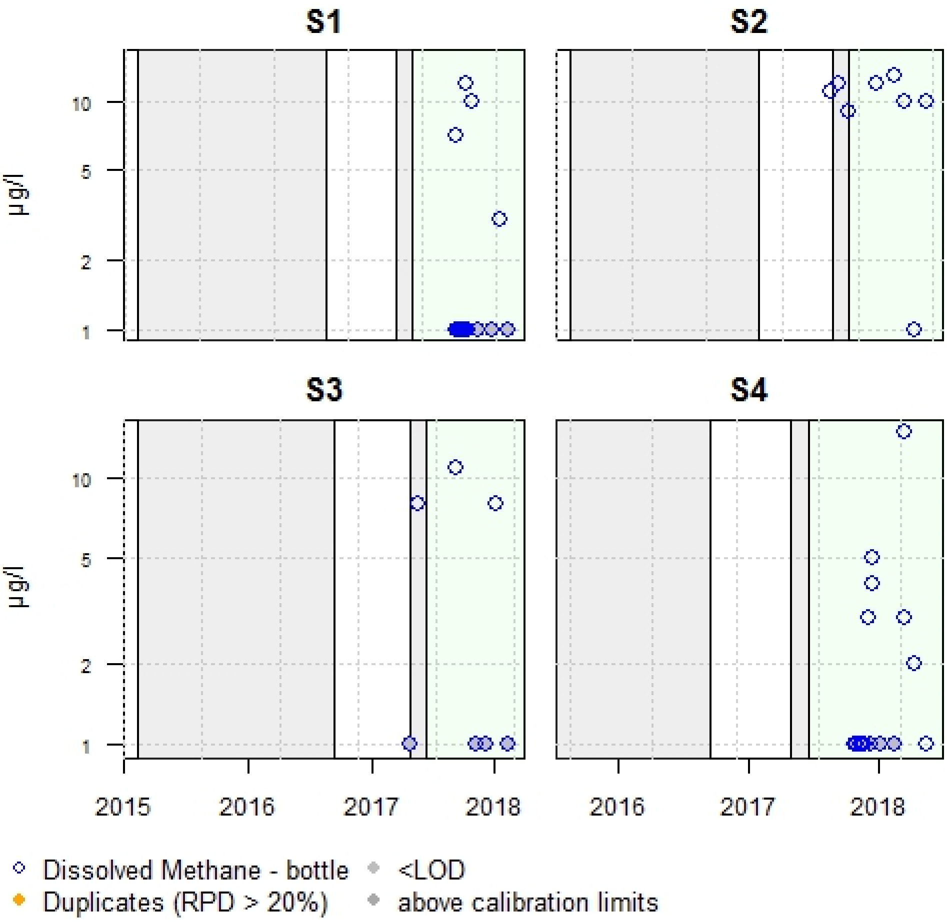
Off-site boreholes



Observations and notes:

- Boreholes G1 and G2 and G4 to G6 have measurements of methane between <1(LOD) and 1,000 µg/l and appear to be of a similar order of magnitude in P1 and P2.
- Boreholes G4 and G5 appear to have values that are relatively consistent between the 2 sites. Borehole G6 shows more variability in measured values in the second lab data set.
- At G6, the values post 2017 are over the calibration limit (indicated by the crosses on the measurements), and range to over 5 mg/l. As with site, Borehole E, the pre-2017 values were measured by a different lab. This lab did not provide any indication of whether or not values were above the calibration limit. While these concentrations appear plausible, absolute values should be treated with some suspicion.

Surface waters



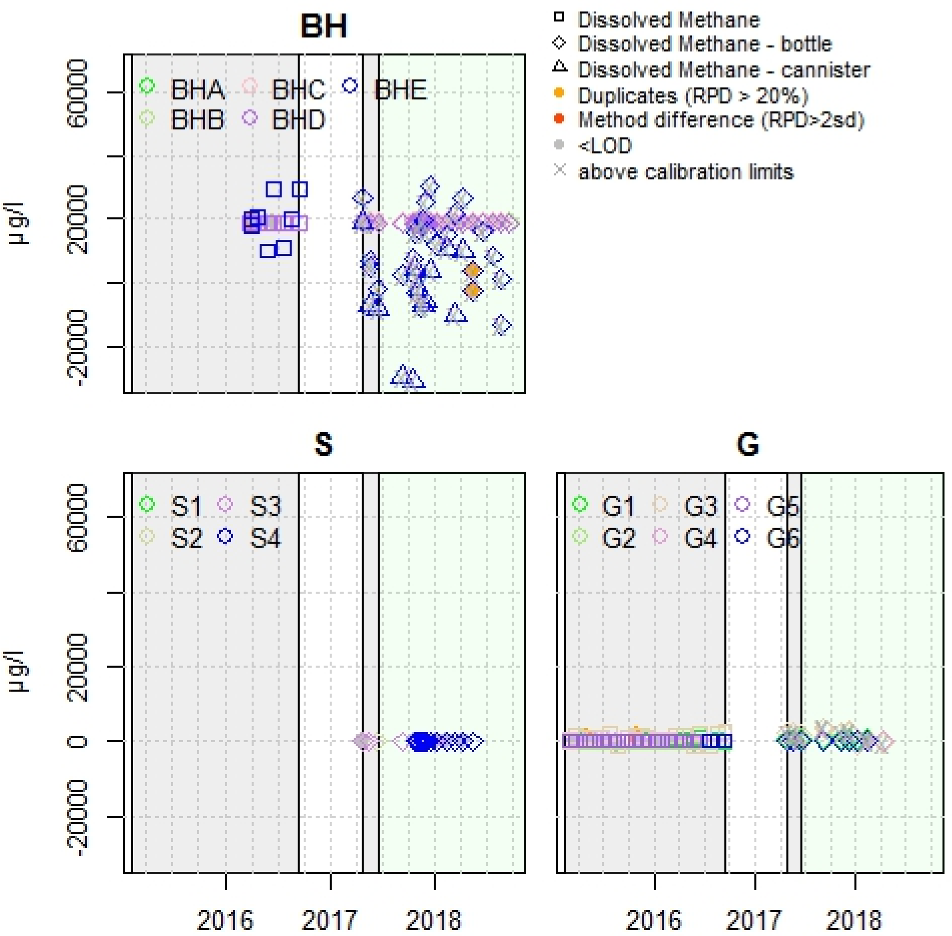
Observations and notes:

- There were limited observations in P1 for methane in surface waters.
- Many of the observations are at the LOD and are 'low' relative to most of the boreholes.
- Consideration could be given to a change in rank of measurements relative to borehole measurements.

Conclusions: Individual site time series

- Use on-site boreholes A to D, and off-site boreholes G1, G2, and G4 to G6 for establishing baselines and for detecting change in absolute values in groundwater at Kirby Misperton.
- For sites G3 and borehole E, assume all values are above the calibration limit for the method. It is recommended that the ranking of methane measurements (comparative to other sites) is used in establishing baselines and detecting change for these sites.

2. Grouped time series



3. Grouped data box plots

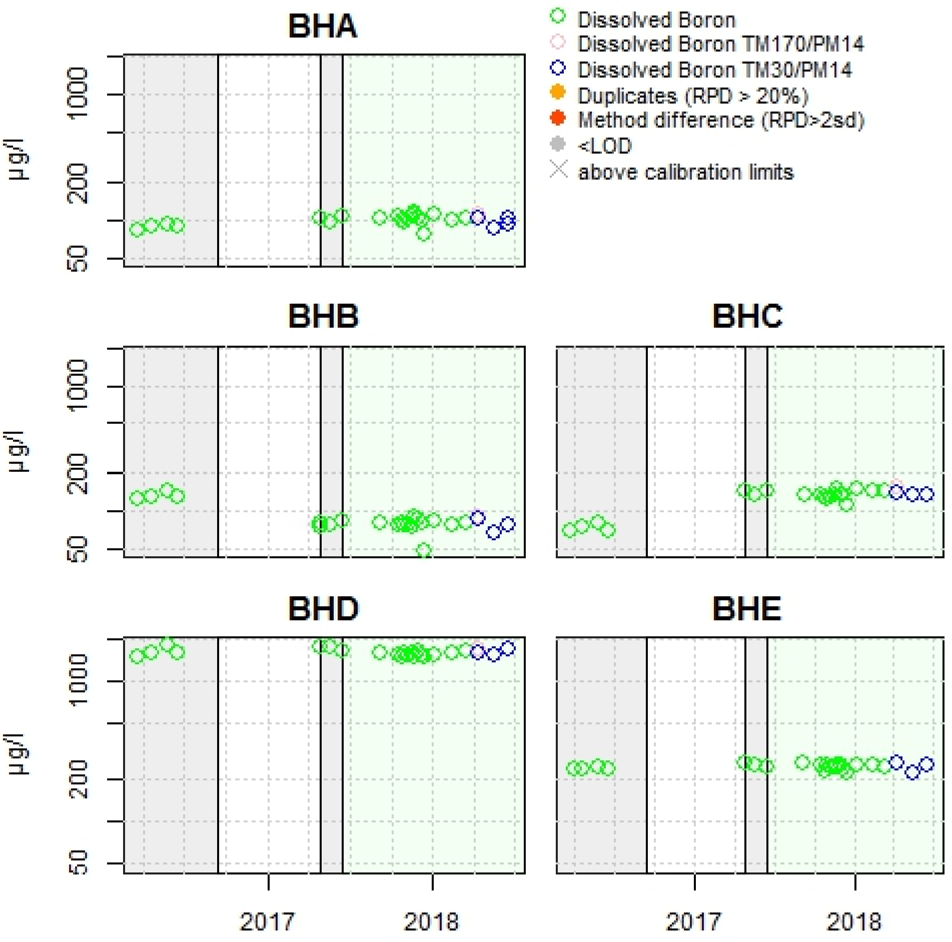
This was deemed inappropriate for this variable.

- Individual site time series.
- Grouped time series data normalised mean across the group.
- Grouped data box plots.

Boron (dissolved)

1. Individual site time series

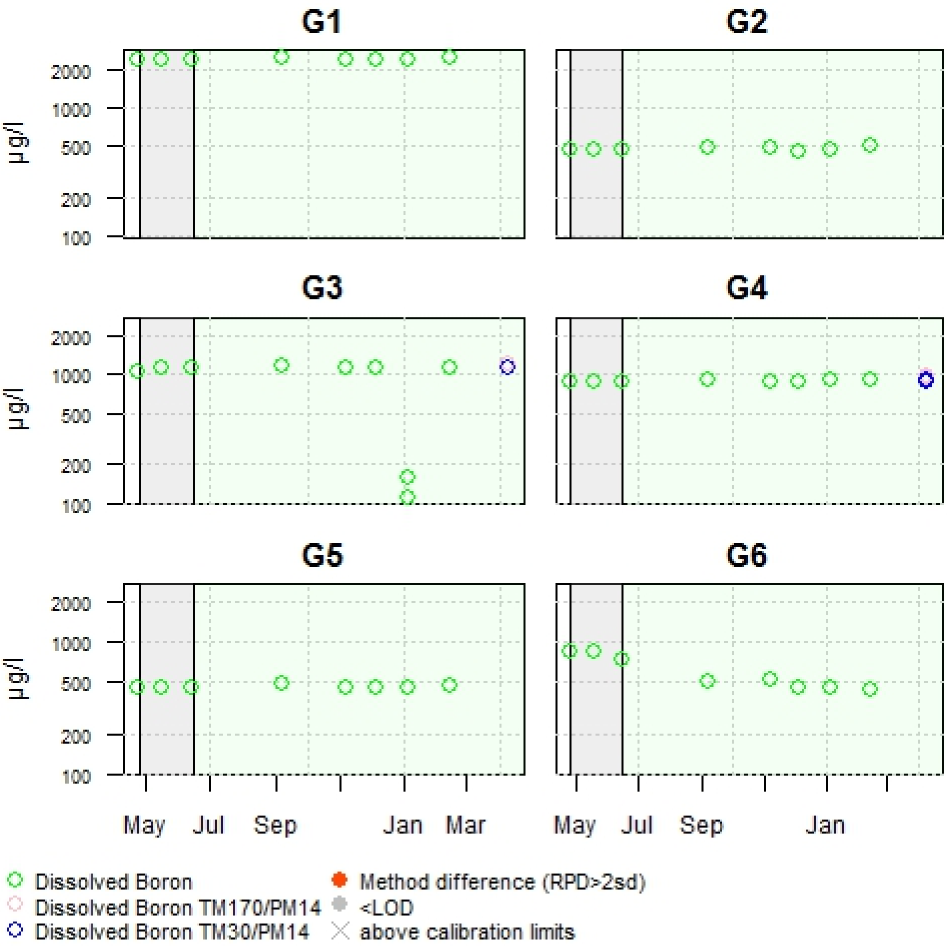
On-site boreholes



Observations and notes:

- Boreholes A to C and E have measurements of boron between 50 and 250 µg/l.
- Borehole D has much higher concentrations of dissolved boron (up to 2mg/l).
- Borehole C appears to have higher concentrations of dissolved boron in the second phase compared with the first phase, though borehole B appears to demonstrate the opposite relationship. This was also an observation with ammoniacal nitrogen.
- There were no duplicate observations and no values were recorded as less than the LOD.

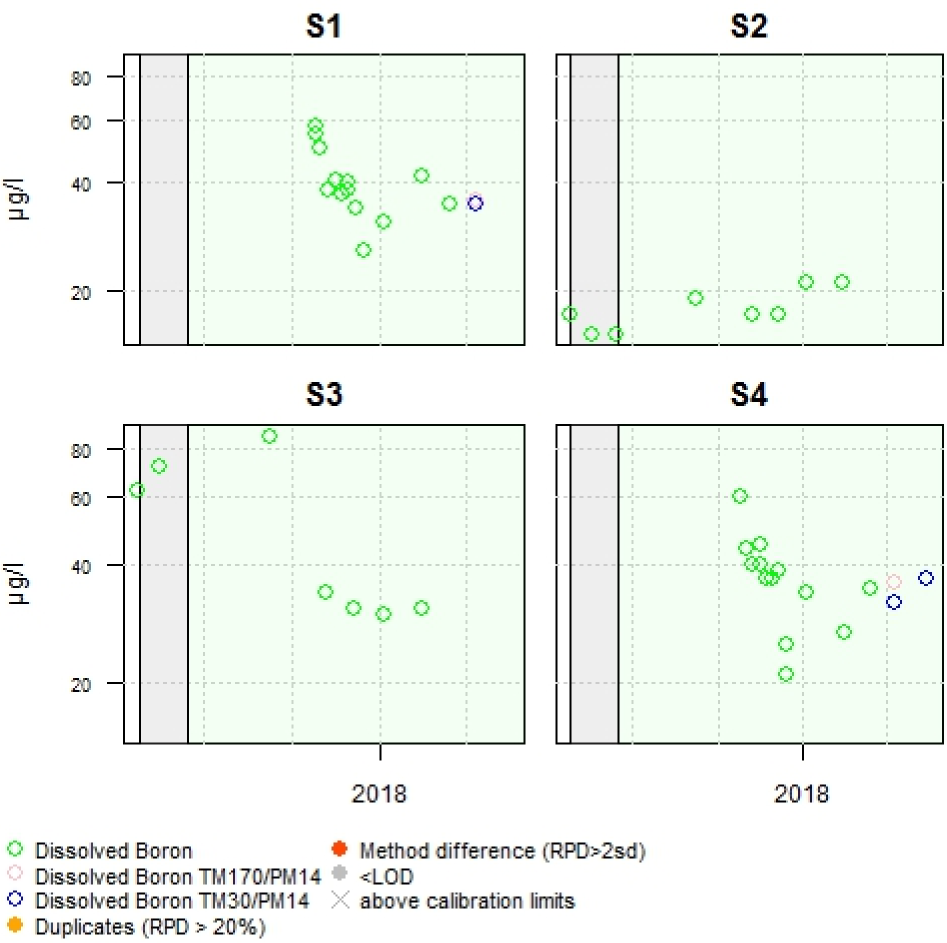
Off-site boreholes



Observations and notes:

- Only single year of observation (with only 3 observations in P1).
- Highest concentrations in G1.

Surface waters



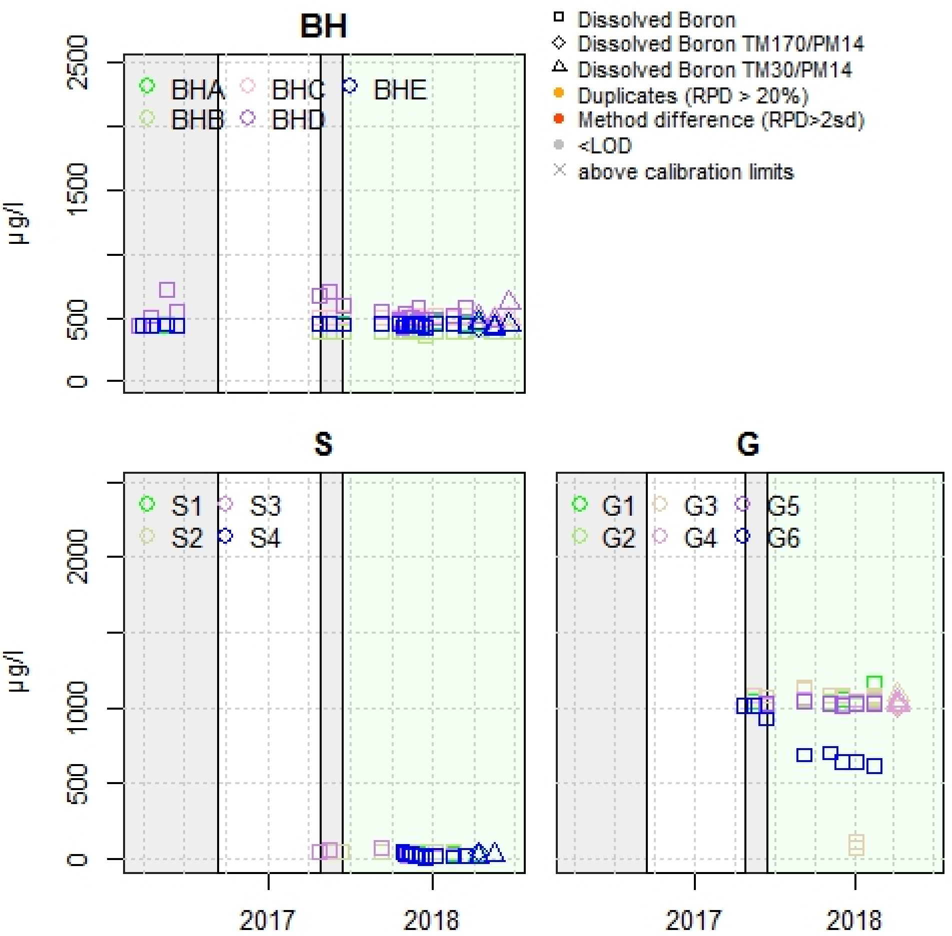
Observations and notes:

- Only single year of observation (with maximum of 3 observations per site in P1).
- Very low concentrations of boron in surface waters, with the lowest concentrations in S2.

Conclusions: Individual site time series

- Despite the single year of observations, concentrations appear relatively stable through time (at least in groundwater where the concentrations are highest).
- The exception appears to be in G6 where concentrations appear to have decreased over the year of measurement. The difference at B6 is most clearly seen on the grouped plots in the following section.

2. Grouped time series



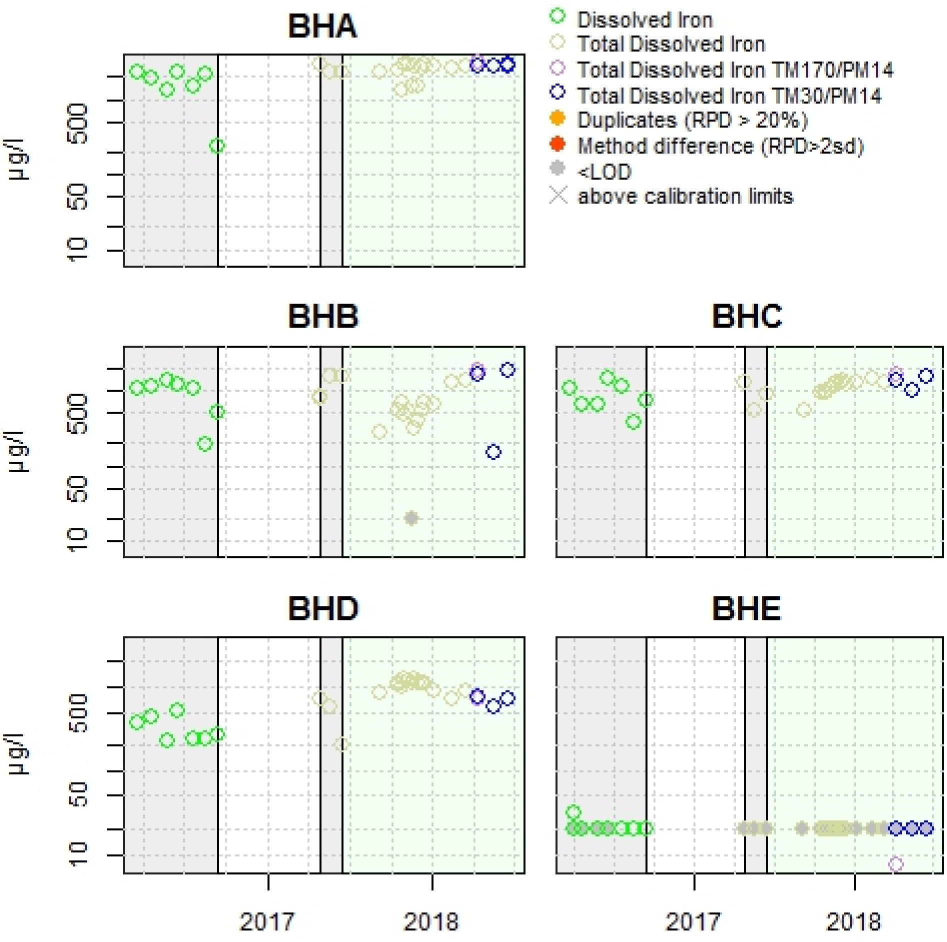
3. Grouped data box plots

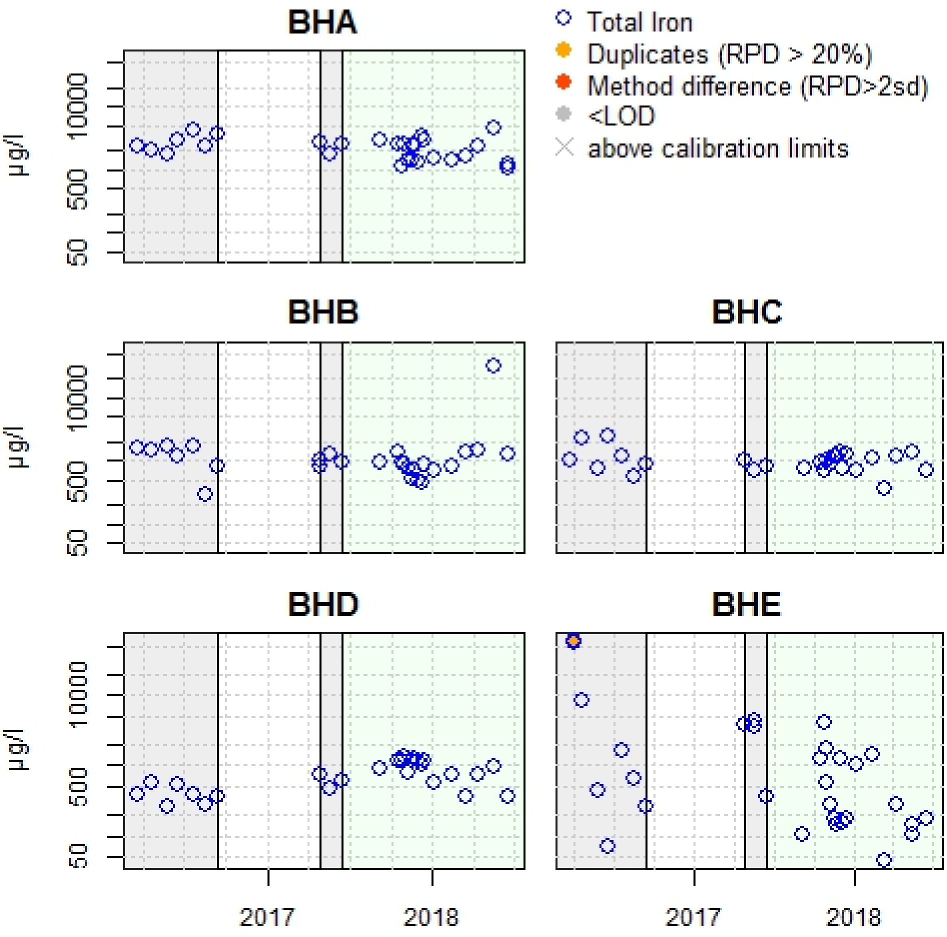
Box plots of BH, S and G sites, though containing non-uniform numbers of observation, can be compared across the full-time period for this parameter.

Iron (dissolved and total)

1. Individual site time series

On-site boreholes

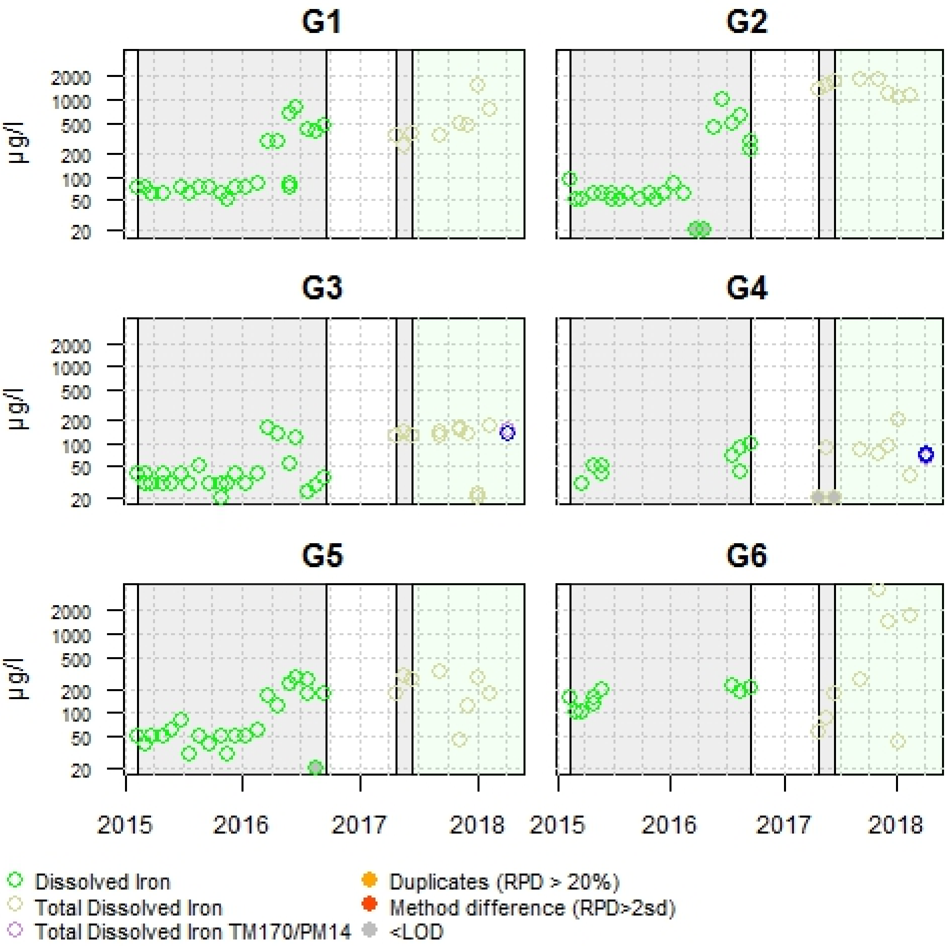


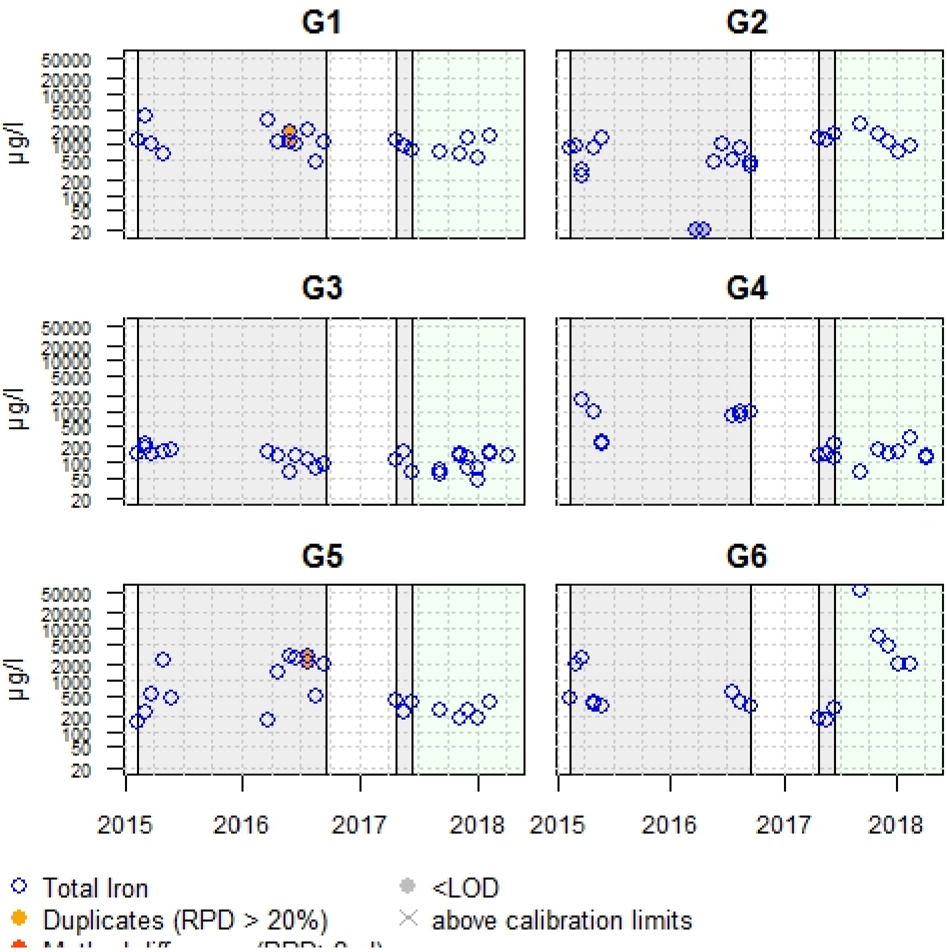


Observations and notes:

- There appears to be some (expected) correlation with dissolved and total iron, with the exception of borehole E.
- Very little total iron is dissolved in borehole E, if it is accepted that values of dissolved iron at this borehole were generally less than the limit of detection.
- Potential outlier in total iron values observed in May 2018 in borehole B.

Off-site boreholes

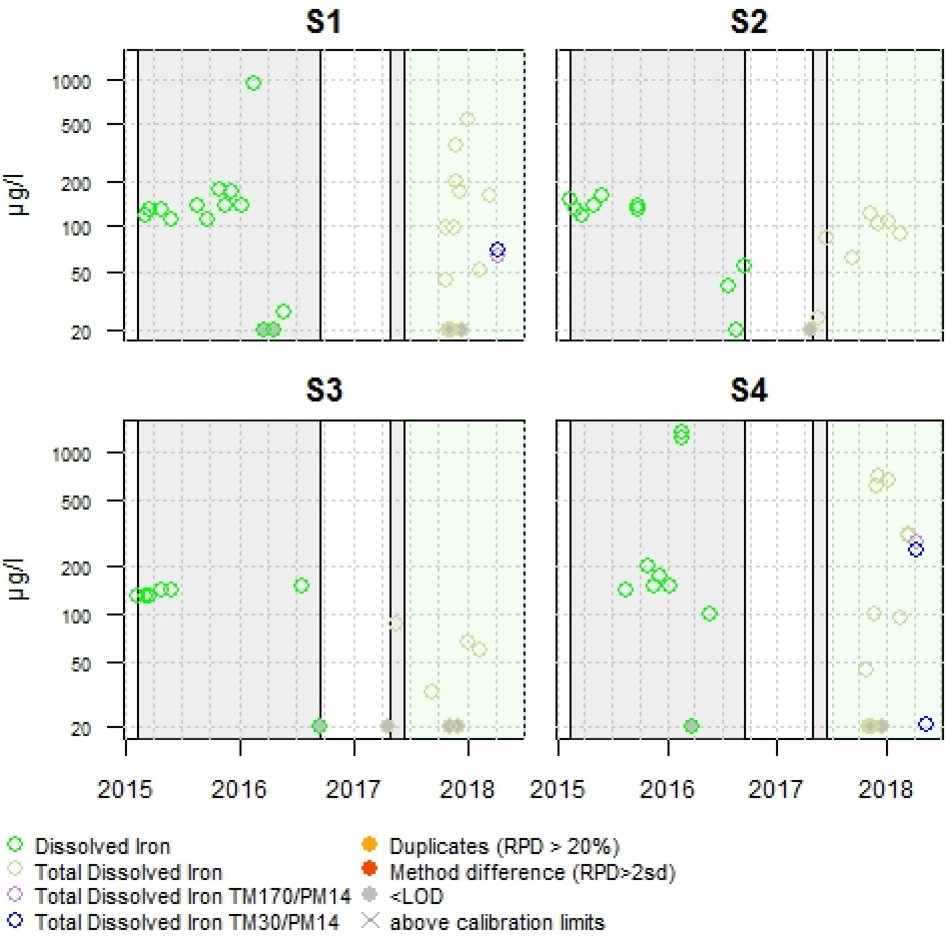


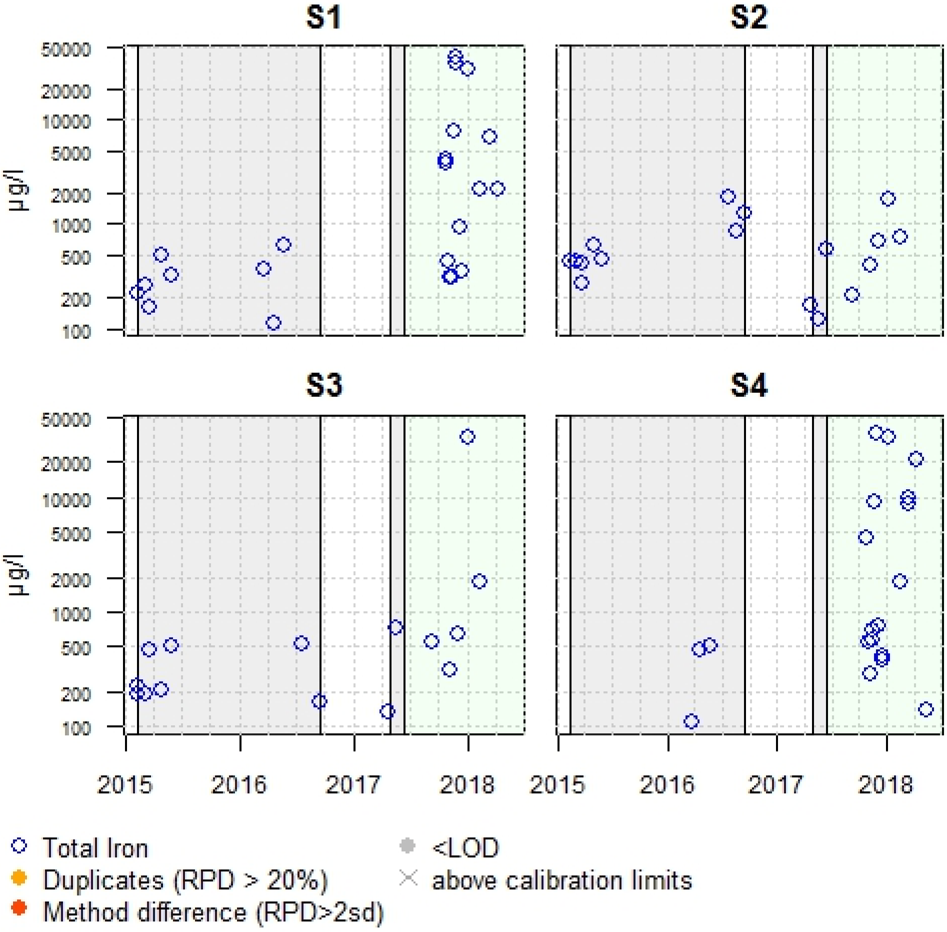


Observations and notes:

- Maximum values of total iron are higher than dissolved iron. The high value observed at G6 in total iron appears to have been a sample that required additional dilution.

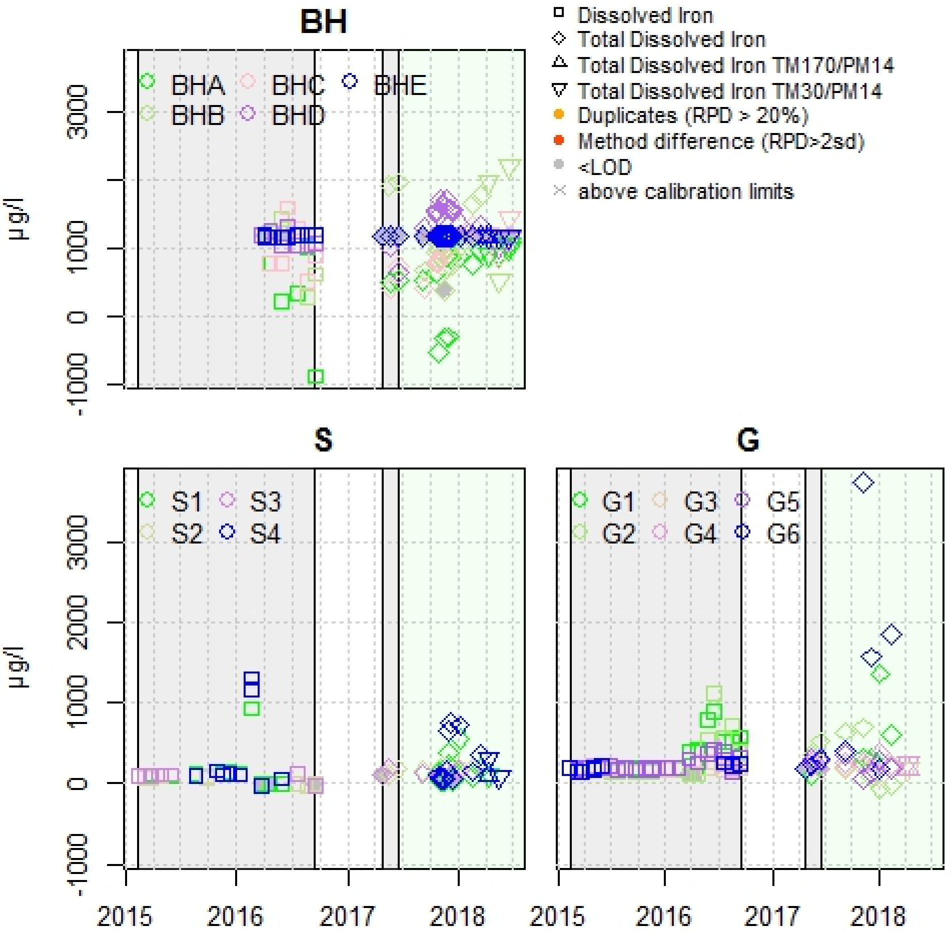
Surface waters





S1
S2
S3
S4
µg/l
µg/l
50000
20000
10000
5000
2000
1000
500
200
100
2015
2016
2017
2018
Total Iron
Duplicates (RPD > 20%)
Method difference (RPD>2sd)
<LOD
above calibration limits

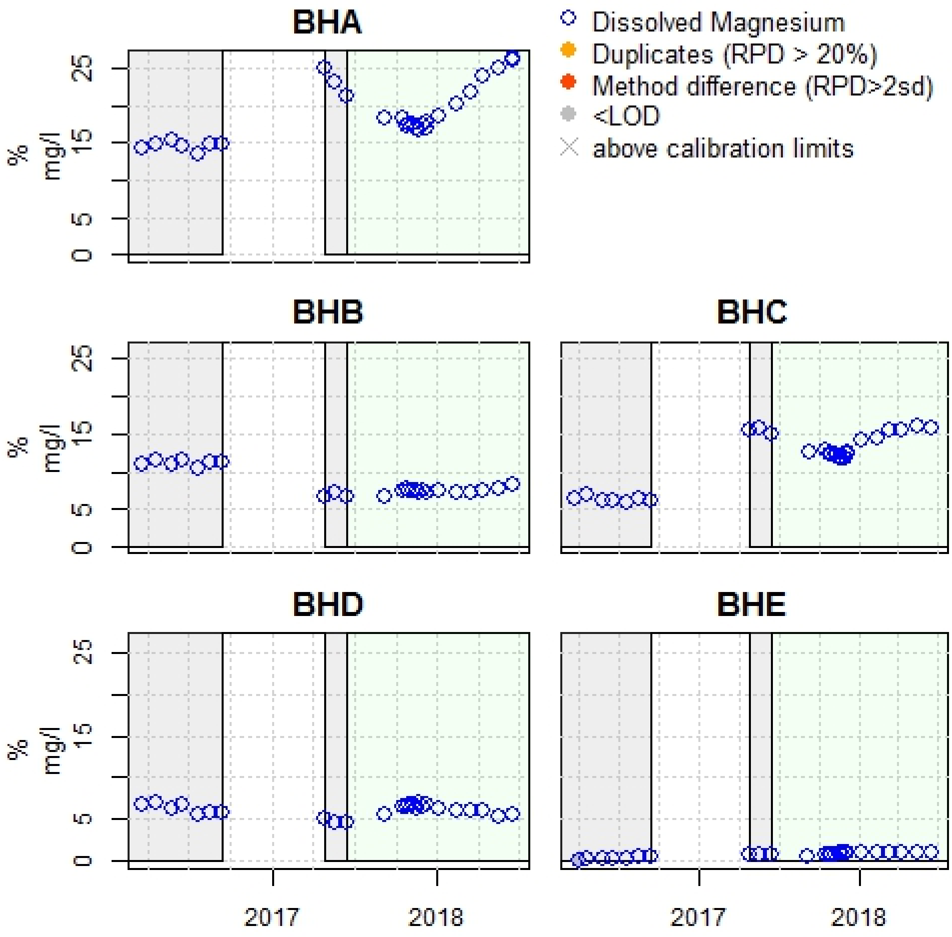
2. Grouped time series



Magnesium (dissolved and total)

1. Individual site time series

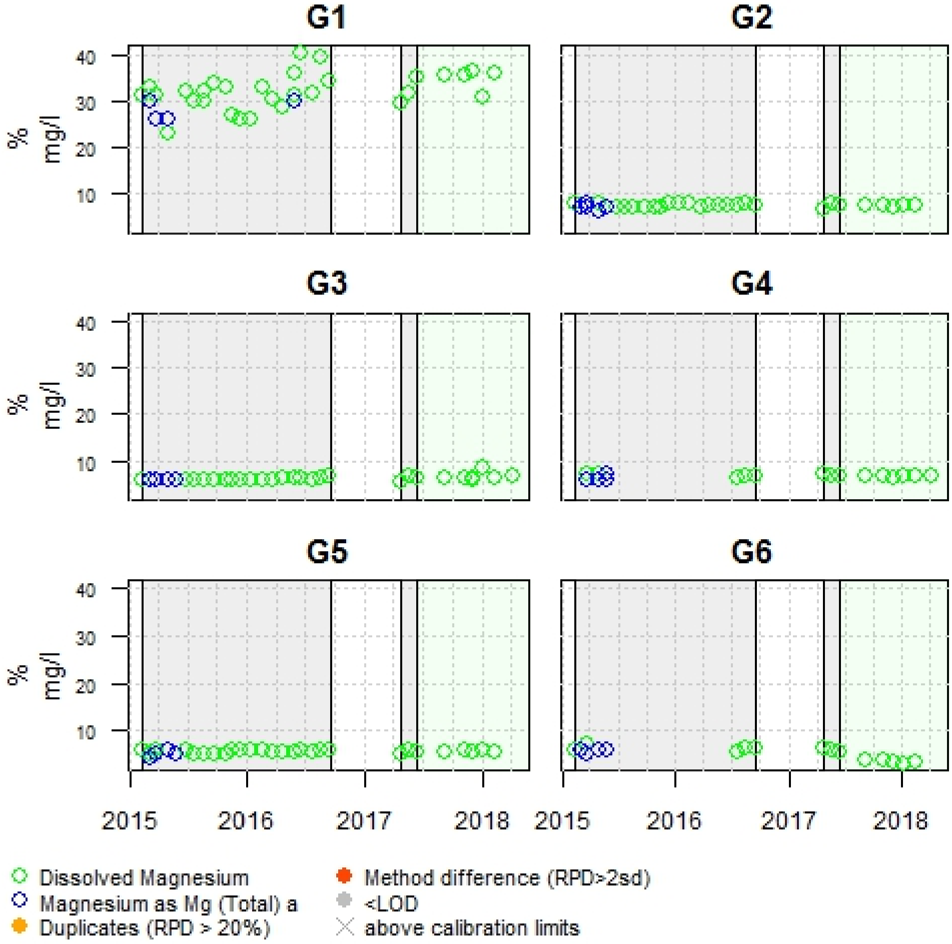
On-site boreholes



Observations and notes:

- No total magnesium measured at the on-site boreholes.
- Very little dissolved magnesium is dissolved in borehole E (as was observed with total iron).
- Increase in dissolved magnesium from the start of measurement to the end of phase 2 in all sites except BH-B and BH-D.
- In boreholes BH-A and BH-C, pattern of failing limb of concentrations from spring 2017 to a minimum in late autumn, when concentrations begin to rise again.
- Concentrations of dissolved magnesium at the start of P1 are similar in BH-C and BH-D, but show different behaviours in the second part of P1 and throughout P2.

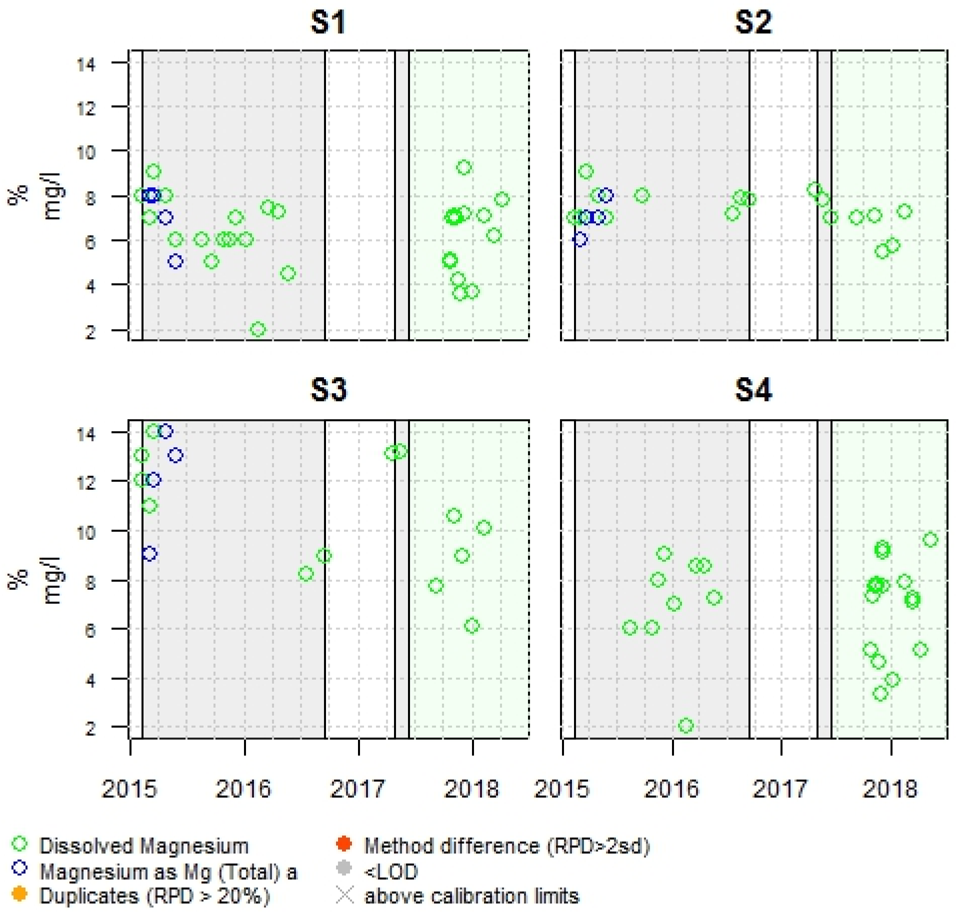
Off-site boreholes



Observations and notes:

- Almost all magnesium appears to be in dissolved form.
- Much higher values and variability in concentrations in G1. Elsewhere magnitudes are of a similar order and appear fairly stable.

