New Brunswick Shale Gas Air Monitoring Study – Report 03

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New Brunswick Shale Gas Air Monitoring Study – Report 03

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List of abbreviations

AQHI	Air Quality Health Index
AQS	air quality standard
BTEX	benzene, toluene, ethylbenzene and xylenes
CAAQS	Canadian Ambient Air Quality Standard
CWS	Canada-wide Standard
DELG	(New Brunswick) Department of Environment and Local Government
EC	elemental carbon
ECCC	Environment and Climate Change Canada
GC/FID	gas chromatography / flame ionization detector
h	hour
ICPMS	inductively coupled plasma mass spectrometry
kg	kilogram
L	litre
LPG	liquefied petroleum gas
LPM	litre per minute
µg/m^3	microgram per cubic metre
µm	micrometre
m	metre
MHV	modified high-volume
m/s	metre per second
MOA	Memorandum of Agreement for Services
NAAQO	National Ambient Air Quality Objectives
NAPS	National Air Pollution Surveillance
NB	New Brunswick
ng/m^3	nanogram per cubic metre
NOx	nitrogen oxides
NPRI	National Pollutant Release Inventory
OC	organic carbon
OVM	organic vapour monitoring
PAH	polycyclic aromatic hydrocarbon
$PM_{2.5}$	particulate matter ≤ 2.5 µm in diameter; fine particulate matter
PM_{10}	particulate matter ≤ 10 µm in diameter
ppb	part per billion
ppm	part per million
TPM	total particulate matter
TRS	total reduced sulphur
TSP	total suspended particulates
US EPA	United States Environmental Protection Agency
VOC	volatile organic compound

Summary

In the fall of 2012, a Memorandum of Agreement for Services between Health Canada and the New Brunswick Department of Environment and Local Government was established to conduct an air monitoring study around shale gas activities in the province of New Brunswick. Environment and Climate Change Canada was also involved in this project through the National Air Pollution Surveillance Memorandum of Understanding and other interdepartmental agreements. The study consisted of four phases that represented the different stages and activities of shale gas development in New Brunswick: Phase I – baseline conditions prior to any development; Phase II – well development and gas production; Phase III – natural gas processing and distribution; and Phase IV – well closure.

A first interim report (Interim Report 01) was released in February 2014. Interim Report 01 outlines the different study phases, the data collection approach, the monitoring and sampling methodologies, and the quality assurance and quality control procedures. It also presents the monitoring data collected between October 2012 and April 2013 at the Phase I site, along with some preliminary analyses of the data set. A second interim report (Interim Report 02) was released in July 2015. Interim Report 02 includes analyses of the data from Phases I, III and IV.

This is the final report (Report 03) of the New Brunswick shale gas air monitoring study. It presents and analyzes the data collected during Phase II, which ran from June 2014 to March 2015, and includes comparisons with baseline conditions, represented by Phase I, and other phases of the monitoring study. Phase II was conducted at well pad F-67 in Penobsquis, New Brunswick, where a hydraulic fracturing event occurred in early September 2014.

The monitoring data collected during Phase II indicate that air pollutant concentrations near well pad F-67 varied depending on several factors, such as activities conducted on the well pad and environmental conditions (e.g., wind direction). Ambient levels of carbon monoxide, ozone and sulphur dioxide were not substantially influenced by well pad activities. In contrast, well pad activities had a measurable impact on concentrations of carbonyls, methane, nitrogen oxides, polycyclic aromatic hydrocarbons, fine particulate matter and volatile organic compounds. These pollutants increased intermittently during specific periods that corresponded to intensive operations, such as drilling, hydraulic fracturing, snubbing, venting and flow testing. In general, the spikes in the air pollutant concentration time series were of short duration and ambient pollutant levels returned to normal or baseline values within minutes or hours. Furthermore, the results from Phase II indicate that a variety of operations before, during and after a hydraulic fracturing event have the potential to influence air pollutant concentrations; in some cases more than the hydraulic fracturing event itself. These include, for example, drilling, well snubbing and gas flow testing activities.

Overall, activities conducted on well pad F-67 had a measurable impact on air pollutant concentrations, especially at downwind locations. However, pollutant concentrations that were measured during Phase II remained lower than current ambient air quality standards and did not reach levels that are of concern to environmental and human health.

The study was conducted in a geographic range not covered in previous air quality reports. Further, Phase II focused on the development of one well on a single well pad. It remains uncertain how well pad F-67 compares with other well pads in the Penobsquis area, or across New Brunswick. The cumulative impacts associated with the development of multiple wells in New Brunswick also cannot be ascertained based on the current study results. Although the study is informative to other jurisdictions, additional local and regional air monitoring data are considered necessary to extrapolate the results from this study to other wells or shale gas plays.

It must be noted that the conclusions in this report are considered the most reasonable based on the data collected at the monitoring sites. Nonetheless, the study design did have some limitations, and uncertainties remain regarding air quality impacts. As such, the interpretations are subject to revision if new relevant data become available in the future.

1. Background and scope

In the fall of 2012, Health Canada and the New Brunswick Department of Environment and Local Government (DELG) signed a Memorandum of Agreement for Services (MOA no. 4500290325) to conduct an air monitoring study around shale gas activities in the province of New Brunswick. The study was also conducted in collaboration with Environment and Climate Change Canada (ECCC), which provided technical and analytical support through the National Air Pollution Surveillance (NAPS) Memorandum of Understanding and other interdepartmental agreements. The overall objective of this project was to collect information in order to characterise the potential impacts on air quality associated with air emissions from shale gas development and operations. This type of information was not readily available and is required for health impact assessments of unconventional oil and gas development. The study consisted of four air monitoring phases that represented the different stages of shale gas development: Phase I – baseline conditions prior to any development; Phase II – well development and gas production; Phase III – natural gas processing and distribution; and Phase IV – well closure.

The study phases were sequentially numbered to reflect a schematic life cycle of shale gas development from an undeveloped site to gas production, gas transport and, finally, well closure. However, they were not completed in that particular order. Further, as it was not feasible to monitor air pollutant levels during all phases at a single site, a different site was selected to investigate each phase. All sites were located near Sussex, New Brunswick, within the Kennebecasis River valley (see figures 1 and 2). As such, it was expected that the overall air quality monitoring would be representative of the life cycle of an individual unconventional gas well or installation in this region.

The first interim report, Interim Report 01, was released in February 2014 (Health Canada 2014). It provides an overview of the study phases, the data collection approach, the monitoring methods, and the quality assurance and quality control procedures. Interim Report 01 also presents a preliminary analysis of data collected at the baseline or Phase I site from October 2012 to April 2013 through descriptive statistics and time series.

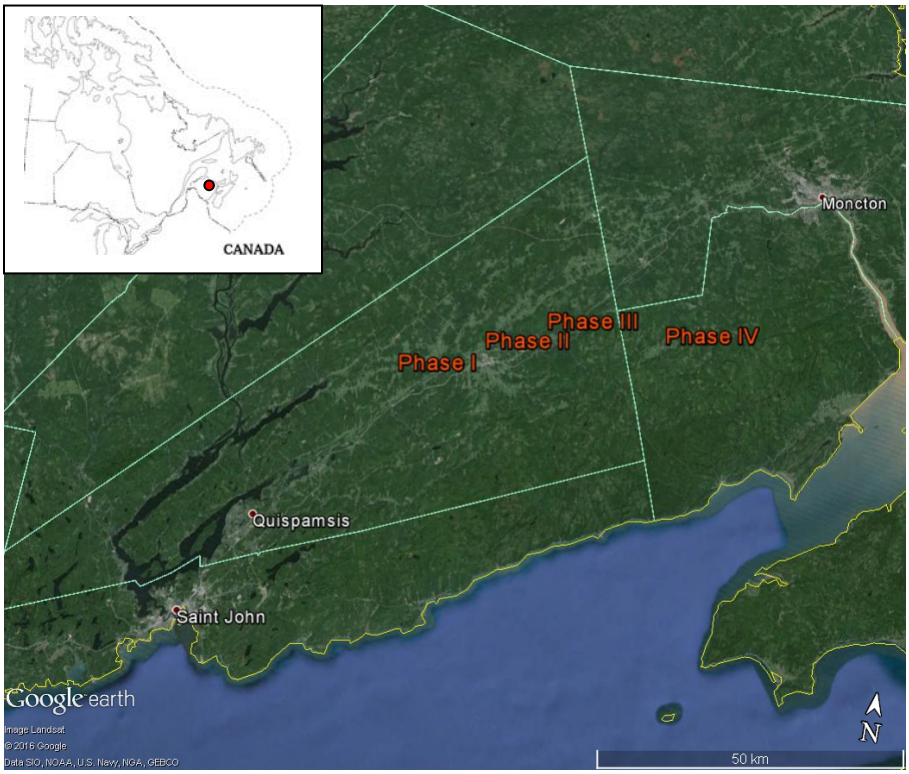

Figure 1. General location of the study phases in southern New Brunswick
(*Source*: Coloured image generated with Google Earth; Canada outline from Natural Resources Canada – http://ftp2.ctis.nrcan.gc.ca/pub/geott/atlas_tif/atlas6/Reference/Bilingual/canada01.pdf)

The second report, Interim Report 02, was released in July 2015 and presents an analysis of the full data set for Phases I, III and IV (Health Canada 2015). The data include continuous measurements for carbon monoxide (CO), ozone (O_3), sulphur dioxide (SO_2), total reduced sulphur (TRS), fine particulate matter (particles that are 2.5 µm or less in diameter or $PM_{2.5}$), total suspended particulates (TSP) and nitrogen oxides (NOx), as well as laboratory measurements of integrated samples for volatile organic compounds (VOCs), polycyclic aromatic hydrocarbons (PAHs), elemental carbon (EC) and organic carbon (OC), and markers of biomass burning (galactosan, levoglucosan and mannitol).

Information covered in the previous two reports is not repeated in this report. It is recommended that readers consult Interim Report 01 and Interim Report 02 for further details regarding these topics.

This report, Report 03, is the final report of the New Brunswick shale gas air monitoring study. It summarizes the activities and findings from Phase II, and is organized as follows: Section 2 presents the monitoring approach and data for all parameters measured during Phase II; Section 3 discusses Phase II results and includes comparisons with other study phases, highlighting major differences and key observations from an air quality and human health perspective; limitations and uncertainties are presented in Section 4, followed by conclusions in Section 5.

Tables, figures and time series representing the data for Phase II are included in Appendix A. Appendix B provides a summary of pollutants that were measured as well as methodological considerations.

Appendix C summarizes the activities that occurred on the well pad during the Phase II air monitoring period. Appendix D presents air quality objectives in New Brunswick and Canada.

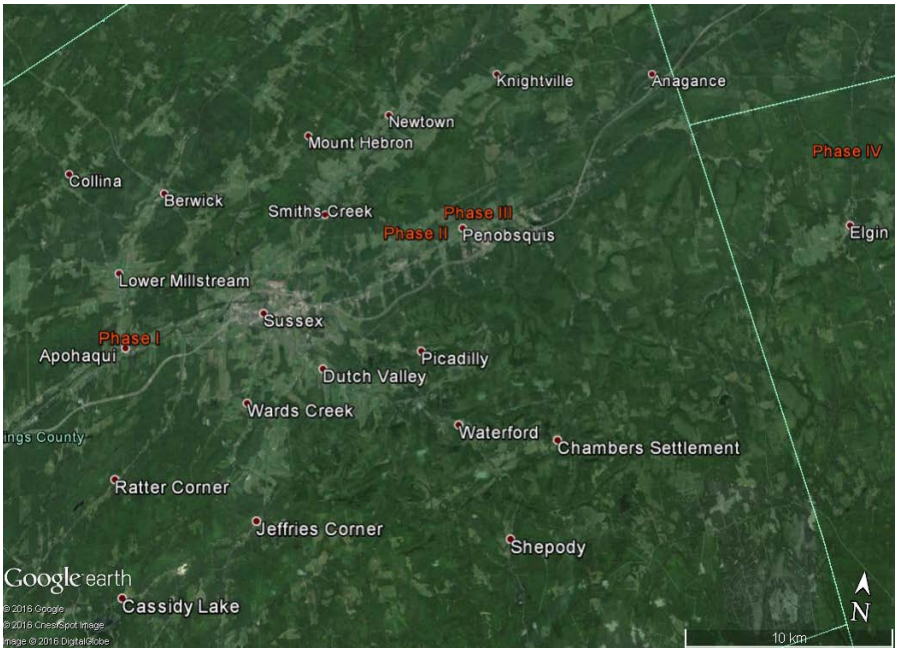

Figure 2. Regional view of the study phases near Sussex, New Brunswick
(*Source*: Image generated with Google Earth)

2. Phase II – Well development and gas production

2.1 Overview of site location and data collection

The monitoring for Phase II was conducted on well pad F-67, located in Penobsquis, New Brunswick, situated northeast of Sussex (see Figure 2). Well pad F-67 is owned and operated by Corridor Resources Inc. and located on private land. There were four existing gas wells on well pad F-67: three were in production and another was inactive. The producing wells were connected via pipeline to the regional gas collection and distribution system. Well pad F-67 was selected in collaboration with Corridor Resources Inc. as well completion[1] activities were planned on one of its existing wells, well E-67B.

Well pad F-67 is located in an area with existing conventional and unconventional (i.e. shale gas) gas development. The well pad is within the McCully Field, a natural gas play estimated to contain an in-place shale gas resource of 67.3 trillion cubic feet.[2] Based on satellite images of the area, well pad F-67 is similar in shape and size to other well pads in Kings County. The number of wells on well pad F-67 (three existing wells other than well E-67B) is not uncommon for well pads in New Brunswick. More

[1] Completion refers to the process of making a well ready for production. The steps involved in a well completion may involve: preparation of the bottom of the hole to the required specifications, installation of production tubing and other tools, tube perforation, well stimulation (e.g., hydraulic fracturing), and cementing.
[2] www.nrcan.gc.ca/energy/sources/shale-tight-resources/17698 (accessed September 23, 2016)

information on nearby oil and gas wells is available on New Brunswick's GeoNB Map Viewer application[3] and the Energy and Resource Development website.[4]

An agreement granting DELG and Health Canada access to the site was obtained from the landowner. Health Canada and DELG had access to monitoring locations around the well pad, just beyond the fence line. The site and its surroundings are described as being mostly agricultural, with a few scattered woodlots and small hills. A Canadian National railway borders the well pad to the south (e.g., Figure 3). Freight trains use this railway daily.[5] Less than five households are located within 1 km of the well pad, with the nearest residence located at approximately 300 m northeast of the centre of the well pad (see figures 3 and 4; Stantec 2014). A PotashCorp facility is located approximately 2 km southwest and upwind of the well pad, while the town of Sussex is located 5 km southwest.

The PotashCorp facility is a large industrial mining complex. Activities at the PotashCorp facility are responsible for air pollutant emissions that may potentially influence local and regional air pollutant levels. Based on emissions data from ECCC's National Pollutant Release Inventory (NPRI), the PotashCorp facility released 137 tonnes of particles that are 10 µm or less in diameter (PM_{10}), 80 tonnes of $PM_{2.5}$, 113 tonnes of VOCs, 40 tonnes of nitrogen dioxide (NO_2) and 27 tonnes of CO in 2014. However, according to the NPRI the facility was closed in July and August 2014, during which time reported emissions are nil. NPRI data for 2015 show that the facility was operational from January to November and that emissions reached 56 tonnes for PM_{10}, 22 tonnes for $PM_{2.5}$, 24 tonnes for SO_2, 183 tonnes for VOCs, 82 tonnes for NO_2 and 56 tonnes for CO.[6]

The main objective of the Phase II air quality monitoring was to capture a hydraulic fracturing event during the completion of well E-67B; this occurred in September 2014. Air quality data were collected from June 20, 2014 until March 31, 2015 – that is, several weeks prior to major well activities, during hydraulic fracturing, and several months following well completion. Therefore, site-specific baseline data were collected before hydraulic fracturing or other interventions occurred on the well pad. Continuous measurements (e.g., every 5 minutes) and integrated samples (e.g., 24 h filter- or canister-based samples) were collected during Phase II. Specific details regarding monitoring periods for each pollutant are discussed in Section 2.2. Table B1 in Appendix B shows the air quality and environmental parameters monitored during Phase II. Specifications for the monitoring equipment used to measure these parameters are provided in tables B2–B7 in Appendix B and in previous interim reports (Health Canada 2014, 2015).

[3] www.snb.ca/geonb1/e/index-E.asp
[4] www2.gnb.ca/content/gnb/en/departments/erd/energy/content/minerals.html
[5] Trains reportedly use the railway bordering the property twice a day.
[6] PotashCorp New Brunswick Division, National Pollutant Release Inventory, Environment and Climate Change Canada; available at: http://ec.gc.ca/inrp-npri (accessed January 13, 2017)

Figure 3. Aerial view of the Phase II site
(*Source*: Image generated with Google Earth Pro)

Photos 1 to 3 show the condition of the well pad prior to activities on well E-67B. The site around well E-67B was clear of any equipment, except for the well head. Gas producing wells, pipelines and some associated equipment were present on the site directly east of well E-67B. Photos 4 to 7 show conditions during well development. Several vehicles and equipment were active on site throughout the day, including 12 pump trucks, a sand column, liquid propane trucks, a blender truck, a control van and others units. A flare was also erected at the northeast corner of the well pad. Photo 8 shows site conditions following the well completion activities. Once equipment and materials were removed, the ground was levelled and only the well head remained on site.

During the Phase II monitoring period, well development activities were reported on several well pads in the region. Two well pads were located near Elgin: the Green Road well pad[7] and the Will de Mille well pad. As these were at a distance of approximately 20 km downwind from the F-67 well pad, they were not expected to influence air pollutant levels at the Phase II site. Well development activities were also conducted on well pads O-76, N-57 and D-48,[8] located in Penobsquis (see Figure 4). The O-76 well pad was located approximately 1.5 km upwind of the Phase II site, whereas well pads N-57 and D-48 were located approximately 1.8 km and 3.6 km downwind, respectively.

[7] Phase IV of the current study was conducted on the Green road well pad; see Interim Report 02.
[8] Well pad D-48 is located within the boundaries of a gas treatment facility, where Phase III of the current study was conducted; see Interim Report 02.

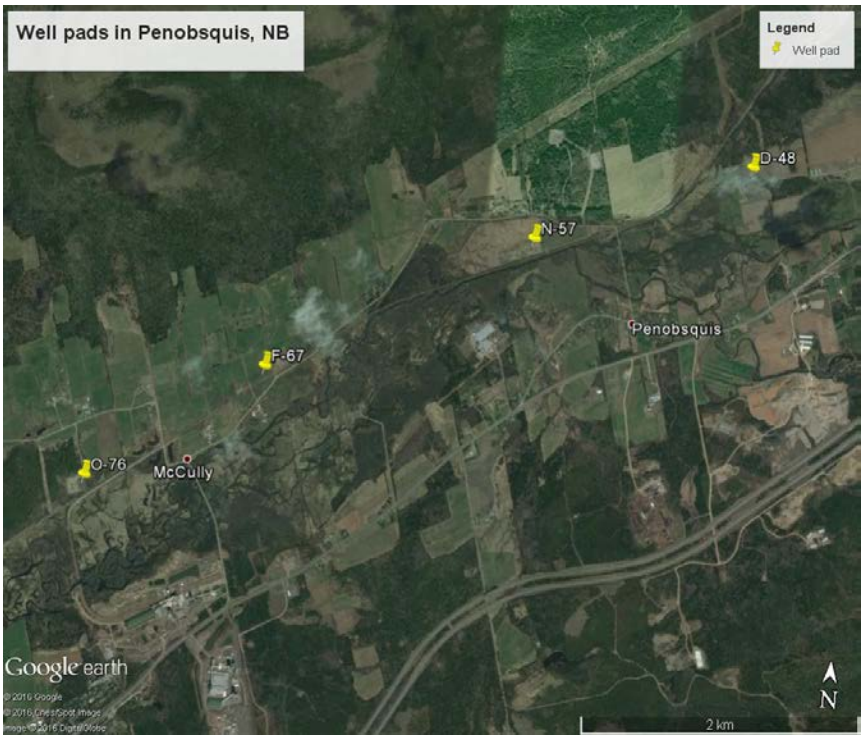

Figure 4. Well pads in the Penobsquis region
(*Source*: Image generated with Google Earth Pro)

The monitoring approach for Phase II consisted of an inner and an outer ring, each with four sampling locations. They are represented in Figure 5. Locations 21, 22, 23 and 24 were situated on the fence line of the well pad. Locations 25, 26, 27 and 28 were approximately 230, 200, 180 and 240 m, respectively, from the nearest point of the well pad fence line.

Continuous data were collected with the DELG's mobile monitoring unit as well as with a 4D Airpointer system from Health Canada. The mobile unit was located downwind from the well pad (location 21). It was activated on June 20, 2014, and data were collected from July 1, 2014, to March 31, 2015. For the DELG mobile unit, measurements were collected every 5 minutes for CO, nitrogen oxide (NO), NO_2, NOx, SO_2, TRS and O_3, hourly for $PM_{2.5}$ and TSP, and every 90 minutes for VOCs. Methane levels were measured continuously at 10-second intervals. Integrated 24 h samples were also collected to measure $PM_{2.5}$ and $PM_{2.5}$ compounds, including EC and OC, and levoglucosan, as well as carbonyl compounds and PAHs. The air inlets for monitors and samplers were generally located on the top of the trailer, at approximately 3.0–3.5 m above ground level, except for the meteorological data measured at 10 m above ground level. The monitors and samplers in the DELG mobile unit were calibrated according to standard procedures prior to the start of data collection. More details on the sampling methods are included in Table B2 in Appendix B.

Photo 1. Well pad F-67 as of May 2014, viewed from the west. Well E-67B is in the foreground; producing wells and gathering lines are visible in the background. (Photo credit: Health Canada)

Photo 2. Well E-67B on well pad F-67 as of May 2014, viewed from the north. The PotashCorp facility is visible in the background. (Photo credit: Health Canada)

Photo 3. Existing wells and pipelines on well pad F-67 as of May 2014, viewed from the north. (Photo credit: Health Canada)

Photo 4. Rig in operation on well E-67B in July 2014, viewed from the location of the DELG mobile monitoring unit. (Photo credit: Environment and Climate Change Canada)

Photo 5. Hydraulic fracturing operations on September 4, 2014, on well E-67B, viewed from the location of the DELG mobile monitoring unit. (Photo credit: DELG)

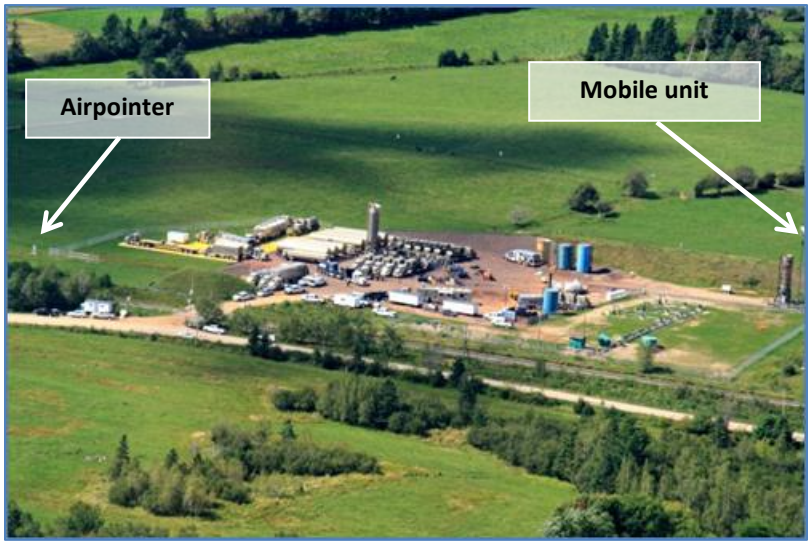

Photo 6. Hydraulic fracturing operations on September 4, 2014, on well E-67B, viewed from the southeast (aerial).[9] The Airpointer is visible left of the fence line. The mobile monitoring unit is not visible in this photo and was located just right of the fence line (see Photo 7).

[9] *Source*: www.wepac.ca/fracking-and-economics/penobsquis-landowner-the-other-side-of-the-story/; accessed September 24, 2015.

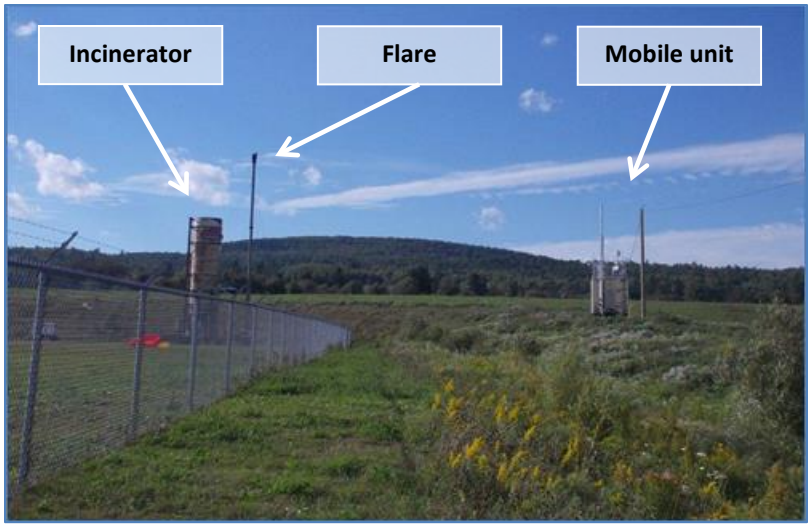

Photo 7. Location of the DELG mobile monitoring unit during Phase II. An incinerator and a flare stack were erected near the unit and were intermittently active during well development activities. (Photo credit: DELG)

Photo 8. Well E-67B on well pad F-67 as of November 2014, viewed from the west. (Photo credit: Health Canada)

The Airpointer was at an upwind location (location 22) and collected data from June 24 to November 12, 2014. The Airpointer ambient air quality monitoring system provided 1 h concentrations for CO, hydrogen sulphide (H_2S), NO, NO_2, NO_X, SO_2, O_3 and $PM_{2.5}$ based on 1 minute measurements. 24 h PAH samples were also collected at location 22. The air inlet for the monitors was located approximately 2.5 m above ground level. Meteorology was measured at approximately 3.0 m above ground level. The Airpointer was calibrated on site according to standard procedures prior to the start of data collection.

Figure 5. Monitoring locations 21–28 during Phase II
(*Source*: Image generated with Google Earth Pro)

In addition, VOC sampling was conducted at all monitoring locations between June and November 2014. 24 h VOC samples were actively collected using clean evacuated 6 L Summa™ canisters at locations 21 and 22, while integrated (weekly) passive VOC samples were collected at all eight locations (see Figure 5) with 3M Model 3500 Organic Vapour Passive Samplers (OVM; Guillevan, Montreal). For locations 23 to 28, the monitoring during Phase II only targeted VOCs. Further details on the sampling and the laboratory analysis methods are available in Appendix B of this report and in previous reports (Health Canada 2014, 2015).

2.1.1 Outline of activities on well pad F-67 and well E-67B during Phase II

The existing natural gas wells and infrastructure on well pad F-67 were built several years ago. Prior to the activities that took place during the summer of 2014, regular well inspection and maintenance were the main activities on the well pad; no natural gas-associated activity likely to release or releasing considerable air emissions was conducted or reported on site. The activities on well pad F-67 during the summer and fall of 2014 involved expansion of the well pad area, and stimulation and testing of well E-67B. They are described below based on information available in the environmental impact assessment report by AMEC (2013) and on discussions with field technicians. They are summarized in Appendix C.

The F-67 well pad was expanded from approximately 14 800 m^2 to 21 600 m^2: the well pad was extended westward on grassland previously used for cattle grazing. The top soil was removed, and the area topped with fill and then levelled with heavy-duty equipment. The equipment consisted of bulldozers, rollers and transport trucks (e.g., gravel and sand). This stage of the project took approximately two weeks and was completed by June 14, 2014.

Well E-67B was initially drilled to 4 130 m in 2008. A steel casing or pipe was then inserted down to 2 709 m and cemented in place. Following well perforation, drilling fluid recovery and testing, the well operations were suspended. Well E-67B does not include a horizontal leg. Interventions planned for 2014 included re-entry and re-completion of the well. Most activities on well E-67B were initiated in early July 2014 and ended in November 2014, with the more intensive ones occurring between July and October. Activities involved the installation and use of a drilling rig and other equipment to condition the well bore and to install and cement a production casing. Once the rig was removed, equipment was brought in to prepare the well for completion and fracture stimulation.[10] Table 1 lists equipment or vehicles that were in operation on well pad F-67 during the well stimulation event. This is not an exhaustive list; additional equipment owned and operated by the operator or service providers was likely used or active on or near the site.

Table 1. Types of equipment used for completion and stimulation of well E-67B during Phase II

Chemical addition	Iron trailer	Nitrogen tube trailer
Chemical transfer	Iron truck	Nitrogen vaporizer
Data van	LPG boost pump	Nitrogen vessel
Fire truck	LPG high pressure pump	Safety trailer
Flameless nitrogen pump	LPG sand addition unit	Tractor
Flare	LPG storage tanks	Well head truck
Incinerator	Manifold trailer	

LPG: liquefied petroleum gas

Fracture stimulation of well E-67B occurred on September 4, 2014. It was planned at a depth of 2 400–3 400 m using liquefied petroleum gas (LPG) as the fluid. Sand was used as the proppant. LPG composition is generally 90–99% propane, 0–5% ethane or propylene, 0–2.5% n-butane and 0.5 parts per million (ppm) of ethyl mercaptan, the latter being used as an odorant.[11] Three chemical additives, blended to concentrations of approximately 4–10 L/1000 L, were used: a gellant, an activator and a breaker. A gellant is used to increase fluid viscosity and allow the fluid to carry more proppant (sand in this case). An activator is used as a catalyst for the gellant to create additional viscosity. A breaker is used to reduce the viscosity of the fluid and increase its recovery once the proppant is in place. For each treatment, approximately 350–600 m^3 of LPG, 50–100 tonnes of sand and 2000 L of liquid nitrogen were expected to be used. One of the uses for nitrogen is to create a "nitrogen blanket" in wells containing large quantities of LPG. This avoids explosive conditions and ensures the safety of those conducting work on the well following LPG injection.

The LPG flowback was directed through flowback piping and manifolds and test separation tanks. Well testing involves sand traps, line heaters, separation equipment and flaring.[12] Flammable fluids and gases were flowed to a flare stack and flared during initial clean-up. Produced water was separated and

[10] Well completion activities include a variety of operations, such as wellbore pressure testing, wellhead preparation and fracture tree installation and testing, and wireline perforation.

[11] Refer to the Material Safety Data Sheet for Propane, commercial or LPG (e.g., Air Liquide Canada Inc., available at http://certs-msds.airliquide.ca/CertSearch.aspx).

[12] Flaring is a disposal method for combustible gases associated with natural gas production, processing and transportation (AMEC 2013). When the flare is active, a flame is visible at the top of the flare stack.

shipped to a flowback tank for disposal off site (by a third party). Liquids were collected in a pressure tank vented to the flare. Flow rates to the flare were continuously monitored and adjusted to limit light, noise and smoke emission pollution. Flaring occurred intermittently at the F-67 site during well testing and completion operations. Incineration also took place during the well completion activities.[13] No intentional venting was planned.[14]

After fracture stimulation and flowback, production tubing and a well head were installed. The well flowed in-line during a testing period from October 9 to 19, 2014. Once testing was completed, the well was then shut down for pressure build up until January 9, 2015. On the latter date, the well was opened and put into production. It remained in-line until May 1, 2015, when it was shut-in along with other wells in the area. It is scheduled to be brought back in-line in the near future and, as such, is still considered a producing well.[15]

The activities described above may be considered normal or routine for this type of operation in the Sussex area. The hydraulic fracturing and well completion procedures were similar to those conducted on nearby well pads during the summer and fall of 2014, by the same operator.

Corridor Resources Inc. filled out daily status reports, which outlined activities planned and occurring at different well pads near Sussex, New Brunswick. For example, it is noted that well preparation activities, such as reaming, blow down and cleaning, occurred in July and August, 2014, and that hydraulic fracturing occurred on September 4, 2014. Intermittent flaring also occurred, although detailed reporting of flare activity is not available. Entries regarding major interventions that occurred at nearby well pads during the Phase II monitoring period, such as hydraulic fracturing, are also included. Pollutant emissions associated with activities at nearby wells could have influenced ambient air pollutant levels at the Phase II site. Appendix C summarizes the relevant entries or notes associated with the F-67 well pad from June to October 2014. The activities listed in Appendix C are included to clarify higher pollutant concentration events observed in the data set and apparent in the pollutant time series shown in Appendix A.

2.1.2 Emission and concentration estimates during Phase II

Throughout Phase II, air pollutant levels were monitored near natural gas operations during well development, well completion and gas production. The investigation did not focus on selected sources of emissions, but considered the influence from all well pad activities on ambient air pollutant concentrations. No effort was made to estimate emissions from the well pad through, for example, a detailed listing of equipment, the use of emission factors, projected fuel use and potential gas releases. However, emission estimates for the F-67 well pad were available from an air quality impact assessment of drilling and completion activities conducted by Stantec for Corridor Resources Inc. (2014). This impact

[13] Incineration is a controlled combustion of natural gas, mixed with air, in a chamber designed to ignite and burn the gas (AMEC 2013). It differs from flaring in that no flame is visible above the unit. Incinerated gas is often reported as flared gas.

[14] Venting is defined as an intentional, controlled release of unburned gases into the atmosphere in the absence of flaring or incineration (AMEC 2013). The practice is generally restricted to gas streams that do not support stable combustion conditions, via a flare stack for example, or where flaring or incineration is not feasible.

