Ambient Air Quality Network Evaluation

Peace River Area Monitoring Program

PRAMP

60680345

December 2022

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Executive Summary

AECOM Canada Ltd. (AECOM) was selected to evaluate the performance of the PRAMP ambient air quality monitoring network. As identified by PRAMP, the purpose of a network assessment is to optimize air monitoring networks to achieve the best possible scientific value and protection of public and environmental health and welfare.

The following emerging issues governed the evaluation:

- Priority 1: emissions reduction, regional air quality improvement, a regulatory framework for cold heavy oil production is in place (Directive 84) and mitigation measures have been implemented. How do these changes inform the optimization of PRAMP's monitoring program?
- Priority 2: determine if or how the overall monitoring network can be optimized to include other continuous air monitoring stations, such as the Peace River Complex (PRC) station and the two Mercer stations (Plant and Town), as well as the 12 passive SO_2 and H_2S monitors around PRC.
- Priority 3: determine if there are monitoring-deficient areas that PRAMP should consider in its monitoring program. In addition, determine how lower-cost new monitoring technologies could be incorporated in the PRAMP monitoring program.

The following general analytical processes were applied to support portions of the assessment:

- Calculation of PRAMP station and instrument uptime as input to data quality assessments
- Preparation of statistics for hourly, daily, and annual averages. Prepare box-and-whisker plots for hourly data.
- Preparation of correlations among ambient measurements for all stations in the network.
- Calculation and plotting of diurnal variations. Calculation and plotting of annual averages for each year in the dataset since inception.
- Preparation of wind and pollutant roses for each site, as well as statistics of wind speed at each monitoring station.
- Trends in annual emissions by facility and total within the PRAMP boundary. As part of this process, it was identified if any facility had significant emissions of unmonitored pollutants. Plot emission rates (density) of all sources within the PRAMP network area.

The key data sources were:

- PRAMP continuous measurements of air quality and meteorology
- VOC canisters samples taken above preset thresholds (e.g., triggered samples by peak VOC detected in continuous gas chromatography measurements)
- PRC passives measurements of sulphur dioxide (SO_2) and hydrogen sulfide (H_2S)
- NPRI emissions for each station in the PRAMP area, and within 50 km of the boundary
- Other reports and modelling results relevant to the evaluation

The key recommendations that followed from this analysis were:

- No stations should be removed from the network after adding PRC and Mercer stations. This was largely driven by the observation that measurements at the stations are essentially independent of

each other, and winds are different at each station. In some cases, nearby emissions sources are unique. Removal of any stations would remove information from the network that could not be replaced by considering data from other stations.

- The need for monitoring in data deficient areas is not sufficient to justify the addition of new currently configured stations. Where deficiency could be considered to exist (some spatial areas and in communities), the use of low-cost sensors or the re-purposing of passive samplers is recommended.
- There was no evidence that any stations should be moved to provide more representative sampling.
- Several pollutants are measured in the network at consistently low concentrations, including SO_2 and VOCs. It is not recommended that monitoring for these should stop. However, PRAMP could consider the replacement of the continuous instruments that currently measure these parameters with alternative technology, like passive samplers or low-cost emerging technology, provided the data quality remains acceptable.
- The passive network around PRC should be discontinued as the SO_2 and H_2S measurements among many of the sites are highly correlated and they agree with those measured at the continuous PRC station which was established to also respond to emissions from nearby well pads. There may be an opportunity to relocate the passive network to other locations currently without monitoring.

The report provides detail to support the recommendations and a suggested implementation plan for them.

Table of Contents

Figures

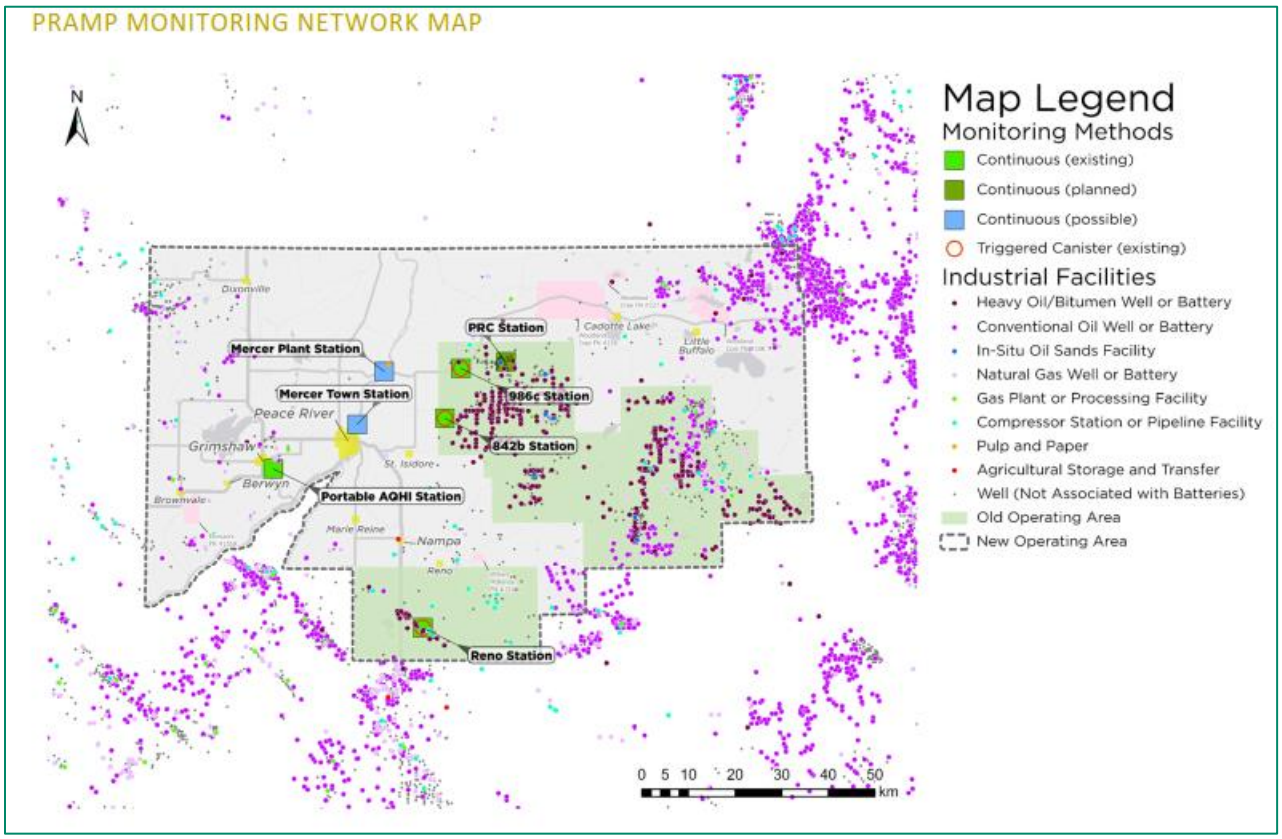
Tables

1. Introduction

1.1 Background

Monitoring in the Peace River area began in 2010 and the Peace River Area Monitoring Program (PRAMP) has been in place since 2016. PRAMP is a multi–stakeholder group, consisting of individuals, companies, municipalities, Indigenous communities, provincial departments, and other levels of government, all dedicated to healthy air quality. A map of the area is shown in **Figure 1** and a monitoring matrix is listed in **Table 1**.

Figure 1: PRAMP Monitoring Network Map



AECOM Canada Ltd. (AECOM) was selected to evaluate the performance of the ambient air quality monitoring network. As identified by PRAMP, the purpose of a network assessment is to optimize air monitoring networks to achieve the best possible scientific value and protection of public and environmental health and welfare. A network assessment includes:

- re-evaluation of the objectives for air monitoring,
- documenting emerging issues,
- evaluation of a network's effectiveness and efficiency relative to its objectives and costs, and
- development of recommendations for network reconfigurations and improvements.

Network assessments often make recommendations that:

- adjust networks to address emerging issues
- aspire to protect today's population and environment and
- maintain the ability to understand long-term historical air quality trends.

Through network assessments air monitoring organizations can take advantage of the benefits of new air monitoring technologies and improved scientific understanding of air quality issues. Reconfiguring air monitoring networks can enhance their value to stakeholders, scientists, and the public.

Table 1: Area Monitoring Network Matrix

		Station Name									
Monitoring Method	**Parameter**	**986c**	**842b**	**Reno**	**AQHI** *(Grimshaw)*	**CNRL** *(PRC)*	**Mercer** *(Townsite)*	**Mercer** *(Plantsite)*	**Peace River** *(above valley)*	**Peace River** *(in valley)*	**Nampa**
Continuous	**Sulphur Dioxide**	√	√	√	√	√	√				
	Total Reduced Sulphurs	√	√	√	√	√	√	√			
	Hydrogen Sulphide					√					
	Hydrocarbons *Total, Methane, & Non-Methane*	√	√	√	√	√					
	Oxides of Nitrogen *Total, Nitric Oxide, Nitrogen Dioxide*				√						
	Ozone				√						
	Fine Particulate Matter *Particles ≤ 2.5 Microns in Diameter*				√		√				
	Wind *Speed & Direction*	√	√	√	√	√	√	√			
	Precipitation	√	√	√							
	Climate Variables *Temperature, Relative Humidity, Barometric Pressure*	√	√	√	√	√	√	√			
	Air Quality Health Index (AQHI) *Third-Party Calculated Multi-Parameter Index*				√						
Intermittent	**Non-Methane Hydrocarbon Canister**	√	√	√							
	Methane Canister	√	√	√							
Passive	**Polycyclic Aromatic Compounds**	√									
Small Sensor	**Fine Particulate Matter** *Particles ≤ 2.5 Microns in Diameter*	√	√	√	√				√	√	√
	Climate Variables *Temperature, Relative Humidity*	√	√	√	√				√	√	√
	Air Quality Health Index Plus (AQHI+) *Third-Party Calculated Single-Parameter Index*	√	√	√	√				√	√	√

1.2 PRAMP Monitoring Objectives

The primary objectives of the PRAMP monitoring network are to:

- Provide high quality ambient data which, when used in conjunction with the appropriate statistical approach, will allow the assessment of:
  - monitoring data trends
  - the spatial distribution of contaminants of concern in the region, including identifying hot-spots and emerging air quality issues.

- Provide ambient information for community monitoring needs including:
  - information for human health risk assessments
  - assessing odours
  - measuring representative ambient concentrations in populated areas, and
  - providing information needed to communicate to the public an Air Quality Health Index (AQHI).
- Provide ambient information on cumulative effects, to assist in understanding the impact of:
  - multiple sources on the quality of air in the Peace River Area. Note that cumulative effects refer to the cumulative impact of multiple emissions sources on air quality; the meaning does not include interaction of air with other media, nor does it include the impact over time.

The secondary objectives of the network are to:

- Support the monitoring and reporting requirements associated with regional, provincial, and national air quality management obligations including:
  - Information required for the implementation of provincial and regional air quality management strategies (e.g., Upper/Lower Peace Air Quality Management Framework),
  - Information required for CAAQS (Canadian Ambient Air Quality Standards) reporting, and
  - Information required for the implementation of provincial and regional acid deposition monitoring, evaluation, and management frameworks.
- Provide ambient information needed to support modelling and remote sensing (e.g., OSM work plans), including suitable input and validation information to verify or calibrate dispersion, transformation, and deposition models and suitable information to ground truth remote sensing data.
- Provide data to assess regulatory compliance.
- Provide information needed to understand transboundary transport including characterizing the quality of air entering and leaving the Region.
- Provide information needed to distinguish sources of industrial of emissions and other natural and anthropogenic sources.

1.3 Emerging Issues

According to PRAMP, the following emerging issues were to govern the evaluation.

Tier One

- Hydrocarbon context: emissions reduction, regional air quality improvement, a regulatory framework for cold heavy oil production (CHOP) is in place (Directive 84) and mitigation measures have been implemented. How do these changes inform the optimization of PRAMP's monitoring program?

Tier Two

- The continuous air monitoring station and 12 passive monitors at the Peace River Complex (PRC), formerly operated by Canada Natural Resources Limited (CNRL) or its operating subsidiary Canada Natural Upgrading Limited (CNUL), were recently added to the PRAMP network. PRAMP would like to understand if or how the overall monitoring network could be optimized while still meeting the monitoring objectives.
- PRAMP has been asked to consider incorporating the two Mercer air quality monitoring stations, Mercer Plant (Peace River Pulp Division - PRPD) and Mercer Town (**Figure 1**) into the PRAMP network. The monitoring would be done on a fee for service basis, and in compliance with Mercer's

EPEA approval. If the two Mercer stations were incorporated into PRAMP's program, PRAMP would like to understand if or how the overall monitoring network could be optimized while still meeting the monitoring objectives.

Tier Three

- There is a large monitoring-deficient area adjacent to PRAMP. To the north and west of PRAMP's boundaries, there is no Airshed and limited or no monitoring. Are there any emerging air quality issues in the area just outside PRAMP's boundaries that PRAMP should consider in its monitoring program?
- With the growth of access to and interest in lower-cost new technologies for monitoring air quality, how could they best be incorporated in the PRAMP monitoring program (e.g., Purple Air sensors).

2. Data Sources and Analysis Procedures

2.1 Data Sources

The locations of facilities within the PRAMP area were taken from two sources, AER and the National Pollutant Release Inventory (NPRI). **Figure 2** shows the type and locations of these facilities according to the AER inventory. Most of these facilities reported emissions of various pollutants to the NPRI database between 1999 and 2020 as shown in Figures A1 to A8 (Appendix A); these emissions are used as a reference for the observed changes in air quality within the PRAMP area over the past decade.

Surface locations of wells from the AER inventory are also mapped in **Figure 3** in terms of Kelly Bushing Elevation and area density (number of wells per unit area). The base map represents the density of wells within and outside the PRAMP area based on AER data. Note the Kelly Bushing elevation is the well depth measured from the drilling platform. For this report, the well depth is irrelevant but well locations are not.

Figure 2: Oil, Gas and Other Facilities within the PRAMP Area and Surroundings (AER Data)

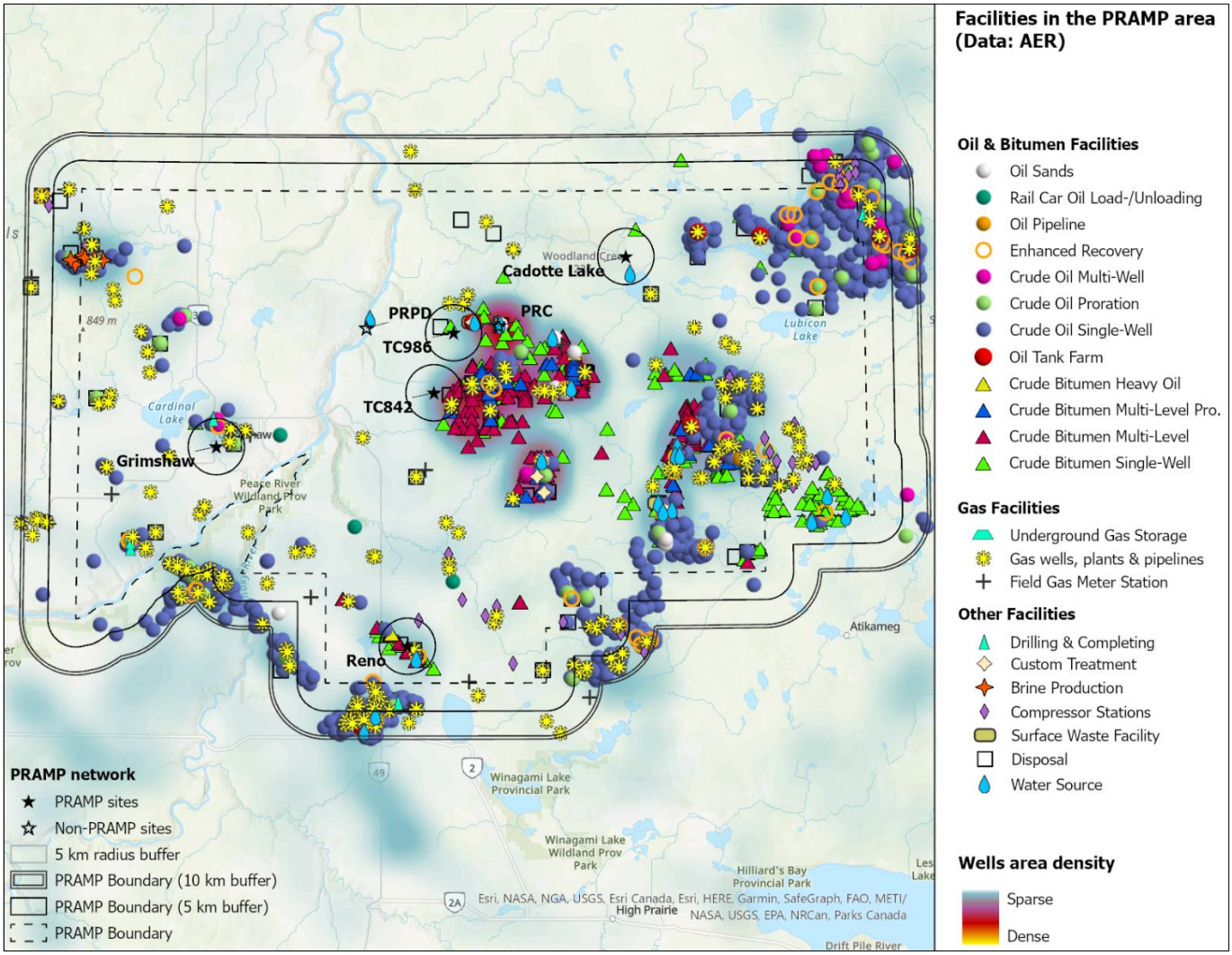
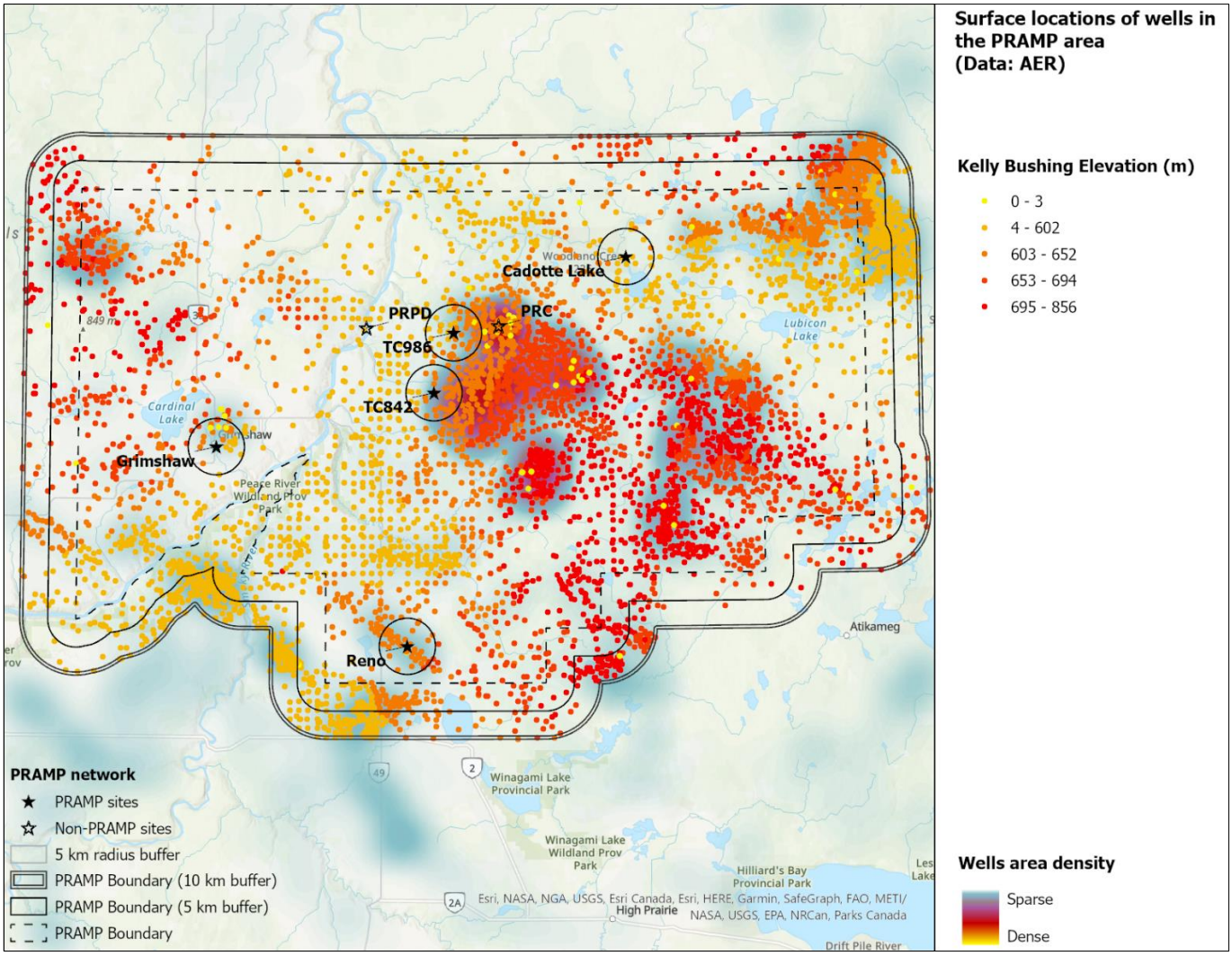


Figure 3: Surface Locations of Wells and Their Elevation in the PRAMP Area



Ambient air quality data for the PRAMP area was taken from:

- Continuous monitoring air quality and meteorology data from 2010 to 2021 was provided by PRAMP; additional data was downloaded from the Alberta Air Data Warehouse (https://www.alberta.ca/access-air-quality-and-deposition-data.aspx)
- Monitoring conducted for compliance with EPEA approvals – continuous, intermittent, passive, and dustfall, taken Alberta Air Data Warehouse or requested from the facility with assistance from PRAMP

In addition, other information sources were considered:

- The most recent photochemical modelling study for the province (Rambol and Novus 2018) provided guidance on the location of stations relative to the location of predicted model concentration maxima.
- All ambient air quality monitoring required by all sources in the PRAMP area.

2.2 Analysis Procedures

The following general analytical processes were applied to support portions of the assessment:

- Calculation of station and instrument uptime as input to data quality assessments
- Preparation and tabulation of data statistics for hourly, daily, and annual averages. Prepare box-and-whisker plots for hourly data. Tables of exceedance frequency for all variables and all stations.
- Calculation and plotting of diurnal variations
- Calculation and plotting of annual averages for each year in the dataset since inception. Information in the Stantec (2014) report was reviewed for additional support.
- Preparation of wind and pollutant roses for each site, as well as statistics of wind speed at each monitoring station.
- Preparation and tabulation of annual emissions by facility, pollutant since network inception. As part of this process, it was identified if any facility had significant emissions of unmonitored pollutants.
- Plot emission rates (density) of all sources within the PRAMP network area.

3. Results of Evaluation

3.1 Priority 1 – AER Directive 084 Impact

3.1.1 Approaches to Evaluate Priority 1

Directive 084 (Requirements for Hydrocarbon Emission Controls and Gas Conservation in the Peace River Area), with an effective date of September 27, 2018, set out requirements for addressing odour and emissions generated by heavy oil and bitumen operations in the Peace River area. This directive applied to all AER-regulated wells and facilities associated with heavy oil and bitumen operations in the Peace River area. This directive did not apply to AER-approved waste disposal facilities located in the Peace River area, which were under the requirements of Directive 060.

The Priority 1/Tier One issue was to assess whether the existing ambient network (PRAMP) can be optimized. The reason is that mitigation of vapour release technologies and changes due to AER Directive 84 have been adapted and should now be evident in the data. Optimization may include reconsidering the number of stations, parameters, and other monitoring/measurements related aspects (location, duration, frequency, methodology, technology).

The PRAMP network consists of four continuous ambient air monitoring stations (986, 842, Reno and portable AQHI) – with recent addition of the PRC station to become the fifth -, each measuring sulphur dioxide (SO_2), total reduced sulphurs (TRS), total hydrocarbons (THCs), methane (CH_4) and non-methane hydrocarbons (NMHCs)) and meteorology (wind, precipitation, temperature and climate variables). Additionally, canister measurements of CH_4 and NMHCs are available at three of the stations (986, 842 and Reno). The key emerging issue is whether the expected reduction in measured concentrations due to improved emission reduction strategies justifies network optimization.

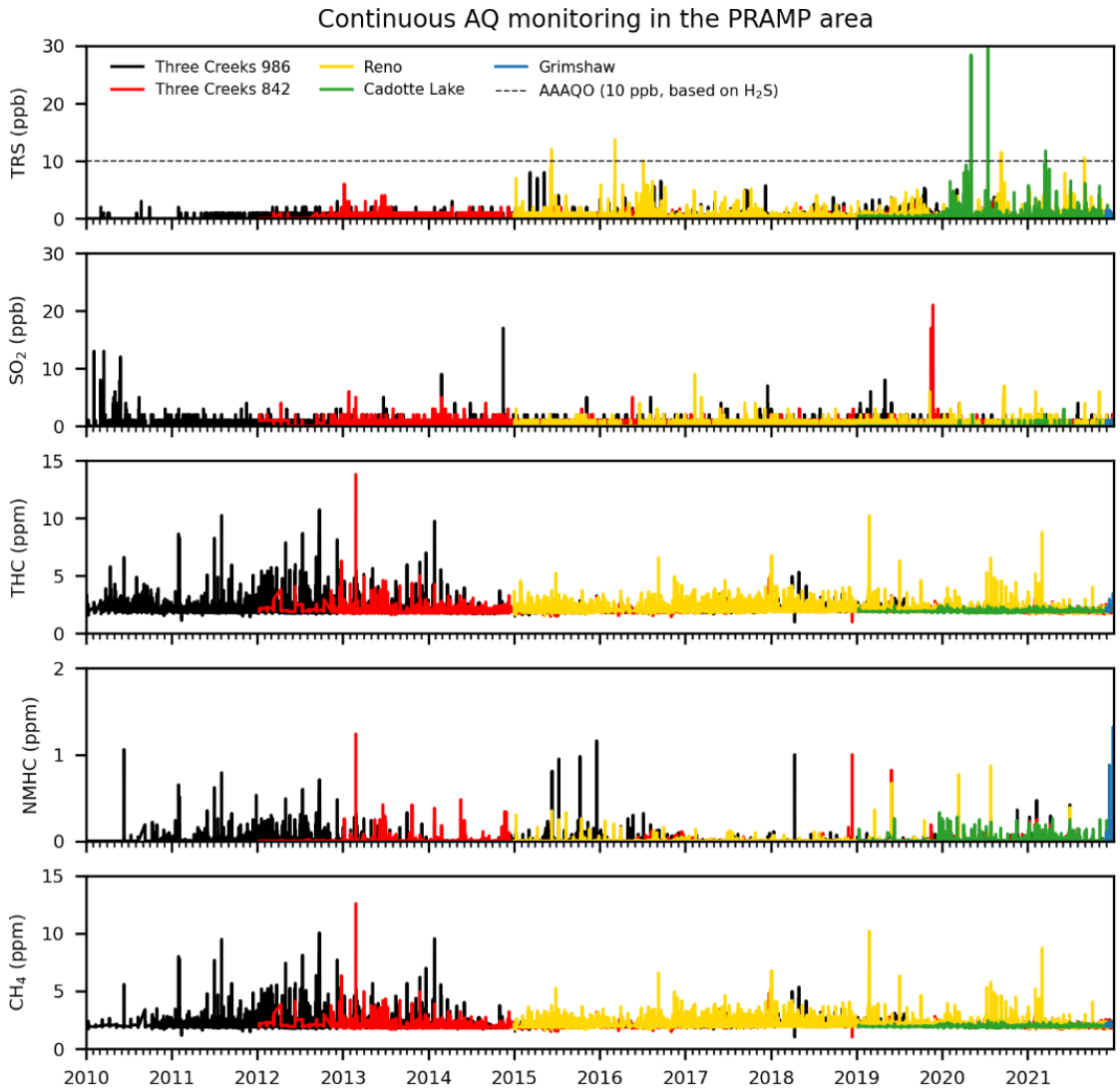
The work steps used to address the issue were:

1. Examined the trend in annual emissions at each source and compared the trend to that of annual average concentrations at monitoring stations. Optimization was not considered if the trends in concentrations or emissions since emission controls were introduced are not downward, or if the trends are not consistent.
2. Examined the extreme concentration statistics. Where exceedances of AAQOs or other thresholds (e.g., odour) are observed at any station, it is unlikely this station could be considered for rationalization. If the only exceedances were of annual averages, it is possible a passive approach rather than a continuous measurement approach could be adopted.
3. Examined the concentration statistics by year. It is possible that trends in annual averages may not be present, but trends in percentiles or other statistics are. Reductions in percentiles or standard deviations would support optimization.
4. Calculated and tabulated inter-station correlations. If hourly concentrations for all pollutants are highly correlated (above a threshold to be defined), one of the two stations could be considered for rationalization.
5. Examined diurnal concentrations of hourly pollutant levels. Dissimilar profiles were a basis for not rationalizing the network.
6. Compared pollutant roses to wind roses at the same site and compared pollutant roses among sites. Pollutant roses significantly different from wind roses or from pollutant roses at other stations were a basis for not rationalizing the network.
7. Reviewed well production data to determine if emission changes were the result of production changes or to emission reduction initiatives.

