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FINAL REPORT

AGL FUGITIVE METHANE EMISSIONS MONITORING PROGRAM – TECHNICAL REPORT

AGL Upstream Investments Pty Ltd

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EXECUTIVE SUMMARY

INTRODUCTION

The Camden Gas Project, operated by AGL Upstream Investments Pty Limited (AGL), is a coal seam gas (CSG) project located to the south of Camden, NSW. The project currently comprises the Rosalind Park Gas Plant (RPGP), 144 coal seam gas wells, and interconnecting gas gathering lines.

AGL understands that the community is concerned about the potential impacts of the Camden Gas Project, including in relation to fugitive emissions and air quality. Accordingly, AGL has undertaken monitoring of fugitive methane concentrations in the vicinity of the existing Camden Gas Project and at selected local background monitoring locations that are geographically removed from the Camden Gas Project.

OBJECTIVES

The objective of the monitoring program is to determine if fugitive methane emissions from AGL CSG operations are influencing methane concentrations at locations within the Camden Gas Project at present. The monitoring program has been designed to measure methane concentrations at 20 sites within the Camden Gas Project, and five background locations, selected by AGL in conjunction with Pacific Environment and the community. These 25 locations collectively make up the study area.

This study is intended to represent an indicative screening analysis of the current conditions in the vicinity of the Camden Gas Project in comparison with background monitoring locations that are geographically removed from the Camden Gas Project.

There are no specific health criteria for methane commonly used in NSW or internationally that are relevant to concentrations that might be expected locally associated with fugitive emissions of coal seam gas into the atmosphere.

RESULTS

The methane concentrations measured in the study area are considered close to the global average background concentrations described in **WMO (2013)**.

Over the 12 week monitoring program the average methane concentration was 2.1ppm. This value is just above the global average of 1.8ppm (**WMO, 2013**) and in-line with methane concentrations measured in urban areas commonly ranging between 1.8ppm and 3.0ppm (**Lowry et al. 2001**). The corresponding average $\delta^{13}C\text{-}CH_4$ was -41‰, similar to values observed in residential areas reported in **Montiel et al. (2011)**.

The range of 15-minute average data was between 1.7ppm and 16.6ppm with a maximum 1 second methane concentration of 23.2ppm for the monitoring period.

Review of the data for monitoring sites located in close proximity to AGL gas wells do not indicate significant fugitive methane emissions were present during the monitoring period.

The highest methane concentrations were observed at Site 11, adjacent to the landfill. Findings indicate that the landfill is likely a contributor to fugitive methane emissions in the study area with influences extending in to the residential area to the north at Site 9. While the $\delta^{13}C\text{-}CH_4$ recorded at this site is indicative that the landfill is a likely source of the methane measured, given the low concentrations of methane observed as a whole, it is not possible to state this categorically.

The coal washery was not shown to be a source of fugitive methane emissions in the study area, assumed to be due to the age of the coal.

Elevated methane concentrations were also measured at Site 17, the closest monitoring site to the RPGP. The $\delta^{13}C\text{-}CH_4$ of these elevated methane concentrations shows a correlation with the $\delta^{13}C\text{-}CH_4$ characterised from a number of AGL well samples. It is understood that the RPGP comprises a number of relief valves and regulators that are designed to release CSG. It is therefore expected that somewhat elevated methane concentrations may be measured at Site 17 due to design requirement for the release of fugitive methane from the RPGP.

The elevated methane concentrations measured on the morning of Week 7 are likely to have been part of wider scale event rather a localised event, such as fugitive emissions from a single CSG field well.

Based on the low concentrations of methane observed, it is not possible to draw clear conclusions as to the contribution of agriculturally sourced methane in the study area.

The background methane concentrations also fall within reasonable approximation of the global average (**WMO, 2013**) with 15-minute average concentrations, with the average concentration for sites 21-25 across the 12 week monitoring period being 2.0ppm.

Characterisation of methane concentrations and $\delta^{13}C\text{-}CH_4$ values observed at the background monitoring sites has been completed and compared with the monitoring results for sites located in the Camden Gas Project area. The methane concentrations at these background sites vary from week to week and with meteorological conditions. Statistical analysis of the methane concentration indicates that the contributions from the sites adjacent to the landfill demonstrate a statistically significant (higher) methane concentration dataset compared with sites geographically removed from this source.

When sites potentially influenced by fugitive emissions from landfill are removed from the dataset, the statistical analysis showed no significant difference between those methane concentrations measured inside of the Camden Gas Project and those located outside (i.e. background locations).

Methane concentrations in urban areas were observed to be 0.2ppm higher than those measured in rural areas. Statistical analysis of the frequency distribution supports these findings. Reference to scientific literature also indicate that methane concentrations are typically higher in urban areas (**Phillips et al. 2013**, **Lowry et al. 2001**).

CONCLUSION

A methane signature anticipated to correspond to fugitive methane releases from the RPGP was observed at the monitoring site closest to this location on several occasions,

Notwithstanding the above, it is concluded that when the study is considered as a whole, methane concentrations and $\delta^{13}C\text{-}CH_4$ values observed within the boundaries of the Camden Gas Project showed no significant difference compared with those located outside (i.e. background locations).

GLOSSARY

Term	Definition
AGL	AGL Upstream Investments Pty Ltd
Anthropogenic	Anthropogenic is a term used to describe activities that are human induced (i.e. farming, CSG activities)
Biogenic	Biogenic is a termed used to describe substances that are generated through life processes (i.e. produced by living organisms or biological processes)
Box and whisker plot	Box and whisker plots are a way of graphically presenting numerical data statistically. The centreline of the box indicates the median value. The left side of the box indicates the lower quartile and the right indicates the upper quartile. The far left and far right error bars indicate the minimum and maximum of the values measured.
Camden Gas Project	The Camden Gas Project is located approximately 60 kilometres south west of Sydney. The Camden Gas Project is 100% owned and operated by AGL and comprises 144 coal seam gas wells, 100Km of gas gathering lines and the Rosalind Park Gas Plant.
Coal seam gas (CSG)	CSG contains CH_4 that naturally occurs in coal seams below the surface of the earth. CSG from the Camden Gas Project comprises approximately 96% CH_4, with the remaining 4% primarily being carbon dioxide nitrogen.
Fugitive methane emissions	Fugitive emissions refer to the release of unintended or irregular gas releases from a non-discrete source (that are not captured or controlled through an emission point such as an exhaust stack or vent). Emissions from livestock and wetlands are considered fugitive emissions as they are not captured first, while emissions from a compressor engine exhaust stack is considered a point source, as the emission is planned and controlled. In relation to AGL's Camden Gas Project fugitive methane emissions are commonly considered those that are due to leaks and pressure relief valves (essentially a designed leak).
Histogram	A histogram is a way of graphically presenting the frequency distribution of a dataset. The dataset is divided into bins, where the frequency of occurrence of values that fall within each bin is shown. A histogram can also display the relative frequency providing information on the percentage of occurrence.
Inversion	During the cooler months where on clear nights, night time drainage flows pool in valleys with the warmer air above trapping the air below. It is not until the mid-morning that an inversion is broken down by the influence of the heat of the morning sun that allows mixing of the stable layer with layers aloft, as experienced during daylight hours.
Isotopic ratio ($\delta^{13}C$-CH_4)	$\delta^{13}C$-CH_4 is a measure of the stable isotopes of carbon (^{13}C:^{12}C) within the CH_4 gas sampled.
Isotopic signature	The isotopic signature can be used to analyse $\delta^{13}C$-CH_4 measurement and distinguish between different sources of CH_4 in the atmosphere. For example, there is a known preferential uptake of ^{12}C over ^{13}C by plants and microbial activity, which means that biogenic CH_4 is generally 'lighter' than thermogenic CH_4 (i.e. that created via the thermal breakdown of heavier hydrocarbons under high temperature/pressure conditions).
Methane (CH_4)	CH_4 is a naturally occurring gas that is present in the atmosphere at trace concentrations. The global average methane concentration is 1.8 parts per million (ppm) in 2009 (**WMO, 2013**). Methane can also be anthropogenically released through activities such as landfill, agricultural practices (i.e. livestock) and CSG projects. In urban areas, CH4 concentrations are found to be slightly higher, with observations commonly ranging between 1.8ppm and 3.0ppm (**Lowry et al., 2001**)
Parts per billion (ppb)	A measure of very dilute concentrations of substances. Just as per cent means out of a hundred, so parts per billion or ppm means out of a billion.
Parts per million (ppm)	A measure of very dilute concentrations of substances. Just as per cent means out of a hundred, so parts per million or ppm means out of a million.
Picarro analyser	The Picarro G-2201-i Cavity Ring Down Spectrometer (CRDS) uses a near-Infra Red laser to measure sample gas passed through an optical measurement cavity. The instrument has an effective path length of up to 20 km inside the cavity, which results in high precision, and low-volume cavity to ensure better temperature stability, faster gas exchange, lower noise and higher sensitivity. The stability of the system means that minimal calibration is required (**Picarro, 2012**).

	The G2201-i is based on Picarro's CRDS technology, but also measures isotopic carbon ratios. Origins of methane (i.e. biogenic and thermogenic) have a characteristic ratio of ^{13}C to ^{12}C. The Picarro G2201-i makes precise $^{13}C/^{12}C$ ratio measurements that can potentially be used to distinguish between methane from different sources. This capability can be useful in measuring CH_4 in the vicinity of coal seam gas operations. This is since the isotopic carbon ratio of CH_4 generated from cattle, for example, will typically have a different signature from that of fugitive coal seam gas. It should be noted that there are limitations associated with the use of the Picarro equipment and the determination of $\delta^{13}C\text{-}CH_4$ values. The higher the concentration of CH_4 observed (i.e. the stronger the signal), the more effective the use of $\delta^{13}C\text{-}CH_4$ as a metric of CH_4 source. Therefore, at low, well mixed CH_4 concentrations (such as those observed during the study period) interpretation of the $\delta^{13}C\text{-}CH_4$ results are considered indicative.
Polar plot	A polar plot, sometimes referred to as a `pollution rose' indicates the direction from which a particular concentration measurement originates from. This is shown when concentration is plotted on a scale proportional to the distance from the centre of the plot, combined with the wind direction (the direction that the wind is blowing from) at the time of observation.
Thermogenic	Thermogenic is a term used to describe hydrocarbons (i.e. methane) created via the thermal breakdown of heavier hydrocarbons under high temperature/pressure conditions. Such conditions occur where hydrocarbons are buried deep below the surface of the earth (i.e. due to the breakdown of fossil fuels), and may be taken as meaning `associated with CSG' in the context of this report.

CONTENTS

1 INTRODUCTION

The Camden Gas Project, operated by AGL Upstream Investments Pty Limited (AGL), is a coal seam gas (CSG) project located 60km south west of Sydney. The project currently comprises the Rosalind Park Gas Plant (RPGP), 144 CSG wells, and interconnecting gas gathering lines.

AGL understands that the community is concerned about the potential impacts of the Camden Gas Project, including in relation to fugitive emissions and air quality. Accordingly, AGL has undertaken monitoring of fugitive methane (CH_4) concentrations in the vicinity of the existing Camden Gas Project and at selected background monitoring locations that are geographically removed from the Camden Gas Project.

The objective of the monitoring program is to determine if fugitive CH_4 emissions from AGL CSG operations are influencing ambient CH_4 concentrations at locations within the Camden Gas Project at present. The monitoring program has been designed to measure CH_4 at 20 sites within the Camden Gas Project, and five background locations, selected by AGL in conjunction with Pacific Environment and the community.

This study is considered to represent an indicative screening analysis of the current conditions in the vicinity of the Camden Gas Project.

2 LEGISLATIVE CONTEXT

CSG from the Camden Gas Project constitutes approximately 96% methane (with the remaining 4% primarily being carbon dioxide and nitrogen). It is therefore important to discuss air quality criteria relevant to this compound, particularly when discussing the potential for fugitive gas emissions.

There are no health criteria for methane commonly used in NSW or internationally that are relevant to concentrations that might be expected locally associated with a fugitive release of CSG.

Internationally, the (United States) National Institute for Occupational Safety and Health (NIOSH) references a maximum recommended safe methane concentration for workers during an 8-hour period (referred to as a Threshold Limit Value, or TLV) of 1,000ppm (0.1 percent) (**NIOSH, 2014**). Methane is considered an asphyxiant at extremely high concentrations (i.e. 500,000ppm, or 50 percent) and can displace oxygen in the blood. Additionally, criteria are available related to explosivity, where a Lower Explosive Limit (LEL) value of 50,000ppm is referenced.

There is currently no standard method for CH_4 monitoring, or the analysis of the $\delta^{13}C\text{-}CH_4$ in NSW or Australia.

Recent documents, relevant to the current study include the "Code of Practice for Coal Seam Gas Fracture Stimulation Activities" by the **NSW Government Trade and Investment Resources and Energy (2012).** This document provides guidance to ensure that fracture stimulation activities from coal seam gas activities are conducted in a safe manner and that communities, the environment and water resources are protected. However, the document does not address gas emissions explicitly.

Other Australian documentation include "Queensland's Code of Practice for Coal Seam Gas Well Head Emissions Detection and Reporting" (**Department of Employment, Economic Development and Innovation, 2011**) and the "National Greenhouse and Energy Reporting System Measurement" (**Department of Industry, Innovation, Climate Change, Science, Research and Tertiary Education, 2013**) however have limited application to the current study design.

The assessment has therefore been guided by good air quality monitoring practice including the

Australian Standard (AS) 2922-1987 "Guide for the Siting of sampling Units" **(AS, 1987)**. This has now been updated to AS 3580.1.1:2007 Methods for Sampling and Analysis of Ambient Air (**AS, 2007**). The specific siting methodologies employed are detailed in **Section 5.4.**

3 METHANE IN THE ENVIRONMENT

Methane is an important trace gas in atmospheric chemistry and climate. The most recent measurements report by the World Meteorological Organisation (WMO) indicate the global average CH_4 concentration to have risen to 1.819[a]ppm (**WMO, 2013**). The methane concentration has reportedly doubled over the past two hundred years determined primarily through ice core analyses.

In urban areas, CH_4 concentrations are generally slightly higher due the potential influence of a greater number of sources known to release fugitive CH_4. As part of this study, preliminary monitoring in Sydney's CBD indicates that CH_4 concentrations typically range between 1.8ppm and 2.0ppm. A recent study investigating CH_4 in the city of Boston, USA (**Phillips et al., 2013**) measured concentrations up to 28.6ppm when mapping urban pipeline leaks across the city using a Picarro fixed within a vehicle. This study was able to differentiate between fugitive emissions of CH_4 from urban pipeline leaks and other known sources of CH_4, such as landfill and sewage systems.

Studies completed by **Lowry et al. (2001)** in London, where the greatest CH_4 contributors were reported to be associated with gas storage and distribution systems as well as sewage treatment, measured CH_4 concentrations as high as 6.1ppm when investigating diurnal patterns of CH_4 and $\delta^{13}C$-CH_4. This study observed hourly averages commonly ranging between 1.8ppm and 3.0ppm. Contributors to the diurnal fluctuations were not only influenced by the prevailing meteorological conditions (i.e. temperature inversions), but also periods when the general population tend to use gas appliances (i.e. cooking, hot water systems etc.) **Lowry et al. (2001)** also identified a relationship between wind speed and CH_4 concentration, with higher concentrations associated with lower (<2m/s) wind speeds.

Methane is an effective greenhouse gas, with a global warming potential 28 times greater compared to carbon dioxide, when considered over a 100 year time frame (**IPCC AR5, 2013**).

Natural sources of fugitive CH_4 can include:

- Micro-organisms that live in wetlands
- Termites (methane generated by micro-organisms contained within their digestive tract)
- Volcanoes
- Naturally occurring open coal seams
- Permafrost thawing
- Hydrates and clathrates (CH_4 trapped in very cold continental and oceanic waters).

Anthropogenic sources (those generated by human activities), are commonly associated with agricultural practices, such as livestock emissions (ruminant digestion processes) or from rice paddies. Fugitive CH_4 emissions from waste, such as sewage and landfill are primarily generated through fermentation processes and are most significant in urbanised areas. Other fugitive sources of CH_4 are released during mining of coal or oil and gas production.

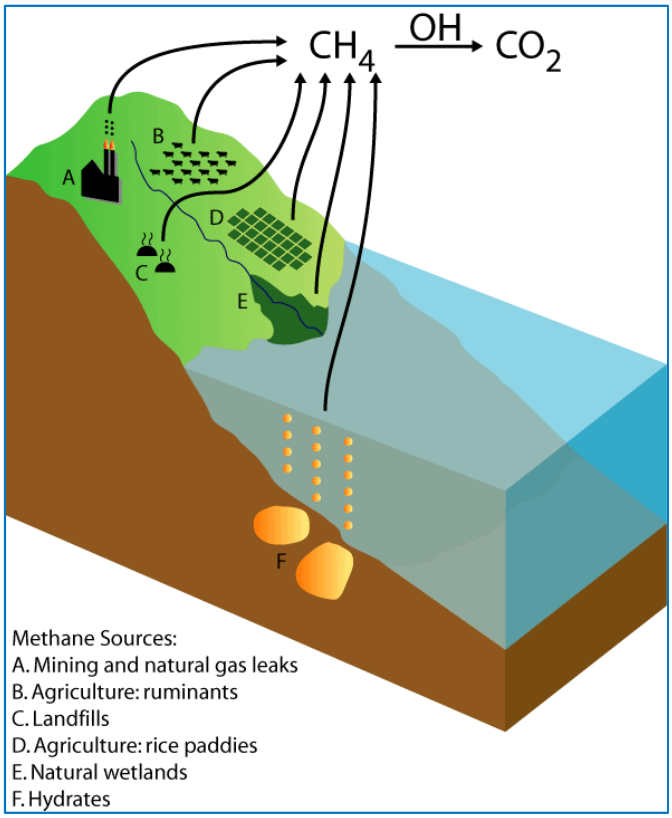
Figure 3-1 graphically depicts the main sources and sinks of methane in the environment. Any of these sources may be expected to yield CH_4 concentrations of >10ppm, however with no implications for health (see **Section** 2).

[a] For the purposes of this report this value has been rounded to 1.8ppm.

There are no known health effects associated with methane and it is not defined as a hazardous air pollutant (**US EPA, 2014**). As discussed in **Section** 2 there are trigger level concentrations for CH_4 that are governed by its potential for asphyxiation or explosivity.

The primary removal mechanism of methane from the atmosphere is through chemical reactions with the hydroxyl radical (OH) forming carbon dioxide (CO_2). The OH reacts with a number of gases in the atmosphere and is commonly referred to as a chemical species that 'cleans' the atmosphere.

As an organic molecule, advanced analytical techniques may be applied to determine the source of the methane. This can be achieved by measuring the proportion of ^{12}C compared with ^{13}C within a given sample of CH_4 molecules (referred to as the isotopic ratio).



(**Source: NASA GISS, 2013**)

Figure 3-1: Known sources of fugitive CH_4 emissions

3.1 Isotopic signature of CH_4

3.1.1 Description

The isotopic ratio of carbon in CH_4 ($\delta^{13}C$-CH_4, referred to above) is a measure of the stable isotopes of carbon (^{13}C:^{12}C) within the CH_4 gas sampled, reported in parts per thousand.

Often referred to as the isotopic signature or fingerprint, this parameter is relevant since different sources and sinks of CH_4 have different affinity for the ^{12}C and ^{13}C isotopes. By analysing the $\delta^{13}C$-CH_4, different sources of CH_4 in the atmosphere may be distinguished.

For example, there is a known preferential uptake of ^{12}C over ^{13}C by plants and microbial activity, which means that biogenic CH_4 is generally lighter than thermogenic CH_4 (i.e. that created via the thermal breakdown of heavier hydrocarbons under high temperature/pressure conditions).

The units of $\delta^{13}C$ are parts per thousand (per mil, ‰), and involve measurement against a calcium carbonate standard referred to as Pee Dee Belemnite. This material has an unusually high ^{13}C:^{12}C ratio, and as a result, most natural material analysed in this manner results in a negative $\delta^{13}C$. The more negative the $\delta^{13}C$-CH_4 value, the lower the ^{13}C:^{12}C ratio, and thus the lighter the CH_4 being sampled.

The isotopic composition of common methane sources has been characterised in a number of studies of the past several decades. **Table 3-1** provides a summary of the most common methane sources and the $\delta^{13}C$-CH_4 for each source. These $\delta^{13}C$-CH_4 are consistent with those established in other studies discussed in *Initial report on the Independent Review of Coal Seam Gas Activities in NSW* (**CS&E, 2013**) where, broadly speaking, $\delta^{13}C$-CH_4 values less than -55‰ are associated with biogenic methane and $\delta^{13}C$-CH_4 values above -55‰ are related to thermogenic sources of methane. It is important to note that the $\delta^{13}C$-CH_4 characteristic of a source is more commonly observed as a range of measurements than a single discrete number (i.e. as shown for site-specific sources in **Figure 4-1**).

Table 3-1: $\delta^{13}C$-CH_4 of common natural and anthropogenic methane sources

Source	$\delta^{13}C$-CH_4 (‰)
Natural sources	
Wetlands (swamps)	-55±3
Wetlands (bogs and tundra)	-65±5
Oceans	-59
Mud volcanoes	-40
Termites	-57
Wild animals	-62
Anthropogenic sources	
Biomass burning (C4 vegetation)	-17±3
Biomass burning (C3 vegetation)	-26±3
Enteric fermentation (C4 vegetation)	-49±4
Enteric fermentation (C3 vegetation)	-70±4
Landfill	-53±2
Domestic sewage	-57±3
Rice paddies	-62±3
Coal extraction	-35±3
Gas extraction (North Sea)	-34±3
Gas extraction (Siberia)	-50±3
Residential	-38

Source: **Montiel et al. (2011), Dlugokencky et al. (2011)**

Scientists are able to ascertain the potential source of a fugitive CH_4 emission by comparing the $\delta^{13}C$-CH_4 of a sample with known ranges of $\delta^{13}C$-CH_4 determined from a reference data set. The reference data set could either be from values published in scientific literature, as shown in **Table 3-1**, or known sources of methane in the area being studied (e.g. landfills, wetlands, mining operations).

It should be noted that there are limitations associated with using of $\delta^{13}C$-CH_4 values to 'categorically identify a CH_4 source, particularly when measuring under ambient conditions. This is because at ambient concentrations (i.e. the global average being 1.8ppm (**WMO, 2013**) will be by definition a mixture of multiple sources, meaning there is significantly more variability (or 'noise') in the $\delta^{13}C$-CH_4 values measured.