[15] Andrea Creemer, Corridor Resources Inc., personal communications 16-10-2015.

assessment was prepared in support of the requirements under the Environmental Impact Assessment Regulation of the New Brunswick Clean Environment Act. In the report, emissions are projected for activities related to the expansion of well pad F-67 and drilling and completion of wells. As a new well was not drilled during the Phase II monitoring period, only the emissions data for the well pad expansion and well completion are reviewed. Exhaust (e.g., truck exhaust), combustion (e.g., flare), fugitive (e.g., dust and gas leaks) and evaporative (e.g., volatilization) emissions were considered by Stantec (2014). The emission estimates were mostly based on activity data and equipment specifications provided by Corridor Resources Inc., and available emissions factors, such as those featured in the United States Environmental Protection Agency (US EPA) AP 42 database.[16]

For the well pad expansion stage CO, NOx, $PM_{2.5}$, SO_2 and total organic compound emissions were estimated at 218 kg, 1 013 kg, 242 kg (71 kg exhaust and 171 kg fugitive), 67 kg and 83 kg, respectively (Stantec 2014). The emission estimates for the expansion of the well pad are based on the use of 14 000 L of diesel fuel by heavy equipment (e.g., bulldozers, rollers and transport trucks) over three weeks, assuming that equipment and vehicles were operating 12 hours a day.

CO, NOx, $PM_{2.5}$, SO_2 and total organic compound emissions from diesel exhaust during well completion were estimated at 626 kg, 2 906 kg, 204 kg, 191 kg and 237 kg, respectively, based on the consumption of 40 000 L of diesel fuel. In addition, gas flaring during the completion stage was estimated to release 2 881 kg, 529 kg, 56 kg, 4 kg and 82 kg of CO, NOx, $PM_{2.5}$, SO_2 and total organic compounds, respectively (see Table 7 in Stantec 2014). Pollutant emissions associated with flaring during the completion stage were based on the combustion of 1 550 m^3 of LPG and 420 000 m^3 of natural gas (Stantec 2014).

Stantec also conducted screening-level air dispersion modelling for contaminants released during well completion activities using the AERSCREEN model. Information on emission rates and source parameters, for multiple source types, were required to simulate pollutant dispersion. Owing to the absence of site-specific baseline data, the marginal contribution from well completion was determined by combining or comparing with a theoretical baseline concentration. Stantec used the 90^{th} percentile of 2011 ambient air quality data from the Forest Hills ambient monitoring station in Saint John, which was considered a conservative approach (Stantec 2014).

Stantec (2014) estimated that the maximum predicted concentrations (including baseline)[17] during well completion were below the applicable air quality objectives or standards applicable in New Brunswick, except for $PM_{2.5}$. For example, maximum 1 h and 8 h CO levels were equivalent to 1% or less of the standards and maximum NO_2 levels were equivalent to less than 70% of the 1 h and 24 h standards. In contrast, maximum $PM_{2.5}$ concentrations reached 173% of the 24 h Canada-wide Standard (CWS), which

[16] Emissions Factors and Quantification. AP 42: Compilation of Air Pollutant Emission Factors. Available at: www.epa.gov/air-emissions-factors-and-quantification/ap-42-compilation-air-emission-factors

[17] Modelled estimates from Stantec (2014) presented in this section are a combination of baseline values and incremental concentrations associated with well pad activities. For example, if the baseline $PM_{2.5}$ concentration is 17 $\mu g/m^3$, contributions of 11 $\mu g/m^3$ or 13 $\mu g/m^3$ will result in an exceedance of the Canadian Ambient Air Quality Standard or the Canada-wide Standard, respectively.

was set at 30 microgram per cubic metre (µg/m^3; Stantec 2014). They would also surpass the newly adopted 24 h Canadian Ambient Air Quality Standard (CAAQS) for $PM_{2.5}$ of 28 µg/m^3 by 185%.

Maximum 24 h $PM_{2.5}$ concentration predictions were above the CWS out to a distance of 500–700 m from the well pad boundary. Predictions of the maximum $PM_{2.5}$ concentrations were also slightly above the CWS at the nearest residential receptor (approximately 250 m from the well pad). The maximum predicted concentration occurred at the F-67 well pad fence line, approximately 100 meters downwind from the source (Stantec 2014). The maximum predicted concentration point corresponded to sampling location 21, downwind from the well and just beyond the well pad fence line. The mobile monitoring unit at location 21 collected continuous measurements and integrated samples of air pollutant concentrations, including $PM_{2.5}$.

For their screening-level assessment, Stantec compared fence line concentration estimates with ambient air quality standards, such as the CWS for $PM_{2.5}$. The CWS or the CAAQS apply to three consecutive years of the annual 98th percentile of ambient 24 h $PM_{2.5}$ concentrations. As such, they are not directly applicable to the short-term (24 h) predictions by Stantec. Comparisons with these standards are nonetheless warranted and common in screening assessments.

Additionally, well completion at a well pad is accomplished within 2–6 weeks, on average. Once well stimulation is finalised and that equipment and vehicles have been demobilized, $PM_{2.5}$ emissions associated with well pad activities are expected to be minimal. It is estimated that, owing to the short duration of well completion activities at a particular site, $PM_{2.5}$ concentrations would likely be lower than those predicted by Stantec, and possibly be below the ambient air quality standard if a longer period was considered. Further, screening-level model predictions take a conservative approach and tend to estimate concentrations that are likely greater than actual ground-level concentrations.

Another important consideration regarding the Stantec screening analysis is the comparison of fenceline or facility air pollutant levels with ambient air quality standards. Facility emissions in New Brunswick are regulated under the Clean Air Act. It is expected that air pollutant levels near industrial facilities that emit air contaminants may be higher than community or regional levels. Fence line levels may be unduly influenced by the industrial facility nearby and, subsequently, may not adequately reflect relevant community levels. In rural areas, air monitoring stations for comparisons with the CWS or the newly adopted CAAQS should be located in areas that reflect the homogeneity in air pollutant levels at the regional scale (CCME 2012). Comparisons by Stantec of fence line projections with ambient air quality standards may not be ideal, but they are useful for providing a measure of the influence of a facility or industry on ambient air quality, in this case unconventional gas development.

2.2 Results and analyses

The mobile monitoring unit at location 21 (downwind) collected data from July 1, 2014, to March 31, 2015 (275 days); whereas the Airpointer at location 22 (upwind) collected data from June 24 to November 12, 2014 (147 days). Integrated samples were collected between June and November 2014 at all locations.

Tables A1 and A2 in Appendix A summarize the descriptive statistics for the continuous data. In Tables A1 and A2, the row *No. of valid measurements* shows the number of measurements in the data set that are considered to be suitable in terms of quality and quantity. The number of measurements differs among pollutants owing to the measurement frequency (e.g., measurements every five minutes or every hour). From a data validation perspective, at least 75% of the data has to be valid for a dataset to be considered valid.[18] For the entire Phase II sampling period, this requirement is met for most pollutants. Exceptions include TSP (54% valid measurements) at location 21 and CO (73% valid measurements) at location 22.

For the mean, median, minimum, maximum and percentile values shown in Tables A1 and A2, the descriptive statistics for a pollutant are calculated for the average period of the corresponding air quality standard (AQS) (*Avg period for stats* row). This allows for a relevant comparison with the reference AQS (*AQS* row). For example, 1 h averages are determined for CO based on the valid 5 minute data (75% of the 5 minute data have to be valid for the 1 h average to be considered valid), and the mean of the 1 h averages is included in the *Mean* row (75% of the 1 h averages have to be valid for the statistic to be valid).

For PM, the same approach is used; in this case, however, the 1 h data are averaged on a daily basis (75% of 1 h data are required to be valid). The daily average values are then used to calculate the statistics for $PM_{2.5}$ in Tables A1 and A2.

For O_3, the 5 minute data are initially converted to hourly averages. The hourly data are then used to estimate 8 h rolling averages. Both hourly averages and the 8 h daily maximum value are used to calculate statistics for O_3. The 75% completeness criterion applies to the 5 minute data and the hourly data. For example, no fewer than six hourly values per each rolling 8 h segment need to be valid.

Also included in Tables A1 and A2 are the relevant Canadian (federal and New Brunswick) air quality objectives for comparative purposes (*Reference* row). Direct comparisons are not always possible owing to the averaging time defined for the air quality objectives. Comparisons are nonetheless informative regarding the relative air quality during the monitoring period and the potential impacts on air pollution concentrations associated with natural gas development activities. Data collected at the Phase II site are also compared , when relevant, with data from other phases of the study, with data from nearby provincial monitoring sites (as shown in *Air quality monitoring results* reports produced by the New Brunswick DELG; NB DELG 2012, 2013a, 2013b), or with data available from the NAPS program.[19]

The following sections provide information regarding the measured criteria air contaminants (i.e. O_3, $PM_{2.5}$, CO, SO_2, VOCs and NO_2) and other measured pollutants or parameters (e.g., TRS, PAHs and meteorological data). When available, continuous data from both monitoring stations are shown separately to highlight the differences in air quality between the upwind and downwind locations.

[18] The 75% criterion applies to the monitoring period under consideration and is not associated with a specific duration. For example, it can be applied to weekly, monthly, seasonal or annual datasets, in accordance with the study objectives.

[19] http://maps-cartes.ec.gc.ca/rnspa-naps/data.aspx?lang=en (accessed February 2, 2015)

2.2.1 Ozone

2.2.1.1 Upwind

The O_3 module in the Airpointer system was active from June 24 to August 21, 2014, at location 22. A malfunction impaired the module on August 21 and data collection ceased for O_3. It was not replaced or repaired in time to collect O_3 measurements during the hydraulic fracturing event on September 4, 2014. The results in Table A2 show O_3 values prior to the equipment failure, during a period that included several activities associated with well development, such as truck traffic, drilling and well preparation. The maximum O_3 value recorded at location 22 is 61.3 parts per billion (ppb), while the mean and the median are 23.4 ppb and 24.8 ppb, respectively.

2.2.1.2 Downwind

Based on hourly O_3 data, a mean concentration value of 25.7 ppb is reported at location 21. Figure A1 in Appendix A shows a time series for 1 h average data. Seasonal variations are expected in relation to several environmental and anthropogenic factors. A maximum of 58.0 ppb is observed on July 27, 2014, which is below the 1 h national air quality objective of 82 ppb (i.e. no exceedance reported). Based on the maximum daily 8 h rolling average for O_3, a mean of 32.8 ppb is estimated for Phase II. Refer to Table A1 in Appendix A for more descriptive statistics.

The 1 h average and the maximum daily 8 h rolling average O_3 concentrations during Phase II are very similar to the levels recorded from October 2012 to October 2013 at the baseline site (Phase I; Health Canada 2015). The mean values for the 1 h maximum and daily 8 h rolling average O_3 concentration during Phase I were 25.2 ppb and 34.4 ppb. As noted in Interim Report 02, O_3 levels during Phase I were comparable to levels measured at several provincial locations (Health Canada 2015). For example, hourly O_3 concentrations averaged 26 ppb across all air monitoring sites in the province of New Brunswick from 2002 to 2010 (NB DELG 2012).

2.2.2 Fine particulate matter – continuous

2.2.2.1 Upwind

The continuous $PM_{2.5}$ module in the Airpointer system was active from June 24 to November 11, 2014, at location 22. Descriptive statistics are shown in Table A2 in Appendix A. The overall median for the sampling period is 4.7 µg/m^3 and the mean is 5.0 µg/m^3. A maximum daily measurement of 14.9 µg/m^3 is noted on July 26, 2014. Although well preparation and drilling activities were occurring on the well pad in July, no specific activity occurred on that day according to activity reports, (refer to Appendix C). At that time, a well rig was erected on the well pad but it was not operational owing to necessary repairs and missing parts. Wind conditions (speed and direction) were normal for that time of the year. Although well pad activities cannot be ruled out as a contributing source of $PM_{2.5}$ emissions on July 26, the influence of other local or regional sources must be considered.

Daily mean concentrations at locations 22 and 21 between July 1 and November 11, 2014, are shown in Figure A3 in Appendix A. Discrepancies between monitoring locations are expected owing to their upwind and downwind locations as well as differences in measurement methods, but overall $PM_{2.5}$ concentrations are comparable. Daily $PM_{2.5}$ concentrations vary in a similar manner at both locations,

both showing higher levels in mid-July and early September. A short period of relatively higher daily mean concentrations is visible around the September 2 mark. This period corresponds to the weeks leading up to and following the September 4 fracturing event. Preparation activities, such as the movement of material and supplies, truck traffic and the set-up of fracking equipment, likely influenced particulate emissions from the well site and contributed to higher $PM_{2.5}$ levels. The mean and median $PM_{2.5}$ values during this two-week period are approximately 7.2 µg/m^3.

2.2.2.2 Downwind

The continuous $PM_{2.5}$ module in the mobile laboratory at location 21 was active from July 1, 2014, to March 31, 2015. Descriptive statistics are shown in Table A1 in Appendix A.

The average 24 h or daily $PM_{2.5}$ concentration over the whole period is 4.8 µg/m^3 (Table A1 in Appendix A). The continuous $PM_{2.5}$ data, reported as daily 24 h averages, are shown as a time series in Figure A2 in Appendix A. Daily $PM_{2.5}$ concentrations are higher in July 2014 compared to the rest of the monitoring period. In addition to well pad activities, seasonal variations are possible. For example, during Phase I, $PM_{2.5}$ concentrations were higher in summer compared to other seasons (Health Canada 2015).

The highest daily $PM_{2.5}$ value at location 21 during Phase II, 18.5 µg/m^3, was recorded on July 26, 2014. As mentioned for the upwind location, no specific well pad activity was reported on that day. As daily $PM_{2.5}$ levels are highest on the same day at both upwind and downwind locations, sources of $PM_{2.5}$ other than well pad activities should also be considered. Regional sources, such as agricultural operations, could have contributed to an elevation of regional $PM_{2.5}$ levels. In comparison, $PM_{2.5}$ data from monitoring sites across New Brunswick (e.g., NAPS network) for July 26, 2014, do not indicate higher than normal particulate concentrations on a regional or provincial scale.[20] $PM_{2.5}$ levels at location 21 are not observed to increase on September 4, 2014, during the hydraulic fracturing event.

The CWS for $PM_{2.5}$, set at 30 µg/m^3, was previously the ambient air quality standard in New Brunswick and most provincial jurisdictions. As of 2015, the $PM_{2.5}$ CAAQS of 28 µg/m^3 is the benchmark for ambient air quality. Both the CWS and the CAAQS refer to the annual 24 h 98th percentile $PM_{2.5}$ ambient measurement, averaged over three consecutive years. As less than one year of data was collected during Phase II, a direct comparison with ambient air quality standards is not possible. Nonetheless, the 98th percentile value for $PM_{2.5}$ at location 21 is 12.2 µg/m^3 during Phase II, lower than the CWS and the CAAQS. The Province of British Columbia has adopted a 24 h air quality guideline of 25 µg/m^3 based on the 24 h 98th percentile ambient measurement annually.[21] The World Health Organization has defined a similar annual $PM_{2.5}$ air quality standard of 25 µg/m^3, based on the 99th percentile of the distribution of daily values over a year (WHO 2006). No ambient air $PM_{2.5}$ value above those limits was reported during Phase II.

[20] http://maps-cartes.ec.gc.ca/rnspa-naps/data.aspx?lang=en (accessed February 3, 2016)
[21] www.bcairquality.ca/regulatory/pm25-objective.html (accessed February 23, 2015)

2.2.3 Fine particulate matter – gravimetric samples

Gravimetric measurements were made from 47 mm Teflon filters that were collected at location 21 (downwind) using ChemComb Speciation Cartridges and a Partisol 2300 sampling system. These were 24 h integrated samples collected approximately every 6 days between July 22 and October 3, 2014. The sampling method is outlined in Appendix B. Table A3 in Appendix A shows gravimetric $PM_{2.5}$ data for Phase II. Median and mean $PM_{2.5}$ concentrations are calculated at 6.3 µg/m^3 and 6.5 µg/m^3, respectively. The mean $PM_{2.5}$ concentration calculated from the gravimetric samples is higher by approximately 35% than the mean estimated from the continuous data at the same location. If the continuous data are limited to July–October 2014, concurring with the filter sampling period, a mean of 5.3 µg/m^3 is obtained (23% difference). Similar discrepancies among measurement methods have been observed by other authors (e.g., Hauck et al. 2004) and are not unexpected. Methodological considerations are addressed in Section 4.

Overall, $PM_{2.5}$ concentrations were higher during well pad preparation, drilling activities, and during the hydraulic fracturation period. Maximum values of 14–16 µg/m^3 were reached on August 4, while values of 8–10 µg/m^3 were reported on September 3 and 4, 2014. The gravimetric data fluctuated similarly to the continuous data, which are shown in Figure A2 in Appendix A. $PM_{2.5}$ concentrations remained below 6–8 µg/m^3 after September 14, 2014.

2.2.4 Fine particulate matter – galactosan, levoglucosan and mannitol

Thirteen of the total 47 mm Teflon filters used to collect $PM_{2.5}$ samples at location 21 (downwind; July 22 to October 3, 2014) were analyzed for galactosan, levoglucosan and mannitol, which are considered markers of biomass burning (e.g., wood stoves and forest fires). Galactosan, levoglucosan and mannitol measurements were made to address potential contributions to $PM_{2.5}$ concentrations from biomass burning that could possibly affect data comparisons among seasons and sites. Natural gas production processes and normal well pad activities are not expected to influence the ambient levels of these compounds.

Phase II results are shown in Table A4 in Appendix A. On average, it is estimated that levoglucosan contributed 0.07% to $PM_{2.5}$ mass, whereas mannitol contributed 0.10%. Galactosan levels were below detection limits. These very low levels, similar to the ones reported for Phase I and Phase III (Health Canada 2015), suggest that emissions from biomass combustion were negligible during Phase II.

2.2.5 Fine particulate matter – metals

Inductively Coupled Plasma Mass Spectrometry (ICPMS) analysis to measure metals was conducted for 14 Teflon filters collected at location 21 (downwind; July 22 to October 3, 2014). The results are presented in Table A5 in Appendix A. Metals detected and measured by ICPMS are estimated to account for 9.6% (571 nanogram per cubic metre or ng/m^3) of the $PM_{2.5}$ concentrations. Silicon (Si), sodium (Na), aluminum (Al), calcium (Ca) and iron (Fe) show the highest mean concentrations and account, on average, for 91% of the total estimated metal concentration.[22] Figure 6 shows the cumulative metal concentrations for samples collected during Phase II. Variations in concentrations among samples are

[22] The total concentration value is based on metals that were detected and measured, exclusively.

mainly driven by variations in Si, Al and Na levels. These common elements have been identified and used as tracers for soil dust in previous investigations (Owoade et al. 2015). The elevated Si measurements in July and August 2014 are possibly associated with site preparation activities and equipment transport, which would lead to soil or dust suspension. Si is a common and major component of mineral and soil compounds.

Sand composed of crystalline silica (silicon dioxide or SiO_2) is commonly used as proppant for hydraulic fracturation. The handling and use of sand during well completion may generate respirable silica dust, which represents a potential health risk for workers or nearby populations. Esswein et al. (2013) evaluated worker exposure to respirable silica during hydraulic fracturing at well pads in the US. They reported respirable crystalline silica levels ten-times higher than occupational health criteria, including: the American Conference of Governmental Industrial Hygienists threshold limit value of 0.025 mg/m^3; the National Institute for Occupational Safety and Health recommended exposure limit of 0.05 mg/m^3; and the Occupational Safety and Health Administration permissible exposure limit of 10 mg /m^3. Esswein et al. (2013) characterised silica exposure as an occupational health hazard for the industry. Silica dust creation is generally associated with specific equipment and activities, such as proppant transfer, filling and blending, and depends on operating practices. New handling methods for proppant, alternatives to silica as proppant, and new techniques for blending proppant in the hydraulic fracturing fluid are available to limit silica exposure.

No occupational health and safety limit or ambient air quality standard specific to silica dust was identified in New Brunswick. The Alberta Occupational Health and Safety code has an 8 h time-weighted average limit for silica of 25 000 ng/m^3 (Alberta Government 2009). In terms of community exposure, the air quality standard for silica is 5 000 000 ng/m^3 in Ontario (OMOE 2012) and 70 ng/m^3 (annual) and 8 600 µg/m^3 (hourly) in Québec (MDDEFP 2013). During Phase II, fence line silica concentrations were less than 700 ng/m^3 prior to hydraulic fracturation (e.g., well pad preparation, drilling) and less than 150 ng/m^3 during and following hydraulic fracturation. Ambient silica levels from air monitoring stations across New Brunswick were not available. The silica levels suggest that dust emissions from proppant handling and use were low or adequately controlled during hydraulic fracturation.

The lower values on August 21, 2014, are possibly the result of site activities and meteorological factors. Wind direction data for August 21 to 23, 2014, indicate that winds were blowing from the well pad towards location 22, which was contrary to dominant wind directions. Consequently, the particulate filter sample collected at location 21 for August 21 was likely less influenced by well pad activities compared to previous and subsequent samples. Figure A14 in Appendix A shows the wind data for August 21, 2014.

Overall, the results suggest that well preparation activities can increase ambient concentrations for some metals (e.g., August 27 and September 2), but hydraulic fracturing (September 4) does not have any apparent impact on ambient concentrations of metals.

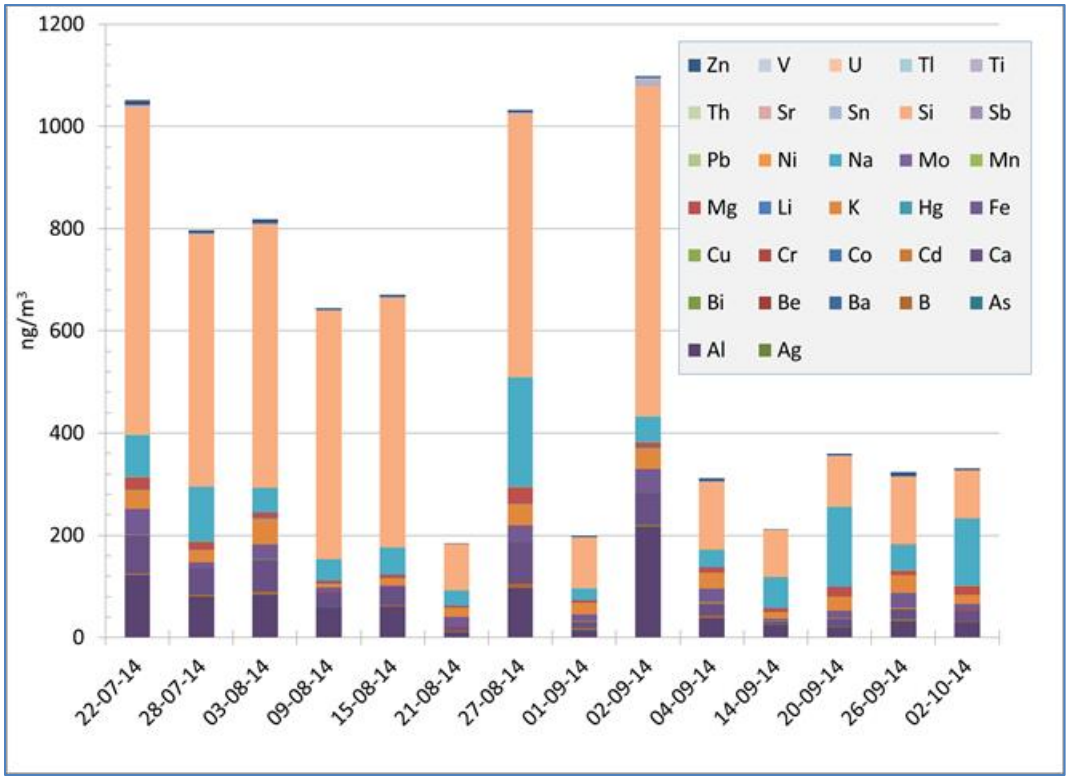

Figure 6. Cumulative metal concentrations based on ICPMS analysis of $PM_{2.5}$ filters collected at location 21 during Phase II

Air quality standards targeting metals have not been adopted by the Government of New Brunswick, but air quality standards exist in Alberta (Alberta Government 2013), Ontario (OMOE 2012) and Québec (MDDEFP 2013). With the exception of Si, the metal concentrations measured during Phase II are considerably lower than air quality standards available for those provinces.

2.2.6 Fine particulate matter – elemental carbon / organic carbon

EC and OC measurements were conducted on 14 quartz filter samples collected between July 22 and October 3, 2014, at location 21 (downwind). EC and OC were determined directly from the filters (the analytical method is outlined in Appendix D).[23] Results are shown in Table A6 in Appendix A.

The OC content in all samples is a least two times greater than the EC content. The data show that OC compounds account for 89% of total carbon concentration, on average, varying from 68–100%. Similar OC to EC ratios were reported at the reference site during Phase I (e.g., mean OC fraction of 87% and range of 72–99%; Health Canada 2015).

[23] $PM_{2.5}$ concentrations for the quartz filters are not determined using a gravimetric method before EC/OC analysis.

2.2.7 Carbon monoxide

2.2.7.1 Upwind

The CO module in the Airpointer system at location 22 was active from June 24 to August 14, 2014. A malfunction impaired the monitor on August 14 and data collection ceased. It was not replaced or repaired in time to collect CO measurements during the hydraulic fracturing event on September 4, 2014. The results in Table A2 in Appendix A show CO values prior to the equipment failure, during a period that included several well development activities, such as truck traffic, drilling and well preparation. The maximum CO value recorded at location 22 is 2.2 ppm, while the mean and the median are 0.1 ppm.

2.2.7.2 Downwind

CO concentrations measured at location 21 are described in Table A1 in Appendix A. For the whole Phase II period, a mean of 0.2 ppm and a median of 0.2 ppm are estimated. A maximum value of 0.6 ppm is noted on August 25, 2014. Levels are considerably lower than the 1 h air quality standard of 13 ppm (see Table D1 in Appendix D). The CO levels reported at locations 21 and 22 are similar and they are comparable to concentrations recorded at other monitoring sites in the current study (Health Canada 2015) and across New Brunswick (i.e. Fredericton, Moncton and Saint John; NAPS 2012, 2013; NB DELG 2012, 2013b).

2.2.8 Sulphur dioxide, hydrogen sulphide and total reduced sulphur

2.2.8.1 Upwind

The H_2S and SO_2 modules in the Airpointer system at location 22 were active from June 24 to October 29, 2014. Measurements were properly collected during the well development and hydraulic fracturing activities but became less reliable as of October 30. Values recorded thereafter are not considered acceptable for the current analysis. The maximum SO_2 value recorded at location 22 is 0.8 ppb, while the mean and the median are 0.1 ppb and less than 0.02 ppb, respectively. The maximum H_2S value recorded at location 22 is 2.5 ppb, while the mean and the median are 0.1 ppb and 0.01 ppb, respectively (Table A2 in Appendix A).

2.2.8.2 Downwind

Hourly SO_2 levels at location 21 were generally very low, with a mean of 0.1 ppb (see Table A1 in Appendix A). TRS levels averaged 0.1 ppb and reached a maximum of 1.1 ppb. Both SO_2 and TRS concentrations are considerably lower than their respective air quality standards (see Table D1 in Appendix D), owing to the absence of a significant source of SO_2 or TRS emissions on or near the well pad.

The H_2S, SO_2 and TRS levels recorded during Phase II are comparable to levels observed at the baseline site (Phase I), and lower than levels recorded at a nearby gas plant during Phase III (Health Canada 2015).

2.2.9 Nitrogen oxides

2.2.9.1 Upwind

NO, NO_2 and NOx concentrations were measured at location 22 from June 24 to November 12, 2014. The estimated mean values for NO, NO_2 and NOx are 1.1 ppb, 1.1 ppb and 2.2 ppb, respectively. Figure 7 shows the hourly NO, NO_2 and NOx concentrations measured at location 22. NOx reaches an hourly maximum of 45.2 ppb on August 22, 2014, mostly attributable to NO (33.5 ppb). Meteorological data for August 21 to 23, 2014, indicate that winds were blowing from the well pad towards location 22, which was contrary to dominant wind directions. Figure A14 shows the wind data for August 21, 2014. Consequently, the higher concentrations on August 22 were likely influenced by well pad activities. A daily maximum of 12.9 ppb is noted for NO_2 on the same day.

In comparison, the NO, NO_2 and NOx values during Phase I averaged 0.3 ppb, 1.2 ppb and 1.5 ppb, respectively (Health Canada 2015).[24] Higher NO concentrations at location 22 reflect the greater presence of combustion source emissions near Phase II compared to Phase I (see Section 3 for more details).

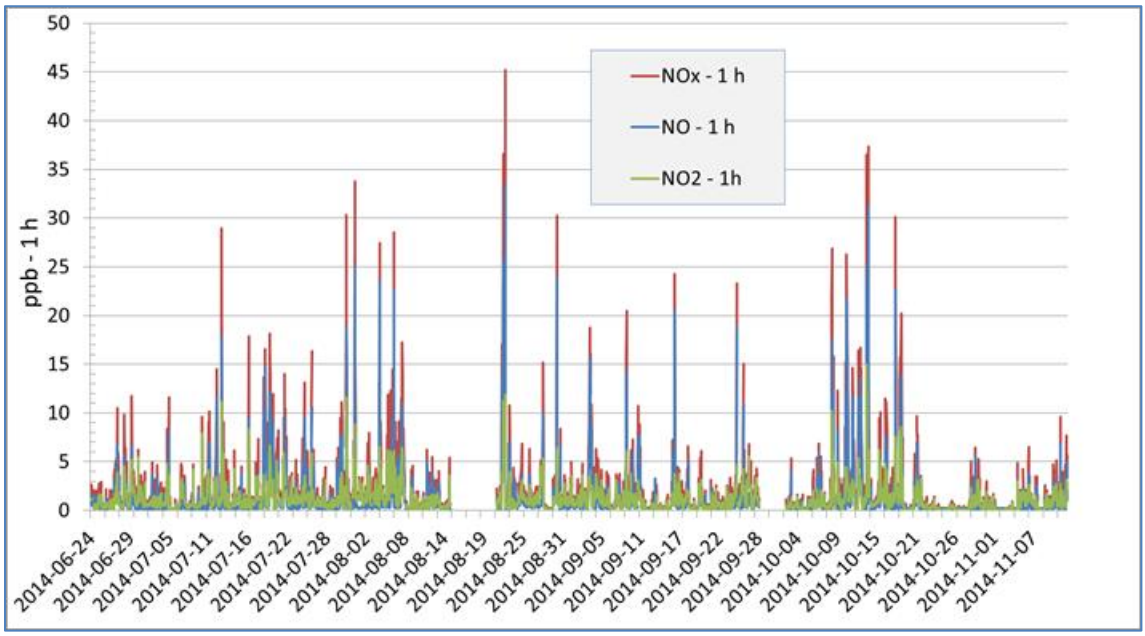

Figure 7. Hourly mean NO, NO_2 and NOx concentrations recorded at location 22 from June 24 to November 11, 2014, at the Phase II site

2.2.9.2 Downwind

Figure 8 shows the hourly concentrations for NO, NO_2 and NOx at location 21 during Phase II. A mean NO_2 concentration of 2.0 ppb is estimated based on hourly average data. NO_2 levels are considerably below the 1 h air quality standard of 210 ppb (see Table D1 in Appendix D). The maximum hourly NO_2 measurement at location 21, 64.3 ppb, was recorded on August 2, 2014. The maximum 24 h NO_2

[24] NOx concentrations never exceeded 23.2 ppb during Phase I (Health Canada 2015).

concentration was approximately 25.0 ppb and recorded on July 29, 2014. This is below the 24 h NO_2 New Brunswick ambient air quality objective of 105 ppb.

NO and NOx hourly results show means of 4.8 ppb and 6.7 ppb, respectively. On July 16, 2014, a maximum NO value of 350 ppb and a maximum NOx value of 376 ppb are observed. The elevated measurements on July 16 correspond to well cleaning and reaming activities that were occurring on the well pad at that time (see Appendix C).

NO, NO_2 and NOx concentrations measured at location 21 are higher than levels at location 22 (both in terms of mean and maximum values), and higher than levels previously reported for the baseline site (Phase I; Health Canada 2015). Higher combustion emissions associated with well preparation (e.g., drilling and reaming), truck traffic and off-road applications (e.g., generators and stationary diesel engines) on or near the well pad were possibly responsible for the higher NO, NO_2 and NOx levels during Phase II.

Overall, the mean NO, NO_2 and NOx levels during Phase II are similar to those observed at urban sites across the province from 2012 to 2014 (NAPS 2012, 2013, 2014). For example, average NOx concentrations of 3–10 ppb are reported in Fredericton, Moncton and Saint John. Similar maximum hourly values—that is, 304 ppb in 2013 and 306 ppb in 2014—are also reported for a NAPS station in Saint John (located at 189 Prince William Street), which is located near the port and influenced by commercial vessel emissions (e.g., cargo and cruise ships).

Hence, although higher NO, NO_2 and NOx concentrations were measured at location 21 (mean and peak values), they remain comparable to concentrations reported at urban locations in New Brunswick. Further, peak NO_2 concentrations are below the NO_2 ambient air quality objectives. Nonetheless, the results show that well pad activities had a measurable impact on NO, NO_2 and NOx levels at the Phase II site; the latter is characterized as a rural area with air pollutant levels generally lower than in urban areas. This suggests that NO, NO_2 and NOx concentrations should be monitored near shale gas operations, especially when large diesel engines or several diesel engines are in operation, such as during drilling or hydraulic fracturing.