3.1.2 Temporal Variations and Trends

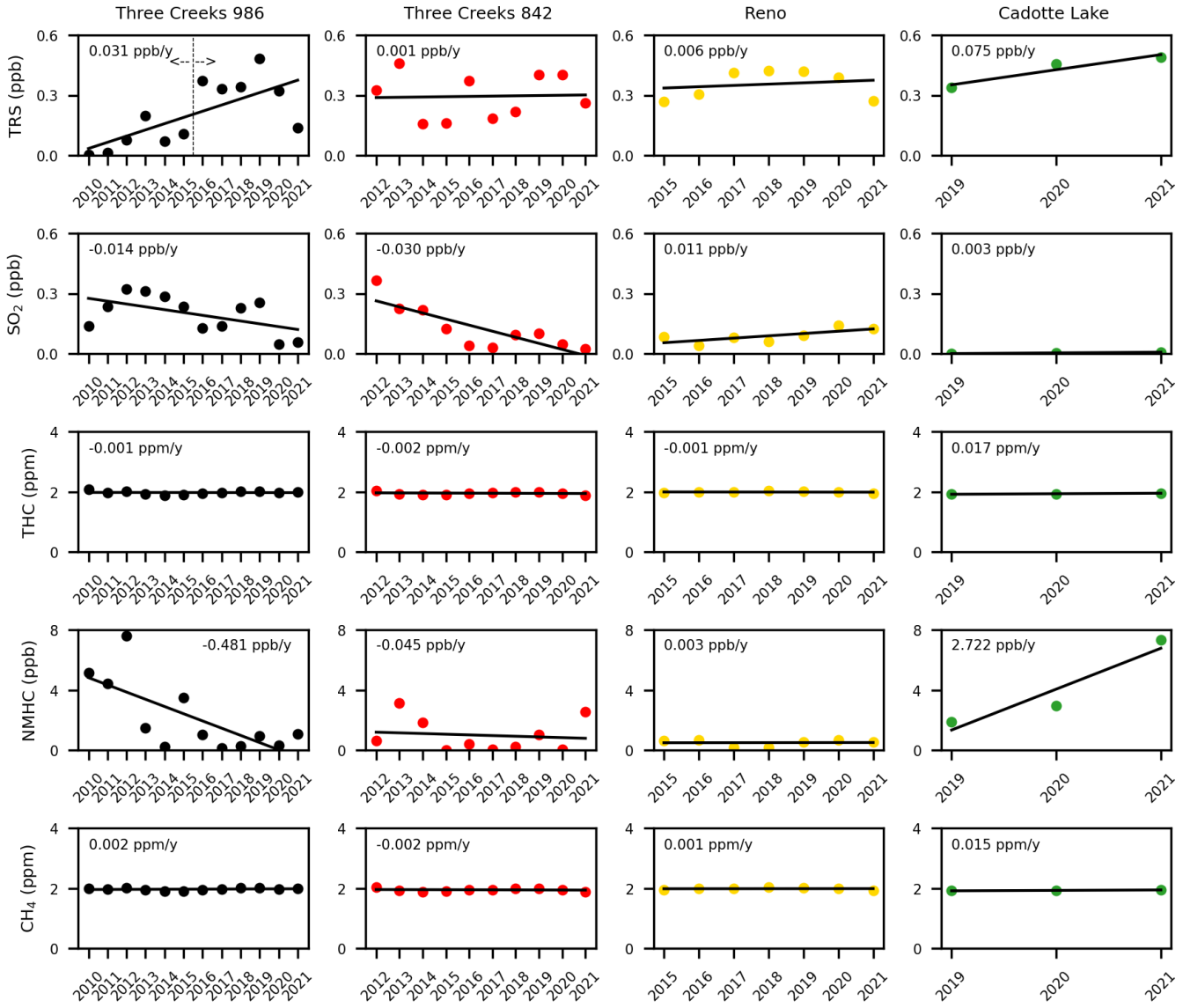
The time series of hourly average data for five pollutant categories (**Figure 4**) show variation over time at all PRAMP continuous monitoring stations, each station having a different starting time. The Three Creeks 986 station has the longest monitoring period among all stations (12 years), followed by Three Creeks 842 (10 years), Reno (7 years), Cadotte Lake (3 years) and Grimshaw (1 month). On average, the stations appear to agree for all pollutants during overlapping time periods, with sporadic high concentration events being recorded differently by each station. The 1-h Alberta Ambient Air Quality Objectives (AAAQOs) for H_2S (assuming TRS is mainly H_2S) of 10 ppb is plotted in the top of **Figure 4** and highlights a few exceedances (4 at Reno and 3 at Cadotte Lake). The SO_2 and CH_4 concentrations were well below the AAAQOs (172 ppb for 1-h average SO_2) and the Environmental Screening Levels (ESL) - based odour thresholds (TCEQ 2015) (20-512 ppb for both short and long-terms of 1-h average CH_4); note that these values are not visible on the graphs as they exceed the scale of the y-axes defined by the measured concentrations. AAAQOs or odour thresholds are not available for lumped categories, such as NMHC and THC.

Figure 4: Temporal Variation of Hourly Pollutant Concentrations at Continuous PRAMP Stations



The temporal trends for all pollutants were further assessed using linear regression of annual average concentrations versus time (**Figure 5**). Because each station covers different periods of time and there are at least 3 years of overlap between most of the stations, linear trends at each station and between stations were reviewed separately.

Figure 5: Temporal Trends in Annual Average Concentration of Main Pollutants



Linear slope values (ppb/y or ppm/y) over the entire monitoring period at each station show the direction and magnitude of change in pollutant concentration per year; slope values closer to zero indicate relatively no change.

To summarize the extreme values and the comparison to AAAQOs, exceedances of the 10-ppb reference concentration for TRS occur at Cadotte Lake and Reno while concentrations of SO_2 are much less than the 1-hour objective.

3.1.2.1 Trends of Pollutant Levels Versus Time by Station

When trends are considered over the available period of monitoring, the following was observed:

- Three Creeks 986 (data from 2010 to 2021)
  - SO_2 and NMHC decreased over time by 0.014 ppb/y and 0.481 ppb/y respectively
  - TRS increased by 0.031 ppb/y
  - No notable change in THC and CH_4 (slopes values nearly zero).
- Three Creeks 842 (data from 2012 to 2021)
  - SO_2 and NMHC decreased over time by 0.030 ppb/y and 0.045 ppb/y respectively
  - No notable change in TRS, THC and CH_4 (slopes values nearly zero).
- Reno (data from 2015 to 2021)
  - TRS and SO_2 slightly increased over time by 0.006 ppb/y and 0.011 ppb/y respectively, but decreased since 2018
  - No notable change in NMHC, THC and CH_4 (slopes values nearly zero).
- Cadotte Lake (data from 2019 to 2021)
  - TRS and NMHC increased over time by 0.075 ppb/y and 2.722 ppb/y respectively
  - No notable change in SO_2, THC and CH_4 (slopes values nearly zero).

3.1.2.2 Trends of Pollutant Levels Versus Time Between Stations

When trends are considered over the available period of monitoring, the following comments are noted:

- TRS:
  - Increased and then decreased over time at all four stations. The trend is a decreasing one since implementation of Directive 84 as can be seen at all stations but Cadotte Lake.
- SO_2:
  - Decreased over time at the Three Creek stations 986 and 842 by 0.014 ppb/y and 0.030 ppb/y
  - Slightly Increased at Reno and Cadotte Lake, but slope values are near zero and all the annual averages are well below 0.3 ppb between 2015-2021.
- THC:
  - No notable change over time is obvious at any station.
- NMHC:
  - Decreased over time at the Three Creek stations 986 and 842 by 0.481 ppb/y and 0.045 ppb/y respectively; the decreasing trend is more significant at 986 compared to 842 due to inclusion of additional two years with high concentrations (2010-2011) and ~3 times larger annual concentration in 2012
  - Increased at Cadotte Lake by 2.722 ppm/y, but trend is based on only 3 years
  - No notable change at Reno station.
- CH_4:
  - No notable change over time is obvious at any station.

Additional pollutants have been measured at the Cadotte Lake (2019-2021) and Grimshaw (December 2021) stations. These pollutants are nitric oxide (NO), nitrogen dioxide (NO_2), oxides of nitrogen (NO_x = NO + NO_2), ozone (O_3) and particulate matter with diameter smaller than 2.5 microns ($PM_{2.5}$). The nitrogen oxides family is known as an O_3 precursor in addition to VOCs and, therefore, they can provide additional context to O_3 contributions in the

PRAMP area, although O_3 pollution is not an issue in this region. The corresponding time series of these pollutants are provided separately for each station due to different temporal resolution.

At Cadotte Lake (**Figure 6**), no exceedances of the 1-h average AAAQOs values were found for any pollutant, except for $PM_{2.5}$ (the 1-hour guideline for $PM_{2.5}$ is not a regulatory objective). The AAAQOs values for 1-hour O_3 (76 ppb) and 1-hour $PM_{2.5}$ (80 µg/m^3) are plotted as a dashed line, while the AAAQO value for 1-hour NO_2 (159 ppb) is not visible as it exceeds the scale on the y-axis. Note that the effective start date of data monitoring at this station was October 1st, 2019. However, prior to that, data was monitored but at a much lower temporal resolution (possibly due to testing of the station).

Figure 6: Temporal Variation of Hourly Concentrations of Complementary Pollutants Measured at Cadotte Lake Station during 2019-2021

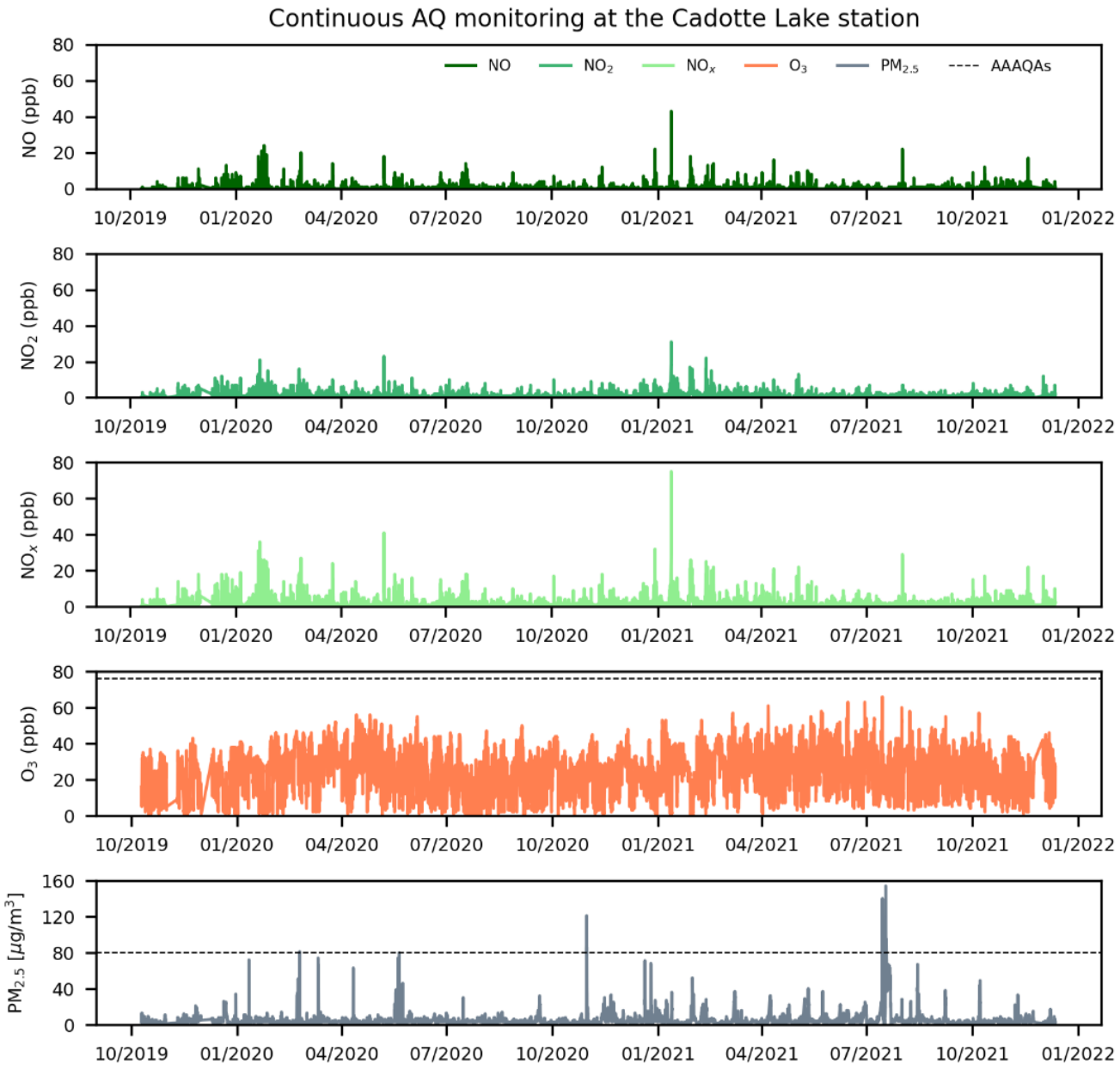


Figure 7 shows the linear trends of the annual average NO, NO_2, NO_x, O_3 and $PM_{2.5}$ measured at Cadotte Lake between 2019 and 2021 (the 2019 average value may be biased due to considerably smaller sample size compared to years 2020-2021). Oxides of nitrogen slightly declined, while O_3 and $PM_{2.5}$ concentrations slightly increased over the past three years at the Cadotte Lake station.

At Grimshaw (**Figure 8**), no exceedances of the 1-h average AAAQOs values were found for any pollutant, respectively values of 159 ppb (NO_2), 76 ppb (O_3) and 80 µg/m^3 ($PM_{2.5}$).

Figure 7: Temporal Trends in Annual Average Concentrations of Complementary Pollutants Measured at Cadotte Lake between 2019 and 2021

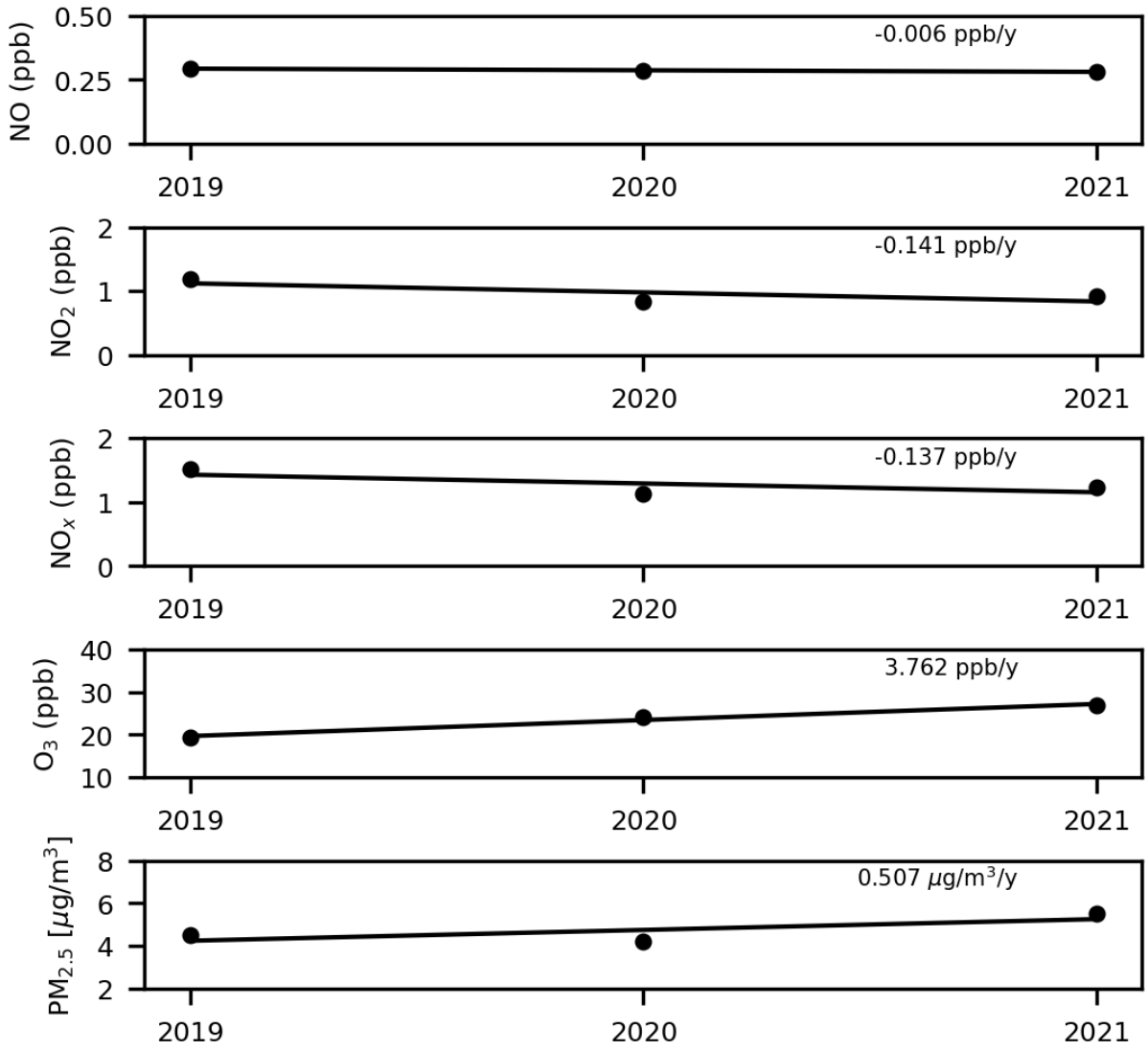
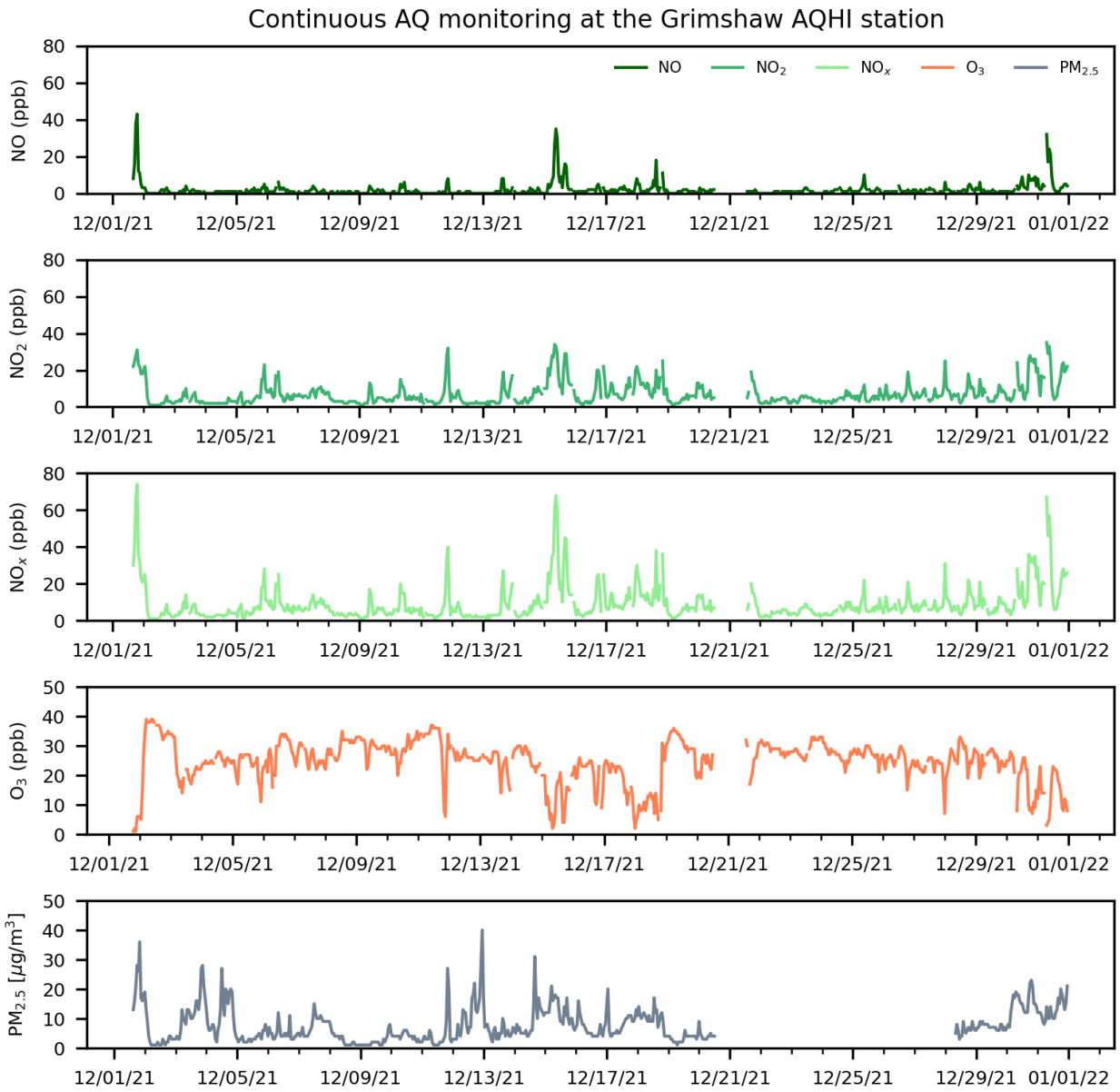


Figure 8: Temporal Variation of Hourly Concentrations of Complementary Pollutants Measured at Grimshaw Station during December 2021



3.1.2.3 Intermittent Canister Data

Canister VOC data from 2010 to 2021 at three of the PRAMP stations (Three Creeks 986 and 842, and Reno) were analyzed. Data from the 2010 to 2014 period are taken from AEP (no records were available for 2015) and represent samples collected at or near the current 986, 842 and Reno stations (past names 986b, 986c, 842b and Reno2). Data from 2016 to 2021 were provided by PRAMP and were based on the canister sampling system installed at continuous monitoring stations (Three Creeks 986 and 842, and Reno). The 1-h canister sampling events are triggered when the 5-minute average concentration measured in real-time at continuous monitoring stations reaches a threshold value (e.g., trigger point). For NMHC, the trigger point is 0.3 ppm. This assessment considered seven VOCs: acrolein, benzene, chloroform, toluene, ethylbenzene, m,p-xylene and o-xylene. Some of

these VOCs are primarily emitted by refineries, petrochemical plants or evaporated from fuel storage tanks and typically are summed into a class of compounds called BTEX (benzene, toluene, ethylbenzene, and xylenes). The approach averaged all available 1-h event data for each year and used the annual averages to infer the trend in VOCs to assess whether these VOCs exceeded their corresponding AAAQO or odour threshold values. **Figure 9** and **Figure 10** shows how the annual average VOC concentration varied over time at each station and whether that average exceeded the corresponding AAAQO or odour threshold value. Note that the number of canister samples that contributed to the average in each year varied from 1 to 51, depending on the VOC. The number of samples is plotted above each bar in **Figure 9** and **Figure 10**; where there was only one sample in a year, the actual concentration is used instead. The VOC with the largest number of sampled events was benzene and, therefore, the corresponding annual average is statistically more significant than those of other VOCs. Overall, the annual average concentration compares well among the stations, and it decreased during 2019-2021 at all stations for all VOCs except for chloroform and o-xylene at Reno/Reno2, which is in line with the decreasing trend in total VOCs emissions over the same period (**Figure 11**), and to a lower extent, with the trend in NMHC concentration (**Figure 5**). Acrolein and benzene show exceedances of the 1-h AAAQO (1.9 ppb and 9 ppb respectively) in 2019 at 986, while benzene also shows exceedances at 842 and Reno in the same year. The number of samples contributing to these exceedances varied from 1 at 986 (for acrolein and benzene), 2 at 842 (for benzene) and 5 at Reno (for acrolein). Other VOCs had concentrations well below the 1-h AAAQO and odour thresholds. The largest BTEX concentration (~40 ppb) was observed at Three Creeks 842/842b in 2013 and was primarily driven by toluene. On average, all stations recorded BTEX below 25 ppb between 2014 and 2021. All stations and especially Three Creeks 986 had fewer canister samples since 2014, the number of samples ranging between 1 and 9 per year.