Surface waters



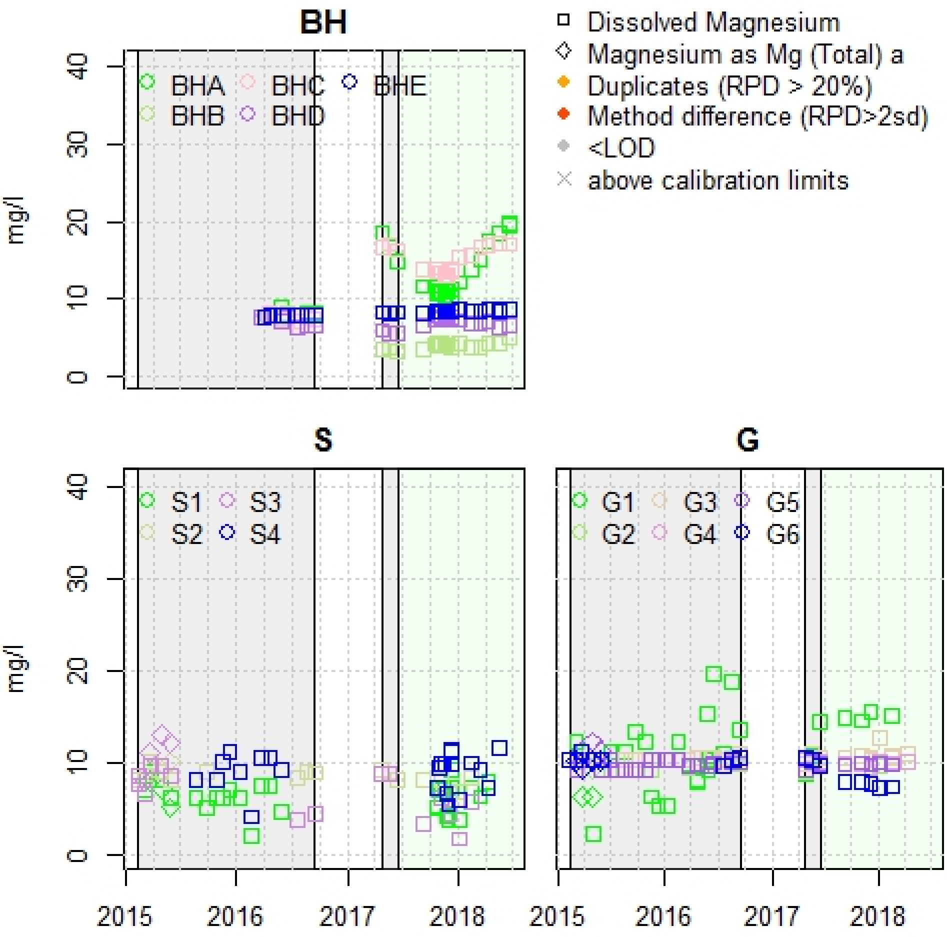
Observations and notes:

- Almost all magnesium appears to be in dissolved form.
- On a visual scale, some similarities with dissolved iron.
- Site S2 shows the least variability through time.
- Potential outlier low concentrations in January 2016 for sites S1 and S4. The measurement would however appear non-erroneous as it is supported by concurrent low concentrations of iron.
- Concentrations generally lower than in groundwaters.
- S3 appears to have generally higher observed magnesium levels.

Conclusions: Individual site time series

- Borehole G1 and the on-site boreholes appear to show slightly different characteristics of magnesium than the off-site boreholes and surface water measurements. Potential for the latter to be considered as a grouping (based on existing data).

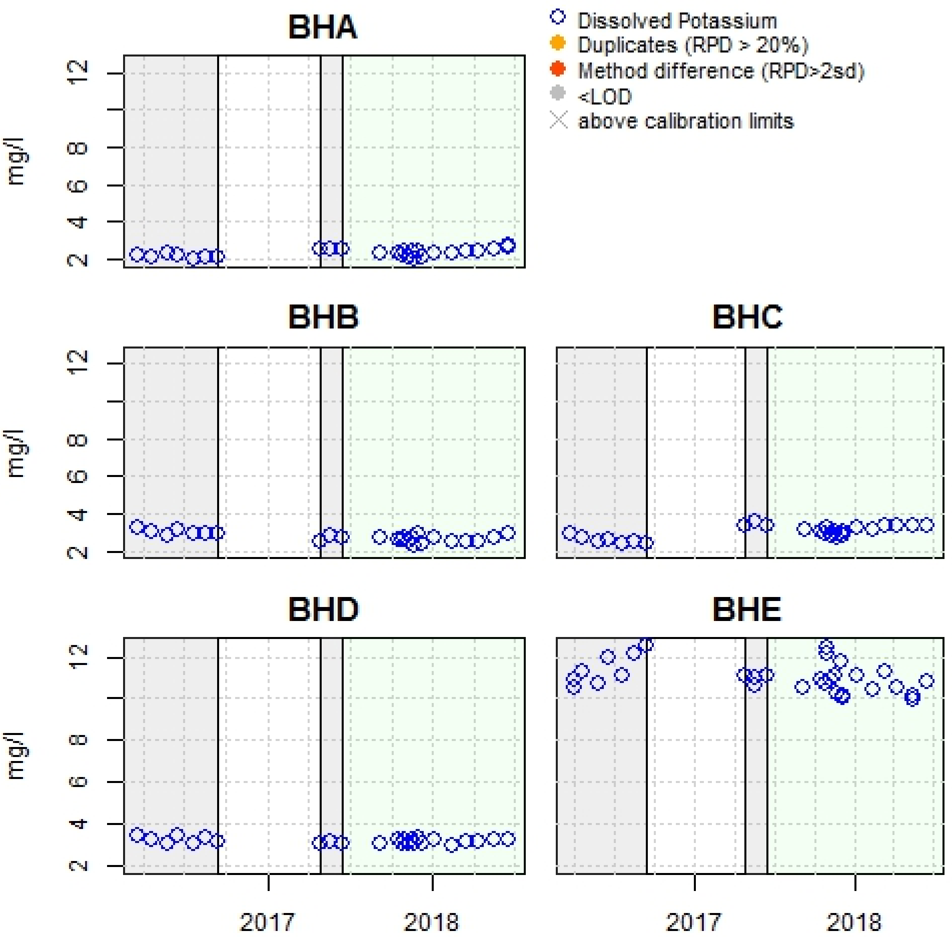
2. Grouped time series



Potassium (dissolved and total)

1. Individual site time series

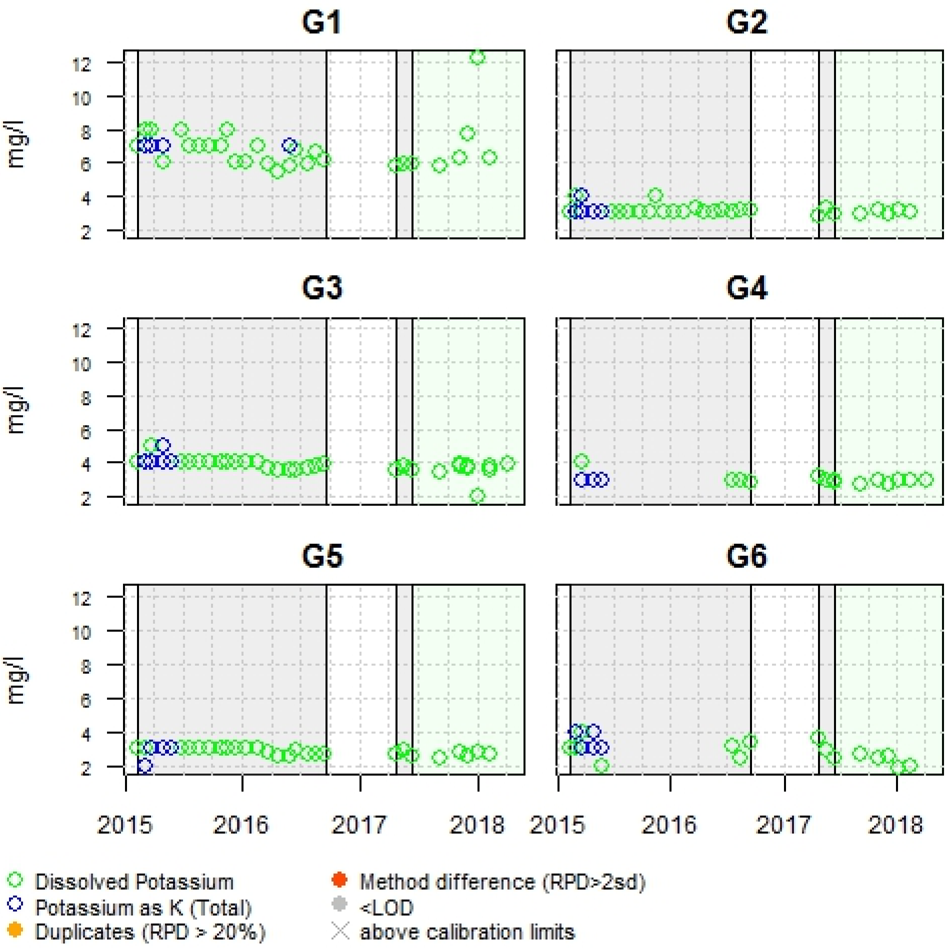
On-site boreholes



Observations and notes:

- No total potassium measured at the on-site boreholes.
- Potential slight Increase in dissolved potassium from the start of the measurement to the end of phase 2 in BH-A, though the start concentration is lower at this site and tends towards a concentration similar to that observed at the boreholes at BH-B, BH-C and BH-D.
- Higher concentrations of dissolved potassium are seen in borehole E.

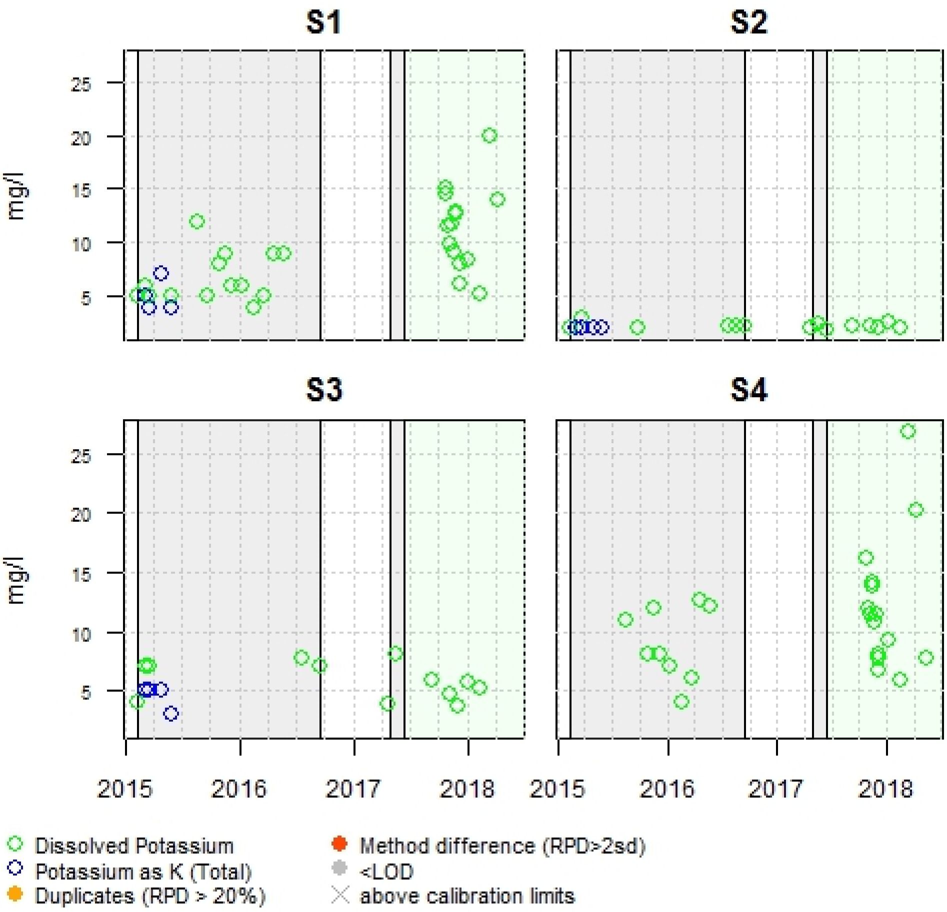
Off-site boreholes



Observations and notes:

- Almost all potassium appears to be in dissolved form.
- Higher values and variability in concentrations in G1. Elsewhere, magnitudes are of a similar order and appear fairly stable.
- Potential high concentration outlier in January 2018 for G1.

Surface waters



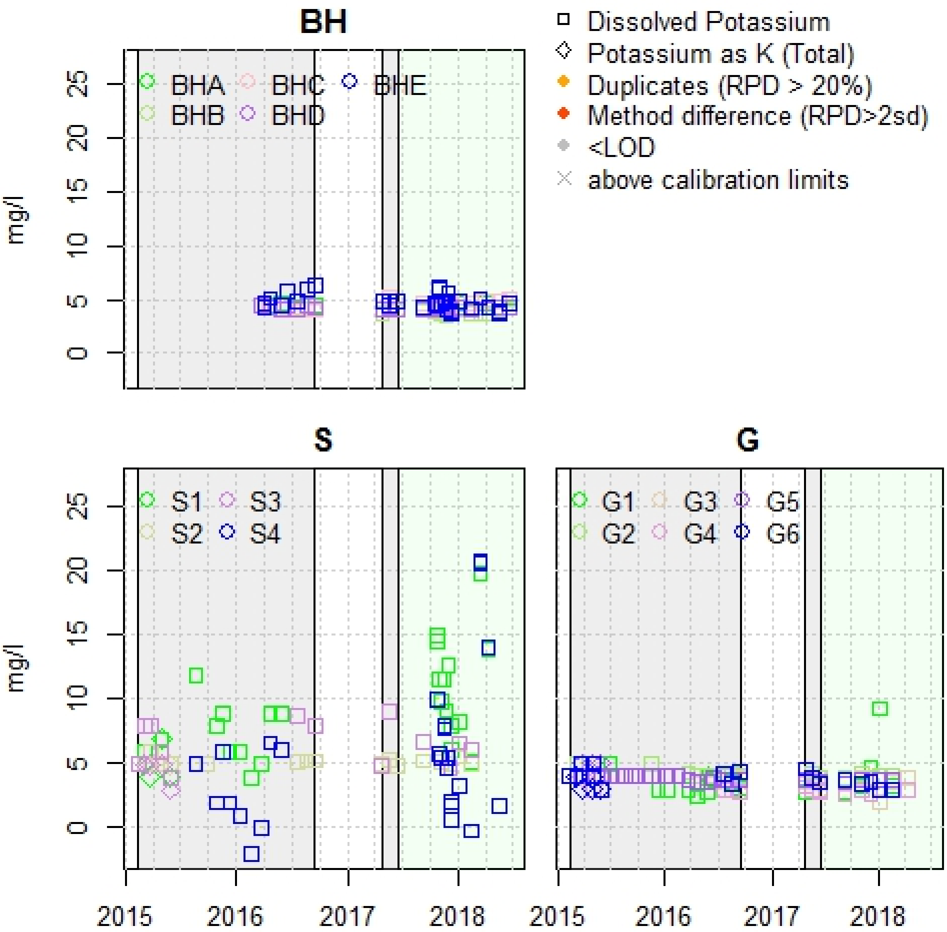
Observations and notes:

- Potassium appears to be mostly in dissolved form. Higher values of dissolved than total at some sites indicates some potential imprecise measurements.
- There appears to be higher variability in P2 than in P1.
- Site S2 shows the lowest concentrations and least variability in this determinand through time.
- Range of values and maximum observed concentrations at S1 and S4 are higher than in groundwaters.

Conclusions: Individual site time series

- Potassium was deemed to be of higher priority interest in groundwaters than for surface waters using the prioritisation framework developed, but is included for completeness. This was a consequence of the observed higher variability in the data in surface waters. The lower utility of the variable as a predictor in surface waters is supported by sources of K that could for instance arise from fertiliser application.
- To be comprehensive and support any conclusions reached, it would however appear sensible to review conclusions in relation to groundwater quality in the light of surface water data.

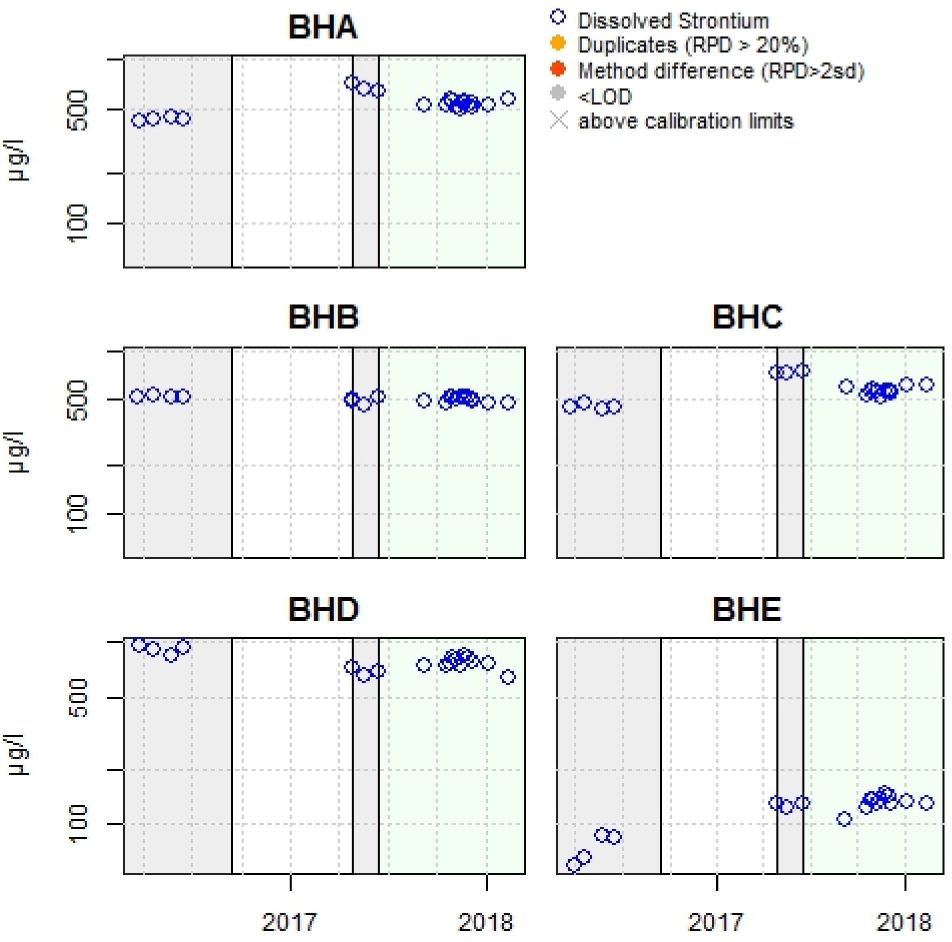
2. *Grouped time series*



Strontium (dissolved)

1. Individual site time series

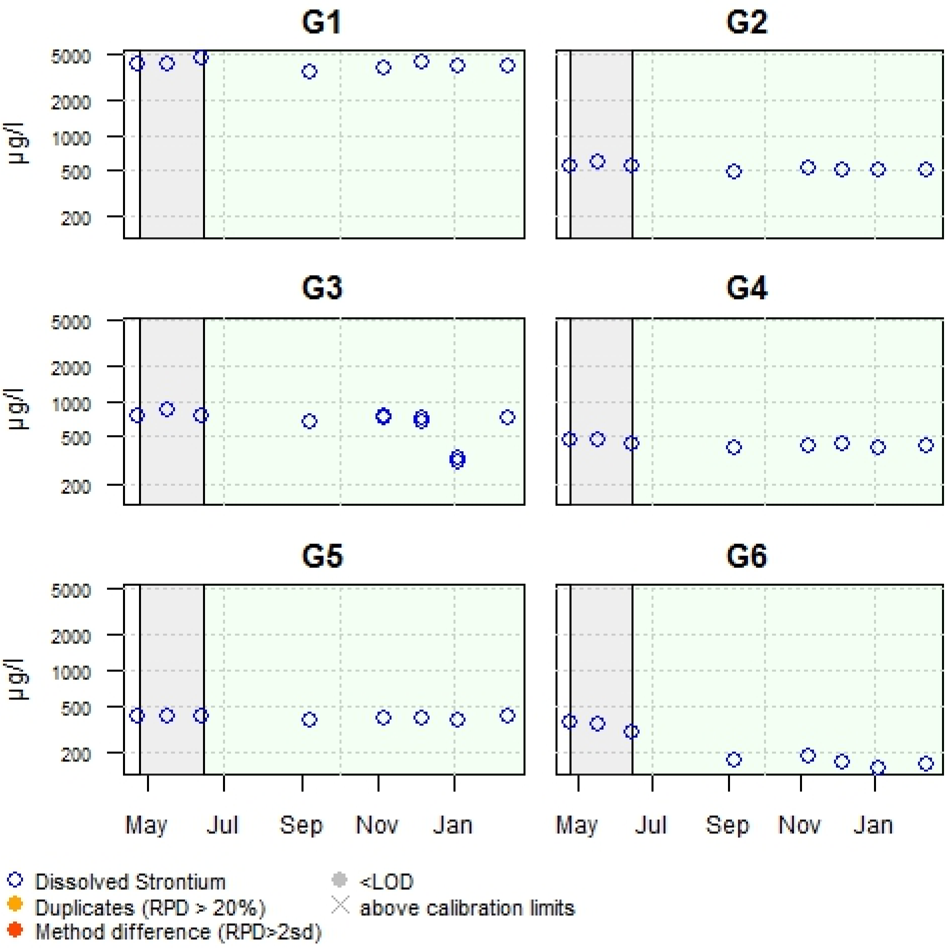
On-site boreholes



Observations and notes:

- Comparatively low concentrations of dissolved strontium in borehole E, though higher levels in P2 seen comparative to the start of P1.
- Concentrations of dissolved strontium at the start of P1 are similar in BH-A to BH-C.

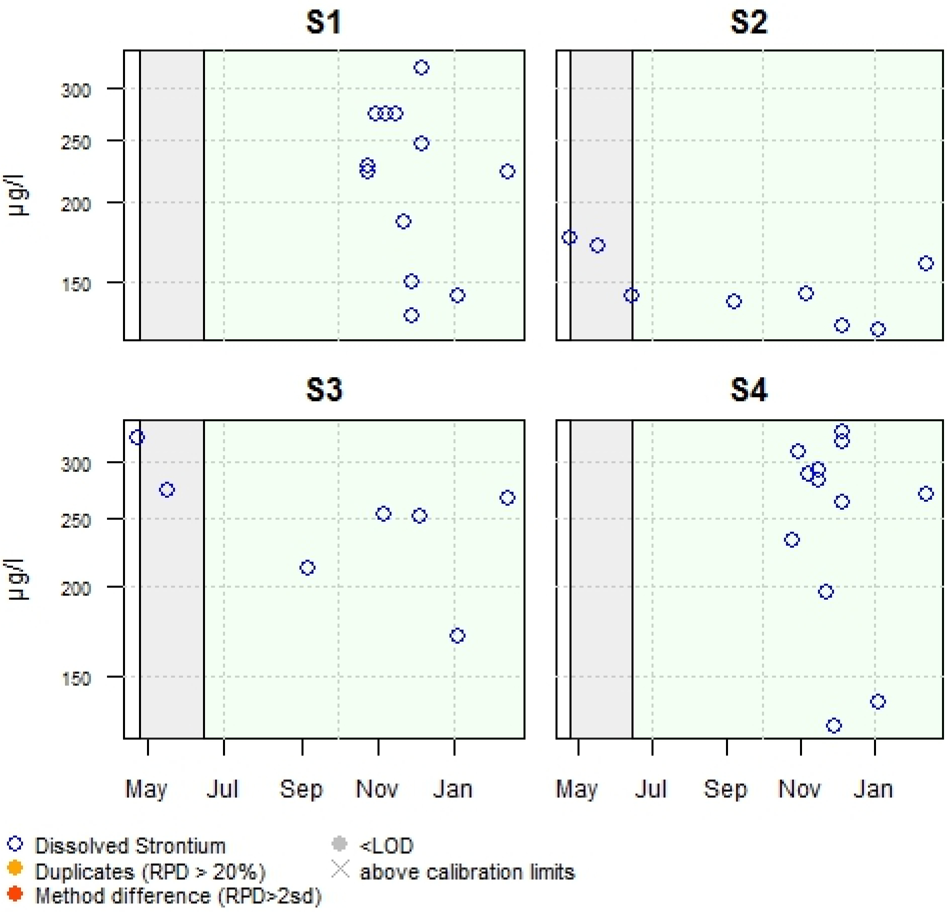
Off-site boreholes



Observations and notes:

- Less than one year of observation. Potential outlier in G3, in January (2018), though this is being non-erroneous and is supported by near identical duplicate sample analysis.
- Measurements are of a similar order of magnitude for G2 to G6 In P1, but are much higher in G1.

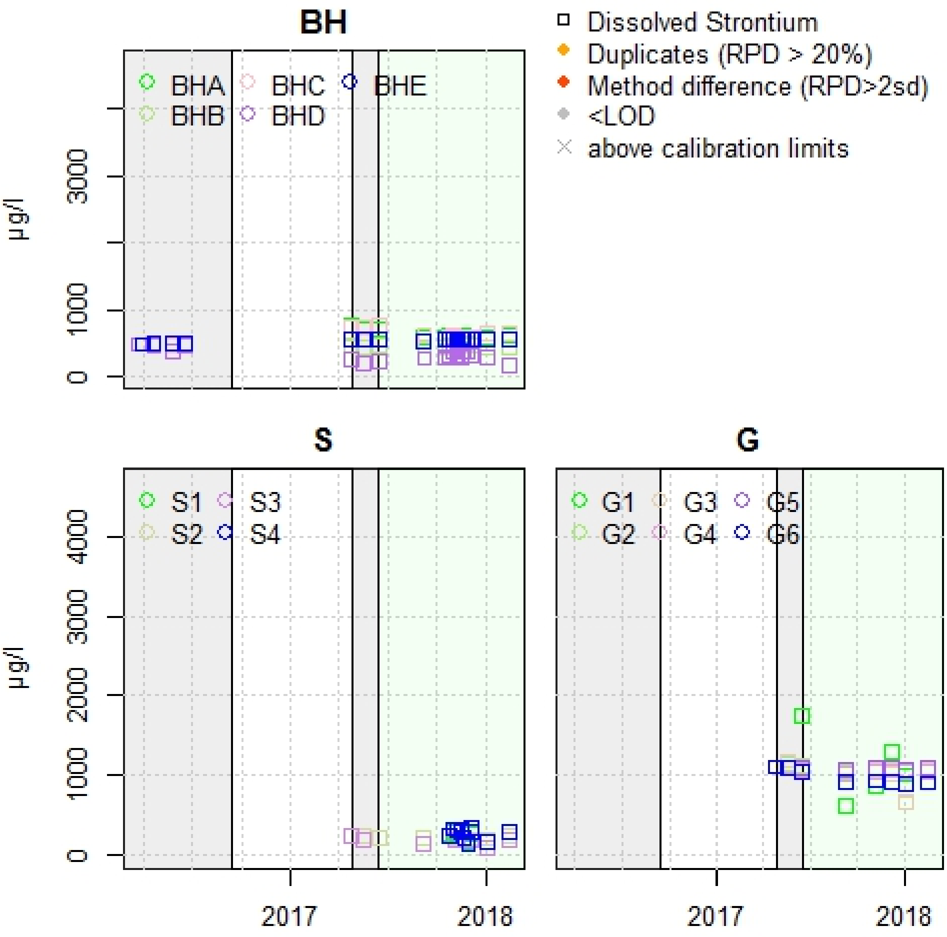
Surface waters



Observations and notes:

- Only single year of observation. At S1 and S2, measurements began in winter 2018.
- Variable with no apparent seasonal pattern.

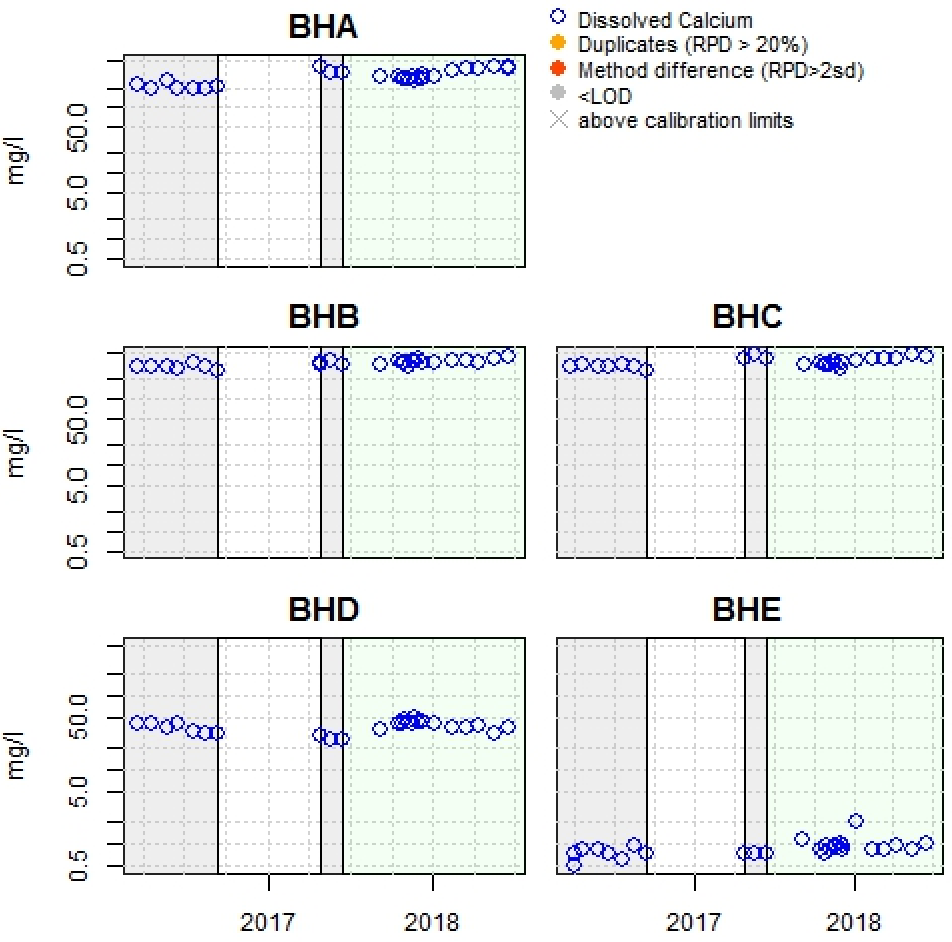
2. *Grouped time series*



Calcium (dissolved and total)

1. Individual site time series

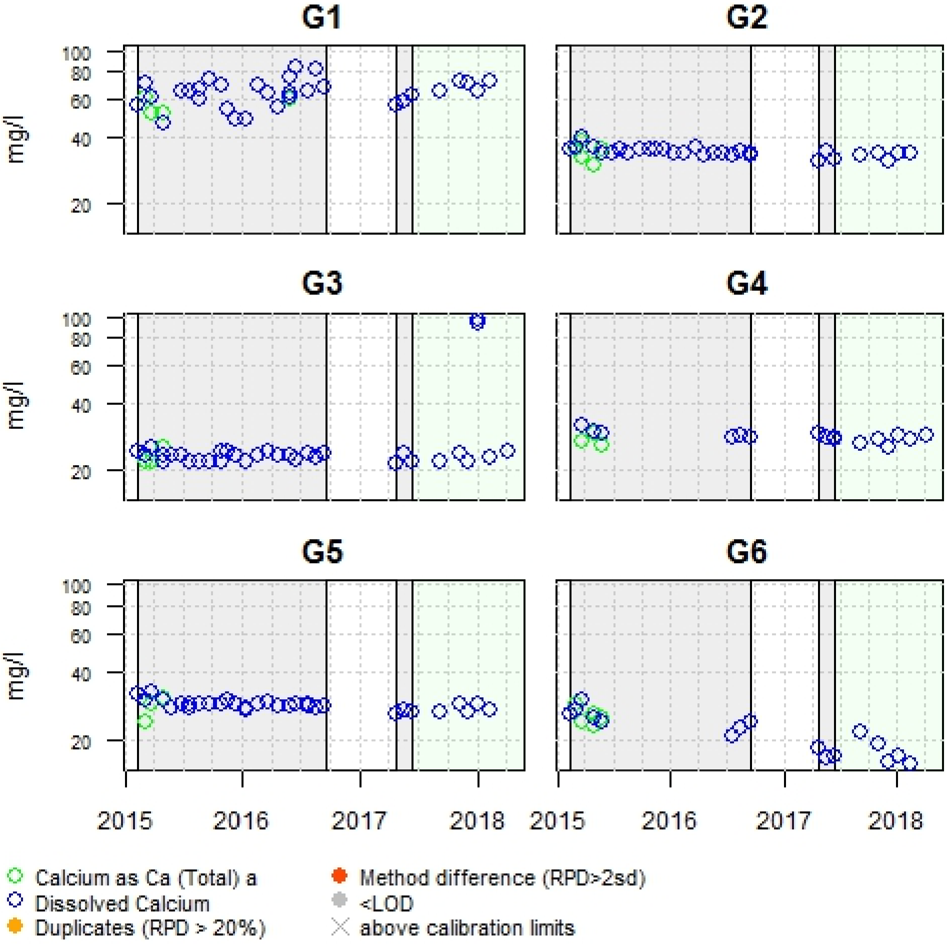
On-site boreholes



Observations and notes:

- No total calcium measured at the on-site boreholes.
- Very little dissolved calcium is dissolved in borehole E.
- Concentrations of dissolved calcium are of a similar magnitude across BH-A to BH-C.

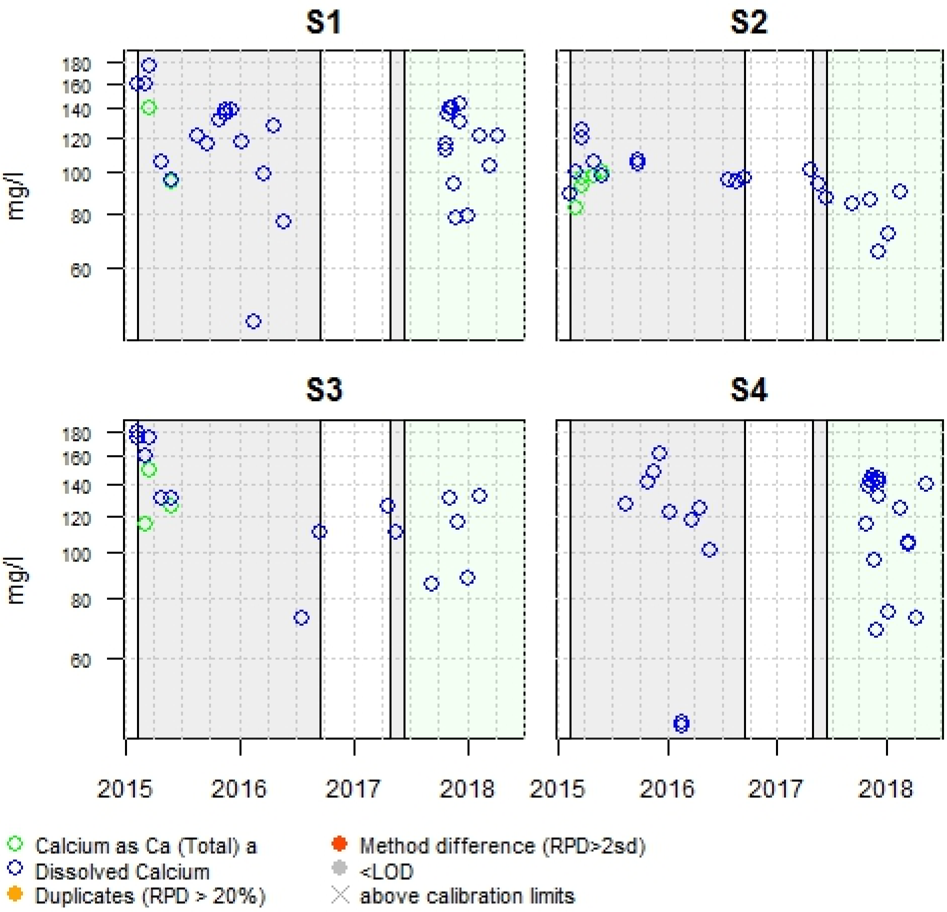
Off-site boreholes



Observations and notes:

- Calcium appears to be mostly in dissolved form. Higher values of dissolved than total at some sites indicates some potential imprecise measurements.
- Potential high concentration outlier in January 2017 for G3.

Surface waters



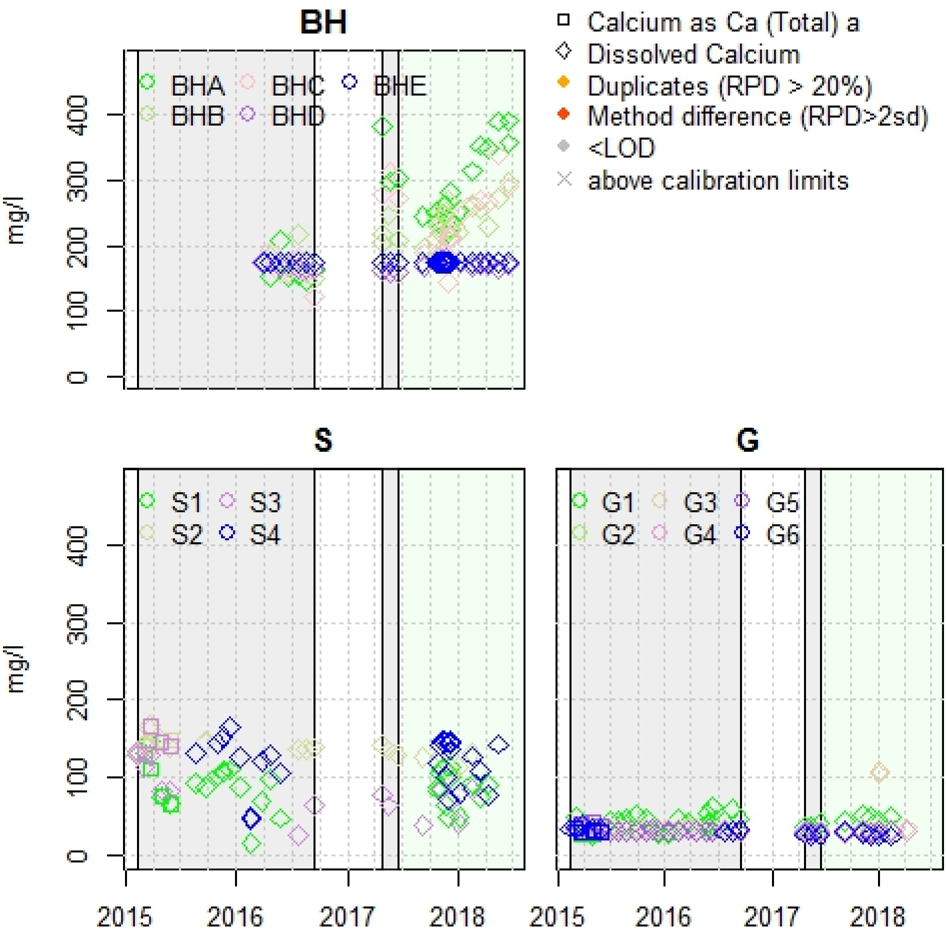
Observations and notes:

- Only single year of observation (with maximum of 3 observations per site in P1).
- Very low concentrations of boron in surface waters, with the lowest concentrations in S2.

Conclusions: Individual site time series

- Despite the single year of observations, concentrations appear relatively stable through time (at least in groundwaters where the concentrations are highest).
- The exception appears to be in G6 where concentrations appear to have decreased over the year of measurement. The difference at B6 is most clearly seen on the grouped plots in the following section.