The higher the concentration of CH_4 observed (i.e. the stronger the signal), the more effective the use of $\delta^{13}C\text{-}CH_4$ as a metric of CH_4 source. Therefore, at low, well mixed CH_4 concentrations (such as those observed during the study period) interpretation of the $\delta^{13}C\text{-}CH_4$ results are to be considered indicative.

4 DETERMINATION OF ISOTOPIC SIGNATURE SPECIFIC TO THE MACARTHUR REGION

4.1 Experimental procedure

As established in **Section 3.1.1**, there are a number of sources of CH_4 especially in urban areas, such as the case for the Macarthur region. An important component of this study is to determine if fugitive CH_4 emissions from AGL's Camden Gas Project are significantly contributing to CH_4 concentrations in the local airshed. By measuring $\delta^{13}C\text{-}CH_4$ within an elevated CH_4 concentration, one is able to differentiate between fugitive emissions from AGL's Camden Gas Project and fugitive emissions released from other known sources.

In this instance, Pacific Environment established a reference dataset specific to the Macarthur region that can be used to characterise and compare the measured $\delta^{13}C\text{-}CH_4$ values during the field study.

The most significant sources of methane identified in the Macarthur region include: landfill, sewage treatment plant, soil mix and composting facility, livestock and AGL's operations. It is important to characterise the $\delta^{13}C\text{-}CH_4$ of these individual sources so that potential elevated concentrations of CH_4 can be attributed to a source in accordance with the measured $\delta^{13}C\text{-}CH_4$ during the field study.

Prior to the commencement of the fugitive CH_4 emissions monitoring program, the $\delta^{13}C\text{-}CH_4$ for significant sources of CH_4 in the Camden area were characterised in *Fugitive Methane Investigation - Camden* (**Pacific Environment 2013**). A summary of the findings of this study are provided in the following section.

Samples of AGL CSG from representative gas wells were collected over an approximate four week monitoring period between 28 March and 30 April 2013. Samples were collected from 7 wells that represented a range of vertical and horizontal wells with varying ages and which were geographically spread across the Camden Gas Project area.

The gas samples from the gas wells were collected directly from an outlet valve at each of the gas well sites and stored in a sterile foil gas sample bag for subsequent analysis. Gas bag samples were collected from wells EM38, MP22, RB10, JD11, SF05, MP09 and MP10. The $\delta^{13}C\text{-}CH_4$ was obtained for CH_4 concentrations ranging between 2ppm and 15ppm.

Three additional sample sites at a nearby landfill and soil mix were selected based on the assumption that these would also be significant contributors of fugitive CH_4 in the local airshed. A description of each gas sample source is as follows:

- Landfill (fresh) – fresh landfill that was placed within the past month (average CH_4 concentration 8ppm);
- Landfill (placed) – landfill that has been placed within the past 6 – 12 months (average CH_4 concentration 8ppm)
- Landfill (capped) – landfill that had been rehabilitated for approximately five years (average CH_4 concentration 3ppm)
- Soil Mix (compost block) – green waste waiting to be transferred to windrow (average CH_4 concentration 4ppm)
- Livestock (cow manure) – fresh cow manure (average CH_4 concentration 13.2ppm)
- Sewage – emission of methane from a sewage storage tank (average CH_4 concentration 29.5ppm)

The landfill, soil mix and sewage samples were collected using an isolation flux hood, configured in similar method as employed for area source odour sampling as described in "AS 4323.4:2009 Stationary Source Emissions Method 4: Area Source Sampling- Flux Chamber Technique"(**AS, 2009**). As the AS 4323.4:2009 relates to area sources, rather than discrete sample analysis, the AS 4323.4:2009 procedure was followed as far as practicable. To avoid significant noise associated with other (background) sources of CH_4, the flux hood was flushed with nitrogen gas (industrial grade, BOC gases) for times ranging between 10 and 30 minutes until a CH_4 concentration of less than 1ppm was achieved.

4.2 Results

The results of the $\delta^{13}C\text{-}CH_4$ analysis are presented in **Figure 4-1**. The median $\delta^{13}C\text{-}CH_4$ across all samples ranged between -39‰ (SF05 2c) and -64‰ (soil mix (compost block)). The samples collected from the landfill, soil mix and sewerage were in general lower (more negative) than the samples for the gas well sites. This is in agreement with the preferential uptake of ^{12}C over ^{13}C by microbial activity discussed above, resulting in typically lighter CH_4, with a lower $\delta^{13}C\text{-}CH_4$, from biogenic sources. The results also compare well with those reported in the literature (**Montiel et al. 2011**and **Dlugokencky et al. 2011**) (see **Table 3-1**).

The exception is the Landfill (capped) sample, with a median$\delta^{13}C\text{-}CH_4$ of -49 ‰. This may be associated with the significantly lower concentration (averaging 3ppm) of CH_4 measured from this site. Given the lower CH_4 signal from this source, it may be that this result was influenced by background sources of CH_4 (global CH_4 background is typically ~1.8ppm).

For the gas well samples, the range of the median $\delta^{13}C\text{-}CH_4$ was between -51‰ (MP22 1b) and -39‰ (SF05 2c). This indicates that the $\delta^{13}C\text{-}CH_4$ of CSG can vary across the gas well network. The $\delta^{13}C\text{-}CH_4$ can also vary within each gas bag sampled as shown in the range of $\delta^{13}C\text{-}CH_4$ measured from each gas bag (e.g. EM38 2a, b, c). Part of this variability can be attributed to the natural variability of the ^{12}C:^{13}C of CSG as well as the relatively low concentrations at which the samples were analysed.

Figure 4-2 shows a histogram of the $\delta^{13}C\text{-}CH_4$ for all well gas samples, as well as the samples collected at the landfill, soil mix, livestock and sewage. The five sample groups show a range of $\delta^{13}C\text{-}CH_4$ values measured. This data can be used to compare with field samples to ascertain the source of the CH_4. The variability the $\delta^{13}C\text{-}CH_4$ values measured highlights the limitations of the Picarro equipment when measuring CH_4 at lower, well mixed concentrations that are approaching background conditions (i.e. in the vicinity of1.8ppm). The purer the source of CH4 observed (and thus the higher the concentration), the more useful $\delta^{13}C\text{-}CH_4$ becomes in 'fingerprinting' the source of CH_4. This has been observed during the study period, where the least variable $\delta^{13}C\text{-}CH_4$ values were seen at CH_4 concentrations between 5ppm and 15ppm. Measured concentrations lower than 5ppm tended to exhibit significantly greater variability (or sample noise). Notwithstanding, the range of CH_4 concentrations referenced for the AGL gas characterisation (i.e. concentration ranging between 2ppm and 15ppm) were adopted so as to be within the accurate range of the Picarro instrument, and are representative of CH_4 concentrations measured during the study period.

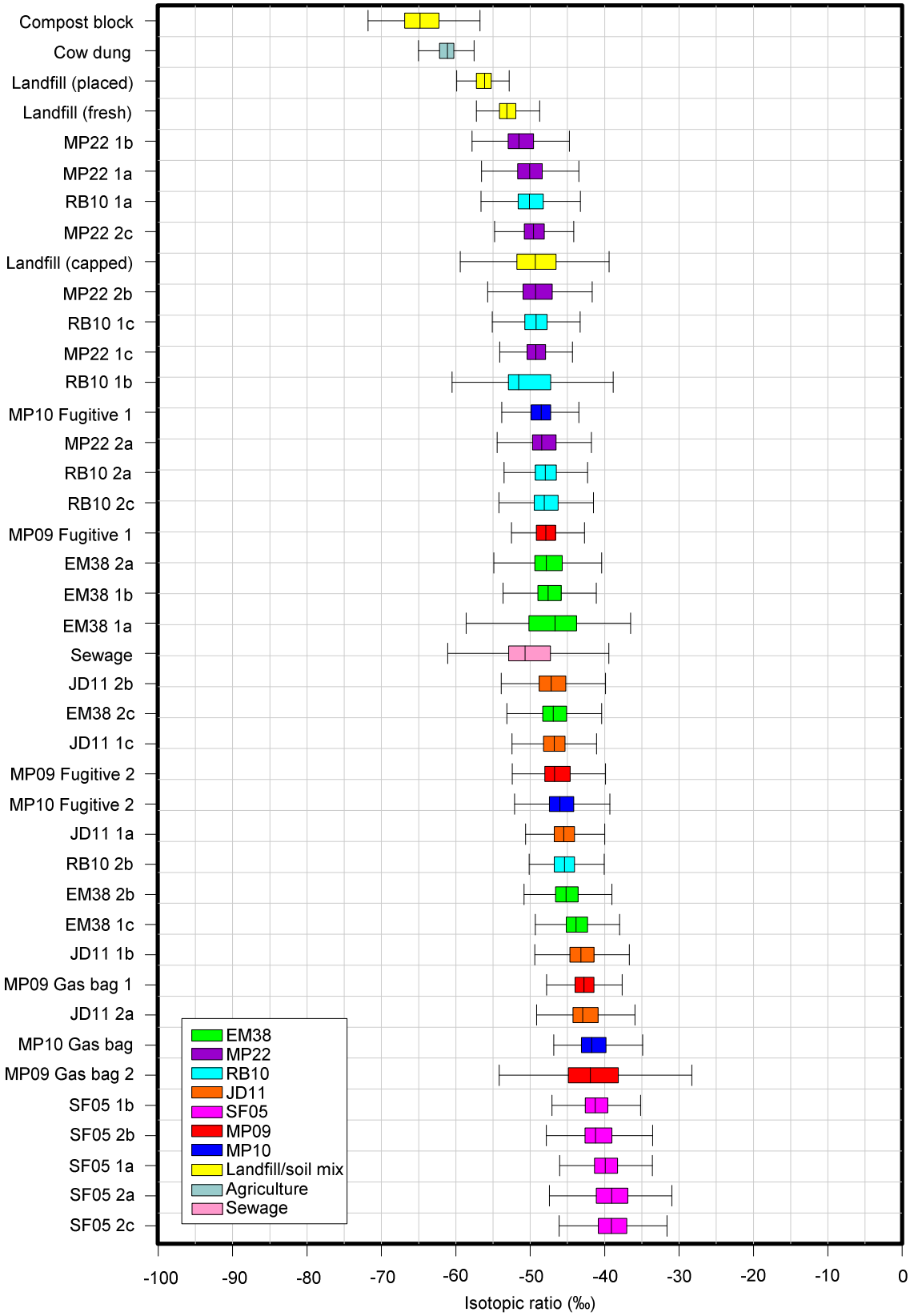


Figure 4-1 Box and whisker plot showing $\delta^{13}C\text{-}CH_4$

Note: The centreline of the box indicates the median value. The left side of the box indicates the lower quartile and the right indicates the upper quartile. The far left and far right error bars indicate the minimum and maximum of the values measured.

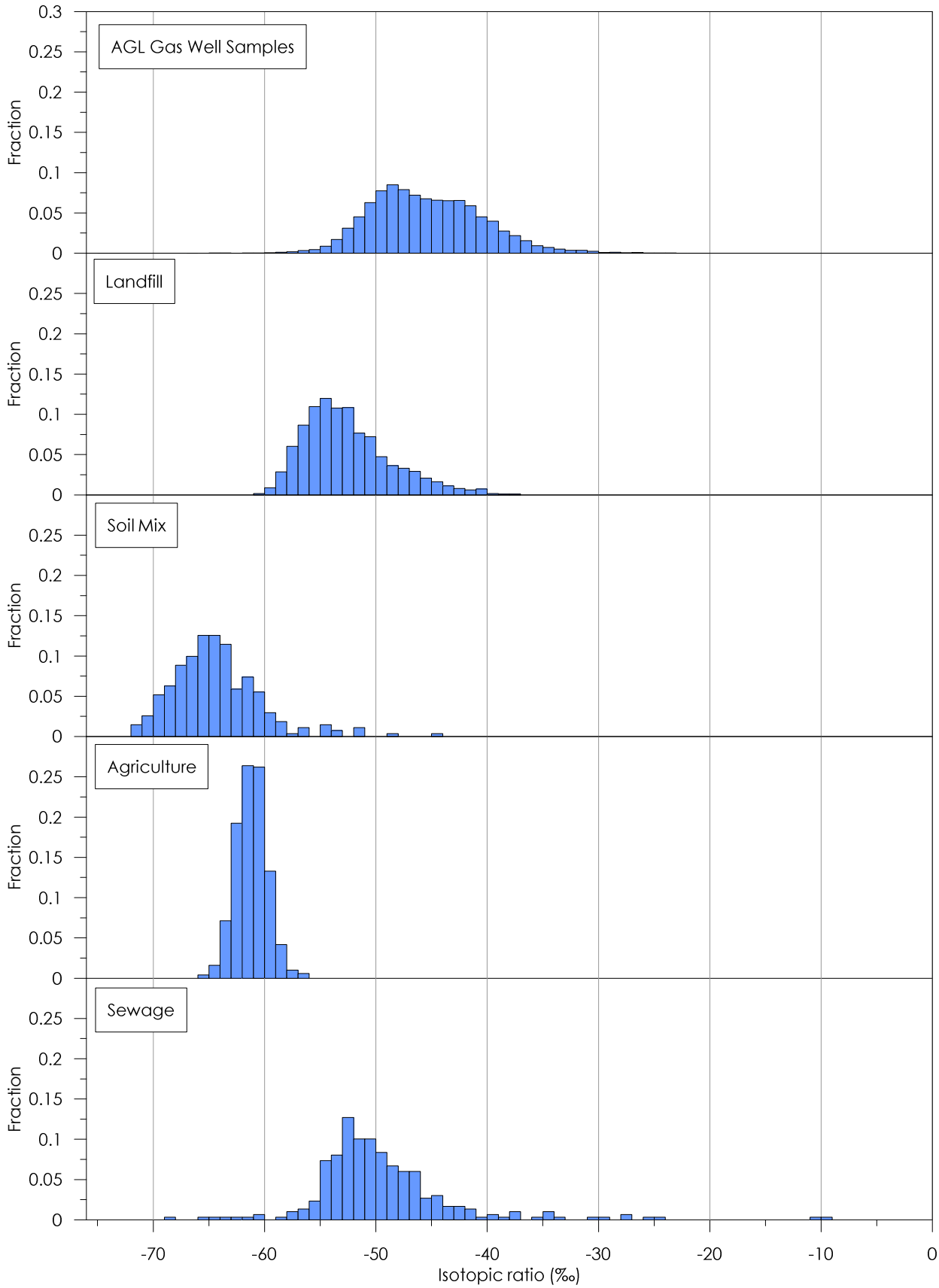


Figure 4-2: Histogram of $\delta^{13}C$-CH_4 of sample groups

5 METHODOLOGY OF FIELD STUDY

5.1 Field monitoring

The field monitoring has been designed to collect CH_4 concentration data from across the Macarthur region. To gather a sufficient dataset for this screening assessment, AGL has committed to completing weekly monitoring over a 12 week period. A 12 week period was chosen to ensure that sufficient data was captured and to enable data collection across changing seasons and also capture a range of meteorological conditions and prevailing wind directions for the detection of potential fugitive emissions from AGL wells.

Monitoring has been completed at each of 25 sites for a 15-minute period. Further detail as to site selection is provided in **Section 5.4**.

The 15-minute monitoring period at each site was adopted to allow sufficient time for any natural variability in CH_4 concentrations to be captured.

To complete the survey of the 25 sites, the monitoring was conducted over two weekdays each week with different days and times of day selected to remove the potential for systematic bias in the sampling.

The field monitoring commenced on 29 April 2013 and was completed on 17 July 2013.

5.2 Field monitoring team

The field monitoring was designed, managed and completed by Pacific Environment Staff Damon Roddis and Justine Firth. A summary of their qualifications and relevant experience is provided below.

DAMON RODDIS – PRINCIPAL/GENERAL MANAGER NSW

Damon Roddis has extensive experience in the field of atmospheric science, specialising in air quality modelling / monitoring. Damon provides technical guidance during the production of air quality impact assessments, and has considerable experience in atmospheric dispersion modelling techniques. Damon designs and implements air quality monitoring campaigns (both ambient and occupational) for a variety of clients and applications and consults with respect to air quality management, energy efficiency, pollution abatement and control and carbon management issues.

Damon has completed a secondment to the NSW EPA Air Policy Unit where he acted as Principal Technical Policy Advisor. During this time he assisted in the development of air pollution policy and provided a technical review role for a variety of complex specialist air quality reports.

JUSTINE FIRTH - SENIOR SCIENTIST

Justine Firth has completed a BSc in Atmospheric Science and completed her Honours in Chemistry, graduating in 2009 from Macquarie University, Sydney. Justine completed a completed a Graduate Diploma in Environmental Law at Sydney University in 2010.

Justine has six years' experience in the air quality field. She has experience in preparation of emissions estimation and inventories, air dispersion modelling, air quality impact assessments for coal-mines and other extractive industries, transport and infrastructure, odour impact assessments for a range of industries, aviation assessments, greenhouse gas assessments, NPI reporting, air quality monitoring and management plans, ambient air quality monitoring and environmental and NGER auditing for coal mine and power stations in NSW. Justine has experience in using a range of air emissions models. Justine has also been involved in working on an Australian Coal Association Research Program (ACARP) research project in the Hunter Valley validating model prediction of inversion breakdowns.

5.3 Instrumentation

5.3.1 Selection of equipment

As part of part of AGL's Environment Protection Licence (EPL) number 12003 for the Camden Gas Project, in 2012 AGL were issued with Pollution Reduction Program (PRP) Condition U4.2 'Investigation of Best Management Practices and Monitoring Techniques'. Condition U4.2 placed a requirement on AGL to investigate best management practices and monitoring techniques for the detection and quantification of volatile organic compound (VOC) emissions from their premises. On behalf of AGL, Pacific Environment completed a scoping study of the techniques available for assessing fugitive emissions of VOCs from coal seam gas projects (**Pacific Environment, 2012**). The techniques investigated included:

- Bubble tests
- Optical imaging
- Ultrasonic detectors
- Semiconductor-type gas sensors and personal monitors
- Hand-held detectors
- Laboratory-grade analysers
- Open-path optical remote sensing

The outcome of the scoping study identified the Picarro CH_4 analyser as a suitable instrument for the completion of the field study. The key advantage that the Picarro equipment offers is the sensitivity of the equipment to detect changes in CH_4 at concentrations in the parts per billion (ppb) range (where 1ppb is equal to 0.001ppm). For example, the Picarro G-2201-i Cavity Ring Down Spectrometer has the capacity to detect fugitive CH_4 emissions 50 m to 10m from the release point. The Picarro equipment also allows for instantaneous analyses of $\delta^{13}C\text{-}CH_4$ to be measured and the robustness of the equipment enables field deployment of what can be considered a laboratory-grade analyser.

5.3.2 Field work

The samples were analysed using a Picarro G-2201-i Cavity Ring Down Spectrometer (Picarro) that measures the CH_4 concentrations and corresponding $\delta^{13}C\text{-}CH_4$. The Picarro was operated in high precision mode.

The Picarro monitoring system has been configured for field monitoring, measuring CH_4 concentration, isotopic values for CH_4 along with wind speed, wind direction and GPS coordinates. The system components are housed within an AGL vehicle (Toyota Landcruiser Troop Carrier) and configured to meet the recommendations of the Picarro Mobile Kit User's Guide (**Picarro, 2011**). **Figure 5-1** provides an image of the set up used in the AGL field study.

In adopting this mobile system, 1-second frequency measurements of Global Positioning System (GPS) coordinates, wind speed and wind direction can be measured simultaneously with the CH_4 concentration and $\delta^{13}C\text{-}CH_4$. This information is essential in determining the source of potential fugitive emissions measured (e.g. from a gas well) to be located and verified. For example, if a potential source is upwind of the monitoring equipment then the plume can be identified and verified that this is the source of the emissions. This can also be useful in discounting known fugitive emission sources and identifying new ones based on the prevailing wind direction.

The Picarro has been used in other studies in overseas (**Phillips et al., 2013**) and in Australia as outline in the *Initial report on the Independent Review of Coal Seam Gas Activities in NSW* (**CS&E, 2013**).

5.3.3 Calibration

Prior to the commencement of the monitoring campaign the Picarro was calibrated using CSIRO's calibration gases located at their Energy Technology Centre in Mayfield West, NSW.

To ensure the ongoing accuracy and consistency of the CH_4 concentrations, weekly single point calibrations were completed using bottled CH_4 gas of known concentration. On a monthly basis, multi-point calibrations were completed over a range of known CH_4 concentrations to ensure instrument linearity. All calibrations gases are certified calibration gases supplied by BOC, a National Association of Testing Authority (NATA) accredited laboratory.

All calibration during the monitoring period showed little deviation in the CH_4 concentration measurements with time, and extremely good instrument linearity.

In view of the issues surrounding availability of isotopic calibration gases, the monitoring of δ13C-CH4 has relied upon the instrument's factory calibration for this aspect. Given that the Picarro instrumentation was sourced direct from the supplier and had not previously been used in the field this approach was considered adequate.

5.4 Monitoring locations

To meet the objective of this study ('to determine if fugitive CH_4 emissions from AGL CSG operations are influencing CH_4 concentrations at locations within the Camden Gas Project at present'), 20 sites in the Camden Gas Project area were selected. In addition, five background monitoring sites have been selected as being representative of locations geographically removed from the Camden Gas Project.

Consultation between the community, Pacific Environment and AGL was completed during the selection of the monitoring locations.

Seventeen preliminary sites were initially determined from aerial mapping showing the location of existing wells sites and other potential CH_4 sources in the study area. These sites were then visited to evaluate sampling suitability. A community consultation session was held on 4 April 2013 that allowed feedback on the proposed monitoring sites (and to share the work completed to date). An additional three sites and five background monitoring sites were included based on feedback from the community consultation session.

The sites identified have been selected ensure that they are representative of the geographical area and meet good sampling practices as per those described in AS 3580,1.1.2007 (**AS, 2007**). The specific siting methodologies adopted are list below:

- 120° clear sky view
- 180° unrestricted air flow around the sample inlet
- >10 metres from the dripline of trees, where feasible
- >10 m from roadside, where feasible.

The selected monitoring sites within the Camden Gas Project boundary are located within reasonable proximity to a Camden Gas Project well site with consideration given to where the nearest potential sensitive receptor (e.g. residence, business, school, nursing home, etc.) would be located. Consideration was also made to ensure that representative land uses were accounted for. For example, sites were selected to allow for a comparison between urban versus rural, in addition to other potential sources of fugitive emission such as the landfill, sewage treatment plant, soil mix and composting as well as livestock activities.