Figure 9: Canister Concentrations of VOCs (Acrolein, Benzene and Chloroform) at or near PRAMP Stations Between 2010 and 2020, when Trigger Thresholds were Exceeded

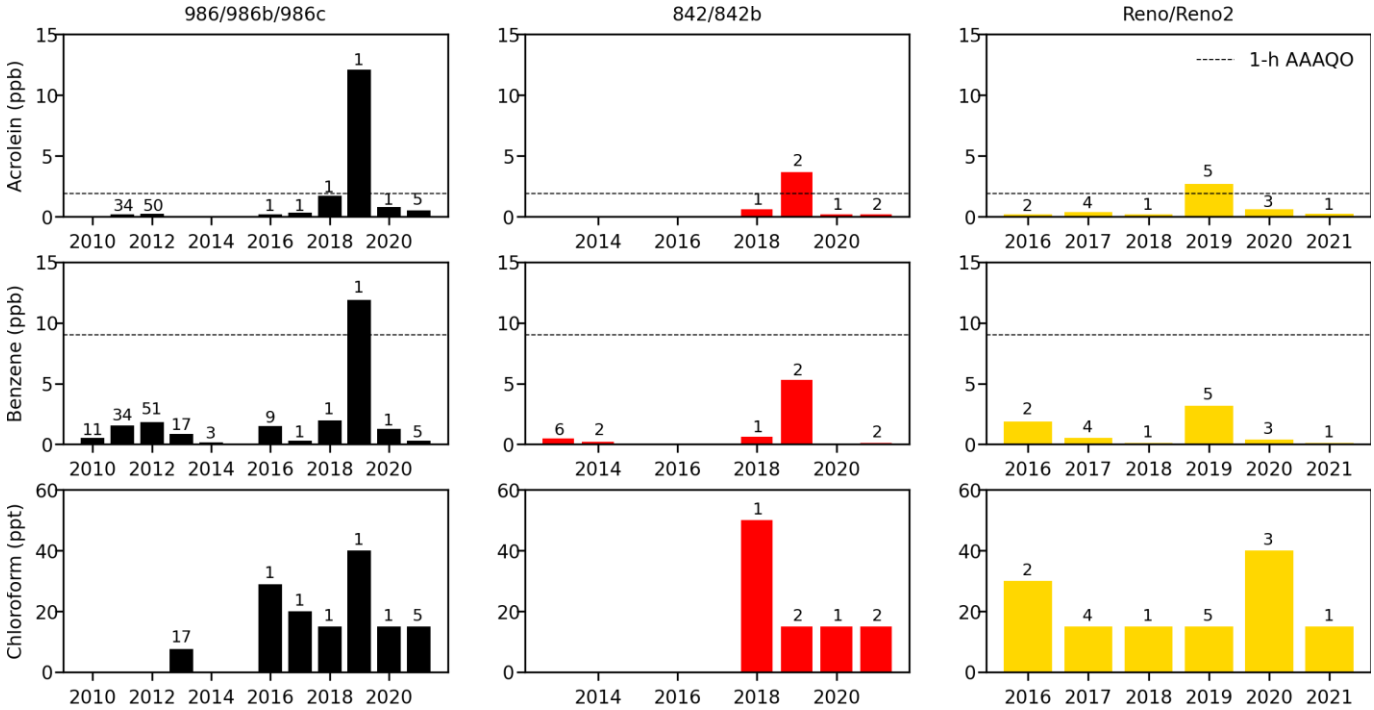
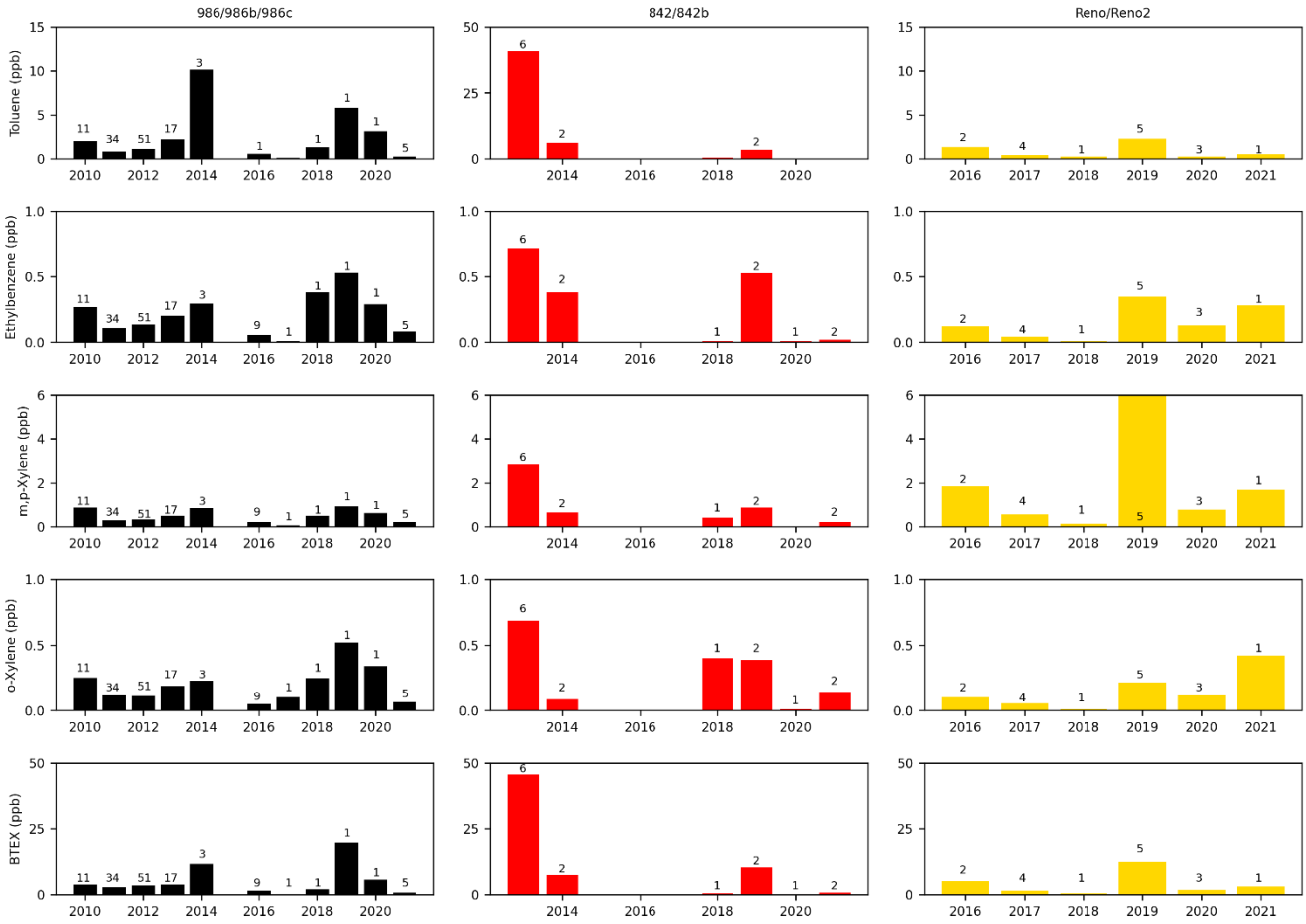


Figure 10: Canister Concentrations of VOCs (Toluene, Ethylbenzene, m,p-Xylene, o-Xylene and BTEX) at or near PRAMP Stations Between 2010 and 2020, when Trigger Thresholds were Exceeded



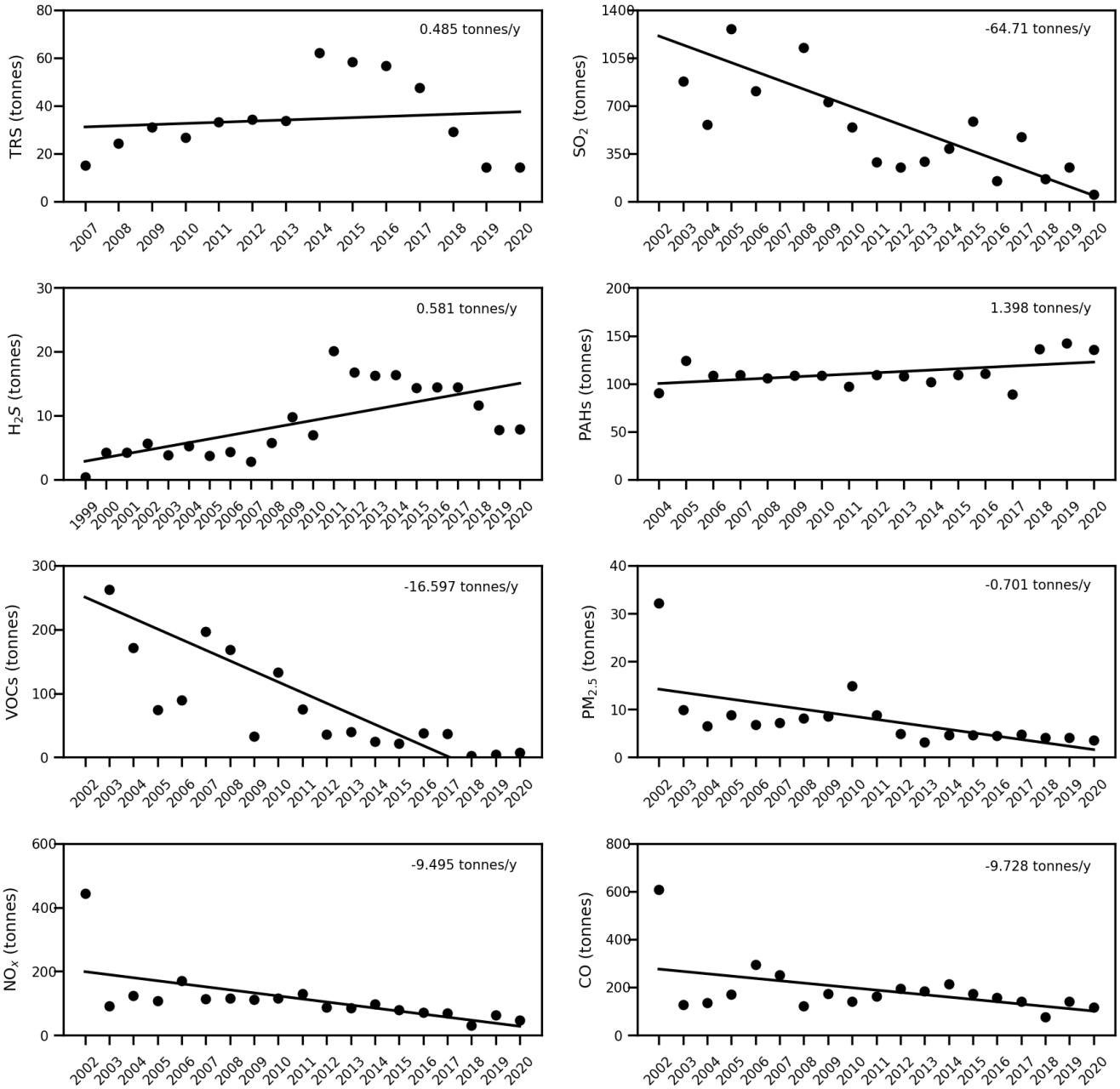
3.1.2.4 Trends in NPRI-Reported Emissions

The trends in historical emissions of similar pollutants measured within PRAMP area are plotted in **Figure 11**, which also include a linear trend line for reference:

- Emissions of TRS and H_2S increased over time and this trend is consistent with that of measured TRS at PRAMP stations over comparable time (**Figure 5**). However, emissions of TRS and H_2S decreased after 2014.
- Emissions of SO_2 generally decreased in the monitoring period, like the trends in measured SO_2 at PRAMP stations (**Figure 5**).
- Emissions of PAHs increased while those of VOCs decreased within the PRAMP area over time (**Figure 11**). These pollutants are not measured directly in the ambient network but correspond broadly to categories of measurements provided as THC and NMHC in **Figure 5**. While THC concentrations did not change at any station and NMHC did not change at Three Creeks 842 and Reno, NMHC increased at Three Creeks 986 and decreased at Cadotte Lake. These changes are not fully reflected in NPRI emission information which does not account for many small oil and gas sources within and near the PRAMP boundary.

- The trends in NO_x at the Cadotte Lake station (**Figure 7**) are consistent with those from similar emissions from the larger PRAMP region between 2002-2020 and, particularly, for the period 2019-2020 (**Figure 11**). $PM_{2.5}$ concentration measured at the same station (**Figure 7**), appears to be increasing due to a slightly higher annual average concentration in year 2021, most likely due to forest fires, but the trend from years 2019-2020 is consistent with that of emissions for the same period (**Figure 11**).

Figure 11: Temporal Trends in Annual Average Emissions of Pollutants as the Sum of All NPRI Reporting Facilities within the PRAMP Boundary



3.1.2.5 Trends in Oil and Gas Production and Relation to NPRI-Reported Emissions

Volumetric monthly production data from the Petrinex Canada Petroleum Information Network (available at https://www.petrinex.ca/PD/Pages/APD.aspx) was used to assess the trends in oil and gas production in the PRAMP region, from January 2018 to August 2022. The data was primarily cross-referenced with the location of the oil and gas wells within the PRAMP boundary and then filtered by activity type (production) and product type (oil or gas). Monthly average and total volumes were computed from these filtered data and plotted in **Figure 12** and **Figure 13** to assess the general trends in production of oil and gas. Both trends in oil and gas production (expressed as monthly average or total oil production volume within the PRAMP region) decreased over time, but the trends in oil production decreased more significantly than gas production (steeper slopes from linear regression). The drop in production of both oil and gas in early 2020 reflects the effect of the pandemic on the oil and gas extraction sector. Overall, production trends reflect the trends in related NPRI emissions of VOCs, TRS, H_2S, and SO_2 over the same period (2018-2020) and the trends in air quality. This report has not determined the extent to which reduced ambient air concentrations are a response to reduced production.

Figure 12: Monthly Trends in Volumetric Oil Production in the PRAMP Region

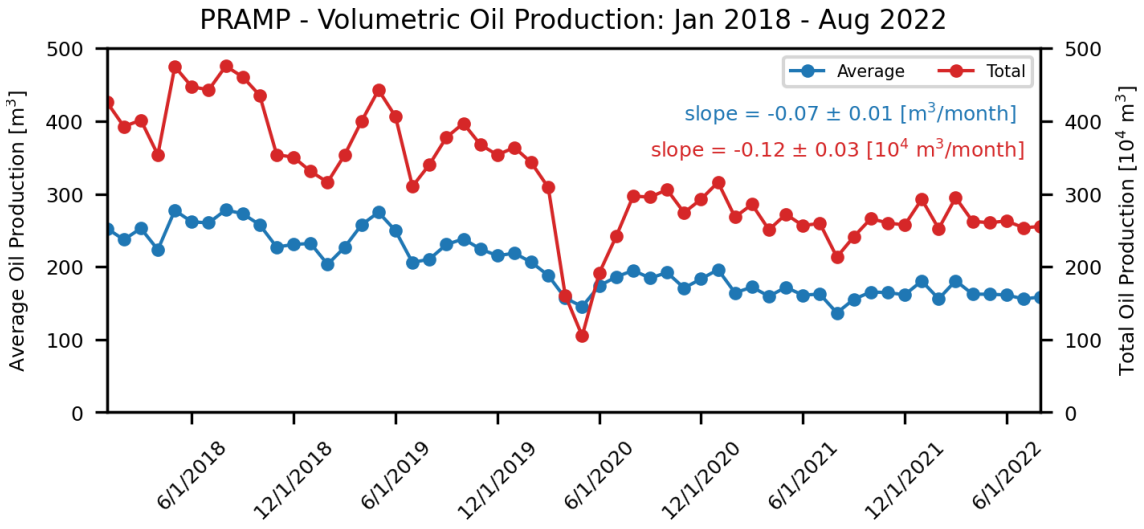
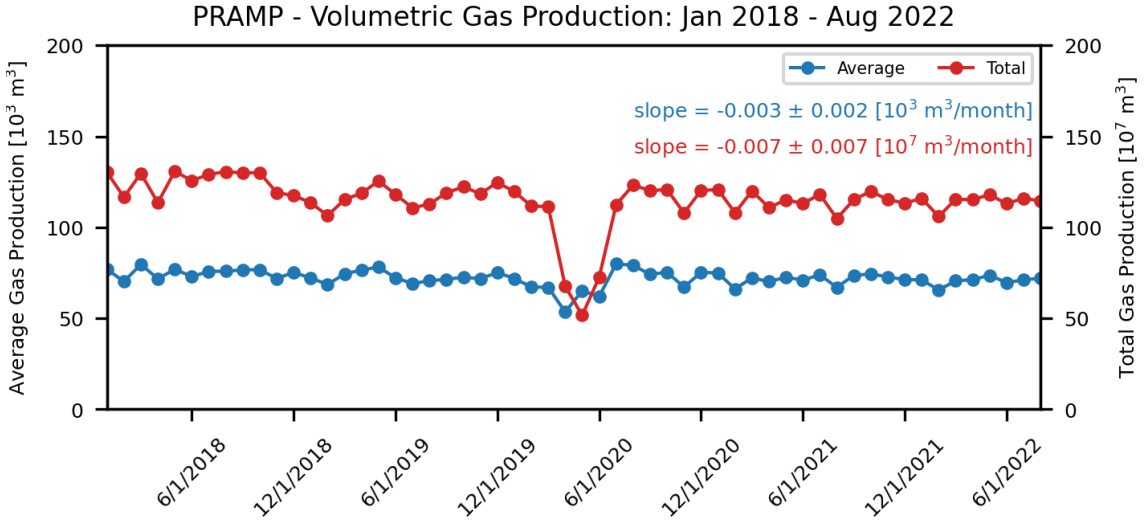
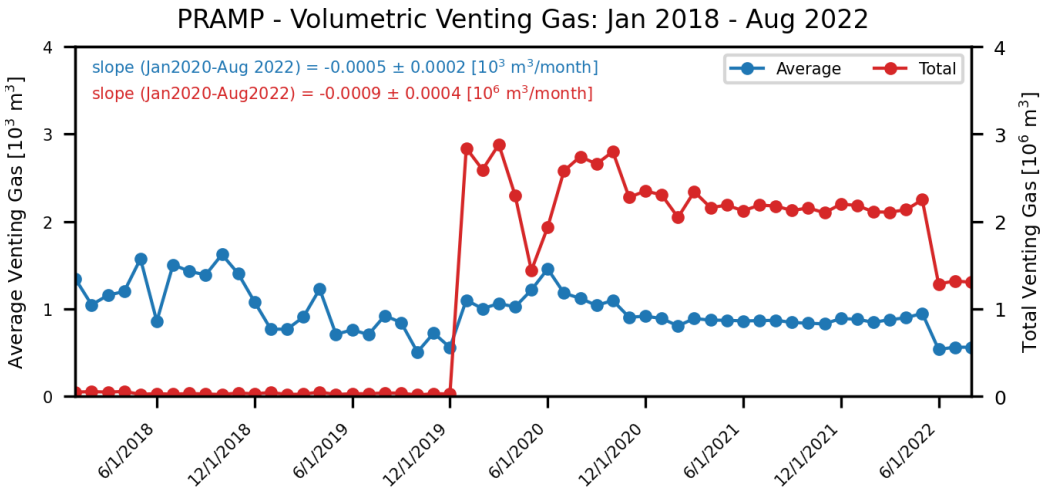


Figure 13: Monthly Trends in Volumetric Gas Production in the PRAMP Region



To address Directive 084 more directly, such as reduced vent gas associated with heavy oil and bitumen in the Peace River area, **Figure 14** shows the average and total volumetric venting gas trends from crude oil, heavy oil, and bitumen batteries within the PRAMP region between January 2018 and August 2022. The average vented gas has been decreasing consistently since 2018 (by 0.0003 ± 0.0001 10^3 m^3/month). For total vented gas, there was a change in reporting beginning in January 2020 (e.g., gas used to drive a pneumatic device is now considered vented), and since that time total vented volumes have also decreased. Both average and total metrics show statistically significant negative slopes since that time, implying that vented gas volumes have been decreasing in the PRAMP region over the past two years.

Figure 14: Monthly Trends in Volumetric Venting Gas in the PRAMP Region



3.1.3 Correlation of Concentrations Among Stations

Correlations of pollutant measured at the continuous stations within the PRAMP area were determined using the Pearson correlation coefficient *r*, which is a measure of covariance and ranges between -1 (strong negative correlation) to +1 (strong positive correlation); an *r* value of zero indicates no correlation. The correlation coefficients were determined for three periods of time when at least two stations have data measured over the same period and at the same temporal resolution, respectively 2012- 2021 (10 years and 2 stations), 2015-2021 (7 years and 3 stations) and 2019-2021 (3 years and 4 stations). The correlation matrices corresponding to these three periods are plotted in **Figure 15** to **Figure 17**.

Figure 15 shows how the pollutants are correlated between the two Three Creeks stations (986 and 842). The Pearson *r* varied from +0.2 to +0.4, overall, suggesting that these stations are modestly related in space and time with respect to the pollutants they measure. The largest correlations (*r* = +0.4) were observed for THC and CH_4, suggesting that these two stations may experience similar influences from hydrocarbon sources in their neighbourhood.

Figure 16 depicts correlation of pollutants between three stations but for a short period of time than in **Figure 15**. The *r* value ranged between +0.1 and +0.5, with the largest value corresponding to THC and CH_4 likely because both are dominated by the “global background” of CH_4 concentrations. The lowest values corresponded to SO_2 and TRS.

Figure 17 illustrates correlation of pollutants between all four stations but only for a period of 3 years. Pearson *r* varied between -0.003 to +0.78. The largest correlation (+0.78) was for NMHC at Three Creeks 986 vs. 842, followed by THC (+0.5). Pearson *r* values near zero were observed for SO_2, TRS and NMHC (Cadotte Lake vs. any other station). The consistent correlations for all pollutants between the two Three Creeks stations (986 and 842) for any of the analyzed time periods suggest that they measure relatively similar air, but the magnitude of correlation coefficients

suggest that they experience some differences (wind direction or proximity to different emission sources) which may prevent them from being more strongly correlated. The Reno station is correlated to the Three Creeks station but weakly, while Cadotte Lake is not correlated to any station for any pollutant considered.

Overall, the strongest correlations (*r* value of 0.78) were derived from the shortest dataset that included data from all the PRAMP stations and associated with NMHC and THC at Three Creeks stations (986 and 842), suggesting these stations might be marginally redundant but only with respect to hydrocarbons. The lower correlations with respect to other pollutants (TRS and SO_2) do not support a reduction in the number of stations.

Figure 15: Bi-variate Pearson Correlations for Main Pollutants at the Three Creeks Stations (2012-2021 data)

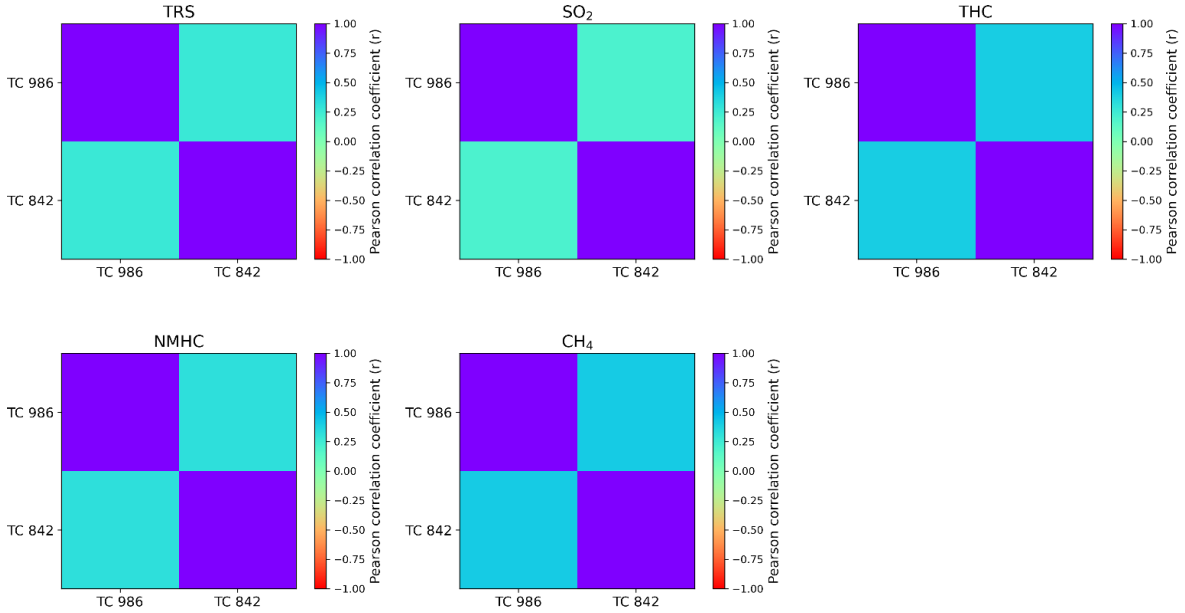


Figure 16: Bi-variate Pearson Correlations for Main Pollutants at the Three Creeks and Reno Stations (2015-2021 data)

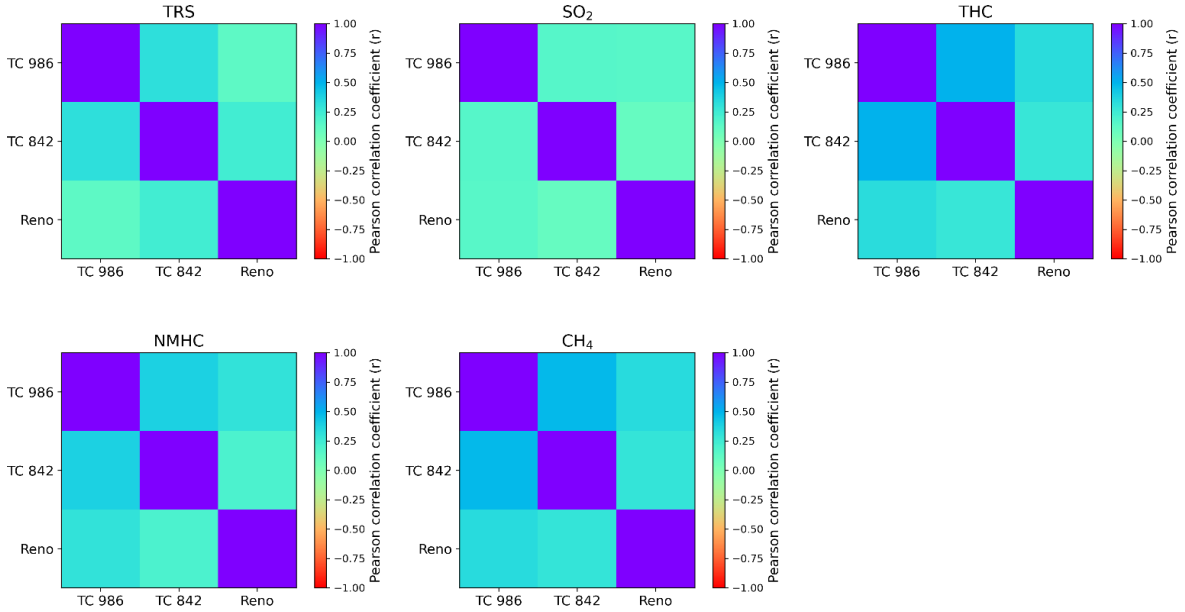
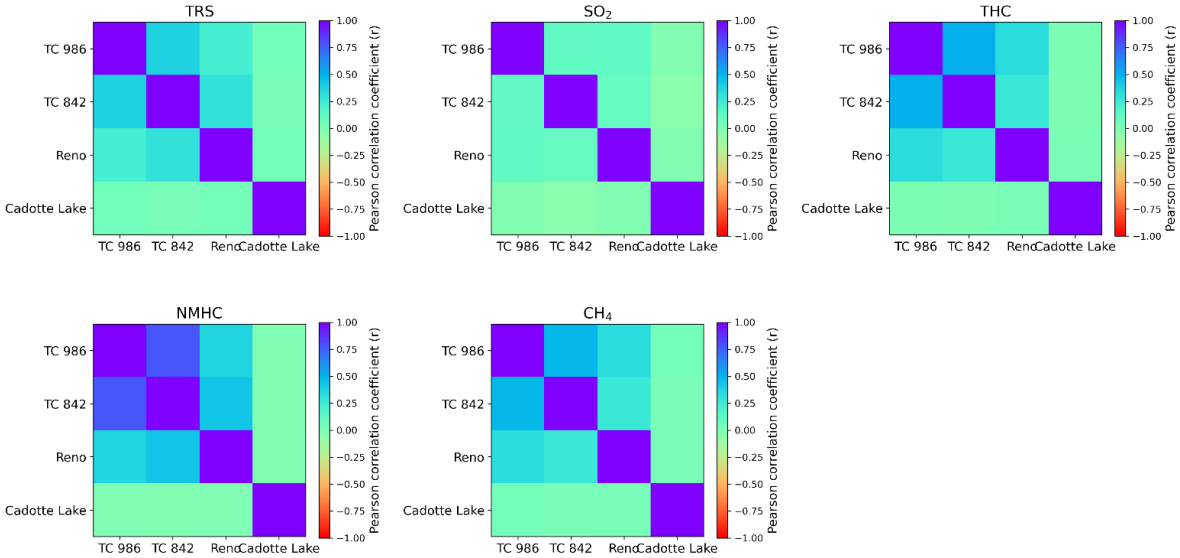


Figure 17: Bi-variate Pearson Correlations for Main Pollutants at the Three Creeks, Reno and Cadotte Lake Stations (2019-2021 data)



3.1.4 Summary

Priority 1 was to establish whether the network can discern changes in measured concentrations with implementation of Directive 84. Implementation was effective September 2018; reductions could begin in 2018 for early adopters of the technical changes, and certainly beginning 2019. As a follow-up, the question can be asked as to whether the network should be modified if the pollutants targeted by Directive 84 showed significant reduction.

The following analyses are important for determining the performance of the network to detect potential changes because of Directive 84:

- Changes of emissions with time in the PRAMP area:
  - Since 2018, emissions of all NPRI reported compounds, except PAHs, have decreased, consistent with the O&G industry downturn after 2014 and consistent with Directive 84 implementation. This supports reduced monitoring for total VOCs, of which emissions are near zero when summed over all NPRI reports within the PRAMP boundary.
  - The NPRI data do not capture all emissions and Directive 84 covered only specific emission sources
  - Since 2018/2019, concentrations of TRS decrease at all stations except at Cadotte Lake. Over longer periods, the trend is different at 986 before and after 2015 due to different analytical/instrument settings such that TRS increased between 2010 and 2015 and generally decreased after.
  - Since 2018/2019, SO_2 concentrations decreased at Three Creeks stations, slightly increased at Reno and were constant at Cadotte Lake.
  - Measured concentrations of THC and CH_4 (at a ppm scale) showed no trend with time over the period of record and post Directive 84.
  - Throughout the monitoring period, and since 2018/2019, trends in concentrations of NMHC were variable depending on the time period and station.
    - It is likely that low levels of VOC emissions from many facilities and well sites contribute to elevated concentrations
    - Similar trends and concentrations generally exist at both Three Creeks stations, suggesting one could be redundant, notwithstanding the generally different trends at other monitoring sites.

- Volumetric oil and gas production trends in the PRAMP area suggest that oil and gas production decreased since January 2018 to August 2022, especially oil production. Reported emissions and measured concentrations also generally decreased during this period; no attempt has been made to determine the extent to which these trends in emissions are functions of reduced production.
- Time series of extreme concentrations of pollutants in the PRAMP network, and AAAQO compliance:
  - Since 2018, exceedances have been measured of the 10-ppb reference concentration for TRS at Cadotte Lake and Reno, suggesting an ongoing potential for occasional odour detection and an ongoing need for ambient monitoring of TRS.
  - 1-hour SO_2 concentrations are much less than AAAQO suggesting continuous monitoring is not required.
- Correlations of pollutants among PRAMP stations for optimization purposes:
  - The strongest correlations were found between Three Creeks stations for NMHC (r = 0.78) and THC (r = 0.5) over the past 3 years, suggesting that the stations might be marginally redundant but only with respect to hydrocarbons.
  - Overall, the weak correlations do not support a reduction in the number of stations, based on correlations alone.
- Canister-based VOC concentrations, when trigger thresholds are met, show maximum values in 2018, 2019, and 2020 depending on the VOC and station. This pattern does not indicate a trend and doesn't provide guidance for a reduction or increase in canister monitoring in future.