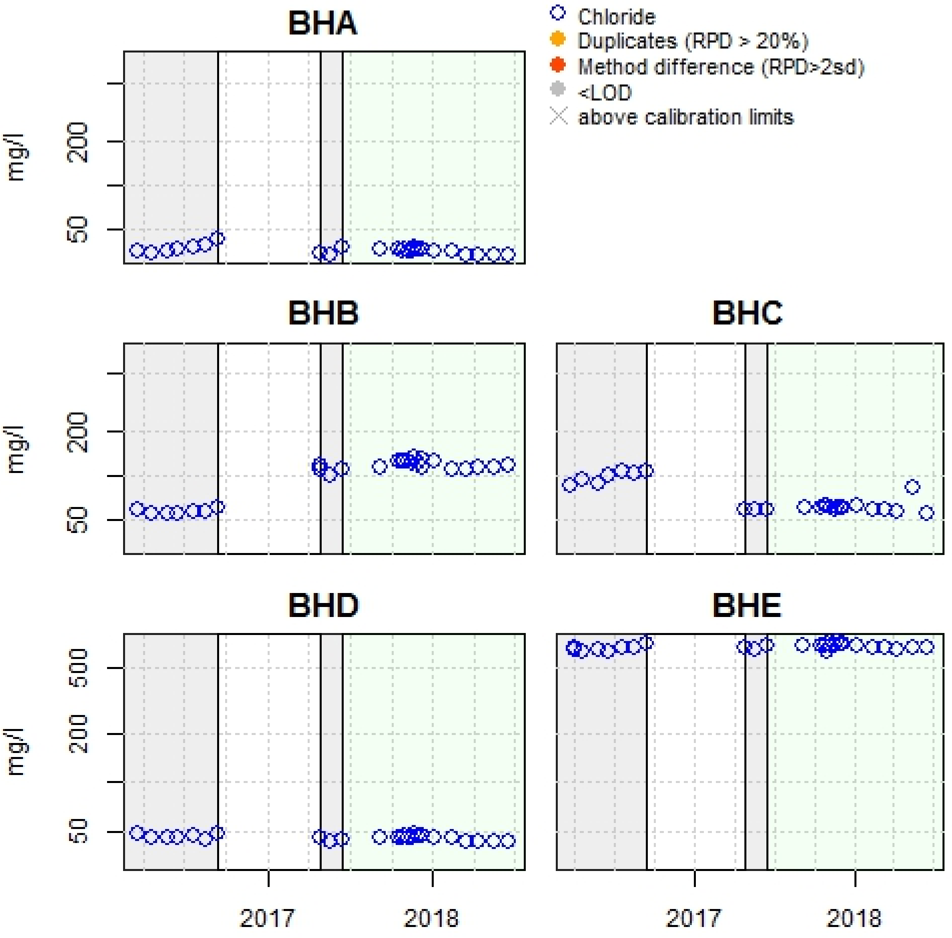
2. Grouped time series



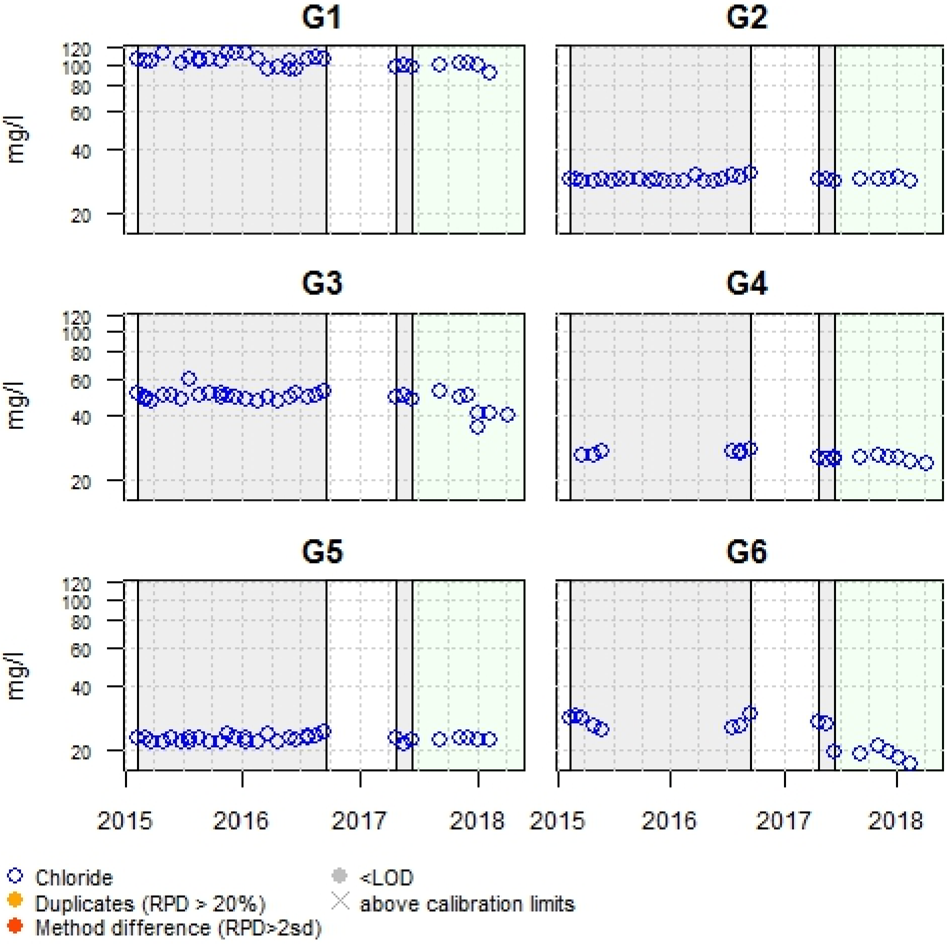
Chloride

1. Individual site time series

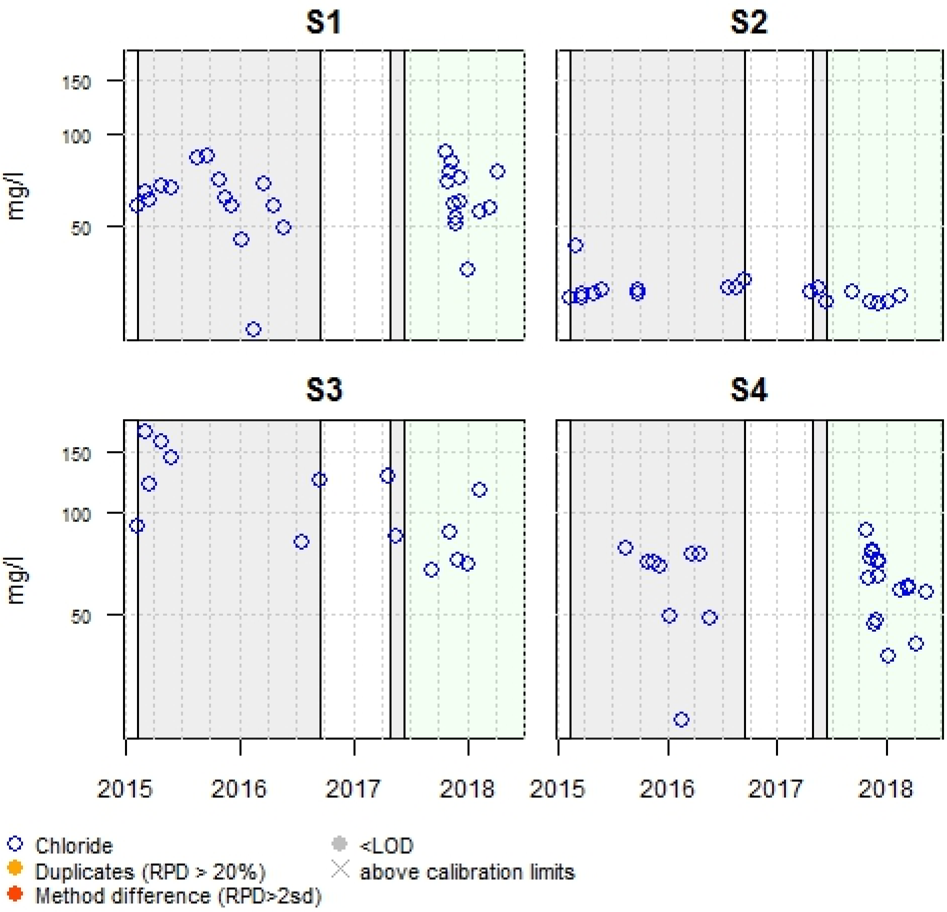
On-site boreholes



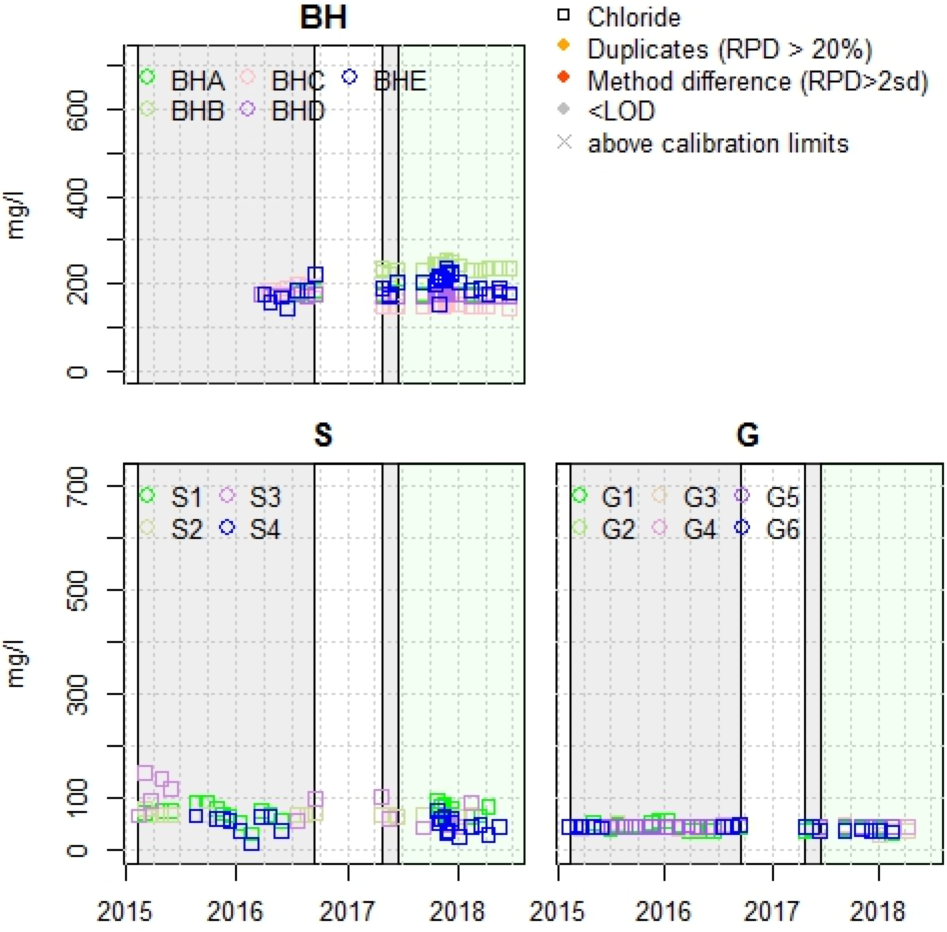
Off-site boreholes



Surface waters



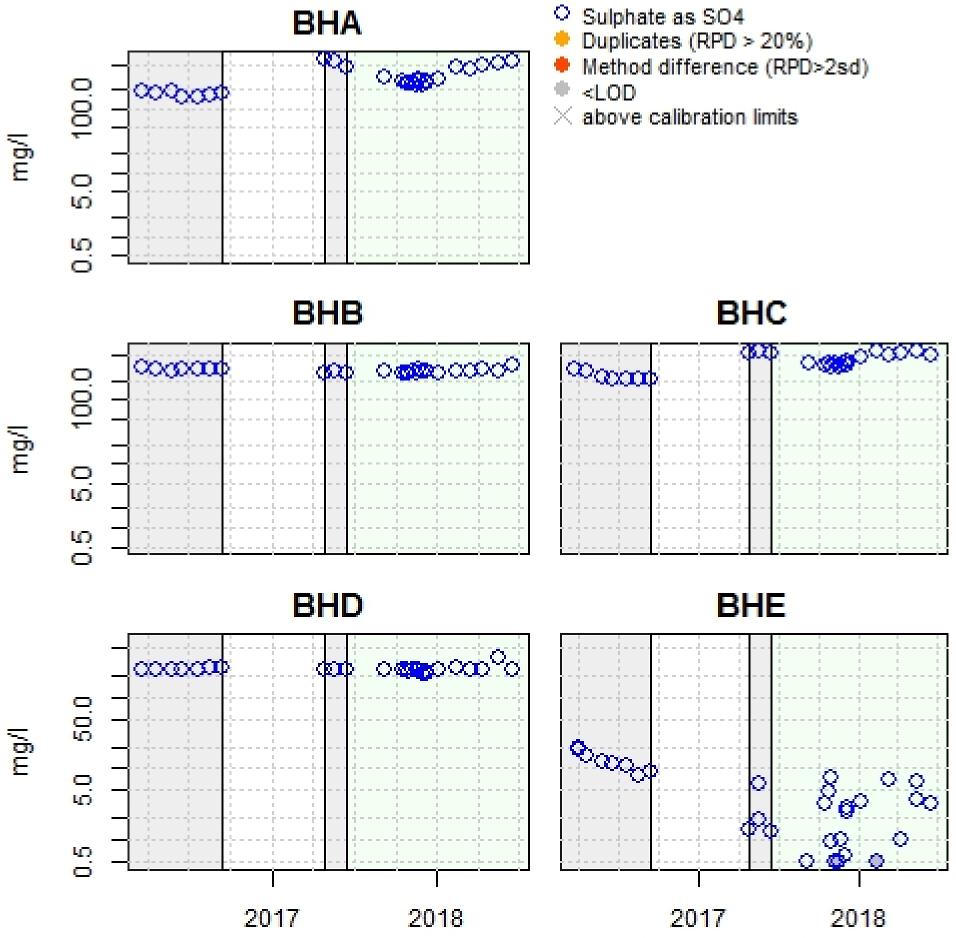
2. Grouped time series



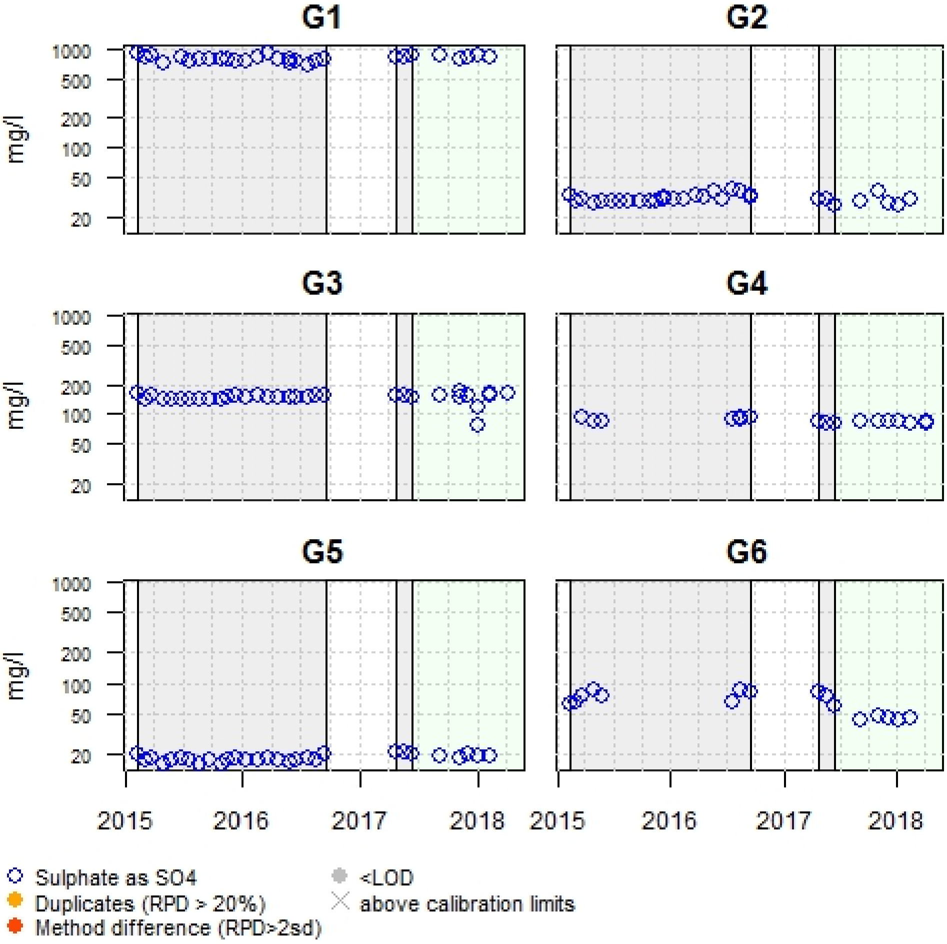
Sulphate

1. Individual site time series

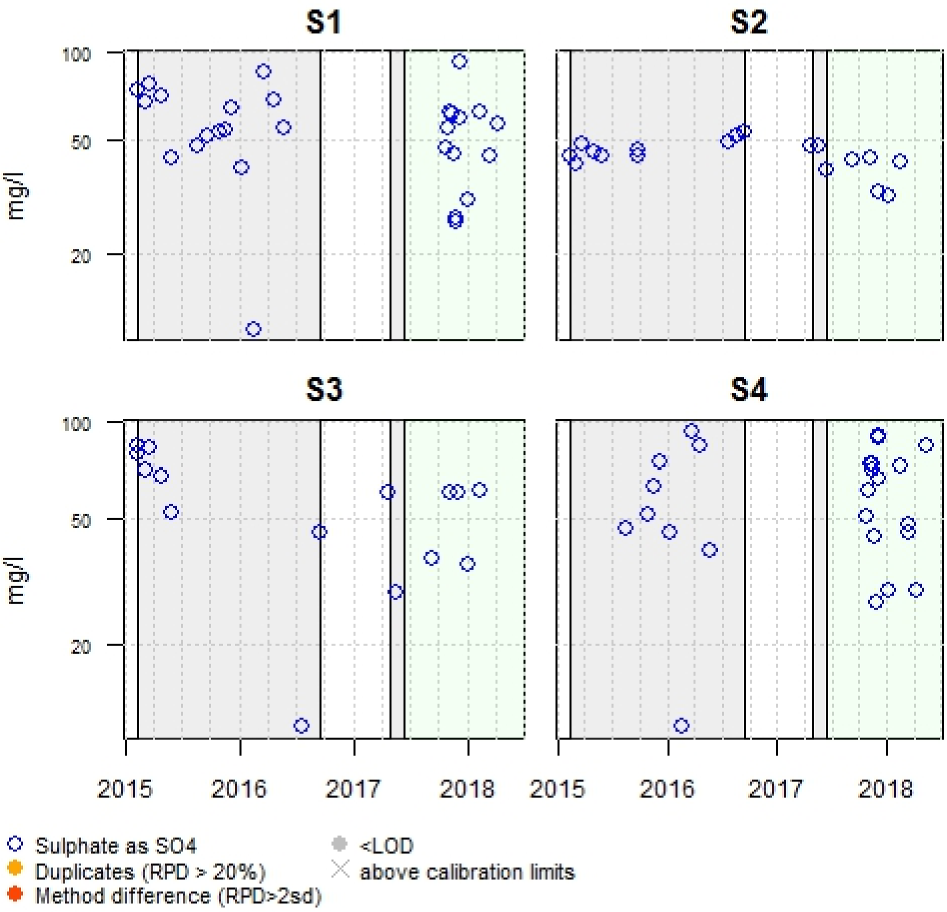
On-site boreholes



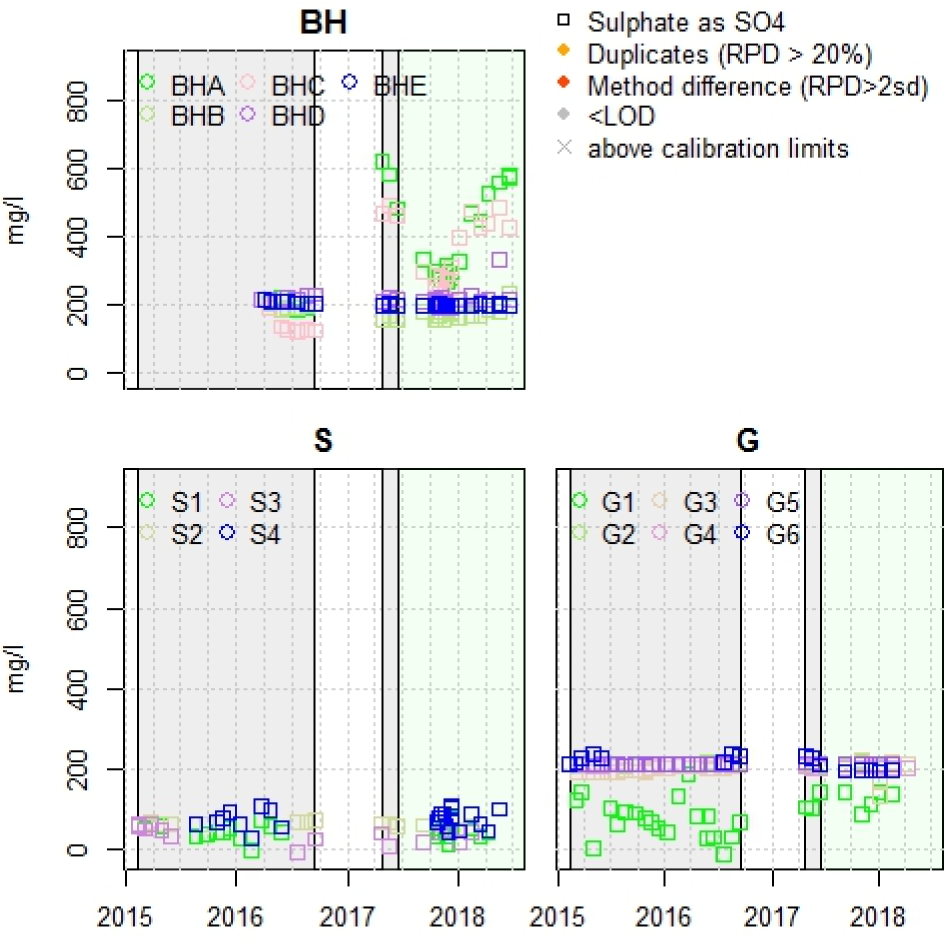
Off-site boreholes



Surface waters



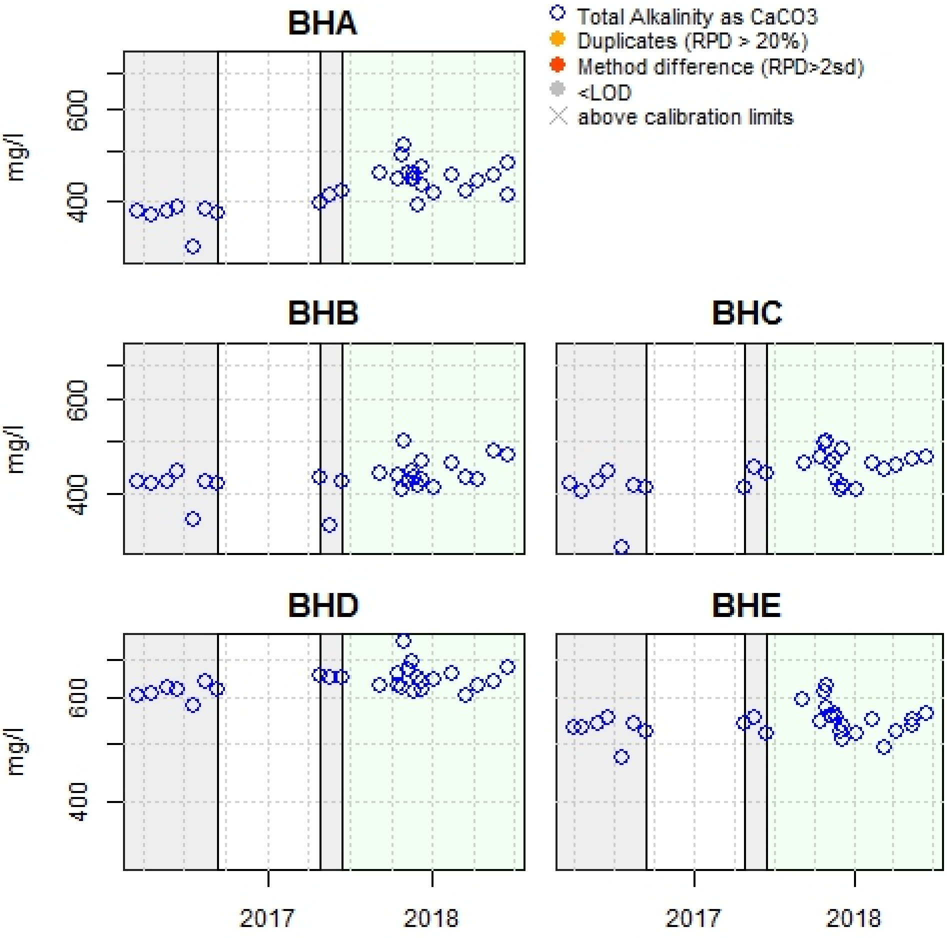
2. *Grouped time series*



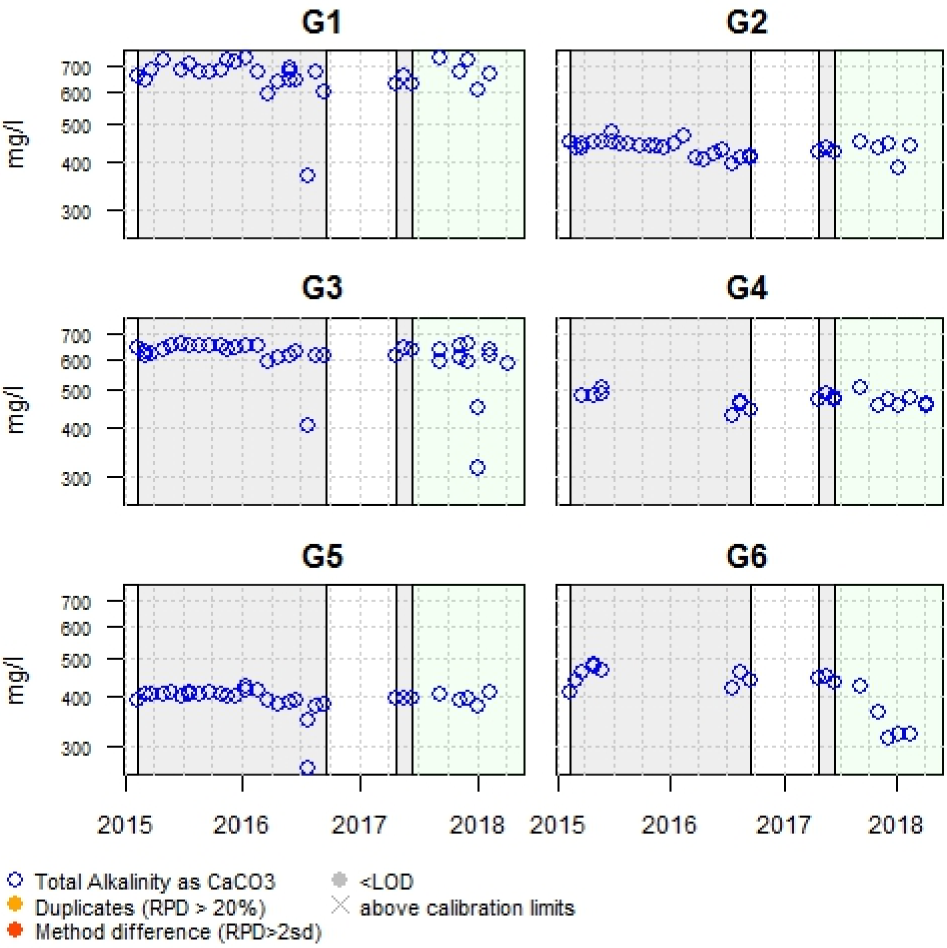
Total alkalinity

1. Individual site time series

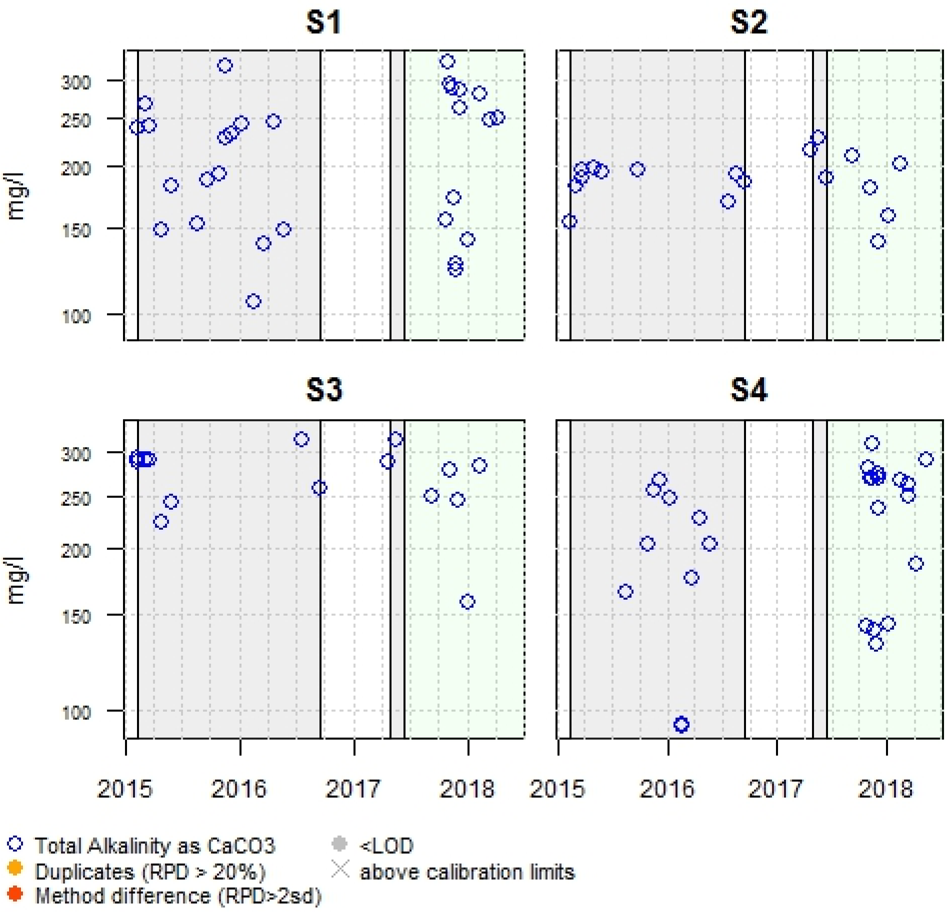
On-site boreholes



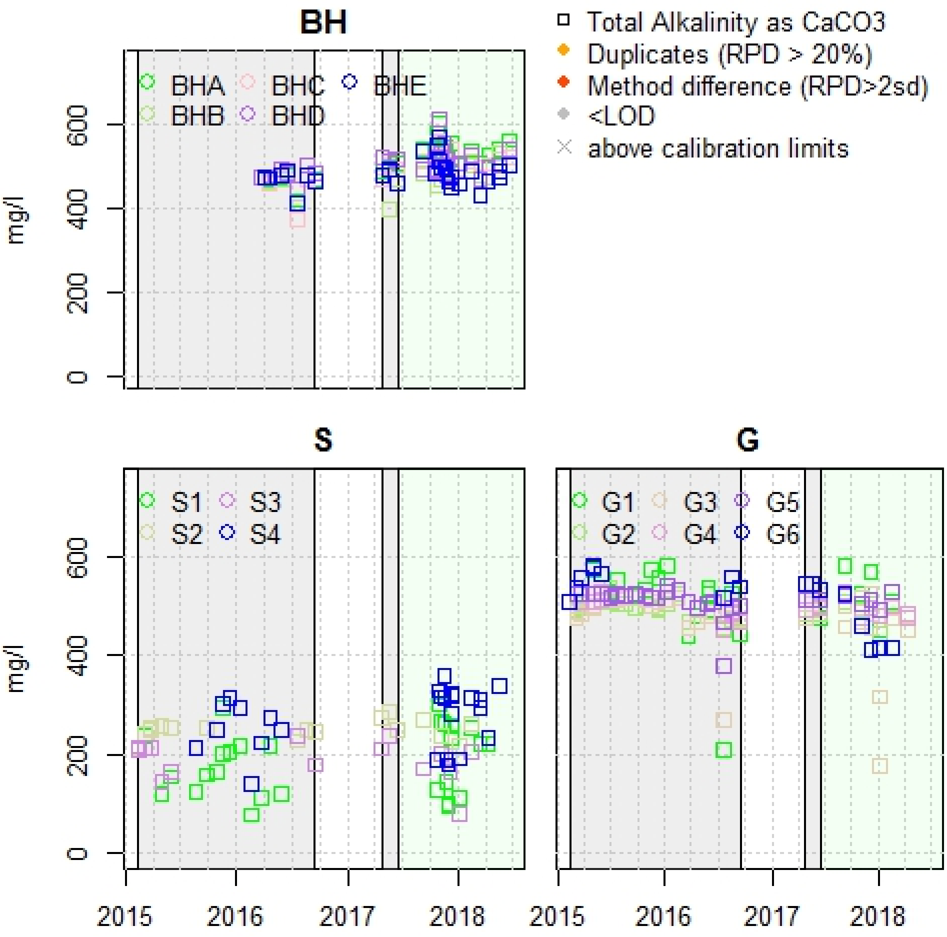
Off-site boreholes



Surface waters



2. *Grouped time series*



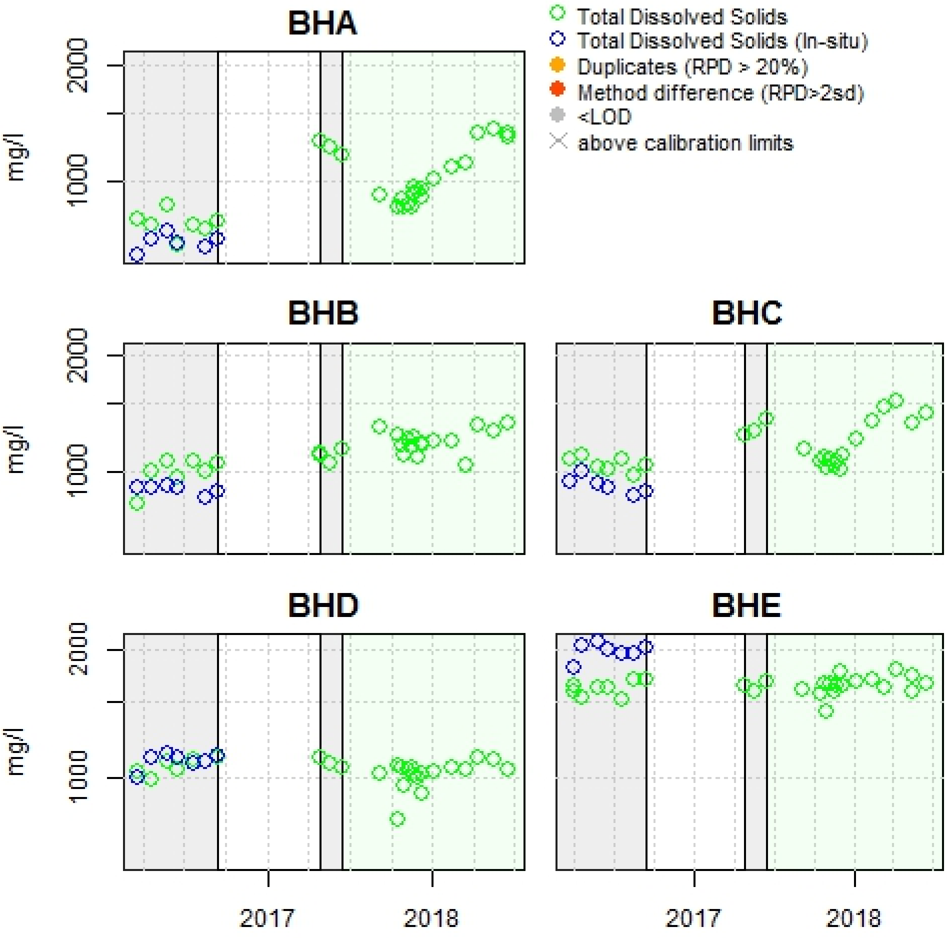
Electrical conductivity

See Section 2.7

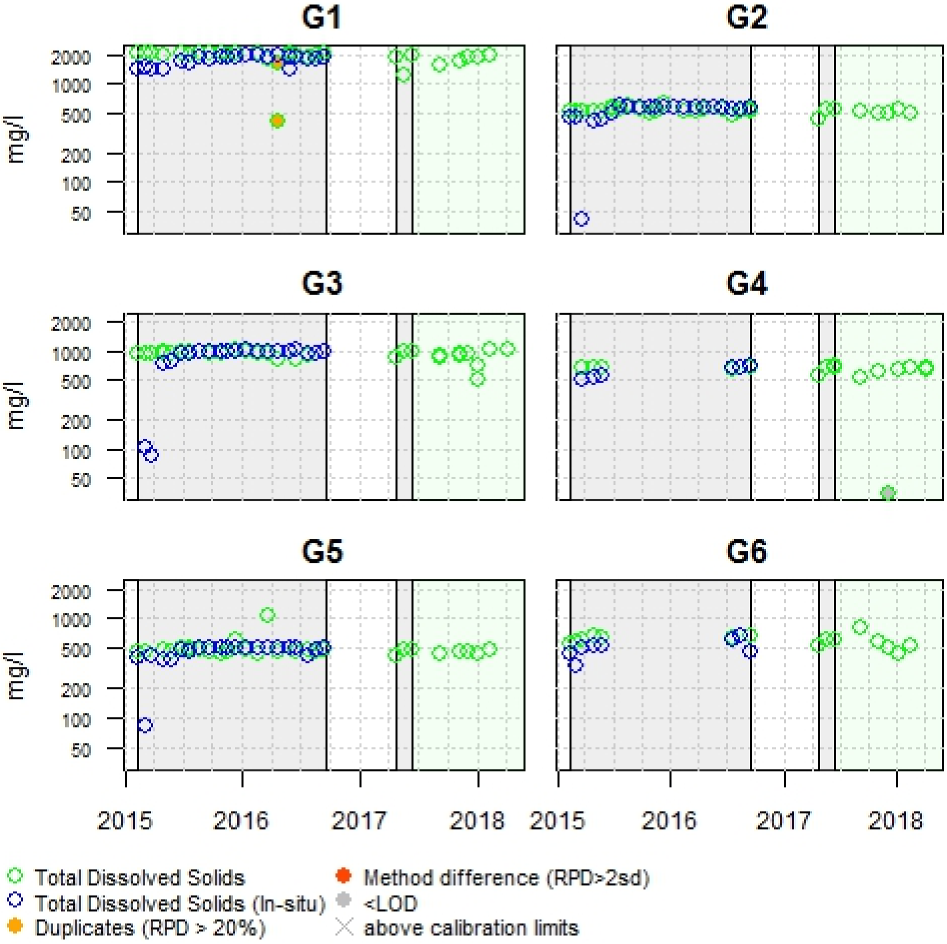
Total dissolved solids

1. Individual site time series

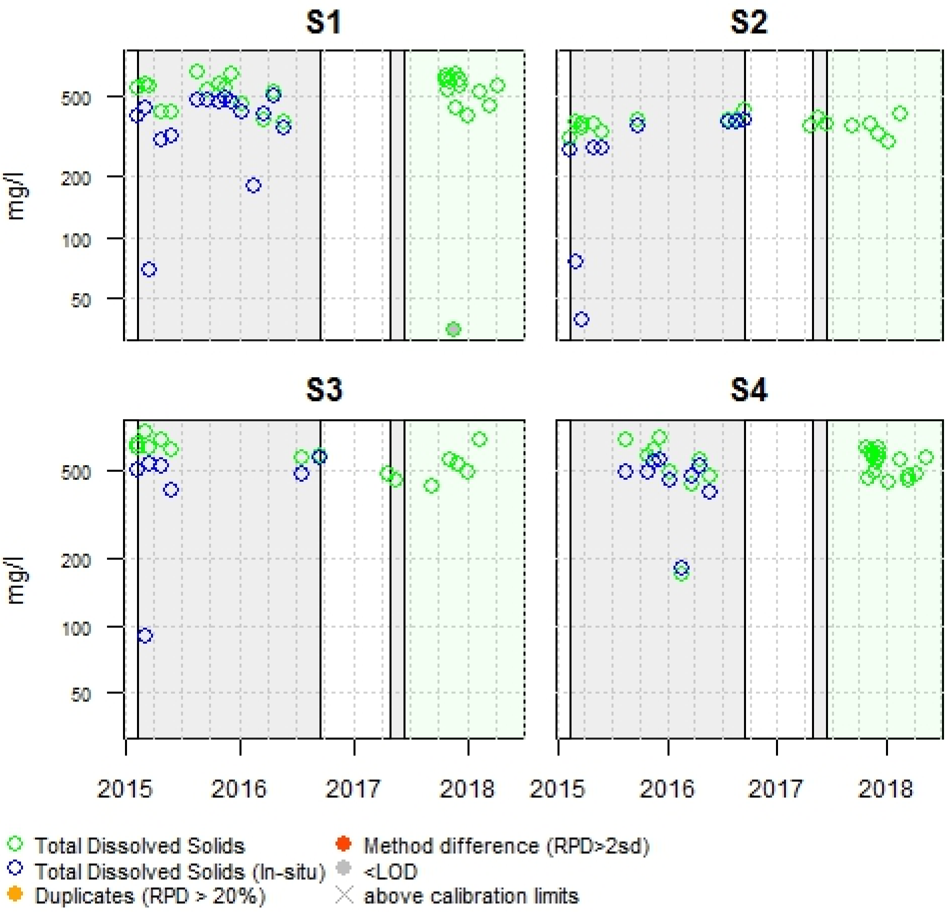
On-site boreholes



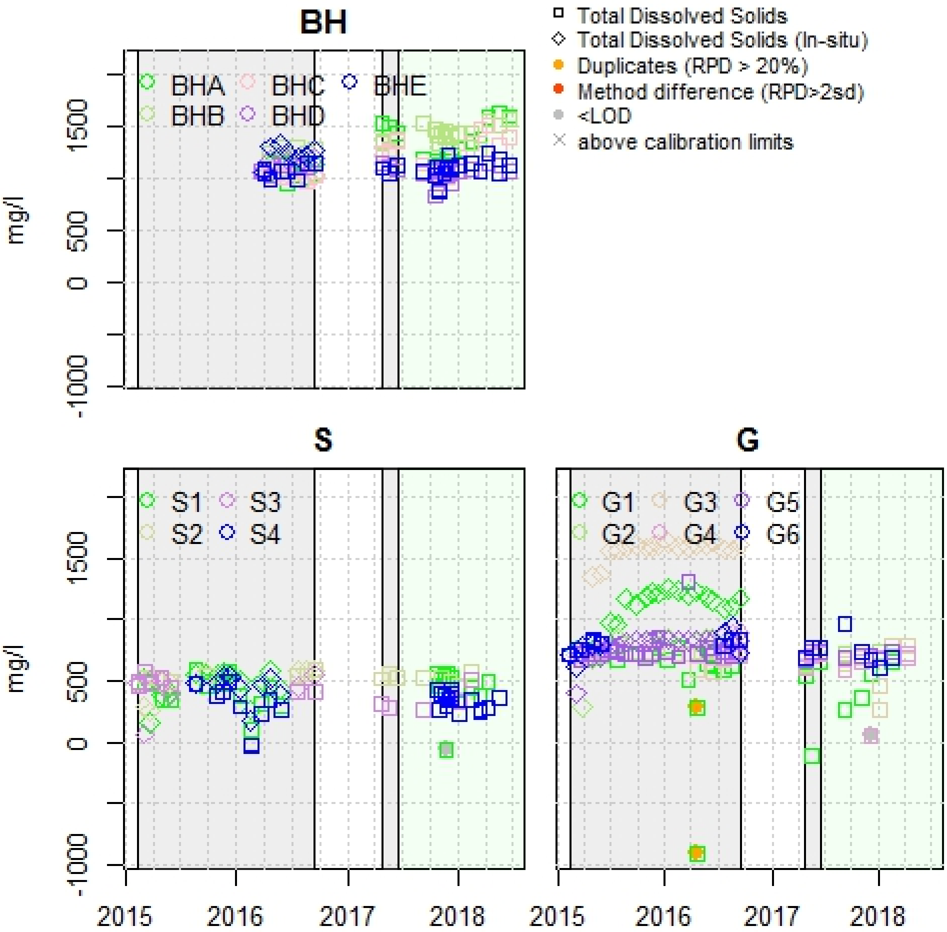
Off-site boreholes



Surface waters



2. *Grouped time series*



A2.1.2. Determinands with majority of values less than the LOD

GRO (>C4-C12)

1. Time series

All values, at all sites, through time are all less than the LOD for this parameter, and therefore time series here do not help to interpret the analysis.

2. Tabular summary

The limits of detection, associated date ranges, and counts of the associated measurements are shown in Table A2.4. At most sites, the LOD used was 10 µg/l, though at some sites on a small selection of dates, a lower value of 5 µg/l was used. For baseline purposes, it may be stated that GRO (>C4-C12) has a baseline value of <10 µg/l across local and regional groundwater and surface waters.

Table A2.4: Limits of detection summary for GRO (>C4-C12). A lower LOD was trialled at the on-site boreholes (5 µg/l) on 14 December 2017, with all values measured beneath this level

Site type (on-site/off-site/surface water)	Site ref	Limit of detection (µg/l)	Start of monitoring (for associated LOD)	End of monitoring (for associated LOD)	Count of observations
On-site borehole	BH-A	10	23 March 2016	18 May 2017	9
	BH-B	10	22 March 2016	17 May 2017	10
	BH-C	10	22 March 2016	18 May 2017	9
	BH-D	10	23 March 2016	18 May 2017	9
	BH-E	10	31 March 2016	18 May 2017	11
Off-site borehole	G1	10	22 March 2016	14 June 2017	10
	G2	10	22 March 2016	14 June 2017	11
	G3	10	22 March 2016	14 June 2017	10
	G4	10	20 July 2016	14 June 2017	8
	G5	10	22 March 2016	14 June 2017	11
	G6	10	20 July 2016	14 June 2017	6
Surface water	S1	5	14 December 2017	14 December 2017	1
		10	22 March 2016	25 May 2016	3
	S2	10	20 July 2016	14 June 2017	6
		5	20 July 2016	1 September 2016	2
	S3	10	24 April 2017	17 May 2017	2
		5	14 December 2017	14 December 2017	2
	S4	10	22 March 2016	25 May 2016	3

Acrylamide

1. Time series

All values, at all sites, through time are all less than the LOD for this parameter, and therefore time series here do not help to interpret the analysis.

2. Tabular summary

The limits of detection used for acrylamide, associated date ranges, and counts of the associated measurements are shown in Table A2.5. For baseline purposes, it may be stated that that acrylamide has a baseline value of <50 µg/l across local and regional groundwaters and surface waters.

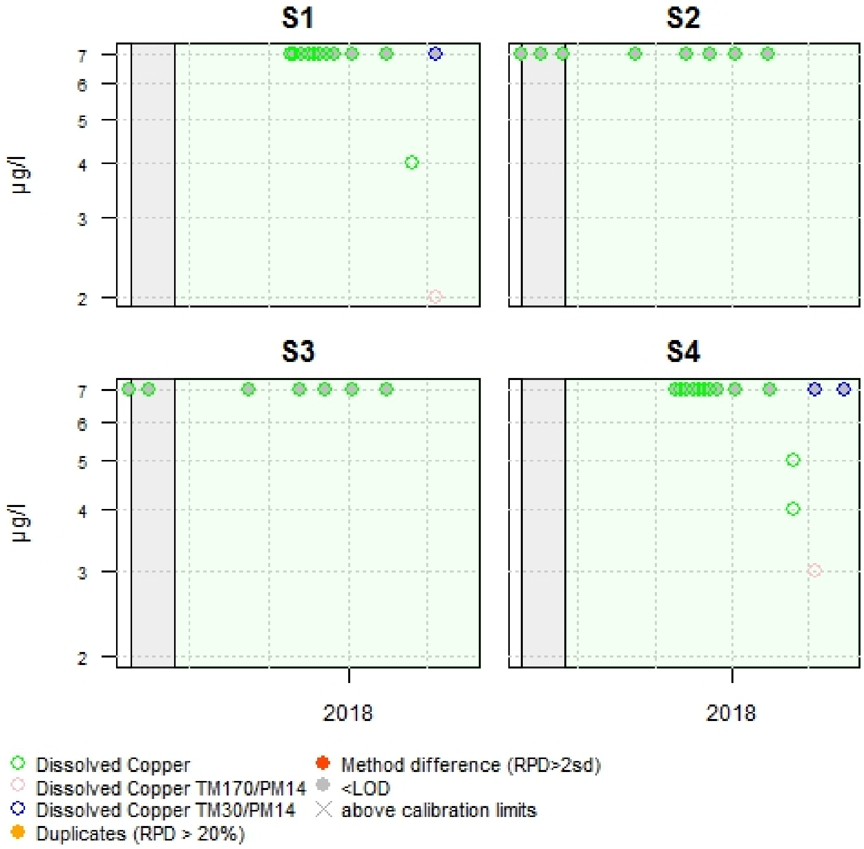
Table A2.5: Limits of detection summary for acrylamide

Site type (on-site/off-site/surface water)	Site ref	Limit of detection (µg/l)	Start of monitoring (for associated LOD)	End of monitoring (for associated LOD)	Count of observations
On-site borehole	BH-A	50	23 March 2016	14 February 2018	20
	BH-B	50	22 March 2016	14 February 2018	20
	BH-C	50	22 March 2016	14 February 2018	19
	BH-D	50	23 March 2016	14 February 2018	20
	BH-E	50	31 March 2016	14 February 2018	21
Off-site borehole	G1	50	24 April 2017	13 February 2018	8
	G2	50	24 April 2017	13 February 2018	8
	G3	50	24 April 2017	13 February 2018	13
	G4	50	24 April 2017	13 February 2018	9
	G5	50	24 April 2017	13 February 2018	8
	G6	50	24 April 2017	13 February 2018	8
Surface water	S1	50	25 October 2017	14 February 2018	12
	S2	50	24 April 2017	13 February 2018	8
	S3	50	24 April 2017	13 February 2018	7
	S4	50	25 October 2017	14 February 2018	12

Copper (dissolved)

1. Time series

Groundwater data not shown. All below the LOD (see tabular summary).



Surface water concentrations of dissolved copper are either at the limit of detection (7 µg/l) or one of 4 observations (4 to 5 µg/l) that are not flagged as being less than the limit of detection but are less than the values of the reported LOD for other time points.

2. Tabular summary

The limits of detection, associated date ranges, and counts of the associated measurements are shown in Table A2.6. At most sites, the LOD used was 7 µg/l, though at some sites on a small selection of dates, a lower value of 1 µg/l was also tested. For baseline purposes, it may be stated that dissolved copper has a baseline value of <7 µg/l across local and regional groundwater and surface waters.

Table A2.6: Limits of detection summary for dissolved copper. A lower LOD was trialled at the on-site boreholes (1 µg/l) on 14 March 2018 and 10 April 2018, with all values measured beneath this level

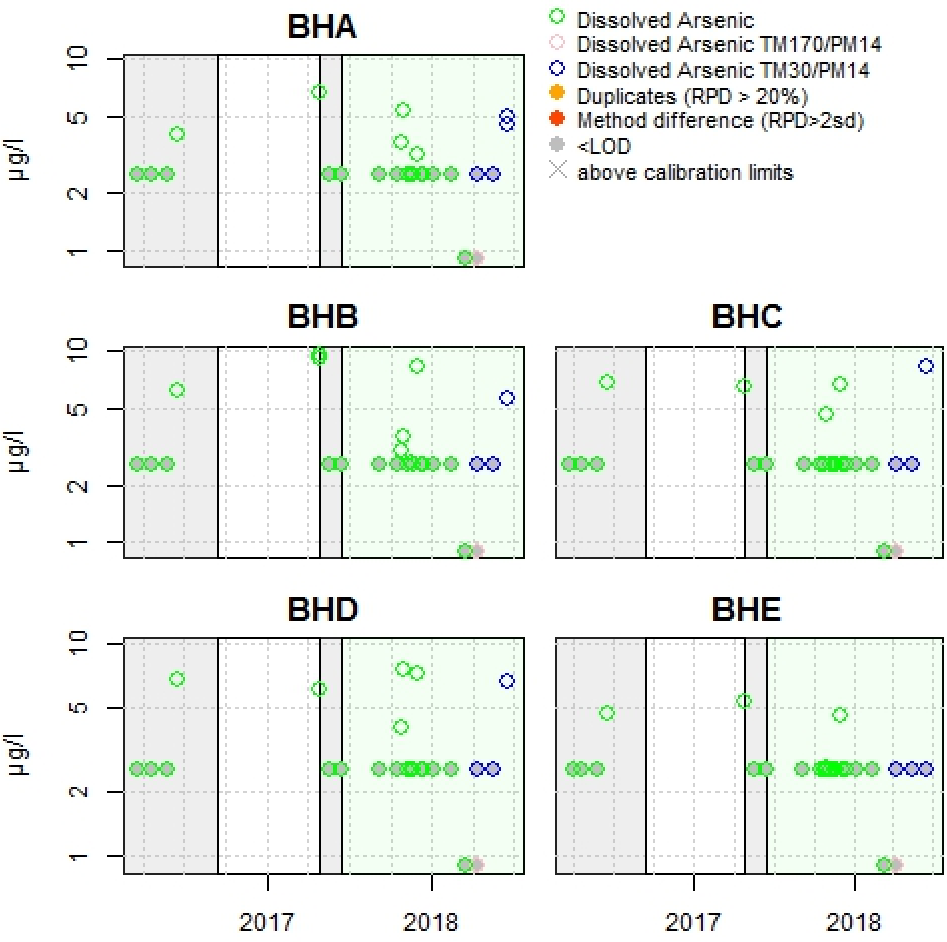
Site type (on-site/ off-site/ surface water)	Site ref	Limit of detection (µg/l)	Start of monitoring (for associated LOD)	End of monitoring (for associated LOD)	Count of observations
	BH-A	7	23 March 2016	18 June 2018	24

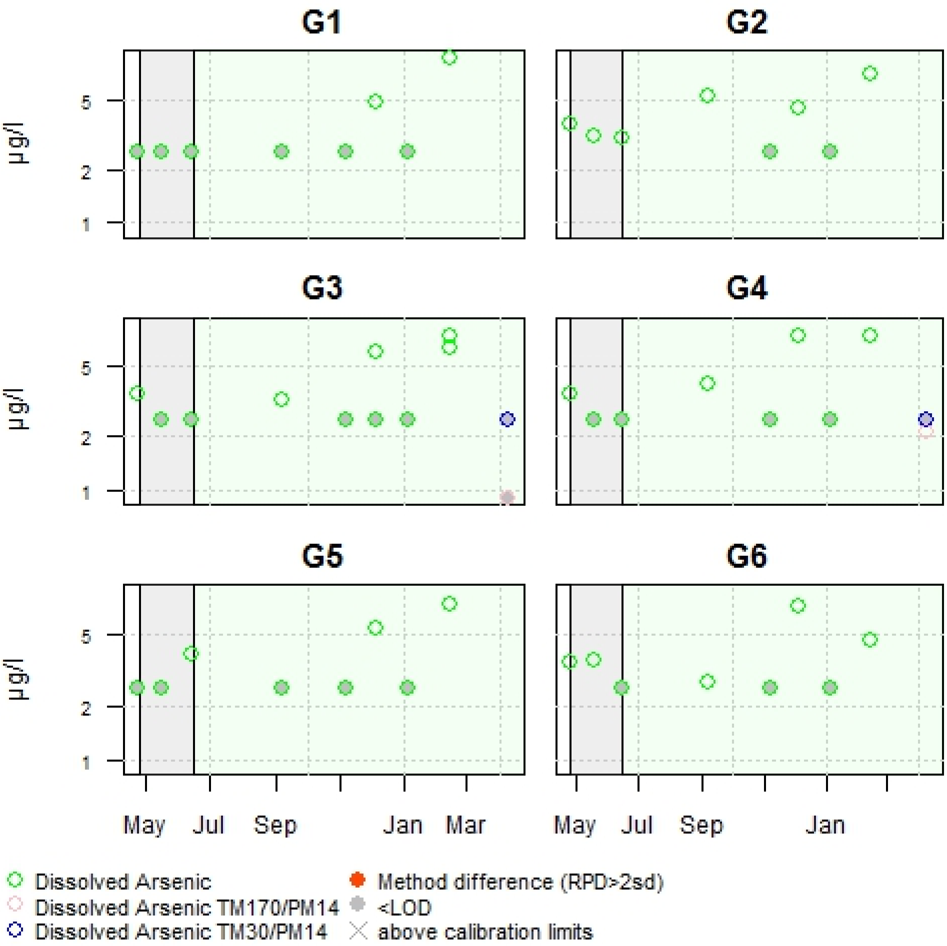
Site type (on-site/ off-site/ surface water)	Site ref	Limit of detection (µg/l)	Start of monitoring (for associated LOD)	End of monitoring (for associated LOD)	Count of observations
On-site borehole	BH-B	7	22 March 2016	18 June 2018	23
	BH-C	7	22 March 2016	18 June 2018	22
	BH-D	7	23 March 2016	18 June 2018	23
	BH-E	7	31 March 2016	18 June 2018	25
Off-site borehole	G1	7	24 April 2017	13 February 2018	8
	G2	7	24 April 2017	13 February 2018	8
	G3	7	24 April 2017	10 April 2018	14
		7	24 April 2017	10 April 2018	11
	G4	7	24 April 2017	13 February 2018	8
	G5	7	24 April 2017	13 February 2018	8
	G6	7	25 October 2017	10 April 2018	13
Surface water	S1	7	24 April 2017	13 February 2018	8
	S2	7	24 April 2017	13 February 2018	7
	S3	7	25 October 2017	15 May 2018	14
	S4	7	24 April 2017	10 April 2018	11

Arsenic (dissolved)

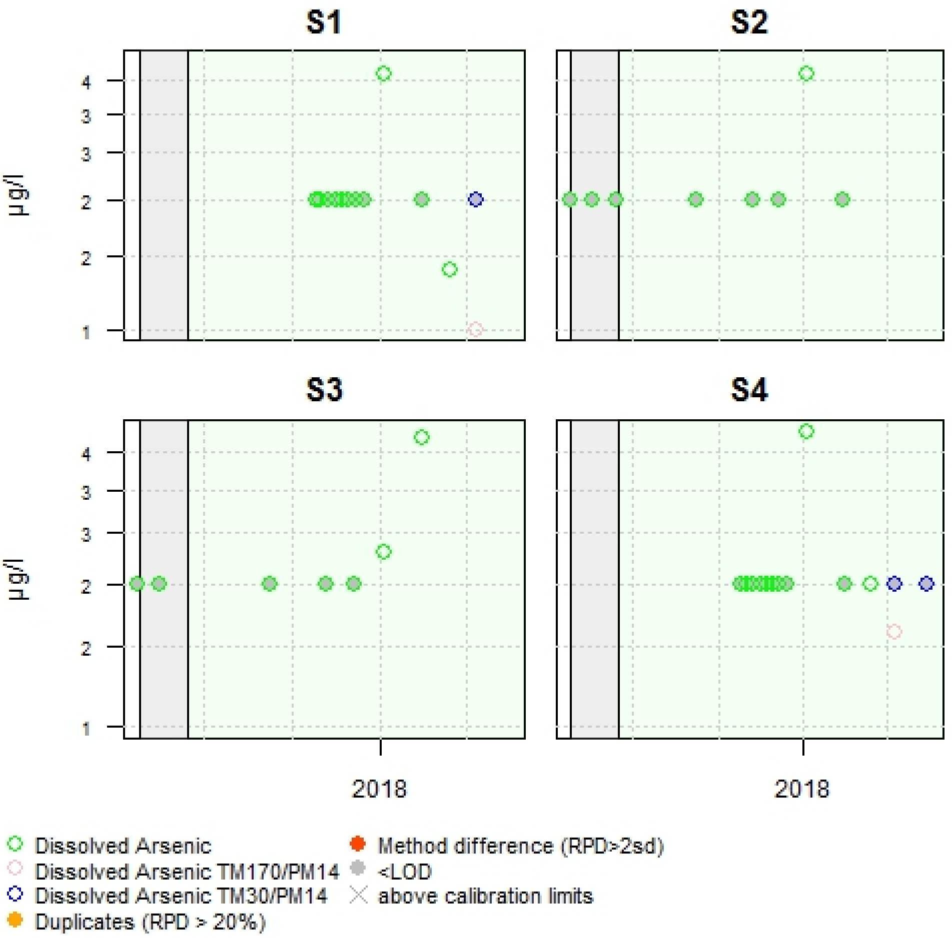
1. Time series

Concentrations of dissolved arsenic are between the limit of detection (2.5 µg/l) and 10 µg/l at all surface water sites. A lower limit of detection was tested, which indicated value concentrations may drop below 1 µg/l. There does not appear to be any apparent trends. Baseline should be characterised from summary statistics LODs taken at half value. Any future change in the LOD should incorporate a similar assumption for direct comparison with baseline (that is, all values <2.5 µg/l should be assumed to have a value of 1.25 µg/l in the calculation of summary statistics).