The background monitoring locations were selected using the criteria that each site be located at least 2 km from the nearest well site and is representative of air quality that would be experienced in the Camden / Macarthur region.

Figure 5-2 shows the location of the 25 monitoring locations. **Table 5-1** provides a summary description of each of the monitoring sites.

Figure 5-1: AGL field monitoring unit

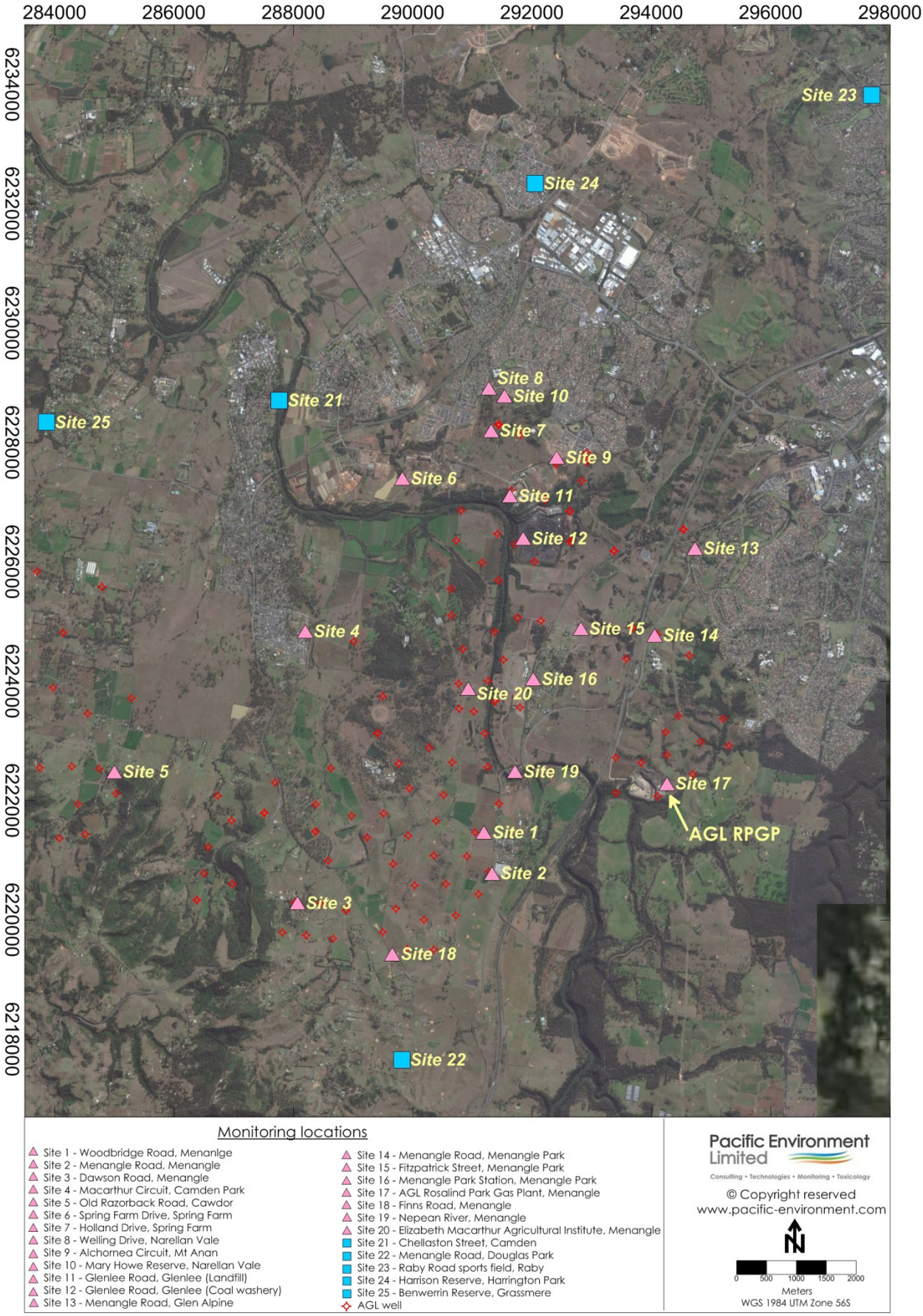


Figure 5-2: Monitoring locations

Table 5-1: Description of monitoring locations

Site number	Site description	Purpose	Distance to nearest well (km)	Distance to RPGP (km)
Site 1	**Woodbridge Road, Menangle**	Camden Gas Project	0.2	3.1
Site 2	**Menangle Road, Menangle**	Camden Gas Project	0.1	3.2
Site 3	**Dawson Road, Menangle**	Camden Gas Project	0.1	6.4
Site 4	**Macarthur Circuit, Camden Park**	Camden Gas Project	0.8	6.5
Site 5	**Old Razorback Road, Cawdor**	Camden Gas Project	0.3	9.1
Site 6	**Spring Farm Drive, Spring Farm**	Camden Gas Project	1.1	6.8
Site 7	**Holland Drive, Spring Farm**	Camden Gas Project	0.2	6.7
Site 8	**Welling Drive, Narellan Vale**	Camden Gas Project	0.6	7.4
Site 9	**Alchornea Circuit, Mt Anan**	Camden Gas Project	0.1	5.9
Site 10	**Mary Howe Reserve, Narellan Vale**	Camden Gas Project	0.5	7.2
Site 11	**Glenlee Road, Glenlee (Landfill)**	Camden Gas Project	0.1	5.6
Site 12	**Glenlee Road, Glenlee (Coal washery)**	Camden Gas Project	0.2	4.9
Site 13	**Menangle Road, Glen Alpine**	Camden Gas Project	0.4	4.1
Site 14	**Menangle Road, Menangle Park**	Camden Gas Project	0.1	2.6
Site 15	**Fitzpatrick Street, Menangle Park**	Camden Gas Project	0.7	3.1
Site 16	**Menangle Park Station, Menangle Park**	Camden Gas Project	0.5	2.9
Site 17	**AGL Rosalind Park Gas Plant, Menangle**	Camden Gas Project	0.2	0.2
Site 18	**Finns Road, Menangle**	Camden Gas Project	0.3	5.3
Site 19	**Nepean River, Menangle**	Camden Gas Project	0.5	2.5
Site 20	**Elizabeth Macarthur Agricultural Institute, Menangle**	Camden Gas Project	0.2	3.7
Site 21	**Chellaston Street, Camden**	Background	3.5	9.2
Site 22	**Menangle Road, Douglas Park**	Background	2.0	6.3
Site 23	**Raby Road sports field, Raby**	Background	7.6	12.2
Site 24	**Harrison Reserve, Harrington Park**	Background	4.6	10.4
Site 25	**Benwerrin Reserve, Grassmere**	Background	2.5	12.1

6 RESULTS AND DISCUSSION

The monitoring program commenced on 29 April 2013 and continued on a weekly basis for 12 weeks with the last data set measured on 17 July 2013. The monitoring results for the 20 sites within the Camden Gas Project boundary and five background sites are summarised in **Appendix B** (**Table B- 1** to **Table B- 12**) Week 1 to Week 12, respectively.

Additional night time monitoring was also completed on 10 July 2013. These results are summarised in **Table B- 13.**

The data for the average CH_4 concentration measured during each weekly monitoring exercise, and the night time monitoring are also presented spatially, in **Appendix B** (**Figure B- 1** through **Figure B- 13**), showing the variability of average CH_4 concentrations across the study area.

More detailed results for each individual site are provided in **Appendix C** that includes:

- A time series of CH_4 concentration with vectors showing the 30 second wind speed and wind direction, pointing the direction that the wind is heading.
- A time series plot showing CH_4 concentration and global background concentration (**WMO, 2013**) together with the corresponding measured $\delta^{13}C\text{-}CH_4$ and range of average $\delta^{13}C\text{-}CH_4$ values established during the field study.

A significant amount of data has been collected during the 12 weeks of monitoring. Rather than discussing all monitoring results, additional discussion is provided where elevated CH_4 concentrations were measured or field observations warranted further investigation.

For the purposes of this study, a CH_4 concentration is considered 'elevated' if the concentration shows to be above the global average of 1.8ppm reported for 2012 as published by **WMO (2013).**

6.1 Overview of CH_4 over monitoring period

Over the duration of the 12 week monitoring period 75 hours of 1 second measurements of CH_4 concentration were recorded. To provide a holistic view of the variability of CH_4 concentration, box and whisker plots of the entire data set by site and by week have been prepared in **Figure 6-1** and **Figure 6-2**, respectively.

The CH_4 concentration data by site shows that the greatest 1 second CH_4 concentrations were measured at Site 11 (Glenlee Road – landfill), followed by Site 9 (Alchornea Circuit), Site 24 (Harrison Reserve) and Site 17 (AGL RPGP). See **Figure 5-2** for the location of the monitoring sites. These sites also showed the greatest variability in the CH_4 concentrations measured.

Site 5 (Old Razorback Road) and Site 18 (Finns Road) provided the most consistent and some of the lowest CH_4 concentrations across the weeks investigated. Both of these sites are located to the southern end of the study area and well removed from urban areas (see **Figure 5-2**).

Week 11 provided the week of the maximum 1 second CH_4 concentration, measured at Site 11 (Glenlee Road - landfill). However, the bulk of the data captured during Week 11 showed relatively little variability.

Week 7 and Week 12 showed the greatest variability in observed CH_4 concentrations while Week 6 provided the most consistent CH_4 concentration readings.

Given the natural variability of ambient CH_4 concentrations, data has also been presented as the 15-minute average at each site.

Table 6-1 presents the data by site, with the average, the minimum and maximum of the 15 minute average data. The average of the 15 minute data ranges between 1.8ppm and 3.8ppm. The minimum 15 minute average data is 1.7ppm or 1.8ppm, while the maximums range between 2.2ppm and 16.6ppm.

Over the 12 week monitoring program the average CH_4 concentration was 2.1ppm. This value is just above the global average of 1.8ppm (**WMO, 2013**) and in-line with CH_4 concentrations measured in urban areas commonly ranging between 1.8ppm and 3.0ppm (**Lowry et al. 2001**).

The background methane concentrations also fall within reasonable approximation of the global average (**WMO, 2013**) with 15-minute average concentrations, with the average concentration for sites 21-25 across the 12 week monitoring period being 2.0ppm.

Table 6-2 presents the data by week, with the average, the minimum and maximum of the 15 minute average data. Week 2, Week 3 and Week 9 experienced the lowest CH_4 concentrations and Week 11 experienced the highest, largely skewed by the high results measured at Site 11.

Figure 6-3 and **Figure 6-4** show the corresponding $\delta^{13}C\text{-}CH_4$ values for the CH_4 concentration data presented in **Figure 6-1** and **Figure 6-2**, by site and by week, respectively. Site 11 averaged the lowest $\delta^{13}C\text{-}CH_4$ and Site 4 averaged the highest. The greatest variability was experienced at Site 20, while the most consistent $\delta^{13}C\text{-}CH_4$ values were recorded at Site 9. By week, the most consistent $\delta^{13}C\text{-}CH_4$ values were measured during Week 5, with greatest variability recorded during Week 3. Over the 12 week monitoring program the average $\delta^{13}C\text{-}CH_4$ was -41‰.

As noted above, there are limitations associated with using of $\delta^{13}C\text{-}CH_4$ values to categorically identify a CH_4 source at the concentrations observed within the study. This is because close to background concentrations (i.e. the global average being 1.8ppm (**WMO, 2013**)), the CH_4 will be by definition a mixture of multiple sources, meaning there is significantly more variability (or 'noise') in the $\delta^{13}C\text{-}CH_4$ values measured.

Notwithstanding the above, the $\delta^{13}C\text{-}CH_4$ results from this study are to act as an indicator in assessing the origins of the CH_4 (i.e. biogenic or thermogenic). More detailed results for each individual site for each of the 12 weeks are provided in **Appendix C**.

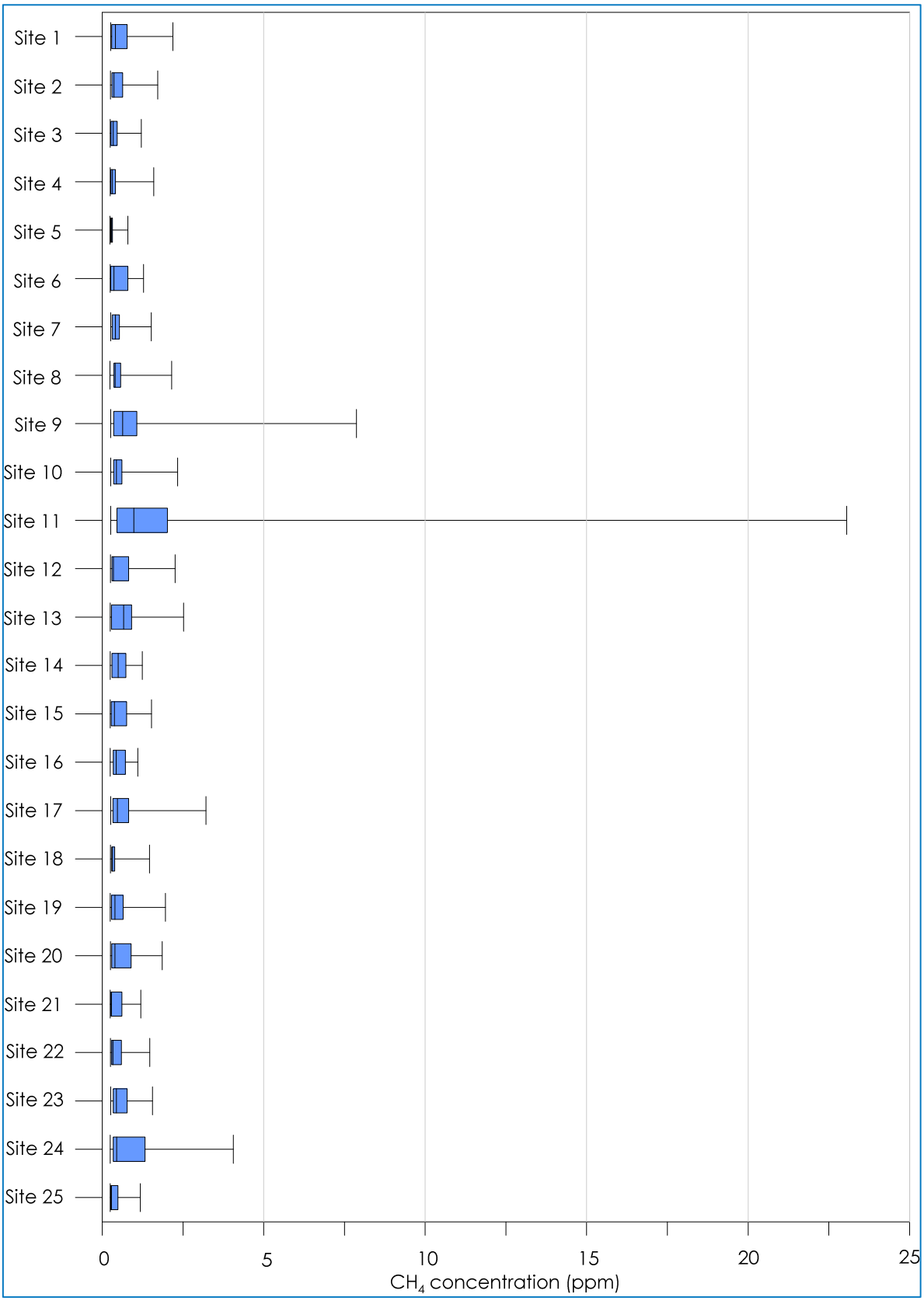


Figure 6-1: Box and whisker plot of CH_4 concentration for all monitoring data by site for the duration of the 12-week monitoring period

Note: The centreline of the box indicates the median value. The left side of the box indicates the lower quartile and the right indicates the upper quartile. The far left and far right error bars indicate the minimum and maximum of the values measured.

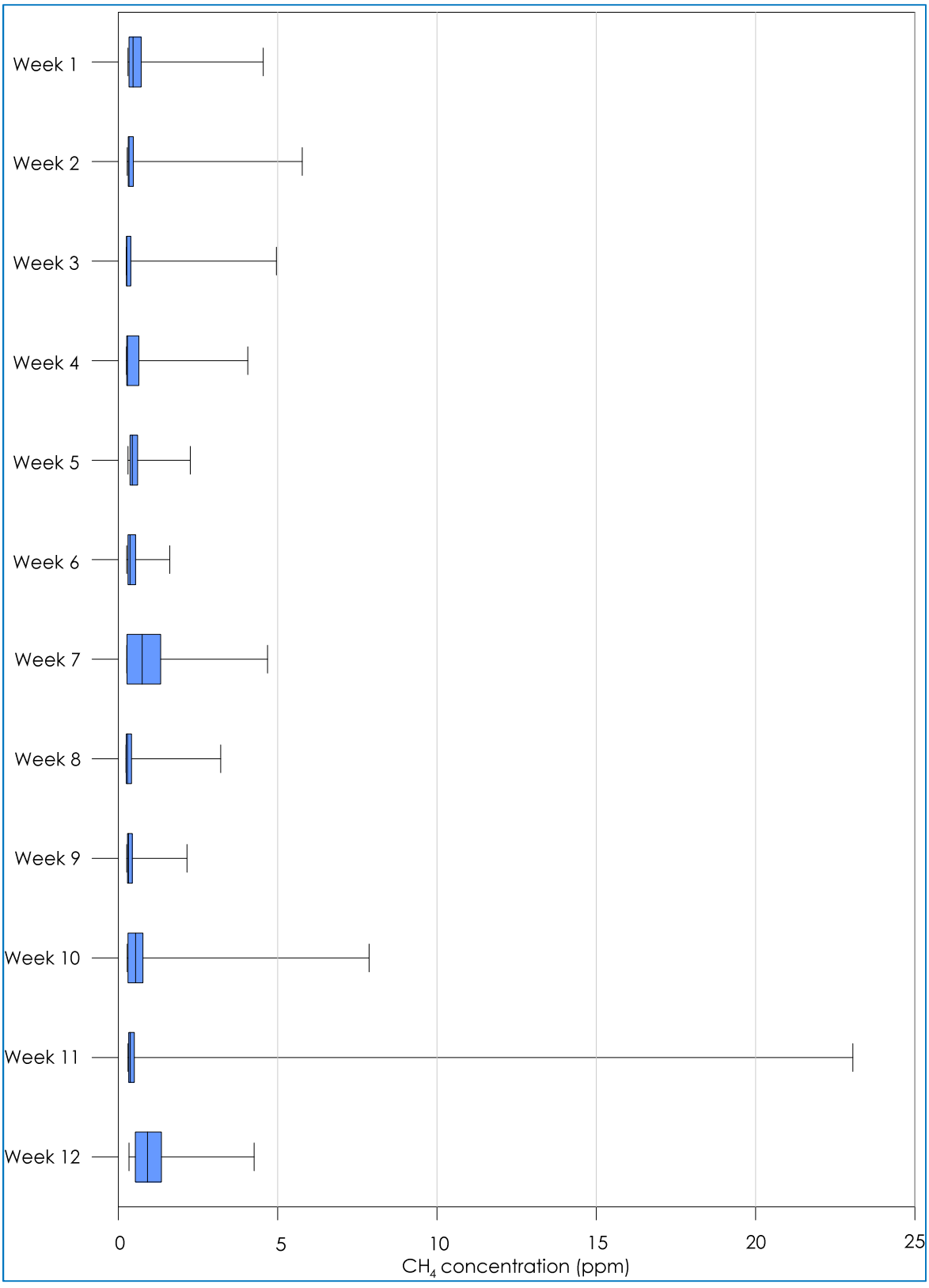


Figure 6-2: Box and whisker plot of CH_4 concentration for all monitoring data by week for the duration of the 12-week monitoring period

Note: The centreline of the box indicates the median value. The left side of the box indicates the lower quartile and the right indicates the upper quartile. The far left and far right error bars indicate the minimum and maximum of the values measured.