The following analyses (results are presented in sections A2 and A3 of Appendix A) are considered to provide secondary levels of support for assessing network performance and should not drive decision making for changes to the network:

- Diurnal variations of pollutants in the PRAMP network:
  - Unique diurnal profiles exist for Cadotte Lake stations for TRS and NMHC
  - Considering all gases, the Three Creeks 986 station is potentially redundant
- Meteorological controls on pollutants in the PRAMP network (pollutant roses):
  - For all pollutants but NMHC, the pollutant roses are similar to the wind rose for each station, suggesting unique sources are not contributing and therefore that some stations are redundant
  - Differences for NMHC suggest the stations are uniquely situated and not redundant. Further work looking at emissions from nearest facilities contributing to concentrations would be needed to reverse this (i.e., a dispersion model study).

3.1.5 Recommendations

Optimization of the PRAMP network may include reducing the number of the stations or parameters, relocation of stations, changing technology, etc. We recommend the following based on the Priority 1 analyses:

- Reducing the number of stations
  - The assessment weakly supports elimination of one of the Three Creeks stations with the 986 being a potential candidate based on temporal trends, diurnal profiles and correlation. However, the support is too weak for this recommendation to be made. No changes in station numbers are suggested because of the analysis.
- Reducing the number of measured parameters
  - Continuously measured VOC or NMHC concentrations did not decrease with time, nor did canister data indicate reductions in concentrations of other investigated compounds over time as a response to Directive 84. These measurements should be maintained given non-reportable sources in the PRAMP area.

  - Sulphur compounds:
    - SO_2 concentration decreased over time. SO_2 is a regionally relevant compound and elimination is not recommended. However, because values are low, a change to lower cost measurement technology should be considered (see below).
    - TRS concentrations are above thresholds at two stations; therefore, elimination is not recommended and no change in technology is recommended.
  - Meteorology: wind direction and speed are key parameters to be measured on a continuous basis. The data are generally site-specific and distinguish between different controls on concentrations (wind vs. emissions sources); therefore, we do not recommend elimination or reduction of wind parameters.
  - THC and CH_4: Given constant concentrations over time and reductions in emissions, it is possible to remove one of these parameters from reports; however, both measurements support the NMHC measurements. No changes are recommended.
- Relocating stations
  - We do not recommend moving the stations unless there is a strong motivation for monitoring air quality in higher emission density areas.
- Changing technology
  - Passive monitoring of SO_2 should be considered given the decreasing trend in measured concentrations and the low values
  - Passive or gas-sensitive semiconductor technology for monitoring hydrocarbons or VOCs is also an option, provided the measurements continue to support the determination of NMHC concentrations which have not shown a decreasing trend with time.

Overall, the timing of the implementation of Directive 84 appears to be correlated with a reduction in NPRI-reported emissions of TRS/H_2S and VOCs in the PRAMP area.

3.2 Priority 2 – PRC and Mercer Network Expansion

The key emerging issue is whether the addition of monitoring stations to the network can result in optimization of the network with no loss of information, where optimization could mean station relocation, station elimination or removal of some instruments at a station. The optimization applies to the new continuous stations as well as the PRC passive network.

3.2.1 Integrate Peace River Complex Network

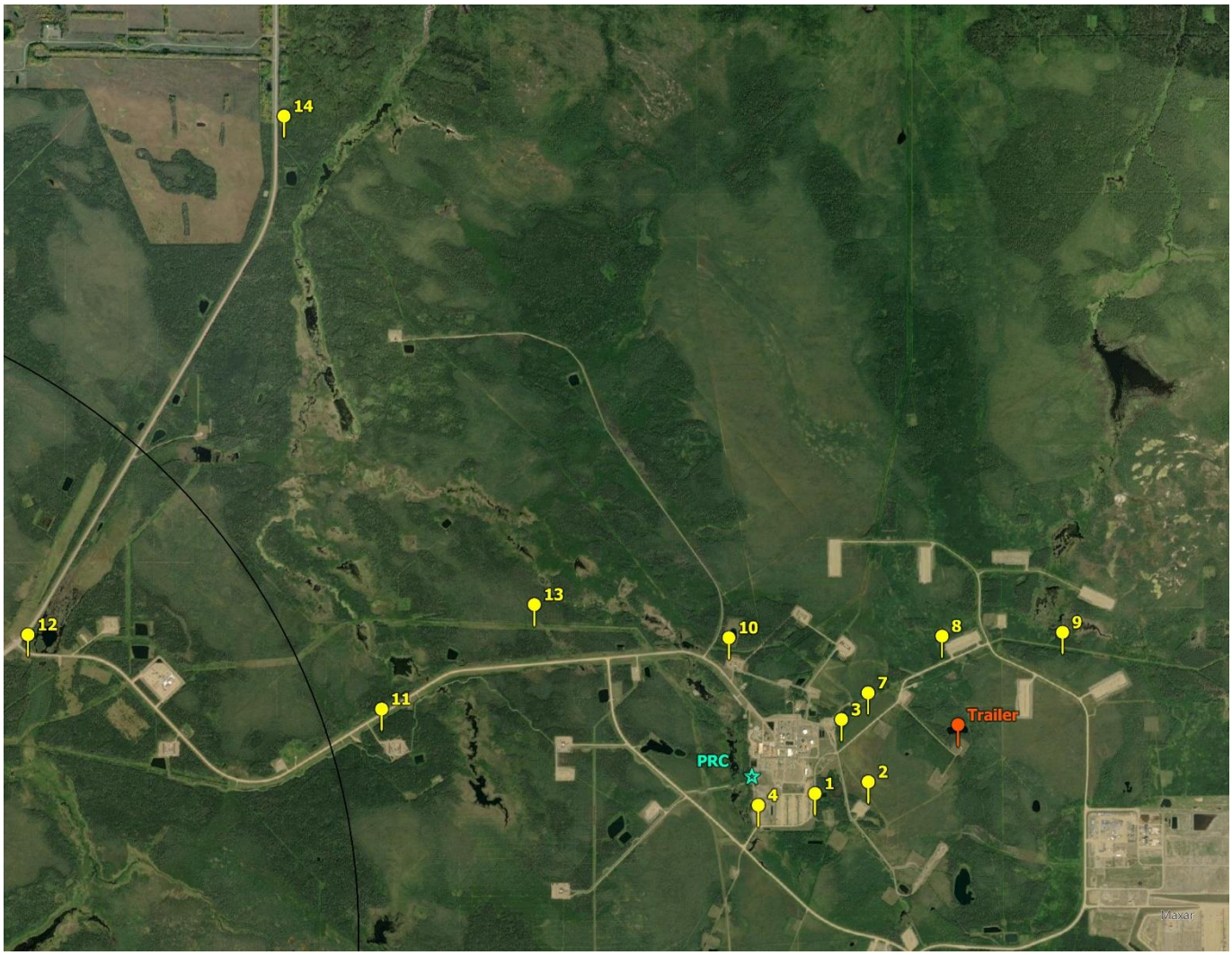
3.2.1.1 Approach

The work provides guidance on whether, after addition of the Canadian Natural PRC continuous station, optimization can occur. In these tasks, it was assumed that PRC station EPEA approval will require the station not to be eliminated; but it was assumed that other stations in the PRAMP network could be if the results supported this conclusion. The tasks involved were:

- Calculated and tabulated inter-station correlations based on hourly data (the PRC station with others) for all common pollutants.
- Documented the trend with time in annual concentrations at the PRC station, the concentration statistics, the diurnal trend, and the pollutant rose for all pollutants measured at PRC.
- Calculated and tabulated inter-site passive data in the PRC network for all pollutants measured.

To assist in interpretation of the analysis, **Figure 18** shows the location of the PRC continuous monitoring station and the passive SO_2 and H_2S network.

Figure 18: Location of PRC Continuous Monitoring Trailer and Passive Network Sites (in yellow) (the star marks the location of the PRC facility)



3.2.1.2 Correlations of Pollutant Concentrations between PRC and Other Stations

Figure 19 presents the correlation of hourly measurements at the PRC station with those at other stations in the PRAMP area. If hourly concentrations for all pollutants were highly correlated (absolute *r* greater than 0.75), one of the two stations in each compared pair was considered for rationalization. If some measurements were highly correlated, some instruments were considered for removal. The results indicated:

- NMHC. PRC is most strongly correlated with Station 986 (r = 0.72), and to a lesser extent 842 (r = 0.60) and Reno (r = 0.36)
- THC and CH_4. PRC is less strongly correlated with other stations (correlation coefficient ranging from 0.16 to 0.35)
- PRC measurements of TRS and SO_2 are weakly correlated with those of other stations.

The analysis also showed that PRC measurements are uncorrelated to Mercer measurements (*r* ranges from 0.02 to 0.03).

Figure 20 presents time series of annual averages of all pollutants measured at PRAMP, PRC and Mercer stations. These trends with time are like the trends shown in Section 3.1.2 figures because Directive 084 applied also to the PRC facilities. Specifically, TRS concentrations at PRC have decreased since 2018, SO_2 and NMHC have decreased generally throughout the monitoring period apart from 2019, and THC and CH_4 are constant since 2013.

Figure 21 shows PRC extreme concentration statistics (1-hour concentration time series) and documents exceedances of the 1-hour TRS threshold at PRC, suggesting an ongoing potential for occasional odour detection (in addition to the PRAMP stations Cadotte Lake & Reno). There are no exceedances of 1-hour SO_2 (1-h AAAQO = 172 ppb); in fact, maximum concentrations in the period of record reach about 10 ppb, suggesting continuous monitoring may not be needed at these stations. Methane measurements appear to reflect global background concentrations at all stations; there is no evidence of the station documenting upset emissions, although longer-term low-level emissions would not be evident.

Figure 22 shows the diurnal trend in TRS measurements at PRC. Diurnal variation may not the best differentiator among stations, as deviations (in TRS) are often similar. PRC data show (larger) standard deviations than other diurnal profiles in spring and summer, suggesting it is somewhat unique.

Figure 23 shows wind and pollutant roses for TRS and NMHC. The monitoring station is about 1 km east of the plant. At PRC, the plant may not be the source of TRS as the highest concentrations are measured under SSW winds (the brightest yellow colouration), not west winds. Similarly, for NMHC, the highest concentrations are measured when winds are from the ENE and the nearest potential sources in that direction are well pads more than 500 m distant. Meteorology is key to understanding the source and interpreting the information and the information provided is site specific. Because of the uniqueness of the application, no reduction in monitoring is recommended.

Figure 19: Correlation Among Continuous Measurements – PRC and Mercer Stations

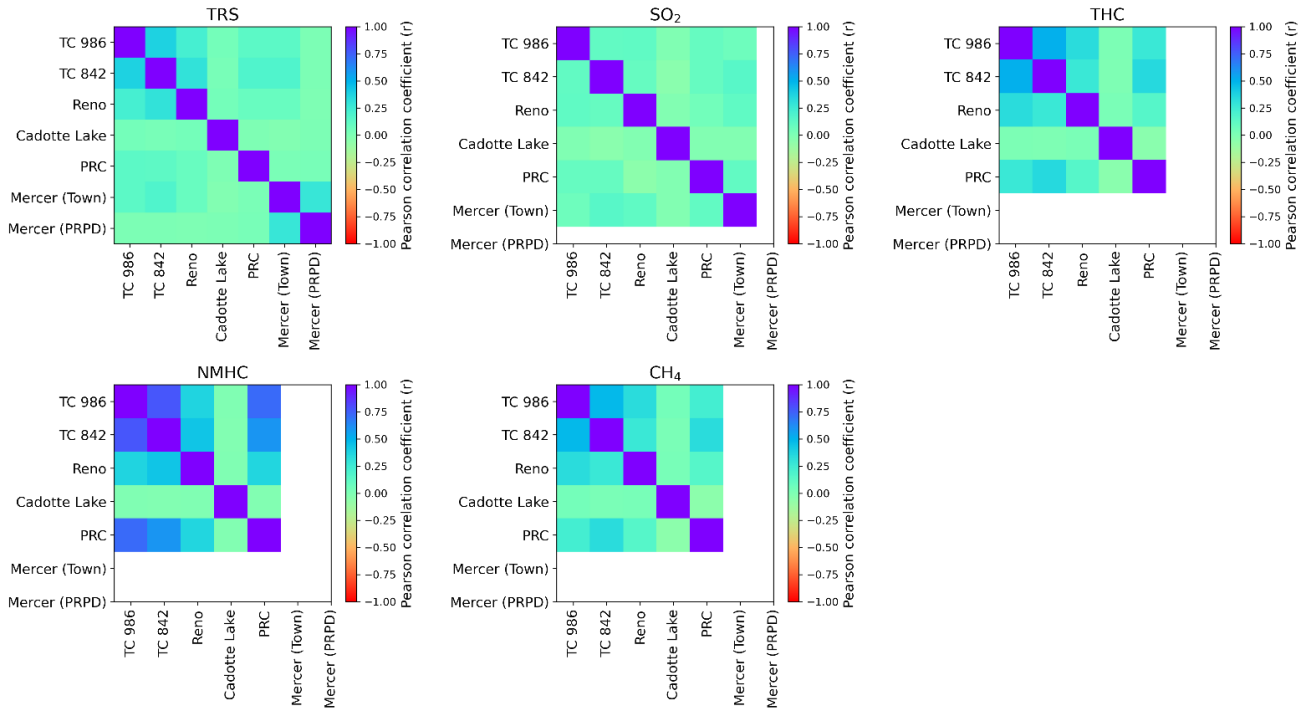


Figure 20: Annual Concentration Trends at PRAMP, PRC and Mercer Continuous Stations

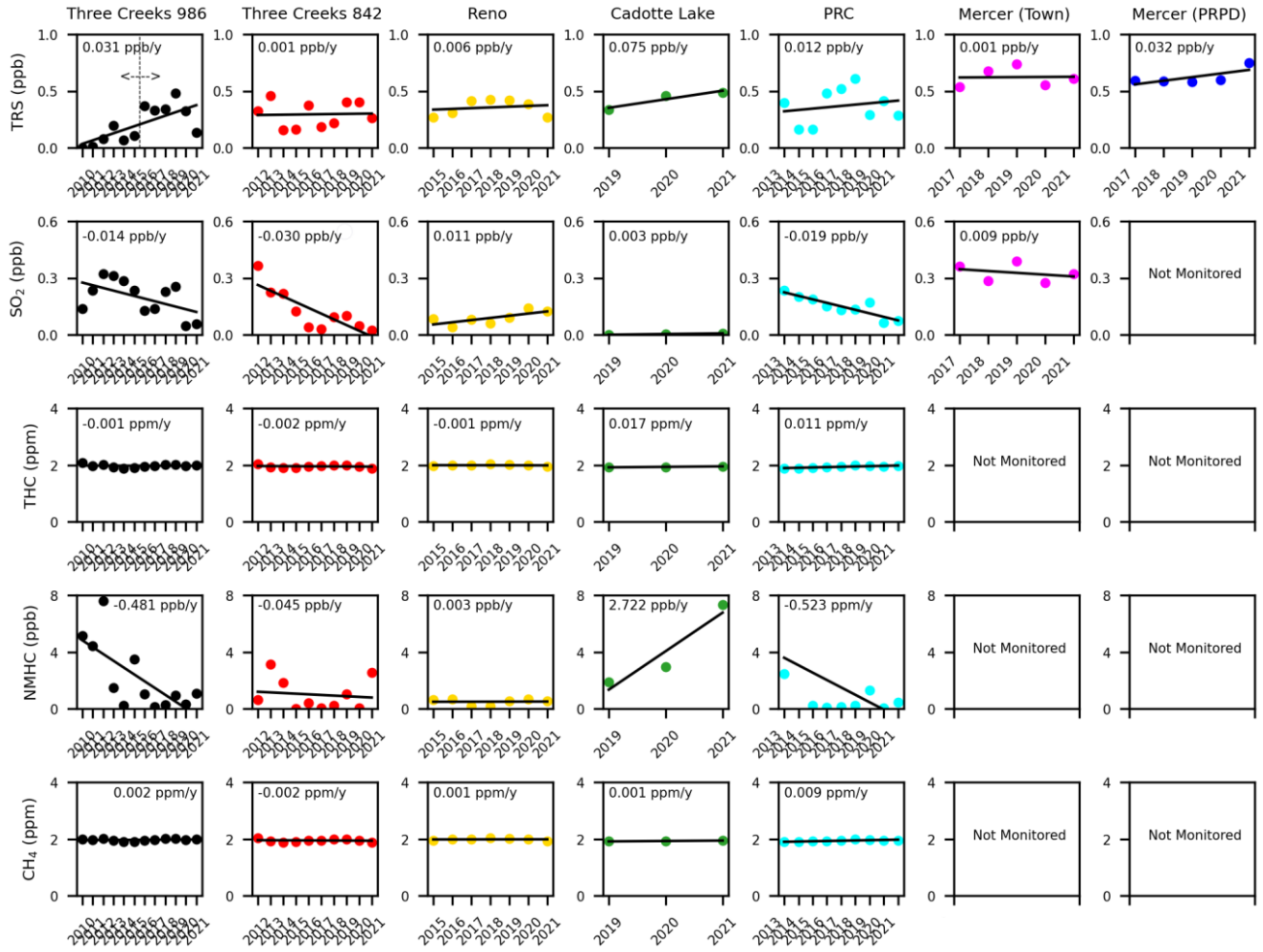


Figure 21: One-hour Concentration Measurements in the PRAMP area, including PRC and Mercer Stations

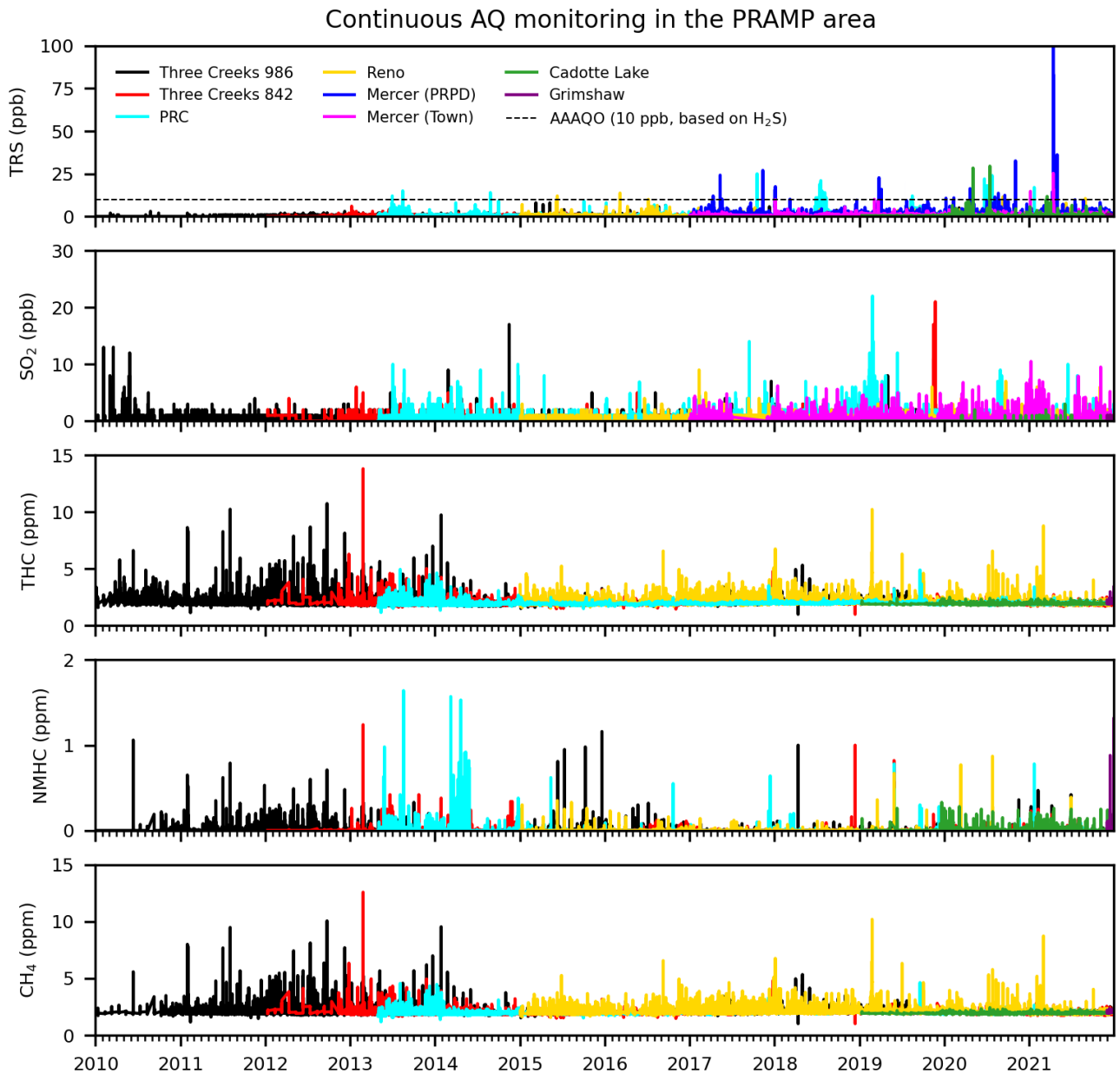


Figure 22: Mean Monthly Diurnal Variation and its Standard Deviation - TRS, 2019-2021

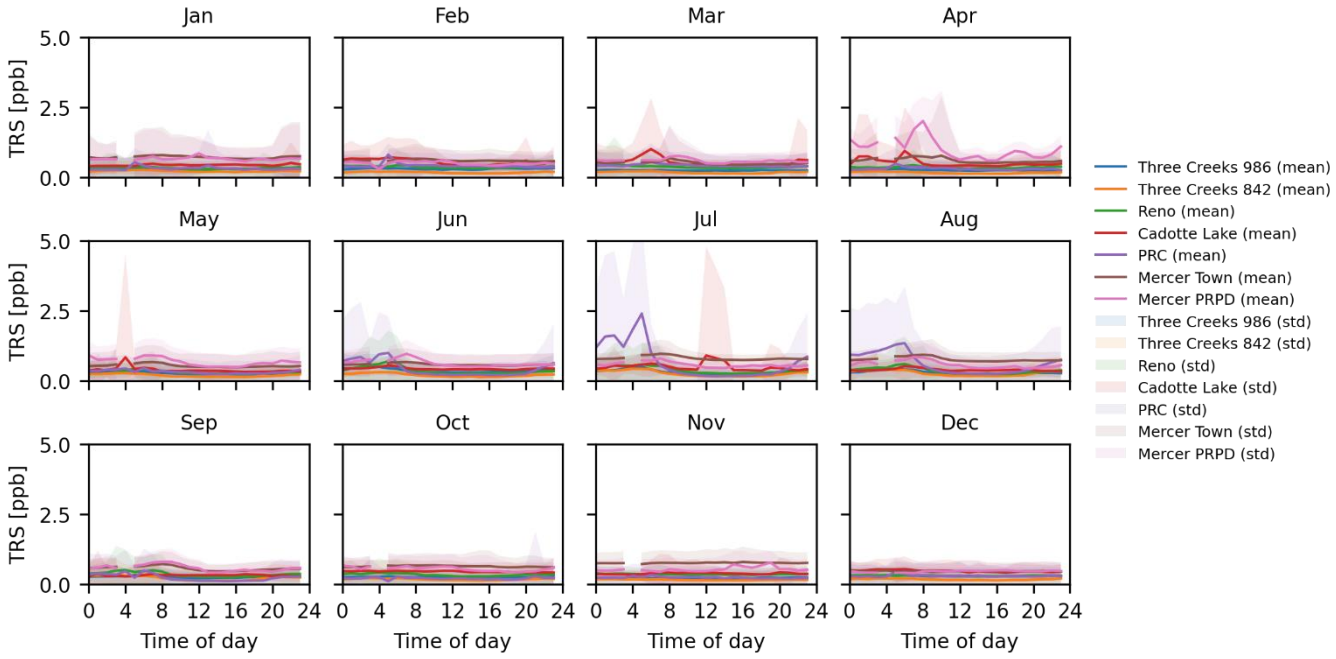
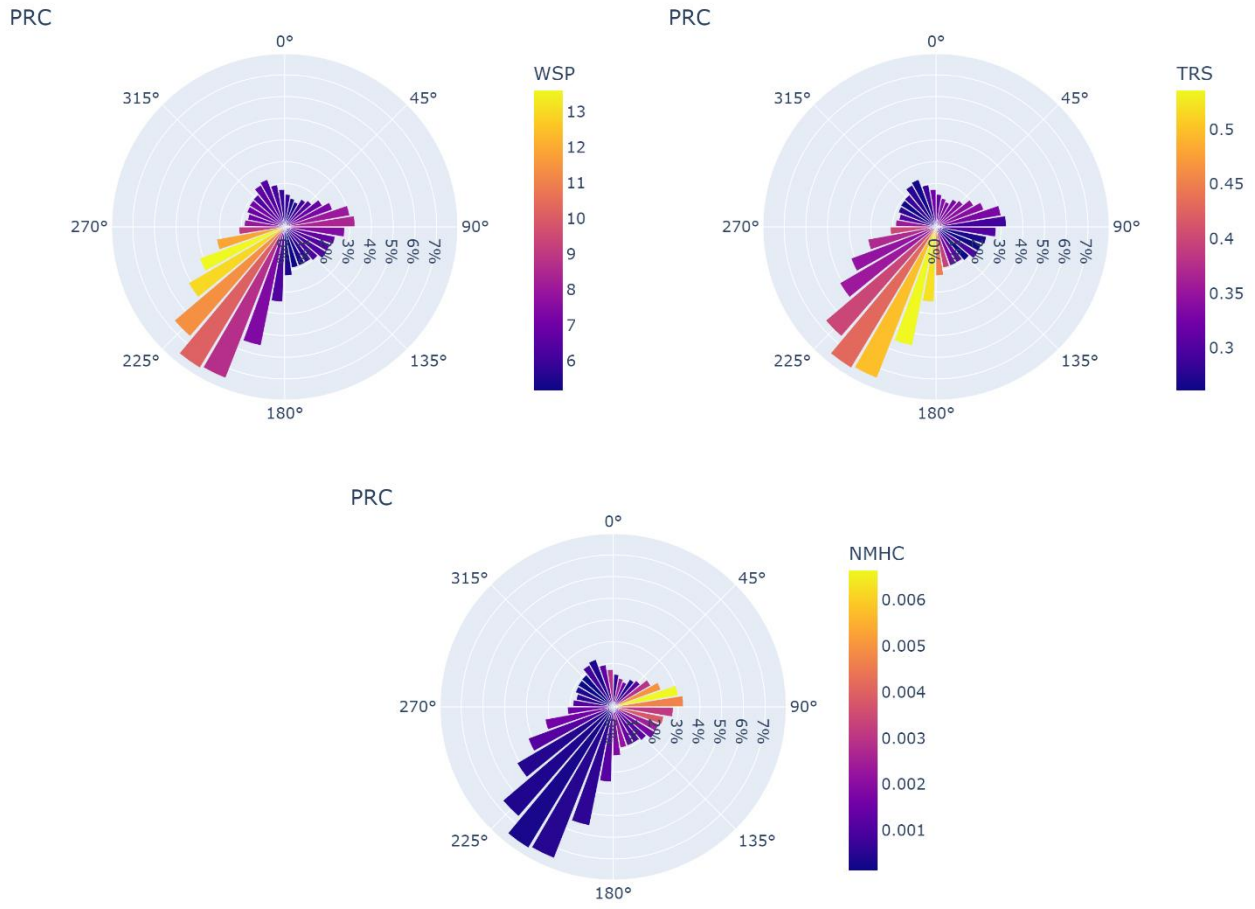


Figure 23: PRC Wind Rose (top left), 2019-2021. Pollution Roses for TRS (top right) and NMHC (bottom)



3.2.1.3 PRC Passive Network Results

The PRC passive network is shown on **Figure 18** indicating 12 sites (yellow locations) for passive sampling of SO_2 and H_2S (monthly accumulated concentrations). The closest continuous air monitoring stations are PRC and Three Creeks 986 (TC986) and we expect similar meteorological conditions for the passive sites at these two sites as two passive sites (11 & 12) are within ≤ 5 km from TC986 and the furthest passive sites are ~ 11 km from TC986.

Correlation results (**Figure 24**) for H_2S indicate the most correlated stations are 1, 2, 7 & 8 (r = 0.70 to 0.75) and the least correlated stations 10, 11, 12 & 13. For SO_2, the most correlated stations are 1, 2, 7 & 3 (r = 0.71 to 0.78) while the least correlated stations are 11, 12, 13 & 14 (r = 0.20 to 0.43). As a minimum, the analysis suggests the highly correlated sites are candidates for optimization.