BHA
BHB
BHC
BHD
BHE
µg/l
10
5
2
1
2017
2018
Dissolved Arsenic
Dissolved Arsenic TM170/PM14
Dissolved Arsenic TM30/PM14
Duplicates (RPD > 20%)
Method difference (RPD>2sd)
<LOD
above calibration limits



G1
G2
G3
G4
G5
G6
µg/l
5
2
1
May
Jul
Sep
Jan
Mar
Dissolved Arsenic
Dissolved Arsenic TM170/PM14
Dissolved Arsenic TM30/PM14
Method difference (RPD>2sd)
<LOD
above calibration limits



2. Tabular summary

Not applicable for this parameter.

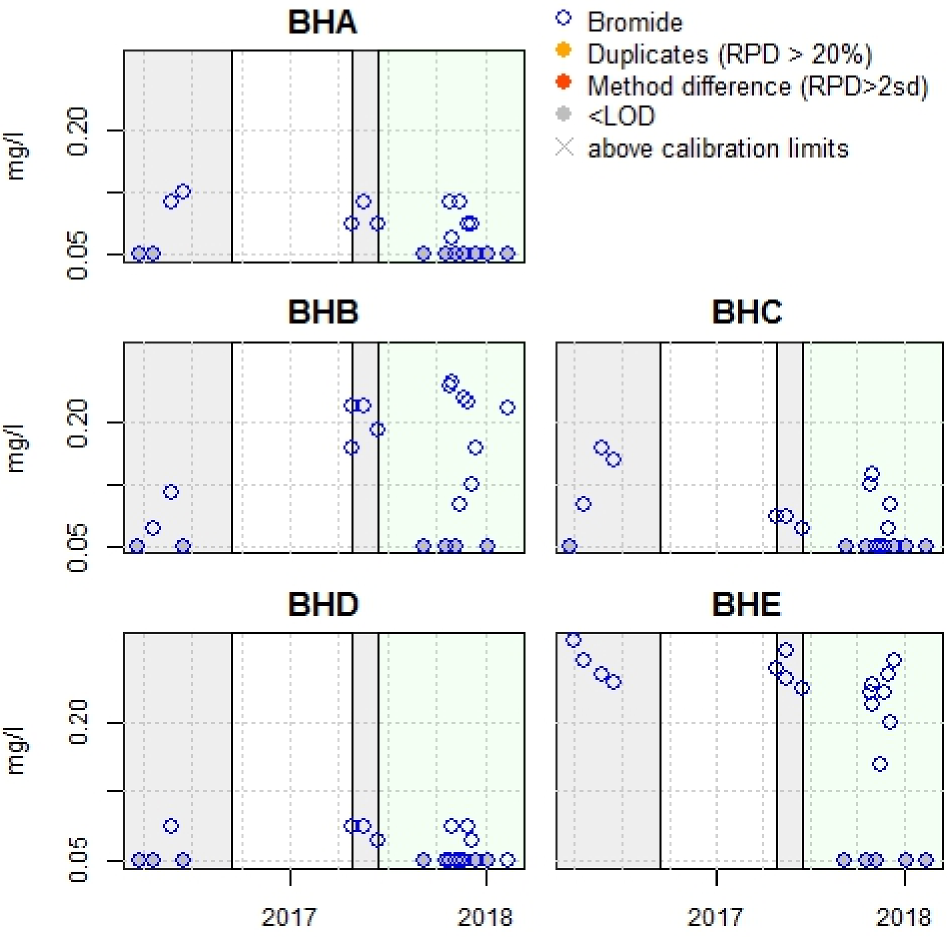
3. Summary statistics

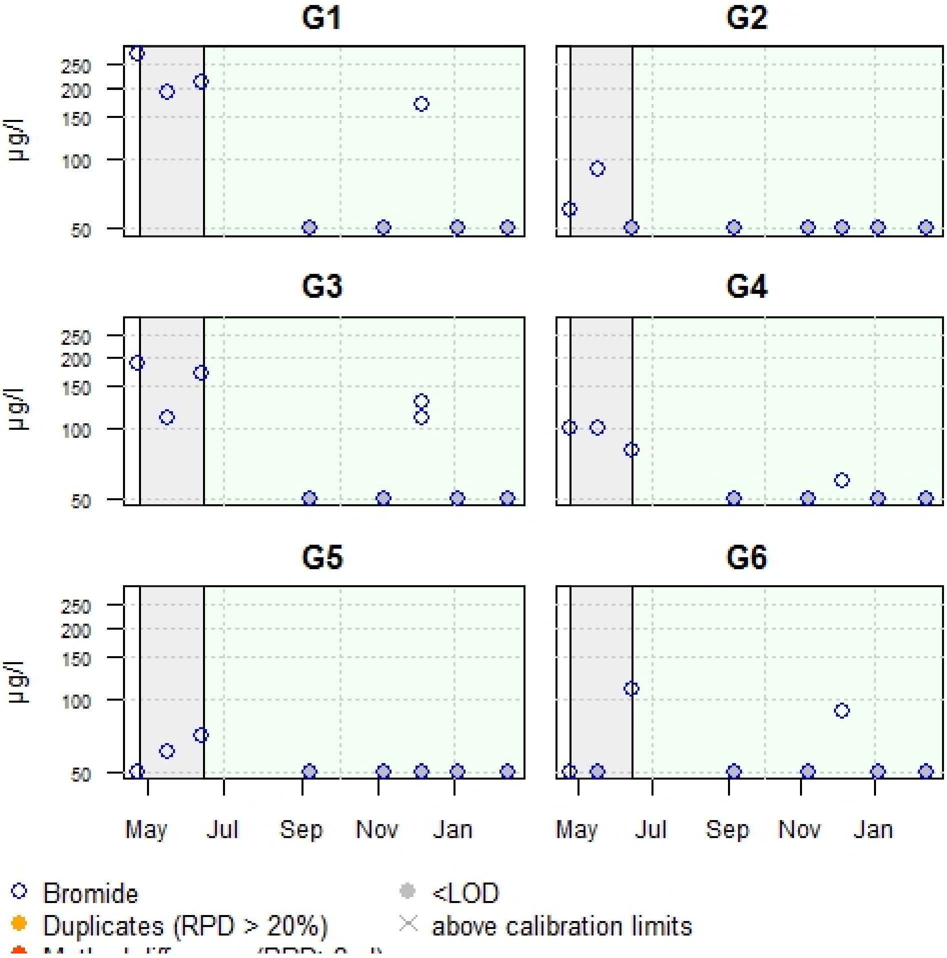
No statistical outliers were identified from the dissolved arsenic data where analysed as a whole, that is all methods with values <LOD assumed to be at the LOD and not taking account of any seasonal effects. This meets expectation from the visual analysis.

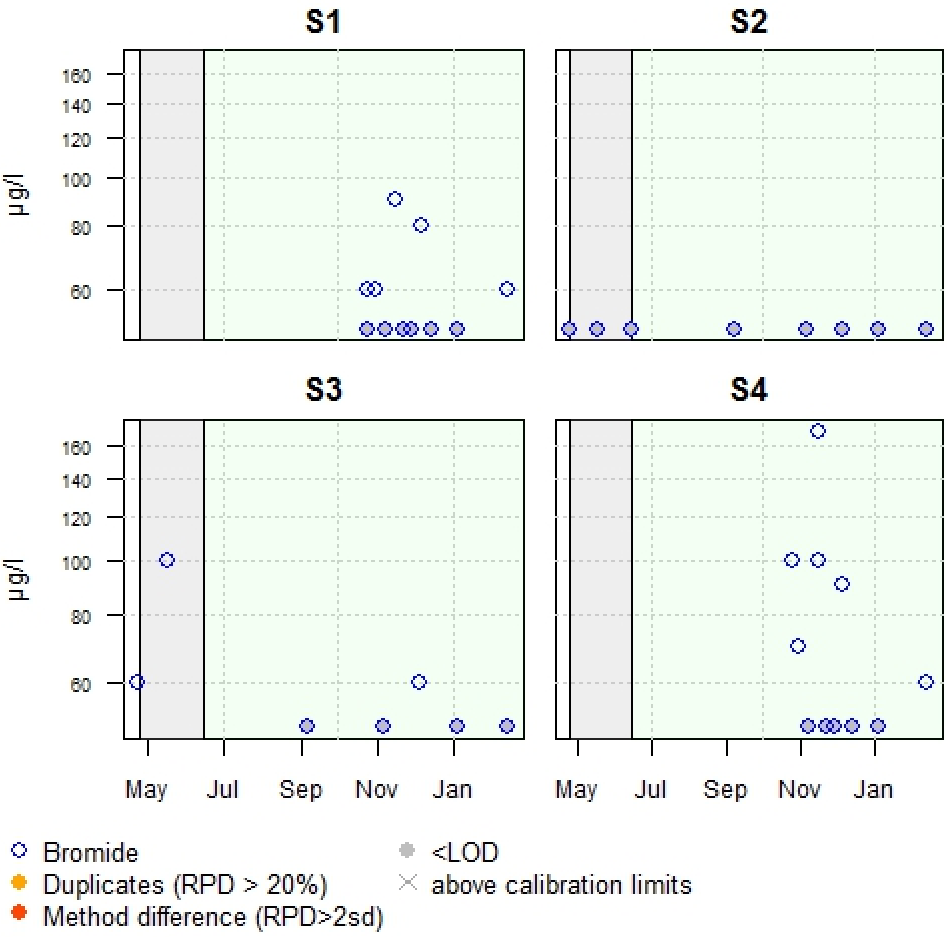
Bromide

1. Time series

Concentrations of dissolved bromide are between the limit of detection (50 µg/l in groundwater) and 500 µg/l. A lower limit of detection was used in surface waters. Only at the off-site boreholes were measurements taken for over a year duration. There does not appear to be any apparent trends. Baseline should be characterised from summary statistics LODs taken at half value. As with arsenic, any future change in the LOD should incorporate a similar assumption for direct comparison with the baseline.


BHA
BHB
BHC
BHD
BHE
mg/l
0.05
0.20
2017
2018
Bromide
Duplicates (RPD > 20%)
Method difference (RPD>2sd)
<LOD
above calibration limits


G1
G2
G3
G4
G5
G6
µg/l
250
200
150
100
50
May
Jul
Sep
Nov
Jan
Bromide
<LOD
Duplicates (RPD > 20%)
above calibration limits



2. Tabular summary

Not applicable for this parameter.

Appendix 3 – Preston New Road air quality baseline data pack

This appendix contains the data presentation pack for measured concentrations of the prioritised substances at the BGS monitoring station at Preston New Road.

Section A3.1: Preston New Road site, BGS monitoring station - nitrogen dioxide

Section A3.2: Preston New Road site, BGS monitoring station - PM_{10}

Section A3.3: Preston New Road site, BGS monitoring station - methane

Section A3.4: Preston New Road site, BGS monitoring station - speciated VOCs

Table A3.1: Preston New Road BGS site information

Aspect	Description for Preston New Road BGS site			
Site location	NGR			
Dates for which data provided	18 August 2017 to 17 August 2018			
Data capture	NO_2	PM_{10}	CH_4	VOC
Site preparation	5 January 2017 to 17 August 2017			
Drilling	17 August 2017 to 1 March 2018 and 1 April 2018 to 14 October 2018			
Hydraulic fracturing	15 October 2018 to 14 December 2018			
Production	2 November 2018 onwards			

A3.1 Preston New Road, BGS site - NO_2

Figure A3.1: Density plot for one year of baseline data for NO_2 (Preston New Road, BGS site)

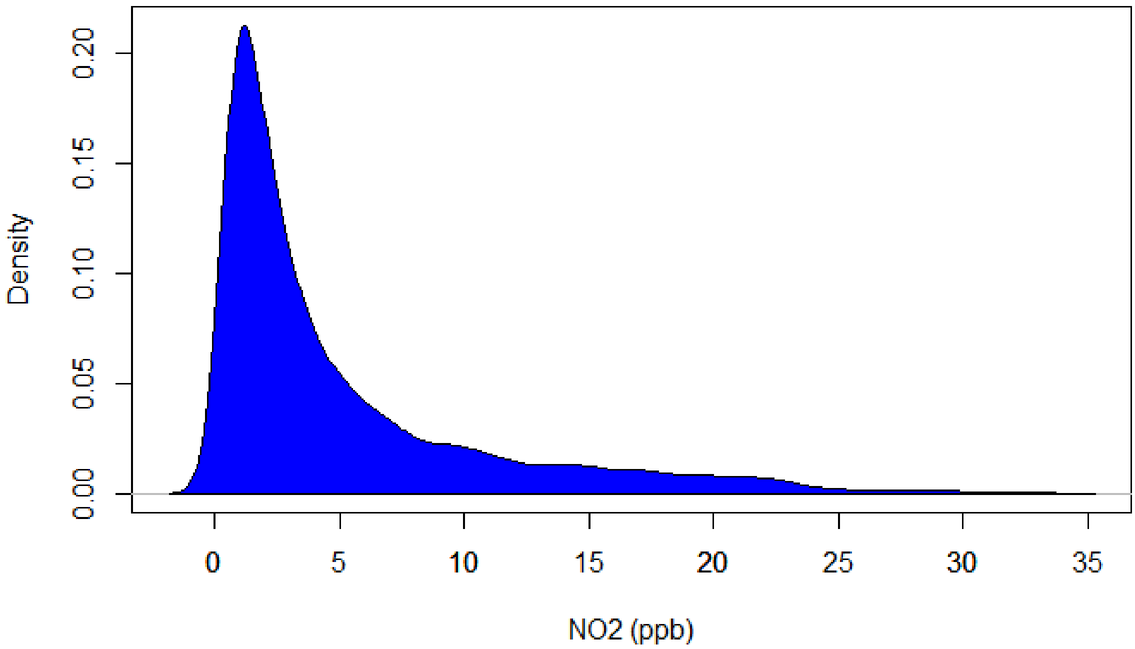


Figure A3.2: Time series for one year baseline data for NO_2 (Preston New Road, BGS site)

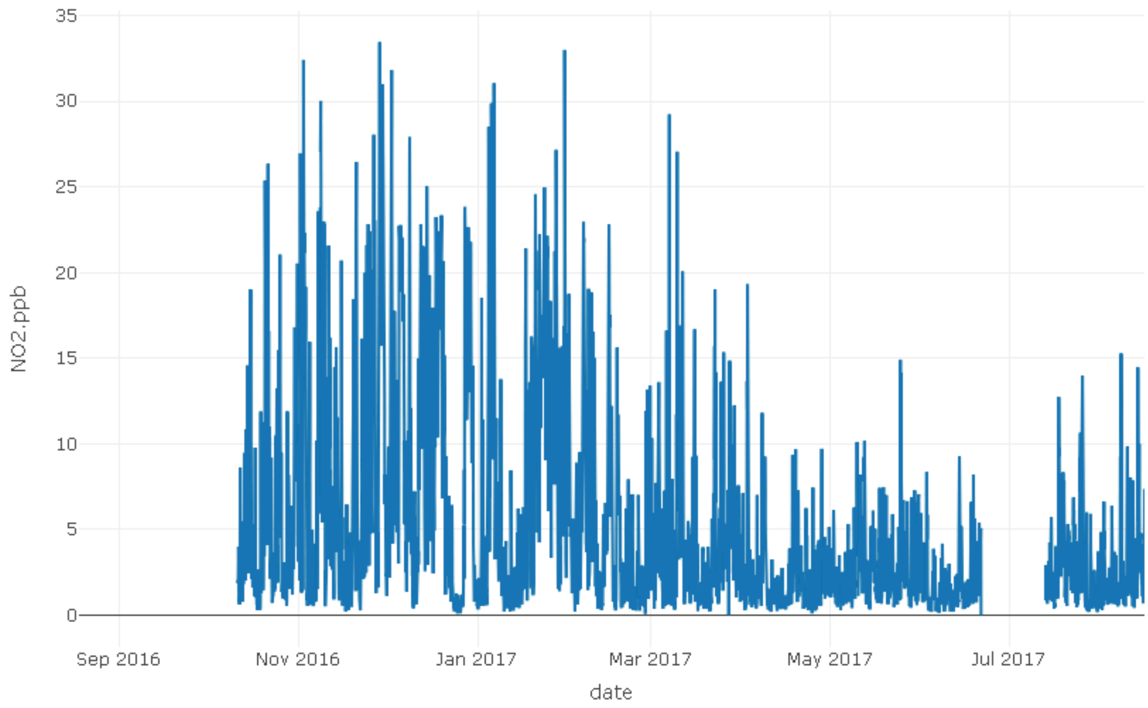


Figure A3.3: Time series plot of different percentiles for one year of baseline data for NO_2 (Preston New Road, BGS site)

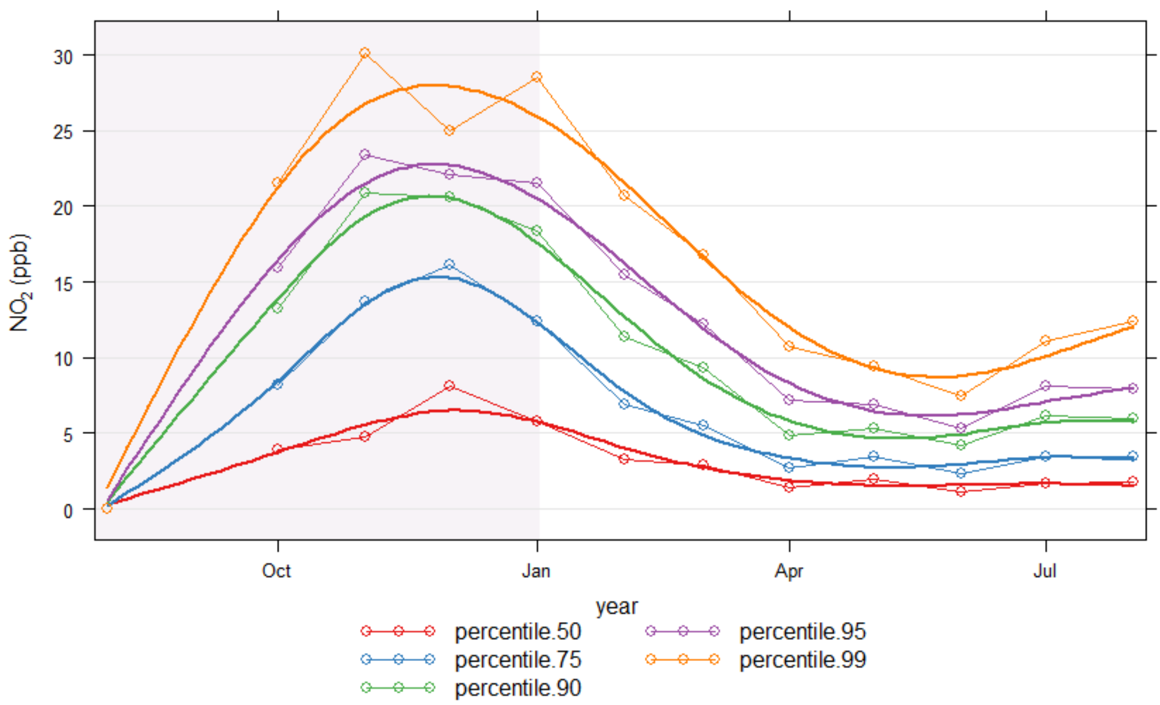


Figure A3.4: Time variation plot for one year of baseline data for NO_2 (Preston New Road, BGS site)

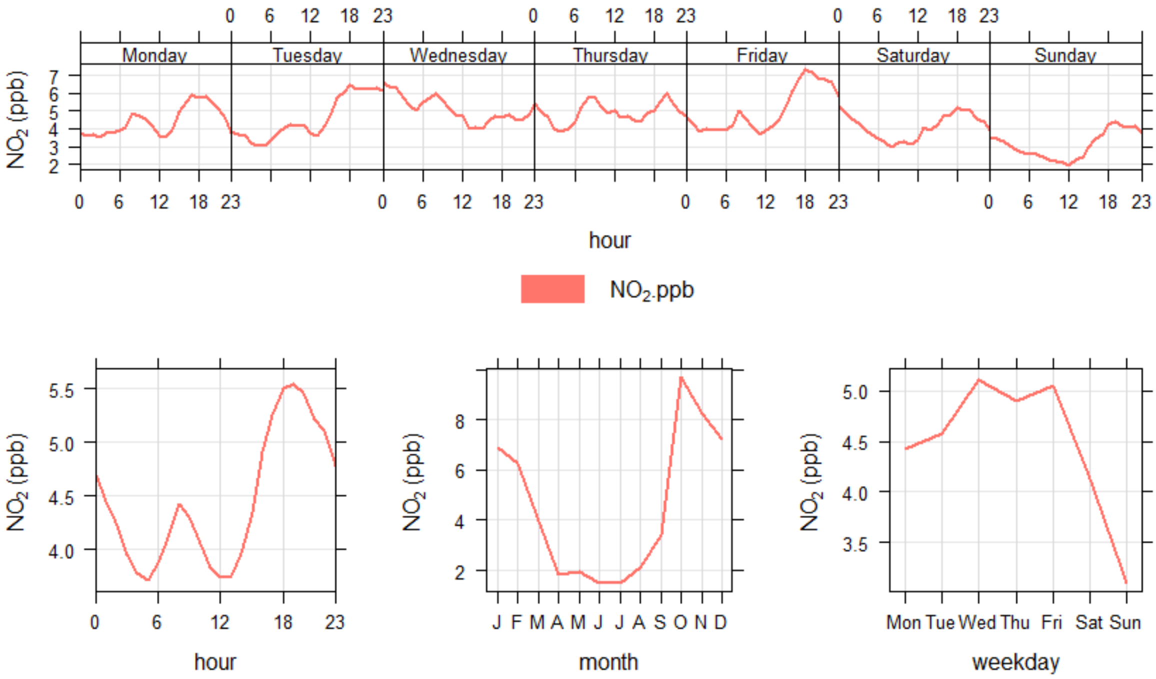


Table A3.2: Summary statistics for one year of baseline data for NO_2 (Preston New Road, BGS site)

Metric	NO2.ppb
Mean	5.06
50%	2.70
75%	6.54
90%	13.82
95%	18.28
99%	24.24
99.8%	29.66

Figure A3.5: Conditional probability plot between the 75th and 90th percentiles for one year of baseline data for NO_2 (Preston New Road, BGS site)

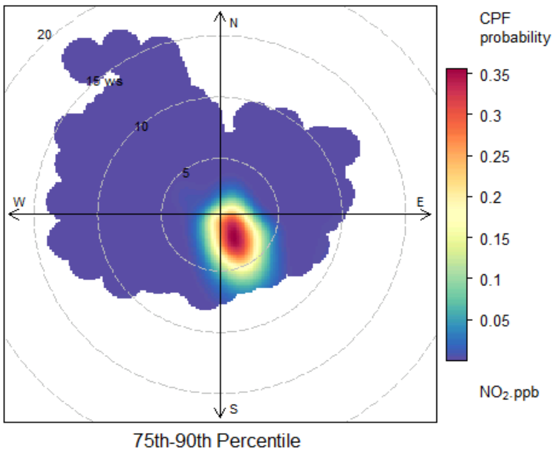


Figure A3.6: Conditional probability plot between the 90th and 95th percentiles for one year of baseline data for NO_2 (Preston New Road, BGS site)

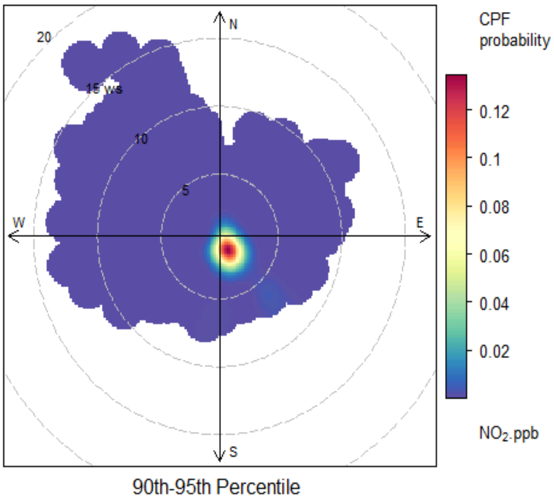


Figure A3.7: Conditional probability plot between the 95th and 99th percentiles for one year of baseline data for NO_2 (Preston New Road, BGS site)

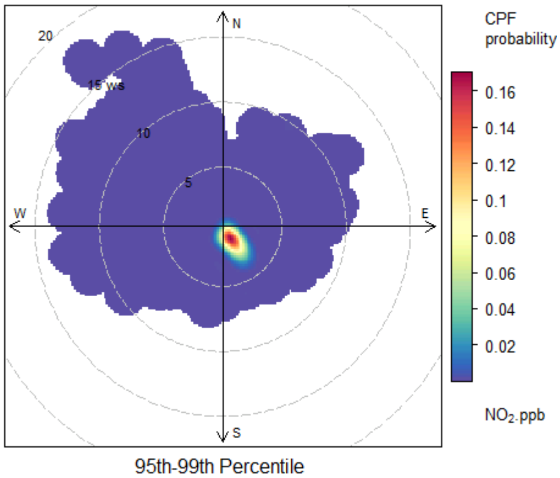


Figure A3.8: Conditional probability plot between the 99th and 100th percentiles for one year of baseline data for NO_2 (Preston New Road, BGS site)

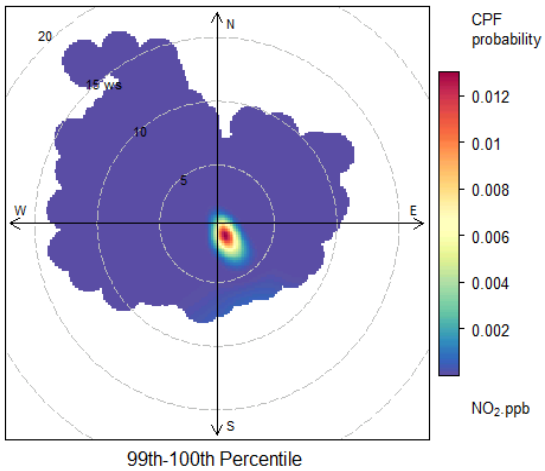


Figure A3.9: Polar plot of the mean concentration for one year of baseline data for NO_2 (Preston New Road, BGS site)

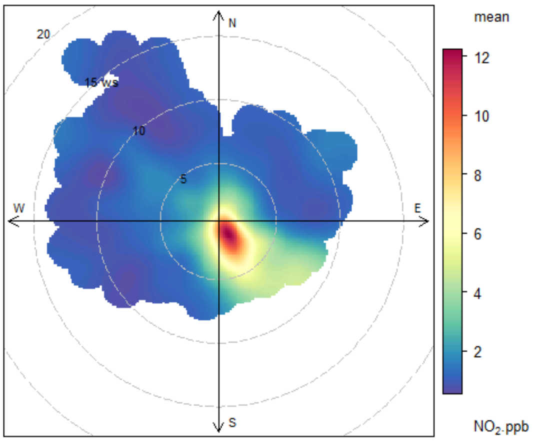


Figure A3.10: Polar plot of the median concentration for one year of baseline data for NO_2 (Preston New Road, BGS site)

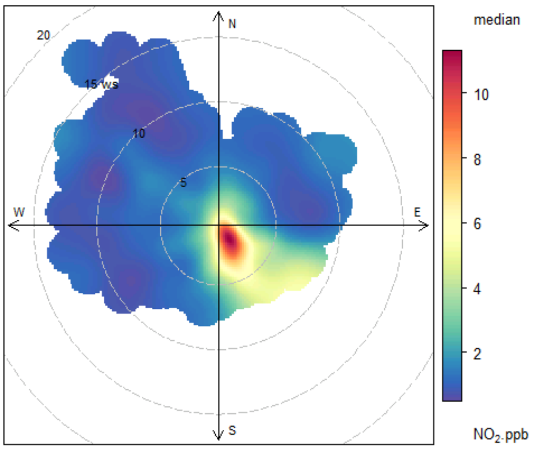


Figure A3.11: Polar plot of the 75th percentile concentration for one year of baseline data for NO_2 (Preston New Road, BGS site)

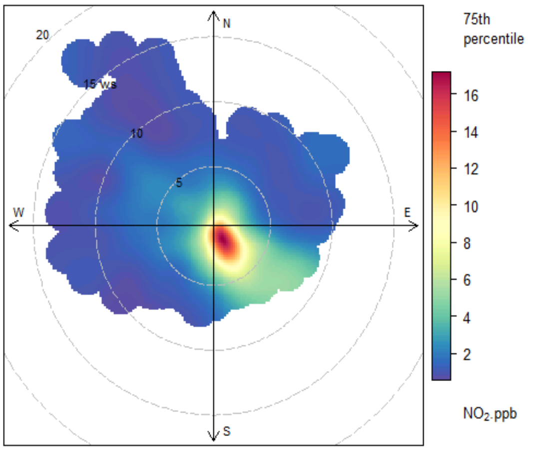


Figure A3.12: Polar plot of the 90th percentile concentration for one year of baseline data for NO_2 (Preston New Road, BGS site)

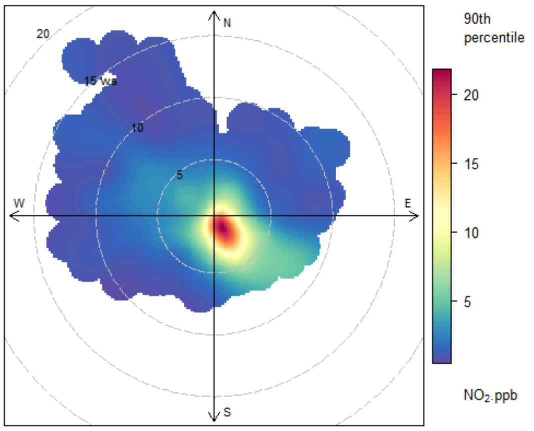


Figure A3.13: Polar plot of the 95th percentile concentration for one year of baseline data for NO_2 (Preston New Road, BGS site)

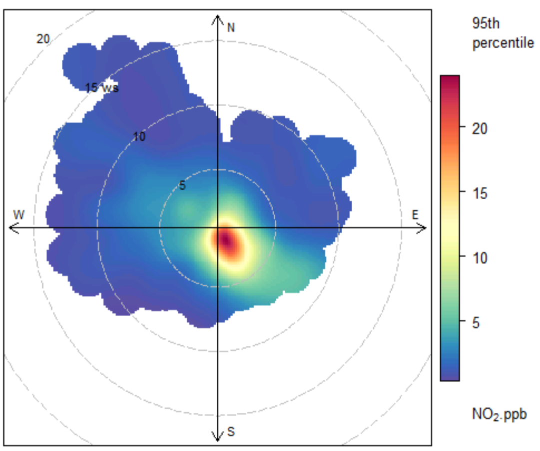


Figure A3.14: Polar plot of the 99th percentile concentration for one year of baseline data for NO_2 (Preston New Road, BGS site)

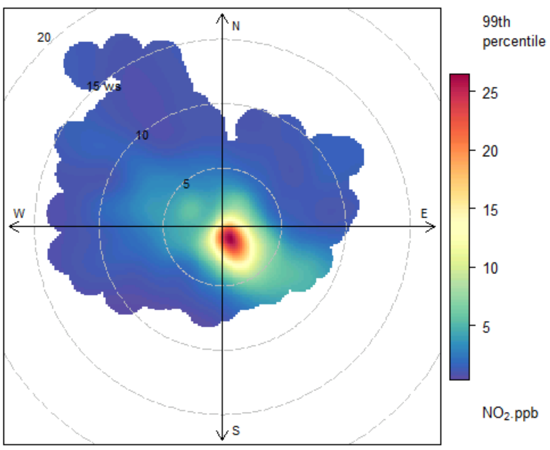


Figure A3.15: Polar plot of the weighted mean (mean/frequency) for one year of baseline data for NO_2 (Preston New Road, BGS site)

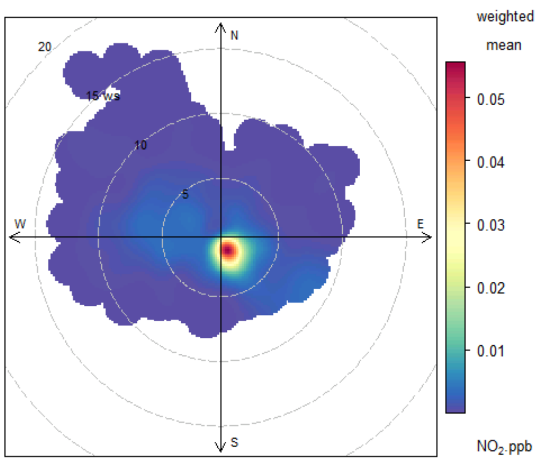


Figure A3.16: Polar frequency plot for one year of baseline data (Preston New Road, BGS site)

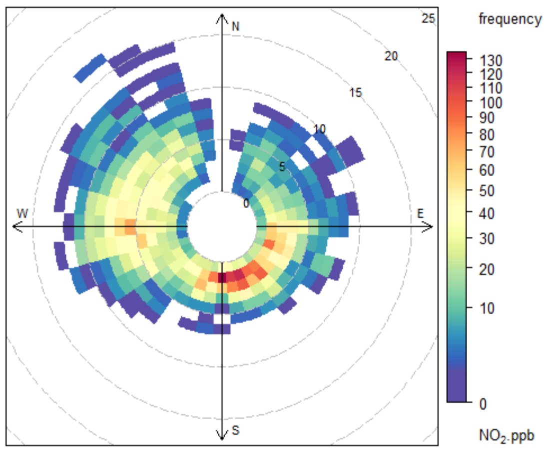
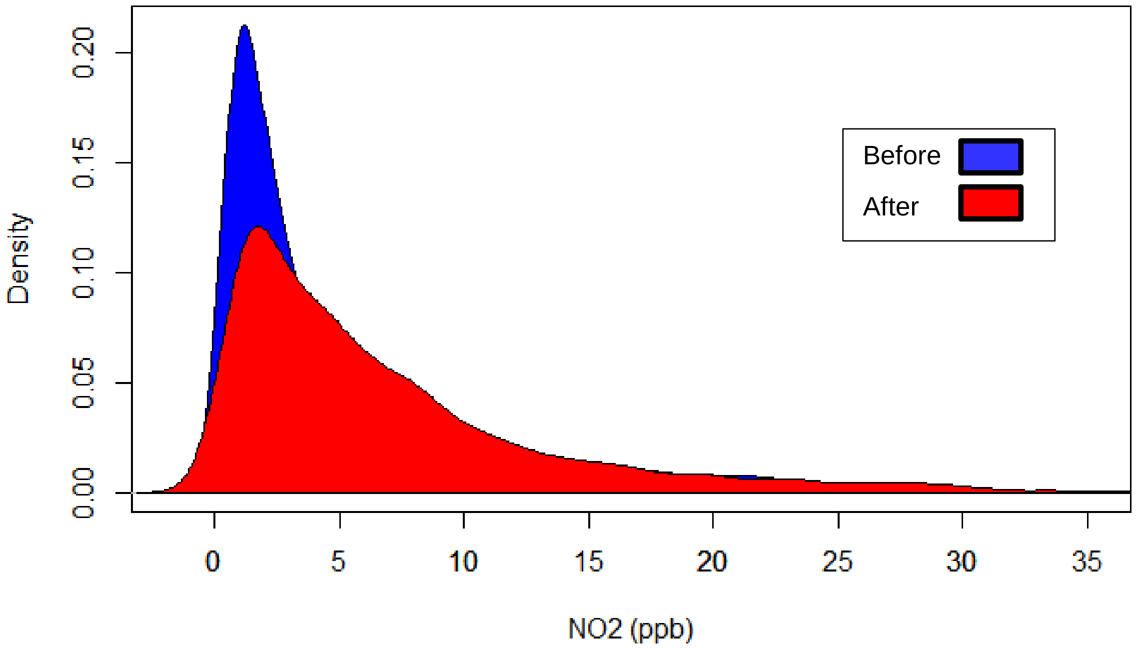


Figure A3.17: Density plot for one year of baseline data for NO_2 (Preston New Road, BGS site) showing before and after site activities began



A3.2 Preston New Road, BGS site - PM_{10}

Figure A3.18: Density plot for one year of baseline data for PM_{10} (Preston New Road, BGS site)

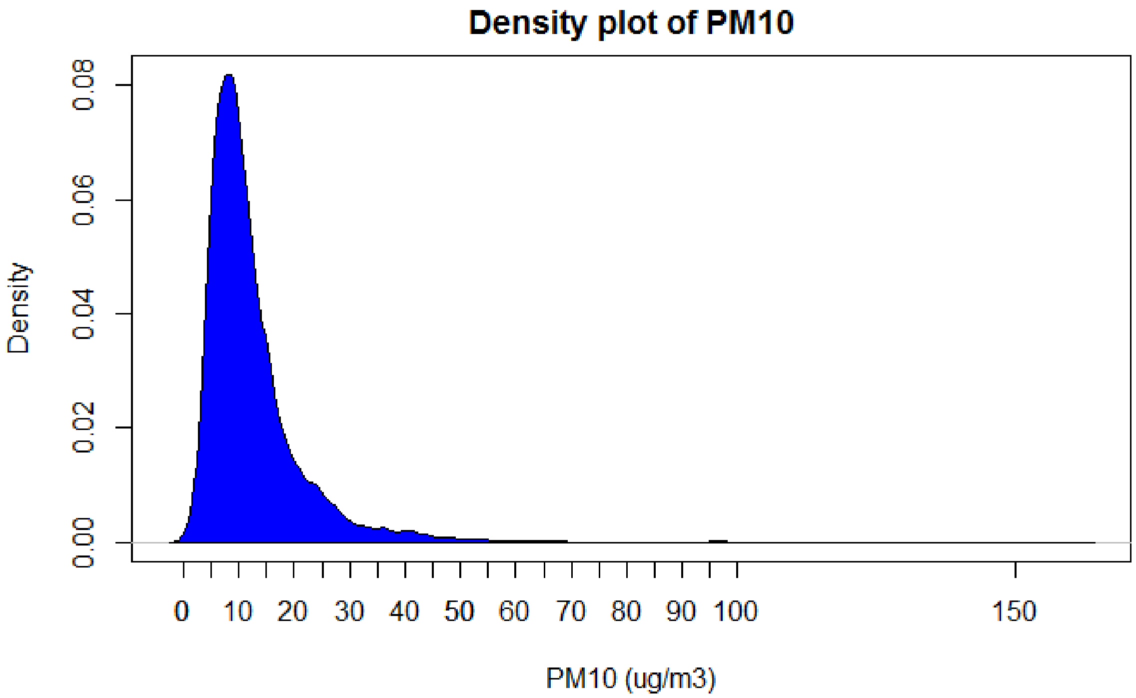


Figure A3.19: Time series for one year baseline data for PM_{10} (Preston New Road, BGS site)

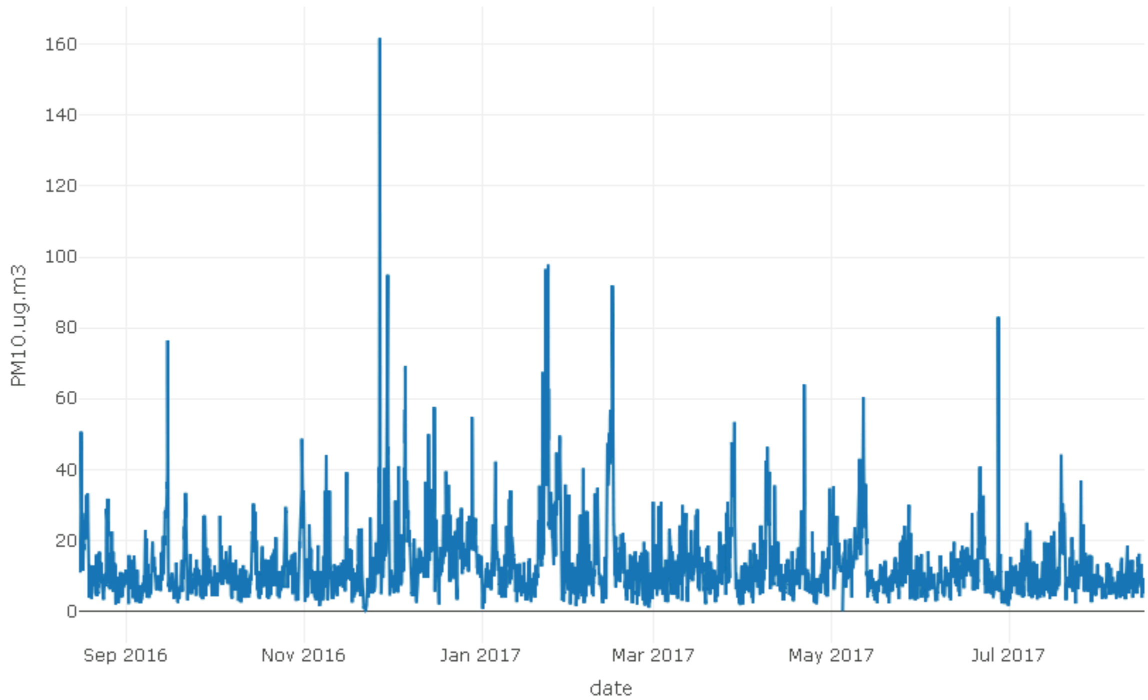


Figure A3.20: Time series plot of different percentiles for one year of baseline data for PM_{10} (Preston New Road, BGS site)

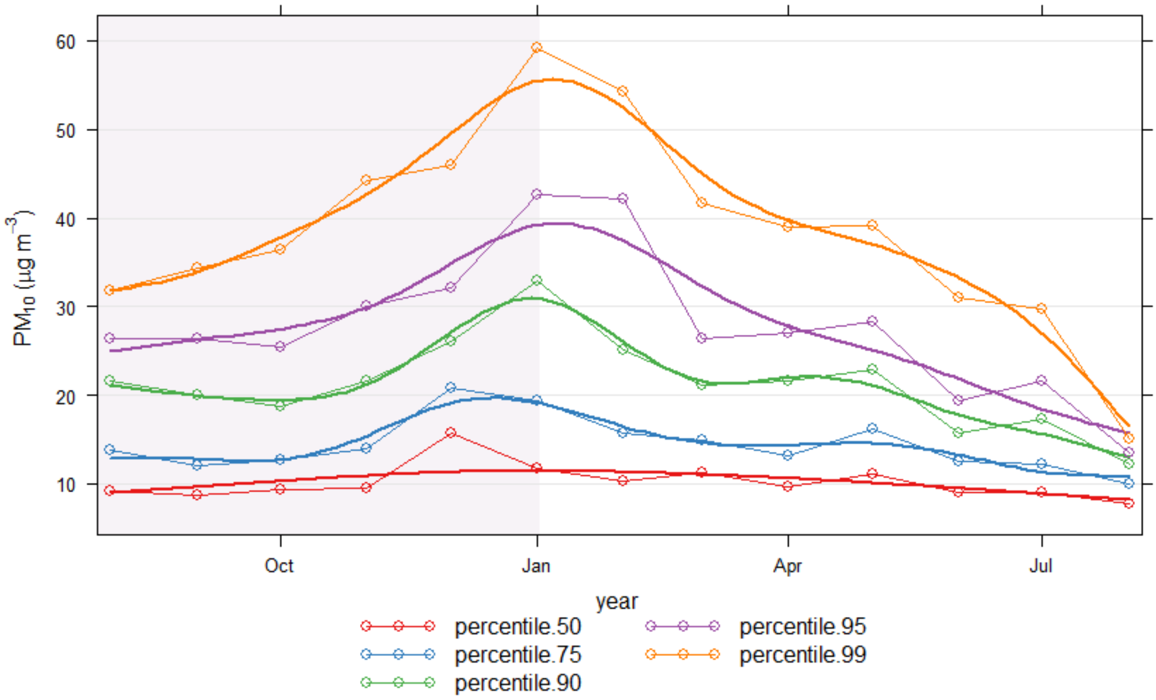


Figure A3.21: Time variation plot for one year of baseline data for PM_{10} (Preston New Road, BGS site)

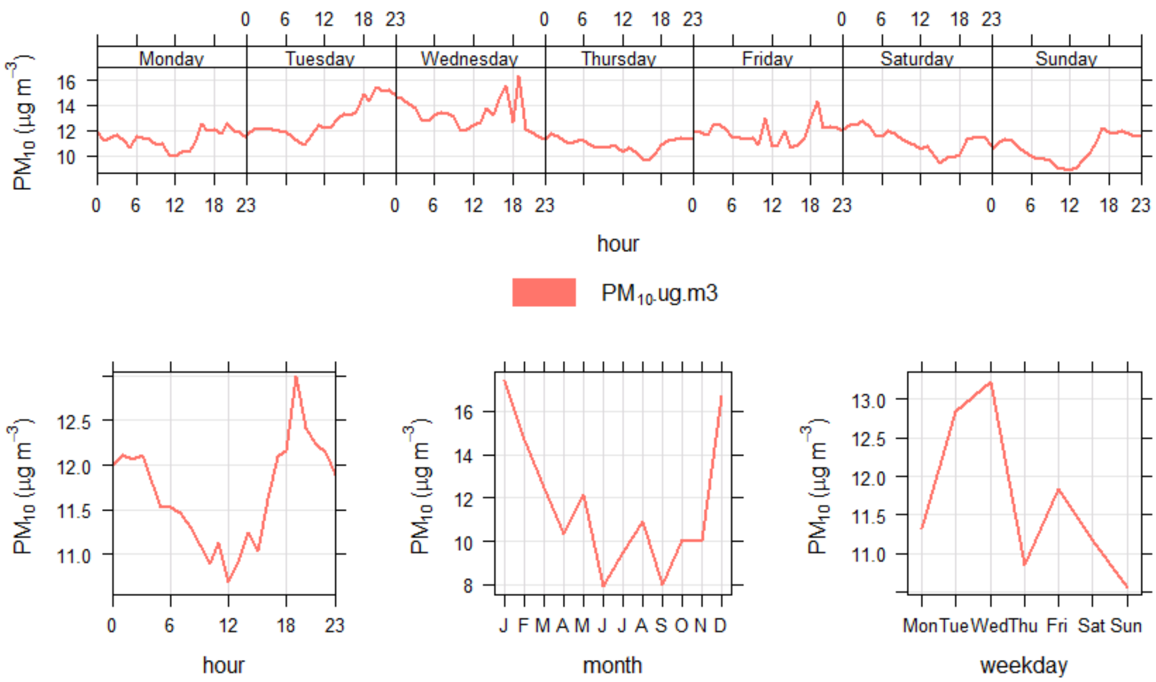


Table A3.3: Summary statistics for one year of baseline data for PM_{10} (Preston New Road, BGS site)

Metric	PM_{10} ug/m3
Mean	12.29
50%	10.01
75%	14.70
90%	22.33
95%	28.25
99%	44.41

Figure A3.22: Conditional probability plot between the 75th and 90th percentiles for one year of baseline data for PM_{10} (Preston New Road, BGS site)

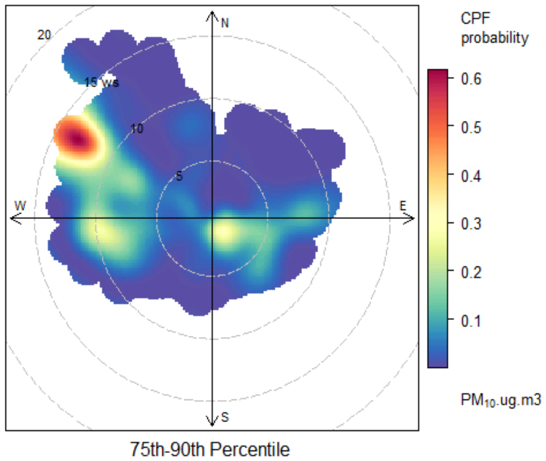


Figure A3.23: Conditional probability plot between the 90th and 95th percentiles for one year of baseline data for PM_{10} (Preston New Road, BGS site)

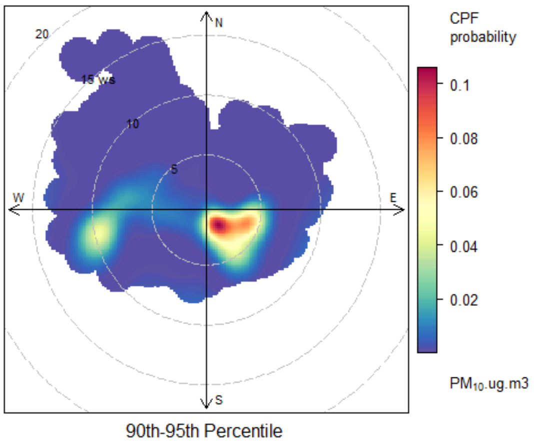


Figure A3.24: Conditional probability plot between the 95th and 99th percentiles for one year of baseline data for PM_{10} (Preston New Road, BGS site)