Table 6-1: Summary of 15 minute data by site

Monitoring site	Average	Minimum	Maximum
Site 1	2.1	1.8	3.3
Site 2	2.0	1.8	2.9
Site 3	1.9	1.7	2.6
Site 4	1.9	1.7	2.8
Site 5	1.8	1.7	2.2
Site 6	2.0	1.7	2.5
Site 7	2.0	1.8	2.7
Site 8	2.0	1.7	2.9
Site 9	2.4	1.7	4.2
Site 10	2.1	1.8	3.5
Site 11	3.8	1.8	16.6
Site 12	2.0	1.7	2.7
Site 13	2.2	1.7	3.2
Site 14	2.0	1.7	2.5
Site 15	2.0	1.7	2.8
Site 16	2.0	1.7	2.4
Site 17	2.2	1.7	3.5
Site 18	1.9	1.7	2.8
Site 19	2.1	1.7	3.1
Site 20	2.1	1.7	3.0
Site 21	1.9	1.7	2.5
Site 22	2.0	1.7	2.6
Site 23	2.1	1.7	2.9
Site 24	2.3	1.8	4.7
Site 25	1.9	1.7	2.5

Table 6-2: Summary of 15 minute data by week

Week	Average	Minimum	Maximum
Week 1	2.0	1.8	2.5
Week 2	1.9	1.8	3.6
Week 3	1.9	1.7	3.5
Week 4	2.1	1.7	4.7
Week 5	2.0	1.8	2.7
Week 6	2.0	1.8	3.0
Week 7	2.4	1.7	3.7
Week 8	2.0	1.7	3.1
Week 9	1.9	1.7	2.6
Week 10	2.2	1.8	4.2
Week 11	2.6	1.8	16.6
Week 12	2.4	1.8	3.1

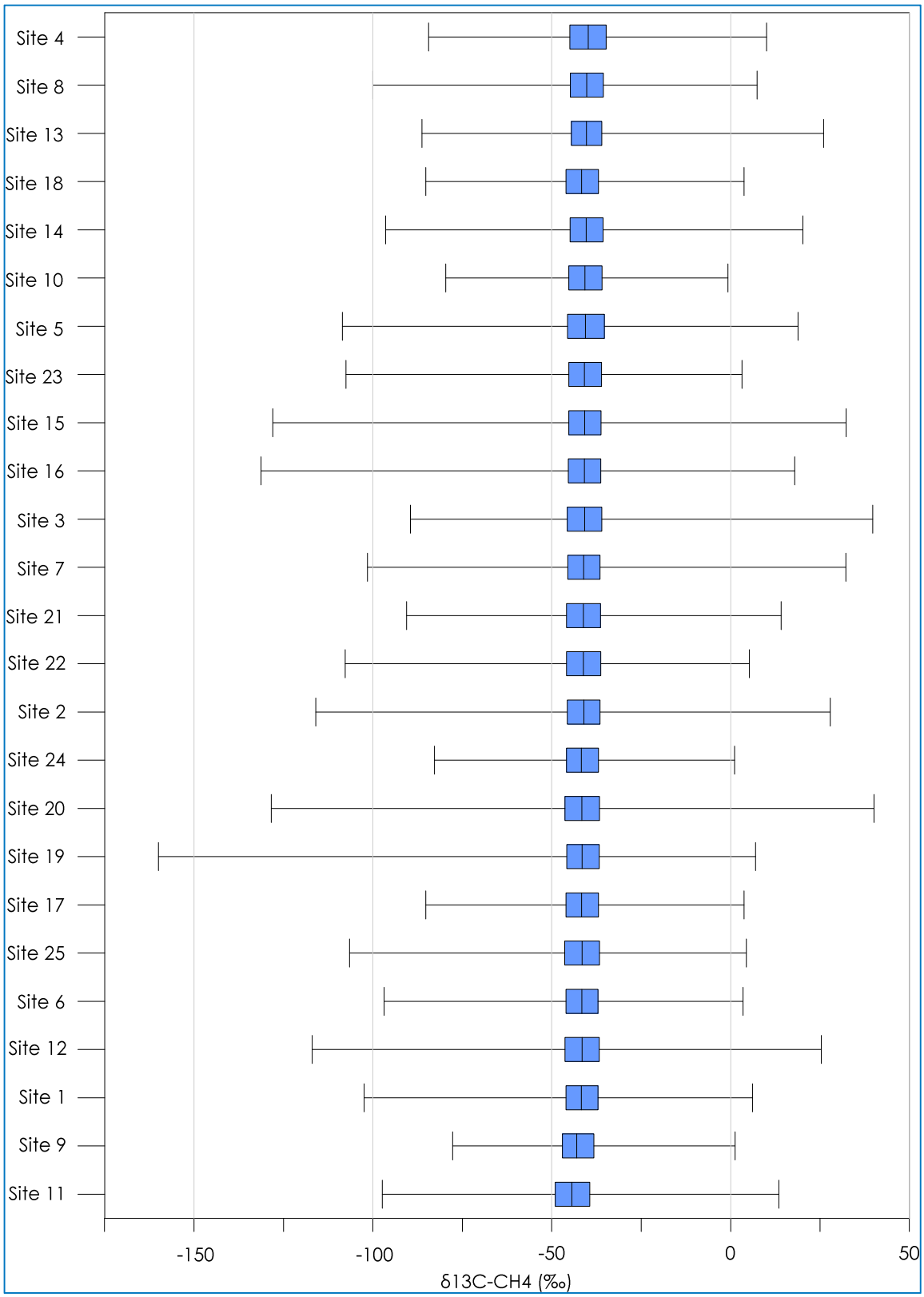


Figure 6-3: Box and whisker plot of $\delta^{13}C\text{-}CH_4$ for all monitoring data by site for the duration of the 12 week monitoring period

Note: The centreline of the box indicates the median value. The left side of the box indicates the lower quartile and the right indicates the upper quartile. The far left and far right error bars indicate the minimum and maximum of the values measured.

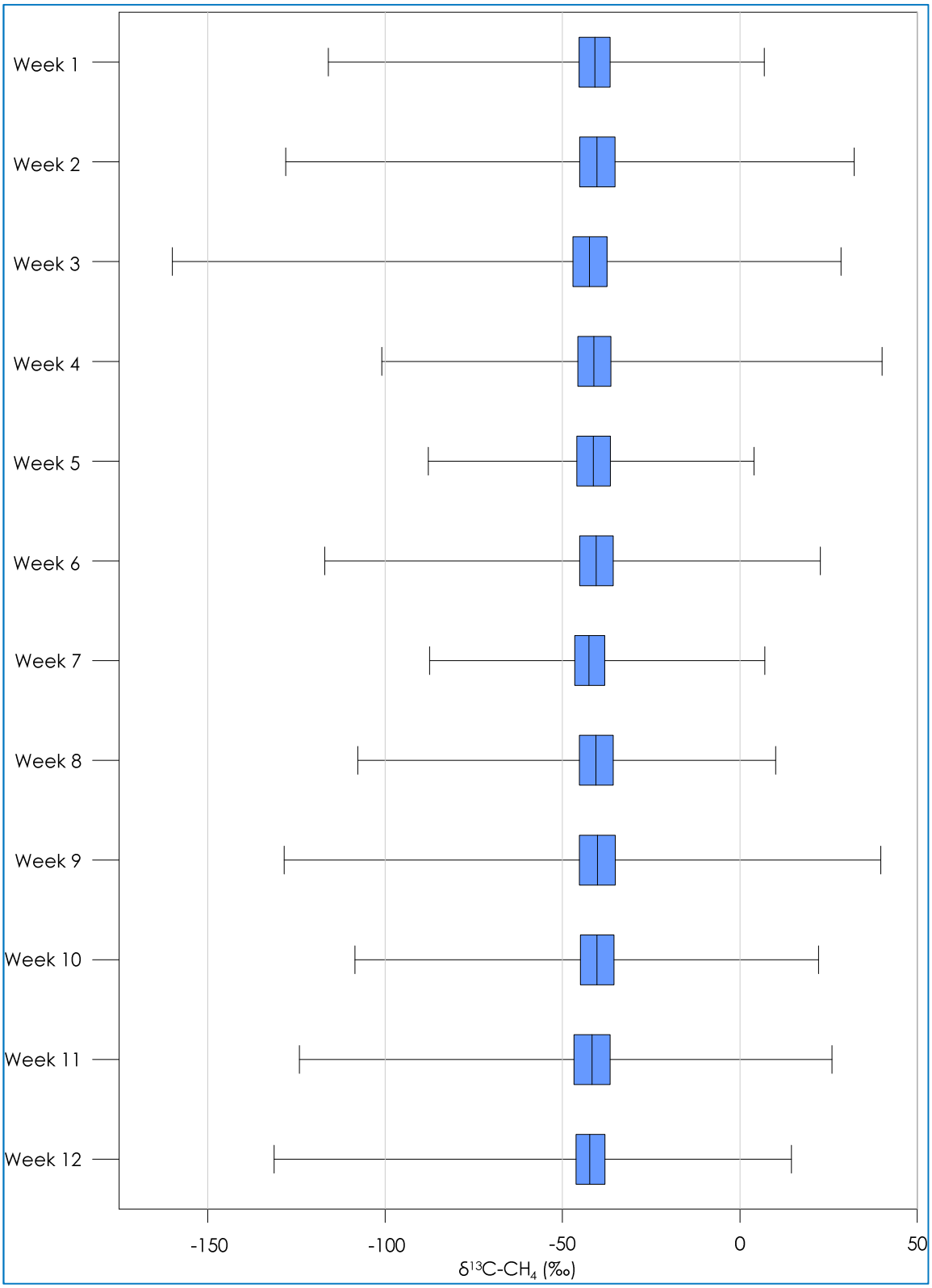


Figure 6-4: Box and whisker plot of $\delta^{13}C\text{-}CH_4$ for all monitoring data by week for the duration of the 12 week monitoring period

Note: The centreline of the box indicates the median value. The left side of the box indicates the lower quartile and the right indicates the upper quartile. The far left and far right error bars indicate the minimum and maximum of the values measured.

6.2 Detection of fugitive CH_4 emissions from gas well operations

To address community concern regarding fugitive CH_4 emissions from the AGL gas well operations, the monitoring data has been analysed to take into consideration the influences of the prevailing winds with respect to emission source locations. Out of the 25 representative monitoring sites, 11 are considered to be in the vicinity of an AGL gas well (i.e. <300m) and have been selected for further investigation into whether fugitive CH_4 emissions are being released. The selection of these sites (Sites 1, 2, 3, 5, 7, 9, 11, 12, 14, 17 and 20) are based on the relative proximity of the monitoring location to an active AGL gas well. A map for each monitoring location with respect to the nearest well is provided in **Appendix A**.

A series of polar plots are presented in **Figure 6-5** and **Figure 6-6**, showing all of the 1 second CH_4 concentrations observed at these monitoring sites combined with the prevailing wind direction that occurred at the time of observation for each of the selected sites. Also shown is the direction and distance to the nearest AGL well. These polar plots indicate the direction from which the CH_4 measurement originates from. The polar plots use the same data presented as a time series in **Appendix C** and **Appendix D**, but act as a useful visual aid in identifying potential clusters of elevated measurements with respect to a given wind direction (and therefore upwind source).

Review of the polar plots indicates the following:

- Site 1: The majority of the time the prevailing wind directions were from the north, east and south, with few measurements made when the wind was blowing from the nearest well towards Site 1. The highest concentrations were measured when the prevailing wind direction was from the south and occurred during Week 11 and Week 12. The nearest AGL wells to the south are located at 0.5km and then 1km. While this is considered a significant separation distance, there is potential that fugitive emissions are detected to a limited extent and part of a larger scale event (further discussed in **Section 6.7**).
- Site 2: It can be seen that for the majority of the time at Site 2, CH_4 concentrations were below 2.3ppm. The outer circle of points (i.e. the highest observed concentrations) indicates that during these measurement periods, the wind originated from all directions, with the majority originating from the northern quadrant. Further analysis indicated that these higher CH_4 concentrations correspond to Week 12 (**Appendix B Table B-12**) with similar trend in readings also observed at Site 1 during Week 12.
- Site 3: For the majority of the time at Site 3 the CH_4 concentrations were below 2.0ppm. The outer ring of data points (i.e. the higher concentrations) were observed during Week 12 and are located in the northern quadrant of the polar plot. These correspond to the higher measurements made during Week 12 (**Appendix B Table B-12**). During Week 12, monitoring commenced at 09:07. The prevalence of diurnal variations, where slightly higher CH_4 concentrations were observed during the morning and late afternoon, is discussed further in **Section 6.7**.
- Site 5: The highest CH_4 measurements made at Site 5 generally originated from the northern and western quadrants. In view of the nearest well (approximately 250 m west), the broad spectrum of wind directions measured during these higher readings, it is considered unlikely that fugitive CH_4 emissions from AGL wells were detected during the monitoring periods.
- Site 7: The polar plot for Site 7 shows a strong relationship between wind direction and CH_4 concentration, with measurements ranging between 4ppm and 5ppm originating from the south-easterly to southerly directions. It is noted that this is also the direction of the landfill (see **Figure 5-2**). Further analysis of the data show that this cluster of readings was measured during Week 11 night-time monitoring campaign (further discussed in **Section 6.7.1**). The corresponding average $\delta^{13}C\text{-}CH_4$ was -48‰, a signature indicative of a biogenic source (such as a landfill) rather than CSG-derived CH_4.
- Site 9: As with Site 7, Site 9 is located in close proximity to the landfill (approximately 700m southwest). The higher CH_4 concentrations (>5ppm) were all measured during Week 10. Further discussion on this event is provided in **Section 6.4**.

- Site 11: Site 11 is located to the immediate south of the landfill and 120m southwest of the nearest AGL gas well. It is noted that the higher CH_4 concentrations were measured at this site from all directions of the compass. Further discussion on the elevated measurements at Site 11 is provided in **Section 6.3**.
- Site 12: At Site 12, the highest CH_4 measurements were observed when the prevailing wind direction originated from the north-western quadrant. The landfill is located northwest of this site, while the nearest AGL well is located to the southwest. This indicates that it is unlikely the higher CH_4 concentrations originated from fugitive emissions from the nearest AGL well.
- Site 14: There is no clear direction associated with the range of CH_4 measurements observed at this site and it is therefore not possible to associate these measurements with a given emission source.
- Site 17: Site 17 is the closest monitoring location to the RPGP. The cluster of CH_4 observations in the range of 2-3ppm in the southwesterly quadrant of the polar plot in **Figure 6-6** is therefore expected given that this is the direction towards the RPGP. Interestingly, clusters of higher readings originated from the west, north and east.
- Site 20: There is a broad cluster of generally higher CH_4 readings that originated from the south-eastern quadrant. Given that Site 20 has five gas wells located within 500m of Site 20 (see **Figure** 5-2), it is anticipated that CH_4 contributions from AGL wells may be expected. This however is not supported by any clear signal within the $\delta^{13}C$-CH_4 values recorded at this site. Of note, Site 20 is well removed from nearby residences in a relatively remote section of the Camden Gas Project that would not commonly be accessed by the general public.

In summary, review of the data for the majority of monitoring sites located in close proximity to AGL gas wells do not show any significant directionality that might be attributed to fugitive CH_4 emissions from gas wells. In the case of Site 17, on occasion, elevated CH_4 concentrations (or 'spikes') are seen within the data set (refer Week 3 in **Figure C-98** and Week 8 in **Figure C-100**). At these times, there is a tightening up of the $\delta^{13}C$-CH_4 values (i.e. the signal becomes less noisy) indicating that an RPGP related CH_4 source was detected at these times. Further discussion on the measurements at Site 17 is provided in **Section 6.6.**

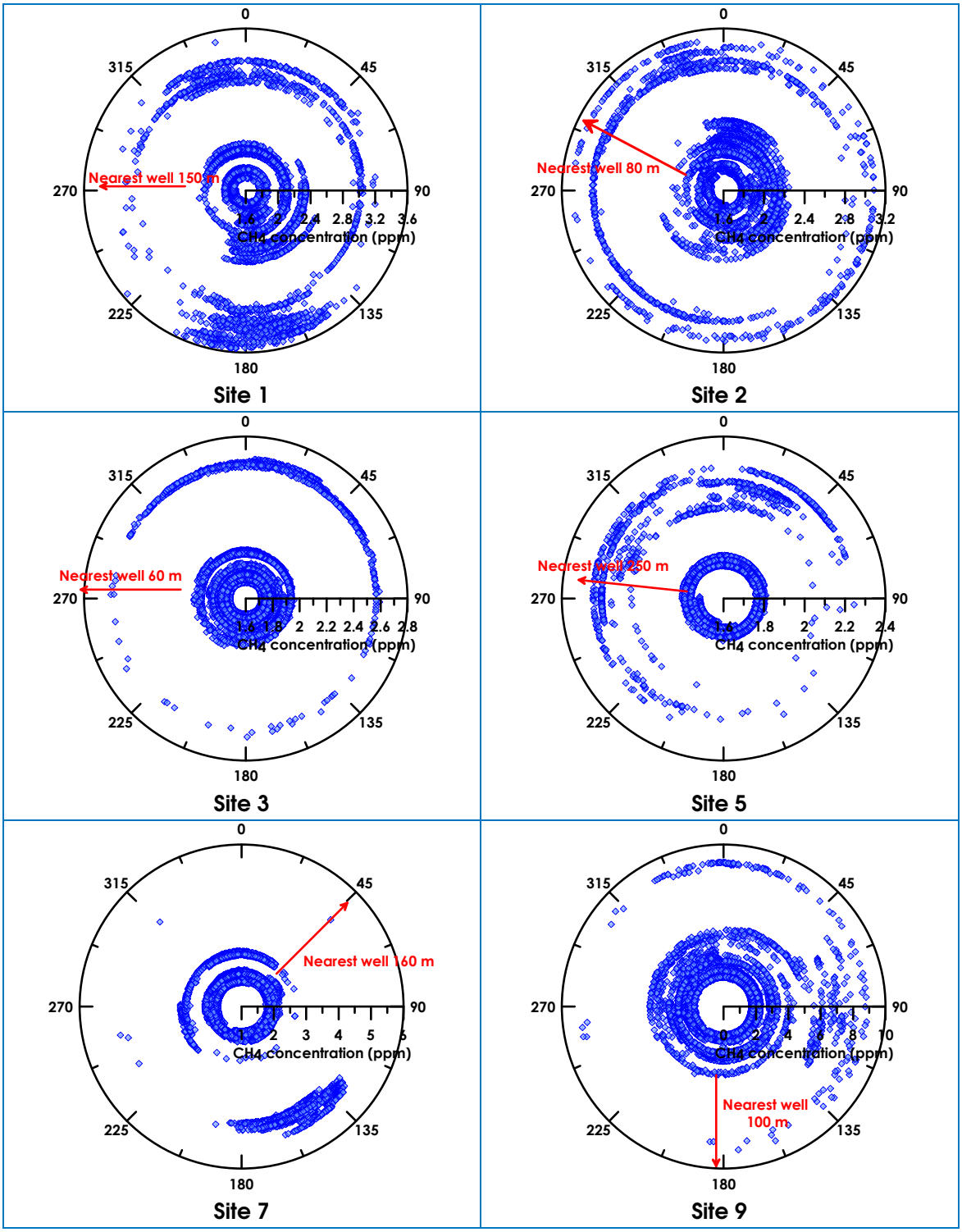


Figure 6-5: Polar plots of CH_4 concentrations for Sites 1, 2,3,5,7 and 9 for Weeks 1 -12

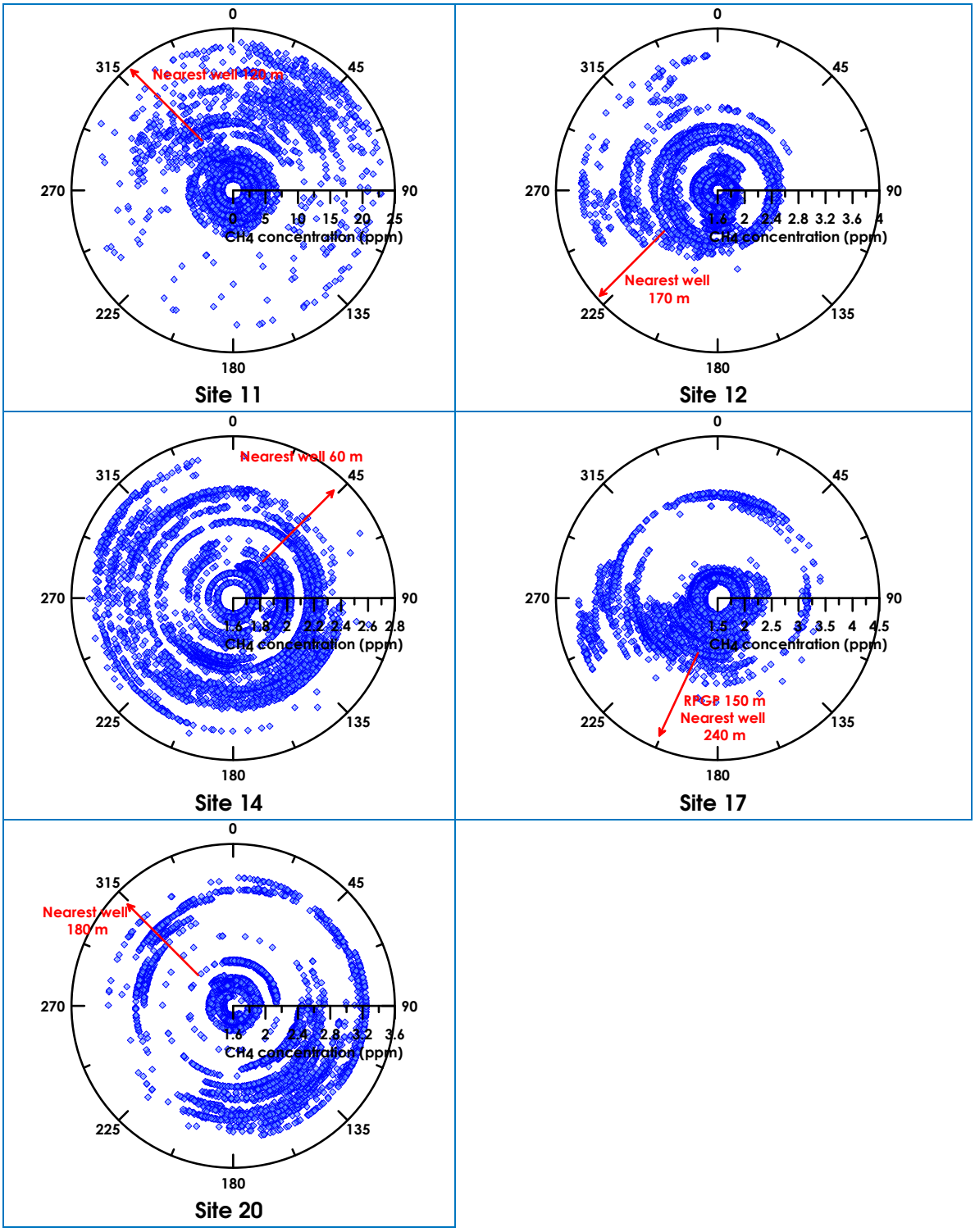


Figure 6-6: Polar plots of CH_4 concentrations for Sites, 11,12,14,17 and 20 for Weeks 1 -12

6.3 CH_4 concentrations at Site 11 – Glenlee Road (Landfill)

The CH_4 concentrations measured at Site 11 showed the greatest variability in the concentration measurements, recording the highest 1 second concentration of 23.2ppm in Week 11 of all the data recorded. The 15-minute average CH_4 concentrations at Site 11 ranged between 1.8ppm and 16.6ppm.

The measurements taken at Site 11 were collected just to the southwest boundary of the Landfill and AGL well. **Appendix A** indicates just how close the landfill and the AGL well are to the Site 11 monitoring location. Based on this close proximity of a known CH_4 source, the adjacent landfill is considered likely to be the most significant contributor to the variability and magnitude of the CH_4 concentrations.

The meteorological conditions on all 12 weeks were generally calm with the average wind speed ranging between 0.5 m/s and 1.4 m/s. The time series data presented in **Appendix C** indicates that the observed wind speeds at this site are low and can originate from any direction. The generally low wind speeds are in part attributed to the blocking effects of localised terrain and vegetation.

Appendix C shows the concentration and $\delta^{13}C\text{-}CH_4$ of the CH_4 during the 15-minute monitoring period for the 12 weeks investigated. On a number of occasions (e.g. Week 1, Week 7 and Week 11), peaks in the CH_4 concentration are observed. During the periods of higher CH_4 concentration, the $\delta^{13}C\text{-}CH_4$ typically exhibits less variability (noise) and becomes more negative, suggesting a source of CH_4 with greater contribution from a biogenic CH_4 source. This is compared to CH_4 measured at lower concentrations during the 15-minute monitoring period, where greater variability in the $\delta^{13}C\text{-}CH_4$ values is shown.

The $\delta^{13}C\text{-}CH_4$ measured in the peaks can be compared with those measured from known sources in the Camden area. Further analysis has been completed for:

- Week 1
- Week 7
- Week 11.