Time series results are shown in **Figure 25**. The main observations are:

- SO_2 remains well below the 30-day average AAAQO of 11 ppb, with recent maxima in the 1-2 ppb range
- Stations closer to PRC (1, 3, 4, 7) generally have higher concentrations and occasionally detect H_2S and SO_2 “spikes”. These stations are generally E and S of the process area. The highest values appear to occur almost exclusively in summer.

- H_2S and SO_2 "spikes" at the same site do not necessarily occur in the same months
- The prevailing wind at the PRC station is from the SW and these winds are usually stronger than those from other directions.

Figure 24: Correlation Results, PRC Passive Network

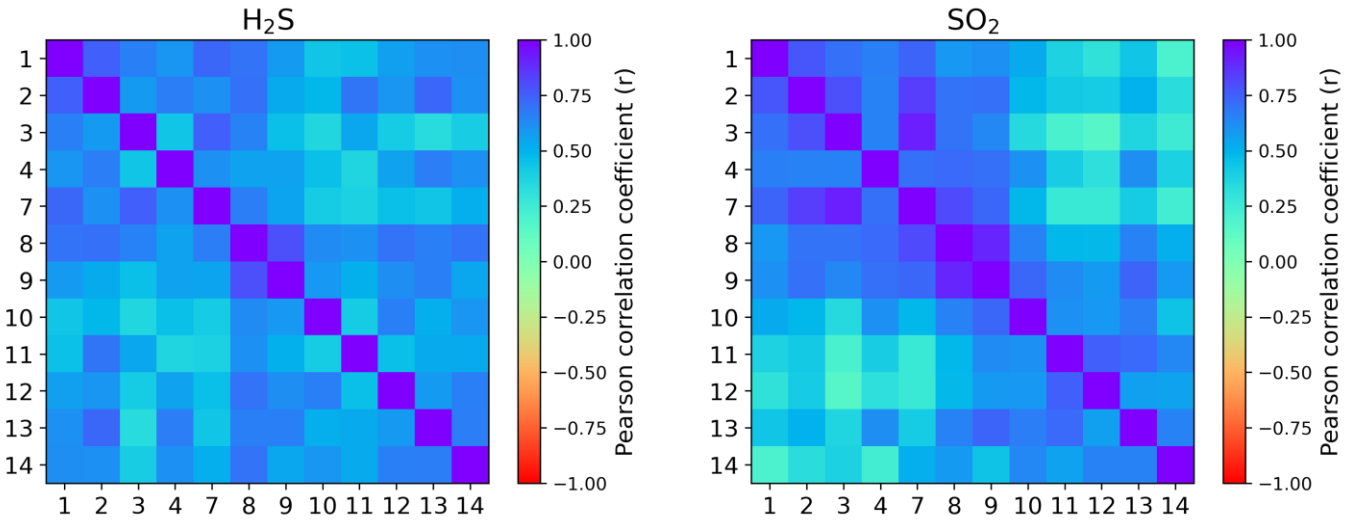
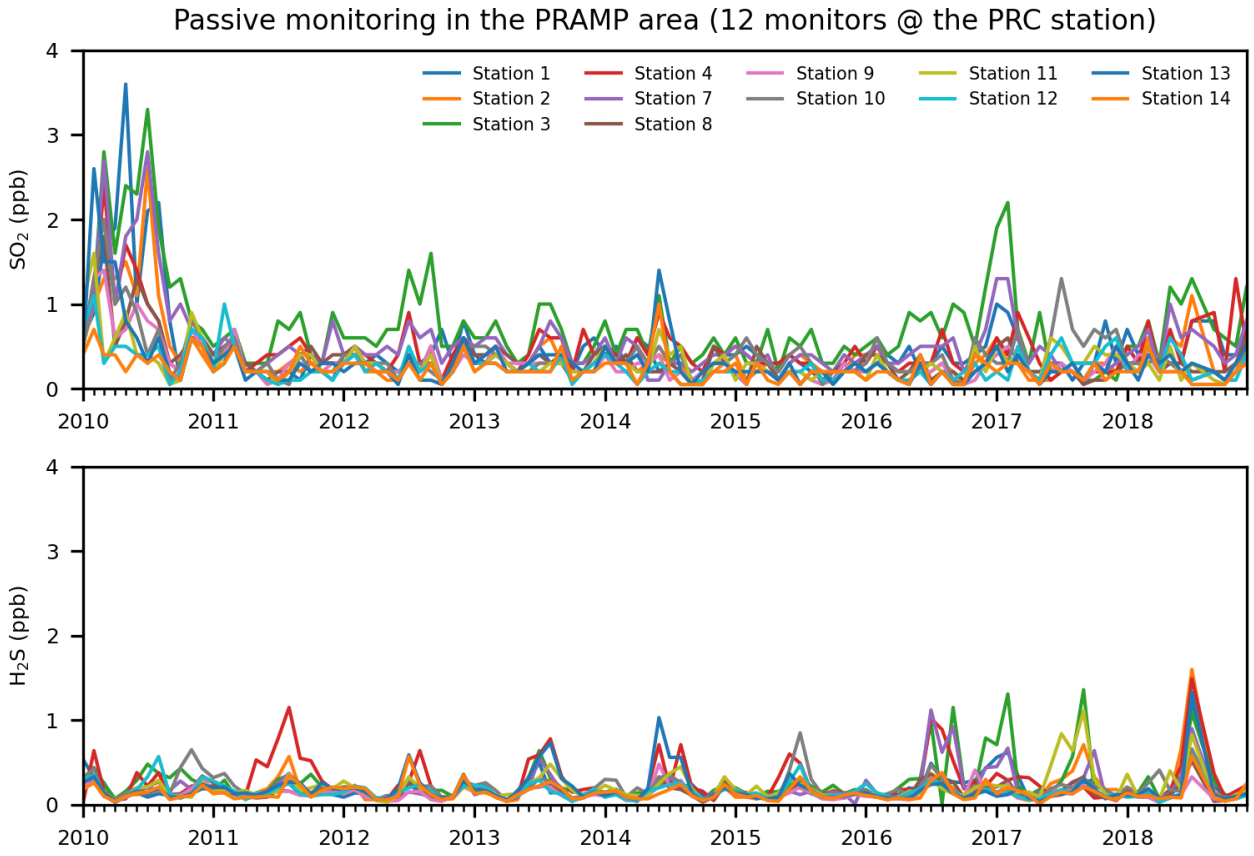


Figure 25: Monthly Time Series, PRC Passive Network



3.2.2 Integrate Mercer Peace River Pulp Mill stations

3.2.2.1 Approach

The two Mercer stations (Mercer Town and Mercer Plant) provide continuous TRS and meteorological measurements only; one of these two stations also provides continuous monitoring of fine PM and SO_2. The work provided guidance on whether, after addition of the stations, optimization could occur. In these tasks, it was assumed that PRC station EPEA approval will require the station not to be rationalized; but it is assumed that other stations in the PRAMP network could be. Therefore, the tasks were:

- Calculated and tabulated inter-station correlations (the two Mercer stations with others).
- Documented the trend with time in annual concentrations at the Mercer stations, the concentration statistics, the diurnal trend, and the pollutant rose for all pollutants measured at them.

To assist in interpretation of the assessment, **Figure 26** shows the location of the two Mercer continuous monitoring stations.

Figure 26: Mercer Continuous Monitoring Stations, PRPD (left) and Town (right)

3.2.2.2 Results

Figure 18 provides the correlation results comparing hourly measurements at Mercer and PRAMP stations for pollutants measured in both networks. TRS is moderately correlated at the two Mercer stations, as expected given the common plant source, potential channeling in the river valley, and the distance between the two stations. SO_2 concentrations at the Mercer town site were weakly correlated with concentrations at PRAMP stations.

The time series of annual averages of all pollutants measured at the Mercer stations (**Figure 19**) are not like the trends shown in Section 3.1.2 because Directive 084 does not apply to Mercer emissions. Concentrations of TRS and SO_2 at the town station are unchanging over the monitoring period. At the plant site, TRS concentrations are also unchanging except for 2021 when they increased. Slightly higher TRS and SO_2 baselines are noted at the Mercer stations compared to PRAMP stations over the same period (2017-2021), reflecting local sources from the plant.

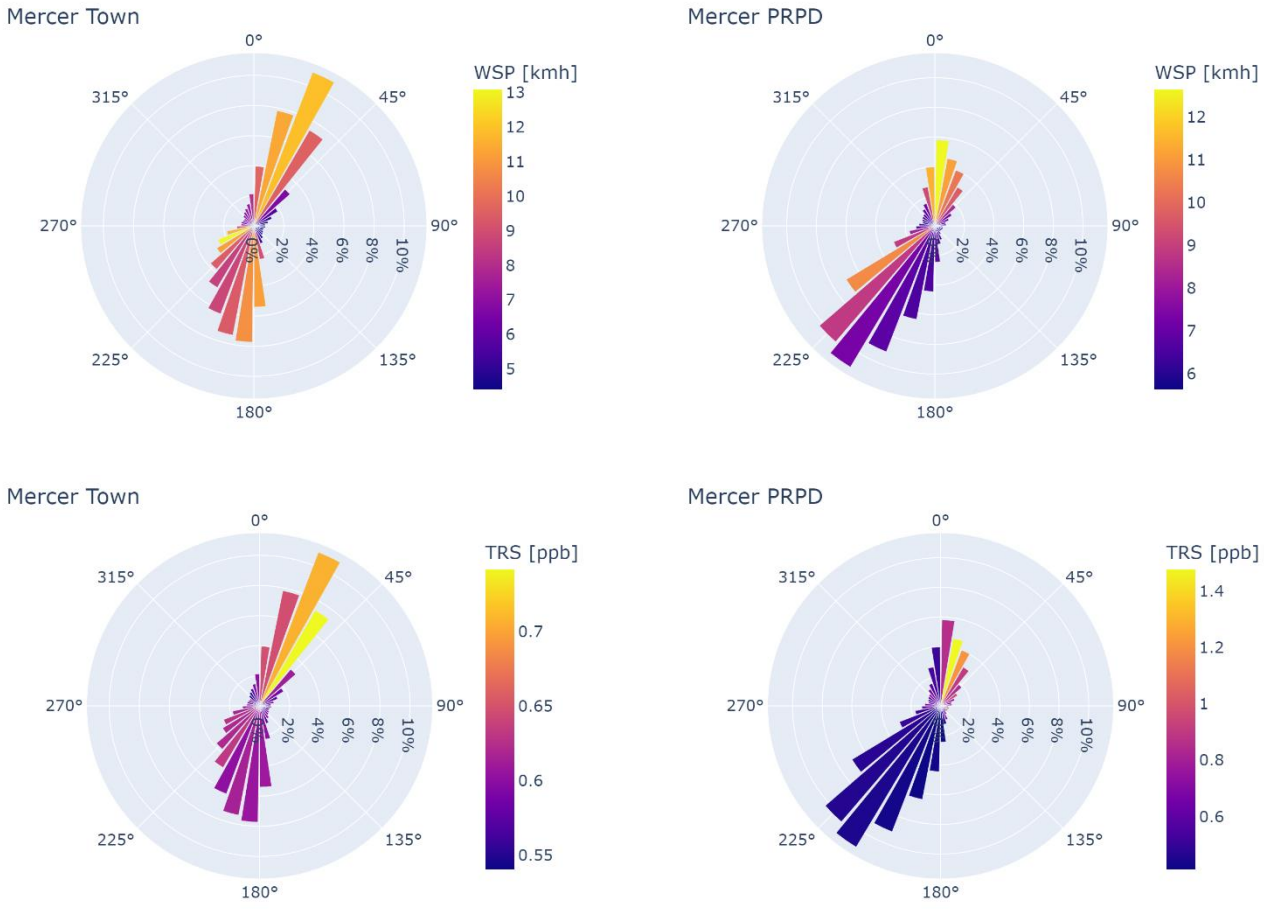
One-hour concentrations of TRS (**Figure 20**) occasionally exceed the threshold at Mercer (PRPD) station, with a peak near 100 ppb in 2021, suggesting an ongoing potential for occasional odour detection at this location. TRS

concentrations at the town site also occasionally exceed the threshold. There are no exceedances of 1-hour SO_2 (1-h AAAQO = 172 ppb); in fact, maximum concentrations in the period of record reach about 10 ppb, suggesting continuous monitoring may not be needed at Mercer, or an alternative approach to continuous monitoring could be investigated.

Figure 22 shows the diurnal trend in Mercer PRPD and town measurements of TRS, both showing show (larger) deviations from other PRAMP station diurnal profiles in spring and summer.

Figure 27 shows wind and pollutant roses at Mercer stations. Considering the monitoring locations in **Figure 24** and observed wind channelling in the valley, at both Mercer stations the PRDP appears to be the source of TRS as the monitoring station at PRPD is at the south end of the plant site (largest concentrations with N winds) and at the town the station is at the north side of the town (highest TRS concentrations under N winds). Again, meteorology is key to understanding the source location.

Figure 27: Mercer Wind Rose (Town, top left and PRPD, top right) and TRS Pollution Roses (Town, bottom left and PRPD, bottom right), 2019-2021



3.2.3 Supporting Information

Rambol and Novus (2018) modelled air quality Alberta-wide using CMAQ with a 4x4 km grid spacing based on emissions from 2012 to 2015. Model results in map format were examined to estimate the extent (radius of

influence) of PRC emissions on the modelled concentration field. This proved to be a challenge given the small scale of the maps which results in the smallest impact being within a grid cell 4 km wide. It is expected, and seen in the model output, only a few sources in PRAMP are evident and not well identified. For most plume models, the extent of spatial influence would be a few kilometres and this influence is less visible in a grid model such as CMAQ. Nonetheless, the following is noted:

- No grid cells have observable 1-h or annual average SO_2
- A small number of grid cells near the town of Peace River showed at the lowest level for 1-h and annual NO_2
- $PM_{2.5}$ was observed at the lowest display level, but not associated with specific sources.

The conclusion is the Rambol and Novus (2018) grid modelling is not helpful to support an assessment of the influence of PRC emissions on observations at the PRC continuous monitoring station or in the PRC passive network, nor was that the focus of the province-wide modelling exercise.

To support recommended changes to the passive network, we compared the temporal trends in annual average SO_2 and H_2S concentrations from all 12 passive stations (**Figure 28** and **Figure 29**) with similar trends derived for the PRC continuous station presented in **Figure 20**. The comparison supports trends in SO_2 at all 12 passive stations are similar with the trends in SO_2 at PRC station, with SO_2 decreasing by 0.002 to 0.061 ppb/y. Concentrations of H_2S both decreased (at stations 4, 9, 10, 12, 13 and 14) and increased (at stations 1, 2, 3, 7, 8 and 11), while the trend in TRS (which is mostly H_2S) at PRC station slightly increased. Passive stations closer to the PRC station show similar increasing trend in H_2S, with slopes ranging from 0.0004 to 0.015 ppb/y. Note that passives stations have data beginning 2010, while PRC station has data from 2013. For the overlapping period (2013-2018), some stations (1, 2, 3, 4, 7, and 10) suggest that SO_2 also increased slightly, while other stations (8, 9 and 11-14) suggest that SO_2 decreased. Trends in H_2S over 2013-2018 are not affected when years 2010-2012 are removed from the linear regression.

Figure 28: Linear Trends in Annual Average SO_2 Measured at 12 Passive Stations near PRC

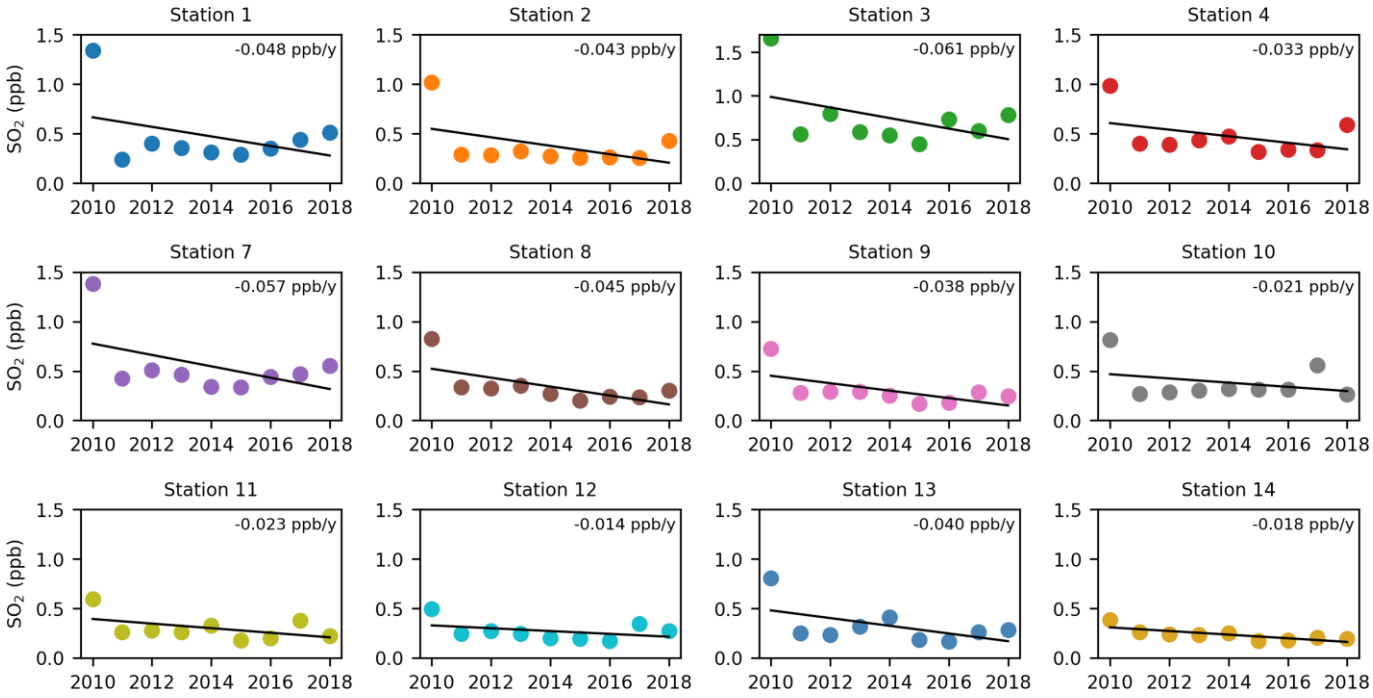
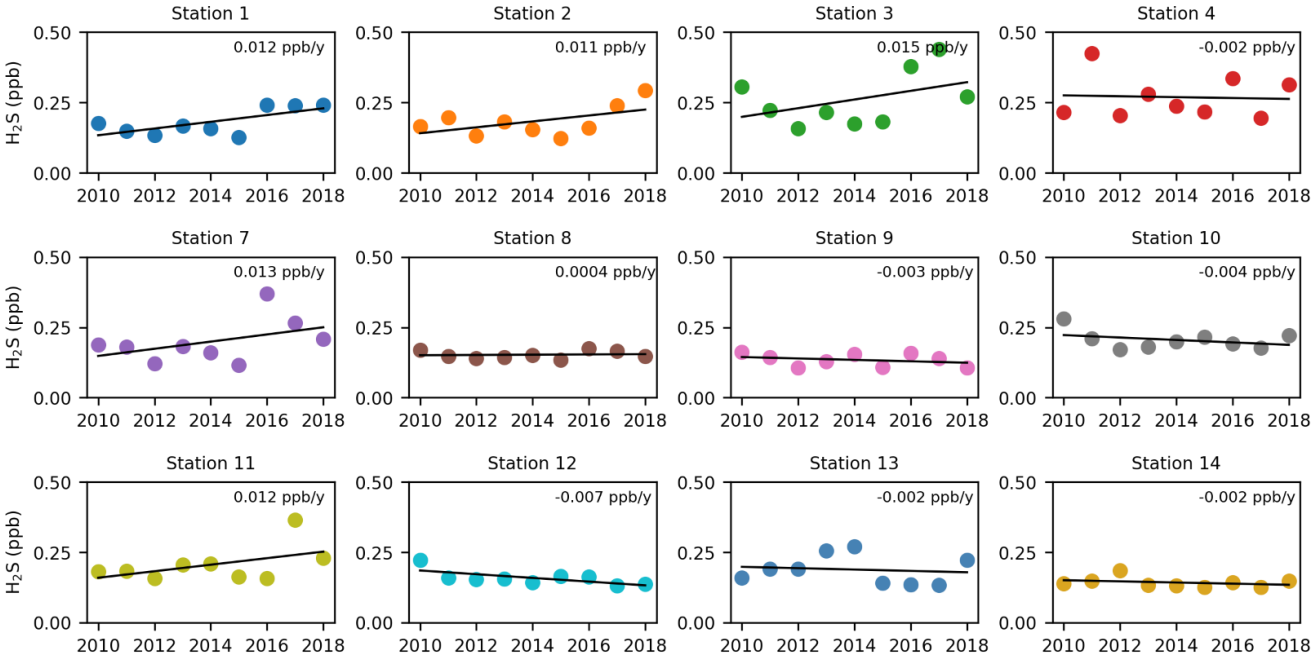


Figure 29: Linear Trends in Annual Average H_2S Measured at 12 Passive Stations near PRC



3.2.4 Priority 2 Summary and Recommendations

The key emerging issue is whether the addition of monitoring stations to the network can result in optimization of the network with no loss of information, where optimization could mean station relocation, station elimination or removal of some instruments at a station. The optimization applies to the new continuous stations as well as the PRC passive network.

The assessment showed:

- PRC and Mercer (PRPD) stations are unlike the core PRAMP stations in that they are adjacent to facilities with specific monitoring needs, and act as compliance stations rather than measuring general airshed air quality.
- Long-term trends at PRC and Mercer stations follow those of PRAMP stations over the same period showing
  - Increasing TRS (but decreasing at PRC since 2018)
  - Decreasing SO_2
  - NMHC, THC, CH_4 variable but relatively constant
- Time series of extreme concentrations and AAAQO compliance
  - Historical and recent exceedances of 1-hour TRS threshold at PRC and Mercer PRPD, suggesting an ongoing potential for occasional odour detection
  - 1-hour SO_2 concentrations are much less than AAAQOs, suggesting that monitoring technology could be changed to passive or lower-cost semiconductor approaches
- The correlation analysis for PRC and Mercer stations indicates that elimination of sites and monitored parameters is not supported. Poor or low correlations indicates stations provide independent data that cannot be replaced (in an interpretive sense) by data from other stations.
  - PRC is correlated with some PRAMP stations for NMHC, and is poorly correlated for THC, CH_4 and TRS

  - Mercer stations are poorly correlated with other PRAMP stations
  - PRC and Mercer TRS are uncorrelated with each other

- Diurnal variations of pollutants (e.g., TRS) presented unique profiles at PRC and Mercer PRPD stations that provided no basis to eliminate measurements
- At all three sites, meteorology is key to understanding the source and interpreting the information. Because of the uniqueness of each site, no reduction in meteorological monitoring is recommended.
- PRC passive network
  - SO_2 measurements well below AAAQO (this observation is supported by the continuous data), with the highest values at the closest sites to the plant
  - Is there continued value in this network? Options:
    - No changes
    - Reduce the number of high-density sites, near-plant sites 1-10
    - Redeploy H_2S network to include well sites
    - Eliminate passives altogether, as the PRC station includes continuous SO_2 and TRS
- Overall, and apart from the passive network, there appears to be no basis for optimizing the continuous stations.

3.3 Priority 3 – Emerging Issues

3.3.1 Tier 3 Emerging Issues

The tasks to evaluate monitoring in adjacent data-deficient areas were:

- Access emission data for high emission sources adjacent to PRAMP boundaries in all directions
- Consider wind and pollution roses near the adjacent sources, which will also provide an indication of the potential for transboundary plume movement
- If the sources are sufficiently large, spatial analysis may be employed for quantifying the point density
- If sources are not large or not near the PRAMP boundary, the assessment will include the density of oil and gas wells as a screening indicator of fugitive emission potential.

To evaluate new technologies, the tasks were to:

- Identify the air quality parameters of most interest
- Review U.S. EPA, Environment Canada, and other data comparisons
- Consider AEP guidance on new technology
- Provide guidance on use of new sensors.

3.3.2 Results of Tier 3 Evaluation

3.3.2.1 Monitoring in Adjacent Data-Deficient Areas

One of the primary monitoring objectives of PRAMP is to provide information related to the spatial distribution of contaminants of concern in the region. **Figure 30** shows the current monitoring locations (including Cadotte Lake) in relation to oil and gas well location and well density (number of wells per unit area). **Figure 31** shows the locations with respect to facilities reporting to the NPRI. Facilities that report to NPRI are generally located in the highest well density areas as well as specific sources such as PRC and Mercer PRPD.