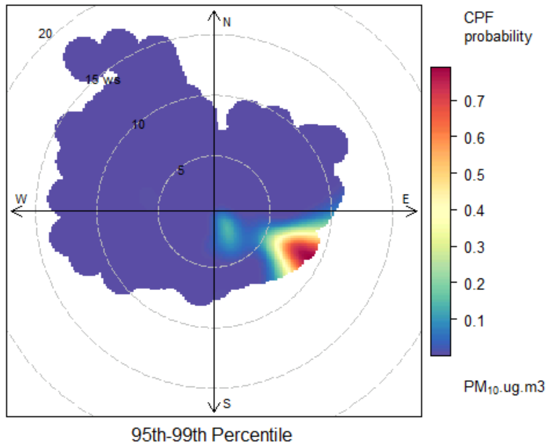


Figure A3.25: Conditional probability plot between the 99th and 100th percentiles for one year of baseline data for PM_{10} (Preston New Road, BGS site)

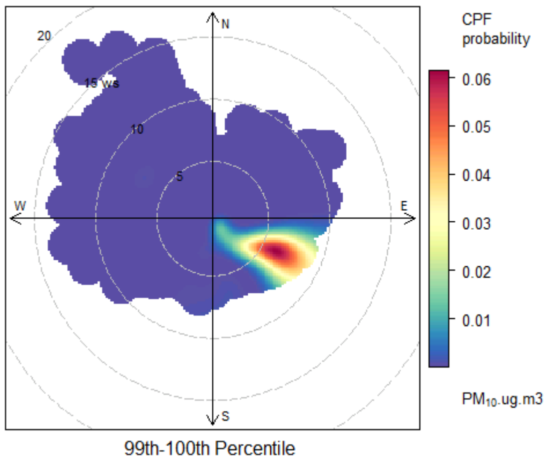


Figure A3.26: Polar plot of the mean concentration for one year of baseline data for PM_{10} (Preston New Road, BGS site)

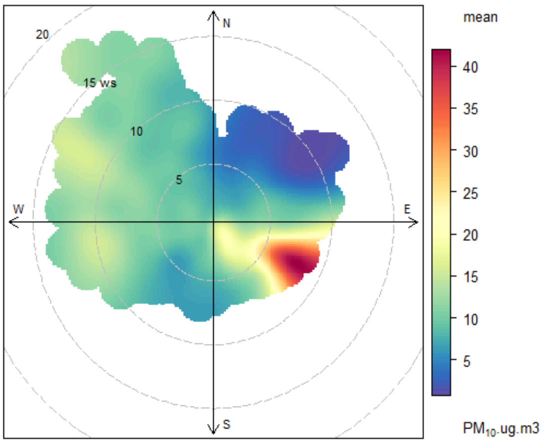


Figure A3.27: Polar plot of the median concentration for one year of baseline data for PM_{10} (Preston New Road, BGS site)

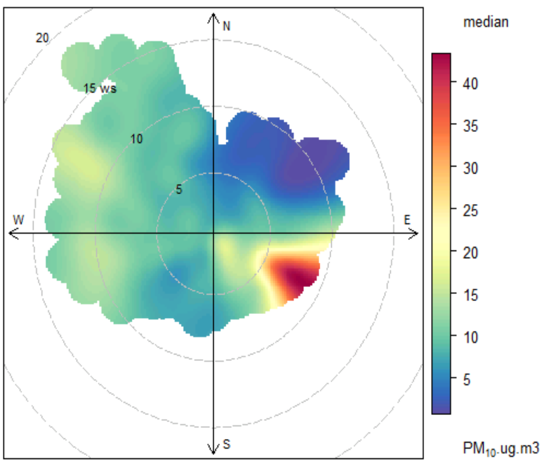


Figure A3.28: Polar plot of the 75th percentile concentration for one year of baseline data for PM_{10} (Preston New Road, BGS site)

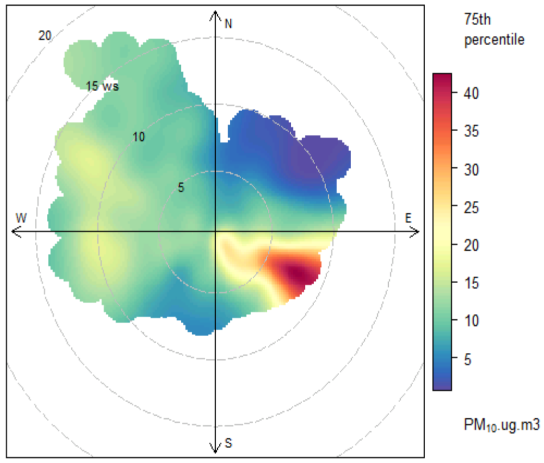


Figure A3.29: Polar plot of the 90th percentile concentration for one year of baseline data for PM_{10} (Preston New Road, BGS site)

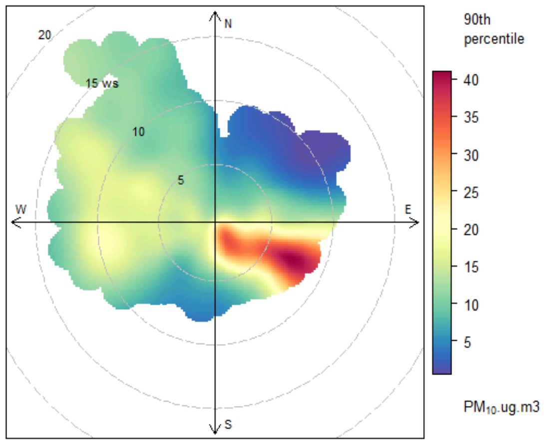


Figure A3.30: Polar plot of the 95th percentile concentration for one year of baseline data for PM_{10} (Preston New Road, BGS site)

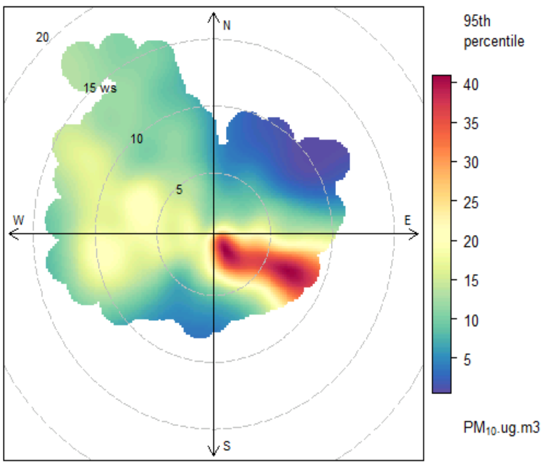


Figure A3.31: Polar plot of the 99th percentile concentration for one year of baseline data for PM_{10} (Preston New Road, BGS site)

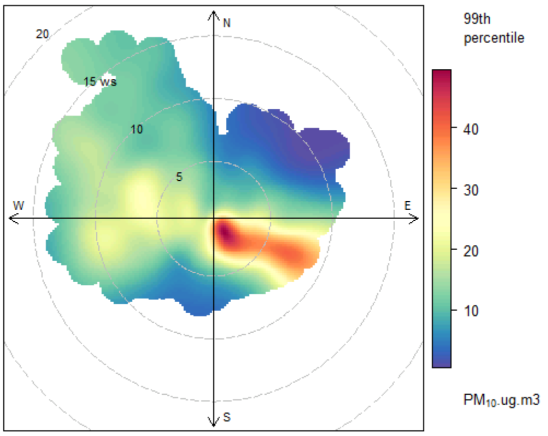


Figure A3.32: Polar plot of the weighted mean (mean/frequency) for one year of baseline data for PM_{10} (Preston New Road, BGS site)

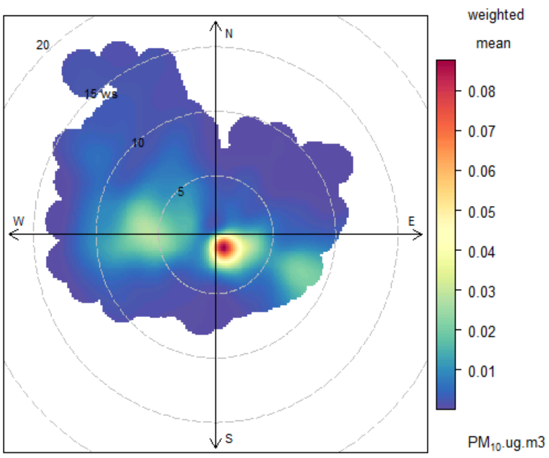
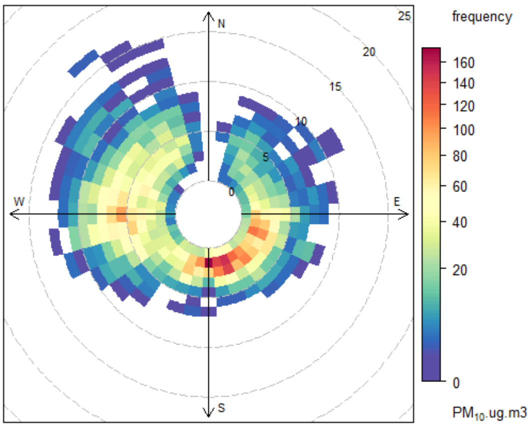


Figure A3.33: Polar frequency plot for one year of baseline data (Preston New Road, BGS site)



A3.3 Preston New Road, BGS site - CH_4

Figure A3.34: Density plot for one year of baseline data for CH_4 (Preston New Road, BGS site)

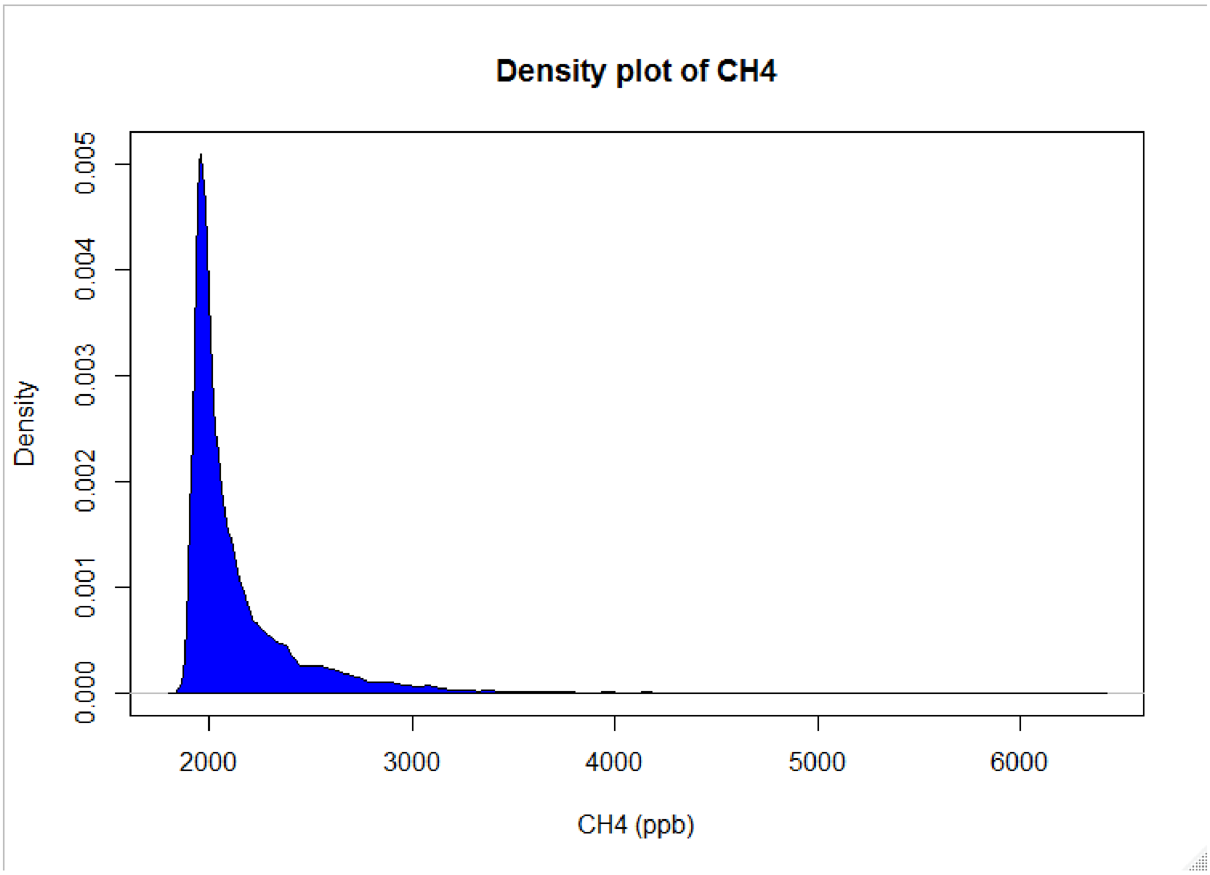


Figure A3.35: Time series for one year baseline data for CH_4 (Preston New Road, BGS site)

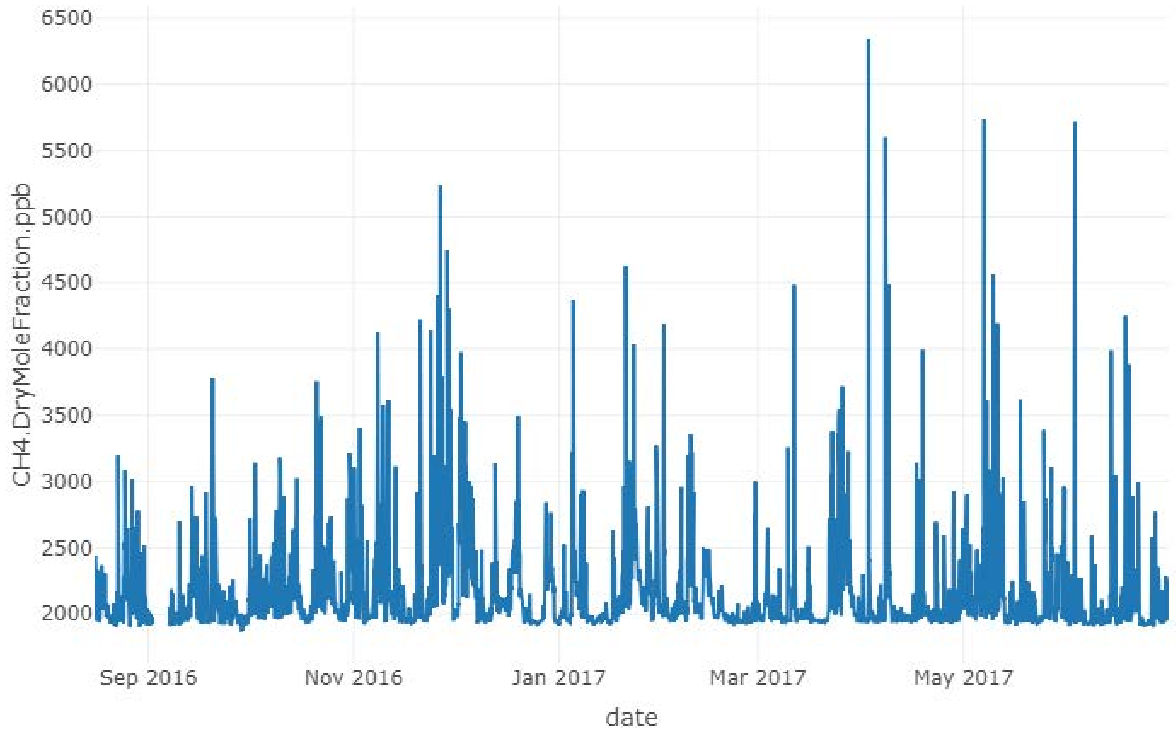


Figure A3.36: Time series plot of different percentiles for one year of baseline data for CH_4 (Preston New Road, BGS site)

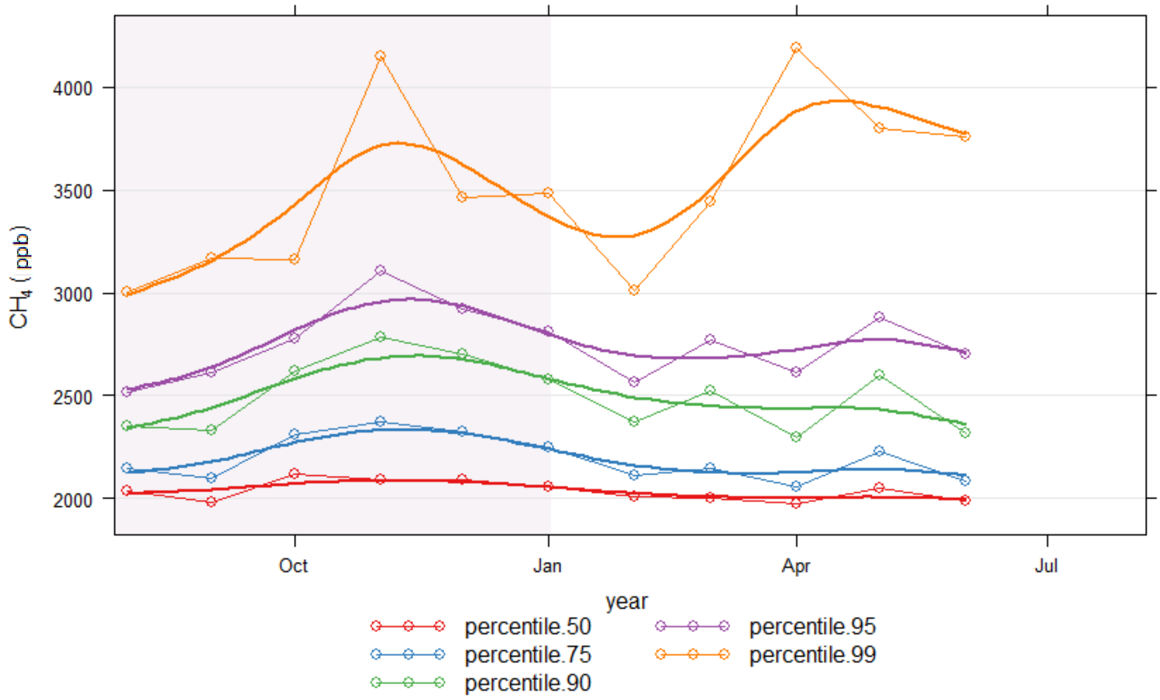


Figure A3.37: Time variation plot for one year of baseline data for CH_4 (Preston New Road, BGS site)

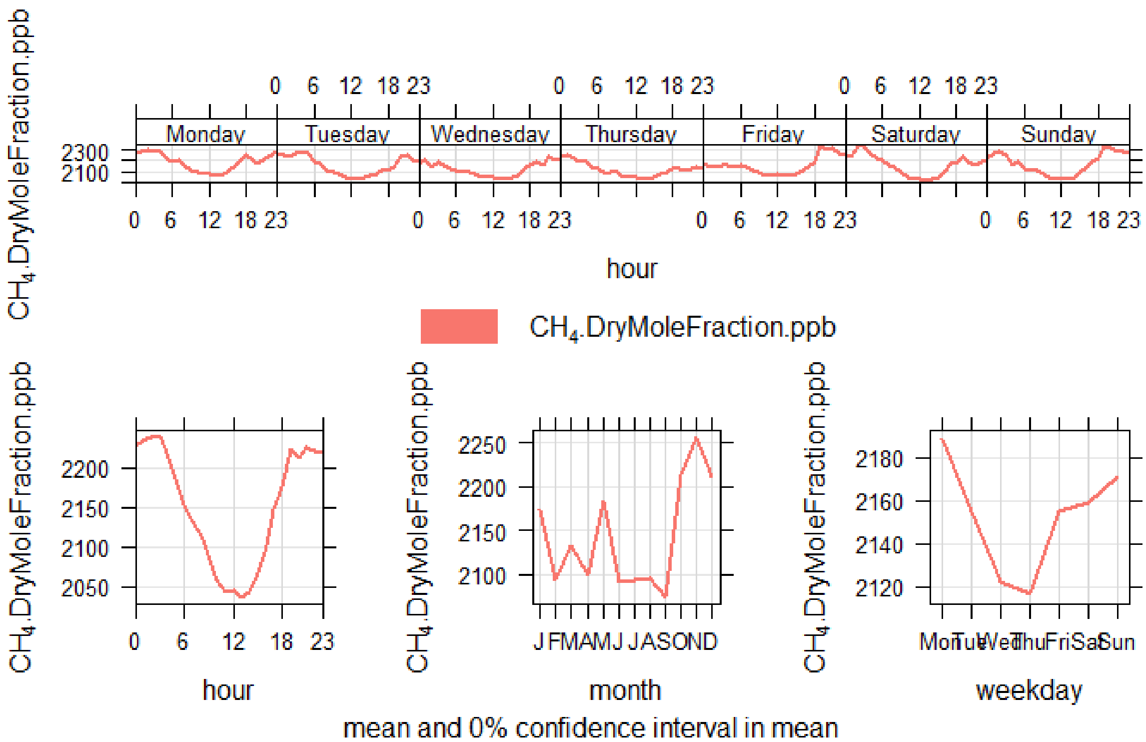


Table A3.4: Summary statistics for one year of baseline data for CH_4 (Preston New Road, BGS site)

Metric	CH_4 dry mole fraction ppb
Mean	2152
50%	2024
75%	2197
90%	2537
95%	2802
99%	3548

Figure A3.38: Conditional probability plot between the 75th and 90th percentiles for one year of baseline data for CH_4 (Preston New Road, BGS site)

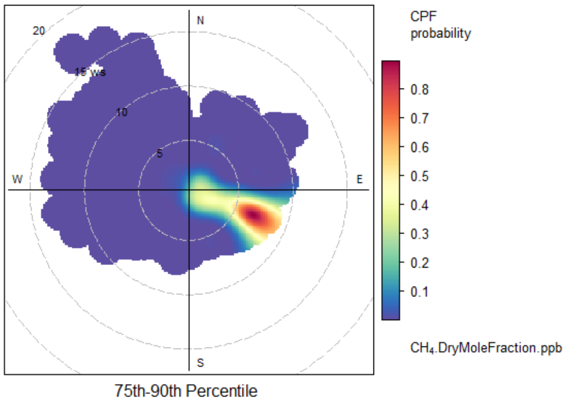


Figure A3.39: Conditional probability plot between the 90th and 95th percentiles for one year of baseline data for CH_4 (Preston New Road, BGS site)

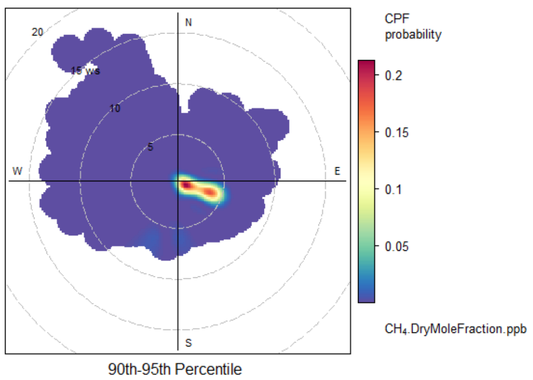


Figure A3.40: Conditional probability plot between the 95th and 99th percentiles for one year of baseline data for CH_4 (Preston New Road, BGS site)

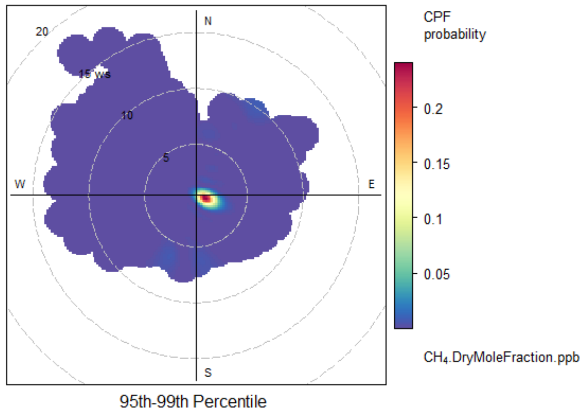


Figure A3.41: Conditional probability plot between the 99th and 100th percentiles for one year of baseline data for CH_4 (Preston New Road, BGS site)

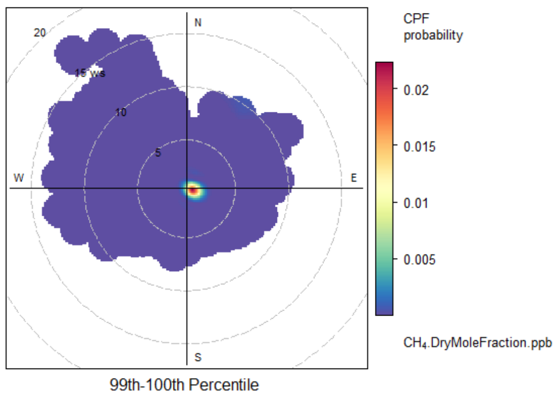


Figure A3.42: Polar plot of the mean concentration for one year of baseline data for CH_4 (Preston New Road, BGS site)

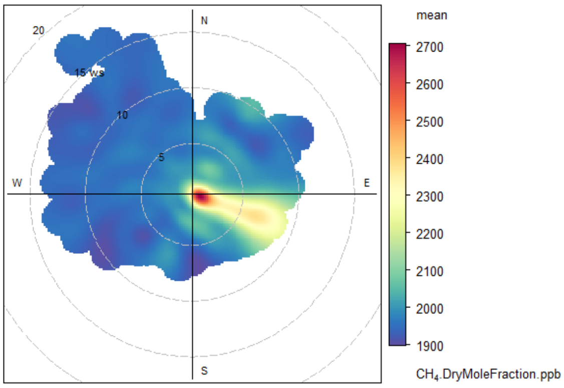


Figure A3.43: Polar plot of the median concentration for one year of baseline data for CH_4 (Preston New Road, BGS site)

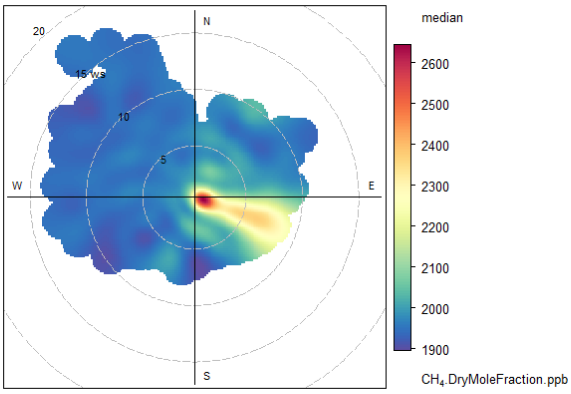


Figure A3.44: Polar plot of the 75th percentile concentration for one year of baseline data for CH_4 (Preston New Road, BGS site)

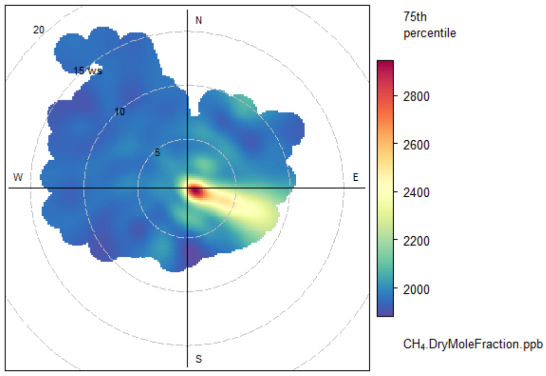


Figure A3.45: Polar plot of the 90th percentile concentration for one year of baseline data for CH_4 (Preston New Road, BGS site)

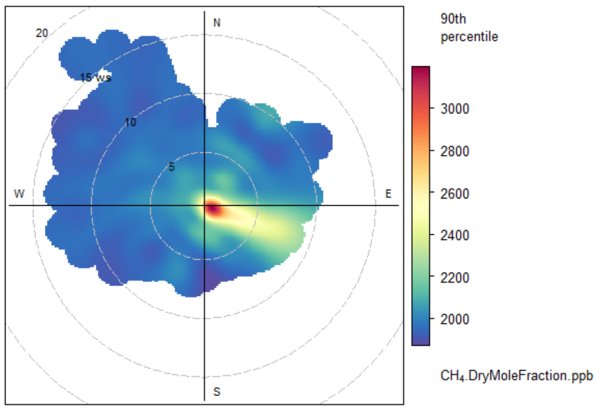


Figure A3.46: Polar plot of the 95th percentile concentration for one year of baseline data for CH_4 (Preston New Road, BGS site)

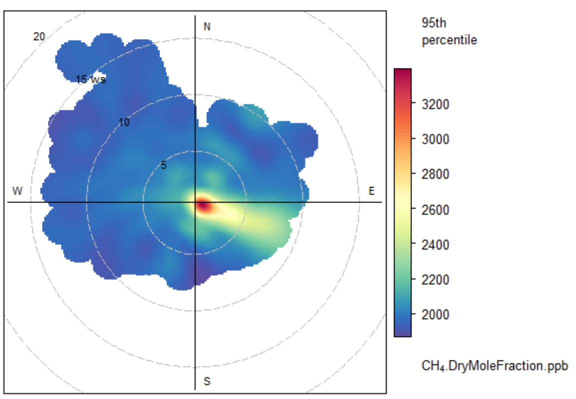


Figure A3.47: Polar plot of the 99th percentile concentration for one year of baseline data for CH_4 (Preston New Road, BGS site)

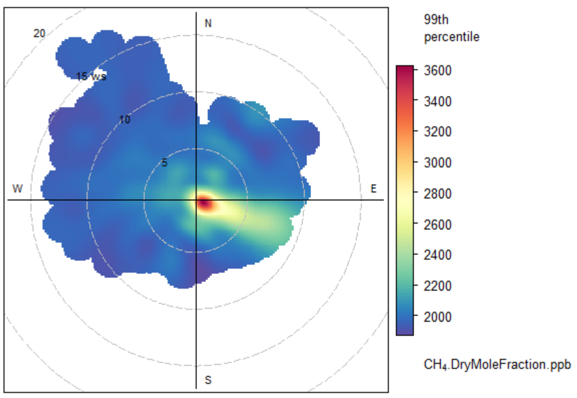


Figure A3.48: Polar plot of the weighted mean (mean/frequency) for one year of baseline data for CH_4 (Preston New Road, BGS site)

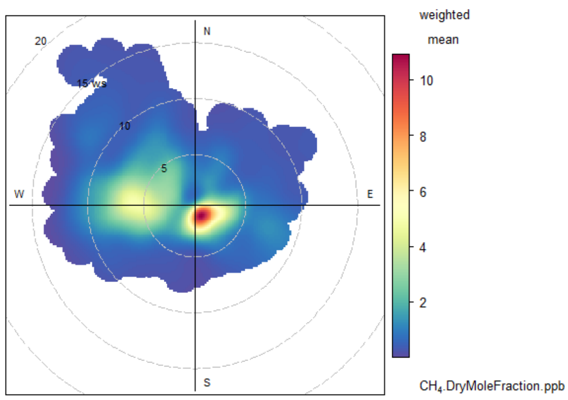
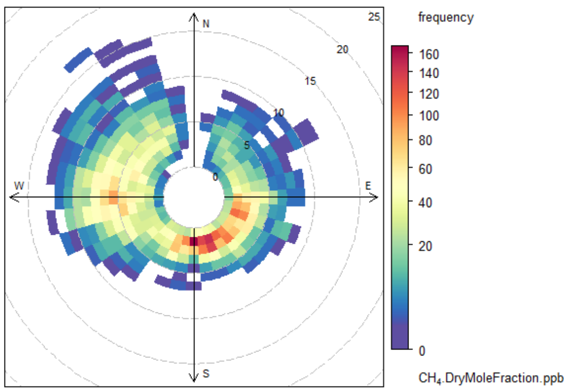


Figure A3.49: Polar frequency plot for one year of baseline data (Preston New Road, BGS site)



A3.4 Preston New Road, BGS site - VOC

Table A3.5: VOC summary statistics before activity (7 November 2016 to 14 August 2017 from 38 measurements)

	ethane (ppb)	ethene (ppb)	propane (ppb)	propene (ppb)	iso-butane (ppb)	n-butane (ppb)	acetylene (ppb)
Mean	3.18	0.77	1.34	0.15	0.38	0.82	0.41
Median	2.41	0.63	0.96	0.11	0.24	0.48	0.34
75%	4.11	0.87	1.57	0.16	0.41	0.84	0.48
90%	8.31	1.88	3.70	0.37	1.19	2.47	0.87
95%	10.25	2.36	4.73	0.47	1.58	3.27	1.05
99%	11.80	2.74	5.55	0.55	1.89	3.92	1.19

	iso-pentane (ppb)	n-pentane (ppb)	isoprene (ppb)	benzene (ppb)	toluene (ppb)
Mean	0.23	0.20	0.01	0.27	0.25
Median	0.16	0.14	0.01	0.19	0.15
75%	0.31	0.23	0.01	0.31	0.25
90%	0.68	0.48	0.02	0.71	1.65
95%	0.85	0.61	0.03	0.90	2.34
99%	0.99	0.71	0.03	1.06	2.90

Appendix 4 – Preston New Road water quality baseline data pack

The section outlines the 'baseline data' for the highest priority determinands from operator measurements at Preston New Road (determinands with a priority score of 2.5 or above). The methodology for identifying these priority determinands is outlined in section 2.7.1 and the finalised list of priority determinands has been replicated below for ease of reference.

Table A4 - 1: Determinands prioritised for baseline characterisation

Determinand group	Determinand	Surface water	Groundwater
Nutrients	Ammoniacal nitrogen	x (as N)	x (as NH4)
	Total organic nitrogen	x	
Major ions	Calcium		x
	Chloride	x	x
	Iron	x	x
	Magnesium		x
	Potassium	x	x
	Sodium	x	x
	Sulphate	x	
	Total alkalinity		x
Trace elements	Chromium	x	
	Cobalt	x	
	Copper	x	x
	Mercury	x	
Natural gas	Dissolved methane	x	x
	Dissolved carbon dioxide		x
Stable isotopes	Carbon (δ13C-CO_2)		x
Other	Acrylamide	x	x
	Total dissolved solids		x

Detailed information on the laboratory methodology used was unavailable, and it was assumed that the data set had already been quality assured by the lab provider. As part of QA/QC checks, the percentage of values that were at or below the limit of detection were analysed. This included using estimated LODs for the PNR groundwater data, where no LODs were provided (see also text in section 3.7).

A number of the determinands had a high percentage of values at or below the LOD (>50%). Analysis of these variables follows the same process as the one used at Kirby Misperton. The remainder of this section is split between parameters that would be deterministically assessed in detecting change (that is, parameters with more than 50% of values at or below the LOD) and those that are assessed using the full method.

Table A4 - 2: Priority determinands that have a majority of measured values at or below the limit of detection and therefore are considered to be taken forward for a deterministic assessment

Parameter	% values at or below the limit of detection
Acrylamide	99.5

Parameter	% values at or below the limit of detection
Dissolved mercury	98.9
Salinity	92.0
Dissolved chromium	86.8
Dissolved copper	79.9
Ammoniacal nitrogen as NH4	64.7

A4.1. Determinands for full quantitative further analysis

Results by determinand are set out in the following subsections for:

- groundwaters by (a) the shallow target response zone BH1-A to BH4-4A, and (b) the deep target response zone BH1-B to BH4-B
- surface waters for ‘upstream’ and ‘downstream’ monitoring points

It should be noted that for some determinands, only groundwater measurements were taken, and for others, values were only measured for surface waters.

Ammoniacal nitrogen as N

1. Individual site time series

Shallow and deep response zone boreholes

Not applicable – Only ammoniacal nitrogen as NH_4 measured.

Surface waters

See main report section 3.7 for consideration of this parameter.

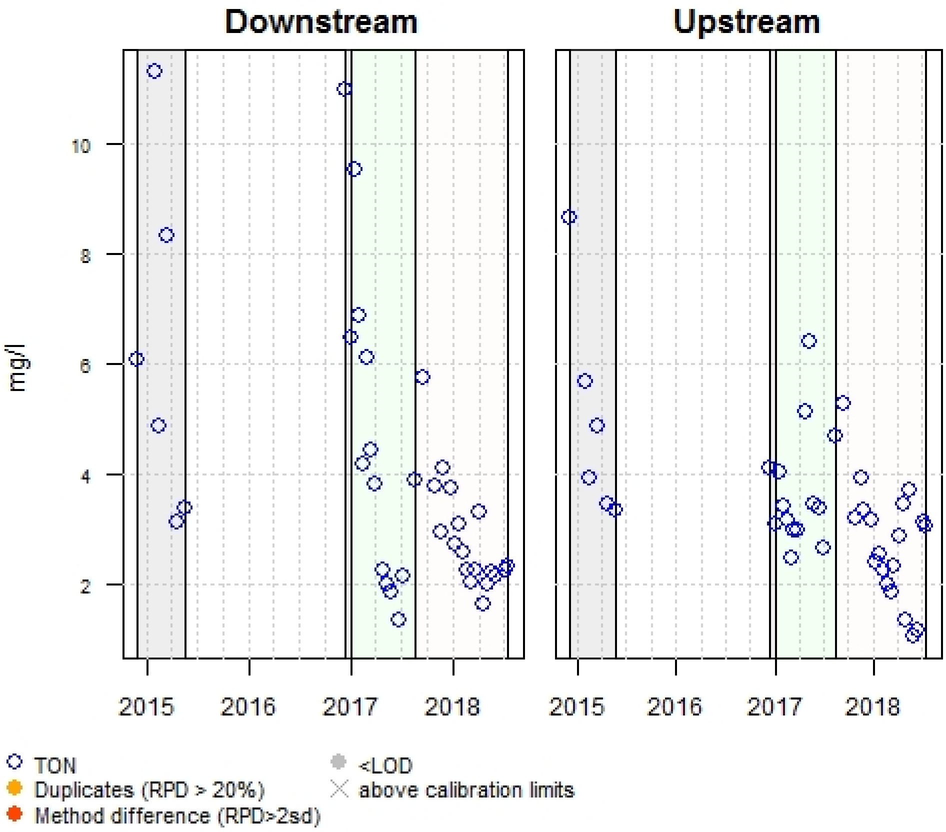
Total organic nitrogen

1. Individual site time series

Shallow and deep response zone boreholes

Not applicable – Not measured.

Surface waters



Observations and notes:

- Concentrations were generally higher/more variable downstream compared to upstream (consistent with the observations from ammoniacal nitrogen as N), particularly during P1 and P2.
- All observations were above the LOD.

2. Grouped time series

This was deemed inappropriate for this variable (surface water sites only which could be directly visually compared).

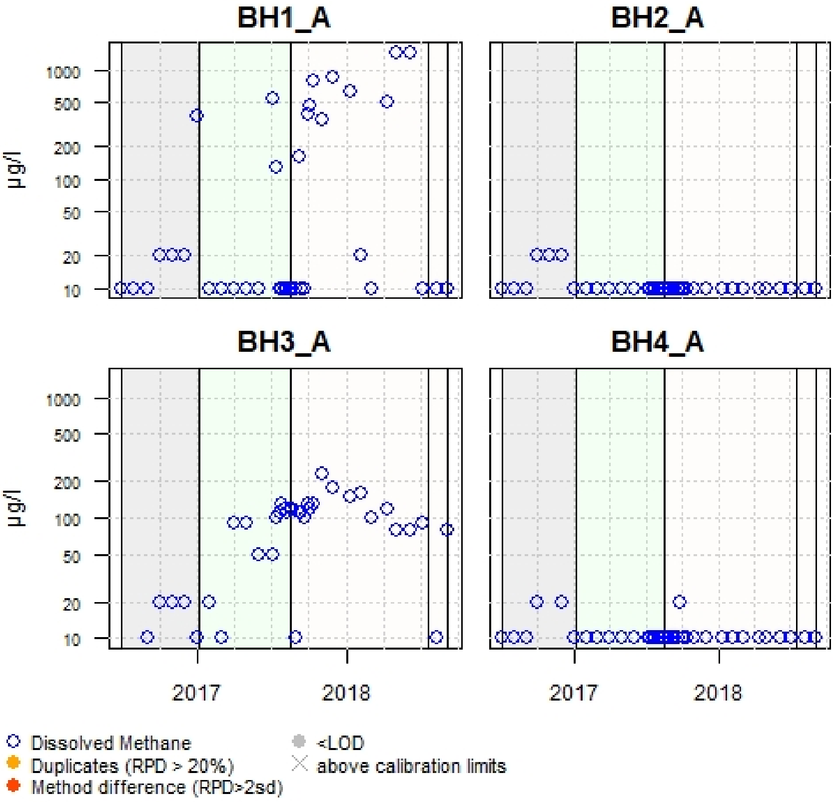
3. Grouped data box plots

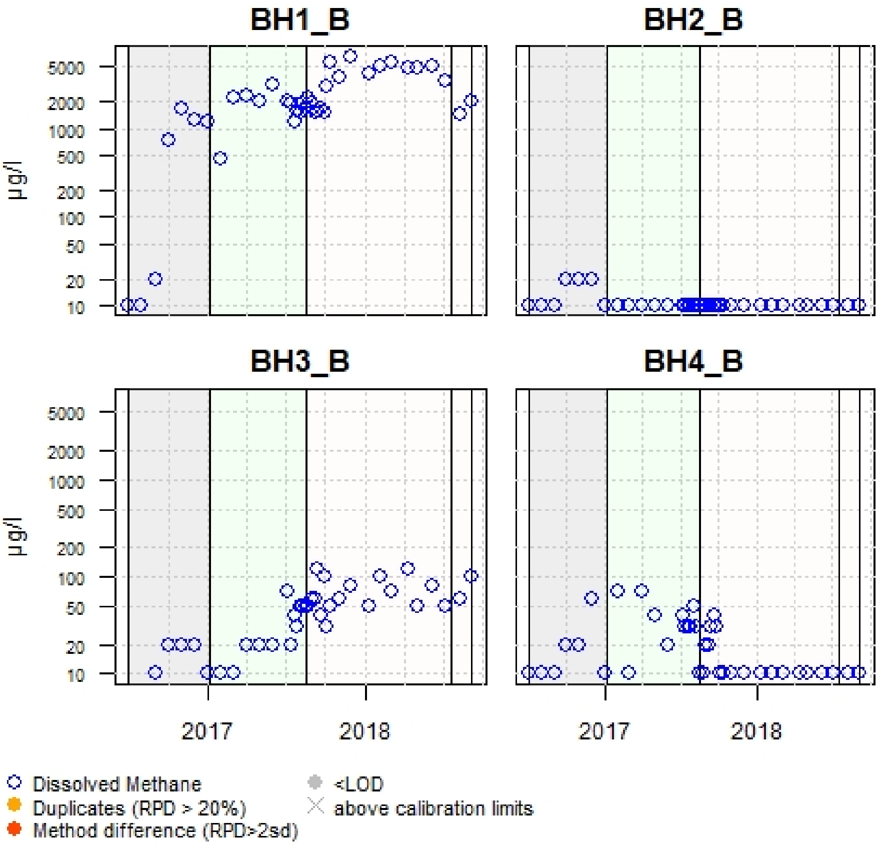
This was deemed inappropriate for this variable due to inconsistencies in the count of observations per season.

Methane

1. Individual site time series

Shallow and deep response zone boreholes





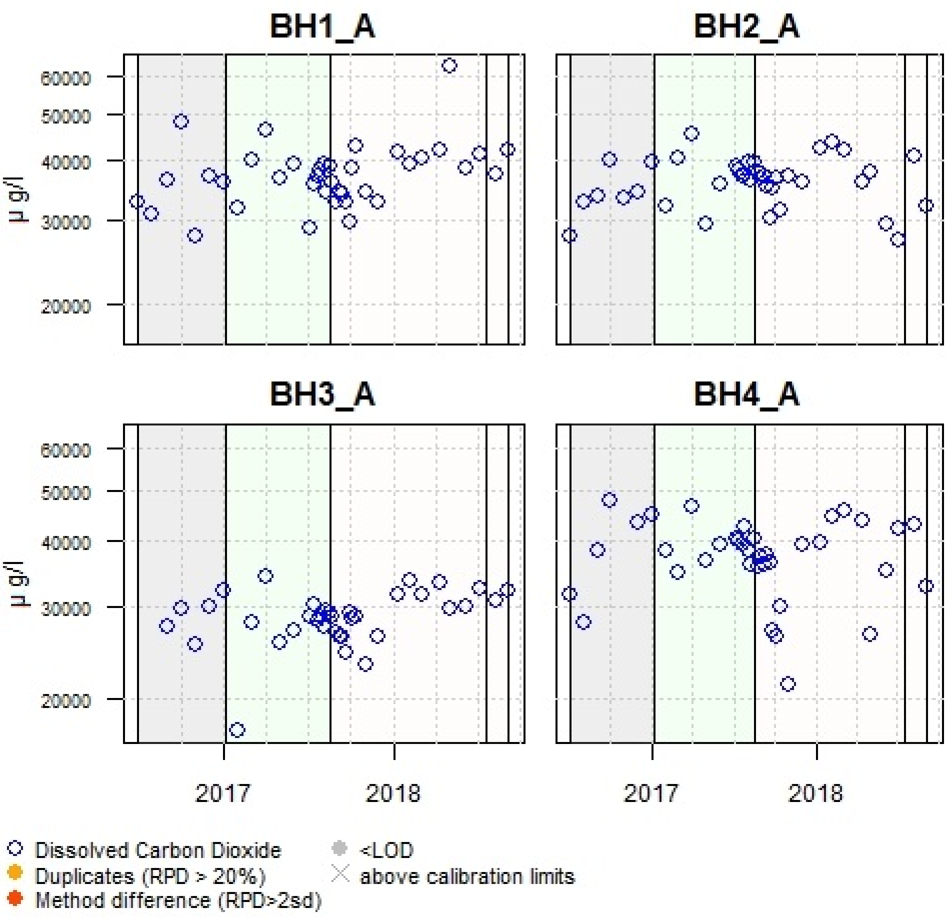
Observations and notes:

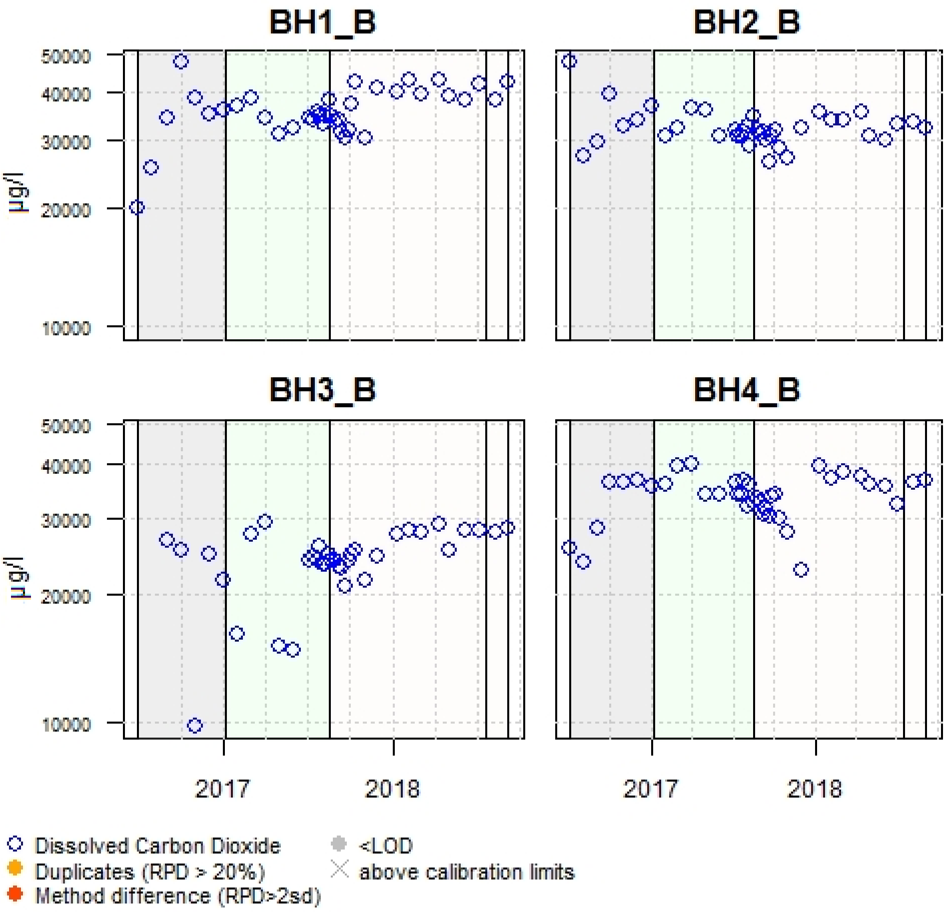
- No LOD was assumed for the groundwater measurements (though it seems plausible from considering the outputs, that there may have been a limit of detection of 10 µg/l).
- Dissolved methane was highest at BH1, both in shallow and deep target response zones, with values exceeding 1mg/L.
- At both BH1 and BH3, the observations indicated a potential increase in methane concentrations through time (starting before the end of P1). Contrary to this, in the deeper target response zone of BH4 (BH4-B), values demonstrate a period of higher concentrations (to levels similar to those seen at BH3-B in P2/P3), before decreasing back down towards 10 µg/l (P3).
- At BH2-A, BH2-B and BH4-A, concentrations remained steady through time at <20 µg/l.
- There were no obvious outliers in the data set. However, concentrations were seen at BH1-A and BH1-B, which may be considered 'high' (within the top 1% of concentrations of BGS's 170 strong data set of aquifer dissolved methane concentrations across the UK[25].