6.3.1 Isotopic analysis for Week 1

Figure 6-7 presents a histogram of the $\delta^{13}C\text{-}CH_4$ measured during the 15-minute monitoring period for Week 1 at Site 11 compared with the data extract from the largest peak (between 12:10:00 and 12:11:30). There is a difference between the $\delta^{13}C\text{-}CH_4$ measured between the 'peak' and the body of the monitoring period, with a greater frequency of measurements falling between -50 ‰ and -48 ‰. The data extracted from the peak show a greater number of readings that are more negative. When compared with the histograms provided for the AGL gas well and landfill in **Figure 4-2**, the $\delta^{13}C\text{-}CH_4$ results for the sample also indicate there may potentially be a thermogenic contribution. Given that the wind direction fluctuated significantly at the time of the peak during the monitoring period (see **Appendix C**), it is not possible to determine the source of the fugitive CH_4 emission.

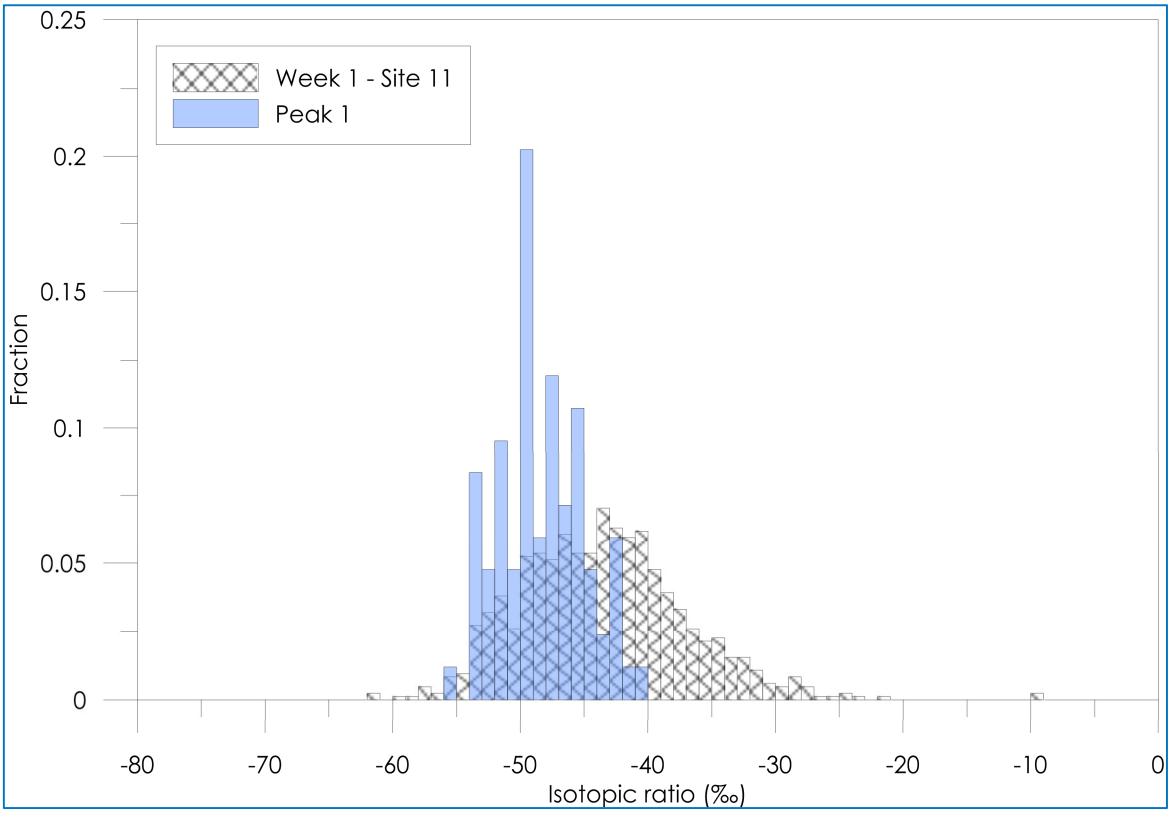


Figure 6-7: Histogram of $\delta^{13}C\text{-}CH_4$ measured at Week 1 – Site 11

6.3.2 Isotopic analysis for Week 7

Figure 6-8 presents a histogram of the $\delta^{13}C\text{-}CH_4$ measured during the 15-minute monitoring period for Week 7 at Site 11 compared with the data extract from the largest peak (between 10:52:45 and 10:55:30). There is a difference in the distribution of the $\delta^{13}C\text{-}CH_4$ measured between the 'peak' and the body of the monitoring period, with the most frequent number of measurements falling between -48 ‰ and -50 ‰. The data extracted from the peak show a greater number of readings that are more negative. As above, when compared with the histograms provided for the AGL gas well and landfill in **Figure 4-2**, the $\delta^{13}C\text{-}CH_4$ results for the sample also indicate there may potentially be a thermogenic contribution. Similar to Week 1, given that the wind direction fluctuated significantly at the time of the peak during the monitoring period (see **Appendix C**), it is not possible to determine the source of the fugitive CH_4 emission.

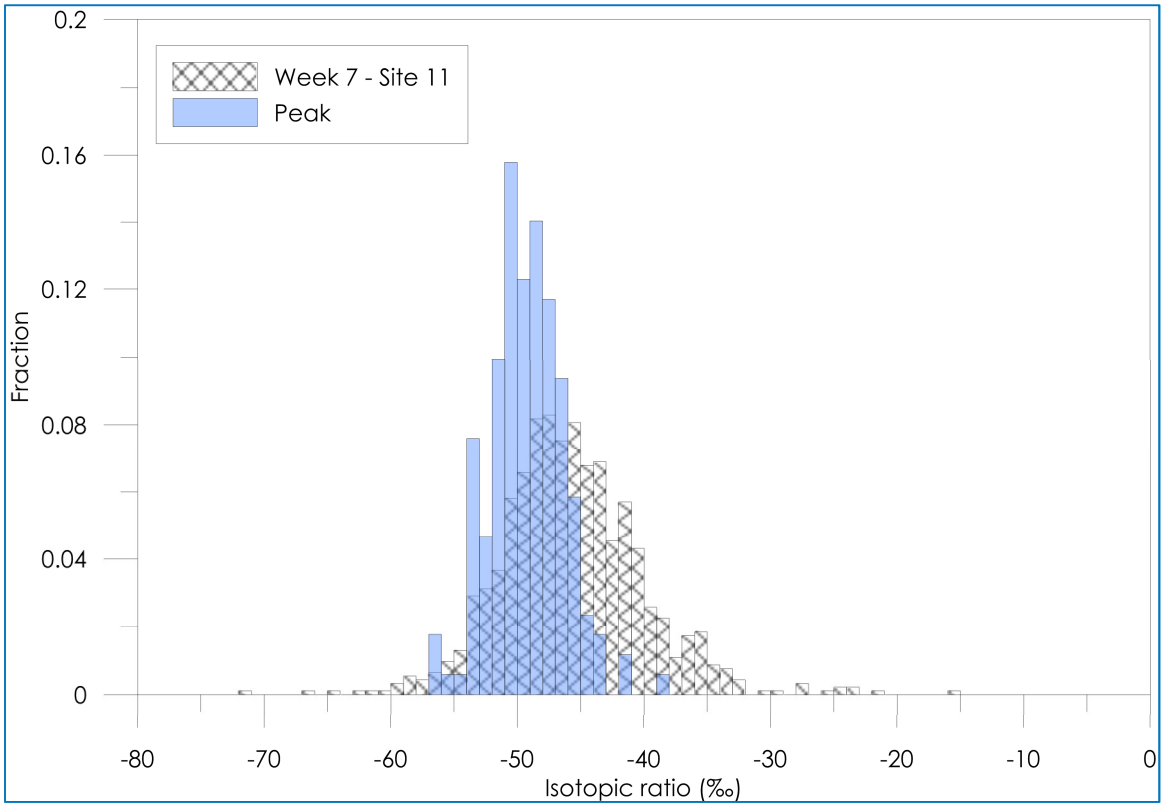


Figure 6-8: Histogram of $\delta^{13}C\text{-}CH_4$ measured at Week 7 – Site 11

6.3.3 Isotopic analysis for Week 11

During Week 11 the highest 1-second CH_4 concentration was measured to be 23.2ppm with a corresponding 15 minute average of 16.6ppm. The time series data presented in **Appendix C** shows that the elevated CH_4 concentrations were consistent during the monitoring period and therefore the whole monitoring period has been evaluated. **Figure 6-9** is a histogram of the $\delta^{13}C\text{-}CH_4$ measured during the 15-minute monitoring period for Week 11 at Site 11 compared with the $\delta^{13}C\text{-}CH_4$ distribution for AGL gas and the landfill sample.

The Week 11 $\delta^{13}C\text{-}CH_4$ data show a high frequency of values between the -50‰ and -55‰ range compared with the histograms provided for the AGL gas well and landfill in **Figure 4-2**, the $\delta^{13}C\text{-}CH_4$ results for the sample also indicate there may potentially be a thermogenic contribution. However, in view of the close proximity of the landfill to Site 11 and the strong odour observed during the monitoring period, it is considered likely that the CH_4 in this peak originates from a landfill source.

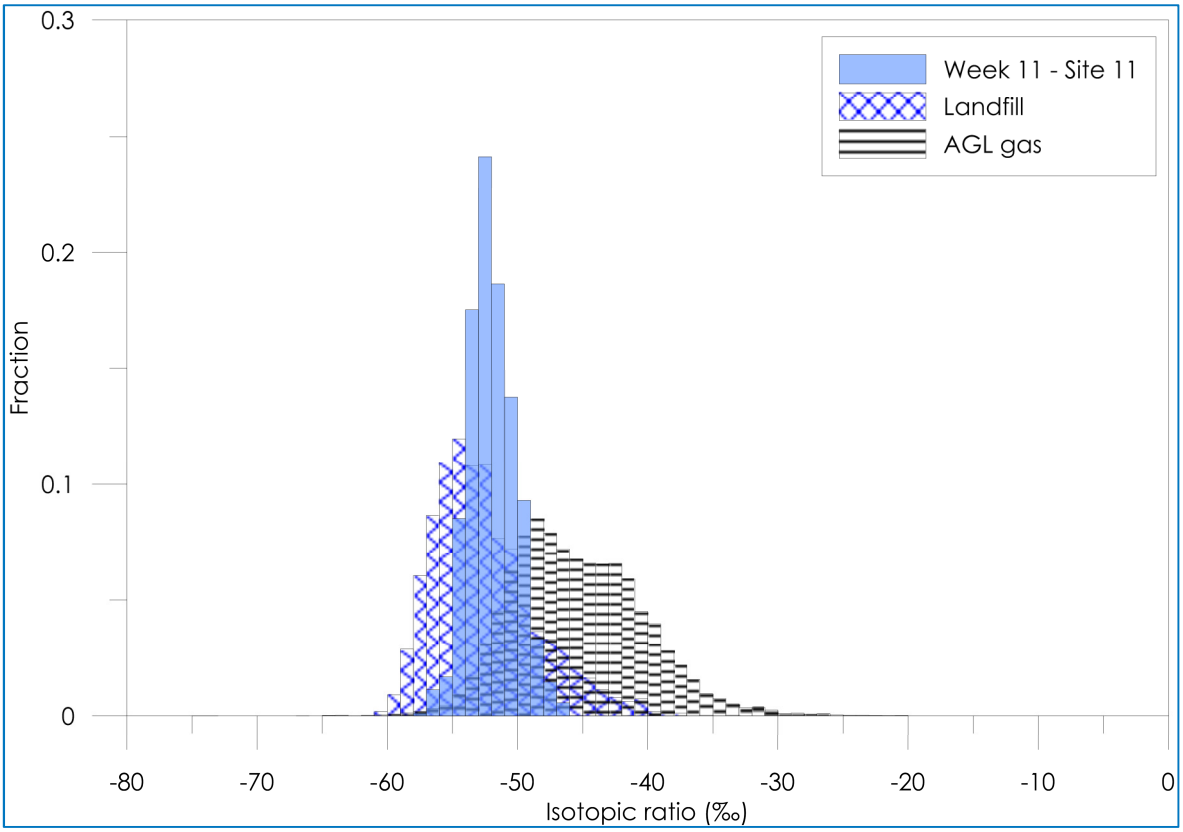


Figure 6-9: Histogram of $\delta^{13}C$-CH_4 measured at Week 11 – Site 11

6.4 CH_4 concentrations at Site 9 – Alchornea Circuit

Site 9 is located just north of the landfill and is located within a recently developed residential area. It should be noted that there are now a number of residences that have been built on Alchornea Circuit as the aerial photography presented in **Appendix A** was taken before the most recent development.

The average CH_4 concentration at Site 9 was recorded as 2.4ppm (see **Table 6-1**), up to 0.5ppm higher, on average, than other monitoring sites located in residential areas (e.g. Site 4 – average of 1.9ppm). These data are generally shown to be consistently higher compared to other monitoring sites in the area (i.e. Site 7, Site 8 and Site 10 shown in **Figure 5-2**). There are no distinct peaks in the data for the weeks investigated, suggesting that the CH_4 at Site 9 is well dispersed, rather than in distinct plumes as observed at Site 11.

The proximity of Site 9 to the landfill (approximately 200 m from the northern boundary – see **Appendix A**) suggests that the landfill could be a potential source of the consistently elevated CH_4 concentrations measured. However, in the same direction as the landfill there are also two AGL wells that should also be considered as a potential CH_4 source.

Figure 6-10 presents CH_4 concentration with respect to the direction of the wind for the 1-second dataset observed at this site. The prevailing wind direction and wind speed for each week can be referenced in **Appendix C**.

Figure 6-10 shows that the lower CH_4 concentration measurements show no trend in direction due to the low wind speeds experienced during the monitoring period (see **Appendix C**), while the higher CH_4 concentrations generally originate from the north and the east. Given that both the gas wells and landfill are located to the south of the monitoring site it would suggest that the CH_4 measured is experienced on a broader local scale. Fugitive CH_4 released from nearby CSG wells would be more likely to be measured in peaks as a distinct plume is measured by the Picarro.

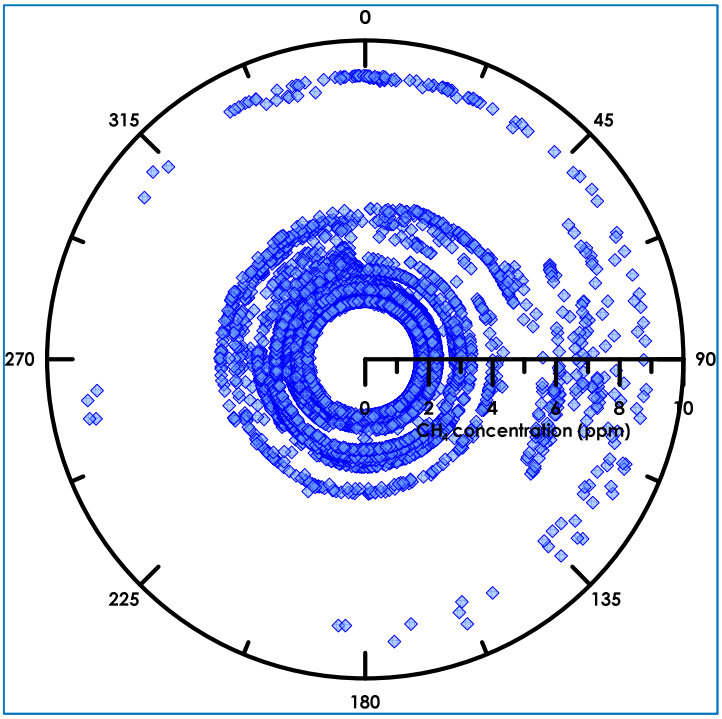


Figure 6-10: Polar plot of CH_4 concentration at Site 9 (Weeks 1 – 12)

Review of the $\delta^{13}C$-CH_4 measured over the 12 weeks at Site 9 shows a minor trend in the data. The average $\delta^{13}C$-CH_4 for the 15-minute monitoring period each week is slightly more negative than for those measured nearby at Site 7, Site 8 and Site 10, as shown in **Table 6-3**.This characteristic is also observed in the $\delta^{13}C$-CH_4 values measured at Site 11(located in close proximity to the landfill, and discussed in **Section 6.3**). This indicates that there may be a biogenic CH_4 source near Site 9. Given that Site 9 is located approximately 200m from the landfill (and that landfills are a known significant source of CH_4) it is likely that fugitive CH_4 emissions from the landfill may be influencing CH_4 levels at Site 9. **Figure 6-11** to **Figure 6-13** are a series of histograms of the $\delta^{13}C$-CH_4 values measured at Site 9 for each week of the monitoring period. It can be seen that the distribution of the $\delta^{13}C$-CH_4 is most similar to that of the reference landfill sample during Week 11.

Table 6-3: 15-minute average $\delta^{13}C$-CH_4 for Sites 7 - 10

	Site 7	Site 8	Site 9	Site 10
Week 1	-42	-41	-45	-42
Week 2	-37	-40	-44	-40
Week 3	-42	-42	-43	-42
Week 4	-41	-42	-43	-42
Week 5	-40	-39	-39	-37
Week 6	-42	-39	-41	-38
Week 7	-41	-43	-45	-45
Week 8	-40	-40	-41	-40
Week 9	-40	-40	-39	-41
Week 10	-43	-38	-43	-40
Week 11	-43	-39	-40	-40
Week 12	-41	-38	-46	-40

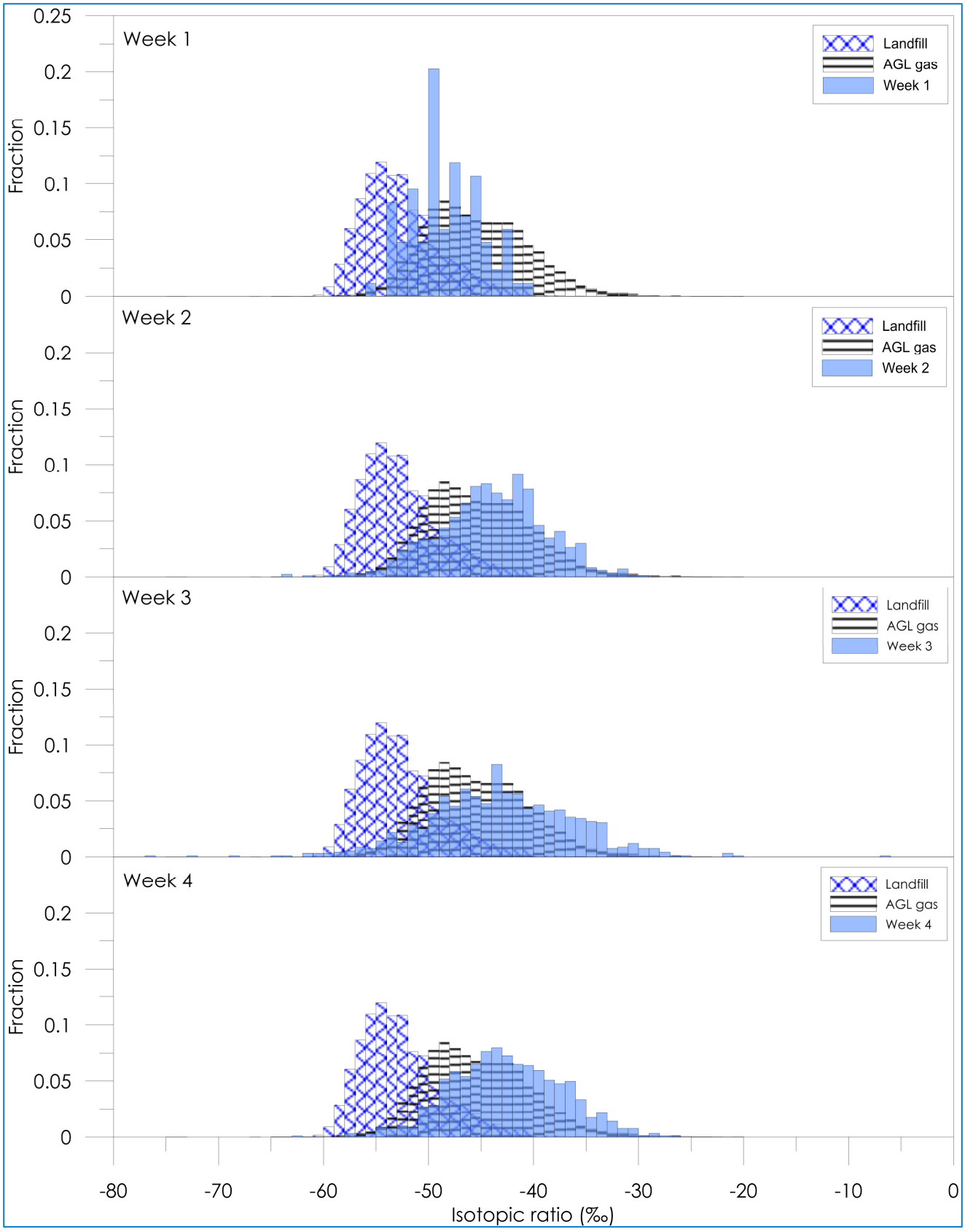


Figure 6-11: Histogram of $\delta^{13}C\text{-}CH_4$ measured at Site 9 Weeks 1 - 4