Figure 30: Well Locations (left) and Well Density (right) as Aids to Identify Monitoring Gaps

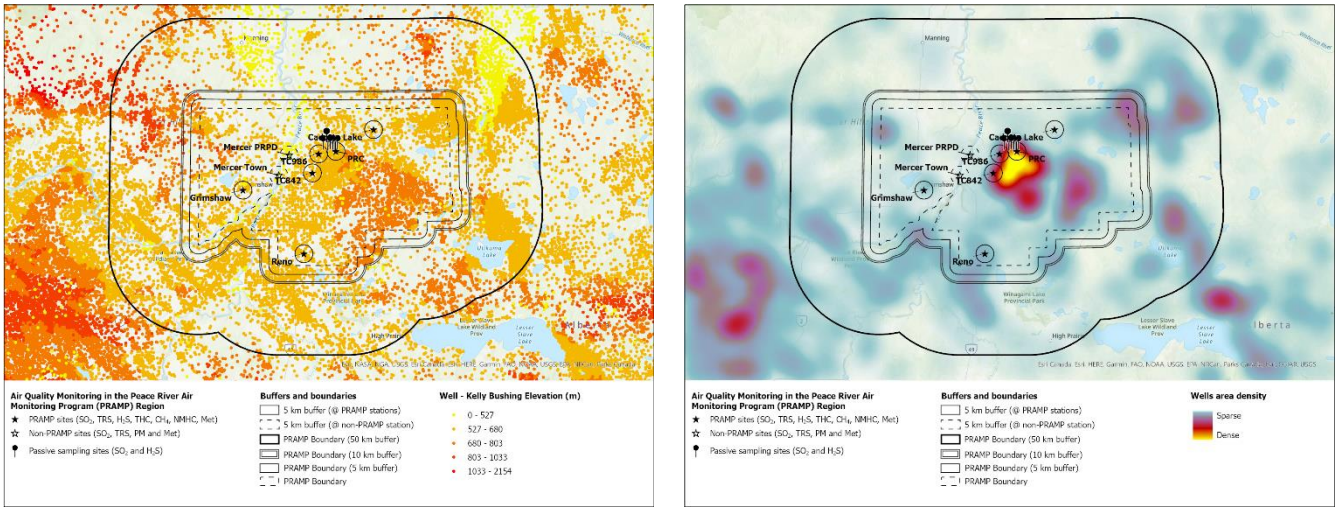
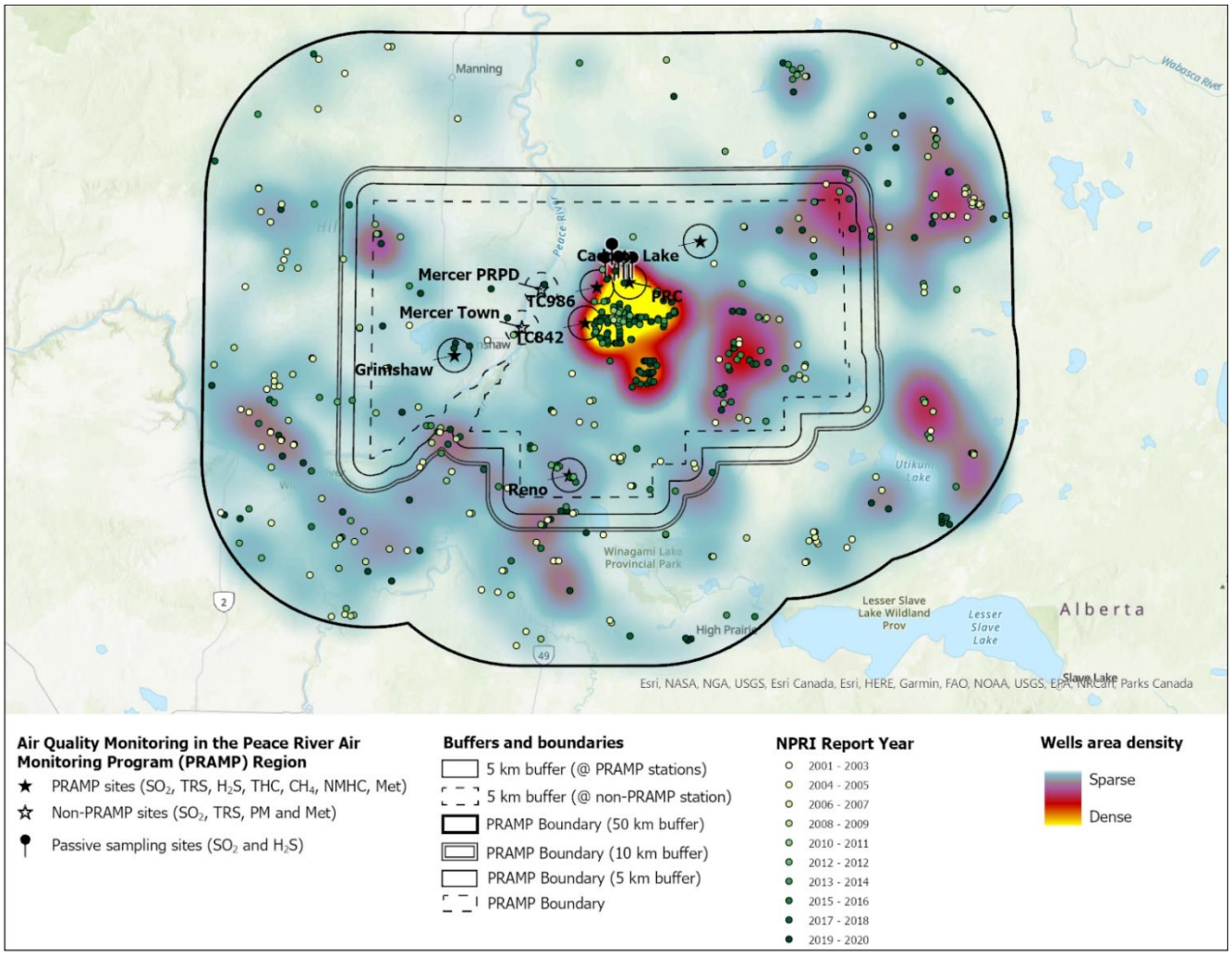


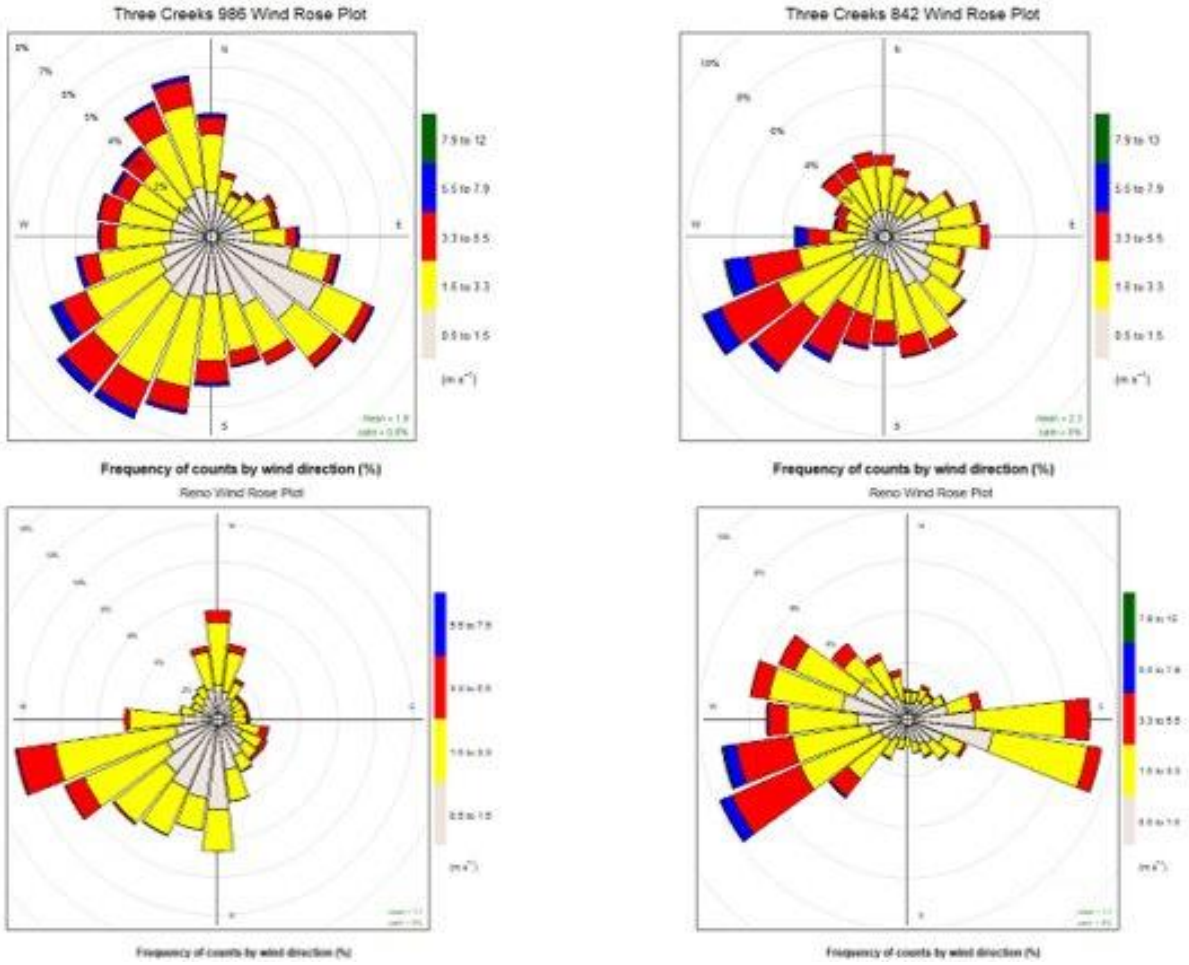
Figure 31: Facilities Reporting to NPRI, to Aid Identification of Monitoring Gaps



The two figures provide the following information on potential monitoring gaps:

- Several locations, notably the Walrus area, have facilities recently reporting to the NPRI in a high well-density area that are not near current PRAMP monitoring locations.
- There are no large NPRI-reporting sources or high-density well regions outside the PRAMP area within 50 km in any direction that could affect air quality to a degree that might require additional PRAMP monitoring. This holds for all directions from which wind might blow frequently according to the wind roses in **Figure 32**.
- There are no locations outside the PRAMP boundary to which emissions from facilities within the PRAMP area would blow that require additional monitoring. This is based on the small number of facilities recently reporting to the NPRI near the PRAMP boundary, with consideration of the wind roses.

Figure 32: Wind Roses at PRAMP Stations



Over the years shown in **Figure 31**, facilities within the PRAMP boundary have reported the following pollutants to NPRI: SO_2, TRS, H_2S, HCl, H_2SO_4, CO, As, Cd, Co, Pb, Mn, Hg, Se, Zn, NH_3, CrVI, dioxins and furans, PM_{10}, $PM_{2.5}$, NOx, etc. PRAMP does not monitor the full range of these pollutants. The most likely reason is that the emissions are sufficiently small that facility approvals do not require monitoring.

Further details on facilities reporting specific pollutant emissions to NPRI are shown in **Figure 33** and **Figure 34**, overlaid onto the well density for context. Reporting years are from 2002-2020, with the emission scaled by the size of the red symbol. These figures show:

- The largest SO_2 sources are the Mercer mill, with a local continuous station nearby and PRC, also with an associated monitoring station. Few other facilities report SO_2 emissions in the region and from an emission perspective, there are no monitoring gaps.
- Similar emission patterns exist for H_2S and TRS, with H_2S continuously monitored at PRC and TRS measured at both sites. From an emission perspective, there are no monitoring gaps. The pattern of emissions is similar for NOx and CO.
- A similar pattern also exists for $PM_{2.5}$, although historical emissions east of Walrus were higher than PRC.
- VOC emissions are shown only for the years 2018-2020, as these are post-Directive 84 and most likely to be influenced by it. Mercer mill emissions are largest within the area, followed by a source well outside the PRAMP boundary, and then PRC.

Figure 33: Facilities Reporting to NPRI for SO_2 (upper left), H_2S/TRS (upper right), VOCs (lower left) and $PM_{2.5}$ (lower right)

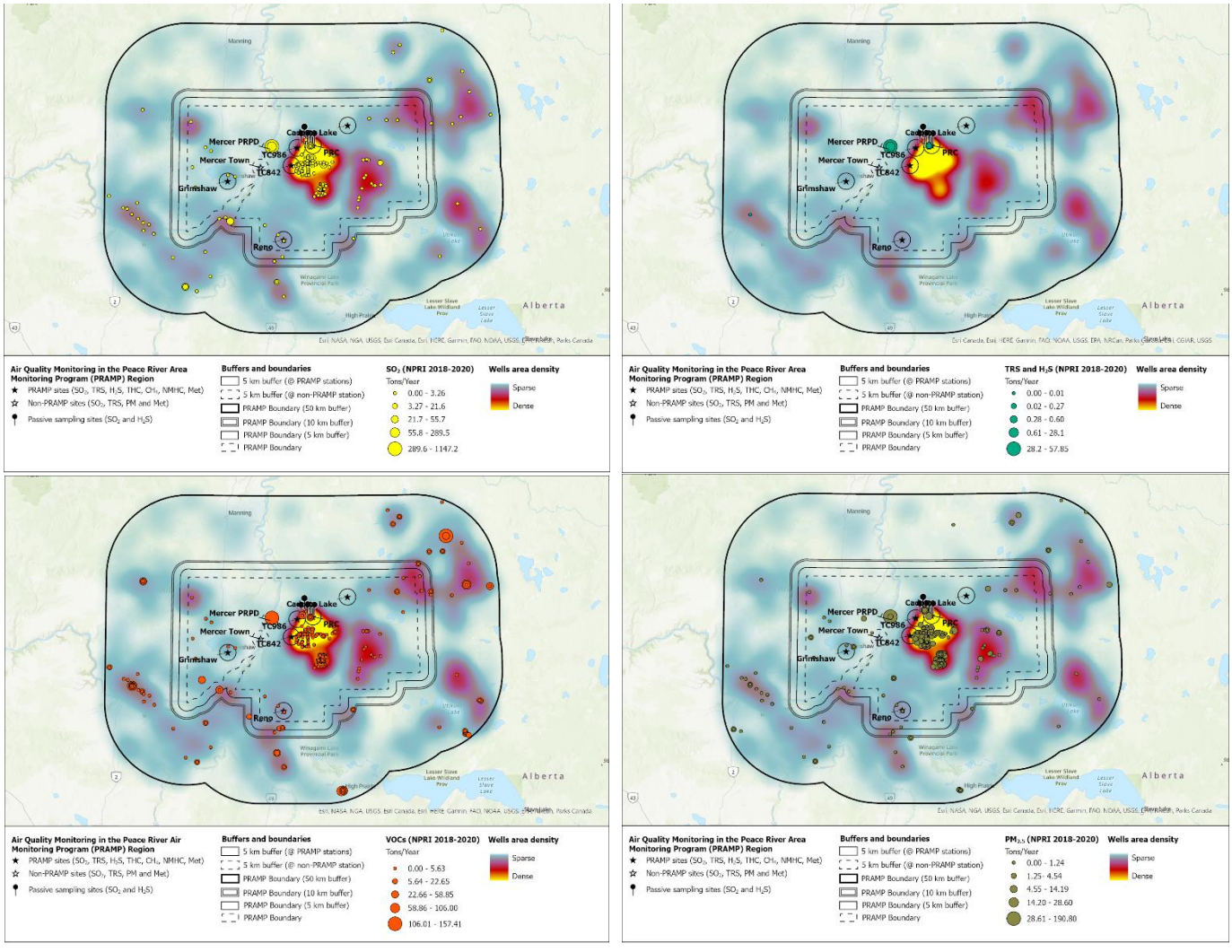
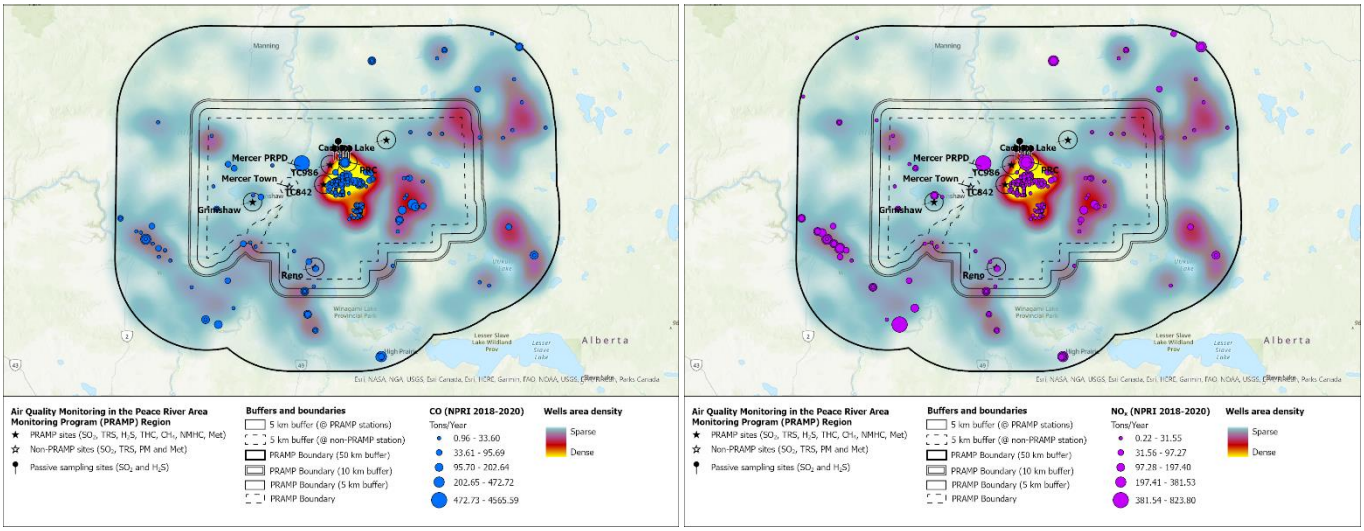


Figure 34: Facilities Reporting to NPRI for CO (left) and NOx (right)



From the perspective of monitoring the largest emissions, no data gaps exist within the PRAMP area. For many pollutants, secondary areas of interest are the Walrus region and the region east of it where several facilities report to the NPRI albeit at relatively low levels. The well density is useful but does not necessarily correlate to emission intensity. The population density in these areas is low.

If additional monitoring in these areas was considered, the following approaches could be used:

- Add a new continuous station with the same level of instrumentation, should the gap be important enough for the additional capital and maintenance.
- Move an existing station to a new area, although this evaluation had not identified any “expendable” stations
- Add a new station with low-cost sensors (or relocate PRC passive monitors), provided adequate data quality is demonstrated

Finally, data deficiency has been considered only from a spatial perspective, but PRAMP should consider whether population size should also be a factor. While an “AQHI” trailer is listed in **Table 1**, it is in Grimshaw. If this is the population threshold for establishing a local AQHI, the town of Peace River would also qualify, where continuous monitoring already occurs but to estimate the contribution of the Mercer mill to community air quality. The Mercer town station is not instrumented to provide measured AQHI.

3.3.2.2 Emerging Sensor Technology

3.3.2.2.1 Application in Urban Areas

New sensor technology has been developed in part to reduce the cost of monitoring in urban areas. Population effects on air quality can be of several aspects:

- air quality in the largest communities affected by population changes
- air quality in smaller communities and
- air quality less directly affected by population but perhaps also by economic conditions – *e.g.,* along major roadways, expanded infrastructure, *etc.*

Currently in PRAMP, limited monitoring is conducted in one urban centre (Peace River), with a portable station located in Grimshaw.

U.S. EPA (2008) recommends at least 1 station for each 350,000 people on which to calculate AQHI but more than one per city if urban monitoring is the goal. The total population within urban areas of PRAMP (including extension) is about 10,000 (of which about 6700 are in Peace River) so this guidance is not applicable to PRAMP.

CASA's (2009) guidance on urban monitoring is to assess the need for two monitoring stations in municipalities with a population greater than 50,000 and for one permanent monitoring station in municipalities with a population greater than 20,000. Again, this guidance would not be applicable to PRAMP with its smaller population.

To address the costs of urban monitoring, and the preparation of local AQHIs, progress is being made to provide high quality, low-cost ambient monitoring technology. The U.S. EPA (2013) proposed tiers of monitoring that are accessible to a wider variety of users based on cost (**Table 2**). Europe established quality monitoring objectives for "indicative" monitoring technologies where the goal is not regulatory or research quality data (*e.g.,* Aleixandre and Gergoles 2012; Snyder *et al*. 2013). Holstius *et al*. (2014), for example, when testing a version of a particulate sensor, found performance at 1 h integration times was comparable to commercially available optical instruments costing considerably more. Zheng *et al*. (2018) tested low-cost aerosol instruments against reference methods in a range of dust concentration environments. These more cost-effective approaches provide a means to better understand the impact of populated areas on air quality.

Table 2: Instrument Tier Definitions by Cost and Anticipated User

Tier	Target Cost Range ($US)	Anticipated User
Tier V (most sophisticated)	10 – 50 K	Regulators (supplement existing monitoring –ambient and source)
Tier IV	5 to 10 K	Regulators (supplement existing monitoring –ambient and source)
Tier III	2 to 5 K	Community groups and regulators (supplement existing monitoring – ambient and source)
Tier II	100 dollars to 2 K	Community Groups
Tier I (more limited)	Less than 100 dollars	Citizens (educational and personal health purposes)

Source: U.S. EPA (2013)

This report recommends the introduction of "indicative" or Tier II or III technology into the network. The recommendation is not in line with the principle of using BATEA technology but rather represents a move to deploy more, and more current, technology available at lower cost. The notion is that with current technology, what is economically achievable can be redefined to the benefit of more communities in the PRAMP airshed.

Air Monitoring Directive protocols are not yet in place to support this new technology and won't be for several years. Therefore, it is not currently recommended to replace stations clearly designed as "compliance stations" near major emitting facilities with new technology. It is considered appropriate to recommend that new community sites use the technology. It may also be appropriate to recommend that TSP and dustfall stations be replaced with continuous $PM_{2.5}$ or PM_{10} measurements given the advantages of the new technology.

In all cases, no matter which supplier or technology is chosen, comparison measurements with existing reference technology are recommended. Alberta Environment and Parks is currently conducting these measurements on several new technology units, but many others are available in the market. Additional comparisons are planned that focus on laser based $PM_{2.5}$ and PM_{10} particle counting technology. Examples of particulate comparison studies include Sousan *et al*. (2017) who evaluated the accuracy, bias, and precision of three inexpensive (< $US 300) consumer aerosol monitors and found that some instruments have a linear response to different aerosol types and good precision and can provide reasonable estimates of $PM_{2.5}$ in the workplace after site-specific calibration to account for particle size and composition.

3.3.2.2.2 Evaluation of Emerging Sensors

According to the U.S. EPA, emerging air quality sensors – with general traits of being more compact, directly reading pollutants, and lower in cost than traditional methods - have a wide appeal to professional researchers, community groups, students, and citizen scientists alike. Since this technology is still under development, little information exists on the quality of data that these sensors produce (U.S. EPA 2022).

The U.S. EPA and other agencies have provided information to allow agencies such as PRAMP a basis to compare instruments and technologies and consider enhancements or changes to the network. As an example, the current evaluation suggested that SO_2 concentrations are well under AAAQOs and appear to be broadly decreasing across the network. An alternative to eliminating SO_2 from the network would be to replace current technology with emerging technology providing sensor performance and data quality are understood.

This section examines the performance of some gas sensors using SO_2 as the example and PM2.5 sensors using the Purple Air as an example.

3.3.2.2.3 SO_2 Example

U.S. EPA (2022) provides the following comparison results only for SO_2 (**Table 3**). The South Coast Air Quality Monitoring District also evaluated a wide variety of sensors; however, the SO_2 component was not reported, as shown in **Table 4**. R^2 values for other parameters range considerably. Other manufacturers also include SO_2 as part of packages not evaluated as part of these programs. Low-cost sensors are most often developed to respond to urban air quality where SO_2 is not a significant concern.

Table 3: U.S. EPA SO_2 Sensor Evaluation

Sensor model (pollutant types)	Detection Approach	Test Conditions	R^2	Comments
AQMesh	Electro-chemical	30-day test in hot humid conditions	0.13-0.17	AQMesh over-estimated reference method concentrations by a factor of 170 on average

Table 4: South Coast AQMD SO_2 Sensor Evaluation

Make (Model)	Indicative Cost (USD)	Type	Meas.	*Field R^2	*Field MAE (ppb)
Air Quality Egg Ver. 2	$240	Electrochemical	O_3	0.0 to 0.20	
			SO_2	n/a	
AQMesh V5.1	$7,800	Electrochemical	CO	0.90 to 0.94	40.0 to 52.3
			NO	0.67 to 0.76	10.9 to 12.3
			NO_2	0.49 to 0.54	7.6 to 8.4
			NO_x	0.73 to 0.84	15.0 to 18.9
			O_3	0.62 to 0.74	12.9 to 14.4
			SO_2	n/a	n/a
Vaisala (AQT410) Ver. 1.11	$3,700	Electrochemical	CO	0.28 to 0.31	
			NO_2	0.0	
			O_3	0.40 to 0.58	
			SO_2	n/a	
Vaisala (AQT410) Ver. 1.15	$3,700	Electrochemical	CO	0.80 to 0.83	222 to 234
			NO_2	0.43 to 0.61	13.0 to 16.3
			O_3	0.66 to 0.82	6.6 to 8.9
			SO_2	n/a	

*Note: *The coefficient of determination (R^2) is a statistical parameter measuring the degree of relation between two variables. Here, it measures the linear relationship between the sensor and the Federal Reference Method (FRM), or Federal Equivalent Method (FEM), or Best Available Technology (BAT) reference instrument. An R^2 approaching the value of 1 reflects a near perfect correlation, whereas a value of 0 indicates a complete lack of correlation. All R^2 values reported in these evaluations are based either on 5-min or 1-hr average data.*

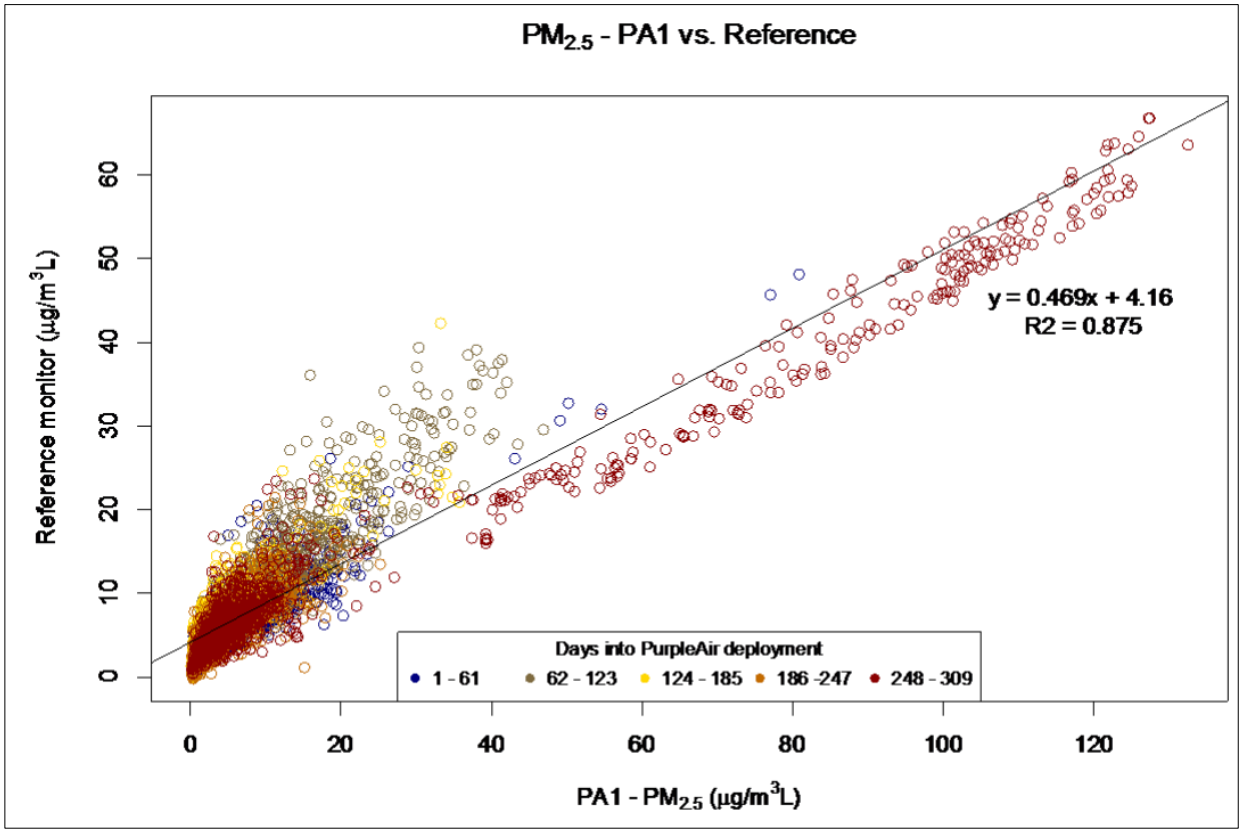
The mean absolute error (MAE) is a statistical parameter measuring the average of the absolute difference between the sensor and the FRM or FEM or BAT reference instruments, without considering the direction of errors. Higher MAE values indicate higher sensor measurement error when compared to the reference instruments. All field MAE values are based either on 5-min or 1-hr average data. If a sensor has not demonstrated good performance in the field, it may not advance to the laboratory chamber test.

3.3.2.2.4 $PM_{2.5}$ Example

Particulate matter (PM) sensors are much more widely tested than SO_2 sensors given their applicability in urban areas. Table B.1 in Appendix B lists the U.S. EPA (2022) evaluation for particulate sensors. Several evaluations took place in hot and humid summer conditions in the southern U.S. and results may differ in colder regions. The South Coast Air Quality Monitoring District (SCAQMD) also evaluated a wide variety of particulate sensors, and the results are shown in Appendix B Table B.2. Again, there is wide variability in R^2 values. Of note in Table B.2 are the very high R^2 (typically 0.99) values when measurements are made in controlled (laboratory) conditions and more modest values in field conditions.

Of specific interest to PRAMP, because it already operates one or more units, is the Purple Air, a sensor made popular during recent forest fires seasons in B.C. and one of the least expensive monitors tested by the SCAQMD where field R^2 values approached 0.95. Brauer and Lee (2018) included the Purple Air in an evaluation of low-cost sensors at two locations in Vancouver (**Figure 35**) where they recorded an R^2 value of 0.88. The Purple Air was a recommended sensor from the study.

Figure 35: Purple Air Performance against Reference Standard (Brauer and Lee 2018)



Li et al. (2020) compared the performance of nine low-cost particulate sensors. The first group, which included the PurpleAir, was evaluated as potential substitutes for two reference instruments. Although all four of the tested monitors demonstrated good linearity with the reference instruments, prior to calibration, they showed poor agreement in measuring some specialized particulate types. One reason may be that these monitors were factory-calibrated using other types of PM, the light scattering signatures of which differ from specialized forms, consequently affecting the measurement. The study also found that the calibration factor varies depending on the size bin requiring separate adjustments for each.

A western Canadian program by Environment and Climate Change Canada (Karch et al. 2019) compared Purple Air sensors to reference instruments in several locations. Preliminary results showed a 0.98 R^2 compared to reference values in Edmonton. The Purple Air had a linear response but over-estimated concentrations. Drift was noted, with the difference between Purple Air and reference monitors increasing with time.

Overall, low-cost PM sensors come with several challenges that must be addressed if their data products are to be used for anything more than a qualitative characterization of air quality (Giordano et al. 2021). The various PM sensors used in low-cost monitors are subject to biases and calibration dependencies, corrections for which range from relatively straightforward (e.g., meteorology, age of sensor) to complex (e.g., aerosol characteristics like source, composition, and refractive index).

The ideal approach when deploying low-cost PM sensors is to perform a series of characterization and calibration tests:

- Collocate the low-cost sensor with a reference method in a similar micro-environment the sensors will be deployed in. Typically, this means having the sensor inlets within a few metres of each other.
- Deploying sensors in the same environment where they will collect data helps minimize the impacts that particle composition and size distribution differences have on LCS, effectively by smoothing over a large ensemble of conditions.
- Separate the data into relevant periods (e.g., relatively clean versus relatively polluted periods, high RH and T versus low RH and T periods, examining different times of day or year to draw general conclusions about source contributions.
- Develop a limited number of comparison metrics. Don't rely only on R^2.
- Do not solely rely on the manufacturer calibration factors. Develop coefficients separately for each size range of the instrument based on comparison to the reference method.

3.3.3 Priority 3

From the perspective of monitoring the largest emissions, no data gaps exist within the PRAMP area. For many pollutants, secondary areas of interest are the Walrus region and the region east of it where several facilities report to the NPRI albeit at relatively low levels. The well density is useful but does not necessarily correlate to emission intensity. The population density in these areas is low. Additional monitoring is not recommended.