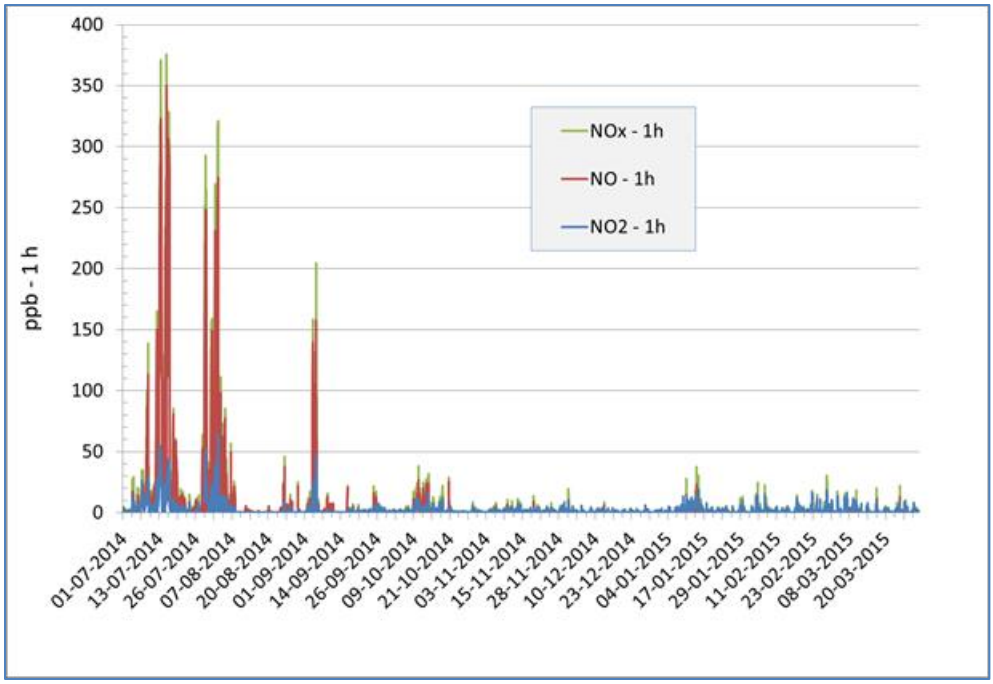

Figure 8. Hourly mean NO, NO_2 and NOx concentrations recorded at location 21 from July 24 to March 31, 2015, at the Phase II site

2.2.10 Volatile organic compounds – continuous

VOCs include a large variety of organic compounds, too many to be accurately identified and measured by a single instrument or sampler. Investigators generally select sampling or monitoring methods that target VOCs of concern or those that are suspected of being released during a given activity or from specific equipment. This selection is generally based on previous investigations or tests. For the current study, it was important to be able to measure light molecular weight VOCs that are generally associated with natural gas development and oil and gas operations. A continuous monitor and two integrated sampling methods were used (see sections 2.2.11 and 2.2.12).

Continuous measurements are available for 55 VOCs at location 21 (mobile unit), using an AMA gas chromatography/flame ionization detector (GC/FID) 5000 unit, from July 11, 2014, to February 9, 2015. The unit provided results at 90 minute intervals throughout Phase II, for a total of 2 829 measurements per VOC. The AMA GC/FID 5000 unit detects VOCs with 2–12 carbons (C2–C12 compounds), with more species in the C5–C9 range. Owing to equipment malfunctions or calibrations and software modifications, data are missing from September 9 to 24 and from November 17 to 25, 2014, as well as during shorter periods of several hours to a few days throughout Phase II.

A time series for all VOC species was generated to identify the highest fluctuations in VOC concentrations during Phase II (not shown). As VOC concentrations were generally lower than 1–2 ppb for all measured species, spikes or intermittent increases were easily identifiable. Spikes and increases were generally associated with the hydraulic fracturing event on September 4, 2014, and flow testing and flaring in mid-October 2014. Species that are observed to have the highest *maximum-to-median*

ratios are generally in the C2–C8 range (refer to Table A7 in Appendix A), and correspond to either gaseous species or volatile liquid species. Descriptive statistics for the continuous VOC data are included in Table A7 of Appendix A.

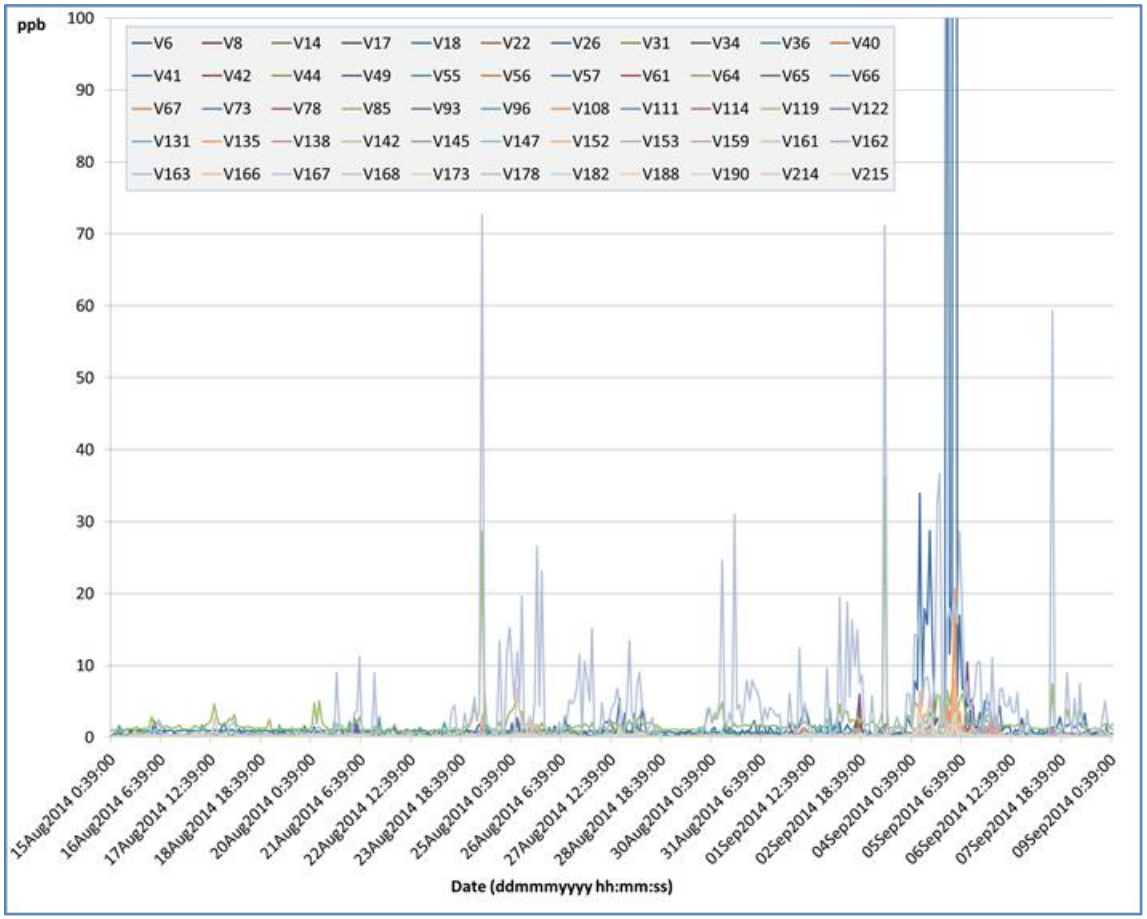

Figure 9. Time series of VOC concentrations from August 15 to September 9, 2014, measured with a GC/FID 5000 unit at location 21

Note: The vertical axis was cut to 100 ppb so as to more clearly show fluctuations in VOC concentrations. 2-methylpentane (V57) reached 201 ppb on September 4 and 896 ppb on September 5. No other VOC exceeded 100 ppb during this period. Full names of VOCs corresponding to *Vxxx* codes in the Legend box are included in Table B3 of Appendix B.

Examples of time series are included to represent the fluctuations in VOC levels in September and October 2014. Figure 9 shows VOC measurements from August 15 to September 9, 2014, and Figure 10 shows measurements from September 25 to October 31, 2014. As all 55 VOCs measured continuously are included in these time series, it is not possible to clearly distinguish each VOC species. The intent for Figures 9 and 10 is to show that VOC levels during Phase II were generally low, that increases were intermittent and that very few VOCs exceeded 5 ppb at any point in time. In addition, the figures show that different subsets of VOCs were influenced by activities occurring on the well pad (i.e. not all VOCs increase simultaneously).

The highest measurements are for 2-methylpentane (V57), which reaches 201 ppb and 896 ppb on September 4 and 5, respectively. At the same time, spikes in heptane (V131) and hexane (V135) of approximately 10–21 ppb are observed, as well as spikes of 6–10 ppb for 3-methylhexane (V65), 2-methylhexane (V56), n-pentane (V166) and octane (V162) (Figure 9).

In Figure 10, ethane (V119) and propane (V167) exceed 100 ppb on October 15, 2014; 2-methylpentane (V57) is also associated with several peaks up to 10–22 ppb in October. Iso-butane (or i-butane; V138) levels fluctuate up to 5 ppb, compared to a median value of 0.17 ppb (Figure 10 and Table A7 in Appendix A).

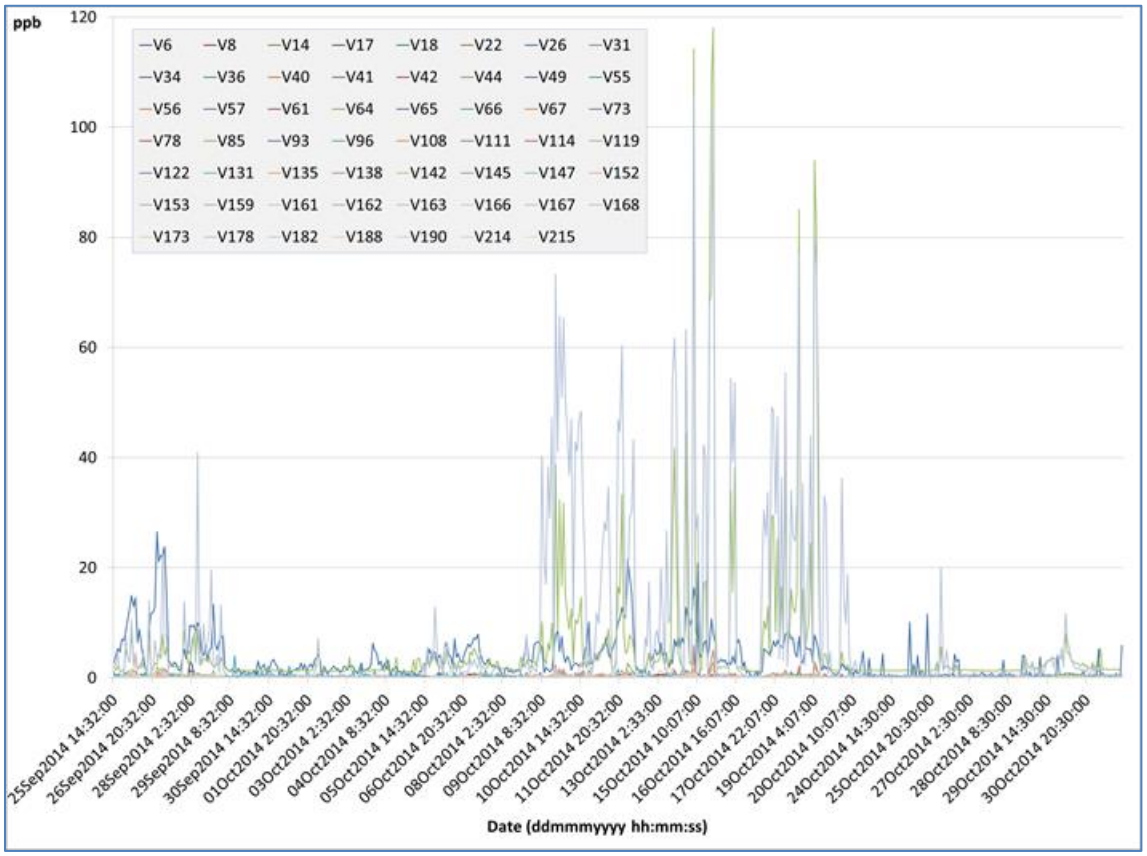

Figure 10. Time series of VOC concentrations from September 25 to October 31, 2014, measured with a GC/FID 5000 unit at location 21

Note: Full names of VOCs corresponding to *Vxxx* codes in the Legend box are included in Table B3 of Appendix B.

Several other VOCs are observed to intermittently increase by 10 times or more during Phase II, including alkanes (e.g., n-pentane [V166] and i-pentane [V215]) and alkenes (e.g., ethene [V214] and propene [V168]). For example, ethene (V214) increases to approximately 7 ppb on August 25, around the time when a well blow-down occurred. Methylcyclopentane (V153), 2,2-dimethylbutane (V36) and cis-2-butene (V93) peak around 14–18 ppb in mid- to late July, corresponding to drilling and reaming activities. Meanwhile, 2,3-dimethylbutane (V41) reaches approximately 16 ppb on January 11, 2015, which concurs with activities on the well pad intended to bring the new well in line for production.

Groups of compounds are also observed to vary similarly during Phase II, suggesting a common origin or activity source. For example, the levels of n-butane (V85), i-butane (V138) and i-pentane (V215) evolve very similarly, showing higher levels in early September and mid-October. Ethane (V119) and propane (V167) also show some similarities (and much higher concentrations). By contrast, other alkanes show relatively unique profiles; some are apparently not influenced by well pad activities (e.g., n-decane [V114]) or are only observed to peak during hydraulic fracturing activities and remain at very low levels during the rest of Phase II (e.g., n-heptane [V131] and n-hexane [V135]).

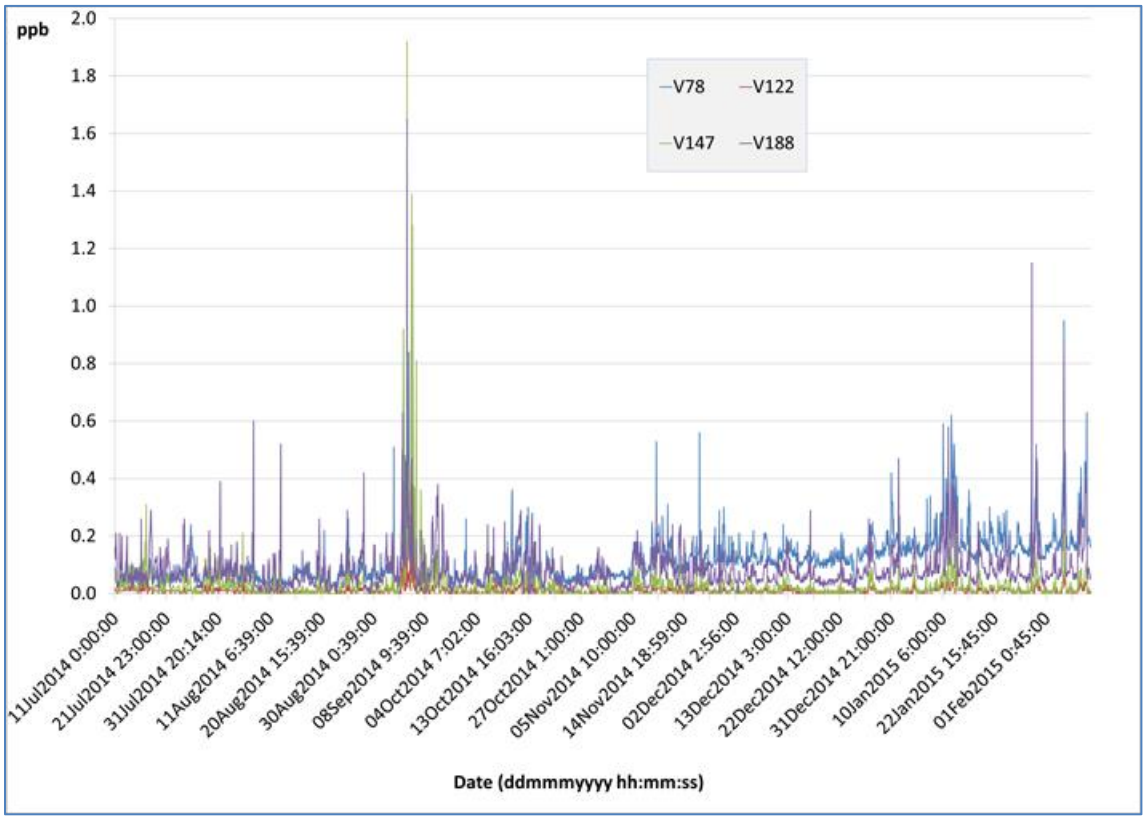

Figure 11. Time series of BTEX concentrations from July 11, 2014, to February 9, 2015, measured with a GC/FID 5000 unit at location 21

V78: benzene; V122: ethylbenzene; V147: m- & p-xylenes; V188: toluene

Figure 11 shows that concentrations of benzene (V78), toluene (V188), ethylbenzene (V122) and m- & p-xylenes (V147), referred to as BTEX compounds, are generally lower than 0.25 ppb and rarely exceed 0.5 ppb throughout Phase II. Spikes are observed around September 4–6, reaching 1.9 ppb for m- & p-xylenes, 1.7 ppb for toluene, 1.1 ppb for benzene and 0.5 ppb for ethylbenzene. Toluene and benzene concentrations are generally higher than those for ethylbenzene and m- & p-xylenes.[25]

BTEX levels are below air quality standards defined by some provincial agencies. Benzene concentrations exceed values equivalent to the 24 h standard in Ontario (2.3 µg/m^3; OMOE 2012) for three 90 minute

[25] When concentrations are centralized to the median (not shown), fluctuations in toluene and benzene are more similar between each other, while variations in ethylbenzene and m- & p-xylenes are more alike.

measurements (e.g., 1.1 ppb or 3.5 µg/m^3 at 3h00 AM on September 5). However, the highest daily average during the monitoring period, also recorded on September 5, is 0.27 ppb or 0.87 µg/m^3, below the defined 24 h standard for benzene.

2.2.11 Volatile organic compounds – organic vapour monitoring badge samples

VOC concentrations are available for 41 compounds based on OVM badge samples collected at locations 21 to 28, between July 16 and October 1, 2014. Table A8 in Appendix A shows the OVM badge results (11 weekly samples) for a limited list of VOCs. Table A8 includes VOC species that corresponded to concentration spikes, species that showed highest mean concentrations and species that have often been reported near oil and gas operations, such as benzene, toluene, xylenes, hexane and pentane (e.g., Bunch et al. 2014; McKenzie et al. 2012; PADEP 2011). Figure 12 (location 21) and figures A4 to A6 (locations 21, 22 and 27) in Appendix A also show the OVM results at different locations during Phase II.

Carbon tetrachloride (V102), decane (V114), dodecane (V118), hexadecane (V211), tetradecane (V212), 2,2,4-trimethylpentane (V34) and α-pinene (V76) are associated with higher mean concentrations than other VOCs at all locations. Naphthalene (V157) and m- & p-xylenes (V147) are also among the VOCs with the highest concentrations at most locations.

Table A8 shows that the three VOCs with the highest mean concentrations are tetradecane, dodecane and carbon tetrachloride. Tetradecane and dodecane are to some degree linked to the manufacture, treatment, use or disposal of petroleum products. Tetradecane may be released to the environment as a fugitive emission during its production and use, in the exhaust of motor vehicles and via industrial processes.[26] Dodecane can also be used as a solvent. Carbon tetrachloride levels are constant during the entire sampling period, consistent with the fact that it is a global pollutant that is not associated with oil and gas development (see V102 in Figure A4 in Appendix B). As noted in Interim Report 02 (Health Canada 2015), carbon tetrachloride was previously used internationally to produce refrigerants that have since been banned (e.g., Montreal Protocol for ozone-depleting substances in 1989). It has also been used in cleaners, solvents and for various industrial applications. Although carbon tetrachloride is no longer widely used, it persists at measurable levels in the atmosphere. It has been detected and measured elsewhere in New Brunswick (e.g., NAPS 2012; NB DELG 2013b).

Locations associated with the highest mean concentrations for each pollutant are also highlighted in Table A8. It is observed that mean VOC concentrations are generally higher at locations 21 and 24. Location 21 was on the fence line and directly downwind, and was expected to be affected by well pad activities. Location 24 was also on the fence line but not entirely downwind of the well pad. It was nearest to the well pad entrance, the railway and a roadway (very low and local daily traffic). Thus, vehicle traffic emissions, whether or not associated with well pad activities, may have contributed to VOC levels at this location.

Based on Figure 12 and figures A4 to A6 in Appendix A, three distinct spikes are identified for locations 21, 22, 23, 24 and 27. These locations were near or downwind from the well pad. The spikes correspond

[26] http://pubchem.ncbi.nlm.nih.gov//compound/12389?from=summary#section=Non-Human-Toxicity-Excerpts (accessed December 11, 2015)

to weekly samples deployed on July 29, September 3 and September 11, 2014. The July 29–August 5 sampling period overlapped with drilling and well preparation activities, the September 3–11 sampling period with hydraulic fracturing activities, and the September 11–18 sampling period with several post-hydraulic fracturing activities, such as gas flow testing (refer to Appendix C for a summary of well site activities).

The July 29–August 5 spike is associated with dodecane (V118), decane (V114) and tetradecane (V211), that is, compounds with 10 or more carbon atoms. To a lesser extent, increases in 2,2,4-trimethylpentane (V34) and m- & p-xylenes (V147) are also observed.

The September 3–11 spike includes 2,2,4-trimethylpentane (V34), 2-methylheptane (V55), 2-methylhexane (V56), α-pinene (V76), heptane (V131), hexane (V135), octane (V162), n-pentane (V166) and hexadecane (V211). Heptane, pentane and octane concentrations are notably higher at location 21 compared to other locations. The September 3–11 sample from location 21 shows concentrations of 1.0–1.5 $\mu g/m^3$ for these three VOCs, considerably higher than any other sample.

The September 11–18 spike includes the same species as in the July 29–August 5 sample (i.e. dodecane, decane and tetradecane). However, the measured VOC levels are lower.

Another spike is observed on August 20–26, only at location 22. It includes 2,2,4-trimethylpentane (V34), 2-methylhexane (V56) and heptane (V131) (see Figure A4 in Appendix A). Wind data show that winds were blowing from the well pad towards location 22 from August 21 to 23 (Figure A14 in Appendix A). The sample for this theoretically “upwind” location was possibly influenced by well pad emissions, whereas samples at “downwind” locations were probably not exposed as expected during that time.

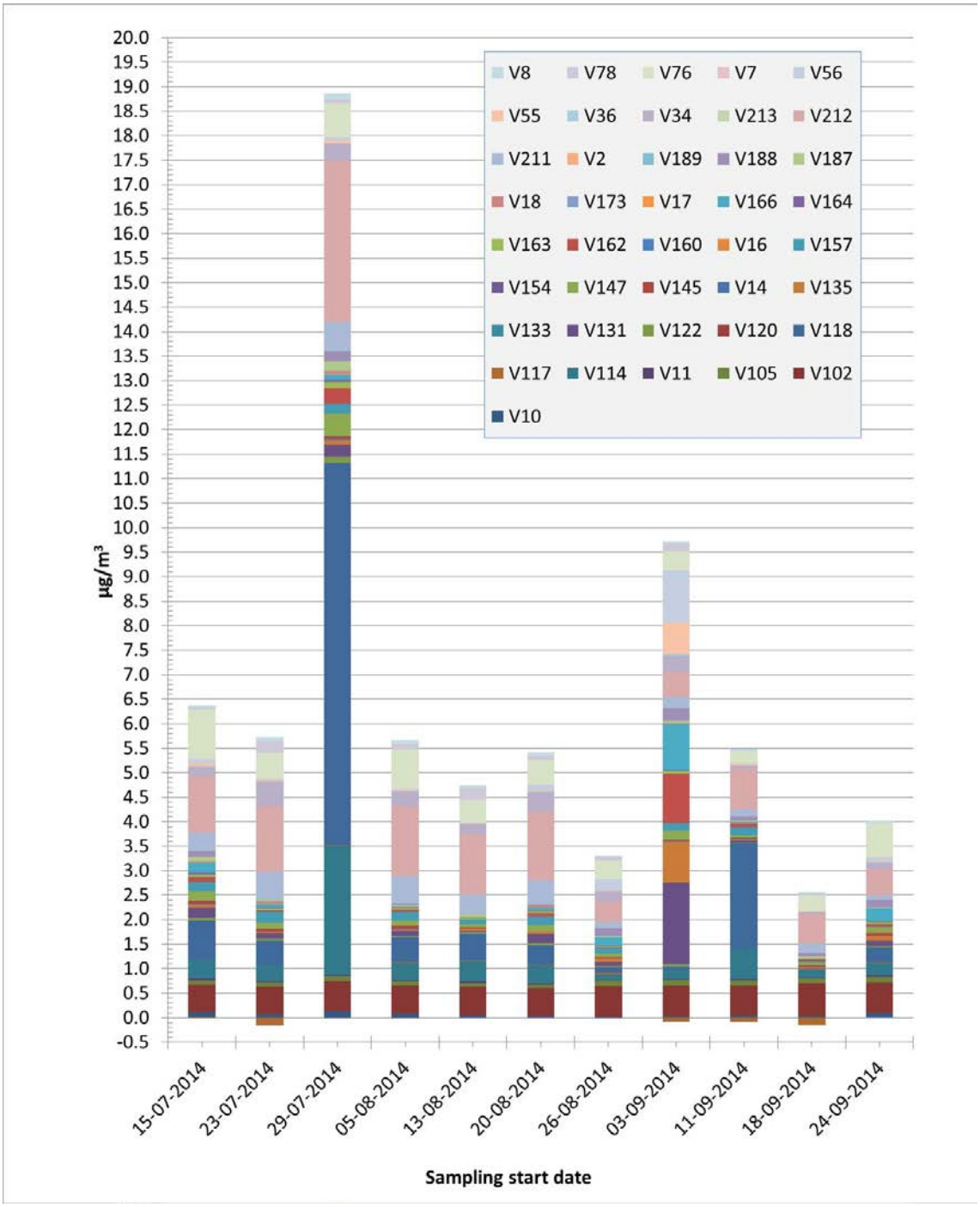

Figure 12. Stacked VOC concentrations at location 21 based on weekly OVM badge samples collected between July 16 and October 1, 2014

Note: Full names of VOCs corresponding to *Vxxx* codes in the Legend box are included in Table B3 of Appendix B.

2.2.12 Volatile organic compounds – Summa canister samples

VOC concentrations are available for 154 compounds based on Summa canister samples collected between July 26 and October 2, 2014, at locations 21 (15 samples) and 22 (6 samples). Table A9 in Appendix A shows the Summa canister results for a limited number of VOCs, including VOCs associated with the highest mean concentrations during Phase II and common pollutants of concern near oil and

gas operations (e.g., benzene, toluene). Also included in Table A9 are VOC species observed to increase considerably in the September 4 sample, that is, the sample collected on the day of the hydraulic fracturing event.

As shown in figures A7 and A8 of Appendix A, VOC levels are much higher for the September 4 sample compared to other samples collected during Phase II, and the increase is driven by approximately 20 VOC species. Notably, 4-ethyltoluene (V167) reaches 280 μg/m^3, whereas heptane (V131) and hexane (V135) are above 12 μg/m^3. Several VOCs are observed at concentrations greater than 4 μg/m^3, including: ethane (V119), 3-methylhexane (V65), 2-methylhexane (V56), n-pentane (V166), octane (V162) and 2-methylpentane (V57). In addition, 3-metyl pentane (V66), n-butane (V85), i-butane (V138), 2-methylbutane (V53), 2-methylheptane (V55) and methylcyclohexane (V152) are measured at 2−4 μg/m^3. Other VOCs also peak in the September 4 sample, but they are limited to less than 2 μg/m^3.

Although elevated 4-ethyltoluene (V167) concentrations correspond to intense well pad activity, the exact source or equipment on the well pad responsible for its release could not be identified. This compound has been detected in gasoline petroleum fuel and vehicle exhaust (e.g., Nordin et al. 2013), but has not been routinely reported in published reports on hydraulic fracturing or natural gas production. In contrast to 4-ethyltoluene, several of the compounds measured at higher levels in the September 4 sample correspond to alkanes commonly reported near oil and gas operations, such as heptane, hexane, ethane and pentane.

VOC concentrations are also higher in the September 1 sample. These higher VOC levels are linked only to increases in 4-ethyltoluene (V167) and ethane (V119). Concentrations of other VOCs are similar to levels observed in most samples collected during Phase II.

Several VOCs at location 21 do not appear to have been influenced by well pad activities and are measured at comparatively high levels, such as α-pinene (V76), chloromethane (V106), Freon 11 (V126), Freon 12 (V129) and isoprene (V142). These VOCs generally correspond to globally mixed pollutants (e.g., Freon 11 and 12) or biogenic VOCs (e.g., α-pinene and isoprene).

Benzene (V78) concentrations measured from Summa canister samples show a mean of 0.18 μg/m^3 and a maximum of 0.65 μg/m^3 at location 21. These levels are lower than benzene levels reported in 2013 at the Champlain Heights and Forest Hills monitoring stations in the Saint John region, which show a mean of approximately 1.34 μg/m^3 and 0.49 μg/m^3, respectively (NAPS 2013).[27] Benzene levels at location 21 are similar to concentrations reported at the Pointe Lepreau NAPS station (mean of 0.21 μg/m^3 and maximum of 0.54 μg/m^3), which is less influenced by anthropogenic activities than monitoring stations in Saint John. Moreover, the 2013 benzene concentrations are fairly representative of the benzene levels reported over the last decade at these urban stations (DELG 2015).

Summa canisters were also collected at location 22. Fewer samples were collected owing to equipment malfunctions and other unpredictable events. The results are included in Table A9 in Appendix A. Ethane levels vary considerably among samples, without any clear link with other pollutants. Freon 12 levels are

[27] The VOC data available on the NAPS website were not recovery and blank corrected.

constant and relatively high compared to other measured VOCs. Higher levels are observed in the August 21 sample than in other samples, notably for Freon 22, heptane, 4-ethyltoluene, 2-methylhexane and 3-methylhexane. This sample coincided with drilling activities or well preparation activities; winds were also blowing from the well pad towards location 22 that day. The Freon 22 concentration is 22.8 µg/m^3 in this sample, compared to 1 µg/m^3 or less in other samples. This value is also considerably higher than Freon 22 measurements from the Summa canister collected at location 21 on the same day (0.77 µg/m^3). The validity of this measurement is questionable as no source of Freon 22 was identified on site. Unfortunately, VOCs measured with OVM badges do not include Freon 22 and results cannot be compared for this period. This data point may be an outlier or considered invalid. Descriptive statistics for Freon 22 without this sample leads to mean and maximum values comparable to those estimated at location 21.

Air quality standards for individual VOCs have not been adopted in New Brunswick, and very few of the VOCs detected at higher concentrations are covered by air quality objectives adopted in other Canadian jurisdictions. Notably, air quality objectives do not exist for 4-ethyltoluene and they are scarce for alkanes (e.g., butane, ethane and propane). Air quality standards for some of the measured VOCs exist in Alberta (Alberta Government 2013), Ontario (OMOE 2012) and Québec (MDDEFP 2013). Compared to standards in other provinces, no exceedance was noted during Phase II. For example, the highest heptane concentration was measured at 13 µg/m^3 at location 21 (see Table A9 in Appendix A), compared to a 24 h air quality objective of 11 000 µg/m^3 adopted by Ontario.

2.2.13 Polycyclic aromatic hydrocarbons

PAH concentrations at location 21 are available for 30 compounds based on modified high-volume (MHV) samples and for 16 compounds based on URG pesticide personal samplers.

Table A10 in Appendix A shows descriptive statistics for PAH data based on MHV samples collected at the Phase II site between July 28 and September 26, 2014. Data from 12 samples are available. The highest mean values for all samples correspond to phenanthrene (9.25 ng/m^3), fluorene (2.95 ng/m^3) and acenaphthene (1.63 ng/m^3), followed by fluoranthene (1.37 ng/m^3) and pyrene (0.85 ng/m^3). Figure 13 shows the PAH composition of the different samples. The highest concentrations were measured on September 4, 2014, corresponding with hydraulic fracturing activities. The higher concentrations on September 4 are attributed to increases in fluorene (PAH4), phenanthrene (PAH5), fluoranthene (PAH7), pyrene (PAH8) and 2-methylfluorene (PAH50). The sum of all detected and measured PAHs is approximately 42.9 ng/m^3 on September 4, 2014, compared to an average of 15.9 ng/m^3 for other samples (Figure 13).

PAH results for Phase I of the current study (the baseline site) showed that the measured PAHs for samples collected during similar months (i.e. July to October) totalled 5 ng/m^3 or less.[28] Naphthalene, fluorene and phenanthrene were generally associated with the highest concentrations, followed by fluoranthene and acenaphthene. Ambient PAH levels are higher during Phase II compared to Phase I,

[28] PAH data for Phase I were re-analyzed without blank correction to match the data analysis approach selected for Phase II; results for Phase I might differ slightly from results presented in Interim Report 02 (Health Canada 2015).

suggesting that activities occurring on or near the well pad, whether or not associated with natural gas development, had an influence on PAH concentrations in ambient air.

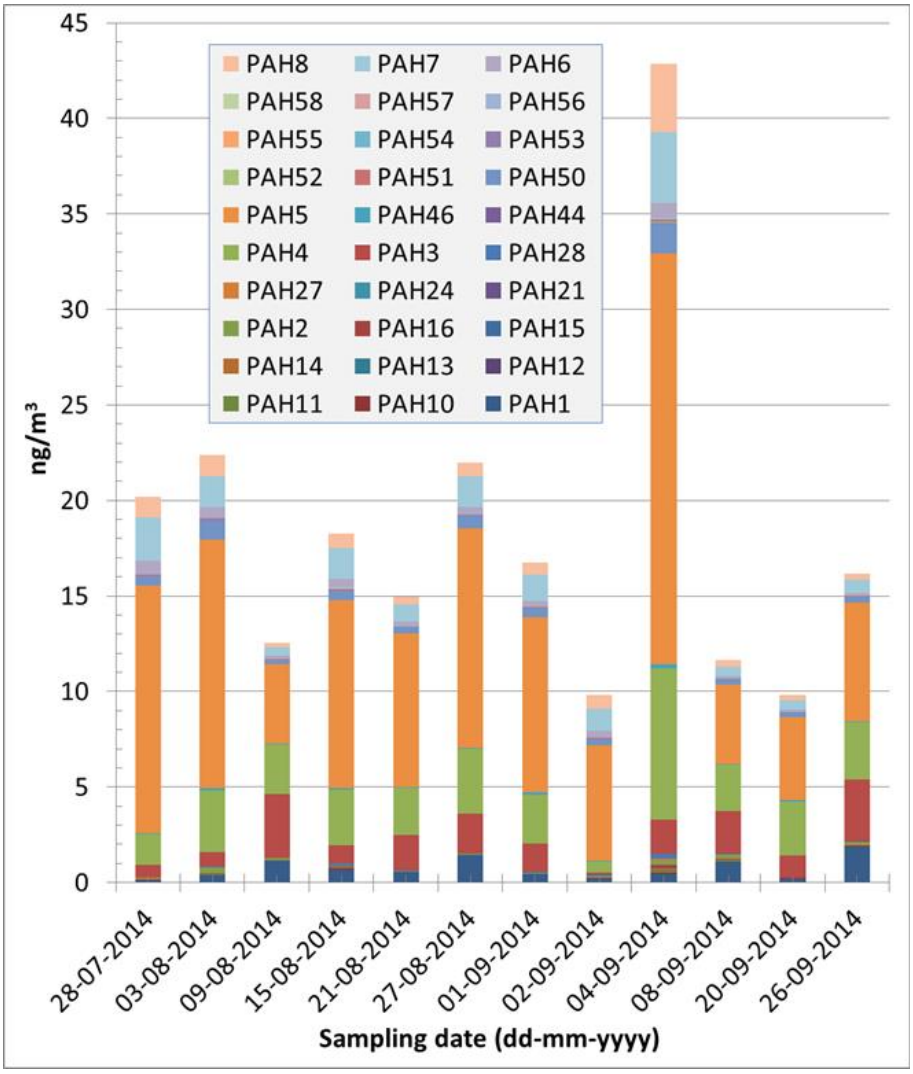

Figure 13. Cumulative PAH concentrations based on high-volume samples collected at location 21 during Phase II

Note: Full names of PAHs corresponding to PAH*xx* codes in the Legend box are included in Table B4 of Appendix B.