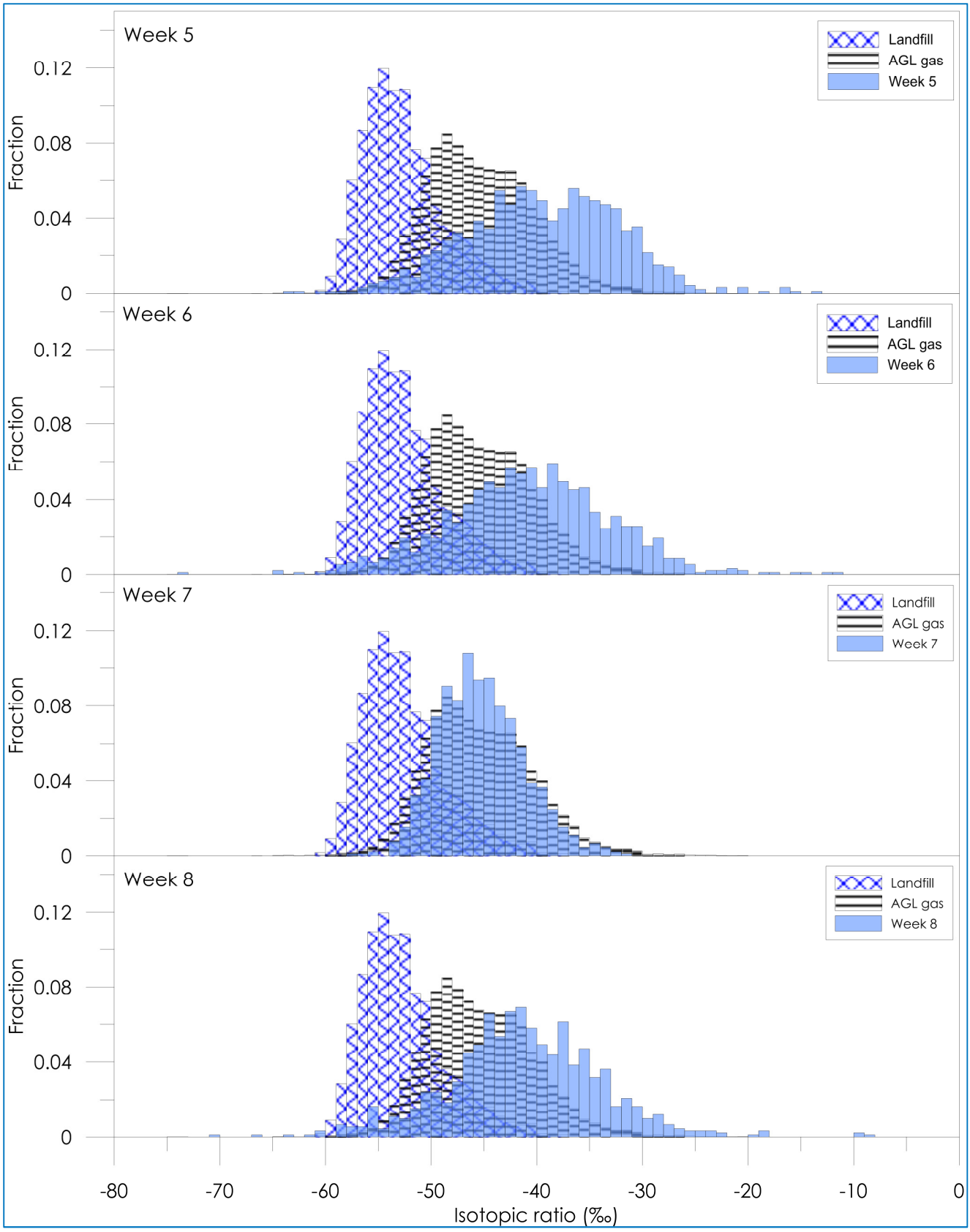


Figure 6-12: Histogram of $\delta^{13}C$-CH_4 measured at Site 9 Weeks 5 - 8

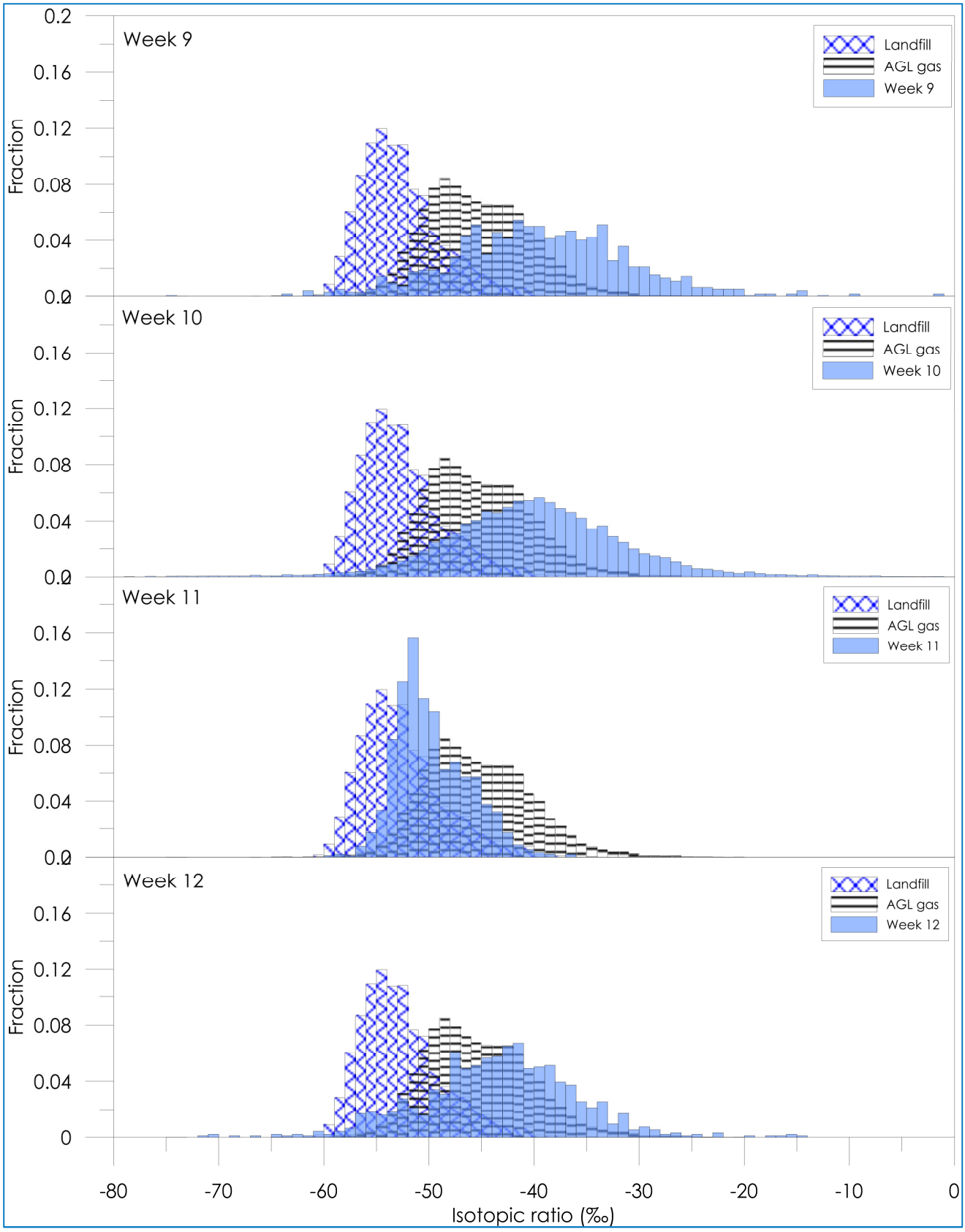


Figure 6-13: Histogram of $\delta^{13}C\text{-}CH_4$ measured at Site 9 Weeks 9 - 12

6.5 CH_4 concentrations at Site 12 – Glenlee Road (Coal washery)

Site 12 is located within the coal washery on Glenlee Road (see **Appendix A**). Coal is an established fugitive CH_4 emission source, and exposed coal fines stockpiles have been identified as a potential significant source of CH_4 in the Camden area.

The monitoring results for Week 1 through Week 12 indicate that the coal washery is not a significant local source of CH_4. The wind direction data presented in **Appendix A** shows that during the 12 weeks the prevailing winds originated from all directions, and thus, capturing potential coal CH_4 sources that surround the monitoring location.

The lower than expected CH_4 concentrations measured at Site 12 are likely attributed to the age of the coal fines stockpiled. It is understood that the coal fines being stockpiled may have been exposed to the ambient environment for several years. It is likely therefore that since the coal was extracted, the CH_4 within the coal has already been released.

6.6 CH_4 concentrations at Site 17 - AGL Rosalind Park Gas Plant

Site 17 is the monitoring site located in closest proximity to AGL's RPGP, where all CSG from surrounding wells is reticulated to and processed. The RPGP comprises a number of pressure relief valves and regulators, that are, for safety and operational purposes, designed to emit CSG (and by association, CH_4). It is therefore expected that slightly elevated CH_4 concentrations may on occasion be measured at Site 17.

In general, CH_4 concentrations were observed to be higher when monitoring was undertaken in the morning or late afternoon, with the lowest concentrations observed in the early afternoon. The CH_4 concentration data indicate there is a diurnal relationship in CH_4 concentration. This is consistent with the occurrence of early morning temperature inversions that will reduce the effective mixing layer that any CH_4 may be dispersed within and is further discussed in **Section 6.7.**

In Week 3, Week 6 and Week 8 the slightly elevated CH_4 concentrations were measured. Review of the $\delta^{13}C$-CH_4 during this monitoring period (see **Appendix C**) show that the $\delta^{13}C$-CH_4 values measured lie mostly within the orange band of average $\delta^{13}C$-CH_4 characterised for the gas extracted as part of the Camden Gas Project. It is acknowledged that such conditions also occur for a range of other sites for the duration of the monitoring period, for example Site 1, Week 11 and Week 12.

This is also evidenced in Week 8 when the highest 1-second CH_4 concentration of 4.6ppm was measured. The CH_4 concentrations correspond to $\delta^{13}C$-CH_4 values that are within the $\delta^{13}C$-CH_4 range for CSG. The distribution of the $\delta^{13}C$-CH_4 is shown in **Figure 6-14** and suggests a potential thermogenic (i.e. CSG) influence. It should be noted that there remains a significant spread in the $\delta^{13}C$-CH_4 readings which, as already discussed is symptomatic of measurements of CH_4 at lower concentrations.

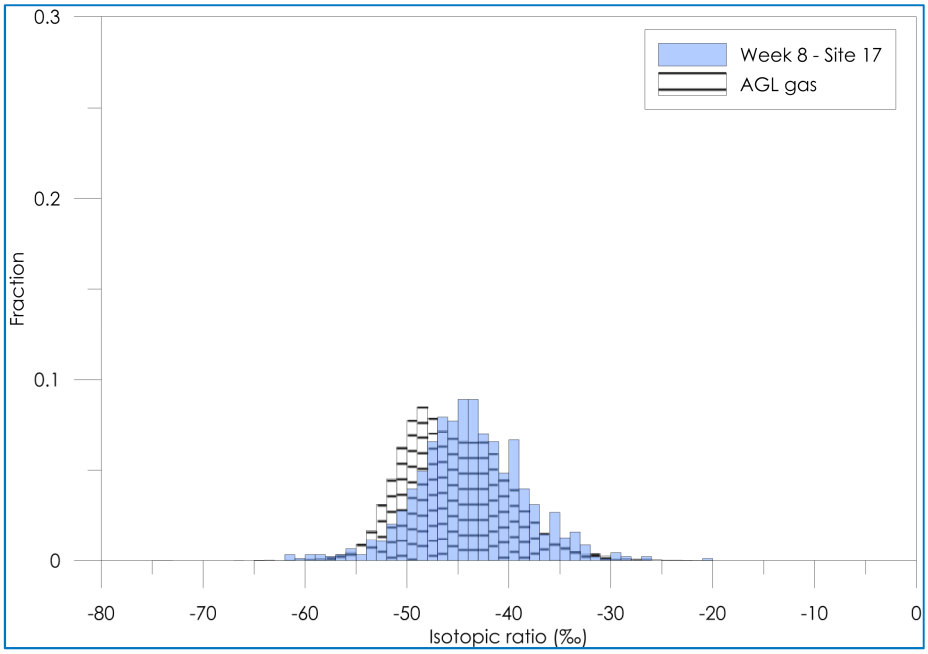
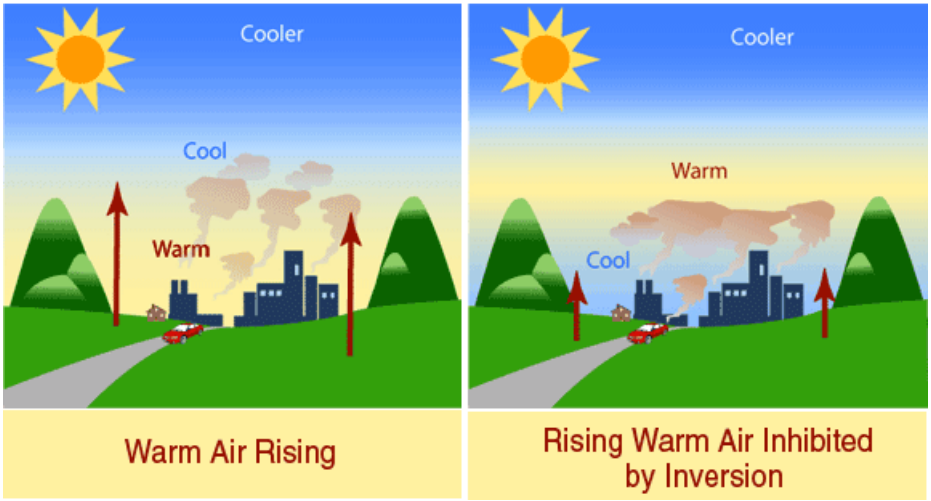


Figure 6-14: Histogram of $\delta^{13}C$-CH_4 measured at Week 8 – Site 17

6.7 Inversion conditions

Inversion conditions are common in areas such as Camden during the cooler months where on clear nights, night time drainage flows pool in valleys with the warmer air above trapping the air below. Inversion conditions are conducive to higher CH_4 concentrations, as any CH_4 is trapped within a shallow (often only 50 meters high) layer of air. It is not until the mid-morning that an inversion is broken down by the influence of the heat of the morning sun that allows mixing of the stable layer with layers aloft, as experienced during daylight hours. This mixing allows any CH_4 to disperse and become less concentrated. **Figure 6-15** shows a graphical comparison of when the dispersion of emissions with and without an inversion.



(**Source: Pollutionfree, 2014**)

Figure 6-15: Temperature inversion

During Week 4, Week 8 and Week 10 monitoring periods, inversion conditions prevailed. Meteorological data sourced from the Bureau of Meteorology' Camden Airport weather station, in combination with field observations (i.e. clear skies during the morning hours) support this observation. See the time series data from **Appendix C** for the detailed results.

A general trend is observed in the monitoring data that CH_4 concentrations are often highest at the beginning and end of the day's fieldwork. This diurnal pattern was also observed as part of the works completed by **Lowry et al. (2001)** in London. These fluctuation were found to be associated with prevailing meteorological conditions (i.e. temperature inversions), as well as when the general population used domestic gas appliances (i.e. cooking, hot water systems etc.).

Figure 6-16 shows the relationship between the 15-minute average CH_4 concentration and the corresponding hour of day for the duration of the monitoring period. The 15-minute average CH_4 concentrations are observed as being higher between 9am and 10am and after 3pm. This trend is most likely due to the lower height of the mixing layer during these hours.

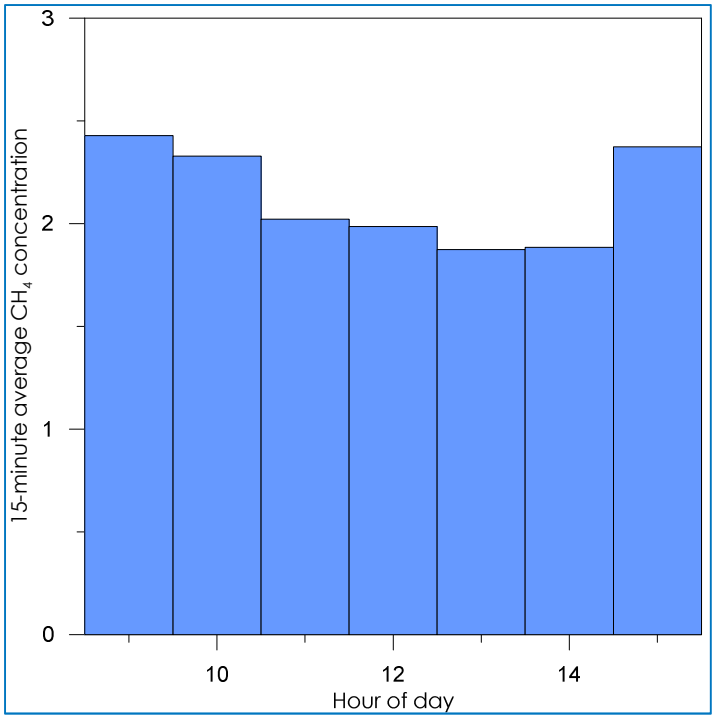


Figure 6-16: 15-minute maximum CH_4 concentration versus hour of day for monitoring period

Note: Data for hours before 9am and after 4pm is not shown given the relatively small data set collected during these periods.

6.7.1 Night time monitoring

To further investigate the diurnal variation in CH_4 concentrations within the study area, night time monitoring was completed. For the purposes of this study, night time hours are considered to be after sunset, which is at this time of year in the study area after 6pm.

Nine of the total 25 sites were selected based on public access during night hours, proximity to wells and background locations. These nine locations are indicative of where the community live, work and play.

To provide comparison, day time monitoring at the selected sites was also completed either the same day, or the day following the night time monitoring.

The results of the night monitoring are presented in **Table B- 11** with the corresponding day time monitoring detailed in **Table B- 13** (**Appendix B**). More detailed results for each individual site for each of the 12 weeks are provided in **Appendix C**.

Figure 6-17 and **Figure 6-18** provide a graphical comparison of the day/ night monitoring at the selected sites for the 15 minute average and 1 second maximum CH_4 concentration measurements.

With the exception of Site 11 (Glenlee Road – landfill), the 15 minute average is higher during the night time monitoring than that measured during the day. The 1 second maximum was higher at all sites during the night time monitoring.

The day time monitoring at Site 11 measured significantly higher CH_4 concentration compared to any other week of monitoring. This also occurred at night, where up 16.7ppm was measured for the 1 second maximum.

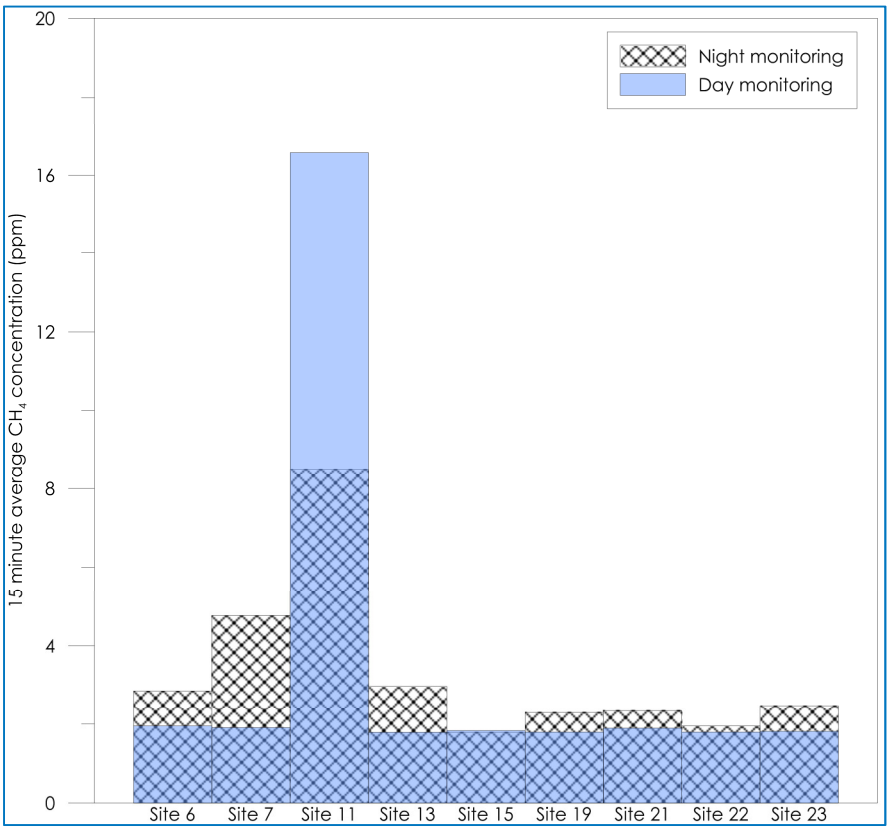


Figure 6-17: Day/night comparison of the 15-minute average CH_4 concentration for Week 11

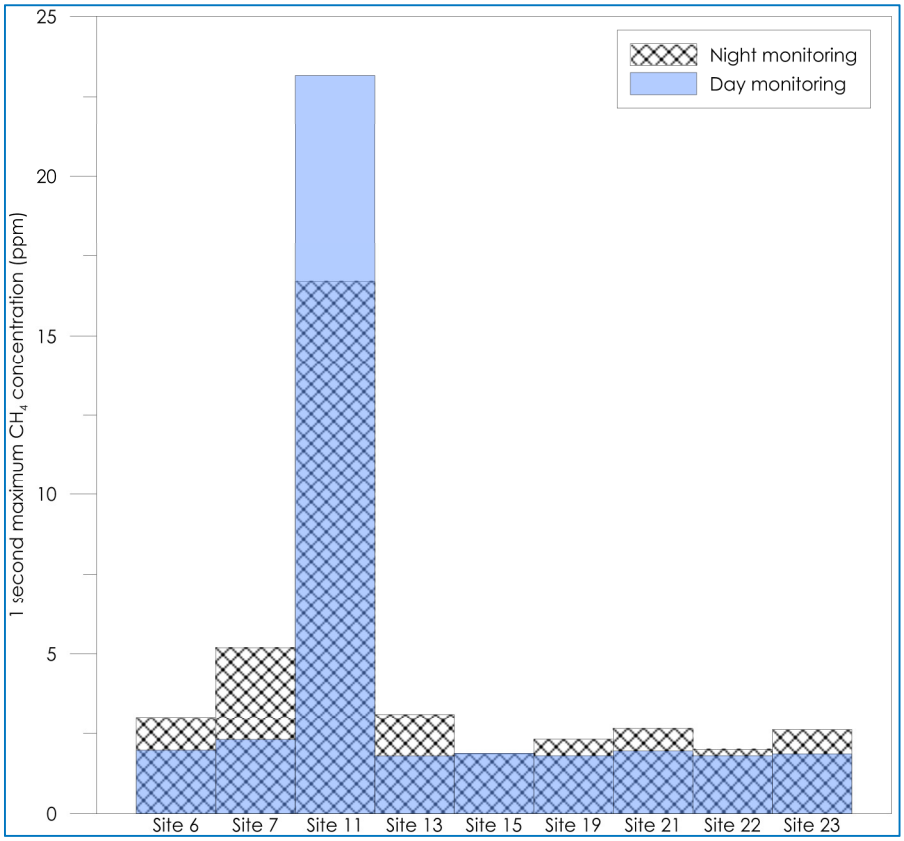


Figure 6-18: Day/night comparison of the 1 second maximum CH_4 concentration for Week 11

6.8 CH_4 concentrations during Week 7

During Week 7, elevated CH_4 concentrations were measured at a number of monitoring sites (Site 7 to 11, Site 15, Site 23 and Site 24) with 15 minute average concentrations ranging between 2.7ppm and 3.7ppm. The spatial distribution of the CH_4 concentrations at the respective sites shown in **Figure 5-2** has also been presented as a contour plot in **Figure 6-19**. It is acknowledged that ideally, CH_4 monitoring would be completed simultaneously for each site to generate a definitive contour plot of the spatial distribution of CH_4 at a given time. Given the impracticalities of installing 25 instruments across the Macarthur region, the contour plot references measurements taken at different times across the two designated days of monitoring. In view of this limitation, the contour plot is regarded as indicative only.