Dissolved carbon dioxide

1. Individual site time series

Shallow and deep response zone boreholes





Observations and notes:

- The shallow response zone borehole concentrations of dissolved carbon dioxide ranged between 1,000 and 7,000 mg/l.
- The deep response zone boreholes demonstrated much lower concentrations of dissolved carbon dioxide (up to 5,000 mg/l).
- Concentrations of dissolved carbon dioxide at borehole 3B notably increase between 2016 (ranging between 1,000 and 3,000 mg/l) and 2018 (ranging between 2,000 and 3,000 mg/l). The remaining boreholes display a similar range of concentrations of dissolved carbon dioxide throughout phases 1 to 3.
- The deep response zone borehole concentrations of dissolved carbon dioxide are however highest in the third phase (2018). Additionally, concentrations of dissolved carbon dioxide in boreholes B show less variability compared to those observed in boreholes A.
- There were no duplicate observations and no values were recorded as less than the assumed LOD.

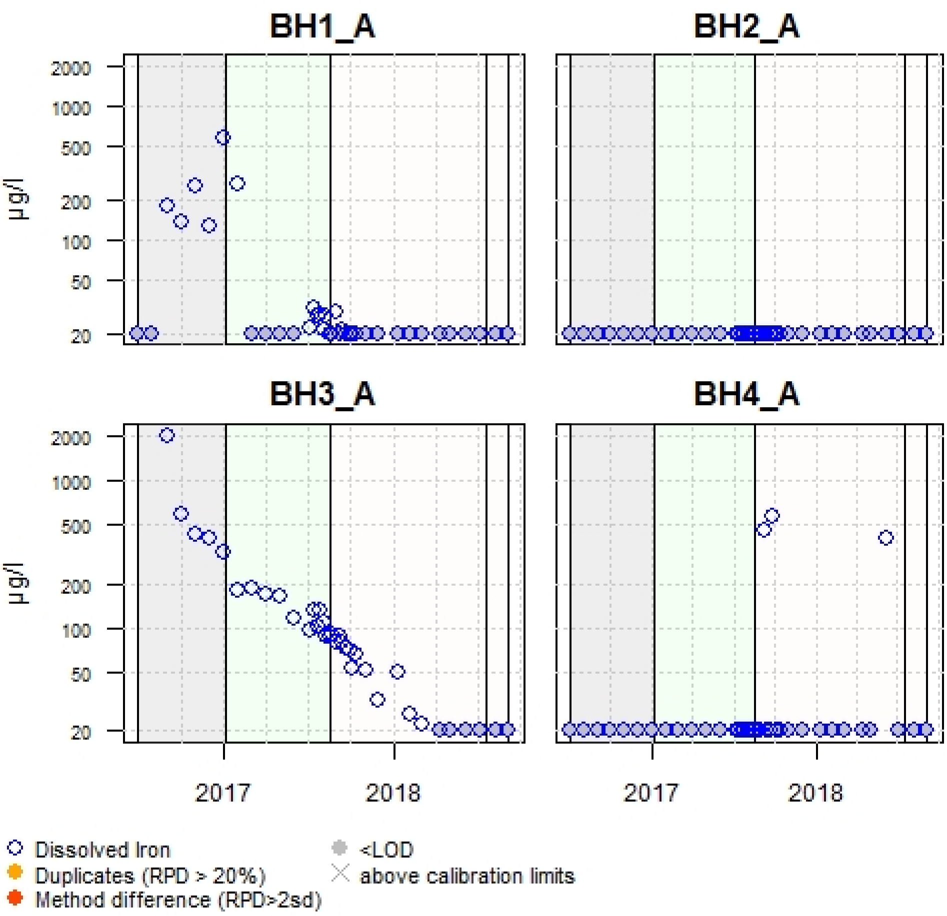
Surface waters

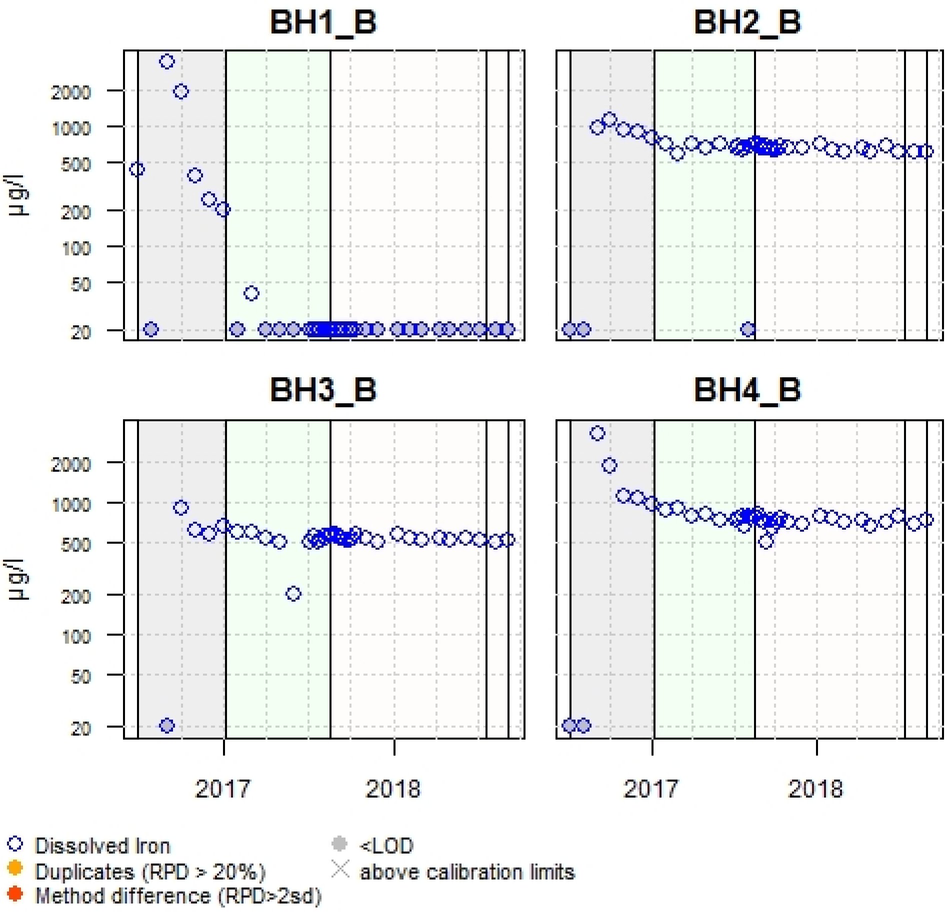
Not applicable – Not measured.

Iron (dissolved)

1. Individual site time series

Shallow and deep response zone boreholes

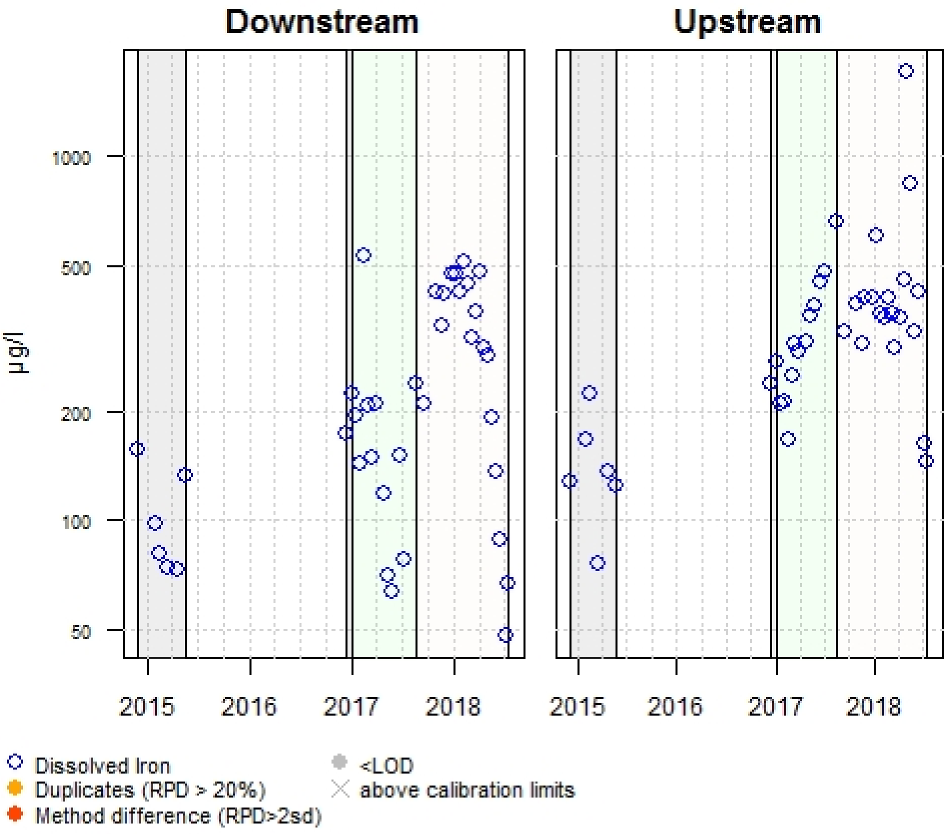




Observations and notes:

- The shallow response zone boreholes illustrated much lower concentrations of dissolved iron than the deep response zone boreholes. At boreholes 1A, 2A and 4A the majority of values were less than the assumed LOD across all phases.
- Borehole 3A displays much higher concentrations of dissolved iron, although a steep decline is observed throughout phases 1 (from 2,000 µg/l) and 2 and into the first half of phase 3.
- The deep response zone concentrations of dissolved iron generally ranged between 200 and 2,000 µg/l. Dissolved iron concentrations in boreholes 2 to 4B show little variation, although measured concentrations decline slightly between 2016 and 2017 in boreholes 2B and 4B. Conversely, most measured concentrations in borehole 1B remain stable and below the assumed LOD in phases 2 and 3.

Surface waters



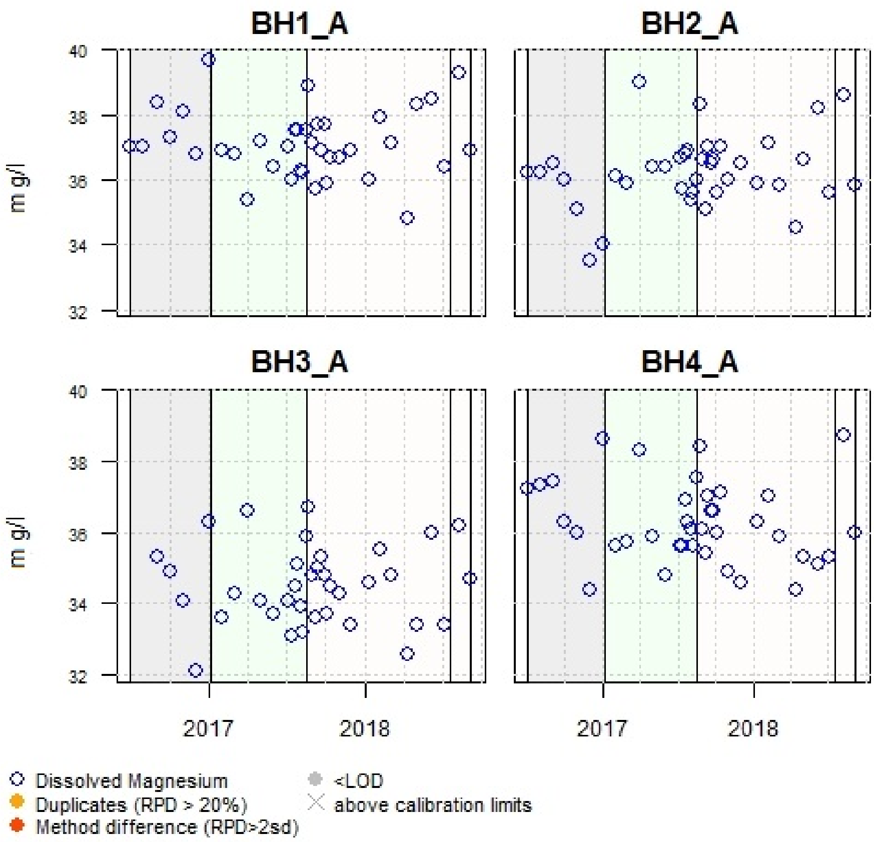
Observations and notes:

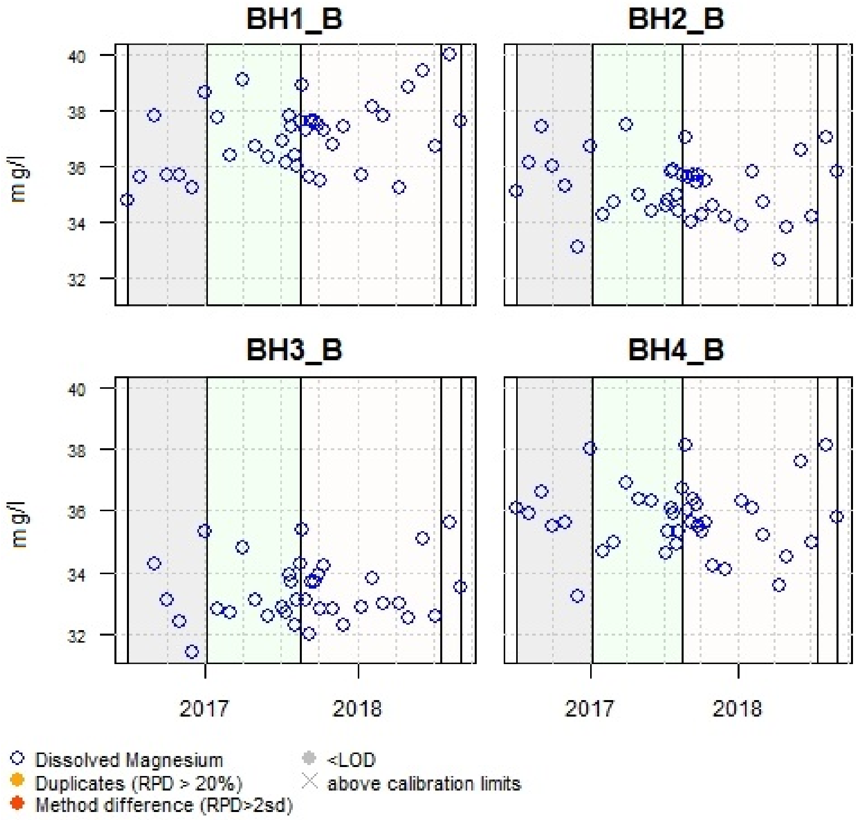
- Dissolved iron concentrations increase through phases 1 to 3, both downstream and upstream.
- In both 2017 and 2018, higher concentrations of dissolved iron are observed upstream (ranging between 100 and 2,000 µg/l) than downstream (ranging between 50 and 500 µg/l).
- No values were at the LOD.

Magnesium (dissolved and total)

1. *Individual site time series*

Shallow and deep response zone boreholes

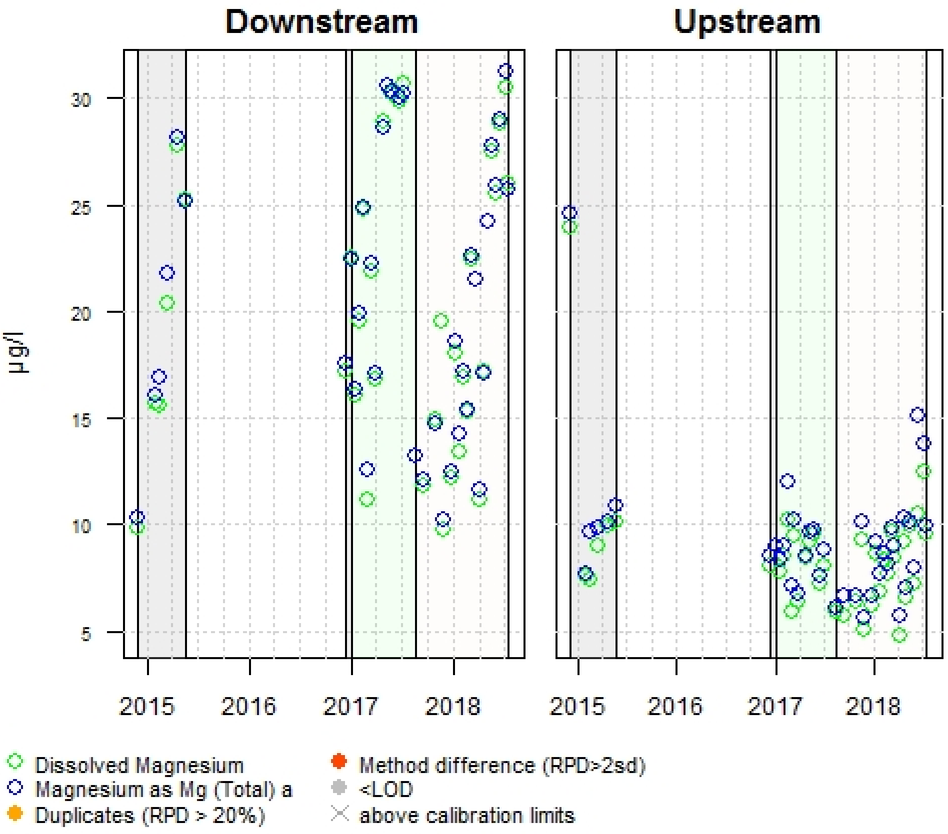




Observations and notes:

- Almost all magnesium appears to be in dissolved form.
- Concentrations of dissolved magnesium for the shallow response zone boreholes, ranged between 32 and 40 mg/l and between 30 and 40 mg/l at the deep response zone boreholes.
- Concentrations of dissolved magnesium were highest in all phases at boreholes 1A and 1B, with concentrations ranging between 34 and 40 mg/l.
- In comparison, concentrations of dissolved magnesium were lowest in all phases at boreholes 3A and 3B, with concentrations ranging between 30 and 38 mg/l.
- No values were recorded at the assumed LOD.

Surface waters



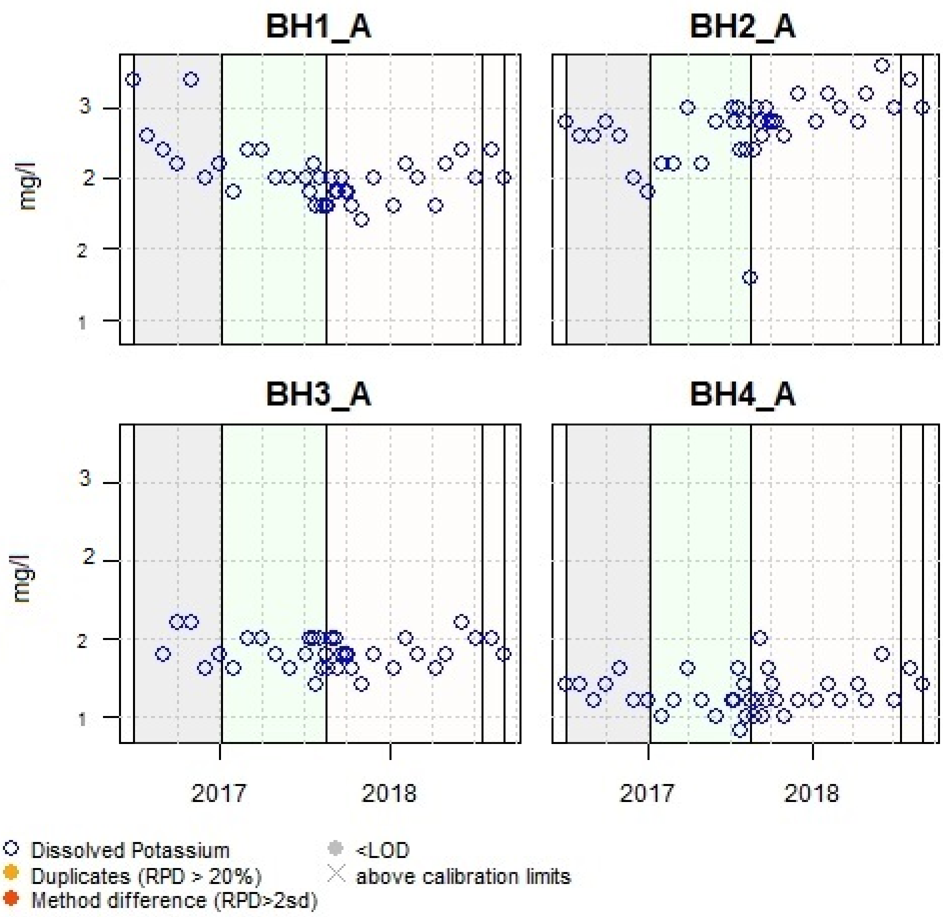
Observations and notes:

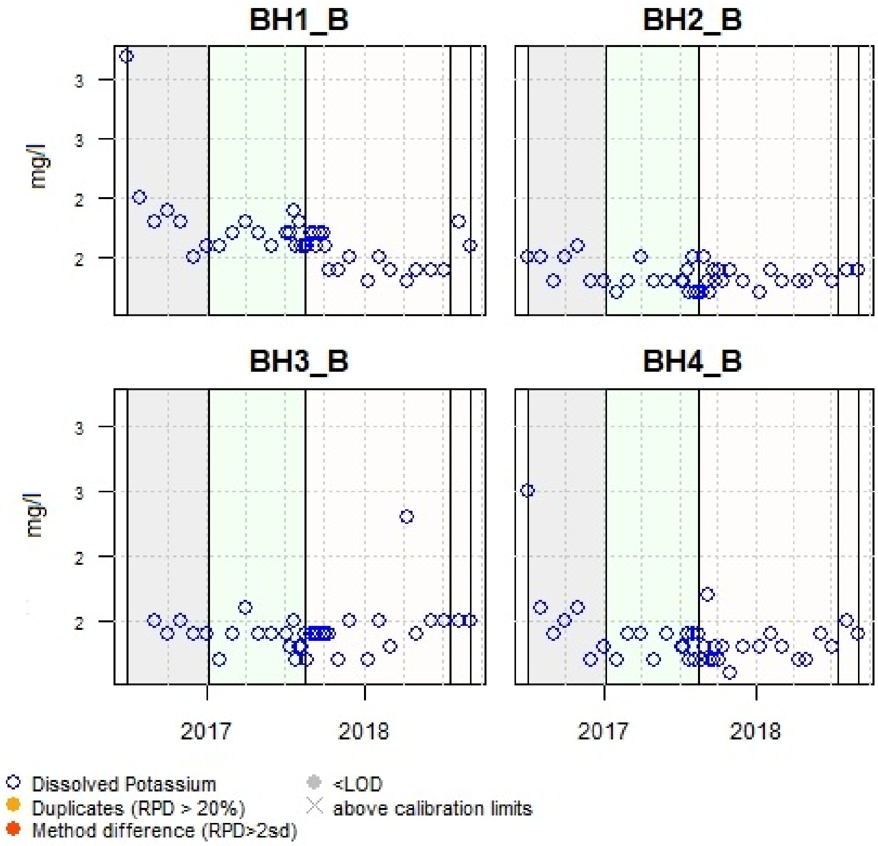
- Almost all magnesium appears to be in dissolved form.
- Upstream shows less variability through time and has lower concentrations relative to downstream.
- Potential outlier high concentration at the start of the monitoring period upstream. The measurement would however appear non-erroneous as it is supported by concurrent high concentration in both dissolved and total form.
- Concentrations lower than in groundwaters.

Potassium (dissolved and total)

1. *Individual site time series*

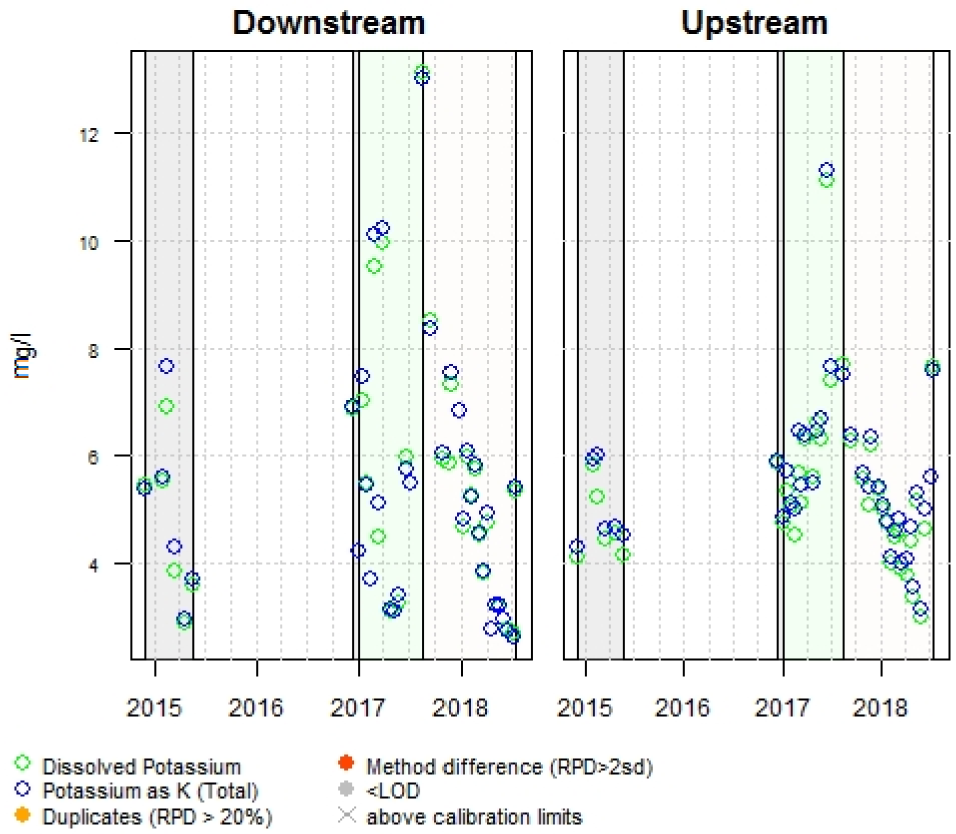
Shallow and deep response zone boreholes





No observations of total potassium in groundwater data.

Surface waters



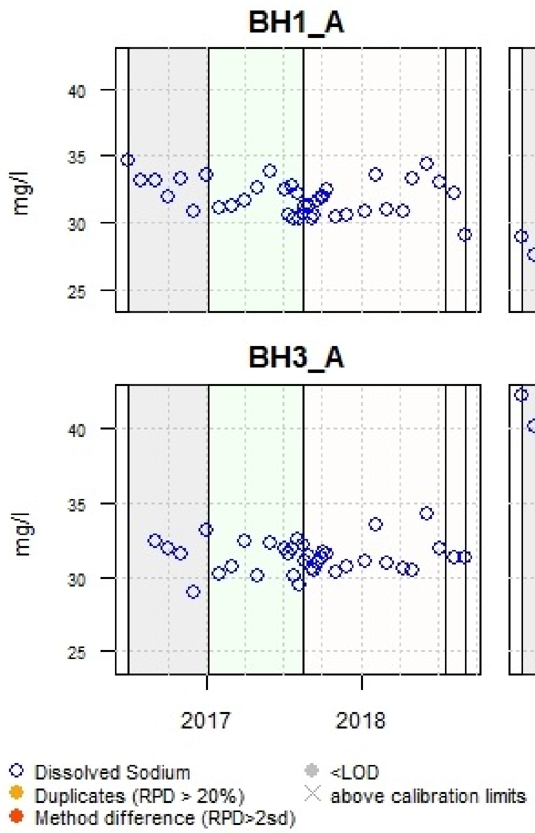
Observations and notes:

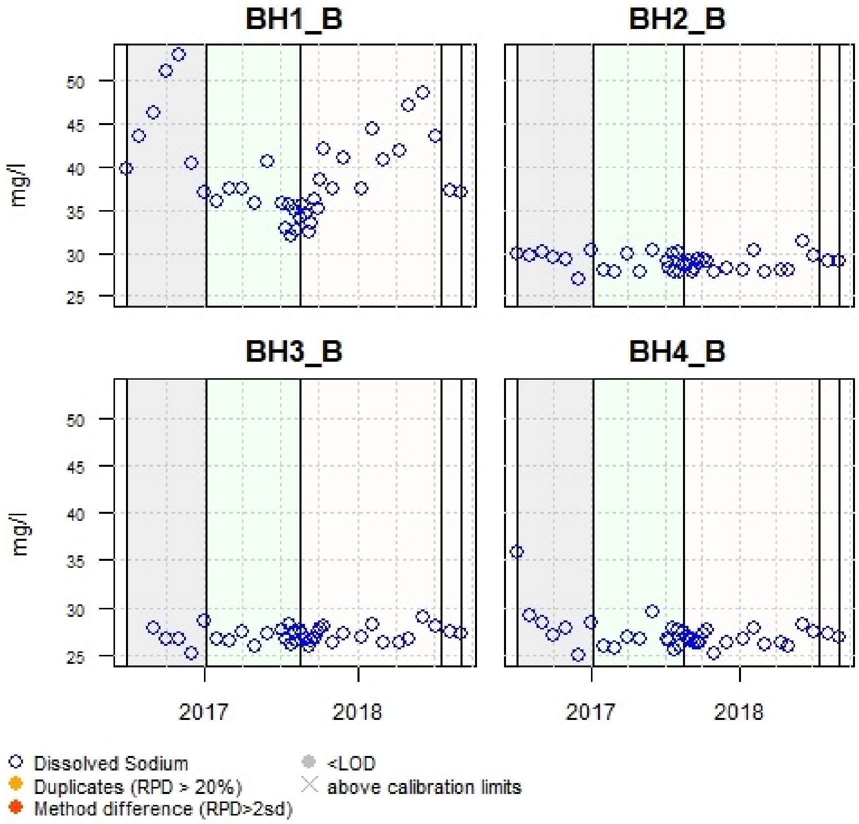
- Potassium recorded upstream and downstream appears to be mostly in dissolved form.
- Higher values of dissolved than total would indicate some potential imprecision in measurement (not apparent here).
- As with some other determinands, there appears less variability upstream relative to downstream.

Sodium (dissolved and total)

1. Individual site time series

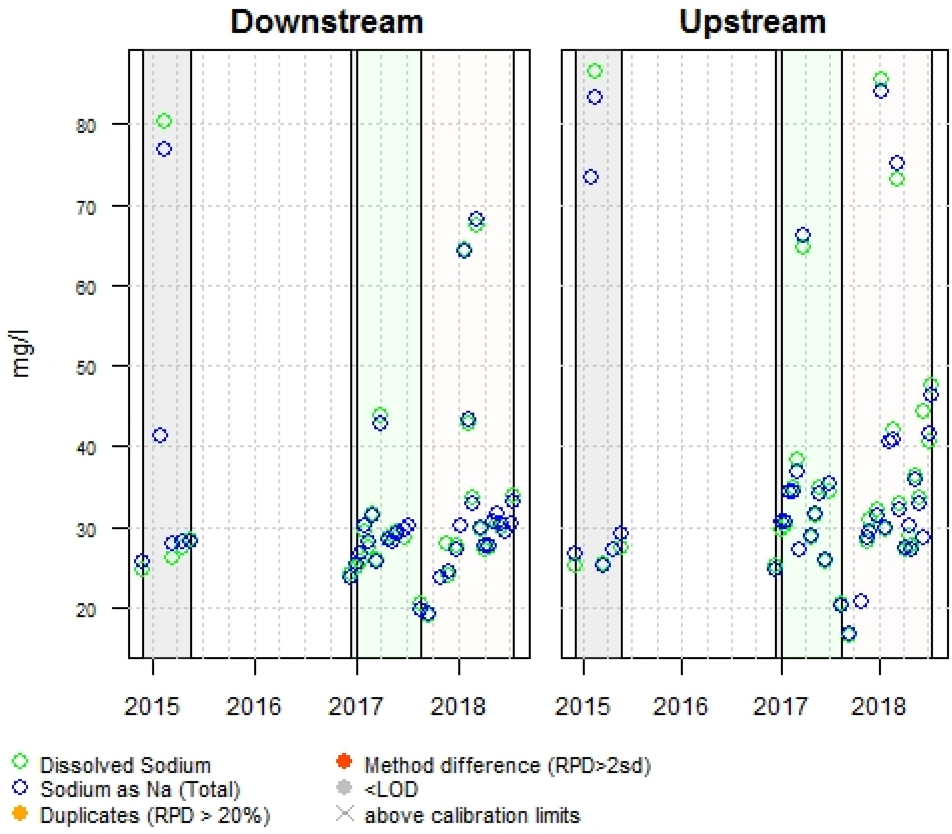
Shallow and deep response zone boreholes





No total sodium measured in groundwaters.

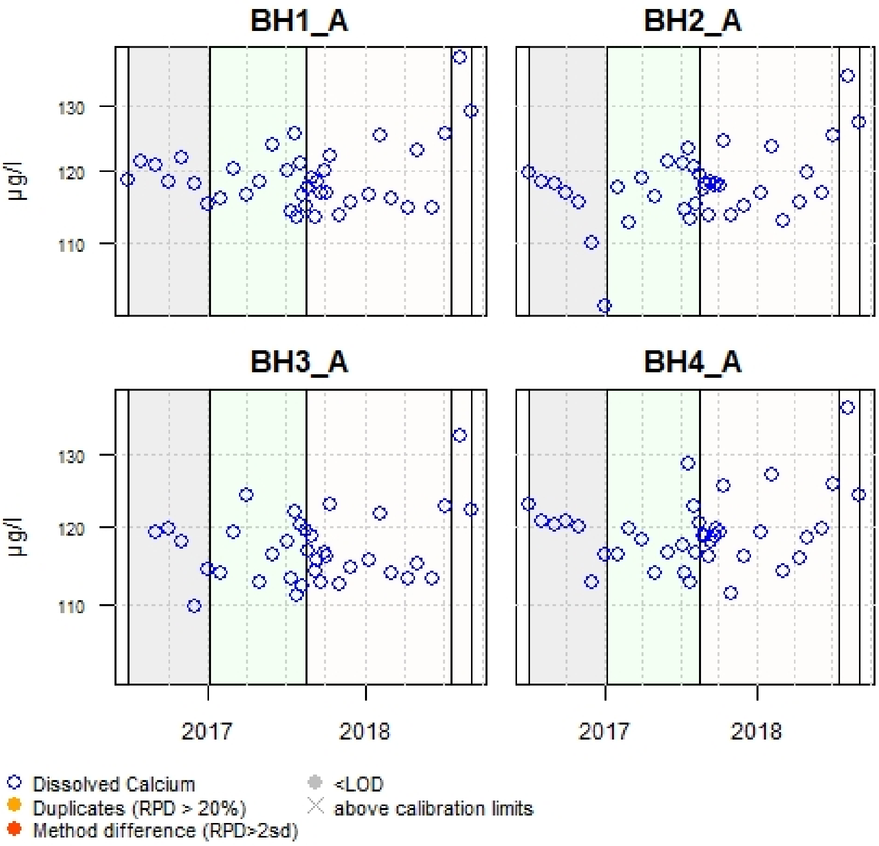
Surface waters

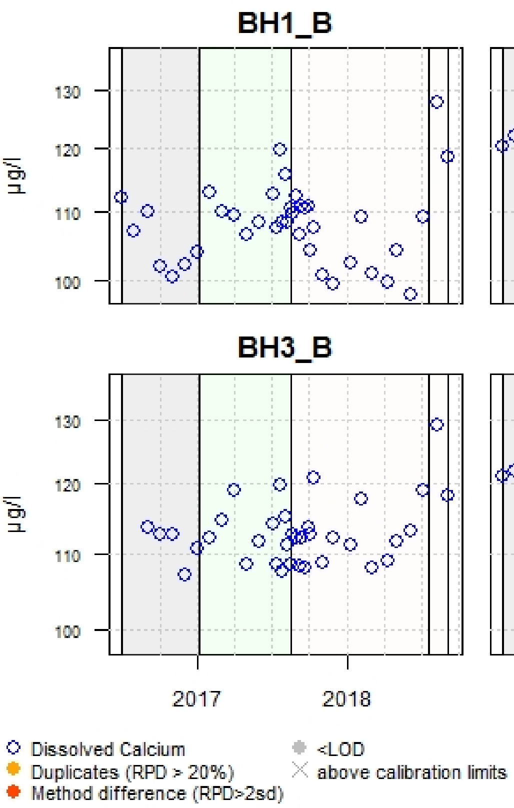


Calcium (dissolved and total)

1. Individual site time series

Shallow and deep response zone boreholes

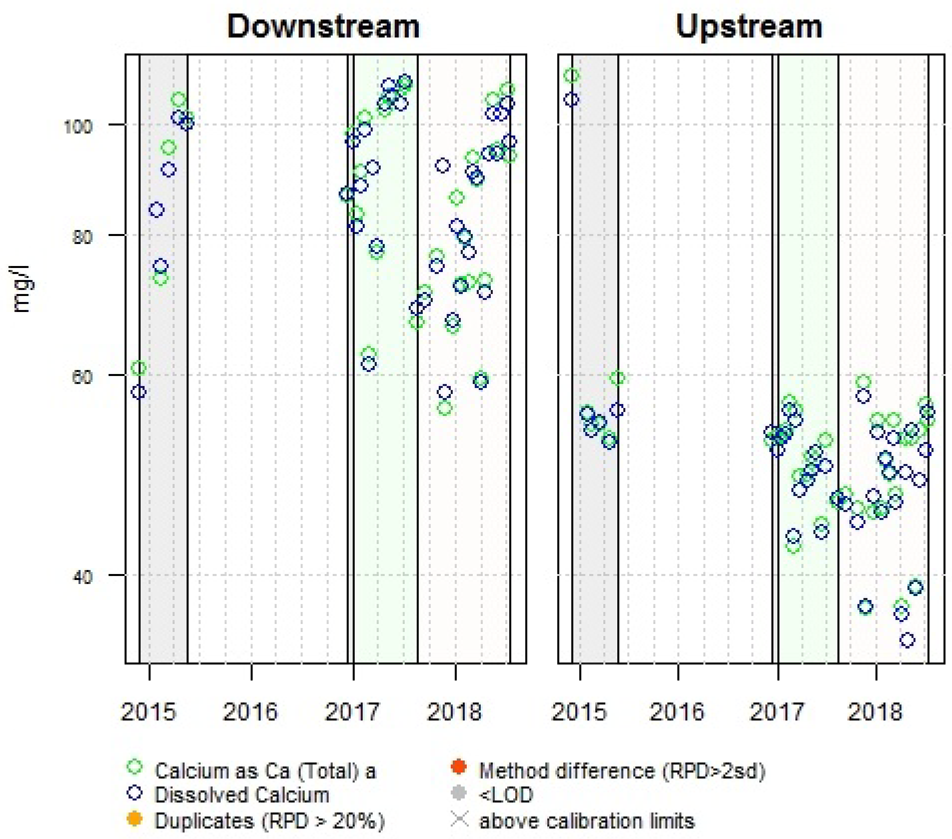




Observations and notes:

- No total calcium measured in the operator groundwater data.
- Concentrations of dissolved calcium show similar ranges across all boreholes and target depths.

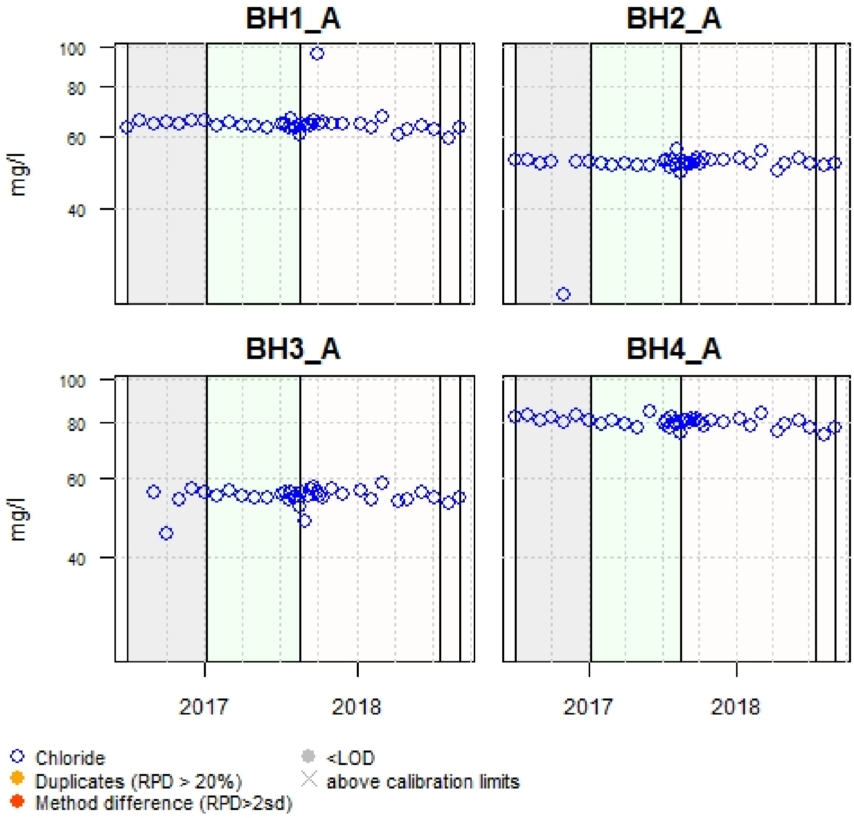
Surface waters

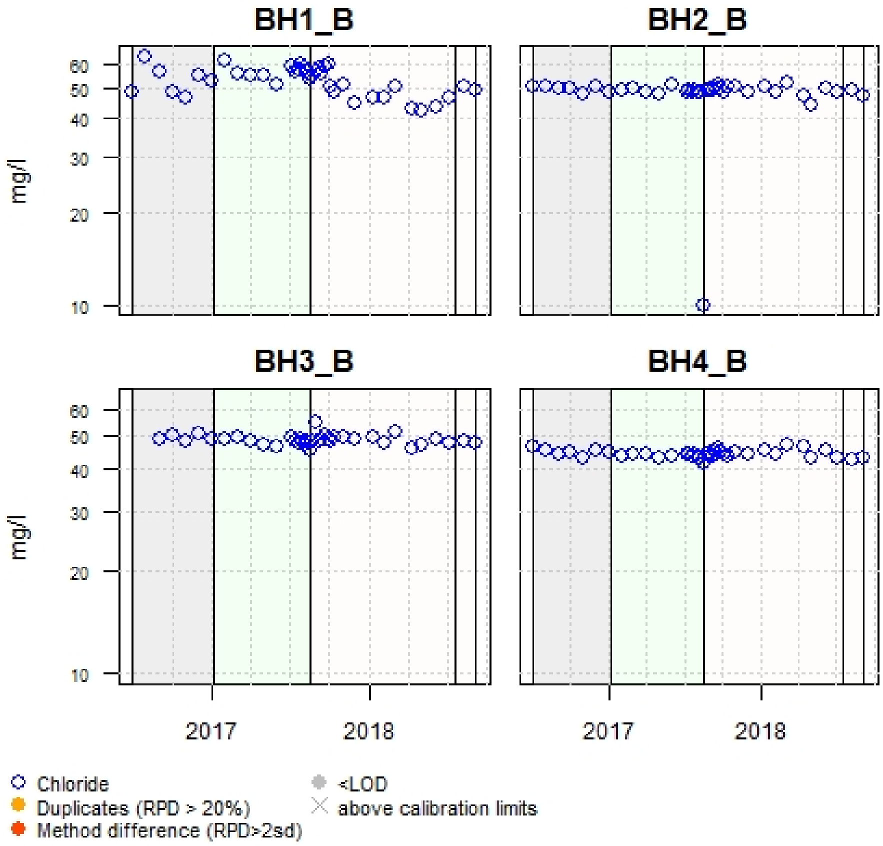


Chloride

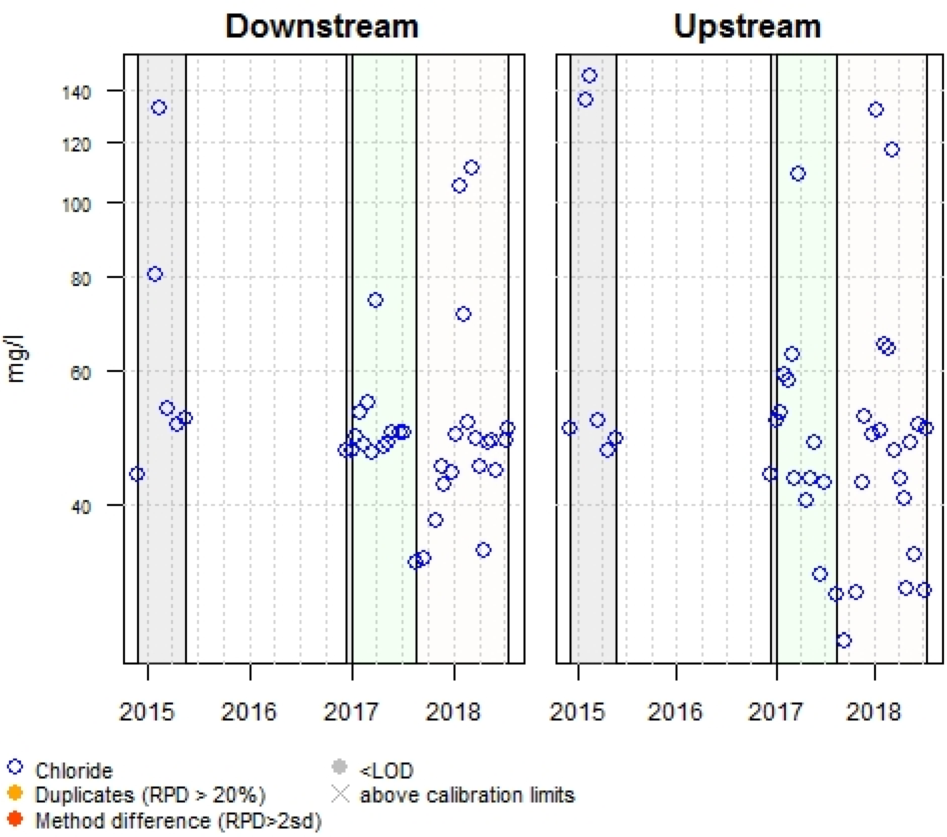
1. Individual site time series

Shallow and deep response zone boreholes




BH1_B
BH2_B
BH3_B
BH4_B
mg/l
60
50
40
30
20
10
2017
2018
Chloride
Duplicates (RPD > 20%)
Method difference (RPD>2sd)
<LOD
above calibration limits

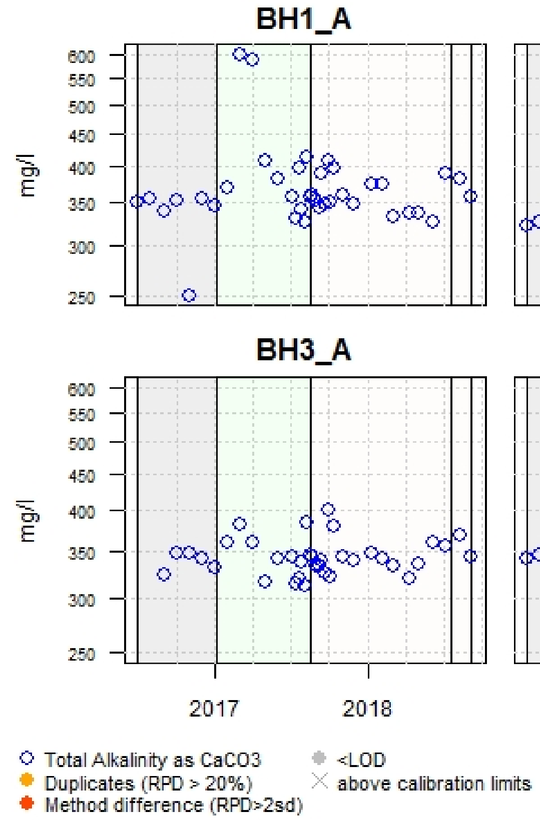
Surface waters

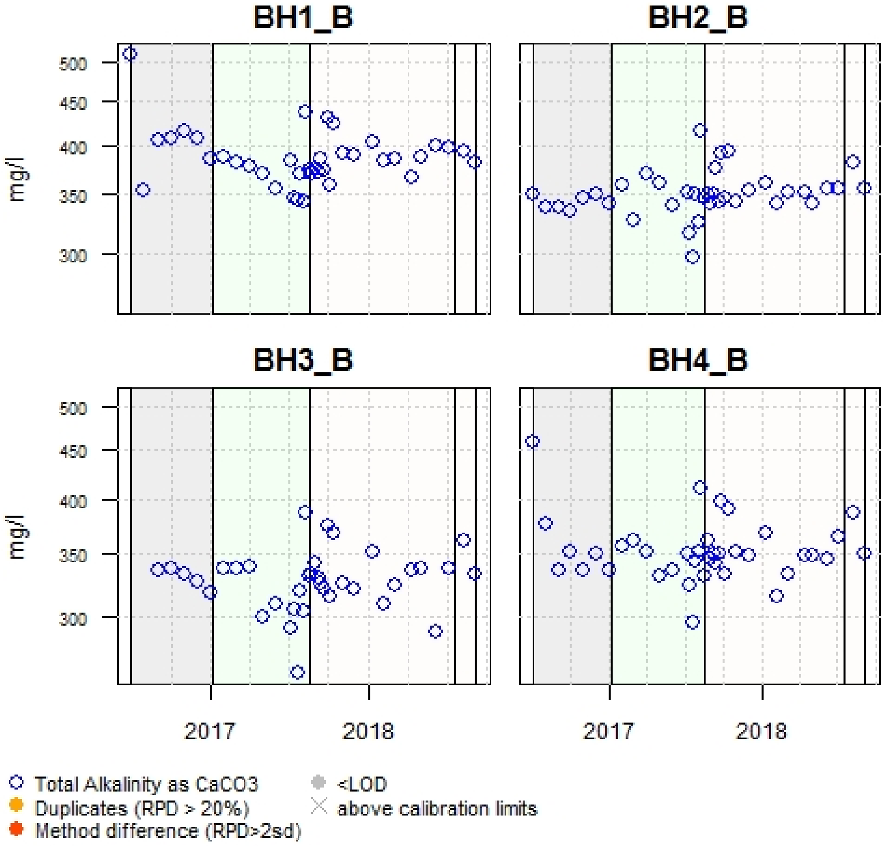


Total alkalinity

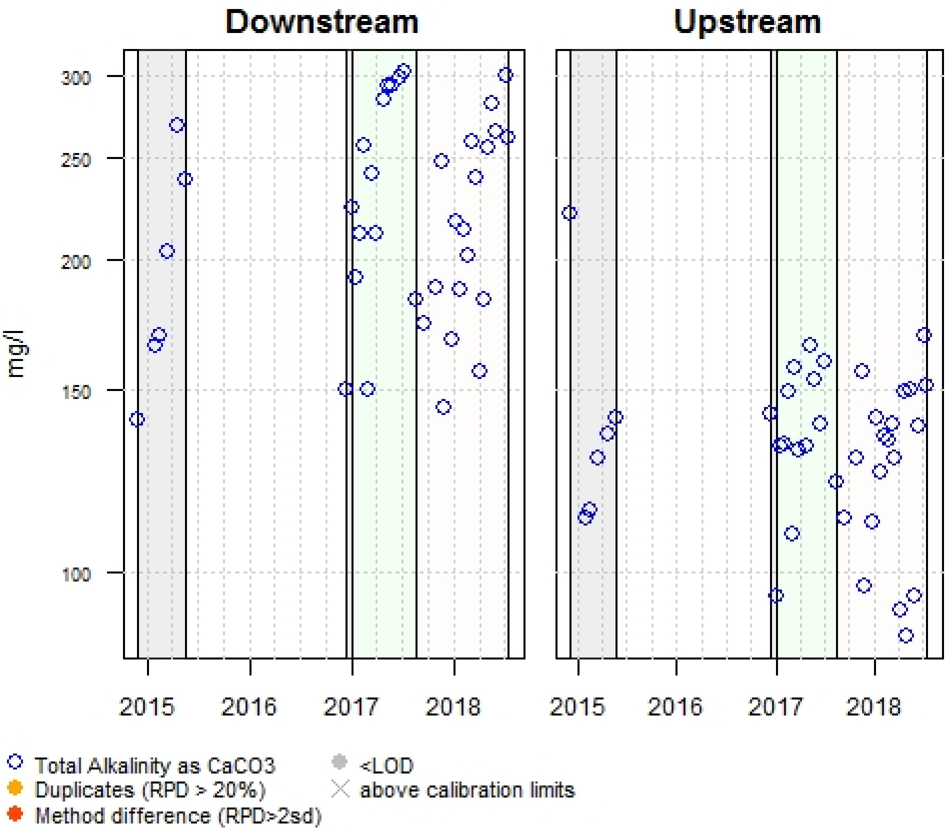
1. Individual site time series

Shallow and deep response zone boreholes


BH1_A
BH2_A
BH3_A
BH4_A
mg/l
600
550
500
450
400
350
300
250
2017
2018
Total Alkalinity as CaCO3
Duplicates (RPD > 20%)
Method difference (RPD>2sd)
<LOD
above calibration limits