PAH results for the Forest Hills site in Saint John are available for 2012 for a comparative analysis (NAPS 2012). PAH results for the Forest Hills site show that phenanthrene (2.14 ng/m^3), fluorene (0.78 ng/m^3), fluoranthene (0.57 ng/m^3) and acenaphthylene (0.55 ng/m^3) were associated with the highest mean values (NAPS 2012).[29] The 2012 Forest Hills samples were collected and analyzed using similar methods. However, since the available NAPS data are not recovery- or blank-corrected, they are not directly comparable. Nonetheless, the results from Phase II suggest that activities occurring on or near the well pad, whether or not associated with natural gas development, increased the average concentrations of several PAHs compared to urban levels.

[29] http://maps-cartes.ec.gc.ca/rnspa-naps/data.aspx?lang=en (accessed April 12, 2016)

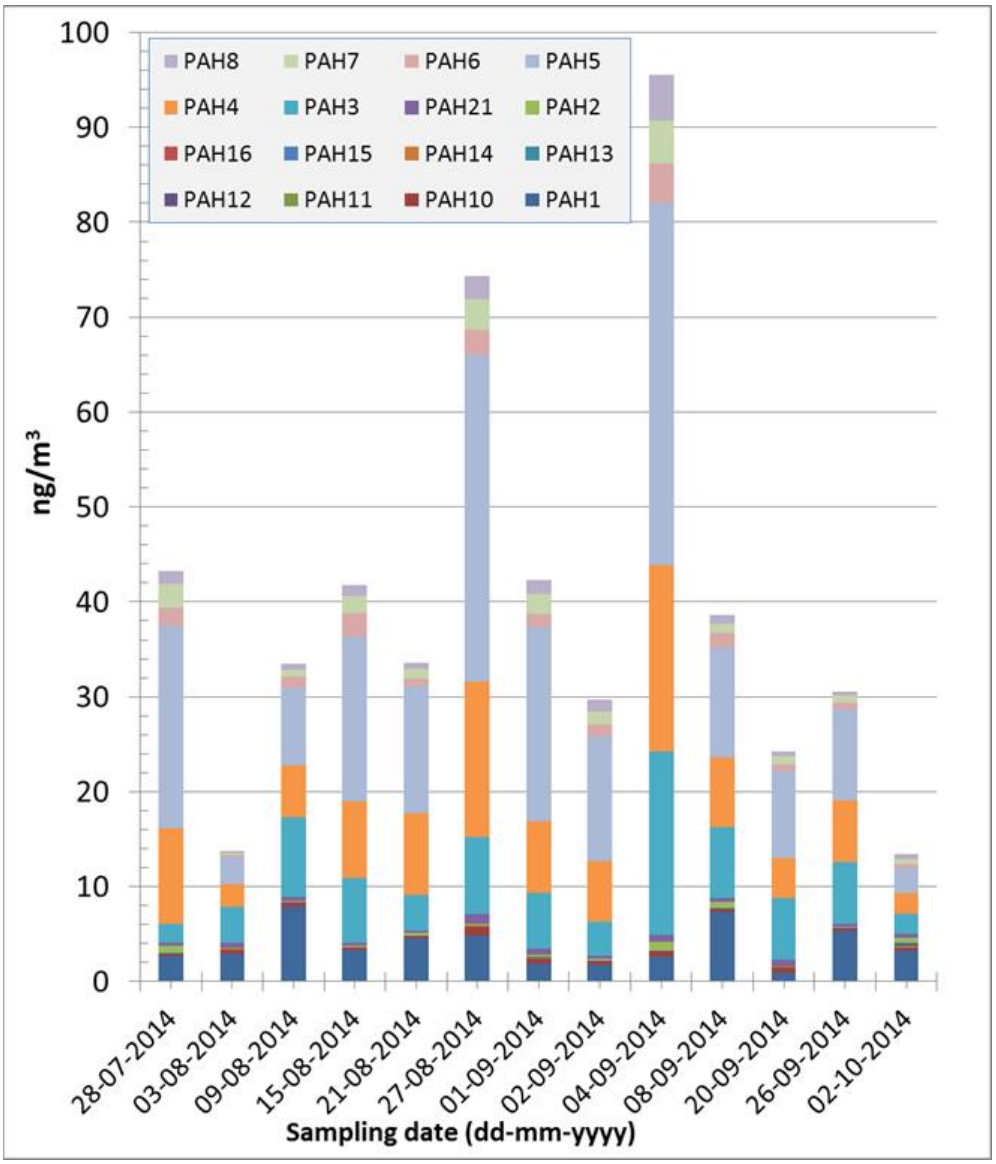

Figure 14. Cumulative PAH concentrations based on URG samplers collected at location 21 during Phase II

Note: Full names of PAHs corresponding to PAH*xx* codes in the Legend box are included in Table B4 of Appendix B.

Table A11 in Appendix A1 shows descriptive statistics for PAH data from the URG pesticide personal sampler collected at location 21 during Phase II, between July 28 and October 2, 2014. Data are available for 13 samples. The highest mean concentrations are reported for phenanthrene (15.54 ng/m^3), fluorene (8.08 ng/m^3) and acenaphthene (6.48 ng/m^3). A mean of 0.02 ng/m^3 is reported for benzo(a)pyrene.

Higher PAH levels are observed in the August 27 and September 4 samples (Figure 14), which correspond to the reporting of well preparation and hydraulic fracturing activities, respectively (refer to Appendix C). The sums of the measured PAHs are approximately double the sums estimated for other samples during Phase II. The increases are essentially associated with higher values for phenanthrene

(PAH5), fluorene (PAH4) and acenaphthene (PAH3), although anthracene (PAH6), fluoranthene (PAH7) and pyrene (PAH8) are also measured at higher levels compared to other samples.

The two methods used to sample and measure PAHs provide different results in terms of absolute concentrations. The sum of PAH measurements in URG samples are generally double the values reported for the high-volume samples, even though fewer PAHs are analyzed in the URG samples (see figures 13 and 14). Differences between sampling and analytical methodologies are suspected of being responsible for these discrepancies, and are not unexpected. Some methodological limitations and uncertainties are addressed in Section 4. Nonetheless, higher concentrations are associated with the same subset of PAHs, which include acenaphthene (PAH3), anthracene (PAH6), fluoranthene (PAH7), fluorene (PAH4), naphthalene (PAH1), phenanthrene (PAH5) and pyrene (PAH8). For samples such as those collected on August 27 and September 4, with noticeably higher PAH levels using both methods, the elevated concentrations are linked to a smaller subset of PAHs, namely acenaphthene (PAH3), fluorene (PAH4), phenanthrene (PAH5) and pyrene (PAH8).

Air quality objectives for PAHs have not been adopted in New Brunswick or at the federal level. Air quality standards have been adopted for three PAHs—that is, benzo(a)pyrene, naphthalene and pyrene—in other Canadian jurisdictions (Alberta, Ontario and Québec). Measured concentrations of naphthalene and pyrene during Phase II are well below available air quality standards.

Levels of benzo(a)pyrene in the URG and the MHV samples are lower than the annual criteria for Alberta (0.3 ng/m^3 or 0.0003 µg/m^3) and Québec (0.9 ng/m^3 or 0009 µg/m^3), whereas some samples showing concentrations of 0.03 ng/m^3 are higher than the Ontario annual standard (0.01 ng/m^3 or 0.00001 µg/m^3). However, the PAH sampling period for phase II was less than one year and direct comparisons with annual standards have several limitations (only annual PAH standards are available for Canadian jurisdictions). In addition, the benzo(a)pyrene concentrations measured during Phase II are lower than concentrations measured in samples from the Phase I site, and comparable to or lower than historical values reported at NAPS stations across Canada (Environment Canada 2013). Hence, benzo(a)pyrene concentrations measured during Phase II are not necessarily high, and possibly reflect regional baseline conditions.

2.2.14 Carbonyl compounds

Twelve samples targeting carbonyl compounds were collected during Phase II at location 21, between August 9 and October 2, 2014. Results are also available for 42 samples collected during Phase I, between October 12, 2012, and June 27, 2013. Table A12 shows descriptive statistics for 17 carbonyl compounds. Formaldehyde (1.489 µg/m^3), acetone (1.278 µg/m^3) and acetaldehyde (0.588 µg/m^3) are associated with the highest mean concentrations during Phase II. The highest value recorded for a single carbonyl compound during Phase II was 3.042 µg/m^3 for formaldehyde.

Figure 15 shows the cumulative carbonyl concentrations for Phase II samples. The results suggest that some well pad activities influenced ambient carbonyl levels, exemplified by the higher concentrations on August 27, September 4 and September 26, 2014. The August 27 and September 4 samples are associated with reports of well preparation and hydraulic fracturing activities, respectively (refer to

Appendix C). No specific activity is reported for September 26. The higher carbonyl levels are mainly driven by increases in acetaldehyde, acetone, formaldehyde, methyl-ethyl ketone/butyraldehyde and propionaldehyde.

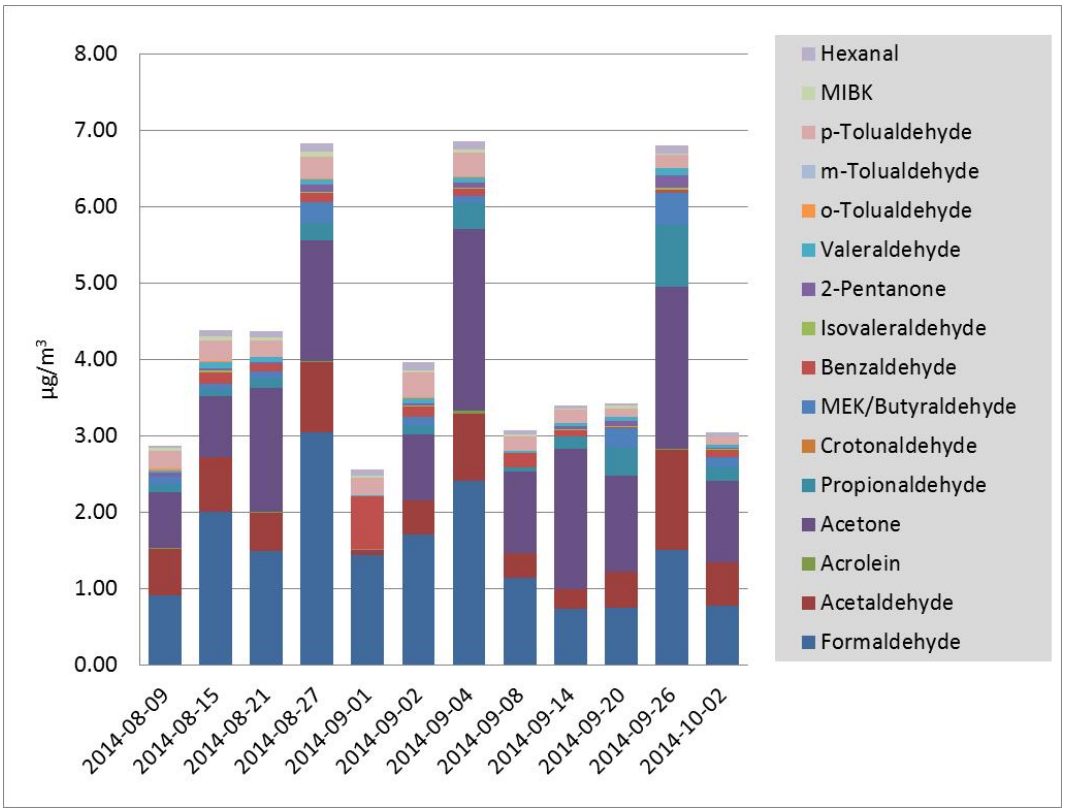

Figure 15. Cumulative carbonyl compound concentrations based on Xonteck samples collected at location 21 during Phase II

MEK: methyl-ethyl ketone; MIBK: methyl isobutyl ketone

Carbonyl concentrations are generally higher for Phase II samples compared to Phase I samples, but several carbonyl compounds show very similar concentrations, such as acetone, methyl-ethyl ketone/butyraldehyde and o-tolualdehyde. The largest relative differences between Phase II and Phase I mean carbonyl concentrations (i.e. those at least three times higher) are observed for formaldehyde, p-tolualdehyde, propionaldehyde, valeraldehyde and isovaleraldehyde. However, the very low concentrations and the limited number of samples collected during Phase II must be considered when interpreting these differences, especially for valeraldehyde and isovaleraldehyde.

Carbonyl compound data for 2014 are also available for the Forest Hills monitoring station in Saint John.[30] Comparisons show that ambient mean concentrations during Phase II and those at the Forest Hills station are very similar. The largest relative difference in mean concentration is estimated for benzaldehyde. Estimated at 0.142 µg/m^3 during Phase II, the mean benzaldehyde concentration is three times higher during Phase II compared to Forest Hills for samples collected between August 3 and

[30] http://maps-cartes.ec.gc.ca/rnspa-naps/data.aspx?lang=en (accessed April 12, 2016)

October 2, 2014 (i.e. carbonyl sampling period in Phase II). The higher benzaldehyde mean value for Phase II is influenced by the maximum benzaldehyde value on September 1, 2014 (0.680 µg/m^3), when most carbonyl compounds were at their lowest concentrations (see Figure 15). Benzaldehyde has many industrial and consumer product applications, and is commonly used in fragrances and food flavourings (e.g., synthetic almond extract). No air quality standard or inhalation exposure limit was found for this carbonyl.

Overall, mean carbonyl concentrations are higher during Phase II compared to Phase I, and they remain mostly comparable to concentrations reported at an urban location in New Brunswick. Air quality standards for carbonyl compounds have not been adopted in New Brunswick, but do exist in other Canadian jurisdictions, including Alberta, Ontario and Québec (Alberta Government 2013; OMOE 2012; MDDEFP 2013). Concentrations measured for Phase II samples are much lower than existing standards or objectives. For example, the Ontario Ministry of Environment has set a 24 h criterion of 65 µg/m^3 for formaldehyde, 11 880 µg/m^3 for acetone, 500 µg/m^3 for acetaldehyde and 0.4 µg/m^3 for acrolein.

2.2.15 Methane

Natural gas produced from the McCully Field has been characterized as 91–94% methane (CH_4), 2–6% ethane and 0.1–1% propane (Al et al. 2013). Natural gas can be released or captured during well development activities. Captured gas that cannot be collected or used on site is generally combusted with a flare.[31] Some variability in volumes of flared CH_4 was expected during Phase II. Intermittent flaring can possibly allow the release of small volumes of uncombusted CH_4. Natural gas may also leak from different equipment or devices used on well pads. All these potential sources of natural gas releases may contribute to increased CH_4 levels locally.

Methane measurements were conducted at location 21 with a continuous CH_4 monitor between July 3, 2014, and March 31, 2015. The data show an average CH_4 concentration of 2.06 ppm and a median of 1.98 ppm. These CH_4 concentration estimates are similar to levels observed during Phase I (Health Canada 2015) and close to global CH_4 concentrations, which have been estimated at 1.8 ppm (Kirschke et al. 2013). Descriptive statistics by month are shown in Table A13 in Appendix A. The highest monthly mean concentration was recorded in October 2014 (2.37 ppm).

Several peaks are reported between July and March 2015, suggesting that CH_4 releases (e.g., venting or leaks) were occurring near the sampling site. In September and especially in October 2014, CH_4 levels frequently and intermittently reached 3–4 ppm or more. These were possibly intermittent releases of natural gas from one or several sources on or near the well pad. Several events of increased CH_4 concentrations correspond to periods of more intense activity on the well pad (e.g., hydraulic fracturing, well testing and tie-in), whereas other intermittent increase events are more random and do not overlap with any specific activity on the well pad (refer to the summary of well pad activities in Appendix C). Peaks of CH_4 are generally of very short duration, lasting for approximately 10 seconds to a few minutes, before returning to normal levels around 2 ppm.

[31] Based on previous investigations, a destruction removal efficiency of 98% for methane is considered appropriate with flares. The destruction removal efficiency reflects how well a flare destroys a specific fuel component, such as methane (Caulton et al. 2014). This high efficiency rate implies that the flare is operating on a continuous basis.

Some 10-second measurements increase up to 93 ppm, which is still well below the lower explosive limit of CH_4 set at 50 000 ppm. Figure 16 shows the variations in CH_4 levels measured over a 24 h period that included the 93 ppm peak. Although some activities on or near the well site had a measureable impact on CH_4 levels during this period of time, levels quickly returned to baseline levels at around 2 ppm. No air quality objective or standard for CH_4 has been adopted in Canada.

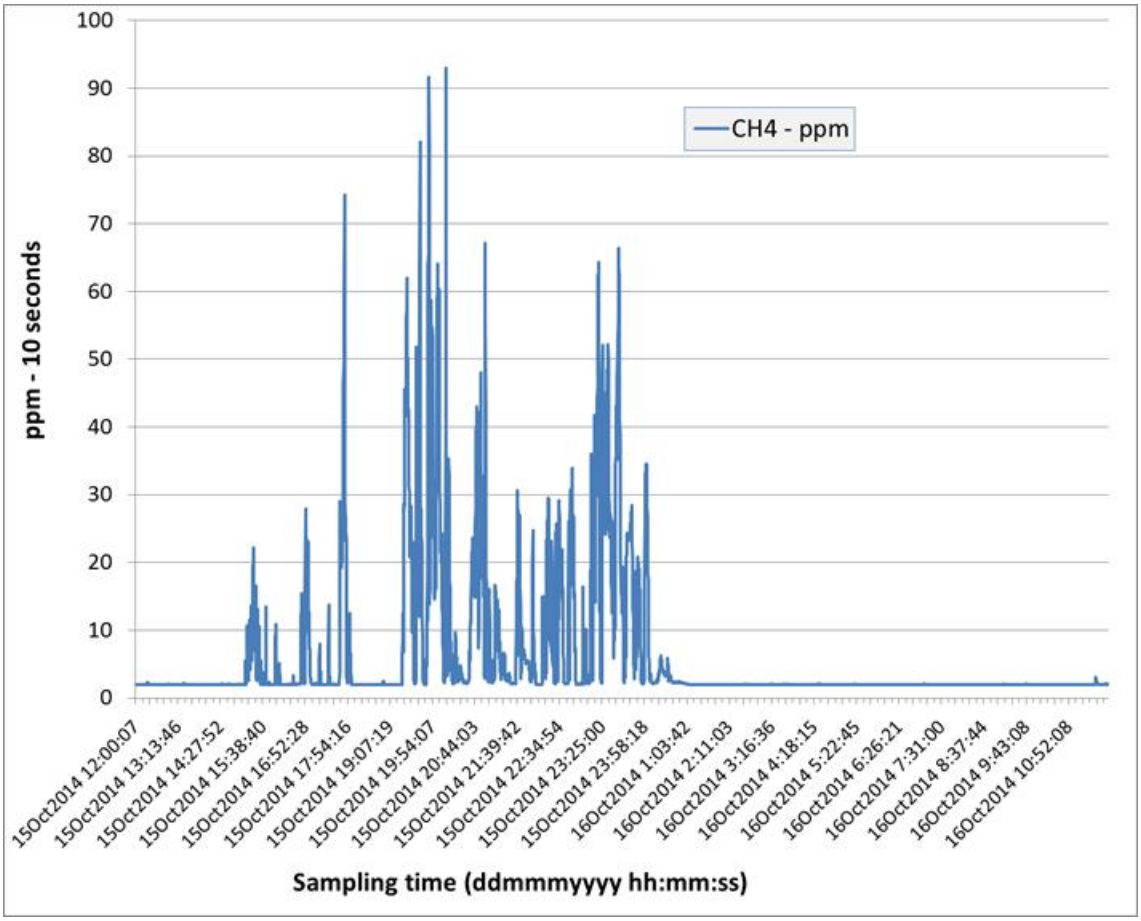

Figure 16. Methane concentration per 10 second increments between 1 p.m. on October 15 and 1 p.m. on October 16, 2014, collected at location 21 during Phase II

2.2.16 Meteorological data

Wind speed and direction data for location 21 and location 22 are represented in wind roses in figures A10 to A14 in Appendix A. Winds are characterized as blowing predominantly from the southwest during summer months (resulting vector of 248–258 degrees; figures A10 and A12), and blowing primarily from the northwest and the northeast during winter months (Figure A11).

Wind conditions on September 4, 2014, were very similar to overall summer and fall conditions (i.e. blowing from the southwest; Figure A13). This confirms that the monitoring stations were suitably located to collect upwind (location 22) and downwind (location 21) ambient pollutant concentrations during the hydraulic fracturing event.

Wind direction data are very similar between monitoring locations. However, average wind speeds differ considerably between locations, averaging 11.7 metres per second (m/s) at location 21 and 2.5 m/s at location 22. The mobile laboratory (location 21) collected wind data at 10 m above ground level and was positioned on top of a knoll, whereas the Airpointer unit collected wind data at 3.0 m above ground level and was positioned on flat terrain. As a result, the height above ground level for the monitors differed by 10−15 m between locations. Owing to surface drag effects, even over a relatively flat grassy surface, wind speeds can increase logarithmically with height above the surface. Thus, differences in average speeds between locations are not unexpected.

The average seasonal temperatures during Phase II were 17.7°C in summer, 5.4°C in the fall and -8.1°C in winter.[32]

3. Discussion

Several working groups in Canada and the US have recommended that ambient air quality be measured at active well sites and be compared to baseline measurements collected in adjacent areas without unconventional natural gas development activities (CCA 2014; Health Effects Institute 2015; Penning et al. 2014). The current study was designed to include a baseline site and an active well site, as represented by Phase I and Phase II, respectively. Baseline data for an entire year of air pollutant monitoring are presented in Interim Report 02 (Health Canada 2015).

Most of the data collected during Phase I are comparable to the data collected at the upwind sampling locations of Phase II (based on dominant wind patterns), that is, locations 22 and 25.[33] Thus, regional (i.e. Phase I) and local (i.e. locations 22 and 25) baseline data are available to evaluate the impact of well pad activities in the current study. This is possible because, for example, Phase I and Phase II sites are located in the same region within the Kennebecasis River valley, there are few major sources of air pollution in the region, and unconventional oil and gas development in the Sussex area was very limited prior and up to 2015.

Ambient concentrations between Phase I and locations 22 and 25 of Phase II differ only for VOCs and PAHs. In contrast to regional pollutants, such as O_3 or $PM_{2.5}$, VOC and PAH levels are influenced by local sources and bound to vary on small geographical scales. Activities and infrastructure nearby or upwind of the Phase II site, such as the railway, highways, the PotashCorp mine and various activities in the town of Sussex, are potential sources of VOC and PAH emissions. These emissions, which may not be directly related to oil and gas development, may influence ambient pollutant concentrations at the Phase II site and lead to differences in VOC and PAH concentrations compared to the Phase I site. Moreover, as VOCs and PAHs are generally measured at very low concentrations, slight differences between Phase I and Phase II results can potentially be misleading when trying to allocate air pollutant concentrations to well pad activities. For VOC and PAH data during Phase II, it may be more relevant to compare downwind measurements (e.g., locations 21, 23 and 27) with upwind measurements

[32] Seasonal values based on measurements at location 21 owing to a more complete dataset.
[33] Only OVM badges were collected at location 25.

(i.e. locations 22 and 25) instead of Phase I measurements. Therefore, when appropriate, pollutant concentrations associated with Phase II upwind locations are considered as site-specific baseline levels.

The monitoring data collected during Phase II indicate that air pollutant concentrations vary depending on several factors, such as the activities conducted on the well pad, the location of the samplers, the sampling duration, the type of pollutant and the meteorological conditions. During Phase II, ambient levels for several pollutants including CO, O_3 and SO_2 were not influenced by well pad activities. Ambient air pollutant levels measured downwind of the well pad (i.e. location 21) were generally similar to levels measured at the upwind location (i.e. generally location 22) or at the baseline site (i.e. Phase I). This is expected for regional pollutants such as O_3. Local emissions generally have a limited influence on O_3 levels. The O_3 concentrations at the Phase II site are consistent with levels observed during Phase I and Phase III (Health Canada 2015), as well as with previous observations and estimates made throughout New Brunswick (NB DELG 2012, 2013a, 2013b).

Although ambient $PM_{2.5}$ concentrations tend to vary on a regional scale, they are influenced by regional atmospheric conditions and local sources, both natural (e.g., meteorology and geography) and anthropogenic (e.g., land use and emission sources). The data from Phase I and Phase II show that $PM_{2.5}$ concentrations are very similar at these sites (mean of 5.0 $\mu g/m^3$ at Phase I and 4.8 $\mu g/m^3$ at Phase II). Similarities among study sites are also noticed for $PM_{2.5}$ compounds, including metals, elemental and organic fractions, and markers of organic combustion. This supports the view that $PM_{2.5}$ concentrations are not influenced substantially by local disturbances (e.g., well pad activities) as much as they are by regional phenomena (e.g., long distance transport of pollutants and prevailing winds). However, higher $PM_{2.5}$ concentrations were measured at location 21 compared to those at location 22 during the month of July 2014. This period corresponded with the mobilisation of equipment and drilling activities, which may have led to fugitive (e.g., dust) and combustion emissions of $PM_{2.5}$. Thus, well pad activities had an intermittent impact on $PM_{2.5}$ concentrations at the downwind location.

NO and NO_2 concentration data show considerable fluctuations at the upwind and downwind sampling locations. Ambient NOx (including NO and NO_2) concentrations were influenced by well pad activities, increasing several fold for intermittent periods, especially at location 21. However, NO_2 concentrations never exceeded provincial or national air quality standards (Section 2.2.9; Appendix D). Data for location 21 (downwind) show mean concentrations of 4.8 ppb and 2.0 ppb for NO and NO_2, respectively. The mean concentrations at location 22 (upwind), over the whole sampling period of Phase II, are 1.1 ppb for NO and 1.1 ppb for NO_2. Mean concentrations at location 22 are slightly higher but similar to mean concentrations calculated at the baseline site during Phase I: 0.3 ppb for NO and 1.2 ppb for NO_2. This suggests that the upwind location was representative of local baseline conditions and likely incorporated normal NOx emissions from local sources. The largest difference between Phase I and location 22 (Phase II) is observed for NO, which possibly reflects the absence of NOx emission sources in the area of the Phase I site. In fact, combustion sources (e.g., vehicle engines and flares) mostly release NO molecules, which then rapidly convert to NO_2. Fresh NOx emissions are thus expected to comprise more NO than NO_2. By comparison, NOx in areas that are devoid of local sources of combustion emissions are expected to comprise higher fractions of NO_2. This is consistent with the measurements at

during Phase II. The increase in ambient NO levels at location 21 (up to 350 ppb) compared to the location 22 and Phase I values suggests that activities on the well pad were releasing NO and having a measurable impact on downwind NO (and NOx) concentrations.

Ambient VOC concentrations were also dependent on well pad activities, as indicated by intermittent increases in VOCs during Phase II. Further, among the suite of measured VOCs, only subsets of species were affected by well pad activities. Despite the use of different analytical methods and distinct sampling periods, the measurements converge to define subsets of VOCs that fluctuated depending on the nature of activities occurring on the well pad.[34] The following VOCs varied in relation to well pad activities and were common to all three methods: heptane, hexane, octane, pentane, 2-methylhexane and 2-methylpentane. Based on VOC data for the short-term samples only (i.e. 24 h canisters and continuous measurements every 90 minutes), ethane, i-butane, propane, 3-methylhexane, 3-methylpentane and n-butane were also noticeably affected by well pad activities. In addition, 4-ethyltoluene reached very high levels in two Summa canister samples just prior to and during the hydraulic fracturing event. As this compound is not routinely reported in air monitoring studies conducted near oil and gas operations, and owing to the general scarcity of environmental information for 4-ethyltoluene, the exact source of this pollutant is uncertain.

Passive VOC samplers were deployed at a total of eight locations during Phase II. These samples were exposed for approximately seven days and provided weekly average concentrations. The results from the passive VOC samplers demonstrate the influence of prevailing winds, with samples from downwind locations showing substantially higher VOC concentrations than upwind locations. The influence of wind direction is also noticeable in weekly samples corresponding to periods of irregular wind conditions. For example, when prevailing winds were reversed in late August 2014, the sample collected at location 22 (i.e. the default upwind location) showed higher VOC concentrations than the sample from location 21 (i.e. the default downwind location).

Comparisons among VOCs detected and measured across all Phase II locations, as well as VOC measurements at the baseline site (i.e. Phase I) and at the gas treatment facility (i.e. Phase III locations) allow for the identification of VOC species potentially associated with well pad and well development activities. Figure A9 in Appendix A shows the OVM badge results from Phases I and III (refer to Interim Report 02; Health Canada 2015). The results show that location 31 (i.e. fence line and downwind of the natural gas processing and distribution facility; Phase III) is associated with higher VOC levels compared to other locations; the VOC species and concentrations are similar across the other Phase III locations (based on the species considered for Figure A9). The increase in VOC concentrations at location 31, as shown in Figure A9, is related to heptanes, hexane, 2-methylhexane and pentane—all compounds that have previously been linked to natural gas production or vehicle use in the literature. These pollutants are also associated with intermittent increases in VOCs during Phase II. These results from Phase II and Phase III suggest that VOCs commonly associated with natural gas production, processing or distribution

[34] VOCs were measured using three different methods, including a continuous monitor, 24 h canister samples and weekly passive badges (sections 2.2.10 to 2.2.12).

were effectively detected, and that their concentrations in ambient air varied in relation to well pad and shale gas-related activities.

Overall, the results indicate that emissions associated with well pad activities can influence VOC concentrations, notably increasing the concentrations of alkane species associated with oil and gas production at downwind locations. Based on the suite of VOC measurements during Phase II, the following VOCs are identified as being most affected by well pad activities: **benzene**, **butane**, **ethane**, **heptane**, **hexane**, **2-methylheptane**, **2-methylhexane**, **octane**, **pentane**, **propane**, **toluene** and **2,2,4-trimethylpentane**. However, the reported VOC levels at all sites remained lower than ambient air quality standards, when available.

The hydraulic fracturing process on September 4, 2014, used LPG as the fluid to fracture the formation and to carry the proppant. As mentioned in Section 2.1.1, LPG is mainly propane with a lesser amount of ethane. Although 350–600 m^3 of LPG (estimated) was injected into the formation, increases in ambient levels of propane and ethane were relatively limited during the fracturing process and in the days that followed (i.e. September 2014; Figure 17). Rather, the continuous measurements show that ambient propane and ethane levels increased and fluctuated similarly during the first weeks of October 2014 at a time when well bleeding and snubbing, blow-down and flow testing activities were occurring.[35] It is suspected that some of the injected LPG could have volatilized in the well and was subsequently released during well interventions, influencing propane and ethane levels. The fact that ethane is more volatile than propane and that the natural gas in the McCully Field contains a larger fraction of ethane than propane could partly explain the higher concentrations recorded for ethane compared to propane.

Higher PAH concentrations are observed in the samples corresponding to the hydraulic fracturing event (Section 2.2.13). The results also indicate that subsets of PAHs are responsible for most of the increase, including: acenaphthene, anthracene, fluorene, fluoranthene, pyrene, phenanthrene and 2-methylfluorene. Most of the PAHs measured at higher concentrations or observed to increase during specific activities on the well pad are PAHs commonly found in engine or vehicle exhaust emissions (Alves et al. 2015; US EPA 2002). These compounds are also among the more commonly found PAHs in indoor and ambient air (Van Winkle and Sheff 2001). Thus, their detection per se is not indicative of specific activities related to oil and gas production. PAHs are mainly associated with the incomplete combustion of organic matter, such as hydrocarbon fuels (e.g., diesel and gasoline). PAHs can be formed during combustion of carbonaceous fuels that already include aromatics (e.g., diesel and gasoline) and even fuels that do not include aromatics, such as methane and other light alkanes (International Agency for Research on Cancer 2013). Hence, all combustion sources that were active during the hydraulic fracturing event could have released PAHs and contributed to higher PAH levels. Based on a report by the Health Effects Institute, diesel exhaust emissions are associated with lower molecular weight PAHs (i.e. containing fewer than 4 rings), which includes species such as acenaphthene, fluoranthene, fluorene and pyrene (Health Effects Institute 2007). It is likely that the intensive use of diesel-powered

[35] Refer to the Occupational Safety and Health Administration Oil and Gas Well Drilling and Servicing eTool (www.osha.gov/SLTC/etools/oilandgas/glossary_of_terms/glossary_of_terms_a.html) and the Schlumberger Oilfield Glossary (www.glossary.oilfield.slb.com/en/Terms/s/snubbing.aspx).

engines on the day of the hydraulic fracturing event was responsible for the increase in ambient concentrations of some lighter molecular weight PAH species (see figures 13 and 14). Nonetheless, the ambient PAH concentrations measured during Phase II were lower than ambient air quality standards, when available.