The contour plot indicates that the measurements made during Week 7 were elevated to the northeast of the study area. Sites 7 to 11 and Site 15 are located within reasonable proximity of the landfill (i.e. less than 2 km away). Site 23 and 24 are well removed from the Camden Gas Project to the north in residential areas.

It is interesting to note that during Week 7, the CH_4 concentrations in the vicinity of AGL's RPGP are relatively low, and thus, could be considered in line with background concentrations measured during Week 7. However, this is not the case for every week of the study period, as on a number of occasions, Site 17 measured relatively higher CH_4 concentrations than the other sites (e.g. Week 3 and Week 4).

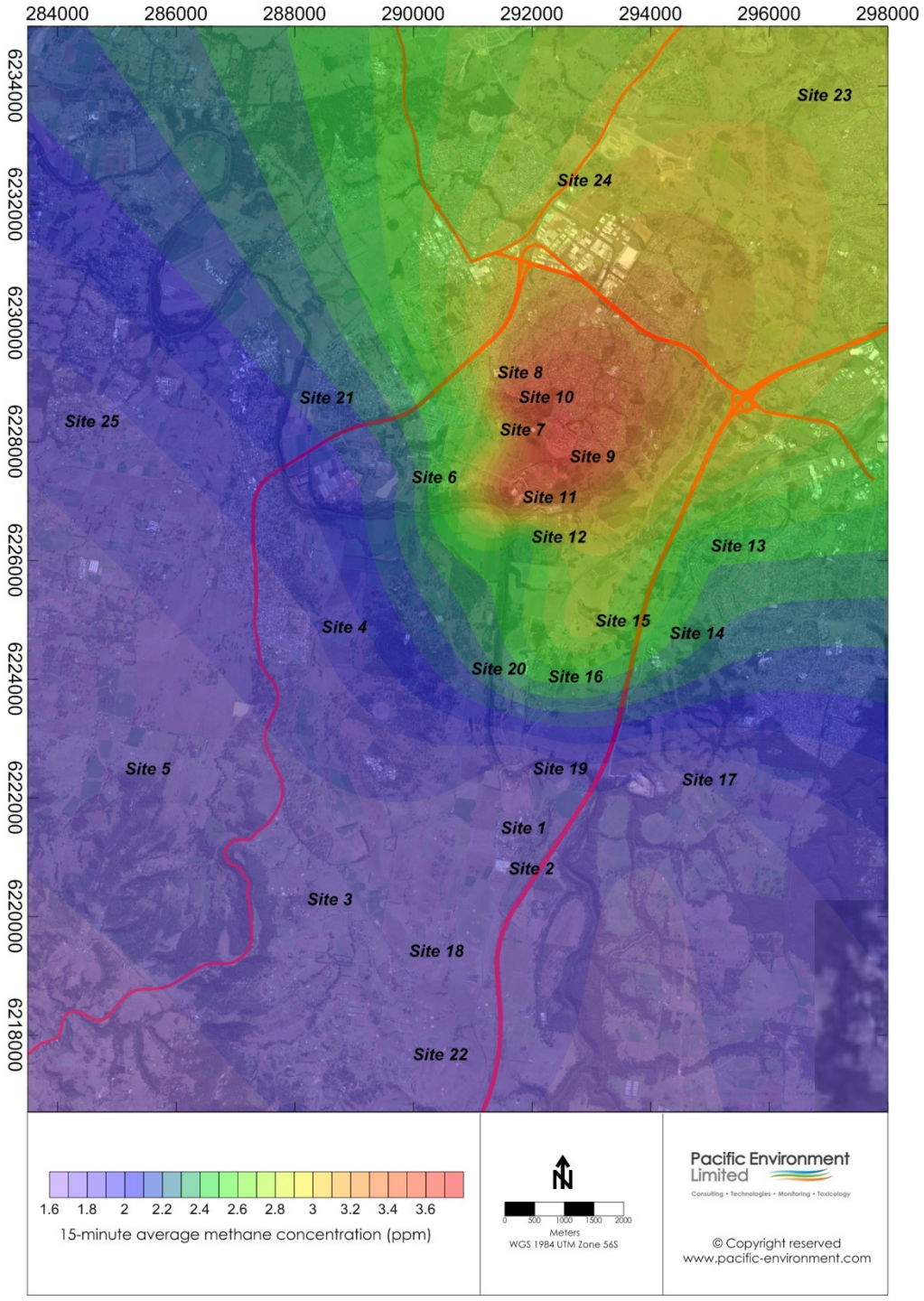


Figure 6-19: Spatial distribution of CH_4 concentrations observed during Week 7

A comparison of the respective sites for Weeks 5 - 8 is shown in **Table 6-4**. The CH_4 concentration measurements show that during Week 7 the concentrations are almost double compared to Weeks 5, 6 and 8.

Table 6-4: 15-minute average CH_4 concentration and $\delta^{13}C$-CH_4 for Sites 7 - 10

	Week 5	Week 6	Week 7	Week 8
CH_4 concentration				
Site 7	2.0	1.9	2.7	1.9
Site 8	1.9	1.9	2.9	1.7
Site 9	1.8	1.8	3.7	2.0
Site 10	1.9	1.8	3.5	2.0
Site 11	2.5	2.3	3.6	1.8
Site 15	1.8	2.2	2.8	1.7
Site 23	1.9	1.9	2.9	1.8
Site 24	2.1	1.9	2.8	1.8
$\delta^{13}C$-CH_4 (‰)				
Site 7	-40	-40	-43	-43
Site 8	-39	-39	-43	-40
Site 9	-39	-41	-45	-41
Site 10	-37	-38	-45	-40
Site 11	-43	-41	-46	-40
Site 15	-40	-42	-43	-38
Site 23	-42	-38	-45	-38
Site 24	-44	-40	-45	-38

Noteworthy are the consistent elevated concentrations at these sites during Week 7 over time, with measurements at these sites taken across the 12 June and 13 June 2013 (see **Table B- 5** to **Table B- 8** in **Appendix B** for dates and time information). Monitoring at Site 9, Site 15, Site 23 and Site 24 was completed on 12 June 2013 with the remaining sites abandoned due to heavy rain. The monitoring at Sites 7, 8, 10 and 11 was completed on the following day (13 June 2013). Prevailing weather conditions on 12 June were overcast during the morning with the onset of heavy rain in the late morning. By 13 June 2013, clear weather conditions prevailed.

Also to be taken into consideration were the prevailing weather conditions for two respective monitoring days, of which on both days heavy rain was experienced on occasion. The elevated CH_4 concentrations are not associated with temperature inversion on the two days. Temperature inversions do not occur when cloud is present, as was the case on 12 June when overcast weather conditions were observed. In addition, given the time of day being the very late morning for the four sites any temperature inversion would have broken down by the time that the monitoring was undertaken.

The proximity of Site 7 through Site 11 to the landfill suggests that the landfill could be a potential source of the consistently elevated CH_4 concentrations measured. However, in the same direction as the landfill there are also two AGL wells that should also be considered as a potential CH_4 source. However, the Site 23 and Site 24 are both located some distance from the landfill suggesting that meteorological conditions on the day may have been conducive to the transportation of fugitive CH_4 emissions from the landfill towards Site 23 and Site 24.

Review of the 15-minute average $\delta^{13}C$-CH_4 presented in **Table 6-4** is shown to be slightly more negative than during the other weeks measured, ranging between -43‰ and -46‰, with the other weeks ranging between -37‰ and -44‰. It is noteworthy that the $\delta^{13}C$-CH_4 was also more negative during Week 7 compared to Weeks 5, 6 and 8, and are more consistent with the 15 minute average $\delta^{13}C$-CH_4 measured at the other sites.

In view of the elevated CH_4 concentrations at Site 23 and Site 24, both of which were measured on 12 June 2013, it indicates that these elevated measurements may have been part of wider scale CH_4 event rather a localised event, such as would likely occur from fugitive emissions from a single CSG field well.

Alternatively, there may have been multiple sources of CH_4 that were measured on this day that exhibited a similar $\delta^{13}C\text{-}CH_4$. To this end, the field notes identify that a number of other sources, such as garbage trucks passing and other agricultural activities (see **Appendix B**).

Given the proximity of CSG wells and the landfill in this area, combined with some ambiguity in the $\delta^{13}C\text{-}CH_4$ observations, it is not possible to definitively identify the source of elevated CH_4 observed during this period.

6.9 Background CH_4 measurements

Five monitoring locations (Site 21 to Site 25) were selected to characterise CH_4 concentration and $\delta^{13}C\text{-}CH_4$ at sites geographically removed from the Camden Gas Project and therefore not subject to potential fugitive CH_4 emissions from AGL's operations. The global average CH_4 concentration was established to be 1.8ppm in 2012 (**WMO, 2013**).

Statistical analysis has been completed to establish if there are differences between the CH_4 concentration measured and the corresponding $\delta^{13}C\text{-}CH_4$ values for the background monitoring sites and those located within the Camden Gas Project area.

6.9.1 Statistical analysis of CH_4 concentration

The CH_4 concentration data presented for each site in **Figure 6-1** in conjunction with **Table 6-1** provide a comparison of the average CH_4 concentration as well as the 1-second variability.

Compared to the global average, the background CH_4 concentrations fall within reasonable approximation of the global average with 15-minute average concentrations ranging between 1.9ppm and 2.3ppm across the monitoring period (see **Table 6-1**).

A histogram of the CH_4 concentration 1 second measurements is shown in **Figure 6-20** and indicates that the frequency distribution is not normally distributed. For both the background sites and the sites in within the Camden Gas Project area, the greatest frequency of occurrence for CH_4 concentration is between 1.7ppm and 1.9ppm. The background dataset shows a greater proportion of CH_4 concentrations measured between 2.4ppm and 3.0ppm.

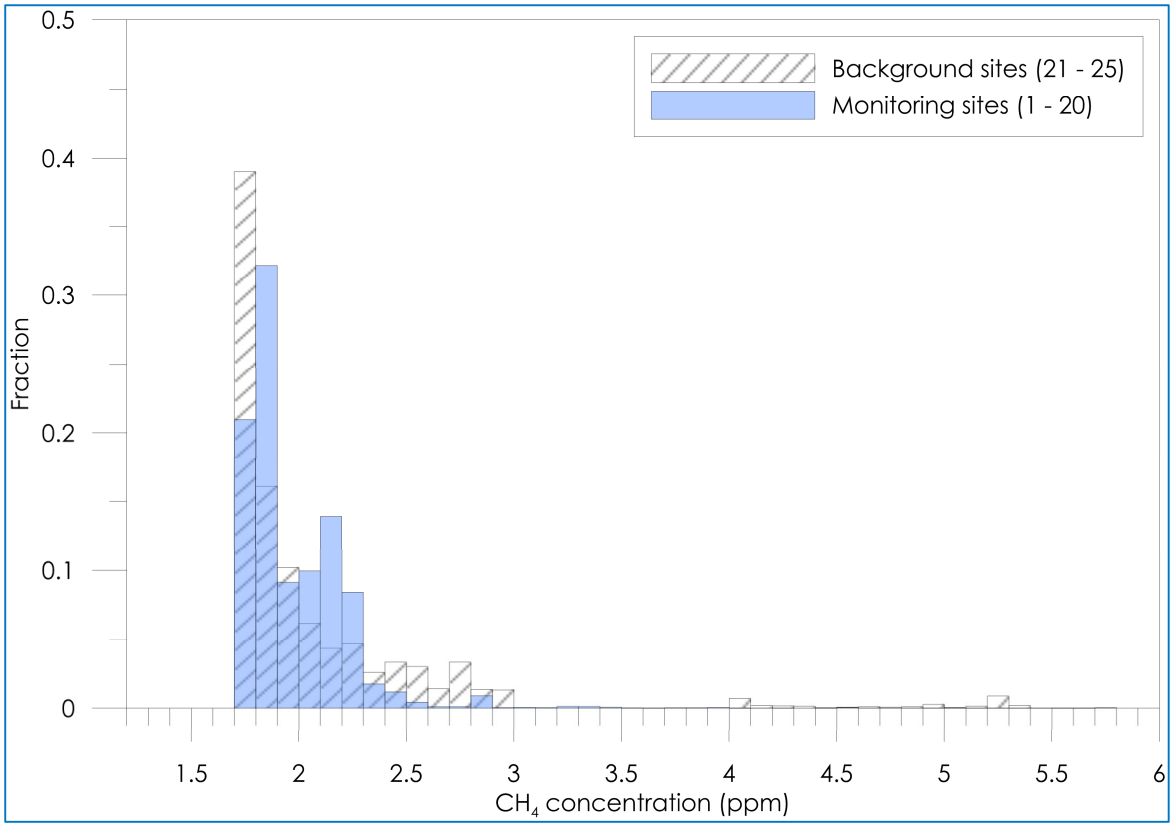


Figure 6-20: Histogram of CH_4 concentration measured background monitoring sites: Week 1 to Week 12

Because the CH_4 concentrations shown in **Figure 6-20** are not normally distributed[b], the main assumptions underlying the use of the simple statistical *t*-test did not conform with the requirements for normality. Therefore, a non-parametric[c] test - the Mann-Whitney test[d] - was used to examine the differences between the distributions. This test was used to determine whether there was a significant difference between the distributions for the monitoring sites within the Camden Gas Project area and background sites at the 95% confidence level. Due to the influences of CH_4 sources from the landfill, additional analysis was completed in removing monitoring sites likely to be subject to landfill CH_4 influences (i.e. Site 9 and Site 11).

The results of these tests are summarised in **Table 6-5**. There was found to be a significant difference between the distribution of CH_4 concentrations at the background sites and that at all non-background monitoring sites (P=0.002). However, this result appears to have mainly been influenced by the landfill-affected sites. There was a significant difference between the CH_4 distributions at the

[b] The Shapiro-Wilk test was used to determine whether the distributions deviated from a normal probability distribution.

[c] The term 'non-parametric' refers here to the statistical methods that are used to analyse data which do not have any characteristic structure (which in the majority of cases means that the data do not conform to a normal probability distribution). In non-parametric tests the order (rank) of the values is used rather than the actual values themselves.

[d] The Mann-Whitney test can be time consuming to run. In this study the run time rendered the use of one-second average CH_4 measurements impractical. The CH_4 measurements were therefore averaged over one-minute periods, and the Mann-Whitney test was conducted on these one-minute averages. Another feature of the Mann-Whitney test is that the probability (P) value can be determined in different ways (exact, approximated, or based on probability using a Monte Carlo approach). Again, the exact method was too time consuming, and so rather than using the approximation we used the Monte Carlo approach). For each comparison of distributions, each Monte Carlo simulation involved 5,000 iterations. This gave a confidence level in the P value of greater than 99%.

background and landfill sites (P<0.0001), but no significant difference between the distributions for the background sites and sites within the Camden Gas Project area when those monitoring sites near the landfill (Site 9 and Site 11) are removed from the dataset.

Table 6-5: Summary statistics for Mann-Whitney tests

Variable 1	Variable 2	P value (two tailed)	Conclusion
CH_4 concentration at background monitoring sites (Sites 21 – 25)	CH_4 concentration at all monitoring sites close to gas wells (Sites 1 – 20)	0.002	Significant difference between distributions
CH_4 concentration at background monitoring sites (Sites 21 – 25)	CH_4 concentration at monitoring sites (Sites 1 – 20) close to gas wells with landfill-affected sites (Site 9 and Site 11) removed	0.328	No significant difference between distributions
CH_4 concentration at background monitoring sites (Sites 21 – 25)	CH_4 concentration at landfill-affected sites (Sites 9 and 11) only	< 0.0001	Significant difference between distributions

In other words, the statistical analysis of the CH_4 concentration indicates that the sites adjacent to the landfill show higher CH_4 concentrations compared with sites located away from this source. When sites potentially influenced by the landfill source are removed from the analysis, this indicates there is no significant difference between those CH_4 concentrations measured inside of the Camden Gas Project and those located outside (i.e. background locations). Thus both areas (inside and outside of the Camden Gas Project) show similar distributions in CH_4 concentrations, consistent with natural variability of CH_4.

6.9.2 Statistical analysis of $\delta^{13}C$-CH_4

Further analysis has been completed to establish approximate background isotopic signature. Histograms of the $\delta^{13}C$-CH_4 for the background sites are presented in **Figure 6-21**.

These have been compared with the $\delta^{13}C$-CH_4 for the monitoring sites in proximity to within the Camden Gas Project area (i.e. Site 1 to Site 20). Both datasets show a similar Gaussian distribution with $\delta^{13}C$-CH_4 ranging between 0 and -75. The distribution of the $\delta^{13}C$-CH_4 measurements for the background sites is slightly different from that of Site 1 – Site 20.

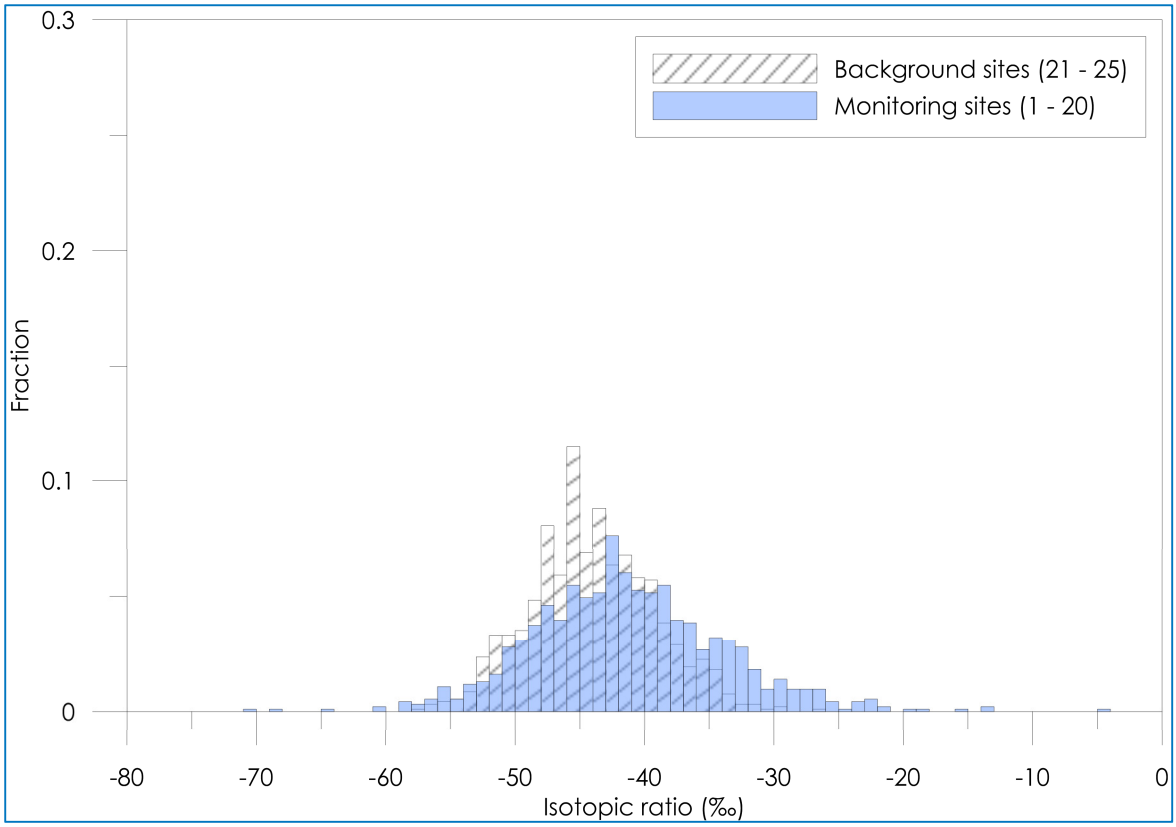


Figure 6-21: Histogram of $\delta^{13}C\text{-}CH_4$ measured background monitoring sites: Week 1 to Week 12

Statistical analysis was completed on the two datasets using an unpaired *t*-test with equal variances and the data as shown to exhibit a normal probability distribution (see **Figure 6-21**). A preliminary test for the equality of variances indicates that the variances of the two groups were not significantly different where $P \geq 0.05$ using a 95% confidence interval.

Therefore, a two-sample t-test was performed that assumes equal variance. Results for the unpaired *t*-test with equal variances indicate that there is no statistically significant difference between the two datasets ($P \geq 0.05$) using a 95% confidence interval. The mean for the background sites (mean = -41.04, number of measurements = 4,581) was similar to the scores for Sites 1 - 20 (mean = -41.01, number of measurements = 217,760).

The mean $\delta^{13}C\text{-}CH_4$ values of -41‰ for both datasets is within range of the $\delta^{13}C\text{-}CH_4$ reported by **Montiel et al. (2011)** for residential areas (-38 ‰). The $\delta^{13}C\text{-}CH_4$ measured as part of this study are more negative than those established as part of **Montiel et al. (2011)** and suggest that there are greater contributions from 'lighter' methane sources (i.e. biogenic sources).

6.10 Livestock in Camden

Field observations indicate that on several occasions the presence of livestock activities (i.e. cattle farming) were noted in the vicinity of the sampling sites with observations including:

- cows in field;
- cow manure in field;
- horses passing; and
- cow odour.

The field observations indicate that during Week 7 at both Site 1 and Site 5 cow odour was observed. During Week 10 at Site 20, cattle were in close proximity to the monitoring equipment (see **Figure 6-22**).

Figure 6-22: Cattle at Site 20 during Week 10

Figure 6-23 and **Figure 6-24** show the distribution of $\delta^{13}C\text{-}CH_4$ for each week of Week 5 through 8 compared with the distribution of $\delta^{13}C\text{-}CH_4$ as determined from cow manure (see **Section 4**) for Site 1 and Site 5, respectively.

The distribution of $\delta^{13}C\text{-}CH_4$ for Site 20 for Week 9 through 12 compared with the distribution of $\delta^{13}C\text{-}CH_4$ as determined from livestock (see **Section 4**) is shown in **Figure 6-25**.