BH1_B
BH2_B
BH3_B
BH4_B
mg/l
500
450
400
350
300
2017
2018
Total Alkalinity as CaCO3
Duplicates (RPD > 20%)
Method difference (RPD>2sd)
<LOD
above calibration limits

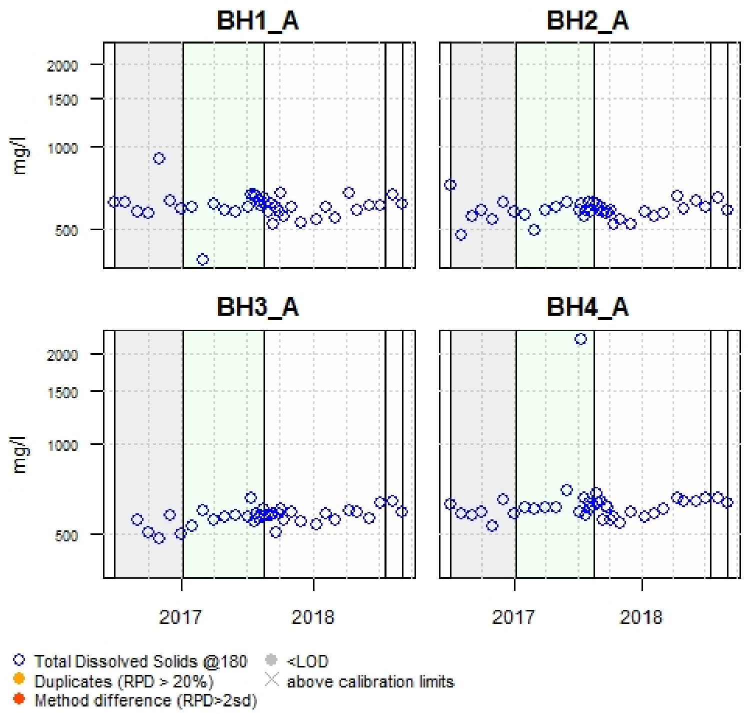
Surface waters

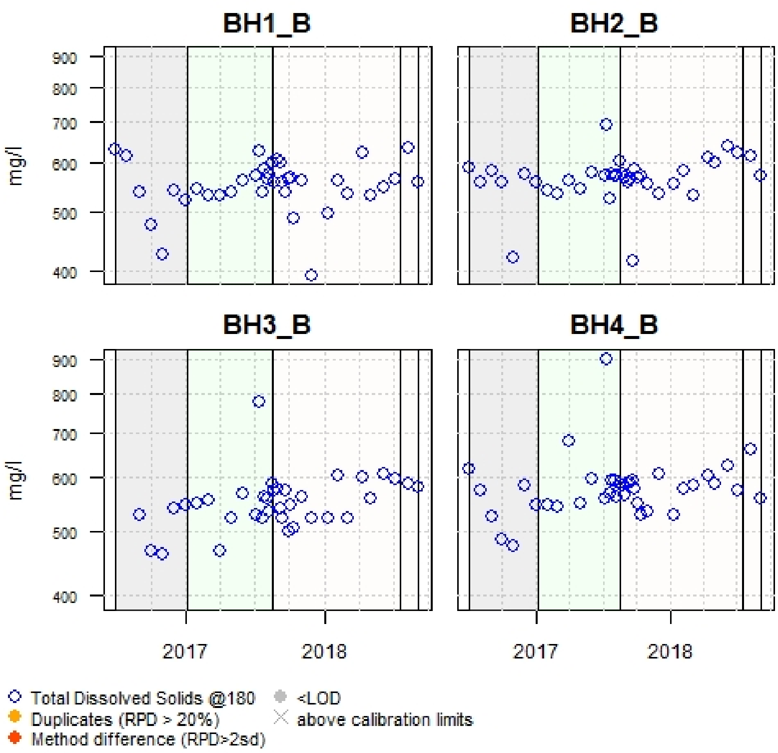


Total dissolved solids

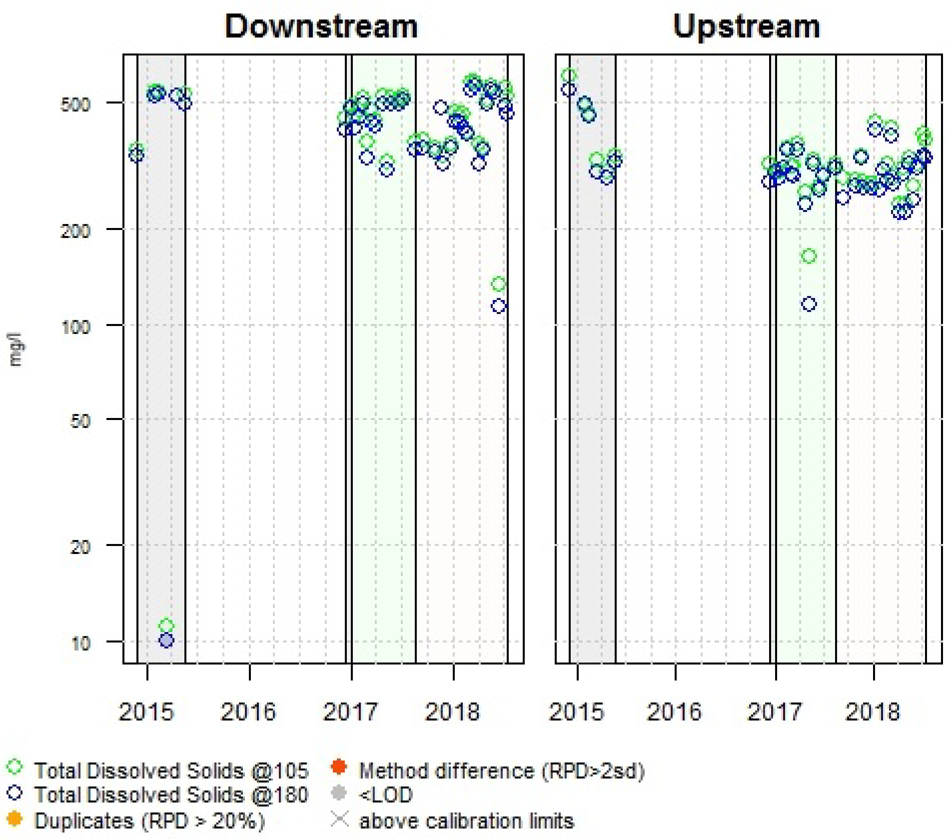
1. Individual site time series

Shallow and deep response zone boreholes





Surface waters



Appendix 5 – Preston New Road air quality operational data pack

This appendix contains the data presentation pack for measured concentrations of the prioritised substances at the Environment Agency monitoring station at Preston New Road.

Section A5.1: Preston New Road site, Environment Agency monitoring station - nitrogen dioxide

Section A5.2: Preston New Road site, Environment Agency monitoring station - PM_{10}

Section A5.3: Preston New Road site, Environment Agency monitoring station - methane

Section A5.4: Preston New Road site, Environment Agency monitoring station - speciated VOCs

A5.1 Preston New Road, Environment Agency site - NO_2

Figure A5.1: Density plot during operational phases (drilling and hydraulic fracturing) for NO_2 (Preston New Road, Environment Agency site)

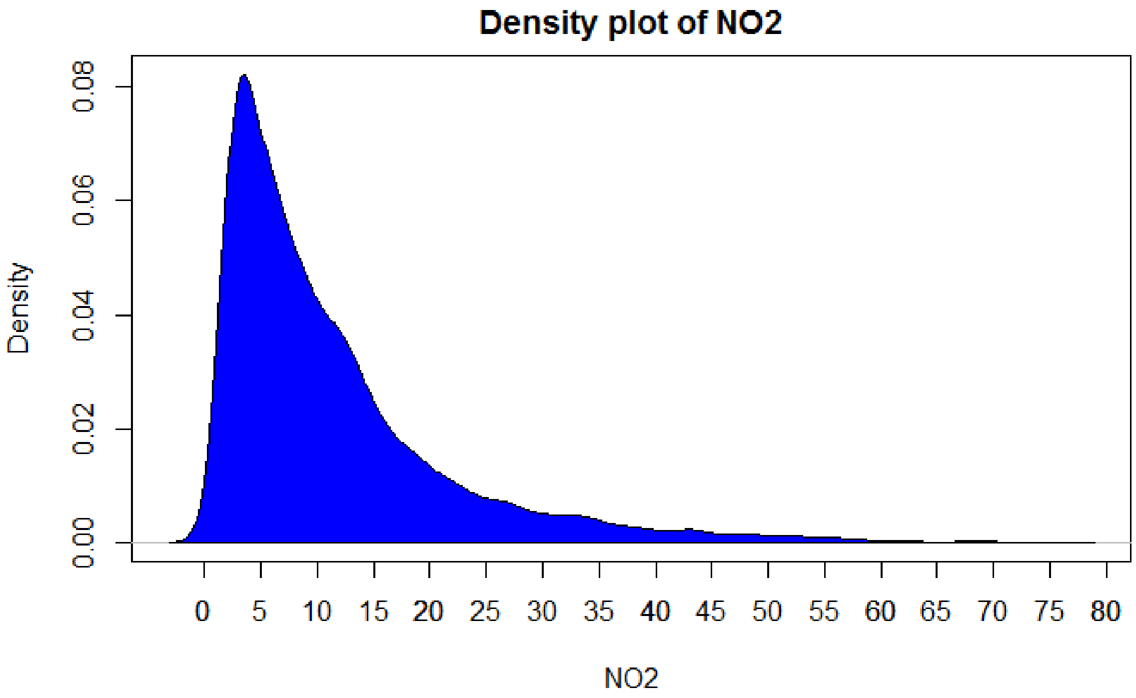


Figure A5.2: Time series for operational phases (drilling and hydraulic fracturing) for NO_2 (Preston New Road, Environment Agency site) (ppb)

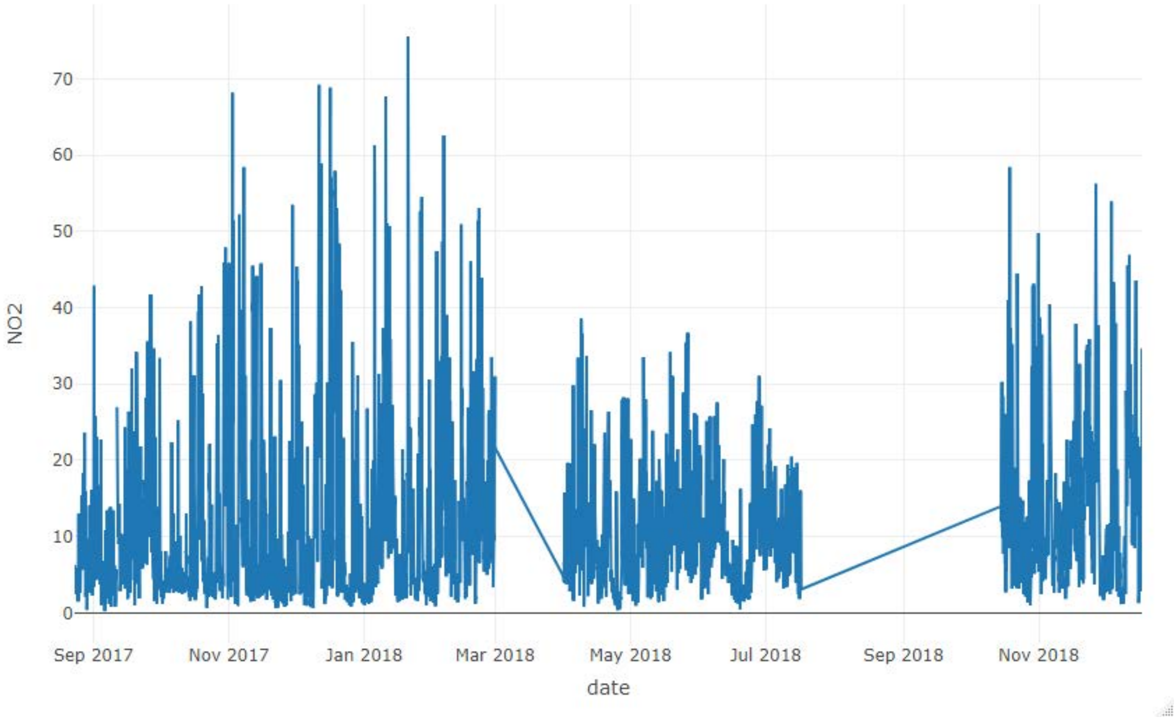


Figure A5.3: Time series plot of different percentiles for operational phases (drilling and hydraulic fracturing) data for NO_2 (Preston New Road, Environment Agency site) (ppb)

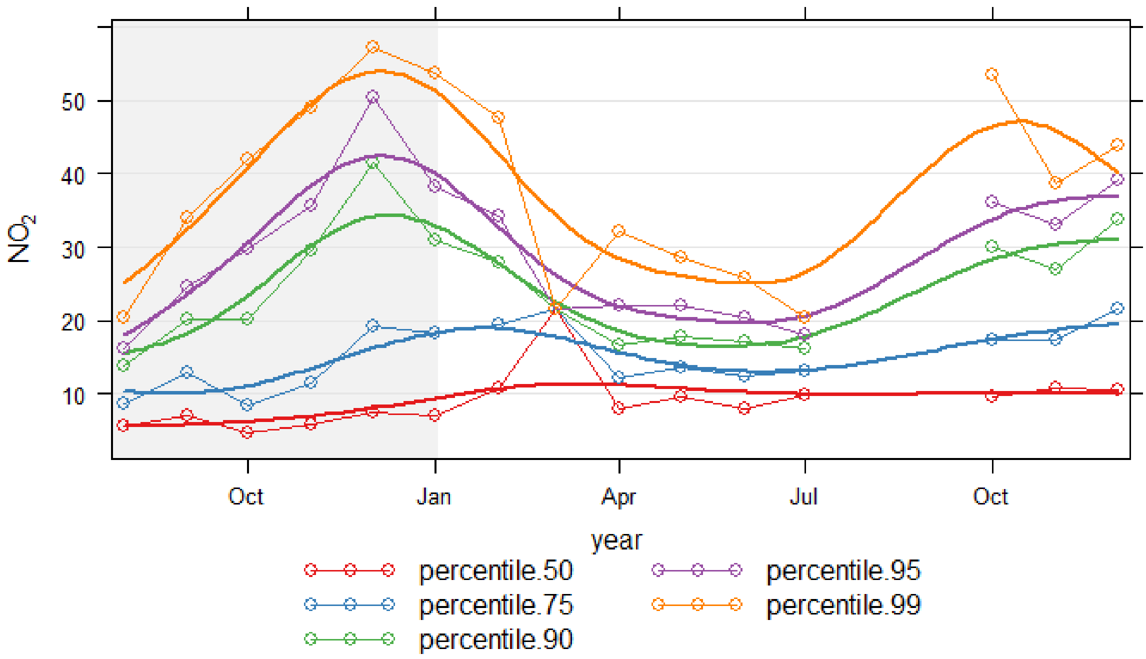


Figure A5.4: Time variation plot for operational phases (drilling and hydraulic fracturing) data for NO_2 (Preston New Road, Environment Agency site) (ppb)

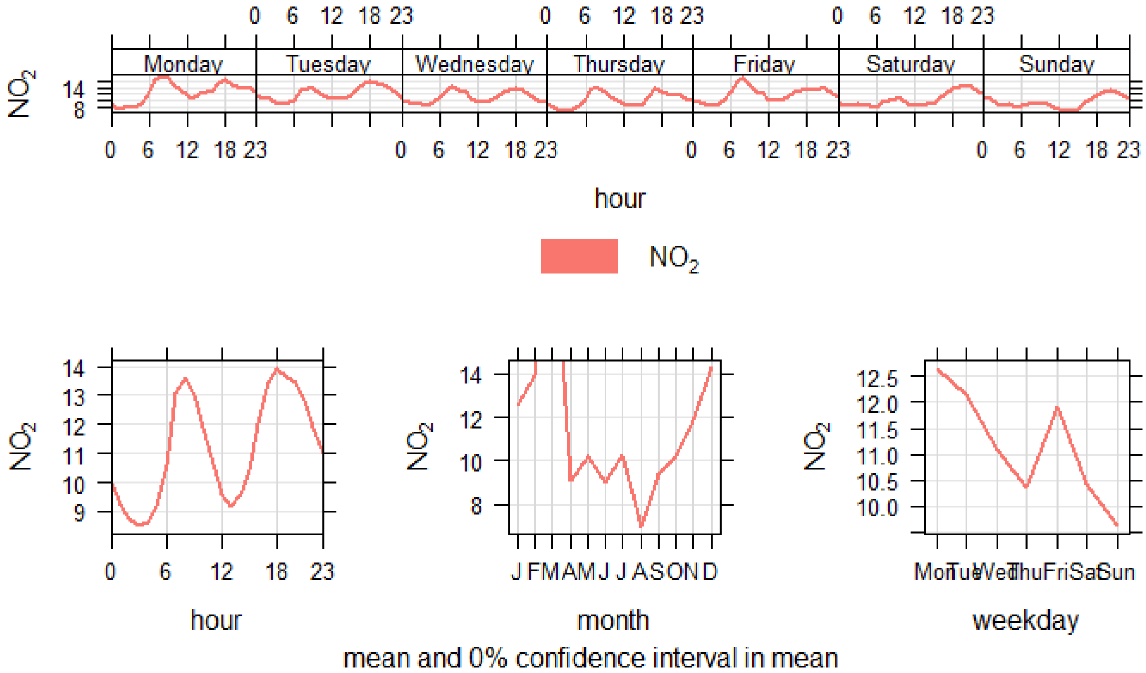


Table A5.1: Summary statistics for operational phases (drilling and hydraulic fracturing) for NO_2 (Preston New Road, Environment Agency site)

Metric	NO_2 (ppb)
Mean	11.2
50%	8.04
75%	14.3
90%	24.3
95%	32.7
99%	49.0
99.8%	57.6

Figure A5.5: Conditional probability plot between the 75th and 90th percentiles for operational phases (drilling and hydraulic fracturing) for NO_2 (Preston New Road, Environment Agency site)

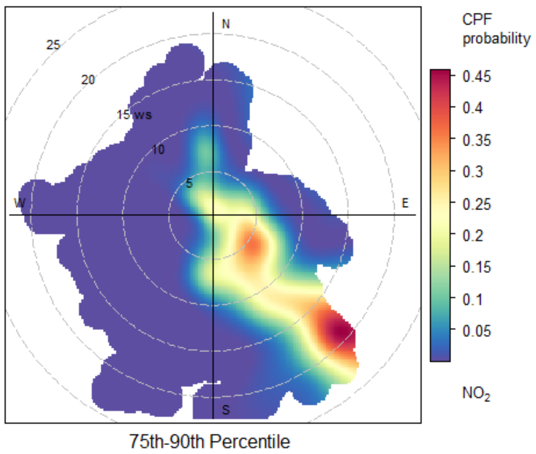


Figure A5.6: Conditional probability plot between the 90th and 95th percentiles for operational phases (drilling and hydraulic fracturing) data for NO_2 (Preston New Road, Environment Agency site)

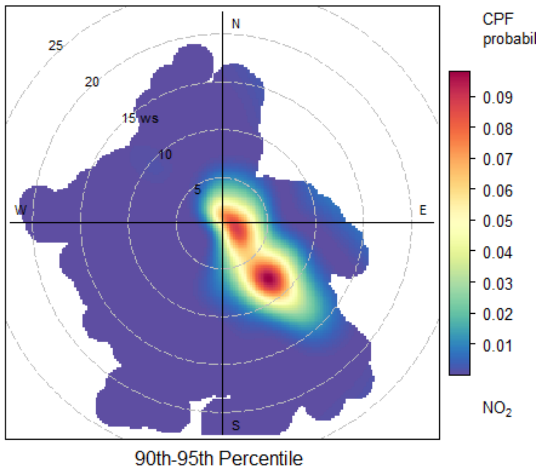


Figure A5.7: Conditional probability plot between the 95th and 99th percentiles for operational phases (drilling and hydraulic fracturing) data for NO_2 (Preston New Road, Environment Agency site)

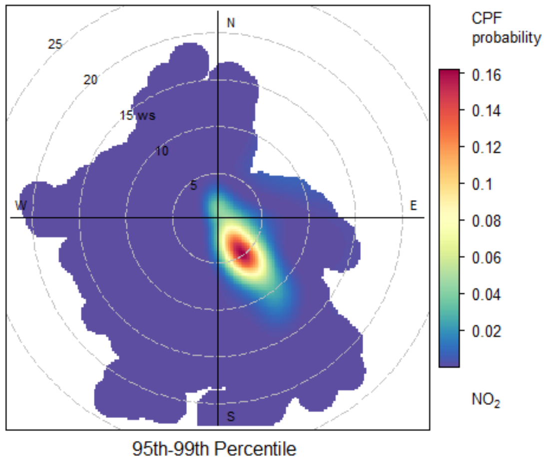


Figure A5.8: Conditional probability plot between the 99th and 100th percentiles operational phases (drilling and hydraulic fracturing) data for NO_2 (Preston New Road, Environment Agency site)

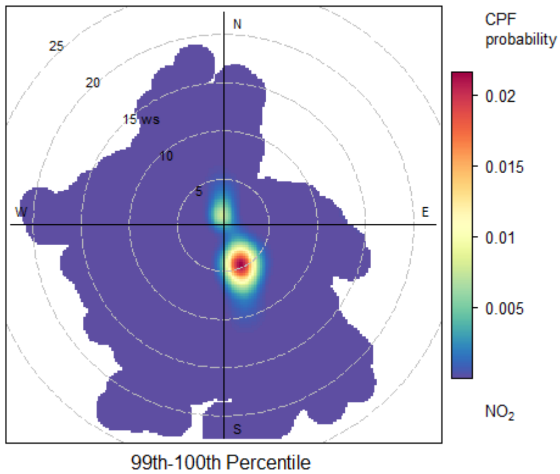


Figure A5.9: Polar plot of the mean concentration for different wind speed wind directions for operational phases (drilling and hydraulic fracturing) data for NO_2 (Preston New Road, Environment Agency site) (ppb)

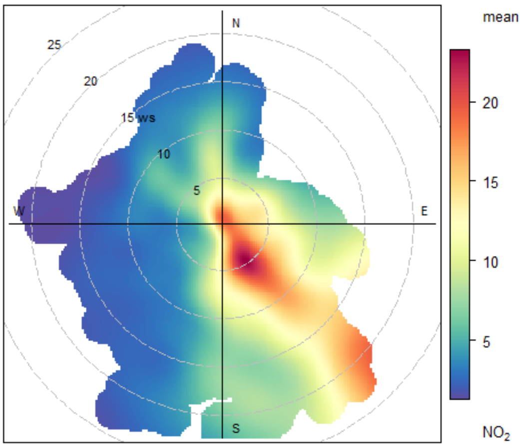


Figure A5.10: Polar plot of the median concentration for different wind speed wind directions for operational phases (drilling and hydraulic fracturing) data for NO_2 (Preston New Road, Environment Agency site) (ppb)

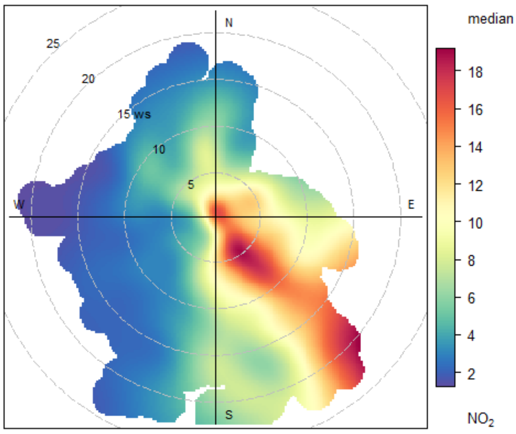


Figure A5.11: Polar plot of the 75th percentile concentration for different wind speed wind directions for operational phases (drilling and hydraulic fracturing) for NO_2 (Preston New Road, Environment Agency site) (ppb)

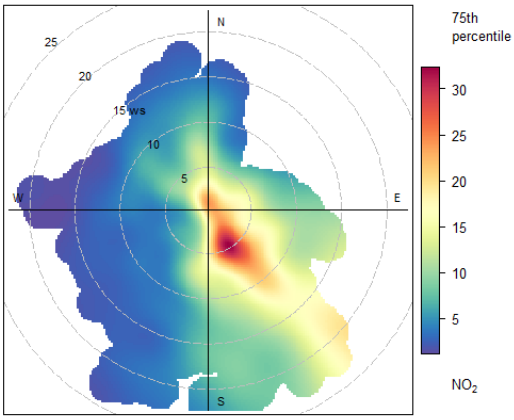


Figure A5.12: Polar plot of the 90th percentile concentration for different wind speed wind directions for operational phases (drilling and hydraulic fracturing) data for NO_2 (Preston New Road, Environment Agency site) (ppb)

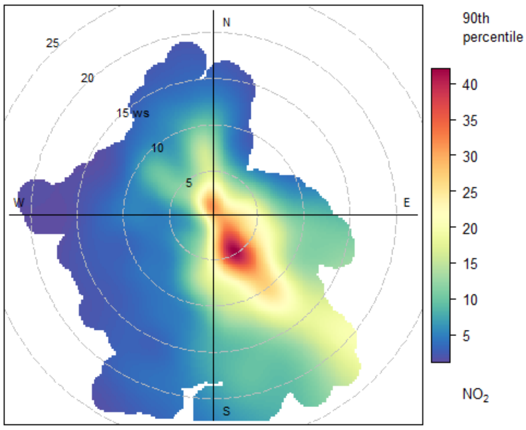


Figure A5.13: Polar plot of the 95th percentile concentration for different wind speed wind directions for operational phases (drilling and hydraulic fracturing) data for NO_2 (Preston New Road, Environment Agency site) (ppb)

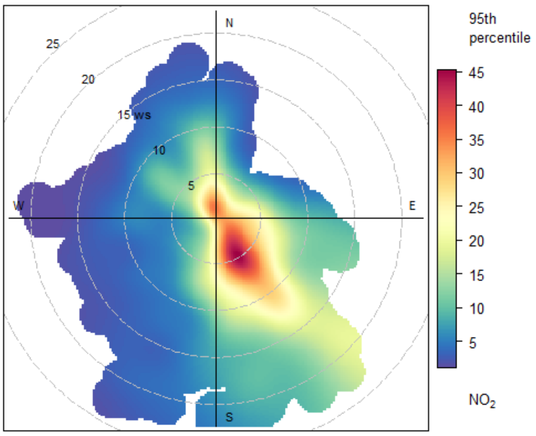


Figure A5.14: Polar plot of the 99th percentile concentration for different wind speed wind directions for operational phases (drilling and hydraulic fracturing) data for NO_2 (Preston New Road, Environment Agency site) (ppb)

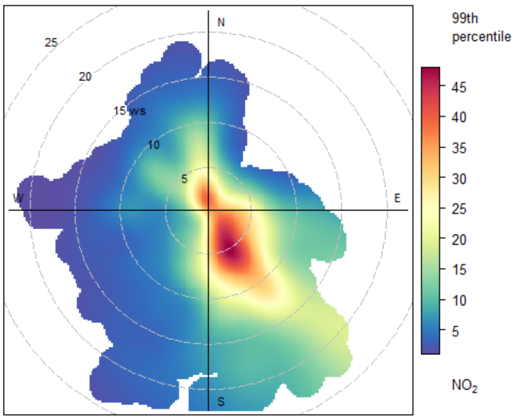


Figure A5.15: Polar plot of the weighted mean (mean/frequency) for different wind speed wind directions for operational phases (drilling and hydraulic fracturing) data for NO_2 (Preston New Road, Environment Agency site)

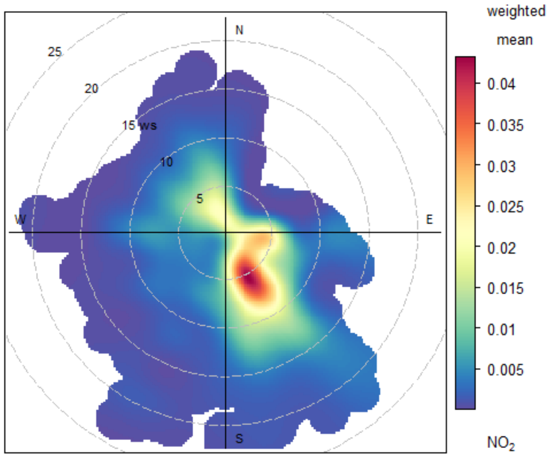
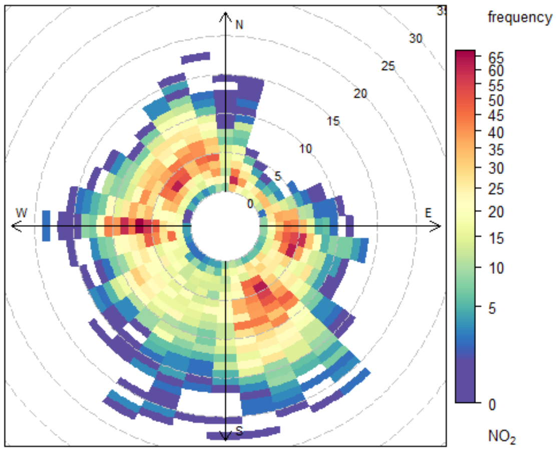


Figure A5.16: Polar frequency plot for operational phases (drilling and hydraulic fracturing) data (Preston New Road, Environment Agency site)



A5.2 Preston New Road, Environment Agency site - PM_{10}

Figure A5.17: Density plot during operational phases (drilling and hydraulic fracturing) for PM_{10} (Preston New Road, Environment Agency site)

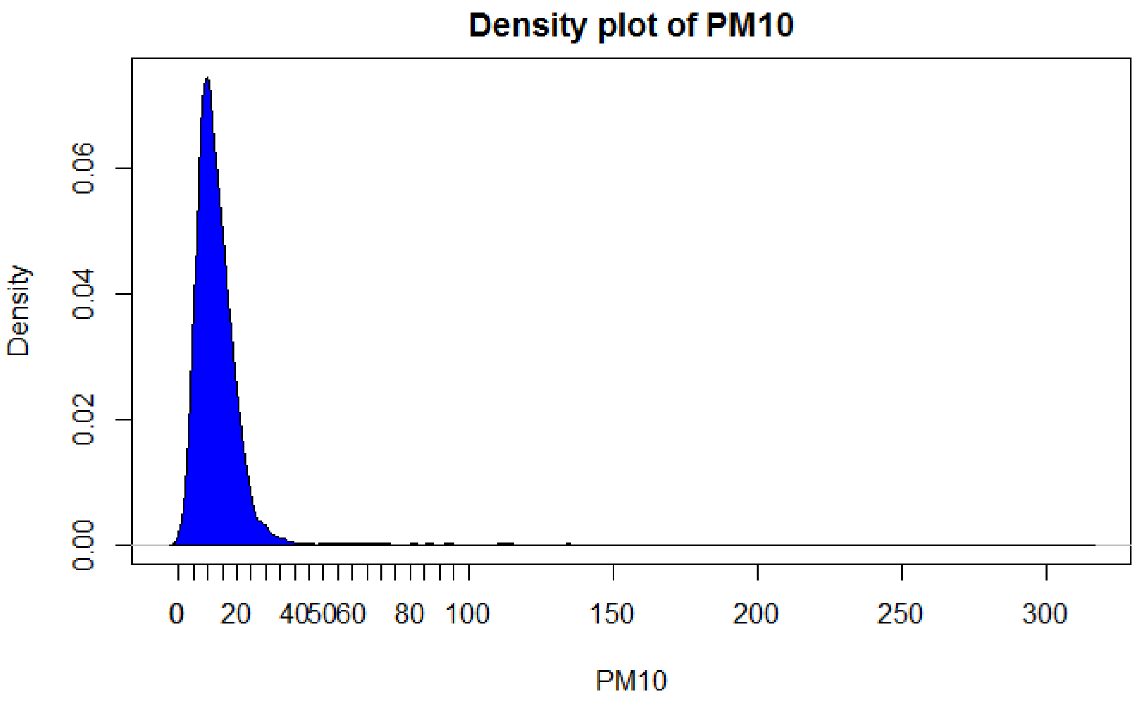


Figure A5.18: Time series for operational phases (drilling and hydraulic fracturing) for PM_{10} (Preston New Road, Environment Agency site) (μg/m³)

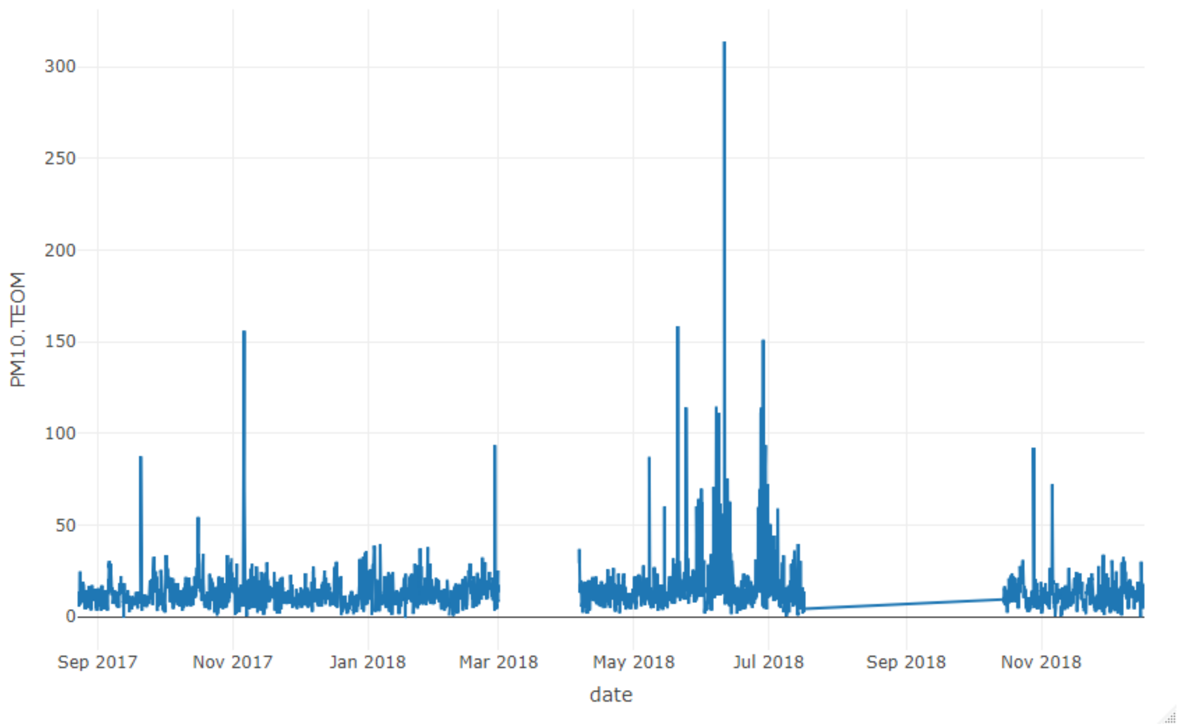


Figure A5.19: Time series plot of different percentiles for operational phases (drilling and hydraulic fracturing) data for NO_2 (Preston New Road, Environment Agency site) (µg/m³)

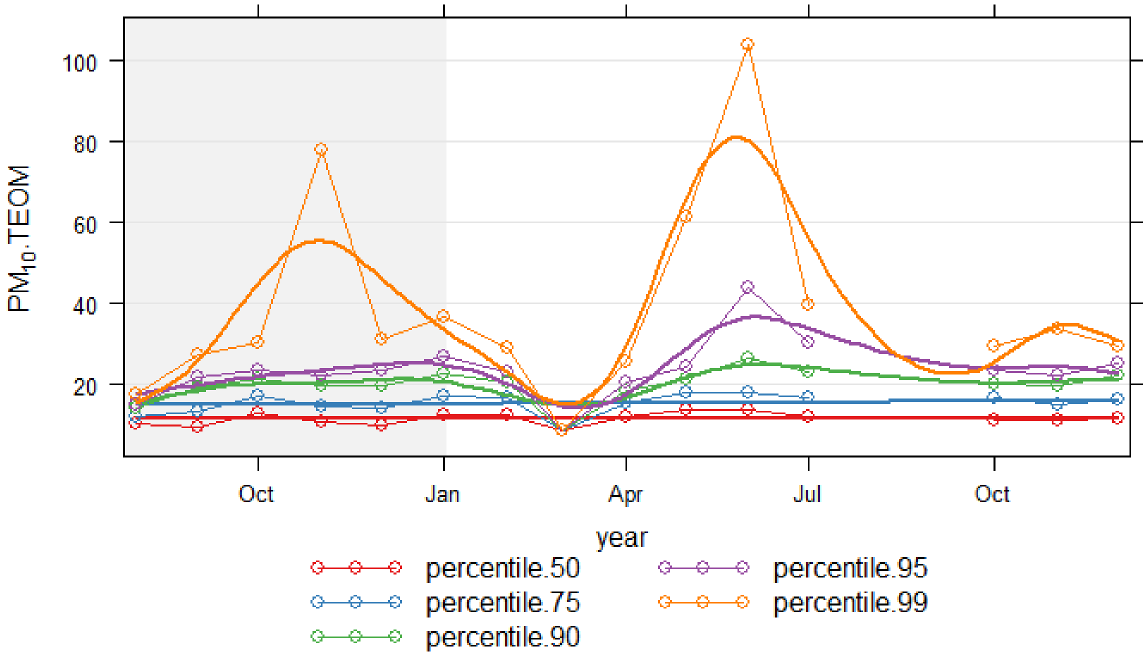


Figure A5.20: Time variation plot for operational phases (drilling and hydraulic fracturing) data for NO_2 (Preston New Road, Environment Agency site) (µg/m³)

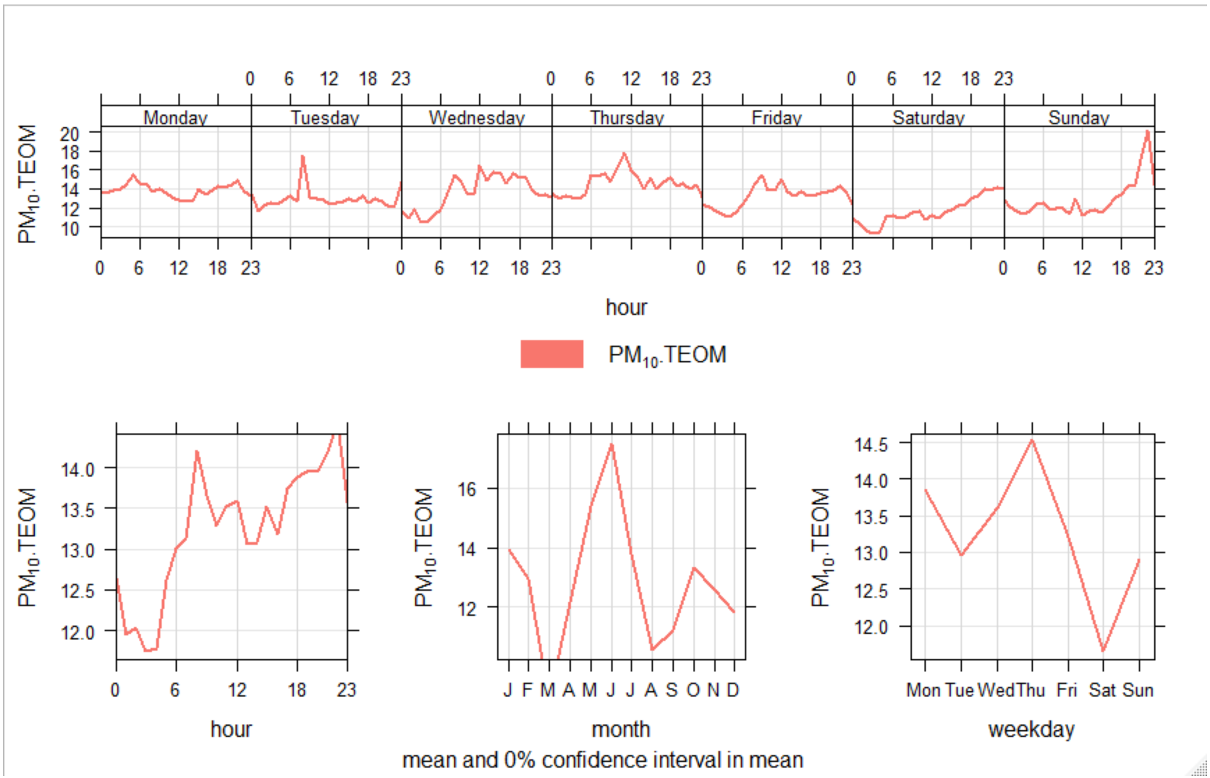


Table A5.2: Summary statistics for operational phases (drilling and hydraulic fracturing) for PM_{10} (Preston New Road, Environment Agency site)

Metric	PM_{10} (µg/m^3)
Mean	13.2
50%	11.7
75%	16.2
90%	20.9
95%	24.4
99%	38.0

Figure A5.21: Conditional probability plot between the 75th and 90th percentiles for operational phases (drilling and hydraulic fracturing) for PM_{10} (Preston New Road, Environment Agency site)

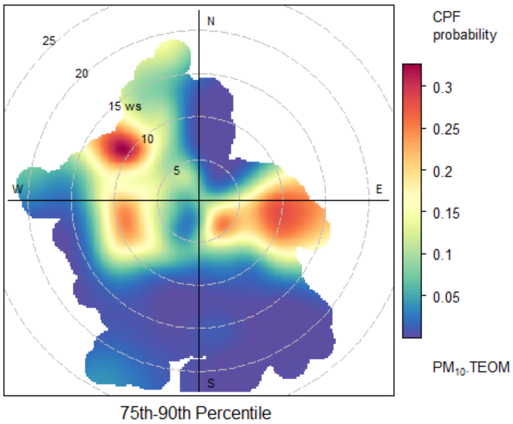


Figure A5.22: Conditional probability plot between the 90th and 95th percentiles for operational phases (drilling and hydraulic fracturing) data for PM_{10} (Preston New Road, Environment Agency site)

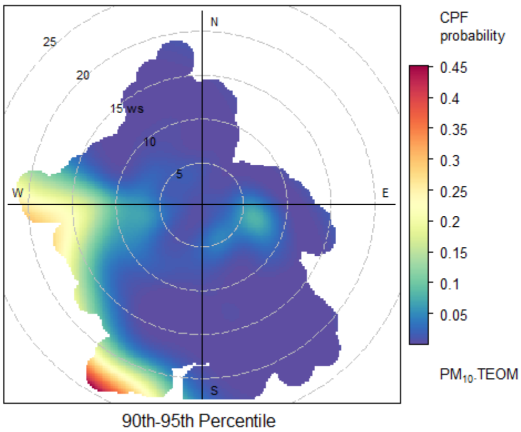


Figure A5.23: Conditional probability plot between the 95th and 99th percentiles for operational phases (drilling and hydraulic fracturing) data for PM_{10} (Preston New Road, Environment Agency site)

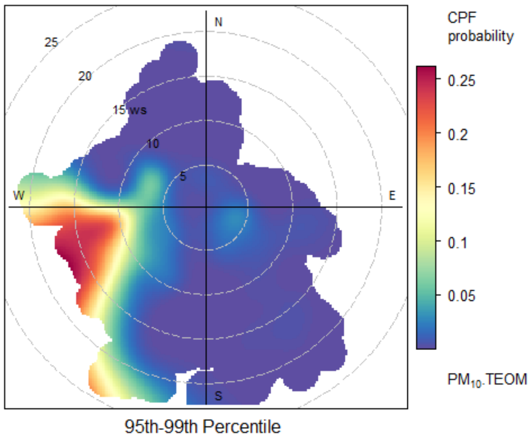


Figure A5.24: Conditional probability plot between the 99th and 100th percentiles for operational phases (drilling and hydraulic fracturing) data for PM_{10} (Preston New Road, Environment Agency site)

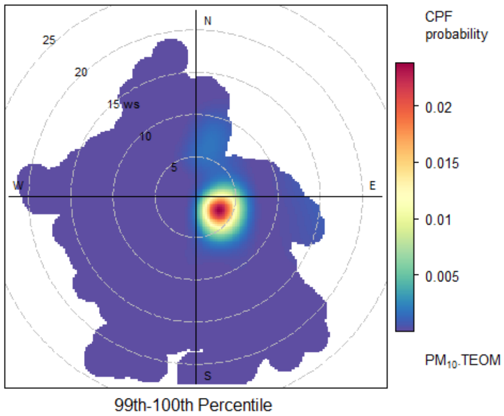


Figure A5.25: Polar plot of the mean concentration for different wind speed wind directions for operational phases (drilling and hydraulic fracturing) data for PM_{10} (Preston New Road, Environment Agency site) (µg/m^3)

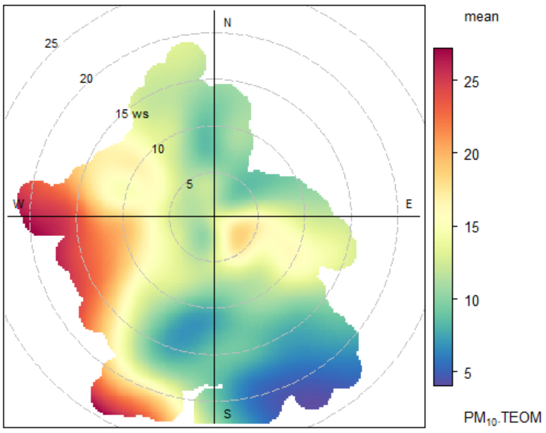


Figure A5.26: Polar plot of the median concentration for different wind speed wind directions for operational phases (drilling and hydraulic fracturing) data for PM_{10} (Preston New Road, Environment Agency site) (µg/m^3)

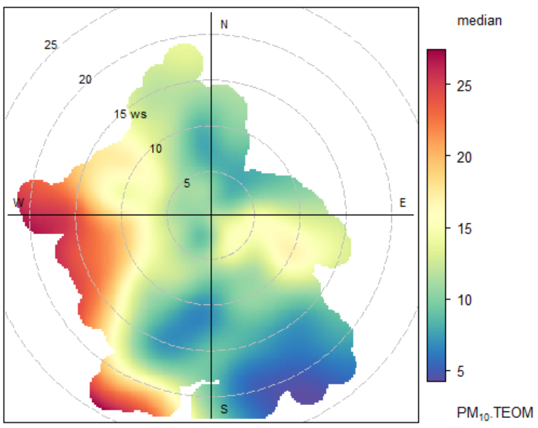


Figure A5.27: Polar plot of the 75th percentile concentration for different wind speed wind directions for operational phases (drilling and hydraulic fracturing) for PM_{10} (Preston New Road, Environment Agency site) (µg/m^3)