However, if PRAMP chooses to consider additional monitoring in these areas, the following approaches could be used:

- Add a new continuous station with the same level of instrumentation, should the gap be important enough for the additional capital and maintenance.
- Move an existing station to a new area, although this evaluation had not identified any "expendable" stations
- Add a new station with low-cost sensors (or relocate PRC passive monitors), provided adequate data quality is demonstrated

Finally, data deficiency has been considered only from a spatial perspective, but PRAMP should consider whether population size should also be a factor. Consideration should be given to the inclusion of emerging technology at Peace River, either to complement the current measurement suite, or to replace it. Consideration should also be given to collocating low-cost SO_2 sensors at one or more permanent stations, with the aim of replacing the SO_2 module with a low-cost module, provided the co-location data analysis proves out.

While the generation of AQHI was not examined as part of this work, information on the direction of community or indicative-level monitoring was investigated. This report recommends that PRAMP conduct further information gathering in this area, including the automatic generation of the AQHI in smaller population centres, and using these monitors as portables because they are very compact and can operate on solar/battery. Furthermore, they measure more chemicals than is currently monitored at several stations in the network and therefore add versatility as well.

It is noted that some next generation analyzers are currently undergoing testing within Alberta Environment and Parks and should not be considered for compliance purposes until testing is completed. It is our view that measuring in communities should not be considered as compliance monitoring.

4. Recommendations for Implementation

4.1 Recommendations by Monitoring Priority

Recommendations are summarized here by Priority/Tier and are followed by overall recommendations in the next section of the report. The following bullets summarize the recommendations following a review of the data from the perspective of performance of the network to detect changes in air quality after the implementation of Directive 84 (**Priority 1**):

- Remove stations? No
- Reduce parameters?
  - Can VOC/NMHC be eliminated given D84? No
  - Can SO_2 or TRS be eliminated? No, because SO_2 is relevant and TRS still shows exceedances at two stations.
  - Can meteorology be eliminated? No, given differences in wind roses at sites.
  - Eliminate either THC or CH_4 from reports? It is possible to report only one or the other, but not to remove the M/NMHC monitor itself.
- Move stations?
  - No, unless PRAMP desires to move a station into more dense emission areas as reflected in well density
- Change technology?
  - Passive or low-cost SO_2? Possible
  - Passive or gas-sensitive semiconductor technology VOC? Possible

The following summarize the recommendations following on the review of the implications of adding PRC and Mercer stations to the network (**Priority 2**):

- Remove any of the new stations? No
- Reduce parameters?
  - Can SO_2 be eliminated given low values? Possibly, or investigate technology changes
  - TRS eliminated? No, TRS shows 1-h exceedances and odour potential
  - What about meteorology? No, given differences in wind roses at sites.
  - Eliminate either THC or CH_4 from PRC reports? It is possible to report only one or the other, but not to remove the M/NMHC monitor itself.
  - Eliminate PM monitoring at Mercer Town? No, given concentration spikes in spring and summer.
- Move stations?
  - No, as all are related to effects of specific plant sources
- PRC passive network changes?
  - Eliminate

The following summarize the recommendations from consideration of spatial gaps in monitoring and the potential for emerging technology **(Priority 3**):

- Any monitoring-deficient areas? Yes, there are data-deficient areas, but they are not important enough to warrant monitoring.
- Transboundary pollution? There is a potential for transboundary movement, based on pockets of higher-density wells but reported emissions are not large and there are few nearby residents. This consideration is not sufficient to be characterized as a gap.

- Monitoring gaps?
  - Mercer PRPD: SO_2, THC, NMHC, CH_4, $PM_{2.5}$, CO, and NO_x are not monitored, but the plant is a high emission source for these pollutants. Other considerations: additional monitoring is not an approval requirement; emissions and their effects are likely to be sufficiently covered by annual emission estimation and stack sampling, and periodic dispersion modelling; there are few residents nearby. Not monitoring these parameters is not considered a gap.
  - Smaller communities? Maybe but this would be a local initiative given that AEP guidance indicates communities are too small to require it.
- New technologies?
  - $PM_{2.5}$: Yes, for forest fire monitoring or for monitoring in communities using proven technologies such as the Purple Air and following recommended procedures.
  - SO_2 or VOCs: Yes, as a replacement for current instruments but need to investigate and then test the right replacement technology.

4.2 Overall Recommendations

Combining these three individual sets of recommendations by identifying commonalities and by considering the monitoring more holistically, we make the following overall recommendations:

1. Remove stations? No
2. New stations in monitoring-deficient areas?
   - Are these areas important enough to warrant monitoring? Not with current technology but possibly with low-cost sensors.
   - Instead, could redeploy PRC passives although it is not expected that SO_2 and H_2S are issues in locations currently not monitored.
3. Move stations?
   - No, unless PRAMP wishes to monitor in Walrus and nearby secondary emission areas.
4. Reduce parameters?
   - Can VOC/NMHC be eliminated? No
   - Can SO_2 or TRS be eliminated? No, because SO_2 is relevant and TRS concentrations exceed thresholds at two stations.
   - Reduce meteorology? No, given differences in wind roses at sites.
   - Eliminate either THC or CH_4 from PRC reports? It is possible to report only one or the other, but not to remove the M/NMHC monitor itself.
5. Change technology?
   - Passive or low-cost SO_2 in place of current continuous monitors? Possible
   - Passive or gas-sensitive semiconductor technology VOC? Possible
   - $PM_{2.5}$: Possible
   - Replace threshold-activated canister sampling with continuous low-cost sensors for specific VOCs? Possible, provided the data quality of the low-cost sensors is adequate.
   - To support AQHI in communities? Possible. Consider the addition of sufficient monitoring capacity to calculate the AQHI in Peace River, through additional sensors at Mercer Town or using low-cost technology at a new station in the heart of the community.
6. PRC Passive network changes? Eliminate the passive network.

4.3 Implementation Priorities

1. Initiate elimination of the PRC Passive Network, with the following actions:
    a. Discuss with the AER what information is needed to remove the requirement from the EPEA approval.
    b. A more thorough evaluation of the data collected to date, to document performance, should be completed.
2. Investigate whether the passives could be used elsewhere to advantage. One example would be additional sampling in the Walrus and nearby areas of higher reported emissions, although as noted earlier, measuring H_2S and SO_2 may not be recommended in those areas.
3. Establish a plan to “calibrate” the Purple Air sensors currently deployed in the network, using as a guide the information in Section 3. 3.
4. Investigate low-cost sensor packages that can be programmed to calculate the AQHI used in Alberta and that provide acceptable data quality, including sufficiently low detection limits.
5. Investigate the elimination of THC reporting from stations, as THC is a calculated parameter with trends and concentrations very similar to methane. Retain methane / non-methane monitoring and reporting capability.
6. Review the potential to eliminate the threshold-triggered VOC canister sampling from network operations
    a. Perform a thorough review of the data to determine when health-based thresholds were and are exceeded (regulatory thresholds are occasionally exceeded). Given the occasional exceedances, but infrequent triggers of the threshold, determine if further monitoring is warranted.
    b. Review low-cost sensors for the pollutants of interest – acrolein, benzene, chloroform, BTEX – should the need for ongoing monitoring be required. Determine whether low-cost sensors meet data quality requirements.
7. Review the availability of low-cost sensors to monitor SO_2 in PRAMP conditions considering expected ambient concentrations and winter weather.

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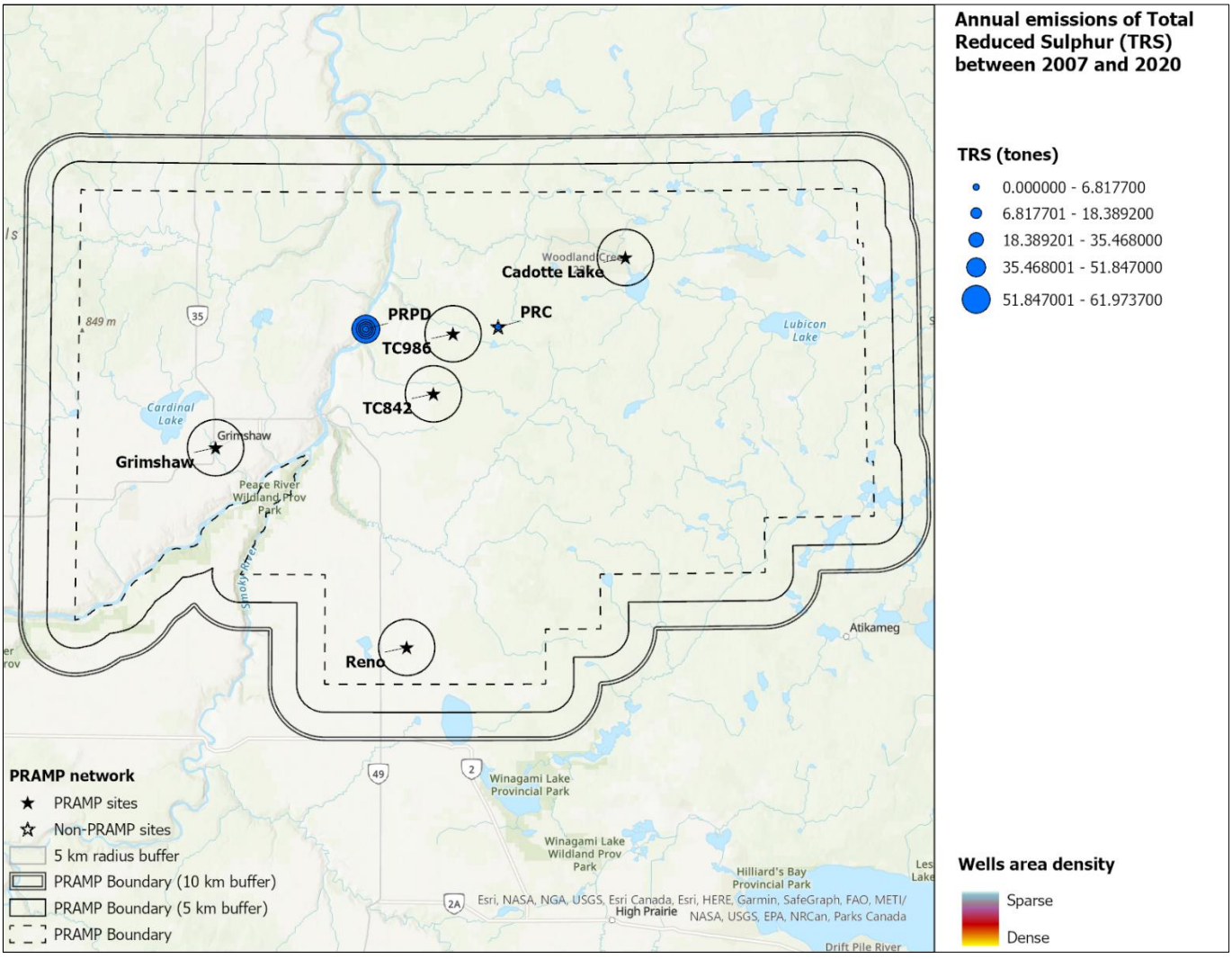
Appendix A. Secondary Network Evaluation Information

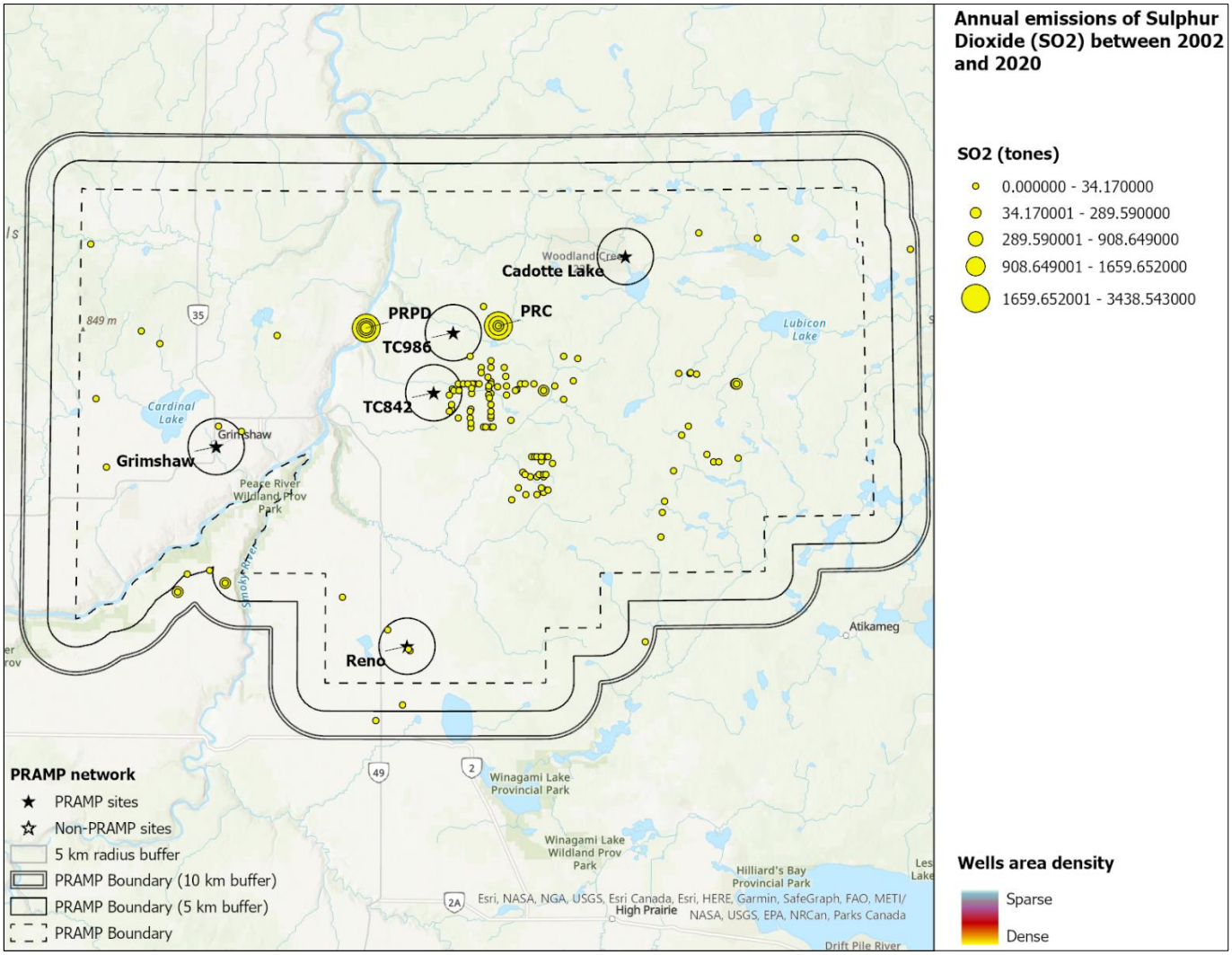
A.1 Historical NPRI Emissions in the PRAMP area

Figure 36: Historical (2007-2020) Annual TRS emissions within PRAMP area. Emissions Facilities are the Peace River Complex (PRC) and the Peace River Pulp Division (PRPD)



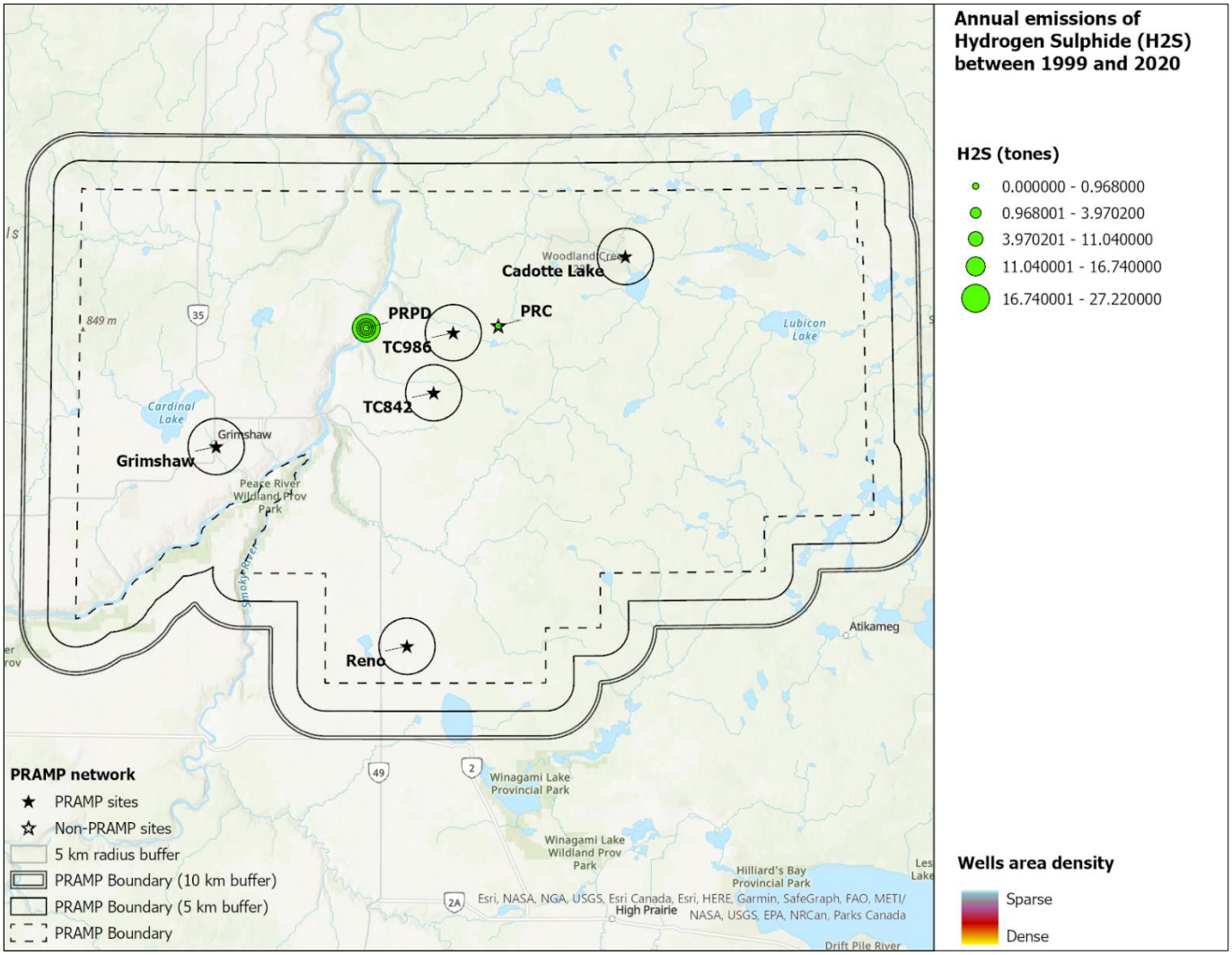
Note that PRPD has the longest history of TRS emissions compared to PRC.

Figure 37: Historical (2002-2020) Annual SO_2 Emissions within PRAMP Area



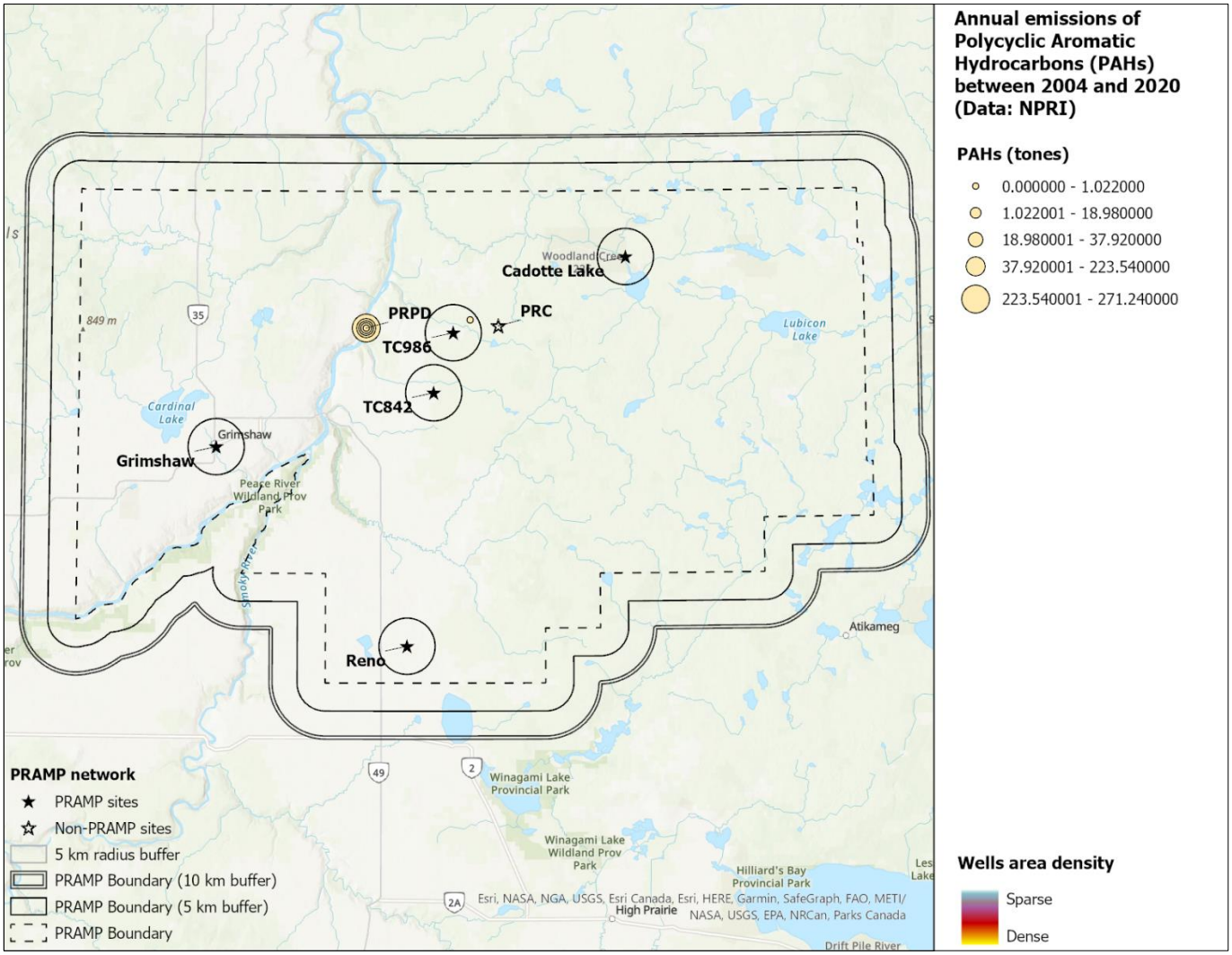
Note: Major emitting facilities are the Peace River Complex (PRC) and the Peace River Pulp Division (PRPD); both show the longest history of emissions and the largest emissions compared to other facilities.

Figure 38: Historical (1999-2020) Annual H_2S Emissions Within PRAMP Area



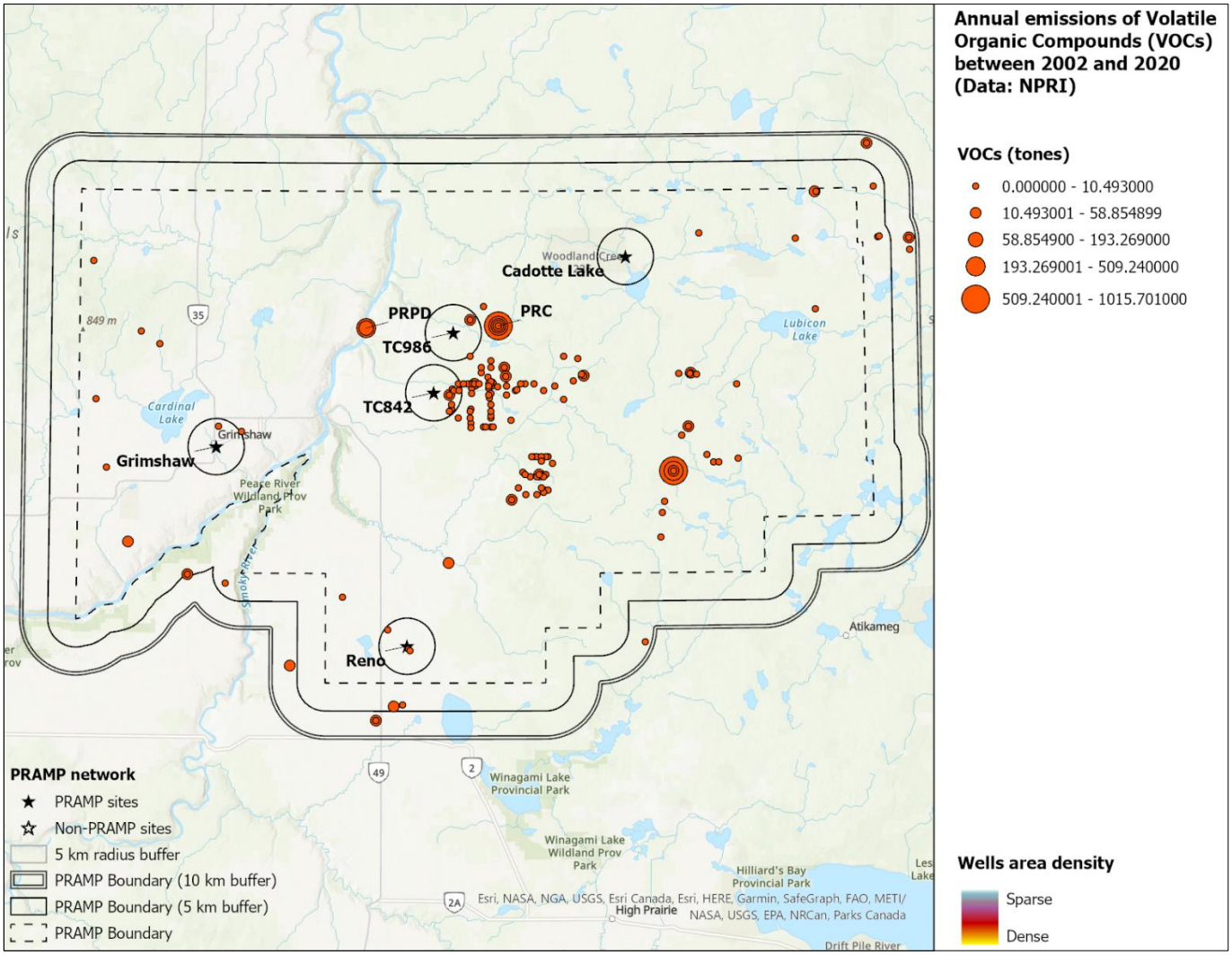
Note: Emitting facilities are the Peace River Complex (PRC) and the Peace River Pulp Division (PRPD); PRPD shows the longest history of emissions and the largest emissions compared to PRC.