At all three sites, a very small contribution of $\delta^{13}C\text{-}CH_4$ between the range of -71‰ and -65‰ are observed during Week 5 and Week 7, noting that odour is only observed during Week 7 and Week 10.

Given the distinct isotopic signature associated with livestock, and the lack of correlation with this in the CH_4 measurements, this indicates that any CH_4 from this source was well dispersed, and did not significantly impact upon the measured CH_4 at these locations during these times.

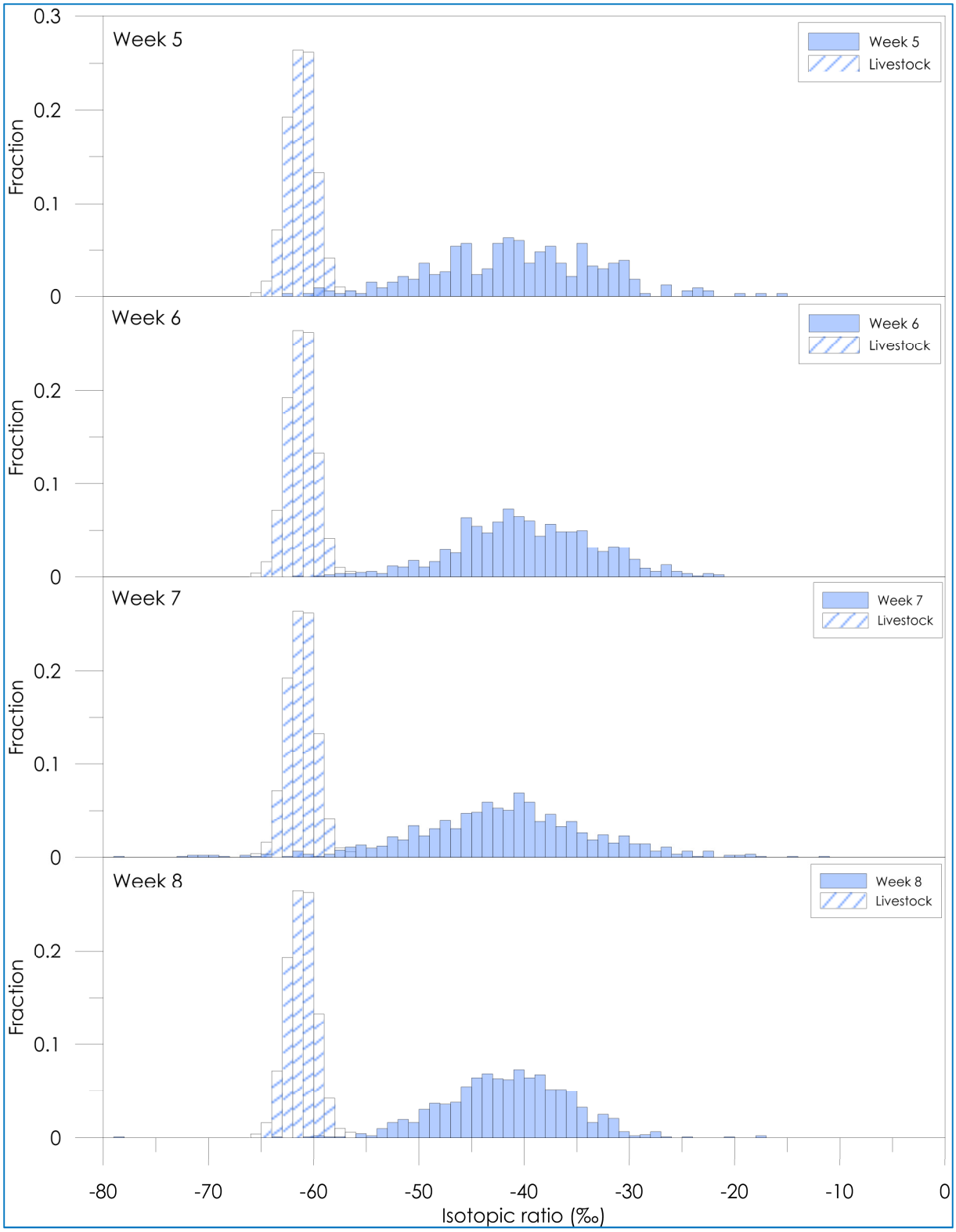


Figure 6-23: Histogram of $\delta^{13}C\text{-}CH_4$ measured at Site 1: Week 5 - 8

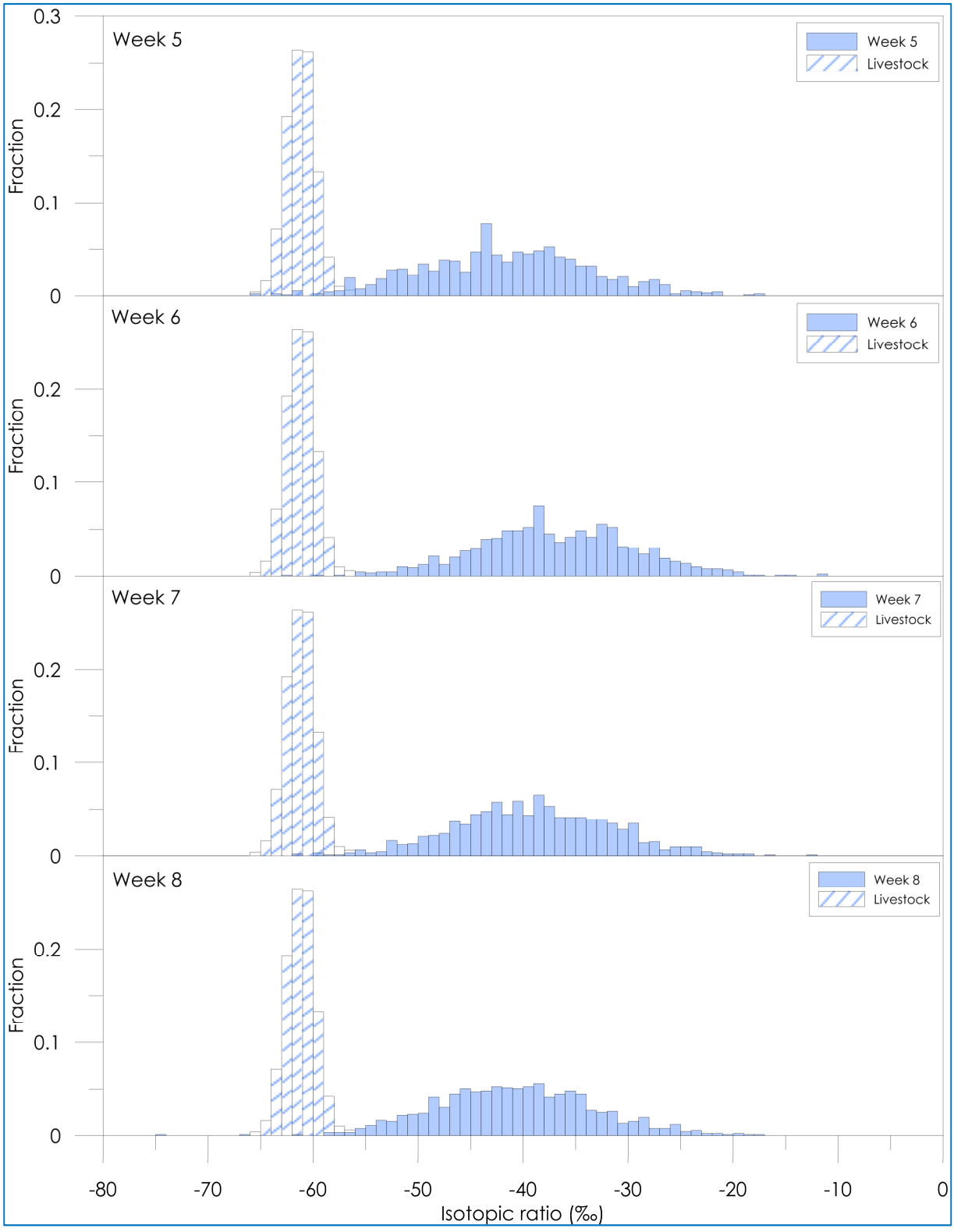


Figure 6-24: Histogram of $\delta^{13}C\text{-}CH_4$ measured at Site 5: Week 5 - 8

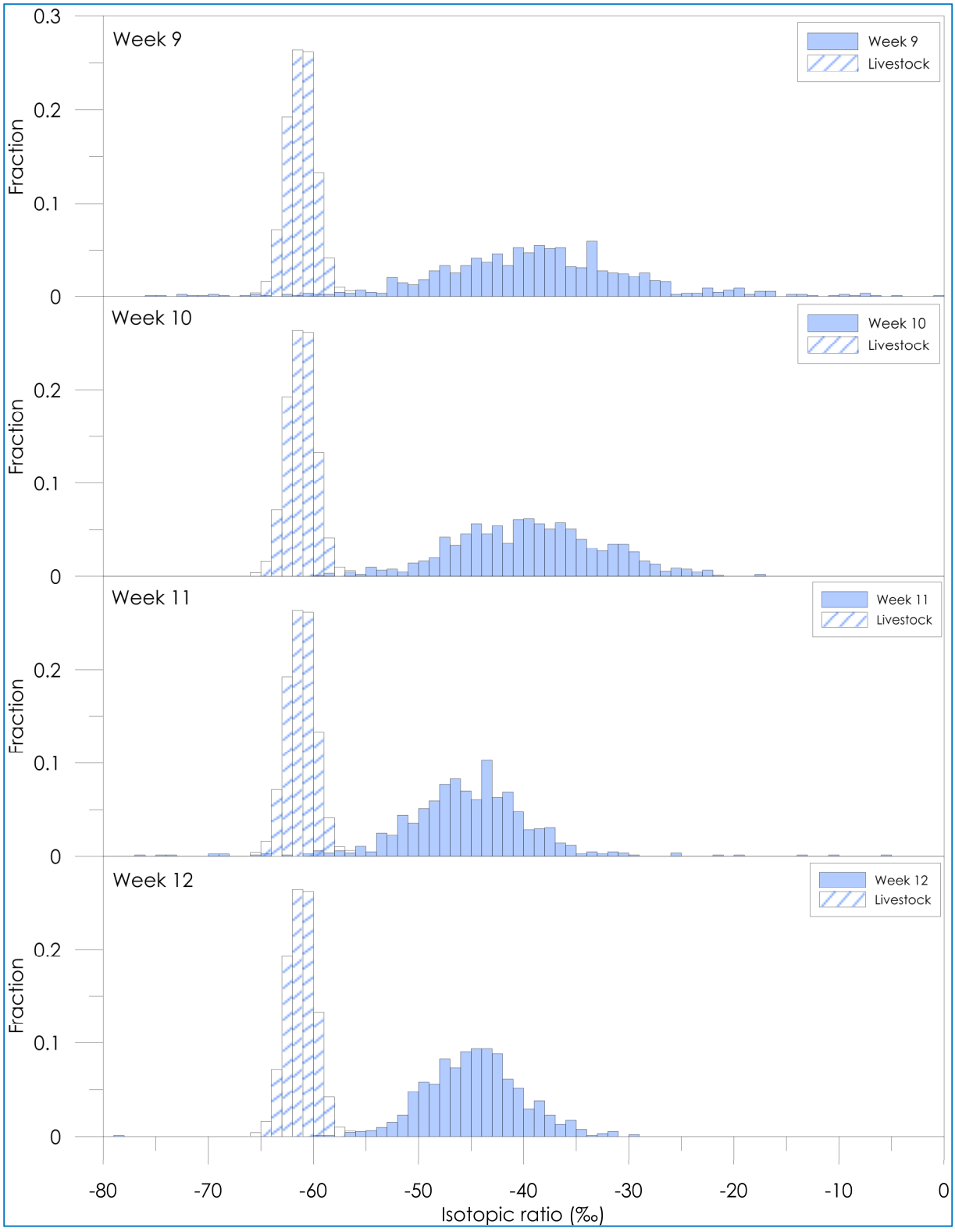


Figure 6-25: Histogram of $\delta^{13}C\text{-}CH_4$ measured at Site 20: Week 9 - 12

6.11 Methane concentration and land use

Analysis has been completed comparing land uses in the study area and the 1-second CH_4 concentration measured for the 12 weeks of data. The data is presented in a box and whisker plot shown in **Figure 6-26**. Land uses have been broadly categorised as rural or urban. Rural area would typically be considered semi-rural to agricultural for the purposes of this analysis.

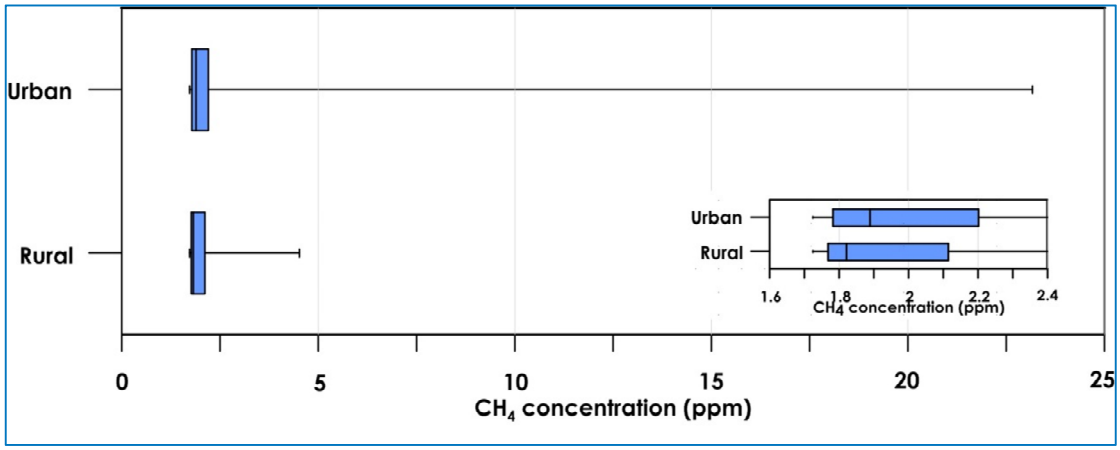


Figure 6-26: Box and whisker plot of CH_4 concentrations in rural and urban areas

Notes: a) Rural includes sites: 1- 3, 5, 14, 15, 17 – 20, 22.

b) Urban includes sites: 4, 6 – 13, 16, 21, 23 – 25.

c) The centreline of the box indicates the median value. The left side of the box indicates the lower quartile and the right indicates the upper quartile. The far left and far right error bars indicate the minimum and maximum of the values measured.

The monitoring results indicate that CH_4 concentrations are slightly lower in rural areas compared to urban in the Camden Gas Project Study area. The mean CH_4 concentrations for the urban and rural sites are 2.2ppm and 2.0ppm, respectively. These results are similar to those measured in London by **Lowry et al. (2001)**. This indicates that there are potentially additional sources of CH_4 in urbanised locations, such as reticulated gas mains.

The normalised frequency distributions for the CH_4 concentrations at urban and rural monitoring sites are shown in **Figure 6-27**.

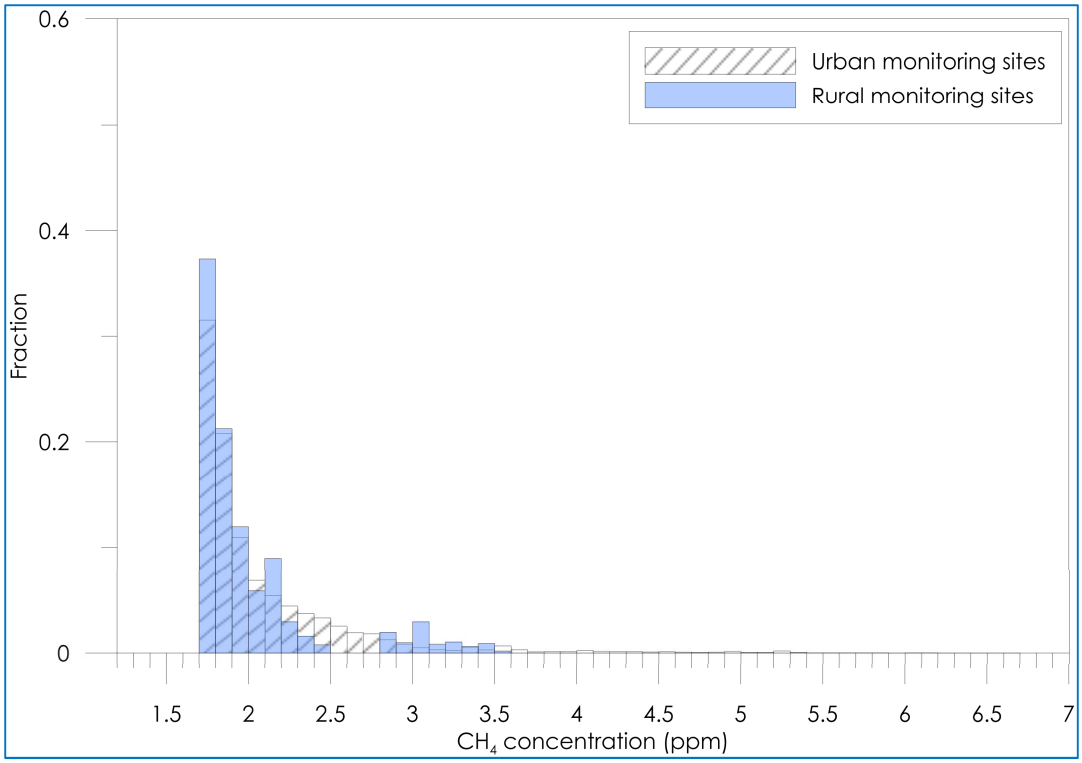


Figure 6-27: Histogram of $\delta^{13}C$-CH_4 concentrations in urban and rural locations

The Mann-Whitney test was again used to examine the differences between the CH_4 concentrations measured at urban and rural sites, using the same approach as that described in **Section 6.9.1.** There was found to be a statistically significant difference between the urban and rural concentrations ($P < 0.0001$).

7 CONCLUSION

This technical report provides the results and analysis of a field monitoring campaign measuring the concentration and $\delta^{13}C\text{-}CH_4$ of fugitive CH_4 emissions in the Camden area completed by Pacific Environment on behalf of AGL.

This study is considered to represent an indicative screening analysis of the current conditions in the vicinity of the Camden Gas Project.

The CH_4 concentrations measured in the study area are considered close to the global average background concentrations described in **WMO (2013)**.

Over the 12 week monitoring program the average CH_4 concentration was 2.1ppm. This value is just above the global average of 1.8ppm (**WMO, 2013**) and in-line with CH_4 concentrations measured in urban areas commonly ranging between 1.8ppm and 3.0ppm (**Lowry et al. 2001**). The corresponding the average $\delta^{13}C\text{-}CH_4$ was -41‰, similar to values observed in residential areas reported in **Montiel et al. (2011)**.

The range of 15-minute average data was between 1.7ppm and 16.6ppm with a maximum 1 second CH_4 concentration of 23.2ppm for the period.

Review of the data for the majority of monitoring sites located in close proximity to AGL gas wells do not show any significant directionality that might be attributed to fugitive CH_4 emissions from gas wells. In the case of Site 17, on occasion, elevated CH_4 concentrations (or 'spikes') are seen within the data set, when a tightening up of the $\delta^{13}C\text{-}CH_4$ values indicated that an RPGP related CH_4 source was detected at these times. The RPGP comprises a number of pressure relief valves and regulators, that are, for safety and operational purposes, designed to emit CSG (and by association, CH_4). It is therefore expected that slightly elevated CH_4 concentrations may on occasion be measured at Site 17. It should be noted that Site 17 is located within AGL's lease, and well removed from nearby residences that would not commonly be accessed by the general public.

The highest CH_4 concentrations were observed at Site 11, adjacent to the landfill. Findings indicate that the landfill is likely a contributor to fugitive CH_4 emissions in the study area with influences extending in to the residential area to the north at Site 9. While the $\delta^{13}C\text{-}CH_4$ indicates that the landfill may be a source of the CH_4 measured, given the low concentrations of CH_4 it's not possible to categorically identify the landfill as a source.

The coal washery was not shown to be a source of fugitive CH_4 emissions in the study area, assumed to be due to the coal age of the coal.

Elevated CH_4 concentrations were also measured at Site 17, the closest monitoring site to the RPGP. The $\delta^{13}C\text{-}CH_4$ of the measured CH_4 shows a correlation with the $\delta^{13}C\text{-}CH_4$ characterised from a number of AGL well samples. It is understood that the RPGP comprises a number of relief valves and regulator. It is therefore expected that slightly elevated CH_4 concentrations may be measured at Site 17 due to the release of fugitive CH_4 from the RPGP.

The elevated CH_4 concentrations measured on the morning of Week 7 are likely to have been part of wider scale CH_4 event rather a localised event, such as would occur from fugitive emissions from a single CSG field well.

Based on the low concentrations of CH_4 observed, it is not possible to draw clear conclusions as to the contribution of agriculturally sourced CH_4 in the study area.

The background methane concentrations also fall within reasonable approximation of the global average (**WMO, 2013**) with 15-minute average concentrations, with the average concentration for sites 21-25 across the 12 week monitoring period being 2.0ppm.

Characterisation of CH_4 concentrations and $\delta^{13}C$-CH_4 values observed at the background monitoring sites has been completed and compared with the monitoring results for sites located in the Camden Gas Project area. The CH_4 concentrations at these background sites vary from week to week and with meteorological conditions. Statistical analysis of the CH_4 concentration indicates that the contributions from the sites adjacent to the landfill demonstrates a statistically significant (higher) CH_4 concentration dataset compared with sites geographically removed from this source. When sites potentially influenced by fugitive emissions from landfill are removed from the dataset, the statistical analysis showed no significant difference between those CH_4 concentrations measured inside of the Camden Gas Project and those located outside (i.e. background locations).

Methane concentrations in urban areas were shown to be 0.2ppm higher than those measured in rural areas. Statistical analysis of the frequency distribution supports these findings. Reference to scientific literature also indicates that CH_4 concentrations are typically higher in urban areas (**Phillips et al. 2013**, **Lowry et al. 2001**).

A CH_4 signature anticipated to correspond to fugitive CH_4 releases from the RPGP was observed at the monitoring site closest to this location on several occasions,

Notwithstanding the above, it is concluded that when the study is considered as a whole, CH_4 concentrations and $\delta^{13}C$-CH_4 values observed within the boundaries of the Camden Gas Project showed no significant difference compared with those located outside (i.e. background locations).

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