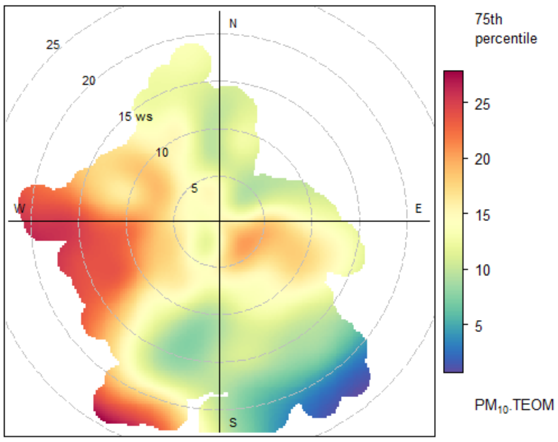


Figure A5.28: Polar plot of the 90th percentile concentration for different wind speed wind directions for operational phases (drilling and hydraulic fracturing) data for PM_{10} (Preston New Road, Environment Agency site) (µg/m^3)

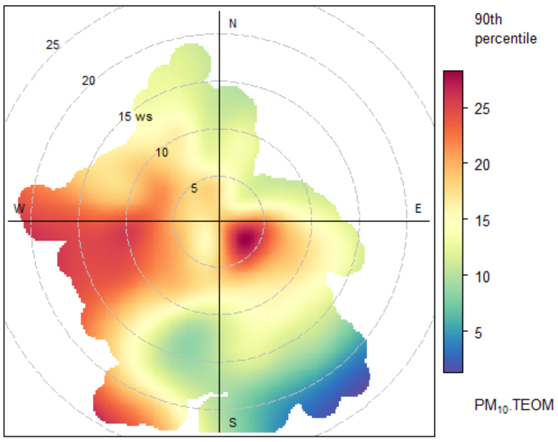


Figure A5.29: Polar plot of the 95th percentile concentration for different wind speed wind directions for operational phases (drilling and hydraulic fracturing) data for PM_{10} (Preston New Road, Environment Agency site) (µg/m^3)

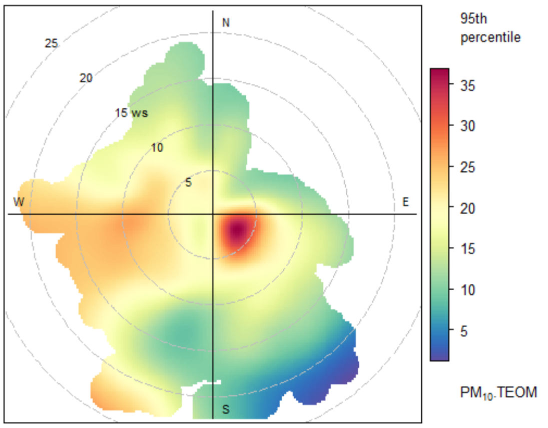


Figure A5.30: Polar plot of the 99th percentile concentration for different wind speed wind directions for operational phases (drilling and hydraulic fracturing) data for PM_{10} (Preston New Road, Environment Agency site) (µg/m^3)

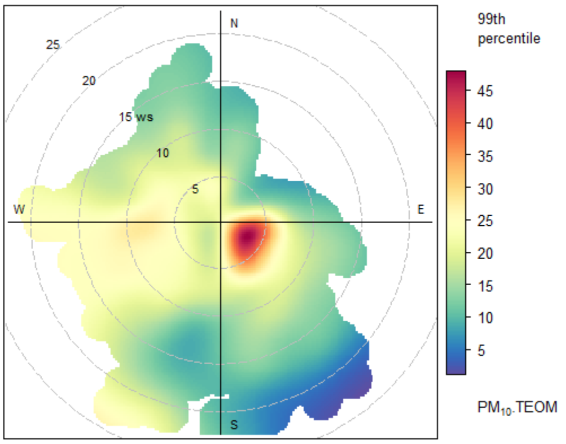


Figure A5.31: Polar plot of the weighted mean (mean/frequency) for different wind speed wind directions for operational phases (drilling and hydraulic fracturing) data for PM_{10} (Preston New Road, Environment Agency site)

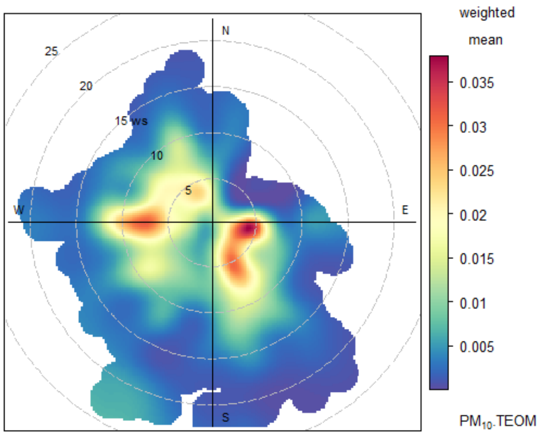
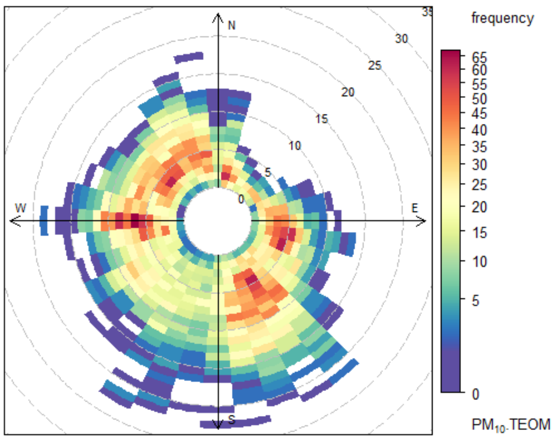


Figure A5.32: Polar frequency plot for operational phases (drilling and hydraulic fracturing) data (Preston New Road, Environment Agency site)



A5.3 Preston New Road, Environment Agency site - CH_4

Figure A5.33: Density plot during operational phases (drilling and hydraulic fracturing) for CH_4 (Preston New Road, Environment Agency site)

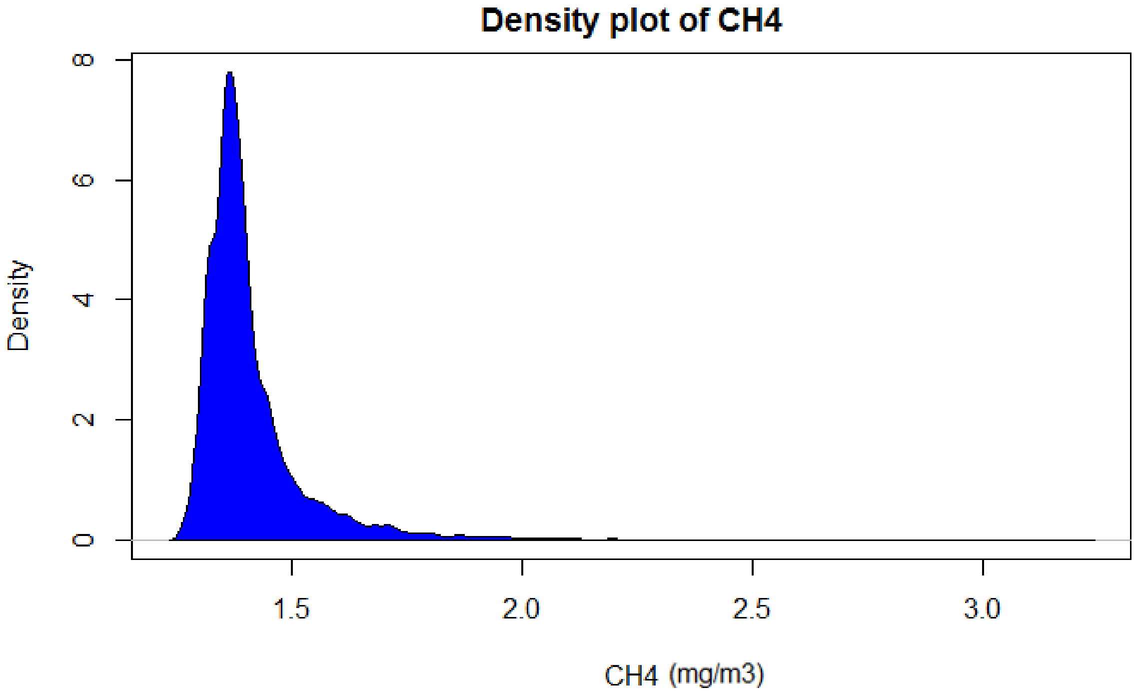


Figure A5.34: Time series for operational phases (drilling and hydraulic fracturing) for CH_4 (Preston New Road, Environment Agency site)

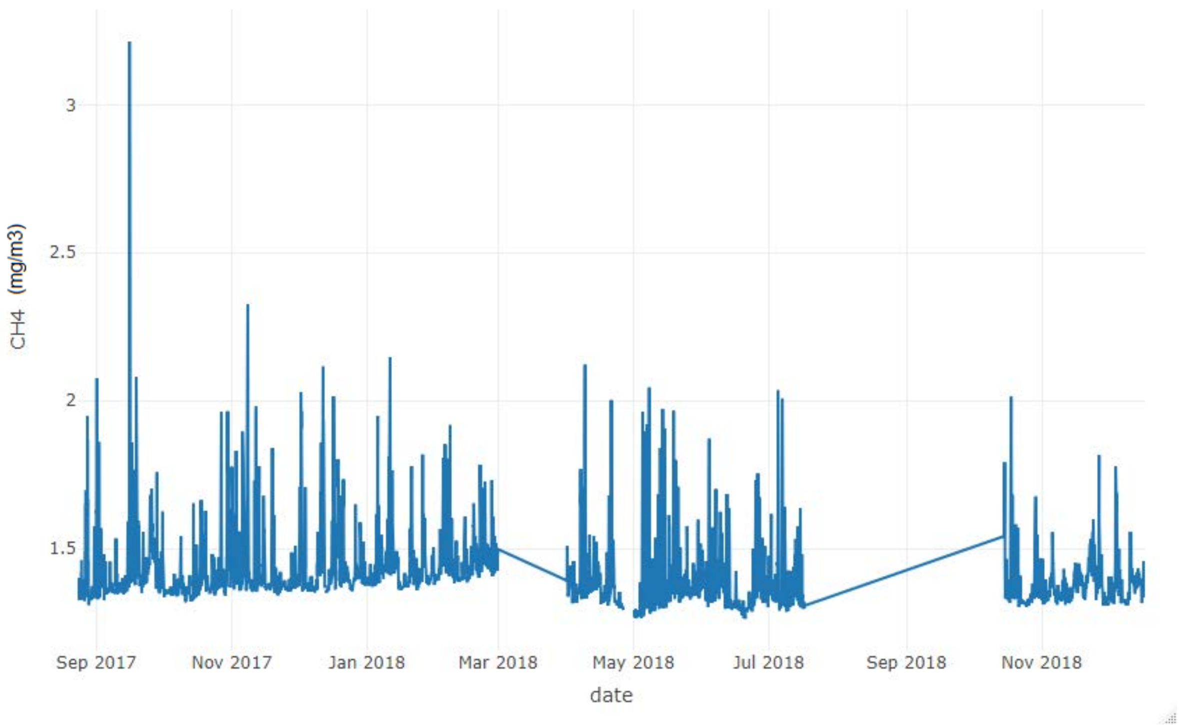


Figure A5.35: Time series plot of different percentiles for operational phases (drilling and hydraulic fracturing) data for CH_4 (Preston New Road, Environment Agency site)

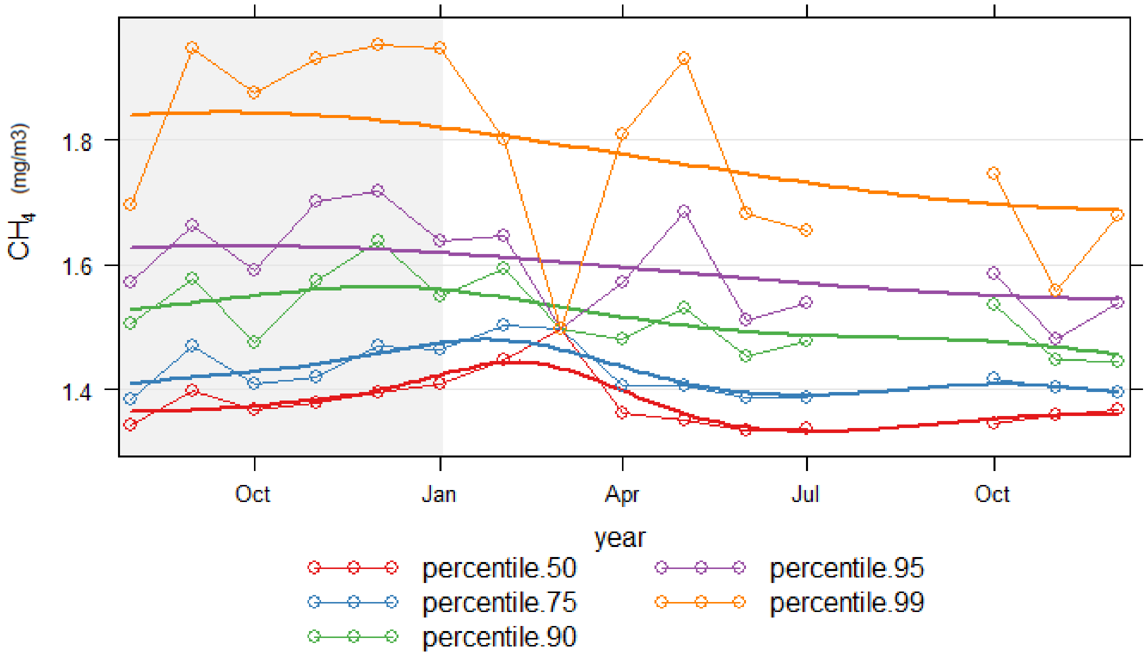


Figure A5.36: Time-variation plot for operational phases (drilling and hydraulic fracturing) data for CH_4 (Preston New Road, Environment Agency site) (mg/m^3)

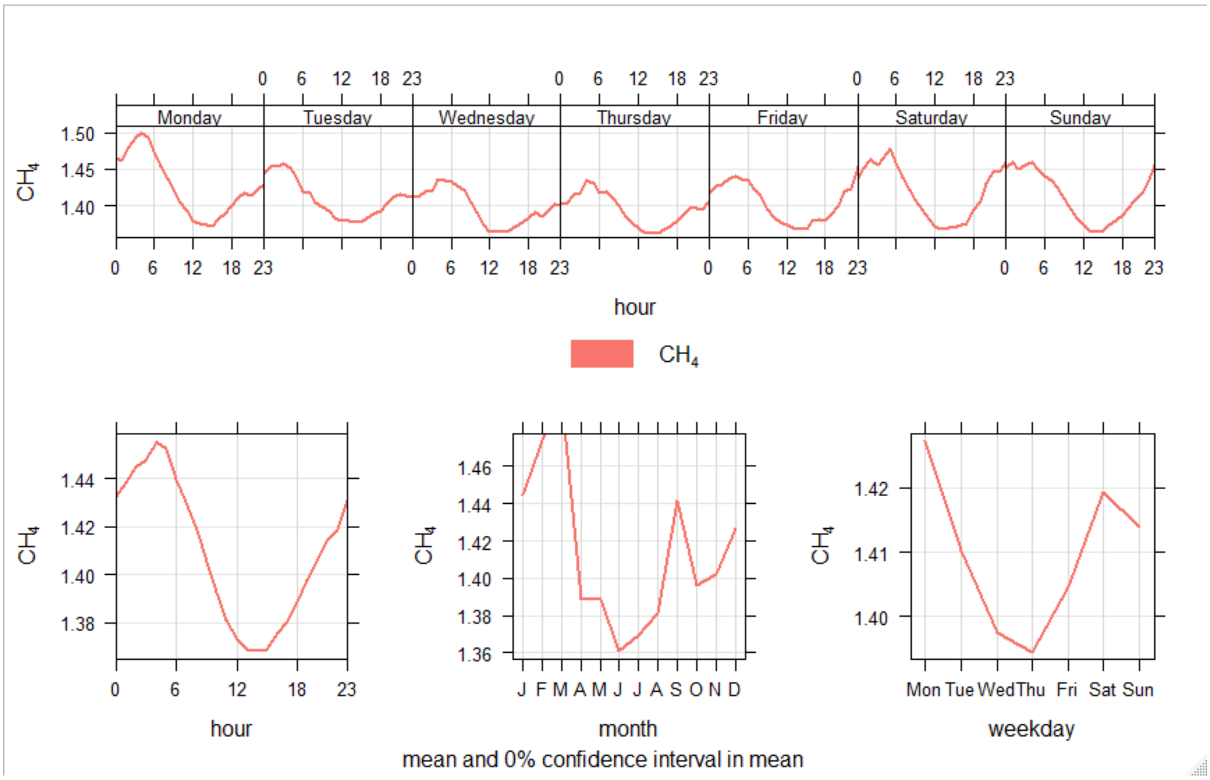


Table A5.3: Summary statistics for operational phases (drilling and hydraulic fracturing) for CH_4 (Preston New Road, Environment Agency site)

Metric	CH_4 (mg/m^3)
Mean	1.41
50%	1.38
75%	1.43
90%	1.54
95%	1.62
99%	1.87

Figure A5.37: Conditional probability plot between the 75th and 90th percentiles for operational phases (drilling and hydraulic fracturing) for CH_4 (Preston New Road, Environment Agency site)

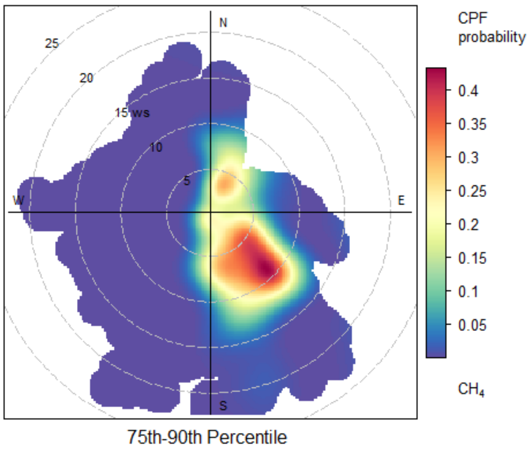


Figure A5.38: Conditional probability plot between the 90th and 95th percentiles for operational phases (drilling and hydraulic fracturing) data for CH_4 (Preston New Road, Environment Agency site)

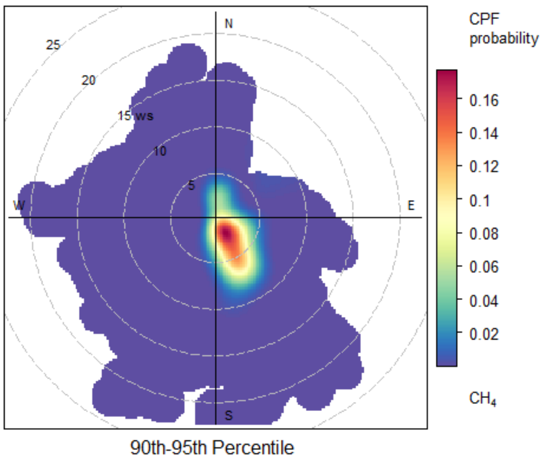


Figure A5.39: Conditional probability plot between the 95th and 99th percentiles for operational phases (drilling and hydraulic fracturing) data for CH_4 (Preston New Road, Environment Agency site)

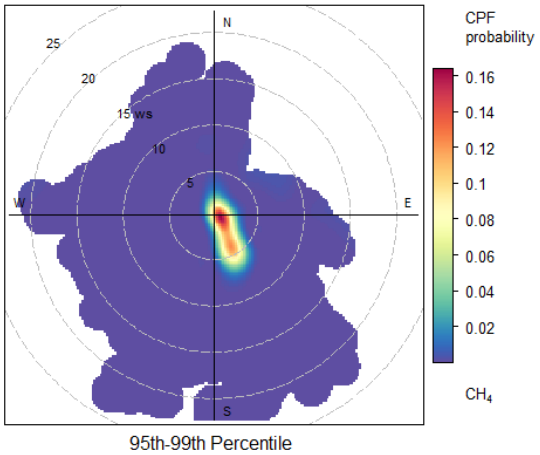


Figure A5.40: Conditional probability plot between the 99th and 100th percentiles for operational phases (drilling and hydraulic fracturing) data for CH_4 (Preston New Road, Environment Agency site)

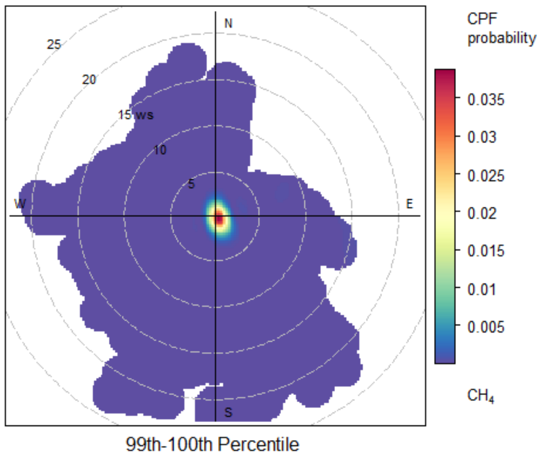


Figure A5.41: Polar plot of the mean concentration for different wind speed wind directions for operational phases (drilling and hydraulic fracturing) data for CH_4 (Preston New Road, Environment Agency site)

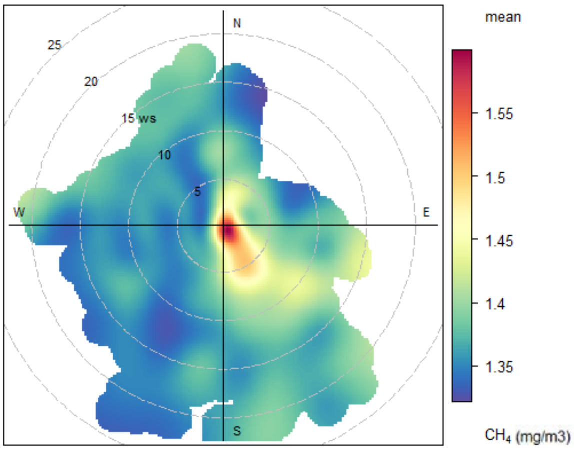


Figure A5.42: Polar plot of the median concentration for different wind speed wind directions for operational phases (drilling and hydraulic fracturing) data for CH_4 (Preston New Road, Environment Agency site)

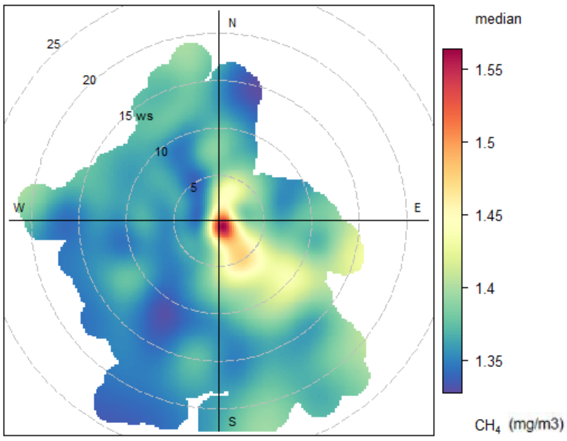


Figure A5.43: Polar plot of the 75th percentile concentration for different wind speed wind directions for operational phases (drilling and hydraulic fracturing) for CH_4 (Preston New Road, Environment Agency site)

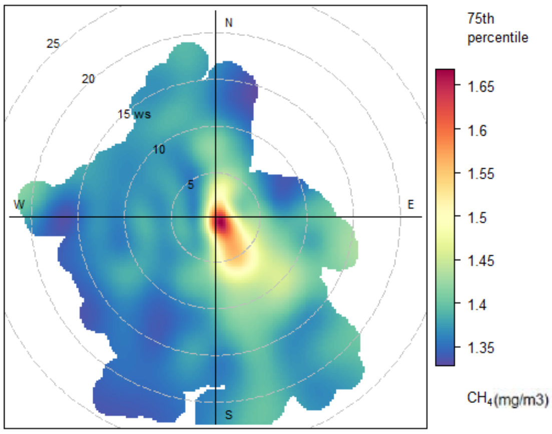


Figure A5.44: Polar plot of the 90th percentile concentration for different wind speed wind directions for operational phases (drilling and hydraulic fracturing) data for CH_4 (Preston New Road, Environment Agency site)

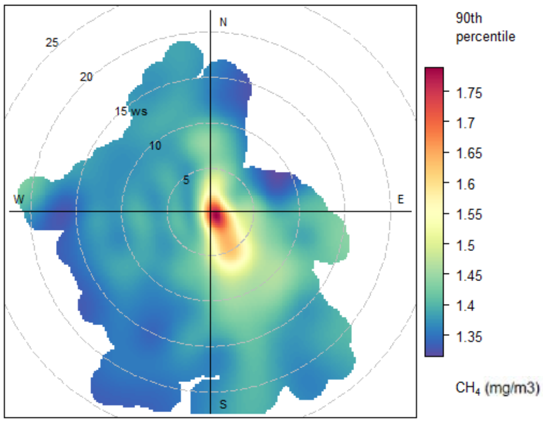


Figure A5.45: Polar plot of the 95th percentile concentration for different wind speed wind directions for operational phases (drilling and hydraulic fracturing) data for CH_4 (Preston New Road, Environment Agency site)

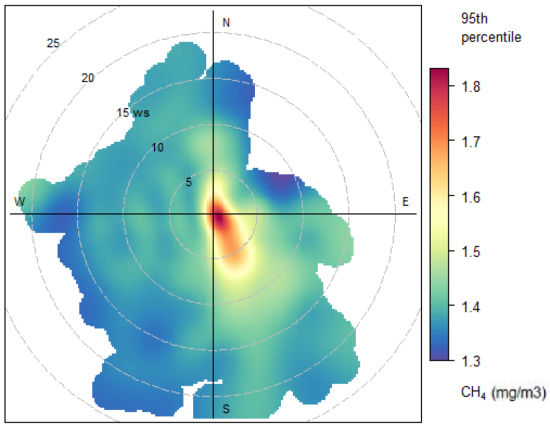


Figure A5.46: Polar plot of the 99th percentile concentration for different wind speed wind directions for operational phases (drilling and hydraulic fracturing) data for CH_4 (Preston New Road, Environment Agency site)

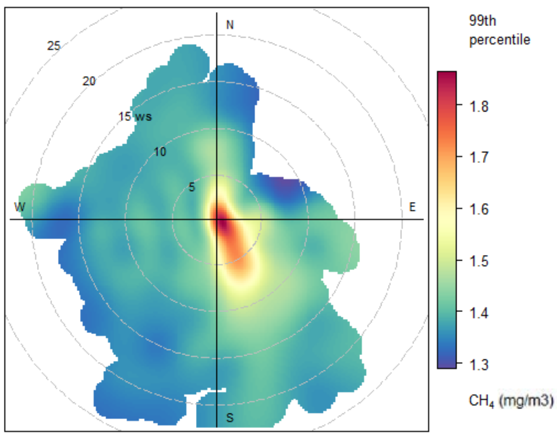


Figure A5.47: Polar plot of the weighted mean (mean/frequency) for different wind speed wind directions for operational phases (drilling and hydraulic fracturing) data for CH_4 (Preston New Road, Environment Agency site)

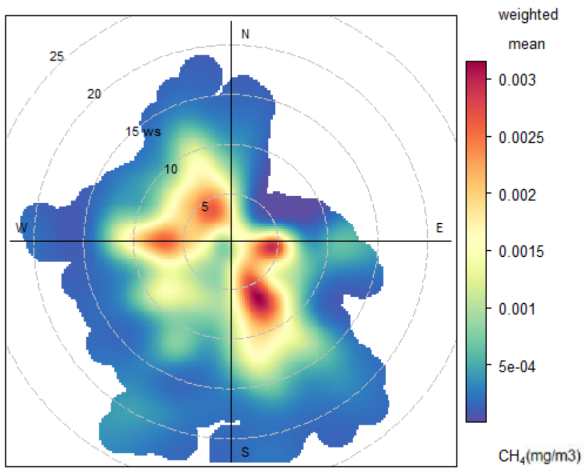
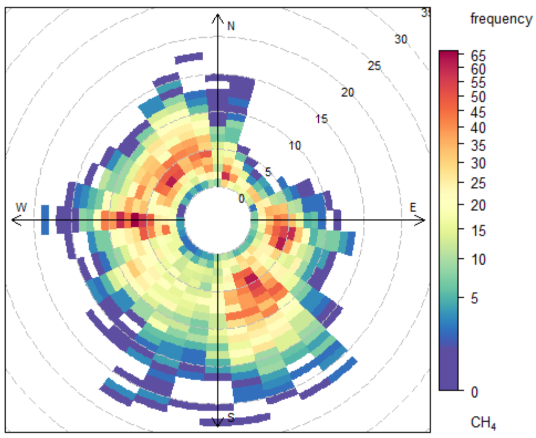


Figure A5.48: Polar frequency plot for operational phases (drilling and hydraulic fracturing) data (Preston New Road, Environment Agency site)



A5.4 Preston New Road, Environment Agency site – VOC: benzene

Figure A5.49: Density plot during operational phases (drilling and hydraulic fracturing) for benzene (Preston New Road, Environment Agency site)

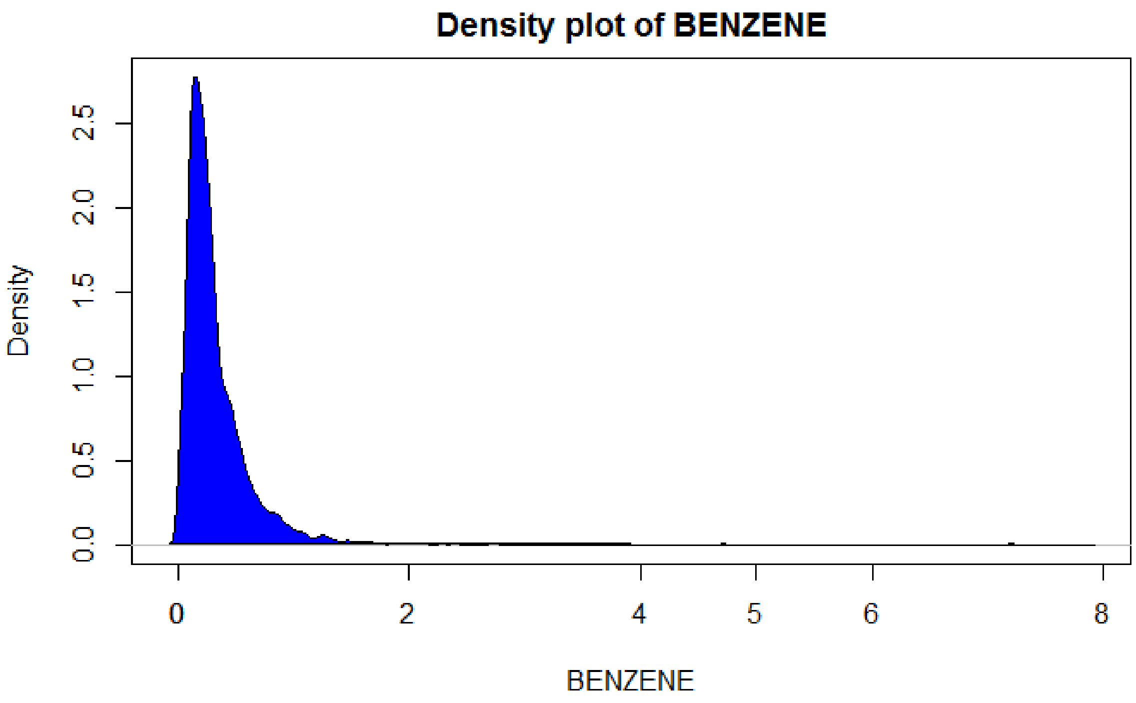


Figure A5.50: Time series for operational phases (drilling and hydraulic fracturing) for benzene (Preston New Road, Environment Agency site) (µg/m³)

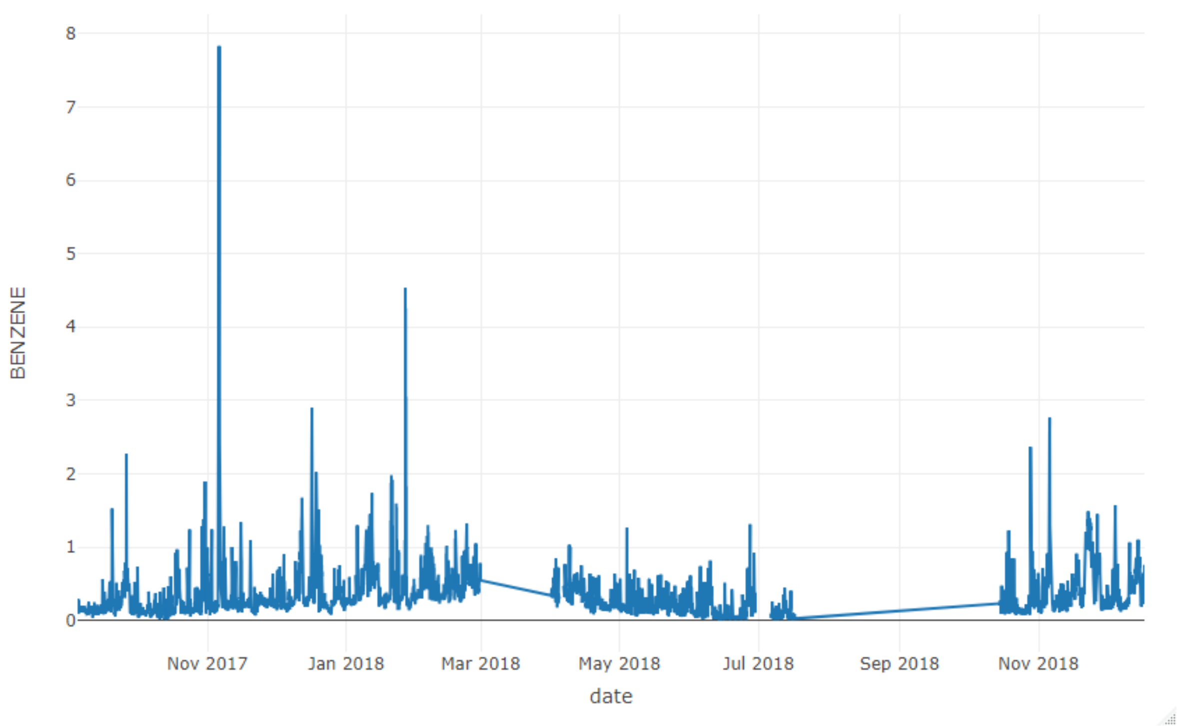


Figure A5.51: Time series plot of different percentiles for operational phases (drilling and hydraulic fracturing) data for benzene (Preston New Road, Environment Agency site) (µg/m³)

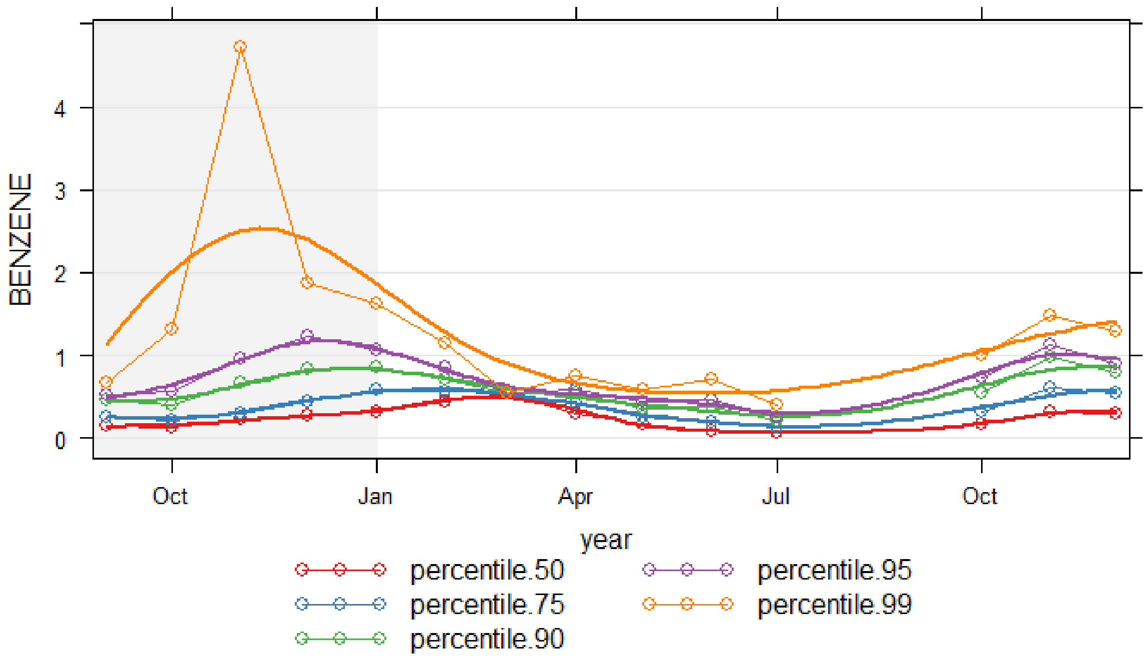


Figure A5.52: Time variation plot for operational phases (drilling and hydraulic fracturing) data for benzene (Preston New Road, Environment Agency site) (µg/m³)

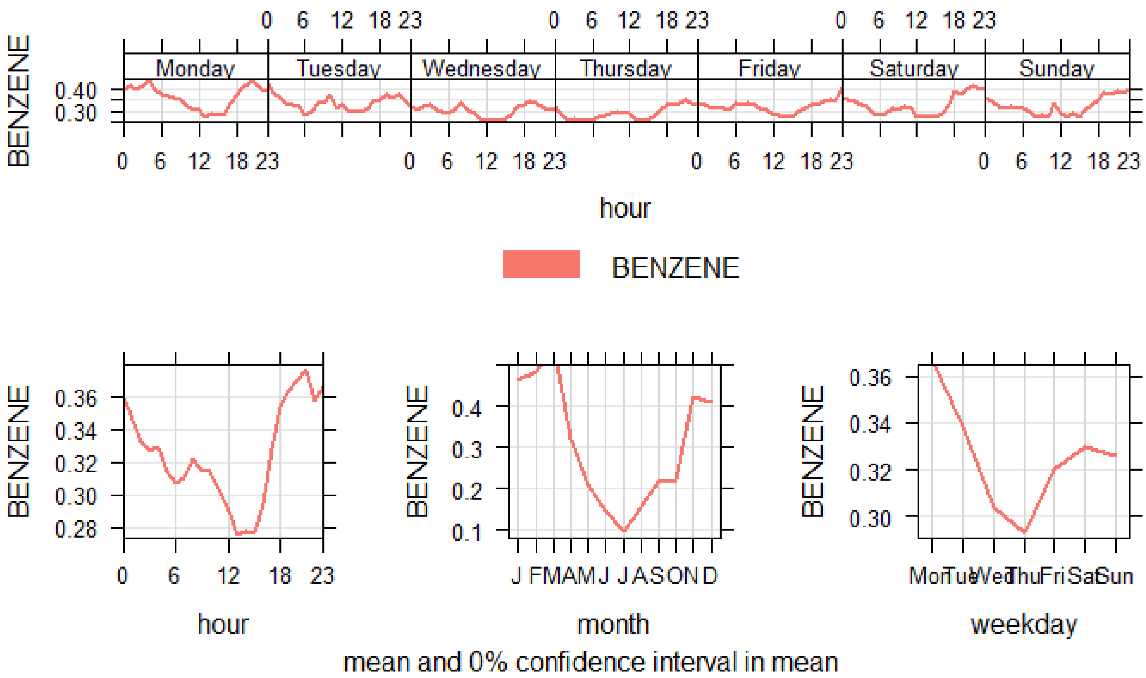


Table A5.4: Summary statistics for operational phases (drilling and hydraulic fracturing) for benzene (Preston New Road, Environment Agency site)

Metric	Benzene (µg/m^3)
Mean	0.33
50%	0.24
75%	0.41
90%	0.64
95%	0.85
99%	1.40

Figure A5.53: Conditional probability plot between the 75th and 90th percentiles for operational phases (drilling and hydraulic fracturing) for benzene (Preston New Road, Environment Agency site)

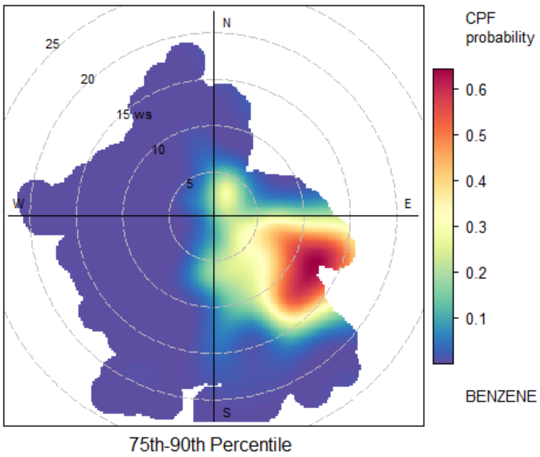


Figure A5.54: Conditional probability plot between the 90th and 95th percentiles for operational phases (drilling and hydraulic fracturing) data for benzene (Preston New Road, Environment Agency site)

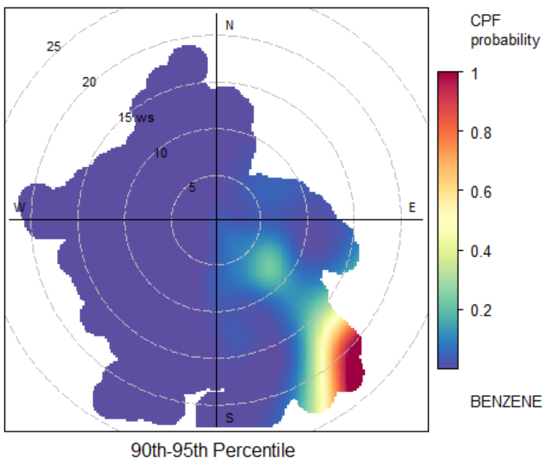


Figure A5.55: Conditional probability plot between the 95th and 99th percentiles for operational phases (drilling and hydraulic fracturing) data for benzene (Preston New Road, Environment Agency site)

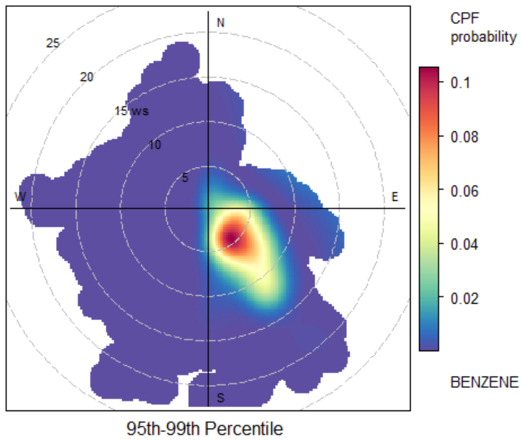


Figure A5.56: Conditional probability plot between the 99th and 100th percentiles for operational phases (drilling and hydraulic fracturing) data for benzene (Preston New Road, Environment Agency site)

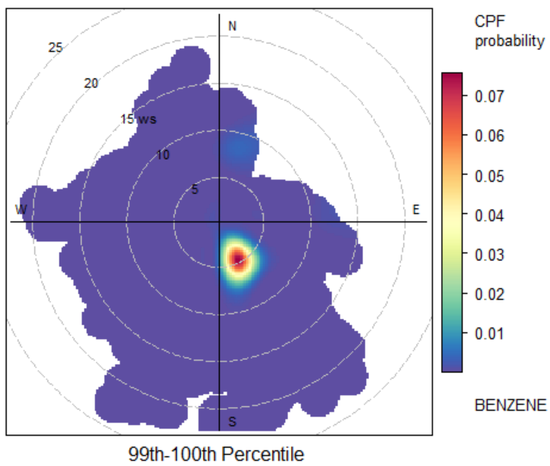


Figure A5.57: Polar plot of the mean concentration for different wind speed wind directions for operational phases (drilling and hydraulic fracturing) data for benzene (Preston New Road, Environment Agency site) (µg/m³)

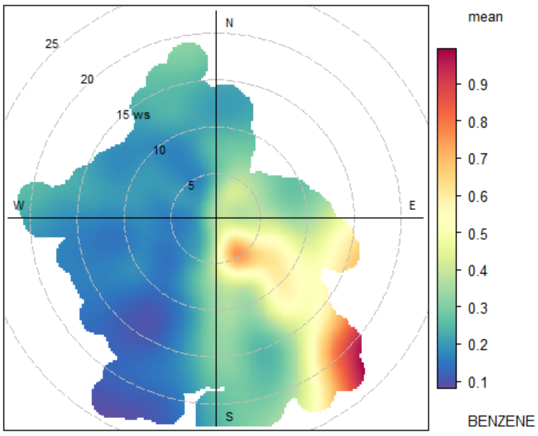


Figure A5.58: Polar plot of the median concentration for different wind speed wind directions for operational phases (drilling and hydraulic fracturing) data for benzene (Preston New Road, Environment Agency site) (µg/m³)

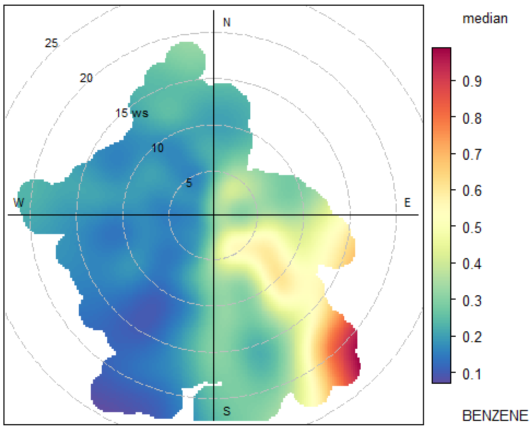


Figure A5.59: Polar plot of the 75th percentile concentration for different wind speed wind directions for operational phases (drilling and hydraulic fracturing) for benzene (Preston New Road, Environment Agency site) (µg/m³)

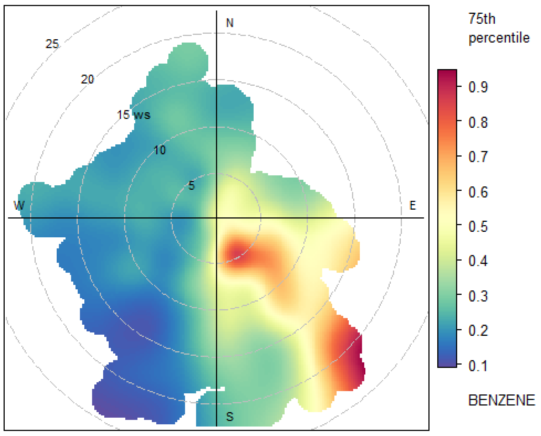


Figure A5.60: Polar plot of the 90th percentile concentration for different wind speed wind directions for operational phases (drilling and hydraulic fracturing) data for benzene (Preston New Road, Environment Agency site) (µg/m³)

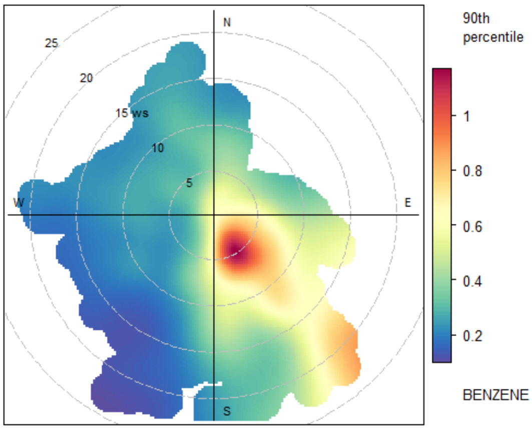


Figure A5.61: Polar plot of the 95th percentile concentration for different wind speed wind directions for operational phases (drilling and hydraulic fracturing) data for benzene (Preston New Road, Environment Agency site) (µg/m³)

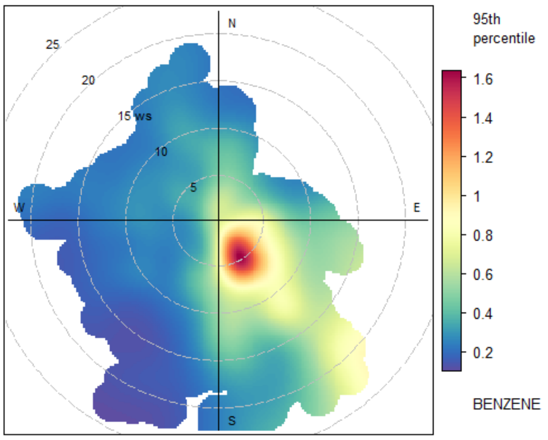
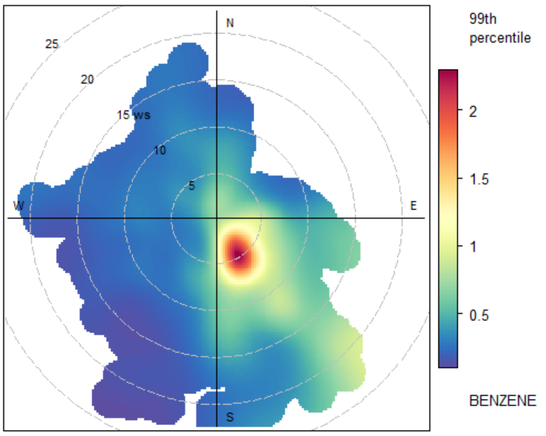


Figure A5.62: Polar plot of the 99th percentile concentration for different wind speed wind directions for operational phases (drilling and hydraulic fracturing) data for benzene (Preston New Road, Environment Agency site) (µg/m³)



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