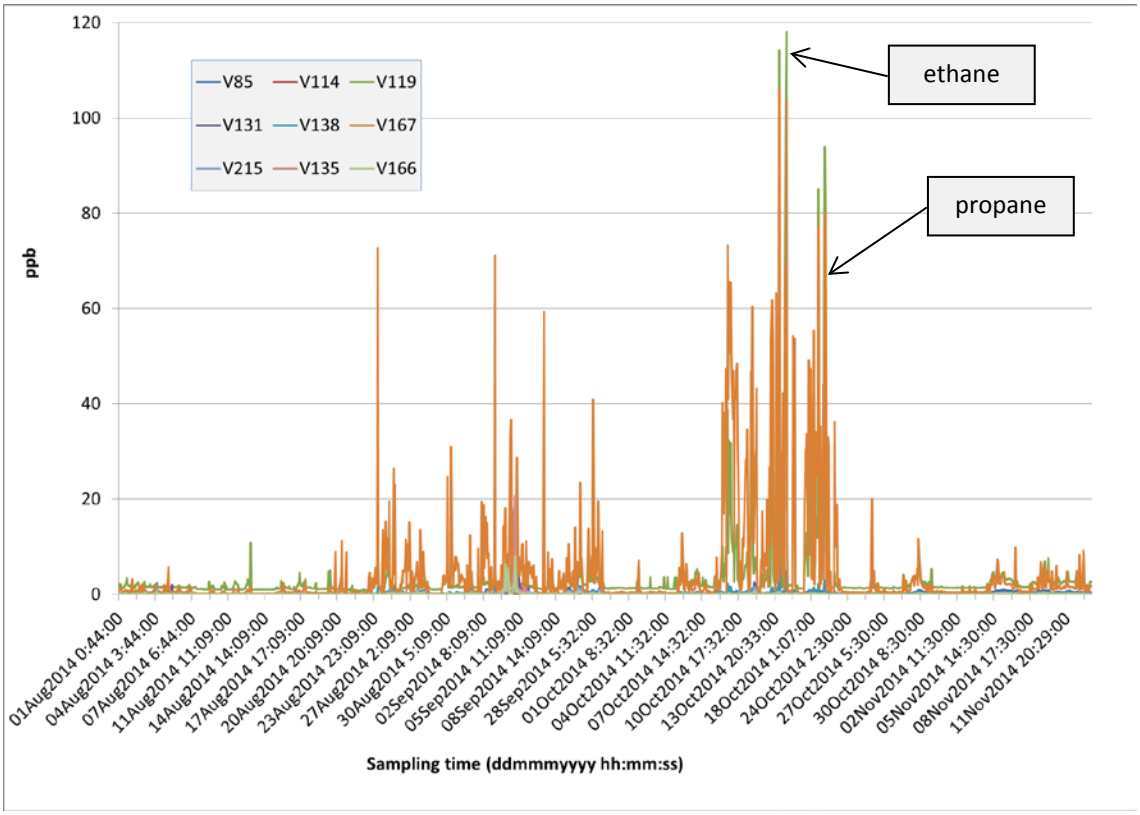

Figure 17. Time series of alkane concentrations from August 1 to November 13, 2014, measured with a GC/FID 5000 unit at location 21

V85: n-butane; V114: decane; V119: ethane; V131: heptane; V135: hexane; V138: i-butane; V166: n-pentane; V167: propane; V215: i-pentane

Concentrations of formaldehyde, acetone, acetaldehyde, methyl-ethyl ketone/butyraldehyde and propionaldehyde varied in relation to well pad activities. These carbonyl compounds are commonly detected in diesel and gasoline vehicle exhaust emissions (e.g., Ballesteros et al. 2012). Overall, the increased use of diesel vehicles and engines during well preparation and hydraulic fracturing activities may have led to higher emissions of carbonyl compounds and to a measurable impact on ambient carbonyl concentrations. However, the levels of carbonyl compounds reported at location 21 are considerably lower than ambient air quality standards, when available.

Concentrations of carbonyls, PAHs and VOCs fluctuated differently during Phase II. Since PAHs are semi-volatile and originate from the combustion of organic matter, they are expectedly released during periods of intensive engine or vehicle use (e.g., during hydraulic fracturing). In contrast, VOC emissions depend on a variety of activities, including those not associated with combustion such as uncontrolled releases during well operations or venting. The preponderance of alkane species in VOC samples suggest

that VOCs originated from non-combustion sources. Although well pad activities had a measurable impact on ambient carbonyl, PAH and VOC concentrations, they did not exceed ambient air quality standards.

Natural gas compounds may be released from a variety of sources during well preparation and completion operations, such as the well itself during work-overs, equipment leaks (e.g., valves, pumps or gauges), pneumatic pumps and controllers, and venting as well as during hydraulic fracturing (Alvarez and Paranhos 2012). As natural gas is composed mainly of CH_4, intermittent releases of CH_4 during well pad activities are not unexpected. CH_4 levels showed a lot of fluctuation during well pad activities. Nonetheless, the overall average during Phase II is very similar to global and regional baseline levels (i.e. approximately 2 ppm). The data set shows that ambient CH_4 concentrations during Phase II never reached levels of concern from an explosive standpoint, and that CH_4 levels quickly returned to baseline levels following spikes. These observations suggest that CH_4 releases were intermittent or quickly controlled (e.g., via flaring).

Overall, ambient air pollutant levels were generally low or below air quality guidelines during Phase II. It is important to point out that Phase II covered and focused on a single hydraulic fracturing event. As such, it is not necessarily indicative of the air quality impacts of a fully developing or developed unconventional gas play. An active play would likely involve the concurrent development of several well pads, concurrent well completions, increased road traffic and off-road activity, and increased flaring, for example. Although individual well pads or natural gas facilities, based on the findings from the current study, may not have a considerable impact on air quality, the cumulative impacts on local or regional pollutants could be greater. For example, a multitude of dispersed well pads (i.e. local sources) could eventually have a measurable impact on regional air quality, for pollutants such as O_3 or $PM_{2.5}$. More local and regional data is necessary to characterise or predict the air quality impacts associated with air pollutant emissions from multiple well pads or natural gas facilities.

The characteristics of the hydraulic fracturing event during Phase II also have to be considered. For example, as outlined in Section 2.1: the hydraulic fracturing relied on LPG, which is not the most common fluid used for well completions in North America; the well did not include a horizontal leg; and a relatively small volume of fluid was required (600 m^3 of LPG compared to high volume water-based hydraulic fracturing events that can require up to 20 000 m^3 of water; CCA 2014). Further, unconventional gas production is limited in New Brunswick and unconventional gas exploration has halted since the December 2014 provincial moratorium on hydraulic fracturing. Hence, it is not possible at this time to assess the representativeness of this single monitored event in New Brunswick or to attempt any extrapolation for unconventional gas development scenarios across Canada.

Based on observations from the current study, comprehensive air monitoring is recommended near well pads in order to gain additional knowledge regarding the air quality impacts of unconventional oil and gas development. The monitoring approach should target NOx, PAH, $PM_{2.5}$ and VOC concentrations, if possible. Detailed characterization of VOCs also provides considerable value by allowing the identification of VOC species that are actually influenced by local oil and gas activities. In fact, “total” VOC values may not correctly reflect the fluctuations of many VOCs by giving too much weight to VOCs

that are not associated with oil and gas operations, such as carbon tetrachloride or biogenic VOCs (e.g., α–pinene). In the event of a broader development of unconventional gas plays in New Brunswick, monitoring key regional air pollutants, notably O_3 and $PM_{2.5}$, in addition to NO_2, should also be envisaged. These common pollutants are known to be harmful to human health and form the basis of the Air Quality Health Index (AQHI), which is a health protection information tool developed by Health Canada and Environment and Climate Change Canada.[36] For example, in Fort St. John, British Columbia, a region with considerable unconventional oil and gas development, daily AQHI forecasts are now available to help communities in that region protect their health from air pollution. Samples and measurements should also be collected using recognized methods, including continuous monitors and integrated samples, for reliable comparisons with air quality standards and data from regional or national surveillance programs, such as NAPS in Canada.

4. Limitations and uncertainties

This section summarizes different categories of limitations and uncertainties identified or encountered during Phase II. The limitations and uncertainties are qualitatively described. When applicable, a general evaluation of the potential direction and magnitude of an uncertainty is included. Quantitative and statistical estimates of these uncertainties are beyond the scope of this report.

4.1 Data collection and analyses

Data collection during Phase II was affected by some equipment malfunctions that caused a series of invalid or missing data collection periods. For example, the CO and O_3 modules in the Airpointer unit (location 22) broke down in August 2014 and were not replaced. Although measuring these pollutants at location 22 was not critical to the study, it would have permitted more comparisons with measurements conducted at location 21 over the same period. Data collected during the overlapping period (i.e. when modules were operational in the Airpointer) did not show any considerable variations between locations 21 and 22 or with baseline levels from Phase I. As O_3 concentrations are more dependent on regional conditions than local emissions, strong local fluctuations (i.e. upwind compared to downwind measurements) were not expected. The impact of these malfunctions is considered minimal.

More importantly, there are gaps in the continuous VOC data at location 21 in the weeks following the hydraulic fracturing event (September 9–24, 2014). Intermittent increases in some VOCs may have been missed during the period the AMA GC/FID 5000 unit was offline. However, data from the integrated VOC samples overlapping with those weeks indicate that VOC levels were relatively low, and activity reports (Appendix C) suggest that well pad activity was minimal from September 9 to early October 2014. The mean VOC concentrations from the continuous measurements are potentially underestimated for this post-hydraulic fracturing period, but the impact on the overall study is considered minimal.

PAH concentrations reported for the MHV samples during Phase II are generally lower than concentrations reported for the URG samples. This concurs with observations regarding PAH measurements during Phase I, which are described in Interim Report 02 (Health Canada 2015). Only for

[36] www.ec.gc.ca/cas-aqhi/default.asp?Lang=En (accessed April 8, 2016)

benzo(g,h,i)perylene were the concentrations in the high-volume samples higher than those in the URG samples. Since the MHV method samples a higher volume of air than the URG method, lower measurements are not necessarily expected. Furthermore, the MHV method collects total particulate matter (TPM), whereas the URG samples are based on $PM_{2.5}$. The sample from the high-volume method should collect more particulate material than the URG samples and, presumably, higher PAH values are expected from the TPM samples (Guo et al. 2003). This was not the case for Phase I and Phase II samples, and the reason for the lower concentrations in the MHV method samples could not be identified. There appears to be many confounders that prevent a fair comparison of the PAH measurements obtained from the two distinct sampling methods. Although this uncertainty was observed during a previous phase of the current study, the decision was made to keep the same sampling approach during Phase II. Direct comparisons between the two methods were avoided and analyses focused instead on identifying concurring trends in the concentrations of PAH species. Additional analyses and comparisons of the different sampling and analytical methods for PAHs used in this study, and considerations of possible sampling artefacts (Ravindra et al. 2008) are necessary but considered beyond the scope of the current study.

Elevated pollutant measurements are observed for unusual pollutants, such as Freon 22 at location 22 (refer to Section 2.2.12). No known or suspected source of Freon 22 emissions was identified near the sampling location. In addition, Freon 22 levels from a sample collected on the same day at a nearby site showed low (and average) ambient concentrations. The validity of the high Freon 22 measurement is questionable, but since the origin or cause of the spike (e.g., sample contamination or laboratory procedure) was not identified, this measurement cannot be invalidated definitively.

During sampling and laboratory analyses, several issues were reported, such as missing log sheet information, lower-than-expected sampling flow and volume, excessive lags between sample collection and laboratory analyses, and samplers used after the suggested expiry date. Depending on different criteria, such as the number of available samples and the general comparability of data, flagged samples were voided or considered valid. For example, several carbonyl samples collected during Phase II were flagged as “cartridges used more than two months after their coating date.” Owing to the limited number of Phase II carbonyl samples available and considering that the visual inspection of data associated with the flagged samples did not appear skewed (i.e. compared to normal samples or baseline and urban data), the flagged samples were considered valid. Nonetheless, uncertainties (for carbonyls and other pollutants) must be acknowledged when interpreting the data.

Given the propensity of methane and other volatile compounds to disperse in air, and the influence of wind speed and direction on the shape and size of the pollutant plumes, methane or VOC releases may also have escaped detection by the monitoring stations or samplers. Nonetheless, there is confidence in the monitoring results given, for example, the dominant wind conditions during the monitoring period, the location of the mobile unit, the detection of pollutant spikes and the sensitivity of the real-time monitors.

A general limitation regarding data collection was the periodic presence of a field technician during Phase II. Owing to the remoteness of the monitoring site, staff availability, as well as technological,

economic and logistical constraints, a first-hand account could not be collected at all times during Phase II to observe and detail all activities that could potentially influence air pollutant concentrations. Further, a detailed inventory of all equipment, vehicle and products used during Phase II was not available. Although the daily activity reports provided by Corridor Resources Inc. (see Appendix C) are very useful, they list only the general daily events, such as “trip pipe,” “run casing” and “reaming,” and do not detail the number and type of equipment or vehicles being used, or the energy (e.g., diesel fuel consumption) required to complete the tasks. Having the necessary resources to increase the presence of a technician for extended periods of time would allow for relevant observations to support some of the fluctuations in air pollutant concentrations. Additional information regarding equipment and activities on the well pad could also provide more insight on specific interventions correlated with increases in air pollutant levels.

4.2 Sources and fate of pollution

It was observed that air pollutant concentrations are generally higher during periods of intense well pad activity compared to normal or less intensive conditions. Pollutant concentrations are also generally higher at downwind locations compared to upwind or remote locations. These observations provide reliable evidence that activities conducted on the well pad influenced pollutant concentrations at the sampling locations. Nevertheless, caution is advised when comparing results among sampling locations, especially in relative terms. High relative differences can reflect very small variations in absolute terms, and further evidence, such as corresponding variations in other pollutants, is necessary to clarify the potential causes of increases in pollutant levels.

Low concentrations may also limit inter-phase comparisons. This was exemplified in the Interim Report 02 (Health Canada 2015), which showed that several pollutants were measured at higher concentrations at the baseline site compared to the natural gas processing and distribution site, even though the latter was a much more active site in terms of industrial operations and vehicle traffic.

An estimate of emission rates was not possible owing to limited information about the vertical extent of the emission plume from the well pad or other sources nearby; therefore, only ground level concentrations close to the well pad are discussed. This is a common limitation of monitoring studies near well pads because of the numerous point sources across the site and the intermittent nature of onsite activities (Warneke et al. 2014). It is possible that the high concentration segments of the pollution plume were missed by the monitors. Nonetheless, dispersion modelling simulations conducted by Stantec prior to the expansion of the well pad showed that the maximum predicted ground level concentrations would be 100 meters downwind from the source (Stantec 2014), which corresponded to the location of the mobile monitoring unit. Further, peaks in NOx concentrations and other pollutants were measured during the well pad activities, indicating that emissions from the well pad were captured by the monitoring equipment.

Although pollutants are expected to vary with distance from the well pad, it is generally not feasible to deploy continuous monitoring equipment at several sites. Air pollutants may react in the atmosphere and lead to spatial heterogeneity in terms of ambient concentrations. Atmospheric transport and dilution may also influence ambient pollutant levels. For example, NO measurements exceeded 300 ppb

at the downwind location in mid-July 2014, while NO_2 reached 44–55 ppb. As NO rapidly converts to NO_2 in the atmosphere, it is uncertain if the NO measured at the downwind location led to higher NO_2 levels further downwind. Additional air quality measurements or modelling would be required to assess the fate and transport of NOx and other pollutants.

Considerations must be given to the fact that integrated samples and continuous measurements do not explicitly capture local activities—in this case, natural gas operations—but reflect community-wide exposures to all likely sources of pollutants. Beyond the local effects of individual wells or facilities, the regional scale also needs to be considered. Larger spatial considerations integrate emissions from multiple sources (e.g. PotashCorp facility, agricultural activities, town of Sussex) and reflect the cumulative air quality impacts. Sorting out sources and allocating effects to individual sources are challenging tasks that were beyond the scope of this report.

4.3 Scope and analyses

The geographic scope of this study is both an interesting feature and a limitation. The study was conducted in a geographic range (i.e. Kings County, New Brunswick) not covered in previous air quality reports associated with unconventional gas development. The results of this study are considered informative about potential air quality concerns associated with shale gas activities in Kings County, New Brunswick. However, in light of the increasing scientific literature on the environmental and human health impacts of unconventional oil and gas development, large differences may be observed among natural gas regions and even within a given area. In addition to geographical, meteorological and geological considerations, the variability in operational conditions and industry practices may lead to significant differences among similarly designed wells. Thus, although the study has the potential to highlight possible air quality impacts that could be relevant to other regions or jurisdictions, additional air monitoring and analyses are considered necessary to further characterize impacts in New Brunswick or to characterize air quality impacts in other shale gas producing regions.

The scope of the study design was geographically limited and covered a single hydraulic fracturing event. It is uncertain if well E-67B and well pad F-67 are representative of wells across the McCully Field and other natural gas areas in New Brunswick, or if the activities conducted during the monitoring period are representative of those conducted at other well sites. Several factors may influence the release, dispersion and fate of air pollutants from natural gas activities and their impact on air quality. For example, Eapi et al. (2014) surveyed CH_4 and H_2S at nearly 4 800 wells on 400 lease sites in the Barnett Shale Fort Worth Basin in Texas using a mobile measurement approach. They found that measured concentrations did not correlate with site characteristics, such as gas production volumes or number of wells. Warneke et al. (2014) also reported large differences in emissions or ambient concentrations near natural gas wells located in the same geographical area. Large differences have even been observed among very similar wells. Industry practices and techniques appear to have considerable influence (Warneke et al. 2014). As many variables were not considered in detail for this study, additional data analysis and air monitoring efforts are required prior to extrapolating the results from this study to other wells or shale gas plays. Additional data are also required to assess the cumulative impacts of multiple well sites across the McCully Field and other natural gas plays.

Well E-67B was stimulated with LPG. Although this fluid is common in the McCully Field, LPG is not widely used in other unconventional gas plays. Air quality data associated with shale gas operations using LPG are not readily available for other shale plays in Canada. Operators more commonly depend on water-based fluids for hydraulic fracturation, which involves a different series of well pad activities. Air monitoring data for well stimulation events using water-based fluids are not available in New Brunswick. Further, the well did not include a horizontal leg and a relatively small volume of fluid was required for the fracturing stage (600 m^3 of LPG compared to high volume water-based hydraulic fracturing events that can require up to 20 000 m^3 of water; CCA 2014). As unconventional gas exploration is currently limited in New Brunswick, and owing to the current provincial moratorium on hydraulic fracturing, it is not possible to conduct further air monitoring of shale gas development. Consequently, there is uncertainty regarding the representativeness of this monitored event for New Brunswick and potential extrapolations to other unconventional gas development scenarios across Canada.

Finally, although analyses and conclusions included herein are considered valid, it must be noted that the data described in Report 03 may be subjected to additional analyses. Thorough statistical analyses of the data may reveal associations among pollutants that are not discernible based on the descriptive analysis approach adopted in this report.

5. Conclusions

The overall objective of the New Brunswick Shale Gas Air Monitoring Study was to collect information in order to characterise the potential impacts on air quality associated with air emissions from shale gas development and operations. This type of information is not readily available and is required for health impact assessments of unconventional oil and gas development. The study consisted of four air monitoring phases that represented the different stages of shale gas development as best as possible: Phase I – baseline conditions prior to any development; Phase II – well development and gas production; Phase III – natural gas processing and distribution; and Phase IV – well closure. As it was not feasible to monitor air pollutant levels during all phases at a single site, a different site was selected to investigate each phase. All sites were located near Sussex, New Brunswick, within the Kennebecasis River valley, and it was expected that the overall air monitoring would be representative of the life cycle impacts of an individual well or installation in that area.

This report summarizes results from Phase II of the study, and covers natural gas production activities conducted at a single well pad from June 2014 to March 2015. The monitoring data include continuous measurements and integrated samples collected during Phase II. The analysis approach is similar to the one adopted for Interim Reports 01 and 02 (Health Canada 2014, 2015) and aims to identify major trends in ambient pollutant concentrations associated with well pad activities during well completion operations, including a hydraulic fracturing event, compared to baseline conditions.

The Phase II monitoring data indicate that air pollutant concentrations can vary depending on several factors. Activities from a single well pad did not necessarily affect ambient levels of CO, O_3 and SO_2. By contrast, CH_4, NOx, PAH, $PM_{2.5}$ and VOC concentrations were influenced by well pad activities. During

Phase II, concentrations of CH_4, NOx, $PM_{2.5}$ and subsets of PAHs and VOCs increased intermittently during specific periods that corresponded to intensive operations, such as drilling, hydraulic fracturing, snubbing, venting and flow testing. In general, the spikes in the time series were of short duration and ambient pollutant levels quickly returned to normal or baseline values. For PAHs and VOCs, subsets of these pollutant families were shown to vary in association with well pad activities, whereas other species were unaffected.

Overall, the analyses show that pollutant concentrations during Phase II were lower than ambient air quality standards adopted in New Brunswick or in other Canadian jurisdictions. Therefore, the results from the current study suggest that air pollutants did not reach levels that are of concern to environmental and human health, or that would trigger mitigation measures to improve air quality. However, measurable air quality impacts were observed and, importantly, the study design did not account for potential cumulative impacts from the development of multiple wells in the area. Further, air quality standards were not reviewed or assessed during this study. The rationale or approach used to define air quality standards may vary among pollutants and jurisdictions, depending on the endpoint or the intent of the standard. Thus, some air quality standards may not be the most relevant for an assessment of population health impacts from air pollution.

The study was conducted in a geographic range not covered in previous air quality reports. Many parameters of well development and hydraulic fracturing operations may influence air pollutant emissions and their impact on ambient concentrations. Environmental parameters are also important to consider. Meteorological conditions (e.g., wind speed, wind direction and mixing height) and equipment or valve maintenance programs, for example, may have a greater impact on ambient pollutant concentrations than well site parameters, thus obscuring any association. The hydraulic fracturing event during Phase II was planned and conducted by the operator based on technological and site-specific considerations (e.g., geological features and available equipment) and constraints. Owing to the limited number of wells that have been hydraulically fractured in New Brunswick, as well as the current provincial moratorium on hydraulic fracturing, it is difficult to assess the representativeness of the monitored event. Further, it is not recommended to extrapolate the results to other unconventional gas development scenarios in New Brunswick. Hence, the potential cumulative impacts of a play-wide development cannot be ascertained. Although the study has the potential to indicate possible human health-related concerns associated with air quality that could be transferable to other jurisdictions, additional data analysis and potentially air monitoring are considered necessary to extrapolate the results from this study to other shale gas plays.

Based on the study findings, comprehensive air monitoring is recommended near well pads in order to capture air pollutant releases from unconventional gas development and to accurately assess the air quality impacts. Owing to the intermittent and frequent releases of air pollutants during the different stages of well development, the monitoring period should include periods prior to, during and following drilling and well completion stages. Continuous monitors should also be selected, if feasible, along with integrated samples (e.g., 24 h samples, weekly samples), as appropriate for the targeted air pollutants. The monitoring approach should target NOx, PAH, $PM_{2.5}$ and VOC concentrations, if possible. Samples

and measurements should also be collected using validated methods for reliable comparisons with air quality standards and data from regional or national surveillance programs, such as NAPS in Canada.

It must be noted that the analyses in Report 03 reflect the data collected during the New Brunswick Shale Gas Air Monitoring Study. The conclusions from this report are considered the most reasonable based on the study findings and provide a reference for discussing air quality impacts associated with unconventional oil and gas development in New Brunswick and Canada. However, limitations and uncertainties remain. As such, the interpretations are subject to revision if new relevant data become available in the future.

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Appendix A: Phase II data

Tables

Table A1. Descriptive statistics for continuous data collected from June 20, 2014, to March 31, 2015, at location 21 (downwind) – Phase II

	CO – ppm	NO – ppb	NO_2 – ppb	NOx – ppb	O_3 – ppb	$PM_{2.5}$ – µg/m^3	SO_2 – ppb	TRS – ppb	TSP – µg/m^3
AQS	13/30		210		82 (63)	28	169.5	11[a]	120
AQS avg period	1 h		1 h		1 h (max 8 h)	24 h	1 h	1 h	24 h
Reference	NAAQO		NBAAQO		NAAQO (CAAQS)	CAAQS	NBAAQO	NBAAQO	NBAAQO
Avg sampling frequency	5 min	5 min	5 min	5 min	5 min	1 h	5 min	5 min	1 h
Avg period for stats	1 h	1 h	1 h	1 h	1 h (max 8 h)	24 h	1 h	1 h	24 h
Mean	0.2	4.8	2.0	6.7	25.7 (32.8)	4.8	0.1	0.1	7.1
Median	0.2	0.1	0.7	0.9	27.1 (32.8)	4.1	< 0.1	0.1	5.6
Minimum / maximum	0 / 0.6	0 / 350.0	0 / 64.3	0 / 375.7	0.1 / 58.0 (8.5 / 52.9)	0.5 / 18.5	0 / 1.9	0 / 1.1	1.6 / 26
5^{th} / 95^{th} percentiles	0.1 / 0.3	< 0.1 / 11.9	0 / 7.4	0 / 17.6	4.3 / 42.3 (21.6 / 45.8)	1.5 / 10.9	0 / 0.4	0 / 0.3	2.7 / 14.7
98^{th} percentile	0.3	61.9	13.9	75.8	45.8 (48.4)	12.2	0.6	0.4	17.7
No. of AQS exceedances	0	n.a.	0	n.a.	0	0	0	0	0
No. of sampling days	275	275	275	275	275	275	275	275	275
No. of measurements[b]	78 912	78 912	78 912	78 912	78 912	6576	78 912	78 912	6576
No. of valid measurements	77 791	78 046	77 055	78 193	77 958	5462	77 981	77 682	3844
% valid measurements	98.6	98.9	97.6	99.1	98.8	83.1	98.8	98.4	58.5

AQS: air quality standard; avg: averaging/average; CAAQS: Canadian Ambient Air Quality Standards; µg/m^3: micrograms per cubic metre; min: minutes; n.a.: not applicable; NAAQO: National Ambient Air Quality Objective; NBAAQO: New Brunswick Ambient Air Quality Objective; ppb: parts per billion; ppm: parts per million; TRS: total reduced sulphur; TSP: total suspended particulates

Notes: Values are based on the duration indicated in the *Avg period for stats* row; averaging periods are fixed, except for O_3, which is based on an 8 h rolling average for comparison with the CAAQS. For CO, 13 ppm is the maximum desirable level and 30 ppm is the maximum acceptable level. Mean, median, minimum/maximum and percentile values are in the same units as the AQS. Concentrations rounded to one decimal point. Non-zero values less than 0.1 are shown as < 0.1. For O_3 maximum 8 h average, the CAAQS is based on the three-year rolling average of the fourth highest daily maximum 8 h average in each year; for $PM_{2.5}$ daily average, the CAAQS is based on the three-year rolling average of 98^{th} percentile daily average value in each year.

[a] A NBAAQO of 11 ppb exists for H_2S. For comparative purposes, the TRS value is considered equivalent to H_2S.

[b] Includes valid, invalid and missing measurements for the number of sampling days considered.

Table A2. Descriptive statistics for continuous data collected from June 24, 2014, to November 12, 2014, at location 22 (upwind) – Phase II

	CO – ppm	NO – ppb	NO_2 – ppb	NO_X – ppb	O_3 – ppb	$PM_{2.5}$ – µg/m^3	SO_2 – ppb	H_2S – ppb
AQS	13/30		210		82 (63)	28	169.5	11
AQS avg period	1 h		1 h		1 h (max 8 h)	24 h	1 h	1 h
Reference	NAAQO		NBAAQO		NAAQO (CAAQS)	CAAQS	NBAAQO	NBAAQO
Avg sampling frequency	5 min	5 min	5 min	5 min	5 min	1 h	5 min	5 min
Avg period for stats	1 h	1 h	1 h	1 h	1 h (max 8 h)	24 h	1 h	1 h
Mean	0.1	1.1	1.1	2.2	23.4 (23.5)	5.0	0.1	0.1
Median	0.1	0.3	0.7	1.0	24.8 (23.5)	4.7	< 0.1	< 0.1
Minimum / maximum	0 / 2.2	< 0.1 / 33.5	0 / 15.0	< 0.1 / 45.2	0.3 / 61.3 (1.0 / 53.0)	0 / 14.9	0 / 0.8	0 / 2.5
5^{th} / 95^{th} percentiles	< 0.1 / 0.25	0.1 / 5.3	< 0.1 / 3.5	0.2 / 8.4	1.7 / 44.5 (4.4 / 42.2)	1.8 / 8.3	0 / 0.3	0 / 0.2
98^{th} percentile	0.4	10.2	5.2	14.5	48.5 (46.6)	9.3	0.4	0.3
No. of AQS exceedances	0	0	0	0	0	0	0	0
No. of sampling days	51	142	142	142	58	142	128	128
No. of measurements[a]	1240	3385	3385	3385	1404	3385	3385	3385
No. of valid measurements	902	2984	2984	2984	1327	3374	2936	2905
% valid measurements	72.7	88.2	88.2	88.2	94.5	99.7	86.7	85.8

AQS: air quality standard; avg: averaging/average; CAAQS: Canadian Ambient Air Quality Standards; µg/m^3: micrograms per cubic metre; min: minutes; n.a.: not applicable; NAAQO: National Ambient Air Quality Objective; NBAAQO: New Brunswick Ambient Air Quality Objective; ppb: parts per billion; ppm: parts per million

Notes: Values are based on the duration indicated in the *Avg period for stats* row; averaging periods are fixed, except for O_3, which is based on an 8 h rolling average for comparison with the CAAQS. For CO, 13 ppm is the maximum desirable level and 30 ppm is the maximum acceptable level. Mean, median, minimum/maximum and percentile values are in the same units as the AQS. Concentrations rounded to one decimal point. Non-zero values less than 0.1 are shown as < 0.1. For O_3 maximum 8 h average, the CAAQS is based on the three-year rolling average of the fourth highest daily maximum 8 h average in each year; for $PM_{2.5}$ daily average, the CAAQS is based on the three-year rolling average of 98^{th} percentile daily average value in each year.

[a] Includes valid, invalid and missing measurements for the number of sampling days considered.

Table A3. Gravimetric analysis of $PM_{2.5}$ based on Teflon filters collected using a Partisol 2300 Chemcomb sampling system between July 22 and October 3, 2014, at location 21 during Phase II

Parameter – unit	Minimum	5th percentile	Median	Mean	95th percentile	Maximum
$PM_{2.5}$ – µg/m^3	0.14	0.66	6.29	6.55	14.26	16.32

µg/m^3: micrograms per cubic metre

Notes: 24 h samples; 29 samples (27 valid; 2 invalid owing to miscellaneous problems); data available for 27 samples; data were blank-corrected; $PM_{2.5}$ mass values below the detection limit (i.e. 4 µg) were substituted by a value equivalent to half the detection limit to calculate concentrations, from which descriptive statistics were calculated; concentrations in µg/m^3 are rounded to two decimal points.

Table A4. Galactosan, levoglucosan and mannitol concentrations based on Teflon filters collected between July 22 and October 3, 2014, at location 21 during Phase II

Parameter – unit	Minimum	5th percentile	Median	Mean	95th percentile	Maximum
$PM_{2.5}$ – µg/m^3	1.12	1.12	8.10	7.22	16.32	16.32
Galactosan – ng/m^3	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
Levoglucosan – ng/m^3	< 0.01	< 0.01	< 0.01	5.40	24.46	24.46
Mannitol – ng/m^3	< 0.01	< 0.01	7.07	7.12	15.27	15.27

µg/m^3: micrograms per cubic metre; ng/m^3: nanogram per cubic metre

Notes: 24 h samples; 14 samples (13 valid; 1 invalid owing to miscellaneous problems); data available for 13 samples; data were blank-corrected; $PM_{2.5}$ mass values below the detection limit (i.e. 4 µg) were substituted by a value equivalent to half the detection limit to calculate concentrations, from which descriptive statistics were calculated; for galactosan, levoglucosan and mannitol, negative mass values and data below detection limits were included as such and were not substituted with below detection limit indicators when estimating the descriptive statistics; concentrations below 0.01 ng/m^3 are expressed as < 0.01 ng/m^3; concentrations in µg/m^3 or ng/m^3 are rounded to two decimal points.

Table A5. Concentration of $PM_{2.5}$–bound metals based on ICPMS analysis of Teflon filters collected between July 22 and October 3, 2014, at location 21 during Phase II

Parameter	Concentration – ng/m^3			
	Minimum	Median	Mean	Maximum
Ag	< 0.01	0.01	0.01	0.03
Al	10.6	48.3	63.5	217.1
As	0.04	0.14	0.15	0.45
Ba	0.10	0.64	0.77	2.17
Be	< 0.01	< 0.01	< 0.01	< 0.01
Bi	< 0.01	0.01	0.01	0.04
Ca	3.47	24.6	34.3	80.2
Cd	0.01	0.02	0.03	0.15
Co	0.01	0.03	0.03	0.06
Cr	0.02	1.44	1.34	3.54
Cu	0.02	0.34	0.54	1.79
Fe	4.02	16.0	21.5	51.4
Hg	< 0.01	< 0.01	< 0.01	< 0.01
K	7.64	25.3	27.3	50.8
Li	0.02	0.54	0.67	1.52
Mg	3.52	9.16	12.0	31.4
Mn	0.10	0.40	0.49	1.14
Mo	0.01	0.04	0.06	0.26
Na	23.1	51.4	77.2	214.4
Ni	0.01	0.37	0.42	1.42
Pb	0.10	0.36	0.38	0.82
Sb	0.02	0.09	0.12	0.48
Si	90.0	308.9	322.8	645.8
Sn	0.03	0.14	0.15	0.37
Sr	0.03	0.12	0.15	0.58
Th	< 0.01	< 0.01	< 0.01	0.01
Ti	0.14	0.94	1.97	13.7
Tl	< 0.01	< 0.01	< 0.01	0.01
U	< 0.01	< 0.01	< 0.01	0.01
V	0.05	0.27	0.31	1.44
Zn	0.83	4.18	4.63	9.05
$PM_{2.5}$ (µg/m^3)	0.14	6.07	5.92	14.3

µg/m^3: micrograms per cubic metre; ng/m^3: nanogram per cubic metre

Notes: 24 h samples; 14 samples (all valid); data available for 14 samples; data were blank-corrected; on average, metals measured via ICPMS accounted for approximately 9.6% of $PM_{2.5}$ concentration; $PM_{2.5}$ mass values below the detection limit (i.e. 4 µg) were substituted by a value equivalent to half the detection limit to calculate concentrations, from which descriptive statistics were calculated; metal mass values below their respective detection limits were substituted by a value equivalent to half the detection limit to calculate concentrations, from which descriptive statistics were calculated; concentrations in ng/m^3 are rounded to two decimal points, except for values of 10 ng/m^3 or higher, which are rounded to one decimal point; negative concentrations and those below 0.01 ng/m^3 are expressed as < 0.01 ng/m^3. Full names of metals are included in Table B5 of Appendix B.

Table A6. Elemental and organic carbon measurements from quartz filter samples collected between July 22 and October 3, 2014, at location 21 during Phase II

Parameter	Minimum	5th percentile	Median	Mean	95th percentile	Maximum
Elemental carbon – µg/m^3	0	0	0.29	0.41	2.01	2.01
Organic carbon – µg/m^3	0.81	0.81	2.17	2.47	4.56	4.56
Total carbon – µg/m^3	0.89	0.89	2.48	2.87	6.18	6.18
EC/TC concentration ratio	0	0.01	0.09	0.11	0.24	0.32
OC/EC concentration ratio	2.08	2.08	9.73	13.65	52.30	52.30
OC/TC concentration ratio	0.68	0.76	0.91	0.89	0.99	1.00

EC: elemental carbon; µg/m^3: micrograms per cubic metre; OC: organic carbon; TC: total carbon
Notes: 24 h samples; 14 samples (all valid); data available for 14 samples; data were blank-corrected; concentration values in µg/m^3 are rounded to two decimal points; ratios are rounded to two decimal points; mass values below detection limits were included as such and were not substituted with below detection limit indicators when calculating concentrations and descriptive statistics.

Table A7. Concentration of volatile organic compounds based on AMA GC/FID continuous measurements, from July 11, 2014, to February 9, 2015, collected at location 21 during Phase II

VOC code	VOC name	Carbon number	Concentration in µg/m^3			Maximum-to-Median ratio
			Median	Mean	Maximum	
V6	1,2,3-Trimethylbenzene	9	0.03	0.08	3.10	103
V8	1,2,4-Trimethylbenzene	9	0	0.01	0.69	–
V14	1,3,5-Trimethylbenzene	9	0	0.02	0.36	–
V17	m-Diethylbenzene	10	0	0.00	0.25	–
V18	p-Diethylbenzen	10	0	0.01	0.24	–
V22	1-Butene	4	0.02	0.02	1.29	65
V26	1-Hexene	6	0	0.00	0.58	–
V31	1-Pentene	5	0.01	0.03	5.72	572
V34	2,2,4-Trimethylpentane	8	0.01	0.02	1.15	115
V36	2,2-Dimethylbutane	6	0.15	0.26	1.36	9
V40	2,3,4-Trimethylpentane	8	0	0.01	0.91	–
V41	2,3-Dimethylbutane	6	0.01	0.09	16.48	1 648
V42	2,3-Dimethylpentane	6	0	0.01	3.01	–
V44	2,4-Dimethylpentane	6	0.01	0.02	5.59	559
V49	o-Ethyltoluene	9	0.01	0.03	0.45	45
V55	2-Methylheptane	8	0	0.01	3.96	–
V56	2-Methylhexane	7	0.01	0.03	8.89	889
V57	2-Methylpentane	6	0.01	1.33	895.63	89 563
V61	m-Ethyltoluene	9	0.01	0.05	1.47	147
V64	3-Methylheptane	8	0	0.01	3.45	–
V65	3-Methylhexane	7	0.02	0.06	10.47	524
V66	3-Methylpentane	6	0.01	0.03	5.96	596
V67	p-Ethyltoluene	9	0.03	0.06	0.60	20

VOC code	VOC name	Carbon number	Concentration in µg/m^3			Maximum-to-Median ratio
			Median	Mean	Maximum	
V73	Acetylene	2	0.34	0.54	20.86	61
V78	Benzene	6	0.1	0.12	1.11	11
V85	n-Butane	4	0.3	0.37	4.60	15
V93	cis-2-Butene	4	0	0.06	13.54	–
V96	cis-2-Pentene	5	0	0.10	4.02	–
V108	Cyclohexane	6	0	0.01	3.30	–
V111	Cyclopentane	5	0.01	0.02	0.32	32
V114	n-Decane	10	0	0.01	0.98	–
V119	Ethane	2	2.08	2.97	118.06	57
V122	Ethylbenzene	8	0.01	0.01	0.43	43
V131	n-Heptane	7	0.02	0.05	16.29	815
V135	n-Hexane	6	0.04	0.08	20.69	517
V138	i-Butane	4	0.17	0.21	5.89	35
V142	Isoprene	5	0.03	0.15	4.50	150
V145	i-Propylbenzene	9	0	0.00	0.15	–
V147	m- & p-Xylene	8	0.01	0.03	1.92	192
V152	Methylcyclohexane	7	0.01	0.02	6.00	600
V153	Methylcyclopentane	6	0.01	0.21	17.99	1 799
V159	n-Nonane	9	0	0.02	1.75	–
V161	n-Propylbenzene	9	0	0.01	0.24	–
V162	n-Octane	8	0.01	0.02	6.54	654
V163	o-Xylene	8	0.01	0.01	0.46	46
V166	n-Pentane	5	0.11	0.13	8.02	73
V167	Propane	3	1.07	2.92	105.83	99
V168	Propene	3	0.06	0.10	5.68	95
V173	Styrene	8	0.01	0.03	0.30	30
V178	trans-2-Butene	4	0.01	0.01	1.87	187
V182	trans-2-Pentene	5	0.01	0.02	0.41	41
V188	Toluene	7	0.06	0.08	1.65	28
V190	n-Undecane	11	0.02	0.05	1.43	72
V214	Ethene	2	0.37	0.42	6.87	19
V215	i-Pentane	5	0.13	0.16	3.51	27

µg/m^3: micrograms per cubic metre

Notes: Samples every 90 minutes; 2829 measurements per VOC; concentration values in µg/m^3 are rounded to two decimal points. Ratios are rounded to unity.

Table A8. Mean concentration of volatile organic compounds based on OVM badge samples collected between July 16 and October 1, 2014, at locations 21–28 during Phase II (partial list)

VOC code	Location	21	22	23	24	25	26	27	28
	VOC name	Concentration in µg/m^3							
V34	2,2,4-Trimethylpentane	0.25	**0.53**	0.45	0.28	0.41	0.27	0.39	0.21
V55	2-Methylheptane	**0.09**	0.03	0.04	0.04	0.03	0.01	0.03	0.02
V56	2-Methylhexane	**0.15**	0.10	0.10	0.05	0.03	0.03	0.05	0.03
V76	a-Pinene	0.55	0.45	0.55	0.50	0.49	0.52	0.47	**0.63**
V78	Benzene	0.09	0.08	0.08	**0.11**	0.08	0.09	0.09	0.07
V102	Carbon tetrachloride	**0.60**	0.57	0.57	0.58	0.58	0.54	0.59	0.53
V114	Decane	**0.53**	0.38	0.47	0.47	0.40	0.42	0.52	0.45
V118	Dodecane	1.20	0.85	0.93	1.18	0.94	0.97	**1.58**	1.14
V131	Heptane	**0.25**	0.18	0.14	0.10	0.06	0.06	0.08	0.07
V135	Hexane	**0.13**	0.05	0.08	0.07	0.05	0.04	0.06	0.04
V147	m- & p-Xylene	**0.14**	0.12	0.13	0.13	0.13	0.11	0.12	0.12
V157	Naphthalene	0.14	0.16	0.13	**0.30**	0.22	0.12	0.12	0.13
V162	Octane	**0.16**	0.08	0.11	0.10	0.06	0.06	0.08	0.06
V166	n-Pentane	**0.16**	0.09	0.11	0.12	0.08	0.06	0.11	0.05
V188	Toluene	0.09	0.09	0.10	**0.13**	0.09	0.05	0.08	0.08
V211	Hexadecane	0.34	0.26	0.34	**0.37**	0.31	0.31	0.27	0.28
V212	Tetradecane	1.16	0.96	1.15	**1.31**	1.07	1.14	1.24	1.15

µg/m^3: micrograms per cubic metre

Notes: 6–7 day samples; 8 sampling locations; 11 samples per location (all valid; total of 88 samples); data available for 88 samples; data were blank-corrected; negative values and data below detection limits were included as such and were not substituted with below detection limit indicators when estimating the descriptive statistics; concentrations in µg/m^3 are rounded to two decimal points. Bolded values represent locations with highest mean for each pollutant.

Table A9. Concentration of volatile organic compounds based on Summa canister samples collected between July 26 and October 2, 2014, at locations 21 and 22 during Phase II

VOC code	VOC name	Location 21			Location 22		
		Concentration in µg/m^3					
		Median	Mean	Max	Median	Mean	Max
V42	2,3-Dimethylpentane	0.03	0.16	1.92	0.02	0.11	0.58
V53	2-Methylbutane	0.19	0.45	2.66	0.27	0.28	0.53
V55	2-Methylheptane	0.02	0.19	2.61	0.01	0.01	0.02
V56	2-Methylhexane	0.05	0.51	6.45	0.03	0.29	1.63
V57	2-Methylpentane	0.06	0.35	4.33	0.05	0.05	0.11
V64	3-Methylheptane	0.01	0.15	1.99	0.01	0.01	0.02
V65	3-Methylhexane	0.06	0.55	6.74	0.03	0.44	2.53
V66	3-Methylpentane	0.04	0.25	3.08	0.04	0.04	0.08
V76	α-Pinene	0.56	0.75	2.22	0.41	0.42	0.77
V78	Benzene	0.14	0.18	0.65	0.16	0.16	0.19
V85	n-Butane	0.33	0.65	2.99	0.48	0.44	0.75
V106	Chloromethane	1.27	1.25	1.43	1.31	1.32	1.55
V108	Cyclohexane	0.02	0.12	1.53	0.01	0.02	0.03
V119	Ethane	1.81	2.93	10.67	2.39	2.96	7.29
V126	Freon 11	1.41	1.46	1.63	1.49	1.49	1.53
V127	Freon 113	0.67	0.67	0.75	0.63	0.63	0.66
V129	Freon 12	2.70	2.71	2.96	2.75	2.74	2.86
V130	Freon 22	0.76	0.76	0.86	0.89	4.51	22.77
V131	Heptane	0.08	0.99	13.25	0.05	0.49	2.70
V135	Hexane	0.07	0.89	12.10	0.06	0.07	0.15
V138	i-butane	0.32	0.49	2.73	0.20	0.20	0.42
V142	Isoprene	0.86	0.94	2.28	1.08	0.93	1.79
V152	Methylcyclohexane	0.03	0.23	2.97	0.01	0.04	0.17
V159	Nonane	0.05	0.19	1.78	0.02	0.02	0.03
V162	Octane	0.04	0.39	5.11	0.02	0.02	0.03
V166	n-Pentane	0.20	0.55	5.31	0.31	0.29	0.53
V167	Propane	2.30	28.19	280.14	1.88	1.99	4.89
V188	Toluene	0.19	0.23	0.96	0.19	0.22	0.42
V209	Freon 134A	0.39	0.40	0.50	0.41	0.50	0.99

µg/m^3: micrograms per cubic metre

Notes: 24 h samples; 16 samples at location 21 (1 invalid owing to sample duration) and 6 samples at location 22 (1 missing); data available for 20 samples; data were blank-corrected; concentrations in µg/m^3 are rounded to two decimal points.

Table A10. Concentration of polycyclic aromatic hydrocarbons based on samples collected with a modified high-volume sampler between July 28 and September 26, 2014, at location 21 during Phase II

PAH code	PAH name	Concentration in ng/m^3		
		Median	Mean	Maximum
PAH1	**Naphthalene**	0.49	0.70	1.87
PAH2	**Acenaphthylene**	0.07	0.12	0.32
PAH3	**Acenaphthene**	1.64	1.63	3.33
PAH4	**Fluorene**	2.71	2.95	7.89
PAH5	**Phenanthrene**	8.63	9.25	21.52
PAH6	**Anthracene**	0.31	0.37	0.81
PAH7	**Fluoranthene**	1.29	1.37	3.72
PAH8	**Pyrene**	0.68	0.85	3.59
PAH10	**Chrysene**	0.02	0.03	0.08
PAH11	**Benzo(b)fluoranthene**	0.01	0.02	0.08
PAH12	**Benzo(k)fluoranthene**	0.01	0.01	0.03
PAH13	**Benzo(a)pyrene**	< 0.01	0.01	0.03
PAH14	**Indeno(1.2.3-cd)pyrene**	0.01	0.02	0.09
PAH15	**Dibenzo(ah)anthracene**	< 0.01	< 0.01	0.02
PAH16	**Benzo(ghi)perylene**	0.01	0.03	0.18
PAH21	**Benzo(a)anthracene**	0.02	0.02	0.04
PAH24	Benzo(b)chrysene	< 0.01	< 0.01	0.02
PAH27	Benzo(e)pyrene	0.01	0.02	0.08
PAH28	Benzo(ghi)fluoranthene	0.02	0.04	0.26
PAH44	Perylene	< 0.01	< 0.01	< 0.01
PAH46	Retene	0.06	0.08	0.24
PAH50	2-Methylfluorene	0.43	0.54	1.55
PAH51	Benzo(a)fluorene	0.01	0.02	0.05
PAH52	Benzo(b)fluorene	0.01	0.01	0.03
PAH53	1-Methylpyrene	0.02	0.04	0.15
PAH54	7-Methylbenz(a)anthracene	< 0.01	< 0.01	0.02
PAH55	3-Methylcholanthrene	< 0.01	< 0.01	0.01
PAH56	Indeno(1,2,3-cd)fluoranthene	< 0.01	< 0.01	0.02
PAH57	Anthanthrene	< 0.01	< 0.01	0.02
PAH58	Triphenylene	0.01	0.01	0.03

ng/m^3: nanograms per cubic metre

Notes: PAHs in bold have been identified as priority substances in Canada or the United States (e.g., Government of Canada et al. 1994; National Toxicology Program 2014); 24 h samples; 14 samples (12 valid; 2 invalid owing to sample duration); data available for 12 samples; data were not blank-corrected; negative values and data below detection limits were included as such and were not substituted with below detection limit indicators when estimating the descriptive statistics; concentrations in ng/m^3 are rounded to two decimal points; concentrations below 0.01 ng/m^3 are expressed as < 0.01 ng/m^3.

Table A11. Concentration of polycyclic aromatic hydrocarbons based on URG personal pesticide sampler samples collected between July 28 and October 2, 2014, at location 21 during Phase II

PAH code	PAH name	Concentration in ng/m^3			
		Minimum	Median	Mean	Maximum
PAH1	Naphthalene	0.95	3.27	3.79	7.87
PAH2	Acenaphthylene	0.02	0.18	0.30	0.91
PAH3	Acenaphthene	2.00	6.48	6.48	19.41
PAH4	Fluorene	2.25	7.30	8.08	19.58
PAH5	Phenanthrene	2.67	13.06	15.54	38.16
PAH6	Anthracene	0.25	1.30	1.50	4.22
PAH7	Fluoranthene	0.25	1.07	1.58	4.48
PAH8	Pyrene	0.21	0.96	1.26	4.83
PAH10	Chrysene	0.16	0.30	0.38	0.92
PAH11	Benzo(b)fluoranthene	0.02	0.05	0.06	0.24
PAH12	Benzo(k)fluoranthene	0.02	0.05	0.06	0.21
PAH13	Benzo(a)pyrene	0.01	0.02	0.02	0.03
PAH14	Indeno(1,2,3-cd)pyrene	0.01	0.02	0.02	0.03
PAH15	Dibenzo(a,h)anthracene	< 0.01	0.02	0.02	0.03
PAH16	Benzo(ghi)perylene	0.01	0.01	0.02	0.03
PAH21	Benzo(a)anthracene	0.22	0.41	0.48	1.10

ng/m^3: nanograms per cubic metre

Notes: All PAHs listed have been identified as priority substances in Canada or the United States (e.g., Environment Canada 2013; Government of Canada et al. 1994; National Toxicology Program 2014); 24 h samples; 14 samples (13 valid; 1 invalid owing to sample duration); data available for 13 samples; data were not blank-corrected; values below detection limits were included as such and were not substituted with below detection limit indicators when estimating the descriptive statistics; concentrations in ng/m^3 are rounded to two decimal points; concentrations below 0.01 ng/m^3 are expressed as < 0.01 ng/m^3.

Table A12. Concentration of carbonyl compounds based on Xonteck samplers collected at locations 21 (Phase II) between August 9 and October 2, 2014, and at the Phase I site between October 12, 2012, and June 27, 2013

Carbonyl name	Phase II Location 21			Phase I		
	Concentration in µg/m^3					
	Median	Mean	Max	Median	Mean	Max
Formaldehyde	1.462	1.489	3.042	0.330	0.388	1.371
Acetaldehyde	0.538	0.588	1.315	0.164	0.205	0.930
Acrolein	0.004	0.009	0.051	< 0.001	0.006	0.032
Acetone	1.162	1.277	2.377	1.462	1.468	2.888
Propionaldehyde	0.146	0.213	0.810	0.012	0.034	0.287
Crotonaldehyde	< 0.001	0.002	0.020	< 0.001	0.012	0.137
MEK/Butyraldehyde	0.096	0.130	0.410	0.127	0.129	0.435
Benzaldehyde	0.096	0.142	0.680	0.051	0.054	0.135
Isovaleraldehyde	0.009	0.010	0.024	< 0.001	0.002	0.015
2-Pentanone	0.040	0.051	0.159	0.033	0.036	0.118
Valeraldehyde	0.056	0.050	0.091	< 0.001	0.007	0.073
o-Tolualdehyde	0.005	0.010	0.025	< 0.001	0.009	0.275
m-Tolualdehyde	< 0.001	< 0.001	< 0.001	0.019	0.023	0.089
p-Tolualdehyde	0.218	0.218	0.314	0.018	0.026	0.204
MIBK	0.033	0.033	0.064	0.024	0.021	0.049
Hexanal	0.080	0.073	0.110	0.022	0.028	0.103
2,5-Dimethylbenzaldehyde	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001

MEK: methyl-ethyl ketone; MIBK: methyl isobutyl ketone; µg/m^3: micrograms per cubic metre

Notes: 24 h samples; 12 samples during Phase II (all valid); 43 samples during Phase I (42 valid; 1 ignored owing to low values [outlier]) data available for 54 samples; data were blank-corrected; negative values were replaced with zero when estimating the descriptive statistics; concentrations in µg/m^3 are rounded to three decimal points; concentrations below 0.001 µg/m^3 are expressed as < 0.001 µg/m^3.

Table A13. Methane concentration based on continuous monitoring with a Thermo Scientific IRIS 5500 methane analyzer between July 3, 2013, and March 31, 2015, at location 21 during Phase II

Monitoring period	Methane concentration in ppm		
	Median	Mean	Maximum
July 2014	1.94	2.02	67.05
August 2014	1.95	2.01	65.40
September 2014	1.96	2.02	7.25
October 2014	1.98	2.37	93.02
November 2014	1.99	2.10	69.59
December 2014	1.96	1.98	12.94
January 2015	1.98	2.00	30.39
February 2015	2.00	2.02	4.30
March 2015	2.03	2.05	35.63
July 2014–March 2015	**1.98**	**2.06**	**93.02**

Notes: Concentrations in ppm rounded to two decimal points

Figures

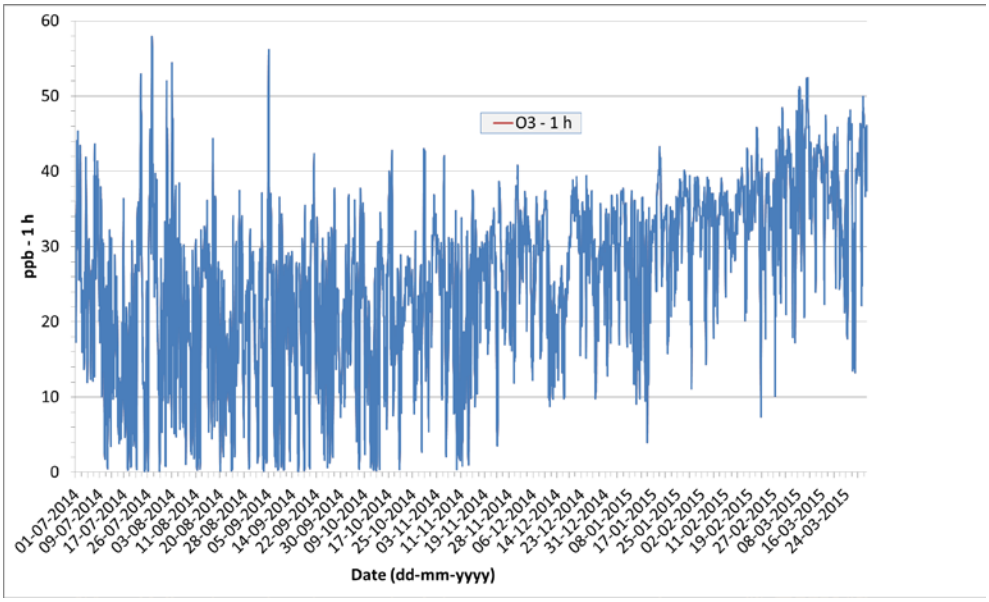

Figure A1. Hourly ozone concentrations recorded between July 2014 and March 2015 at location 21 during Phase II

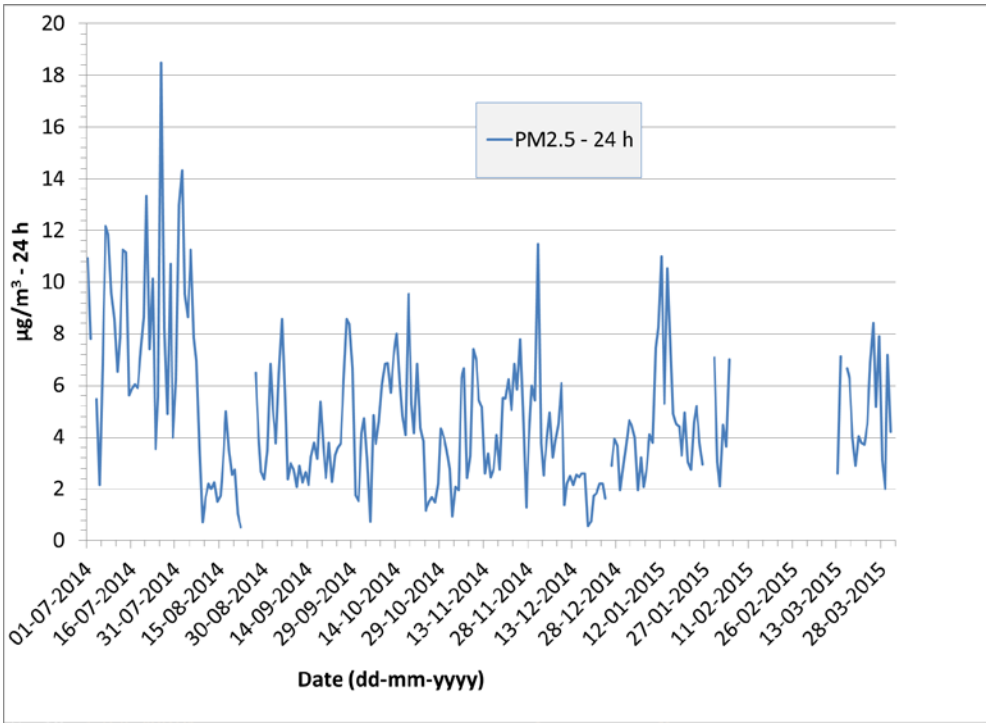

Figure A2. Daily mean fine particulate matter concentrations recorded between July 2014 and March 2015 at location 21 during Phase II

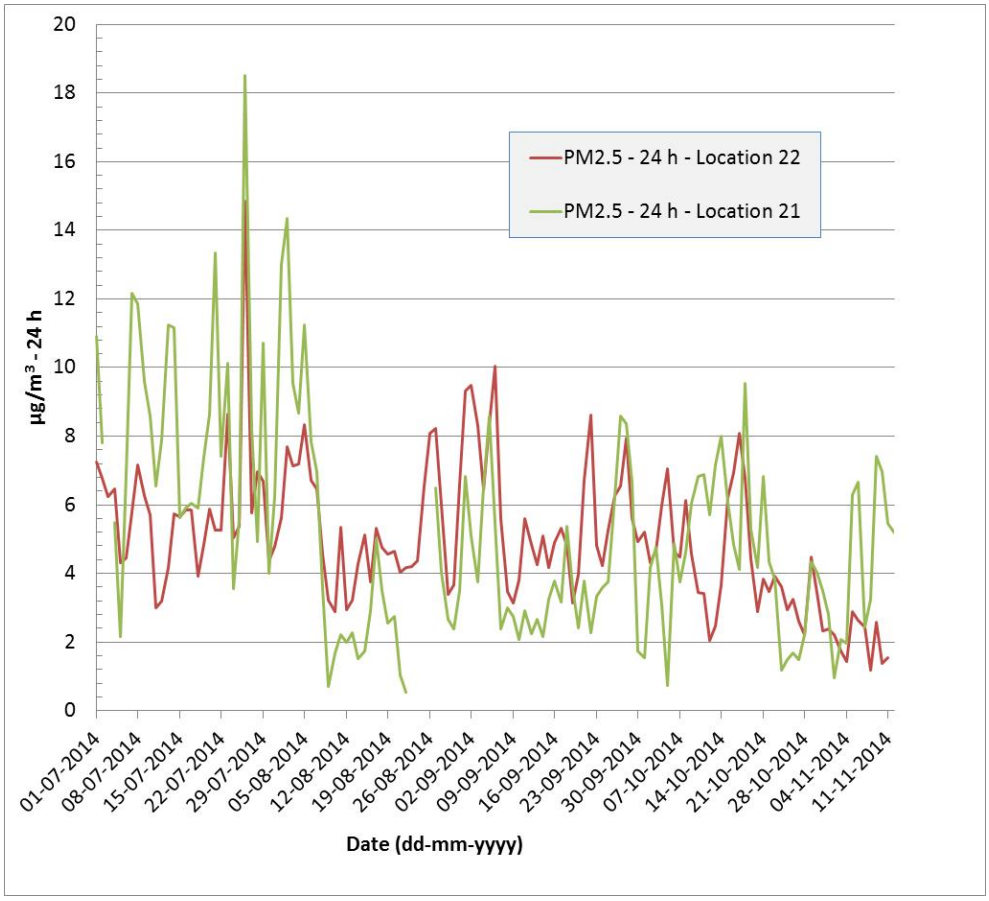

Figure A3. Daily mean fine particulate matter concentrations recorded from July 1 to November 11, 2014, at locations 21 and 22 during Phase II

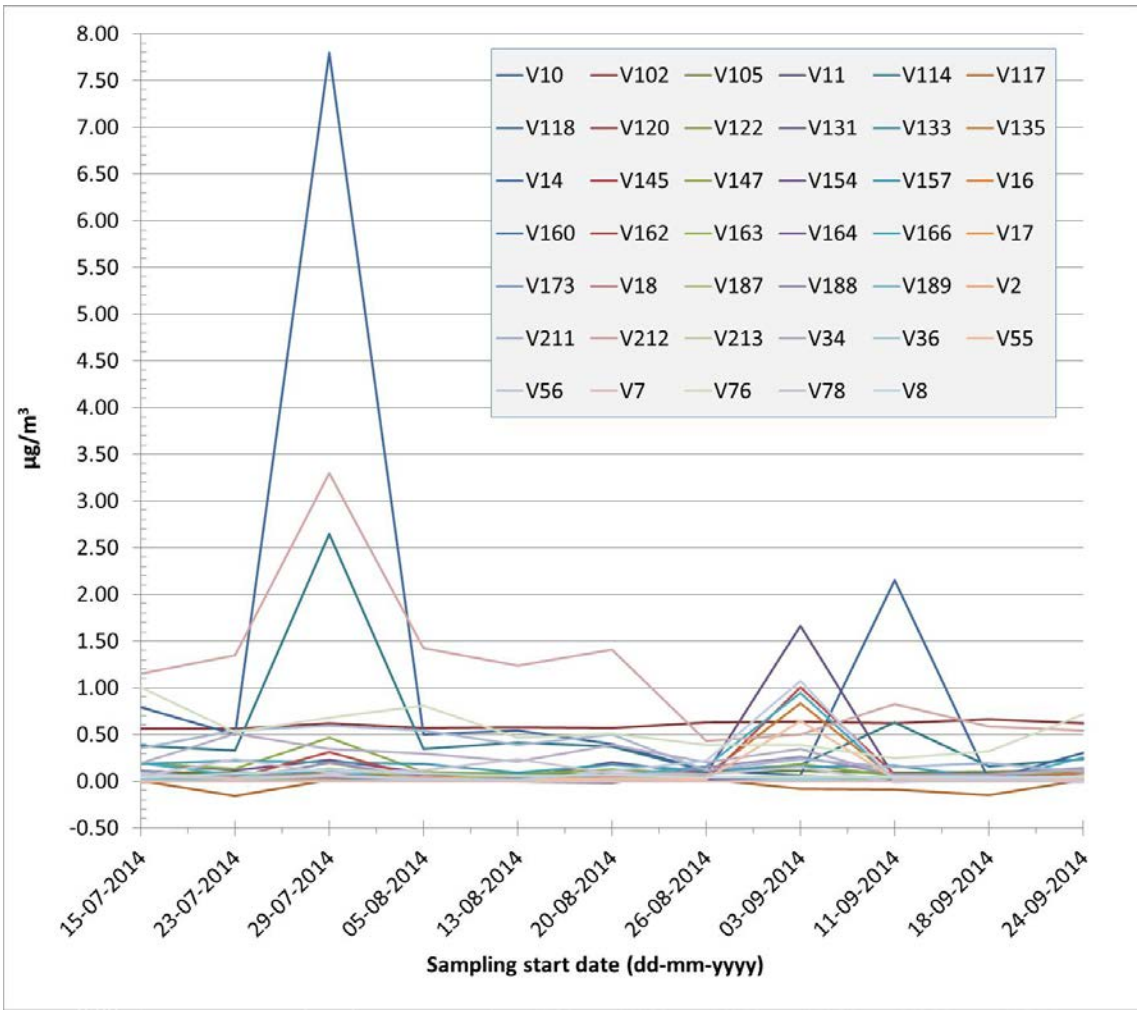

Figure A4. VOC concentrations based on weekly OVM samples collected between July 15 and October 1, 2014, at location 21 during Phase II

Note: The dates indicate when samples were deployed; sample exposure was 6–7 days. Full names of VOCs corresponding to *Vxxx* codes in the Legend box are included in Table B3 of Appendix B.

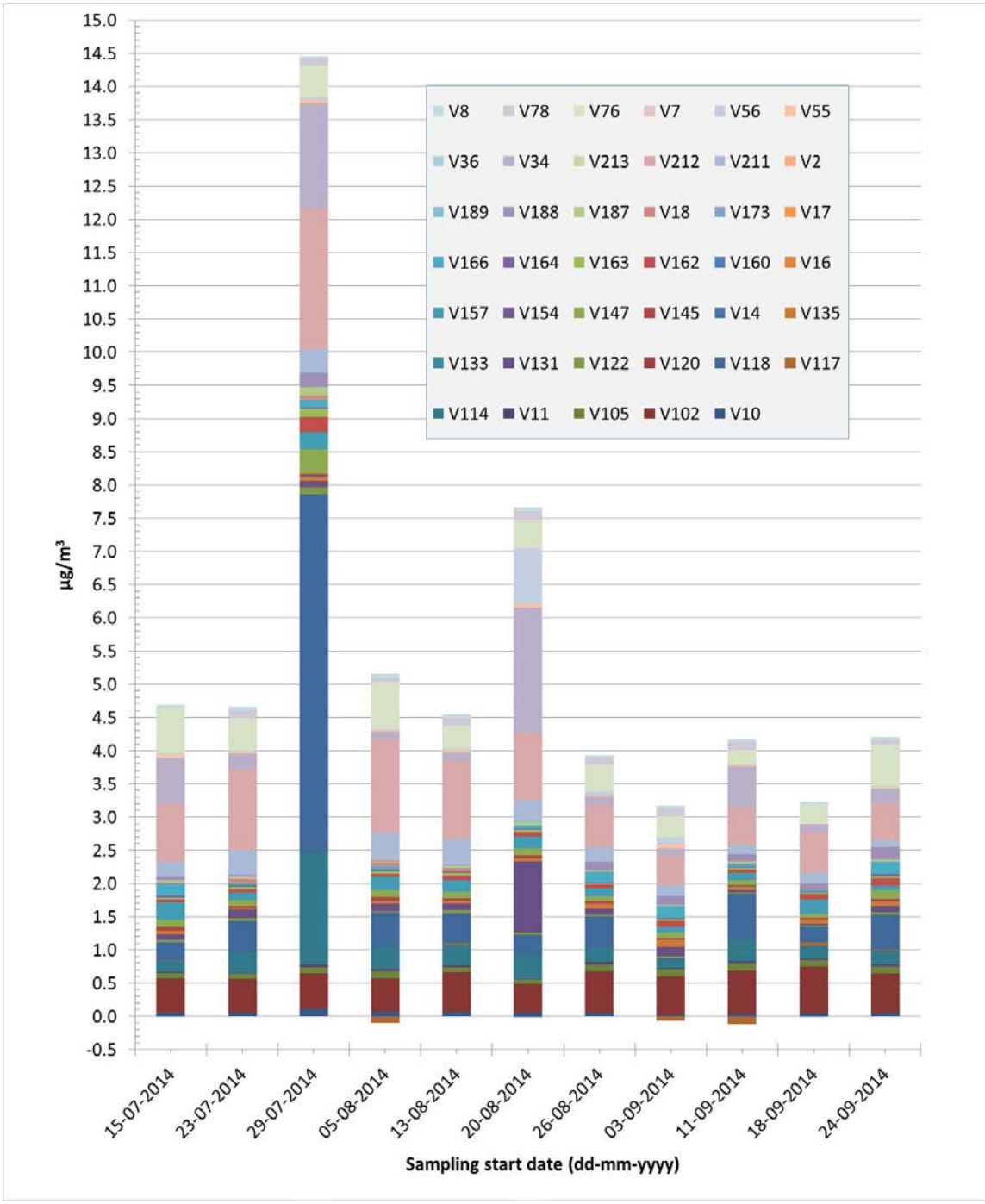

Figure A5. Stacked VOC concentrations based on weekly OVM badge samples collected between July 16 and October 1, 2014, at location 22 during Phase II

Note: The dates indicate when samples were deployed; sample exposure was 6–7 days. Full names of VOCs corresponding to *Vxxx* codes in the Legend box are included in Table B3 of Appendix B.

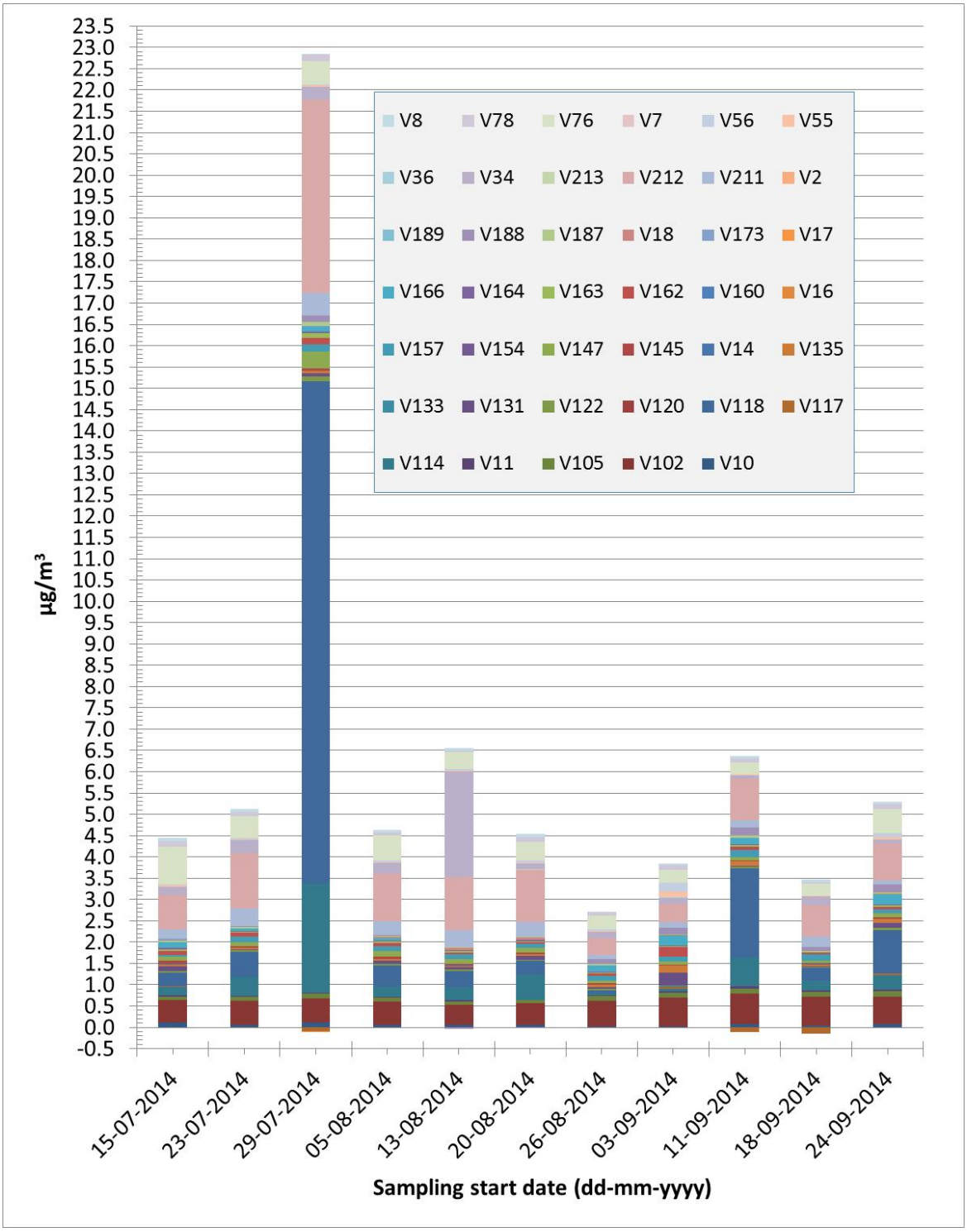

Figure A6. Stacked VOC concentrations based on weekly OVM badge samples collected between July 16 and October 1, 2014, at location 27 during Phase II

Note: The dates indicate when samples were deployed; sample exposure was 6–7 days. Full names of VOCs corresponding to *Vxxx* codes in the Legend box are included in Table B3 of Appendix B.

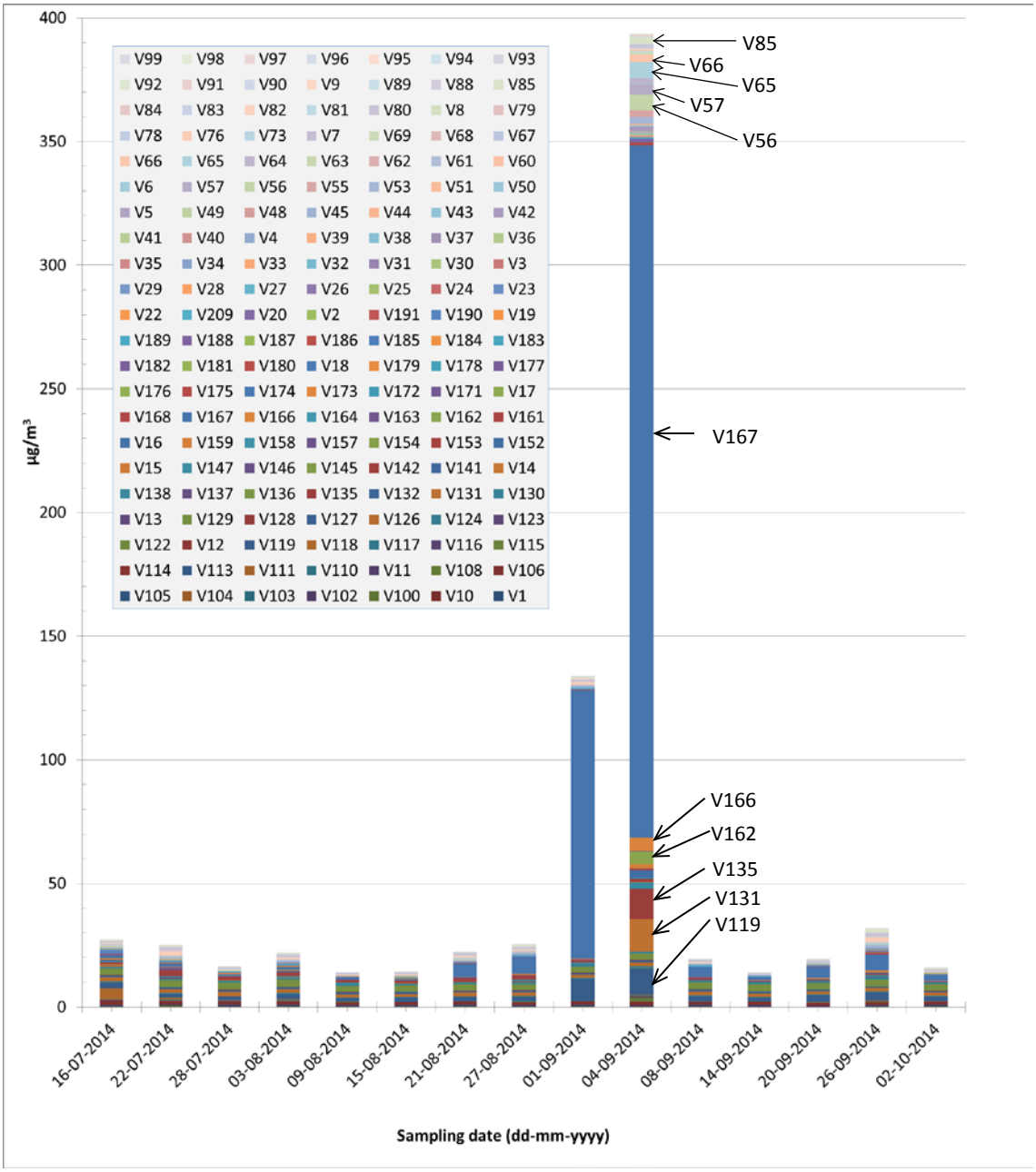

Figure A7. Stacked VOC concentrations based on 24 h Summa canister samples collected between July 16 and October 2, 2014, at location 21 during Phase II

Notes: The dates indicate when 24 h samples were collected. Full names of VOCs corresponding to *Vxxx* codes in the Legend box are included in Table B3 of Appendix B. The objective of this figure is not to distinguish all 154 VOC species measured for Summa canister samples, but to compare the sum of VOC concentrations among samples collected during Phase II. For example, samples collected on September 1 and September 4 show higher VOC concentrations and correspond to periods of intense activity on or near the well pad.

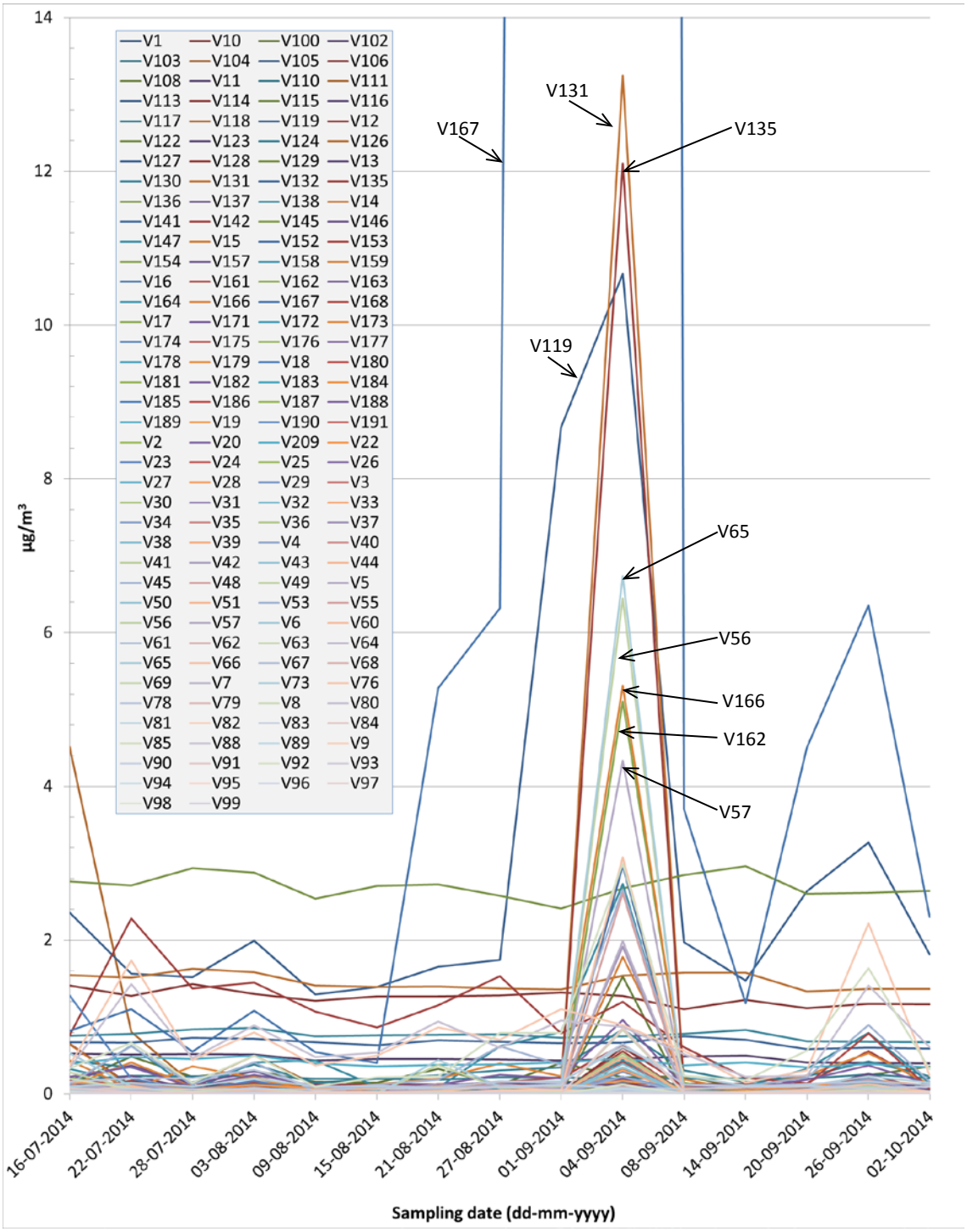

Figure A8. VOC concentrations based on 24 h Summa canister samples collected between July 16 and October 2, 2014, at location 21 during Phase II

Notes: The dates indicate when 24 h samples were collected. Full names of VOCs corresponding to *Vxxx* codes in the Legend box are included in Table B3 of Appendix B. 4-ethyltoluene (V167) was measured at 280 µg/m^3 in the September 4 sample. The vertical axis was cut to 14 µg/m^3. The objective of this figure is not to distinguish all 154 VOC species measured for Summa canister samples, but to compare the variation of VOC concentrations among samples collected during Phase II. For example, the sample collected on September 4 shows higher VOC concentrations and corresponds to periods of intense activity on or near the well pad.

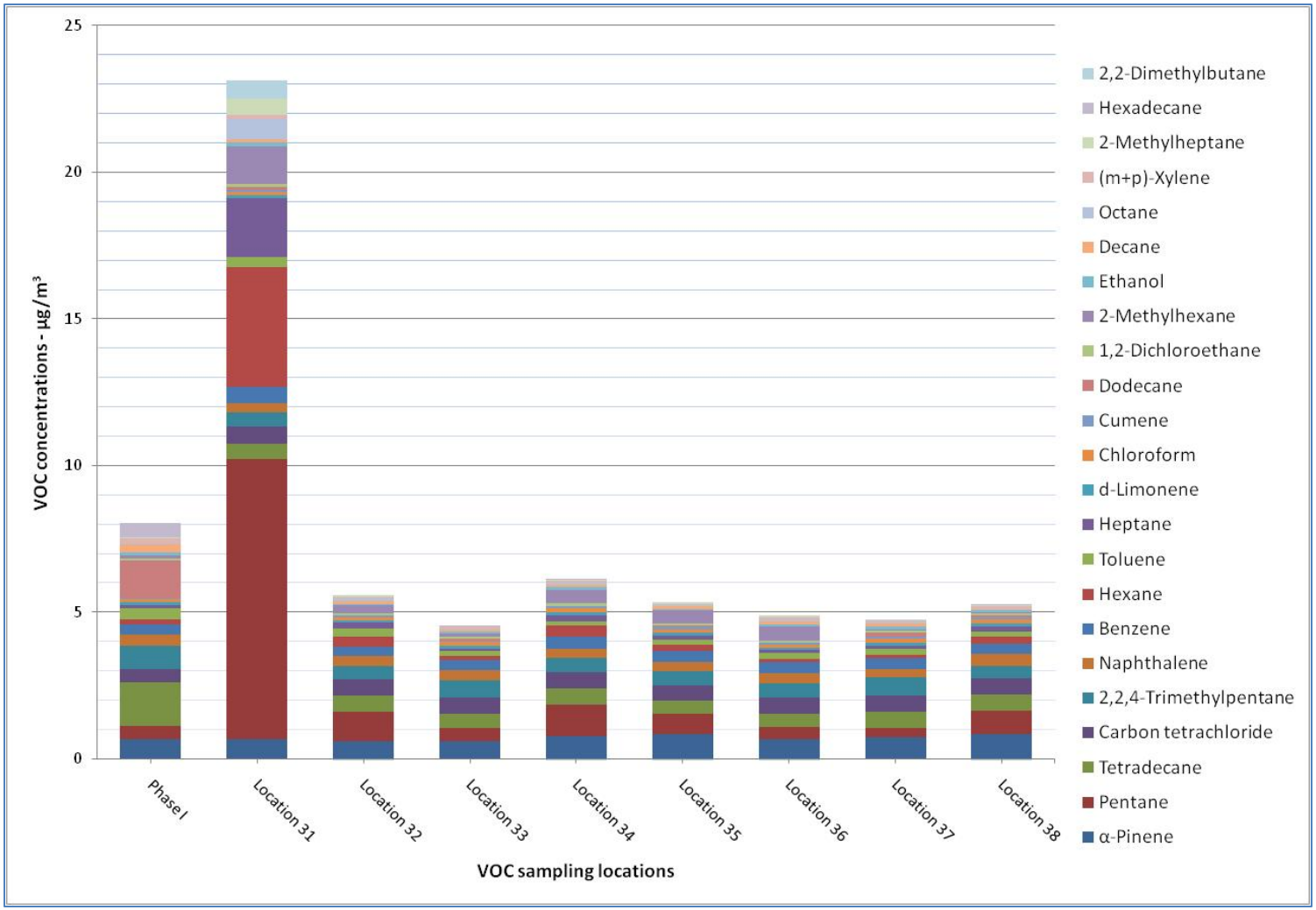

Figure A9. Stacked mean concentrations for VOCs measured at Phase I and Phase III locations based on OVM badges

Note: The 15 VOCs with the highest mean concentrations at each sampling location were retained to generate the stacked columns. As the 15 VOCs with the highest mean concentrations differ slightly among sampling locations, this actually results in a total of 24 species per column. The columns do not represent a measure of "total" VOCs. They reflect the sum of the 24 selected VOCs. (*Source*: Health Canada 2015)

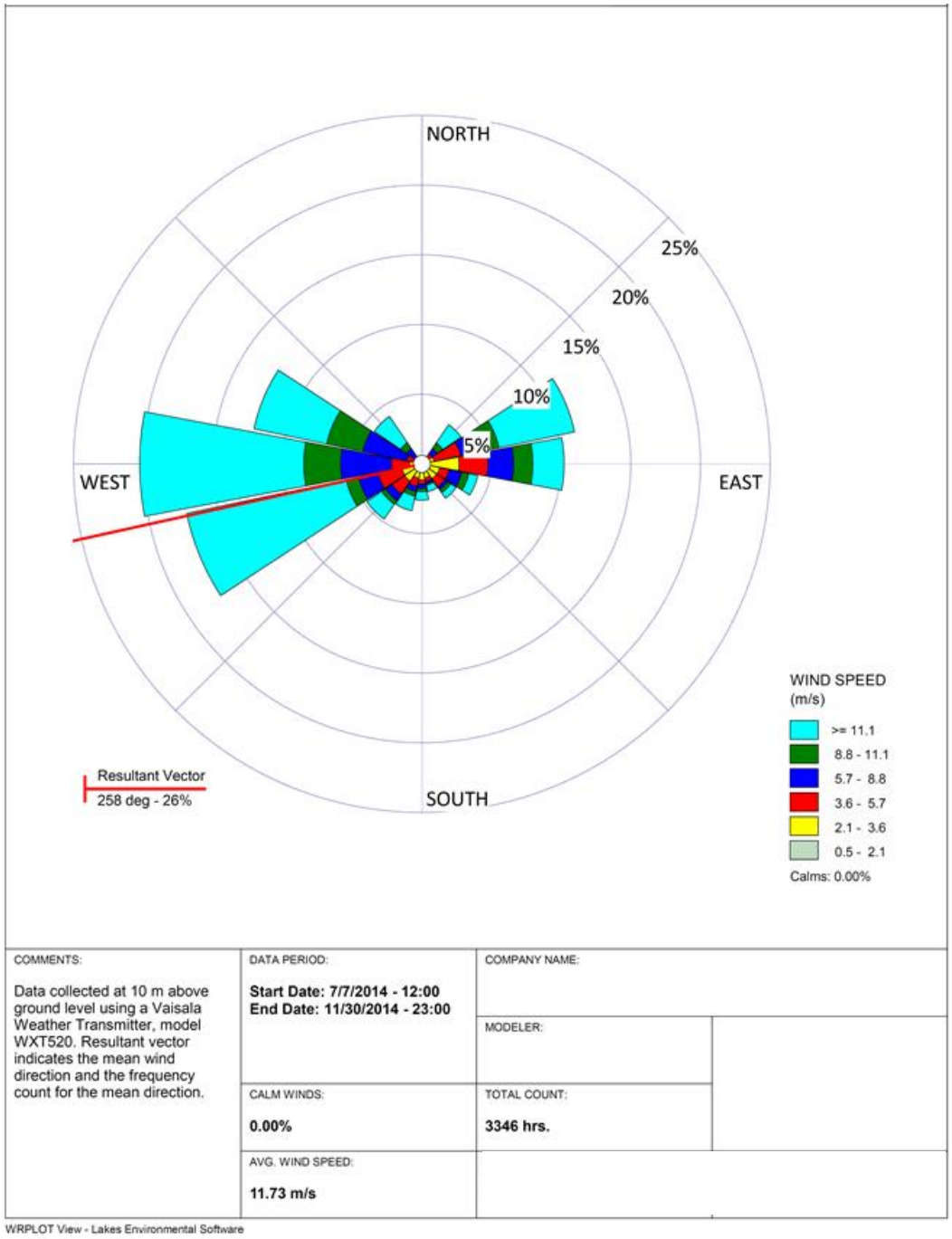

Figure A10. Wind direction (in degrees; blowing from) and speed (m/s) data collected between July and November, 2014, at location 21 during Phase II

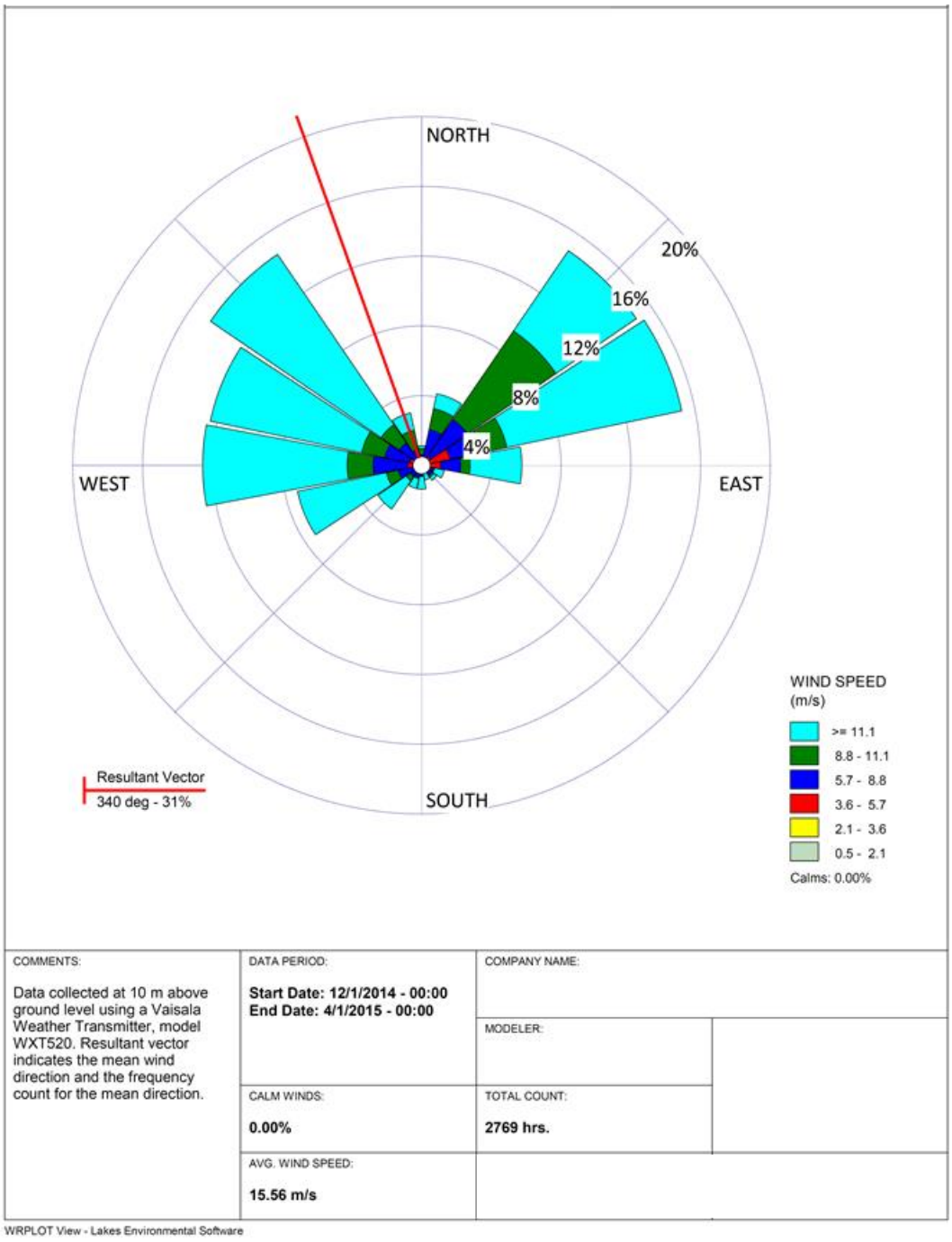

Figure A11. Wind direction (in degrees; blowing from) and speed (m/s) data collected between December 2014 and March 2015 at location 21 during Phase II

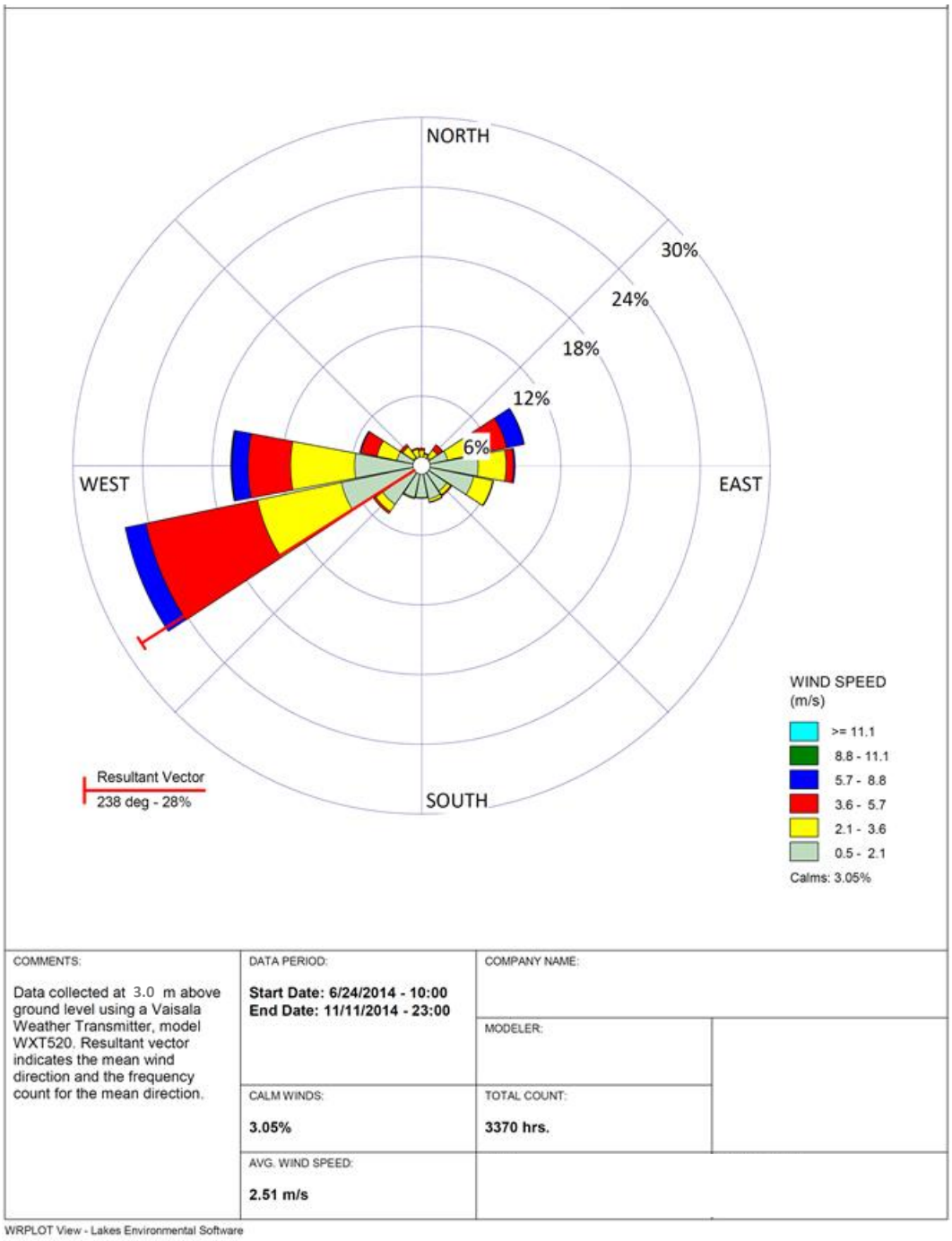

Figure A12. Wind direction (in degrees; blowing from) and speed (m/s) data collected between June and November, 2014, at location 22 during Phase II

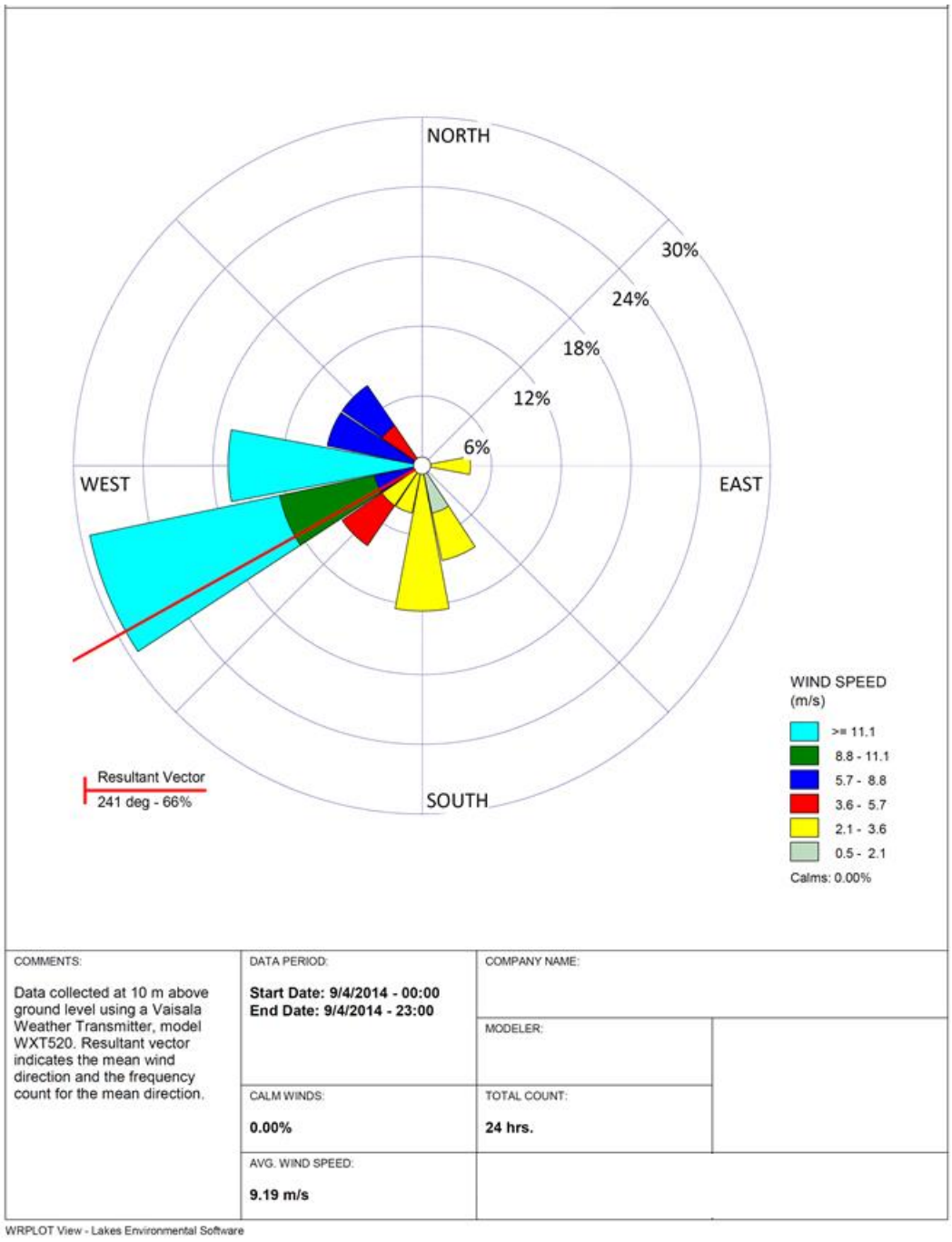

Figure A13. Wind direction (in degrees; blowing from) and speed (m/s) data collected on September 4, 2014, at location 21 during Phase II

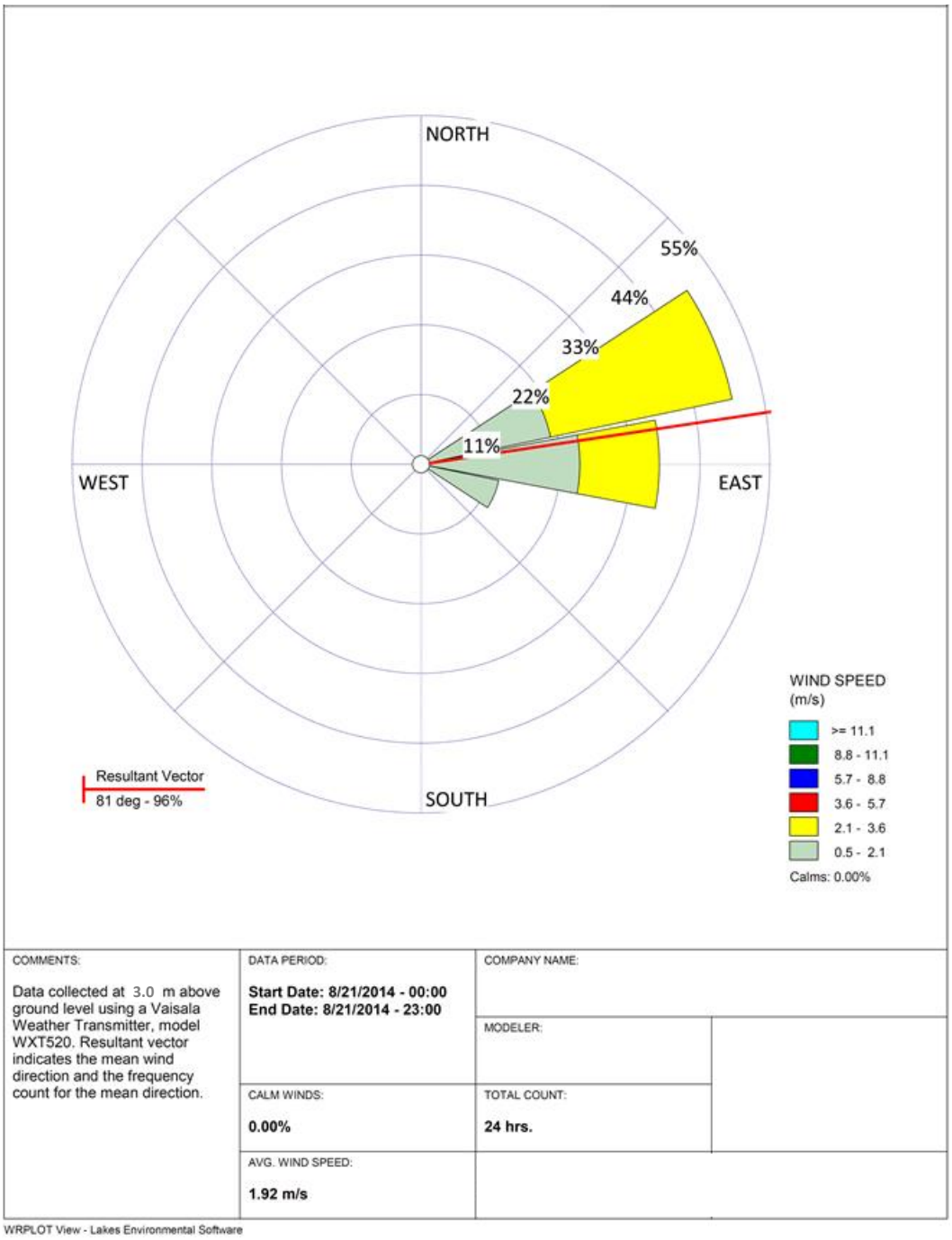

Figure A14. Wind direction (in degrees; blowing from) and speed (m/s) data collected on August 21, 2014, at location 22 during Phase II

Appendix B: Monitoring equipment and laboratory analysis

Table B1. Air pollutants monitored during Phase II

Parameter	Sampling type	Notes	Sampling locations
Carbon monoxide	Continuous (1, 5 or 60 minutes)		21, 22
Carbonyl compounds	Integrated (24 h)	24 h samples every 6 days with 926 two-channel carbonyl sampler (Xonteck)	21
Fine particulate matter ($PM_{2.5}$)	Continuous (1, 5 or 60 minutes)		21, 22
Methane	Continuous (10 seconds)		21
Nitrogen oxides (NO, NO_2, NOx)	Continuous (1, 5 or 60 minutes)		21, 22
Ozone	Continuous (1, 5 or 60 minutes)		21, 22
$PM_{2.5}$ speciation - gravimetric - metals - elemental and organic carbon - biomass combustion markers	Integrated (24 h)	24 h samples every 6 days	21
Polycyclic aromatic hydrocarbons	Integrated (24 h)	24 h samples every 6 days; particle-bound and gaseous	21
Sulphur dioxide	Continuous (1, 5 or 60 minutes)		21, 22
Temperature, relative humidity and barometric pressure	Continuous (1, 5 or 60 minutes)	Measurements at 10 m and 3.0 m above ground	21, 22
Total reduced sulphur – Hydrogen sulphide	Continuous (1, 5 or 60 minutes)		21, 22
Total suspended particulates	Continuous (1, 5 or 60 minutes)		21
Volatile organic compounds	Continuous (every 90 minutes); integrated (24 h and 6–8 days)	24 h samples every 6 days with Summa canisters; weekly samples with passive badges	21–28
Wind speed / direction	Continuous (1, 5 or 60 minutes)	Measurements at 10 m and 3.0 m above ground	21, 22

Table B2. Sampling and laboratory analysis methods for continuous monitors and integrated samples

Carbonyl compounds
Carbonyl compound samples were collected from the mobile monitoring unit using a Xonteck Model 926 Carbonyl Sampler. Air samples were collected on a solid adsorbent cartridge of 2,4-dinitrophenylhydrazine-coated silica gel. Samples were sent to Environment and Climate Change Canada laboratories for acetonitrile extraction and analysis by high-performance liquid chromatography. The normal flow rate for a 24 h sample was 1000 cm^3 (1 litre or L) ± 100 cm^3 per minute with a final volume of 1 500L ± 200L. Volume was estimated at actual conditions of temperature and pressure during sampling as measured by the sampler. The volume correction method was similar to the one outlined for polycyclic aromatic hydrocarbons (see below).
Methane
Continuous ambient methane measurements were collected with a Thermo Scientific IRIS 5500 methane analyzer.
Polycyclic aromatic hydrocarbons
Location 21: Polycyclic aromatic hydrocarbon (PAH) samples were collected over a 24 h period using a modified high-volume (MHV) sampler equipped with a Roots meter (model 8C175-CTR-NPDL-MTC-SA). Air was drawn through a Teflon-coated glass fibre filter followed by a PUF plug, allowing for the collection of both gaseous and TPM-bound PAHs. The sampling flow rate was set to approximately 500 L per minute. Samples were volume-corrected (see below) to adjust for variable sampling volumes. Samples were analyzed by Environment and Climate Change Canada using gas chromatography/mass spectrometry (GC/MS; Method No. 3.03/5.1/M). Measured PAHs are listed in Table B4 in Appendix B. Volume correction method for PAH concentration estimates: The sample volumes were corrected for 25°C (or 298.15°K) and a pressure of 1 atmosphere (or 101.325 kilopascal or kPa). Site-specific meteorological data—that is, sampling day temperatures (temp; high and low) and pressure—were provided by the field operators and were used for the correction. This approach is the same as that used for PAH samples collected at National Air Pollution Surveillance stations across Canada.[37] The method was as follows: (i) Final Gas Meter Volume (m^3) – Initial Gas Meter Volume(m^3) = **Volume (m^3)** [as recorded on the data sheet] (ii) (Final Gas Meter Vacuum (inches of H_2O) + Initial Gas Meter Vacuum (inches of H_2O)) / 2 × 0.249 = **Average Gas Meter Vacuum (kPa)** [0.249 is a constant expressing the kPa in 1 inch of H_20 at 4°C] (iii) (Sampling Day High Temp (°C) + Sampling Day Low Temp (°C)) / 2 + 273.15 = **Average Temp (°K)** (iv) Sampling Day pressure (in mm of Hg) [from sampling data sheet] × 0.133324 = **Sampling Day pressure in kPa** (v) ((Sampling Day pressure (kPa) – Average Gas Meter Vacuum (kPa)) / 101.325 kPa) × (298.15°K / Average Temp (°K)) × Volume (m^3) = **Corrected Volume (m^3)** Field sample acceptance criteria were 500–1200 m^3 for corrected sample volume and 24 ± 1 h for sample time. Location 22: PAH samples were collected using the URG personal pesticide sampler (Chapel Hill, NC, USA), within which a glass fibre filter collects $PM_{2.5}$-bound PAHs; a 5 cm plug of polyurethane foam (PUF) collects gaseous PAHs. A BGI pump set to 4 litres (L) per minute was used to collect air samples. The flow was checked and recorded when the filter was installed. The stop flow was assumed to be the same unless the operator included a comment stating that the pump needed adjustment. A value of 4.000 L per minute was presumed for all the flow rates. Samples were sent to Airzone One laboratories (AirZOne, Mississauga, ON) for analysis with a Gas

[37] May Siu, Environment and Climate Change Canada. Personal communications. 2014-07-15

Chromatography / Mass Spectrometry (GC/MS) according to a method approved by the Canadian Association for Laboratory Accreditation Inc. Measured PAHs are listed in Table B4 in Appendix B.
$PM_{2.5}$ gravimetric analysis and speciation
The Partisol 2300 speciation sampling system (ThermoScientific) consisted of four independent sampling cartridges. Three ChemComb cartridges (Model 3500, ThermoScientific, Waltham, MA, USA) were connected to separate $PM_{2.5}$ impactor inlets and dedicated mass flow controllers that maintained a constant flow rate of 10 L per minute. A fourth cartridge was used for field blanks. One Chemcomb cartridge contained a pre-fired quartz fibre filter for collecting $PM_{2.5}$ for analysis of organic carbon and elemental carbon. The quartz filters were analyzed by thermal optical reflectance (TOR) combustion for organic carbon and elemental carbon using a DRI Model 2001 Thermal/Optical Carbon Analyzer (Atmoslytic Inc Calabasas, CA). One 47 mm Teflon filter was analyzed for $PM_{2.5}$ mass and used for metals analysis via Inductively Coupled Plasma Mass Spectrometry (ICPMS). ICPMS analysis was done using a Perkin Elmer Elan DRC-II Inductively Coupled Plasma Mass Spectrometer following United States Environmental Protection Agency (US EPA) method 6020A (US EPA 2007) (samples identified by DC in the log sheet database were sent for metals analysis). A second 47 mm Teflon filter was analyzed for $PM_{2.5}$ mass and used for levoglucosan analysis via ion chromatography by Environment and Climate Change Canada (adapted from Jeong et al. 2013). Another cartridge was an active blank containing a Teflon filter and a pre-fired quartz backing filter in series. The blank quartz filters were analyzed for positive carbonaceous sampling artefacts arising from trapping of vapour phase carbon species. The carbon content of the quartz backing filter was subtracted from the organic carbon of the organic carbon and elemental carbon cartridge to give the corrected organic carbon content of the aerosol. Gravimetric analysis was conducted by the Alberta Research Council using the method outlined in the US EPA Quality Assurance Guidance Document 2.12 (US EPA 1998). Summary statistics for all species were calculated as follows: mass values reported below the detection limit were replaced by one half of the detection limit for each species and all missing data values were excluded from the calculation. Outliers were identified based on a visual analysis of results and removed from the calculation.
Volatile organic compounds – AMA GC/FID 5000
Volatile organic compounds (VOCs) were measured continuously using an AMA GC/FID 5000 unit. This monitor uses two GCs to measure organic pollutants in ambient air in the range of C2–C12, with detection capabilities down to part per trillion. Measurements were recorded for 55 VOCs every 90 minutes.
Volatile organic compounds – 3M organic vapour monitoring badges (OVM)
VOCs were collected using 3M Model 3500 organic vapour monitoring (OVM; Guillevan, Montreal) badges. This passive air monitoring device uses a charcoal sorbent to collect organics in ambient air via diffusion. OVM badges were installed under a protective cover at approximately 1.2–1.6 m above ground level and they were exposed for 7 days (target duration). OVM badges were analyzed by Airzone One (AirZOne, Mississauga, ON) using gas chromatography with a mass selective detector (GC/MSD).
Volatile organic compounds – Summa canisters
VOC samples were actively collected using clean evacuated 6 L Summa™ canisters. Summa canisters were equipped with pre-calibrated flow controllers that operated at a flow rate of 3.5 ml per minute and automatic timers to allow the collection of 24 h samples on specific days of the week. Summa canisters in the New Brunswick mobile laboratory were collected with a pump. The air samples were analyzed for a suite of VOCs using GC/MS, according to US EPA method TO-15, at Environment and Climate Change Canada laboratories.

GC/FID: gas chromatography / flame ionization detector; GC/MS: gas chromatography / mass spectrometry; GC/MSD: gas chromatography / mass selective detector; ICPMS: inductively coupled plasma mass spectrometry; L: litre; NB DELG: New Brunswick Department of Environment and Local Government; OVM: organic vapour monitoring; PUF: polyurethane foam; Temp: temperature; US EPA: United States Environmental Protection Agency; VOC: volatile organic compound

Table B3. Volatile organic compounds measured for Summa canisters, OVM badges and the continuous AMA GC/FID 5000 unit

VOC code	VOC name	Summa	OVM	GC/ FID	VOC code	VOC name	Summa	OVM	GC/ FID
V1	1,1,1-Trichloroethane	x			V97	c-3-Heptene	x		
V2	1,1,2,2-Tetrachloroethane	x	x		V98	c-3-Methyl-2-Pentene	x		
V3	1,1,2-Trichloroethane	x			V99	c-4-Methyl-2-Pentene	x		
V4	1,1-Dichloroethane	x			V100	Camphene	x		
V5	1,1-Dichloroethene	x			V102	Carbon tetrachloride	x	x	
V6	1,2,3-Trimethylbenzene	x		x	V103	Chlorobenzene	x		
V7	1,2,4-Trichlorobenzene	x	x		V104	Chloroethane	x		
V8	1,2,4-Trimethylbenzene	x	x	x	V105	Chloroform	x	x	
V9	1,2-Dibromoethane	x			V106	Chloromethane	x		
V10	1,2-Dichlorobenzene	x	x		V108	Cyclohexane	x		x
V11	1,2-Dichloroethane	x	x		V110	Cyclohexene	x		
V12	1,2-Dichloropropane	x			V111	Cyclopentane	x		x
V13	1,2-Diethylbenzene	x			V113	Cyclopentene	x		
V14	1,3,5-Trimethylbenzene	x	x	x	V114	Decane	x	x	x
V15	1,3-Butadiene	x			V115	Dibromochloromethane	x		
V16	1,3-Dichlorobenzene	x	x		V116	Dibromomethane	x		
V17	1,3-Diethylbenzene	x	x	x	V117	Dichloromethane	x	x	
V18	1,4-Dichlorobenzene	x	x	x	V118	Dodecane	x	x	
V19	1,4-Dichlorobutane	x			V119	Ethane	x		x
V20	1,4-Diethylbenzene	x			V120	Ethanol		x	
V22	1-Butene / 2-Methylpropene	x		x	V122	Ethylbenzene	x	x	x
V23	1-Butyne	x			V123	Ethylbromide	x		
V24	1-Decene	x			V124	Ethylene	x		
V25	1-Heptene	x			V126	Freon 11	x		
V26	1-Hexene or 2-Methyl-1,Pentene	x		x	V127	Freon 113	x		
V27	1-Methylcyclohexene	x			V128	Freon 114	x		
V28	1-Methylcyclopentene	x			V129	Freon 12	x		
V29	1-Nonene	x			V130	Freon 22	x		
V30	1-Octene	x			V131	Heptane	x	x	x
V31	1-Pentene	x		x	V132	Hexachlorobutadiene	x		
V32	1-Undecene	x			V133	Hexachloroethane		x	
V33	2,2,3-Trimethylbutane	x			V135	Hexane	x	x	x
V34	2,2,4-Trimethylpentane	x	x	x	V136	Hexylbenzene	x		
V35	2,2,5-Trimethylhexane	x			V137	Indane	x		
V36	2,2-Dimethylbutane	x	x	x	V138	i-butane	x		x
V37	2,2-Dimethylhexane	x			V141	i-Butylbenzene	x		
V38	2,2-Dimethylpentane	x			V142	Isoprene	x		x

VOC code	VOC name	Summa	OVM	GC/ FID	VOC code	VOC name	Summa	OVM	GC/ FID
V39	2,2-Dimethylpropane	x			V145	i-Propylbenzene or Cumene	x	x	x
V40	2,3,4-Trimethylpentane	x		x	V146	Limonene	x		
V41	2,3-Dimethylbutane	x		x	V147	m & p-Xylene	x	x	x
V42	2,3-Dimethylpentane	x		x	V152	Methylcyclohexane	x		x
V43	2,4-Dimethylhexane	x			V153	Methylcyclopentane	x		x
V44	2,4-Dimethylpentane	x		x	V154	Methyl-t-butyl ether	x	x	
V45	2,5-Dimethylhexane	x			V157	Naphthalene	x	x	
V48	2-Ethyl-1,Butene	x			V158	n-Butylbenzene	x		
V49	2-Ethyltoluene	x		x	V159	Nonane	x		x
V50	2-Methyl-1,Butene	x			V160	Pentachloroethane		x	
V51	2-Methyl-2-Butene	x			V161	n-Propylbenzene	x		x
V53	2-Methylbutane	x			V162	Octane	x	x	x
V55	2-Methylheptane	x	x	x	V163	o-Xylene	x	x	x
V56	2-Methylhexane	x	x	x	V164	p-Cymene	x	x	
V57	2-Methylpentane	x		x	V166	n-Pentane	x	x	x
V60	3,6-Dimethyloctane	x			V167	Propane	x		x
V61	3-Ethyltoluene	x			V168	Propene	x		x
V62	3-Methyl-1,Butene	x			V171	Propyne	x		
V63	3-Methyl-1,Pentene	x			V172	sec-Butylbenzene	x		
V64	3-Methylheptane	x			V173	Styrene	x	x	x
V65	3-Methylhexane	x		x	V174	t-1,2-Dichloroethene	x		
V66	3-Methylpentane	x		x	V175	t-1,2-Dimethylcyclohexane	x		
V67	4-Ethyltoluene	x		x	V176	t-1,3-Dichloropropene	x		
V68	4-Methyl-1,Pentene	x			V177	t-1,4-Dimethylcyclohexane	x		
V69	4-Methylheptane	x			V178	t-2-Butene	x		x
V73	Acetylene	x		x	V179	t-2-Heptene	x		
V76	α-Pinene	x	x		V180	t-2-Hexene	x		
V78	Benzene	x	x	x	V181	t-2-Octene	x		
V79	Benzyl Chloride	x			V182	t-2-Pentene	x		x
V80	β-Pinene	x			V183	t-3-Heptene	x		
V81	Bromodichloromethane	x			V184	t-3-Methyl-2-Pentene	x		
V82	Bromoform	x			V185	t-4-Methyl-2-Pentene	x		
V83	Bromomethane	x			V186	tert-Butylbenzene	x		
V84	Bromotrichloromethane	x			V187	Tetrachloroethene	x	x	
V85	n-Butane	x		x	V188	Toluene	x	x	x
V88	c-1,2-Dichloroethene	x			V189	Trichloroethene	x	x	
V89	c-1,2-Dimethylcyclohexane	x			V190	Undecane	x		x
V90	c-1,3-Dichloropropene	x			V191	Vinylchloride	x		
V91	c-1,3-Dimethylcyclohexane	x			V209	Freon 134A	x		
V92	c-1,4 / t-1,3-Dimethylcyclohexane	x			V211	Hexadecane (C16)		x	

VOC code	VOC name	Summa	OVM	GC/ FID	VOC code	VOC name	Summa	OVM	GC/ FID
V93	c-2-Butene	x		x	V212	Tetradecane (C14)		x	
V94	c-2-Heptene	x			V213	1,2,3-Trichlorobenzene		X	
V95	c-2-Hexene	x			V214	Ethene			x
V96	c-2-Pentene	x		x	V215	i-Pentane			x

GC/FID: gas chromatography / flame ionization detector (continuous monitor); OVM: organic vapour monitoring (weekly badges)

Table B4. PAHs measured based on selected sampling and laboratory analysis methods

Code	Name	MHV	URG	Code	Name	MHV	URG
PAH1	Naphthalene	x	x	PAH21	Benzo(a)anthracene	x	
PAH2	Acenaphthylene	x	x	PAH24	Benzo(b)chrysene	x	
PAH3	Acenaphthene	x	x	PAH27	Benzo(e)pyrene	x	
PAH4	Fluorene	x	x	PAH28	Benzo(ghi)fluoranthene	x	
PAH5	Phenanthrene	x	x	PAH44	Perylene	x	
PAH6	Anthracene	x	x	PAH46	Retene	x	
PAH7	Fluoranthene	x	x	PAH50	2-Methylfluorene	x	
PAH8	Pyrene	x	x	PAH51	Benzo(a)fluorene	x	
PAH9	Benz(a)anthracene		x	PAH52	Benzo(b)fluorene	x	
PAH10	Chrysene		x	PAH53	1-Methylpyrene	x	
PAH11	Benzo(b)fluoranthene	x	x	PAH54	7-Methylbenz(a)anthracene	x	
PAH12	Benzo(k)fluoranthene	x	x	PAH55	3-Methylcholanthrene	x	
PAH13	Benzo(a)pyrene	x	x	PAH56	Indeno(1,2,3-cd)fluoranthene	x	
PAH14	Indeno(1,2,3-cd)pyrene	x	x	PAH57	Anthanthrene	x	
PAH15	Dibenzo(ah)anthracene	x	x	PAH58	Triphenylene	x	
PAH16	Benzo(ghi)perylene	x	x	PAH59	Chrysene	x	

MHV: modified high-volume sampling; URG: pesticide personal sampler

Table B5. Elements measured based on ICPMS analysis of fine particulate matter samples

Symbol	Name	Symbol	Name	Symbol	Name	Symbol	Name
Ag	Silver	Cl	Chlorine	Mn	Manganese	Si	Silicon
Al	Aluminum	Co	Cobalt	Mo	Molybdenum	Sn	Tin
As	Arsenic	Cr	Chromium	Na	Sodium	Sr	Strontium
B	Boron	Cu	Copper	Ni	Nickel	Th	Thorium
Ba	Barium	Fe	Iron	P	Phosphorous	Ti	Titanium
Be	Beryllium	Hg	Mercury	Pb	Lead	Tl	Thallium
Bi	Bismuth	K	Potassium	S	Sulphur	U	Uranium
Ca	Calcium	Li	Lithium	Sb	Antimony	V	Vanadium
Cd	Cadmium	Mg	Magnesium	Se	Selenium	Zn	Zinc

Table B6. General monitoring and sampling information for the mobile unit (location 21) during Phase II

Parameter	Make	Model	Notes
Wind speed	Vaisala	WXT 520	Activated July 7, 2014. Final shutdown March 31, 2015.
Wind direction	Vaisala	WXT 520	Activated July 3, 2014. Final shutdown March 31, 2015.
Temperature	Vaisala	WXT 520	Activated July 3, 2014. Final shutdown March 31, 2015.
Barometric pressure	Vaisala	WXT 520	Activated July 3, 2014. Final shutdown March 31, 2015.
Sulphur dioxide	Thermo	43i	Activated July 1, 2014. Final shutdown March 31, 2015.
Total reduced sulphur	Thermo	43C	Activated July 1, 2014. Final shutdown March 31, 2015.
Carbon monoxide	Thermo	48C	Activated July 1, 2014. Final shutdown March 31, 2015.
Nitrogen oxides (NO, NO_2 and NOx)	Thermo	42C	Activated July 1, 2014. Final shutdown March 31, 2015.
Fine particulate matter ($PM_{2.5}$)	MetOne	BAM1020	Activated July 1, 2014. Final shutdown March 31, 2015. Offline from February 5 to March 12, 2015.
Total suspended particulate	MetOne	E-BAM	Activated July 1, 2014. Final shutdown February 5, 2015 (equipment malfunction).
Ozone	Thermo	49i	Activated July 1, 2014. Final shutdown March 31, 2015.
Methane	Thermo	IRIS 5500	Activated July 1, 2014. Final shutdown March 31, 2015.
Volatile organic compounds – C2-C12 compounds – Continuous real-time monitoring	AMA	GC/FID 5000, VOC and BTEX	Activated and installed July 7, 2014. Offline during several periods (e.g., September and November 2014; February and March 2015). Final shutdown March 21, 2015 owing to software issues.
Volatile organic compounds – full suite	Xonteck	910A	Canister-based sampling every 6 days; sampling from July to October 2014.
SVOC – dioxin and furan compounds and polycyclic aromatic hydrocarbon compounds	Modified high-volume sampler	----	Polyurethane foam (PUF) high-volume sampling every 6 days; sampling from July to October 2014.
Carbonyl compounds	Xonteck	926	Canister-based sampling every 6 days; sampling from July to October 2014.

Table B7. General monitoring and sampling information for the Airpointer unit (location 22) during Phase II

Parameter	Make	Model[a]	Notes
Wind speed	Vaisala	WXT 520	Activated June 24, 2014. Final shutdown November 12, 2014.
Wind direction	Vaisala	WXT 520	Activated June 24, 2014. Final shutdown November 12, 2014.
Temperature	Vaisala	WXT 520	Activated June 24, 2014. Final shutdown November 12, 2014.
Barometric pressure	Vaisala	WXT 520	Activated June 24, 2014. Final shutdown November 12, 2014.
Sulphur dioxide / Total reduced sulphur	Thermo	Airpointer	Activated June 24, 2014. No valid data after November 5, 2014. Final shutdown November 12, 2014.
Carbon monoxide	Thermo	Airpointer	Activated June 24, 2014. Final shutdown August 14, 2014. Module malfunction.
Nitrogen oxides (NO, NO_2 and NOx)	Thermo	Airpointer	Activated June 24, 2014. Final shutdown November 12, 2014..
Fine particulate matter ($PM_{2.5}$)	SHARP (Nephelometer only)	Airpointer	Activated June 24, 2014. Final shutdown November 12, 2014..
Ozone	Thermo	Airpointer	Activated June 24, 2014. Final shutdown August 25, 2014. Module malfunction.

[a] The pollutant benches or modules inside the Airpointer are technically the same as the ones in the mobile unit (Table B6). However the modules have been modified and customised to fit inside the Airpointer. Therefore, the model is indicated as Airpointer.

Appendix C: Summary of activities reported at well pad F-67

June 2014

- Well pad preparation and extension
  - Clay layer, geotextile, gravel, crushed rock; adjust elevation and containment pond
  - Prep work completed June 14, 2014
  - No additional work until arrival of equipment

July 2014

- Arrival of equipment, set-up, work-over (e.g., rig and snubbing unit)
- Tropical storm Arthur expected to hit Sussex early morning Saturday, July 5; heavy rainfall warning and tropical storm winds possible (60–90 km/h)
- Switched to oil-based muds on July 13
- Washing/drilling through fill at 2 967 m (July 14)
- Log / run production casing / cement
- Drilled to 3 008 m; tripping for new bottom hole assembly (July 17)
- Run in hole and ream to bottom (enlarge the wellbore by drilling it again with a special bit)
- Work suspended due to necessary repairs; waiting for parts (July 21–25)
- Resume reaming and cleaning at 3 000+ m (July 28)

August 2014

- Trip pipe from 3 080 m for bit change; reaming and cleaning
- Run casing (August 7)
- Fracture stimulation took place at other locations:
  - B-41 (Elgin G-41 Pad), location of Phase IV site (Aug 4; Aug 5; and Aug 14), approximately 20 km downwind
  - L-37 (D-48 Pad), location of Phase III site (Aug 17; Aug 23), 3.6 km downwind
  - P-67 (N-57 Pad; Aug 20), 1.9 km downwind
- Coiled tubing blow-down (August 25)
- Install frac tree (August 27)
- Well perforation (August 28)
- Well stimulation on well pad O-76 (well J-76; August 30), located approximately 1.7 km upwind of well pad F-67

September 2014

- Move in and rig up fracturing equipment
- Propane deliveries (truck traffic)
- Fracture stimulation (September 4); several fly-overs during activities (planes and helicopters)
- Flaring expected (intermittent)
- Rig down equipment (September 5)
- Flow test well (September 11)

- No activities at E67-B from September 9 to October 6
- Well stimulation (well J-76; September 9) and incinerator maintenance (September 17–18) on well pad O-76, located approximately 1.7 km upwind of well pad F-67

October 2014

- No activities at E67-B from September 9 to October 6
- Move in and rig up incinerator and test vessel (October 7)
- Rig in test equipment for bleed down and snubbing (October 9)
- Bleed down and snubbing (October 10)
- Bleed well pressure down to plant and incinerator to be ready to snub tubing (October 11)
- Pumped N_2 blanket into well and snubbed tubing string in place (October 12)
- Pump out plugs and open well to flow test (October 13)
- Incinerator burning off propane to reduce pressure to allow cleaning
- Flow well (October 15–19); flare active
- Forward plan as of October 21, 2014 (final report): shut-in for pressure buildup
- Heavy equipment movement the last couple of weeks

November 2014

- Pressure gauges out (November 19)

January 2015

- In-line production (January 9)

May 2015

- Well shut-in (May 1)
- Still considered a producing well

Appendix D: New Brunswick and Canadian air quality objectives

New Brunswick recognizes a number of air quality objectives and standards, some of which are regulated or voluntary in nature. New Brunswick ambient air quality objectives (NBAAQOs) for CO, H_2S, NO_2, SO_2 and TSP are included in Table D1. These objectives are established under the province's *Clean Air Act*, which also includes a provision for required annual reporting to the province's Legislative Assembly on achievement of the objectives. No NBAAQO exists for ground-level O_3.

New Brunswick is also a signatory to the Canada-wide Standards (CWS) for $PM_{2.5}$ and O_3. The Canadian Council of Ministers of the Environment endorsed standards for $PM_{2.5}$ and O_3 in June 2000, which came into force for the 2010 reporting year. These standards are slightly different from NBAAQOs, as they apply to long-term trends. The CWS for O_3 is 65 ppb, calculated as a three-year rolling average of the fourth highest daily average in each year. The CWS for $PM_{2.5}$ is 30 µg/m^3, calculated as a three-year rolling average of the 98th percentile (i.e. nearly the highest) daily average value in each year. Although not legally binding, the national objectives for O_3 and $PM_{2.5}$ are the benchmark. The Canadian Ambient Air Quality Standards (CAAQS) under Canada's Air Quality Management System were established as objectives on May 25, 2013. They are more stringent and comprehensive than the CWS, which they are replacing. CAAQS provide a new approach for managing O_3 and fine PM pollution via different objective levels. Provinces and territories will implement actions to meet the CAAQS as of 2015.

Table D1 also includes National Ambient Air Quality Objectives (NAAQOs), which are set by the federal government based on recommendations from a National Advisory Committee and Working Group on Air Quality Objectives and Guidelines. Provincial governments have the option of adopting these either as objectives or as enforceable standards, according to their legislation. NAAQOs must be consistent with the philosophy of the *Canadian Environmental Protection Act, 1999* and must be based on recognized scientific principles that include risk assessment and risk management.

The monitoring results from the current study were compared against applicable values from Table D1 to verify whether any exceedances were recorded during the different phases of the study. The values in Table D1 also provide some perspective on the analysis of recorded levels during the different phases. As the monitoring for each phase was limited to a maximum of one year, it was not always appropriate to compare the air monitoring data for $PM_{2.5}$ with the $PM_{2.5}$ CAAQS or CWS, which are based on long-term monitoring data (i.e. three-year average of the 98th percentile). Since there are no daily limits for $PM_{2.5}$ under the Canadian or New Brunswick objectives and standards, the British Columbia and the World Health Organization 24 h average $PM_{2.5}$ air quality standards of 25 µg/m^3 were also considered.

Table D1. National and New Brunswick air quality objectives

Air contaminant		Concentrations			
National Ambient Air Quality Objectives (not to be exceeded)[a]					
		Maximum desirable level		Maximum acceptable level	
SO_2	1 h average	450 µg/m^3	0.17 ppm	900 µg/m^3	0.34 ppm
SO_2	24 h average	150 µg/m^3	0.06 ppm	300 µg/m^3	0.11 ppm
SO_2	Annual arithmetic mean	30 µg/m^3	0.01 ppm	60 µg/m^3	0.02 ppm
PM (TSP)	24 h average			120 µg/m^3	
PM (TSP)	Annual geometric mean	60 µg/m^3		70 µg/m^3	
CO	1 h average	15 mg/m^3	13 ppm	35 mg/m^3	30 ppm
CO	8 h average	6 mg/m^3	5 ppm	15 mg/m^3	13 ppm
O_3	1 h average	100 µg/m^3	51 ppb	160 µg/m^3	82 ppb
O_3	24 h average	30 µg/m^3	15 ppb	50 µg/m^3	25 ppb
O_3	Annual arithmetic mean			30 µg/m^3	15 ppb
NO_2	Annual arithmetic mean	60 µg/m^3	0.03 ppm	100 µg/m^3	0.05 ppm
NO_2	1 h average			400 µg/m^3	0.21 ppm
NO_2	24 h average			200 µg/m^3	
Canada-wide Standards[b]					
O_3	Maximum 8 h average	65 ppb			
$PM_{2.5}$	Daily average	30 µg/m^3			
Canadian Ambient Air Quality Standards (management levels; 2015)[b,c]					
		Achieve	Prevent exceedance	Prevent air quality deterioration	Keep clean areas clean
O_3	Maximum 8 h average	63 ppb	56 ≤ 63 ppb	50 ≤ 56 ppb	≤ 50 ppb
$PM_{2.5}$	Daily average	28 µg/m^3	19 ≤ 28 µg/m^3	10 ≤ 19 µg/m^3	≤ 10 µg/m^3
$PM_{2.5}$	Annual average	10 µg/m^3	6.4 ≤ 10 µg/m^3	4.0 ≤ 6.4 µg/m^3	≤ 4.0 µg/m^3
New Brunswick Ambient Air Quality Objectives					
CO	1 h average	30 ppm			
CO	8 h average	13 ppm			
H_2S	1 h average	11 ppb			
H_2S	24 h average	3.5 ppb			
NO_2	1 h average	210 ppb			
NO_2	24 h average	105 ppb			
NO_2	Annual average	52 ppb			
SO_2[d]	1 h average	339 ppb			
SO_2	24 h average	113 ppb			
SO_2	Annual average	23 ppb			
TSP	24 h average	120 µg/m^3			
TSP	Annual average	70 µg/m^3			

[a] Conditions of 25°C and 101 kPa are used as the basis for conversion from µg/m^3 to ppm.
[b] For O_3 maximum 8 h average, three-year rolling average of the fourth highest daily maximum 8 h average in each year; for $PM_{2.5}$ daily average, three-year rolling average of 98th percentile daily average value in each year.
[c] Canadian Ambient Air Quality Standards for SO_2 and NO_2 currently under development.
[d] The standards for SO_2 are 50% lower in Saint John, Charlotte and Kings counties.
Sources: NB DELG (2012); www.ec.gc.ca/rnspa-naps/