Figure 39: Historical (2004-2020) Annual PAHs Emissions within PRAMP Area



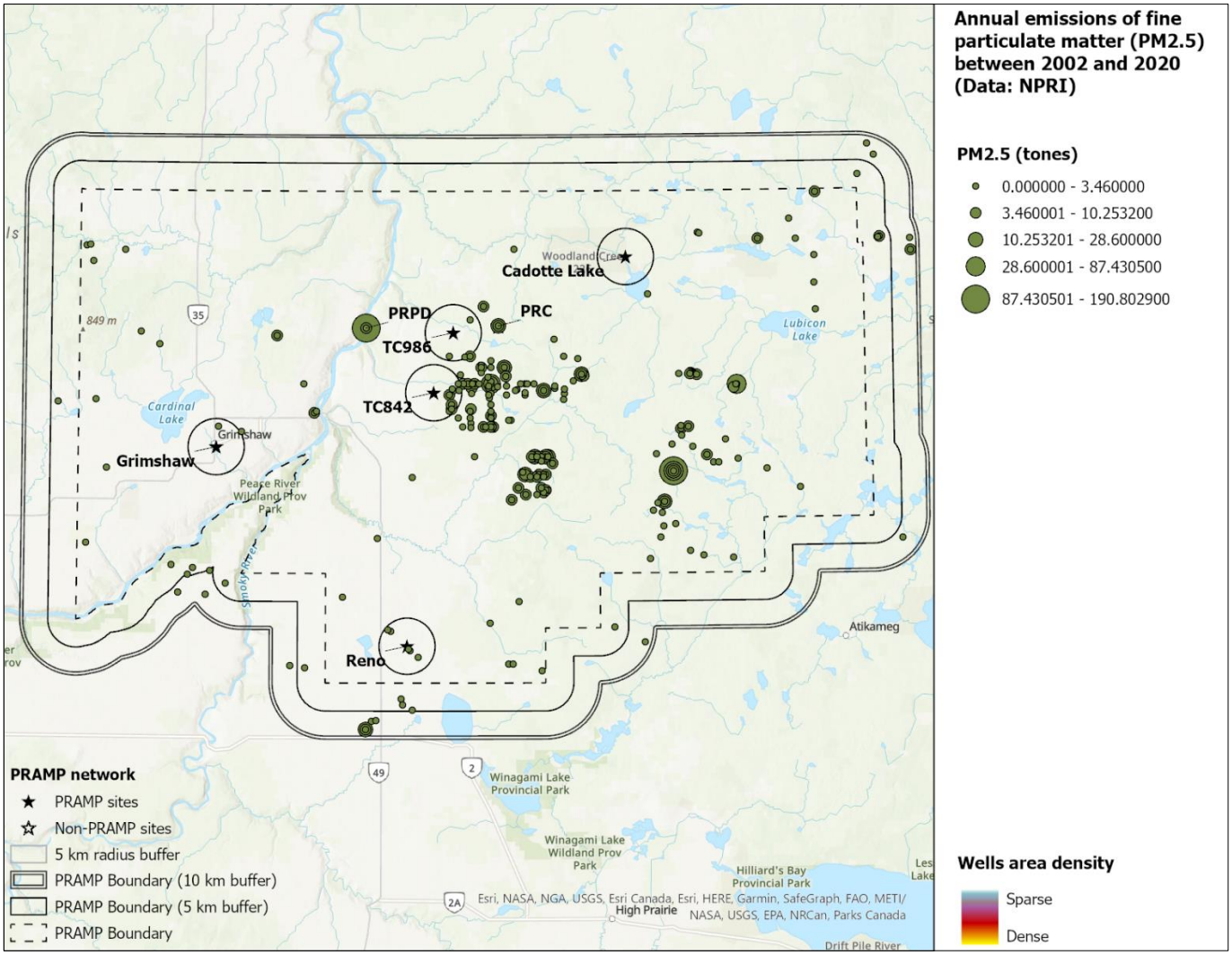
Note: Emitting facilities are the Peace River Complex (PRC), Peace River Pulp Division (PRPD) and CCS/Tervita Corporation

Figure 40: Historical (2002-2020) Annual VOCs Emissions within PRAMP Area



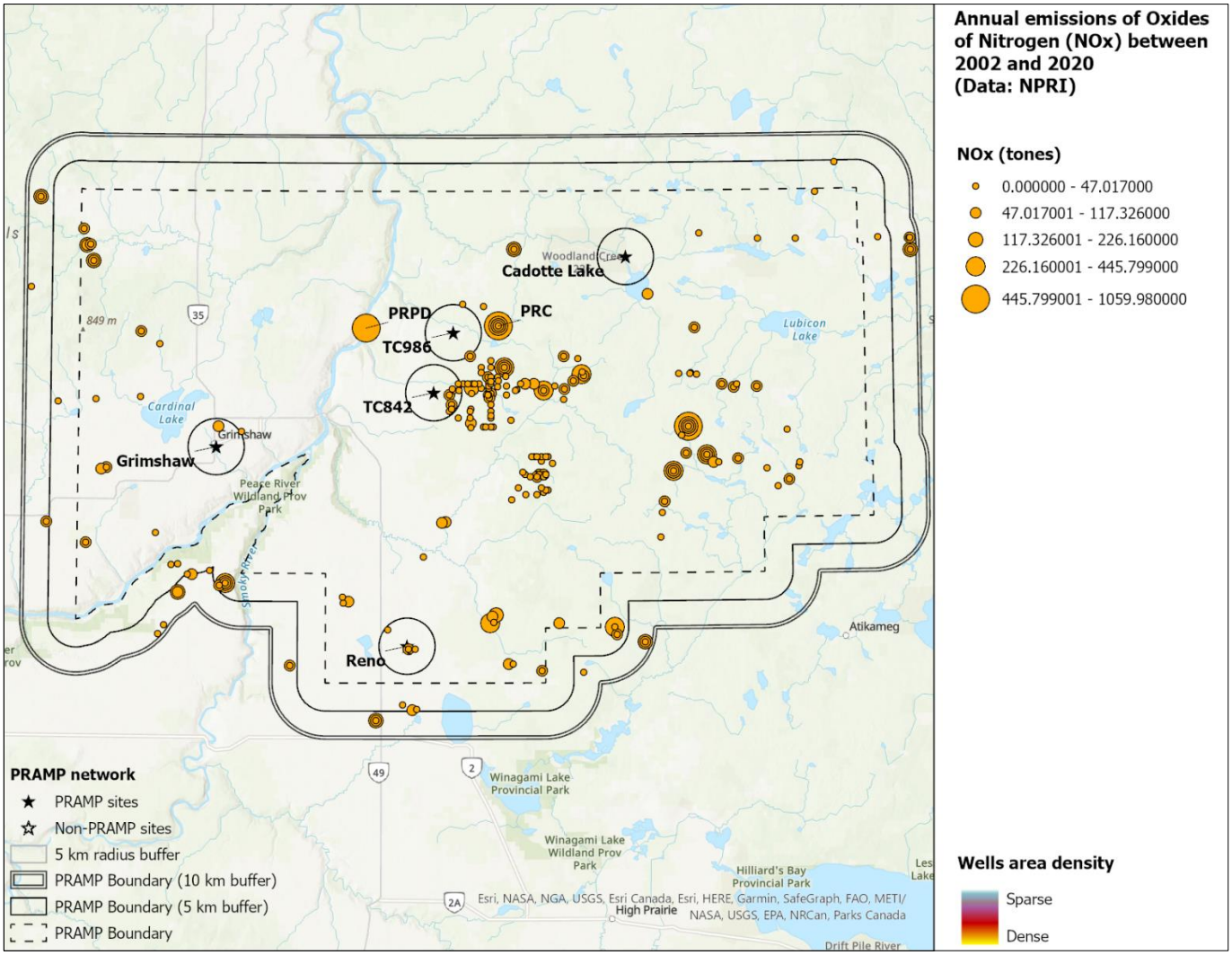
Note: Major emitters with long history of emissions are the Peace River Complex (PRC), Murphy Oil Canada Limited and Peace River Pulp Division (PRPD).

Figure 41: Historical (2002-2020) Annual $PM_{2.5}$ Emissions within PRAMP Area



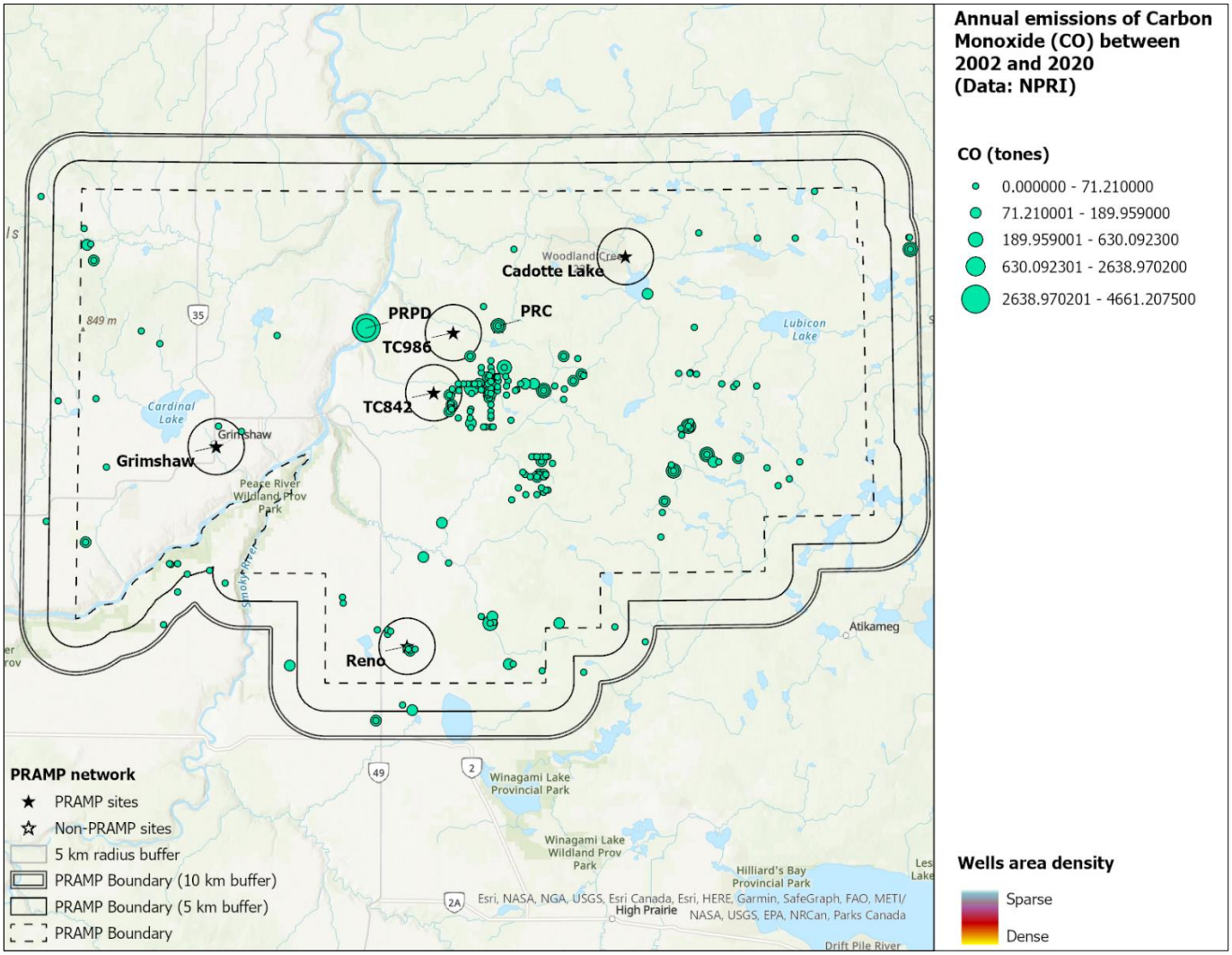
Note: Major emitters with long history of emissions are Peace River Pulp Division (PRPD) and Murphy Oil Canada Limited.

Figure 42: Historical (2002-2020) Annual NOx Emissions within PRAMP Area



Note: Major emitters with long history of emissions are Peace River Complex (PRC) and several energy companies (Baytex, Obsidian, WCSB, etc.)

Figure 43: Historical (2002-2020) Annual CO Emissions within PRAMP Area



Note: Major emitters with long history of emissions are Peace River Complex (PRC), Peace River Pulp Division (PRPD) and Baytex Energy Limited

A.2 Diurnal Concentration Profiles

A comparison between all the continuous monitoring PRAMP stations using the diurnal profiles of hourly concentration for each pollutant over a period of three years when measurements were made at all stations (2019-2021).

Figure 44 shows how the monthly mean of the TRS concentration along with its standard deviation varied diurnally over the three years period at each station. There is little seasonal variation observed at each station, particularly during spring and summer months; overall, the stations agreed well in terms of diurnal TRS concentration. Cadotte Lake recorded the highest TRS concentration among all stations, followed by Reno. The Cadotte station also showed unique (and likely infrequent) increases in concentration in March, April, May and July and this uniqueness indicates it is not a candidate for elimination. The two Three Creeks stations show relatively similar average TRS diurnal profiles, suggesting that one of the stations could be removed from the network for optimization purposes. For meeting monitoring objectives of the network, the best candidate for elimination in this case could be Three Creeks 842, because of the lowest average diurnal concentration recorded over the past three years compared to Three Creeks 986.

Regarding SO_2, (**Figure 45**) all stations but one (Cadotte Lake) agreed very well in diurnal concentrations. Cadotte Lake uniqueness may be the result of a short data set. The Three Creeks 842 station shows the largest diurnal concentration among all stations, suggesting that it should be kept in the network for further monitoring if the network is to be conservative.

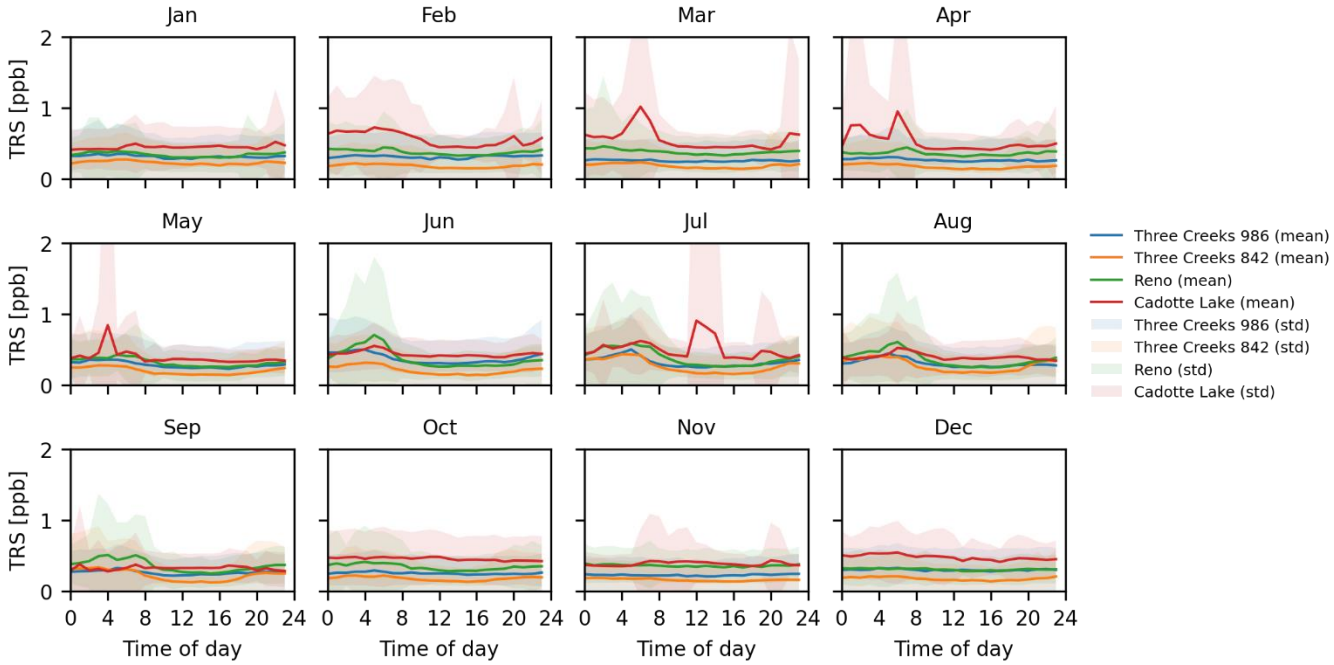
The Reno and Three Creeks 842 stations tend to show slightly larger THC concentrations during morning and late evening hours (**Figure 46**). Overall, all four stations show remarkably similar diurnal concentrations. Therefore, the 3-year diurnal profiles of THC also support the potential elimination of one of the Three Creeks stations (986) due to consistent but slightly lower diurnal concentration compared to Three Creeks 842.

Diurnal concentrations of NMHC (**Figure 47**) are very small, with many zero ppm occurrences, which do not allow for a clear interpretation. Apparently, Cadotte Lake has the best data coverage/completeness among all stations over the 3-year span. The NMHC mean at the Three Creek 842 station is consistently above the one at 986 for most of the months, suggesting it provides a more conservative indication of air quality in the network.

Diurnal profiles of CH_4 (**Figure 48**) are almost identical to those of THC (**Figure 46**). This is probably because THC is highly driven by the CH_4 concentration among all the hydrocarbons in the THC mix. Overall, all four stations show very similar diurnal concentrations, given the common global background of methane. Therefore, the 3-year diurnal profiles of CH_4 also support the eventual elimination of the Three Creeks 986 station due to consistent but slightly lower diurnal concentration compared to Three Creeks 842.

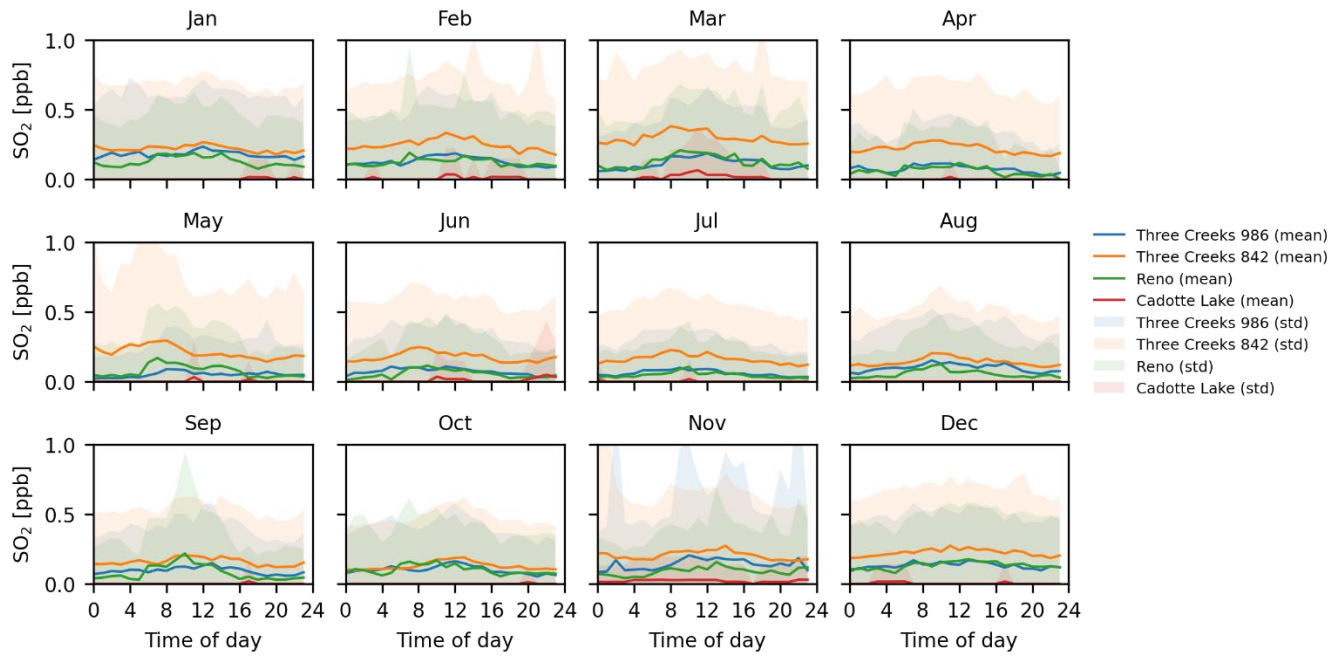
Overall, the diurnal patterns of the 842 and 986 stations are similar, although in some cases 986 tends to show slightly higher average diurnal concentrations and for this reason only 986 potentially may be considered a candidate for elimination.

Figure 44: Three-year (2019-2021) Diurnal Profiles of TRS at Continuous Monitoring PRAMP Stations



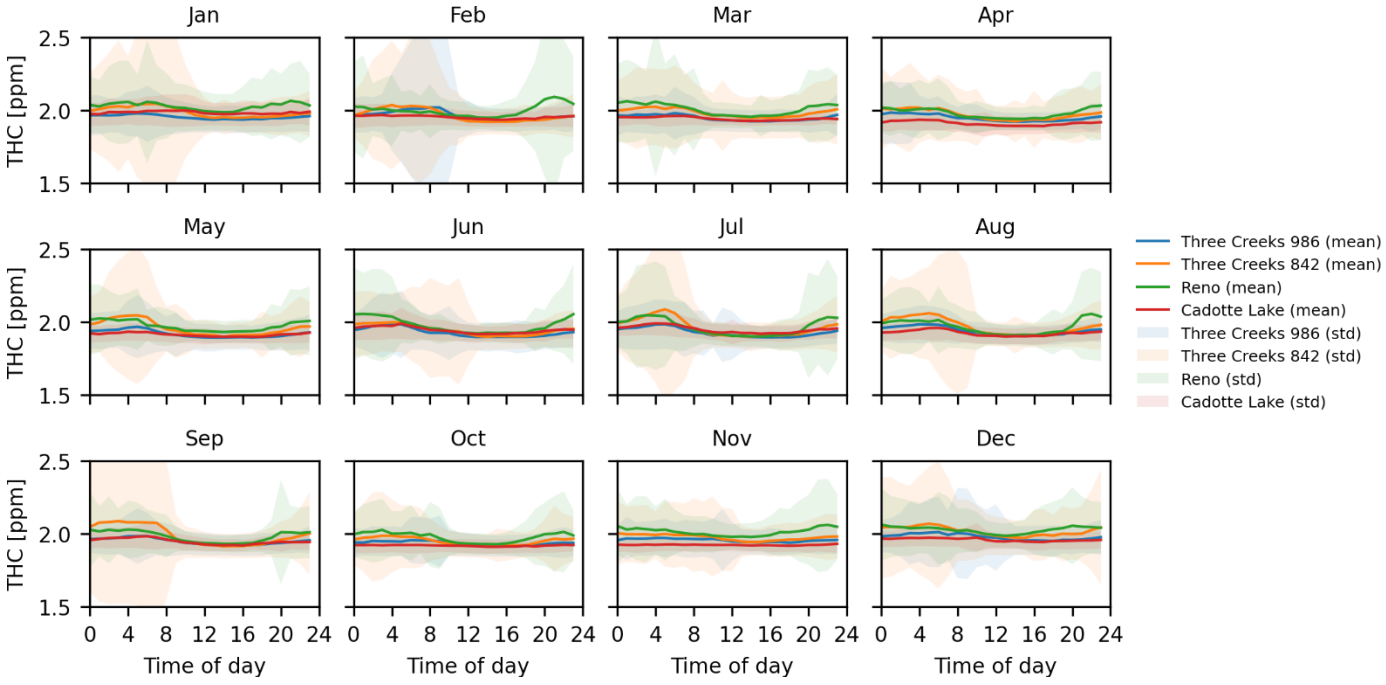
Note: Lines represent the 3-year averaged monthly mean of TRS concentration for each hour of the day. Shaded areas represent one standard deviation of that mean.

Figure 45: Three-year (2019-2021) Diurnal Profiles of SO_2 at Continuous Monitoring PRAMP Stations



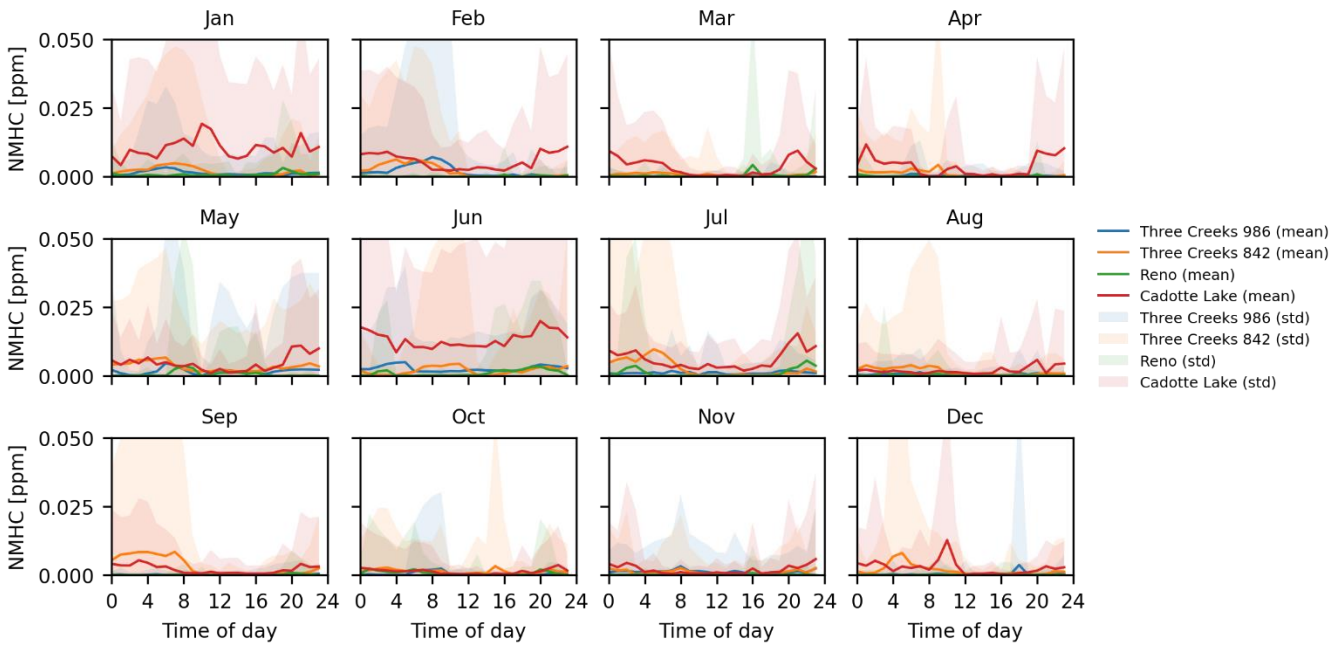
Note: Lines represent the 3-year averaged monthly mean of SO_2 concentration for each hour of the day. Shaded areas represent one standard deviation of that mean.

Figure 46: Three-year (2019-2021) Diurnal Profiles of THC at Continuous Monitoring PRAMP Stations



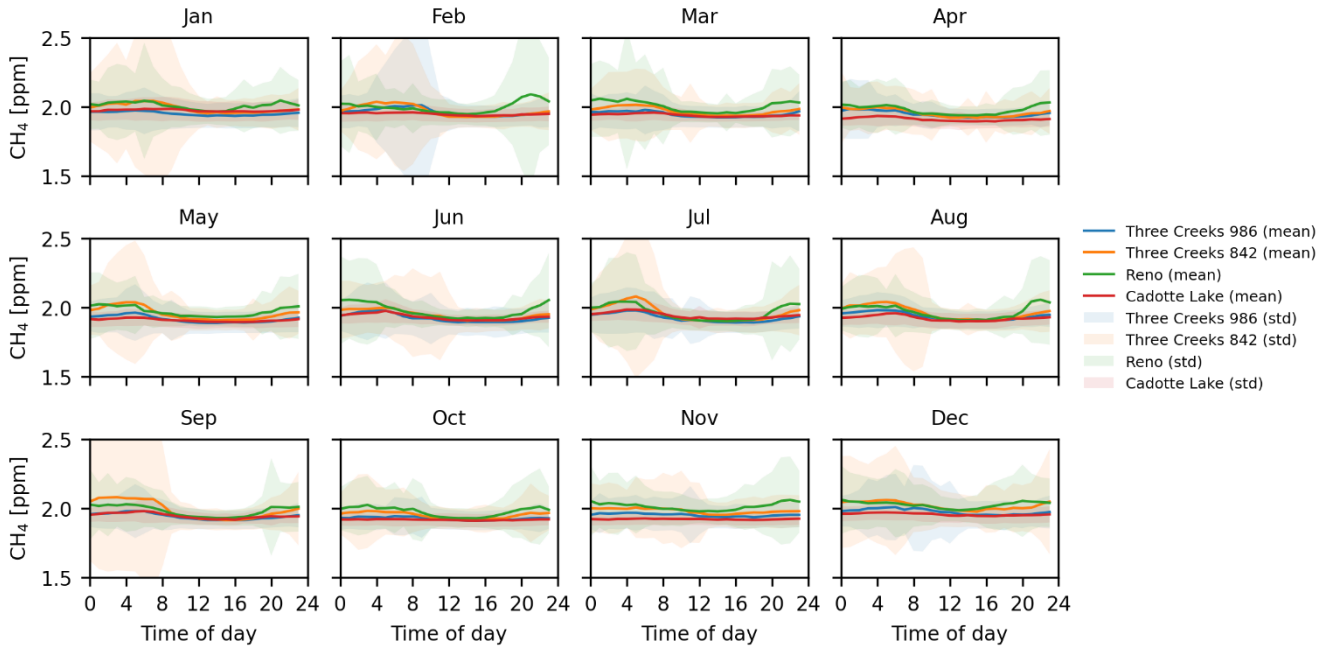
Notes: Lines represent the 3-year averaged monthly mean of THC concentration for each hour of the day. Shaded areas represent one standard deviation of that mean.

Figure 47: Three-year (2019-2021) Diurnal Profiles of NMHC at Continuous Monitoring PRAMP Stations



Notes: Lines represent the 3-year averaged monthly mean of NMHC concentration for each hour of the day. Shaded areas represent one standard deviation of that mean.

Figure 48: Three-year (2019-2021) diurnal profiles of CH_4 at continuous monitoring PRAMP stations



Notes: Lines represent the 3-year averaged monthly mean of CH_4 concentration for each hour of the day. Shaded areas represent one standard deviation of that mean.

A.3 Wind and Pollutant Roses

Wind and pollution roses were compared between stations by combining continuous data sets for three overlapping periods of time:

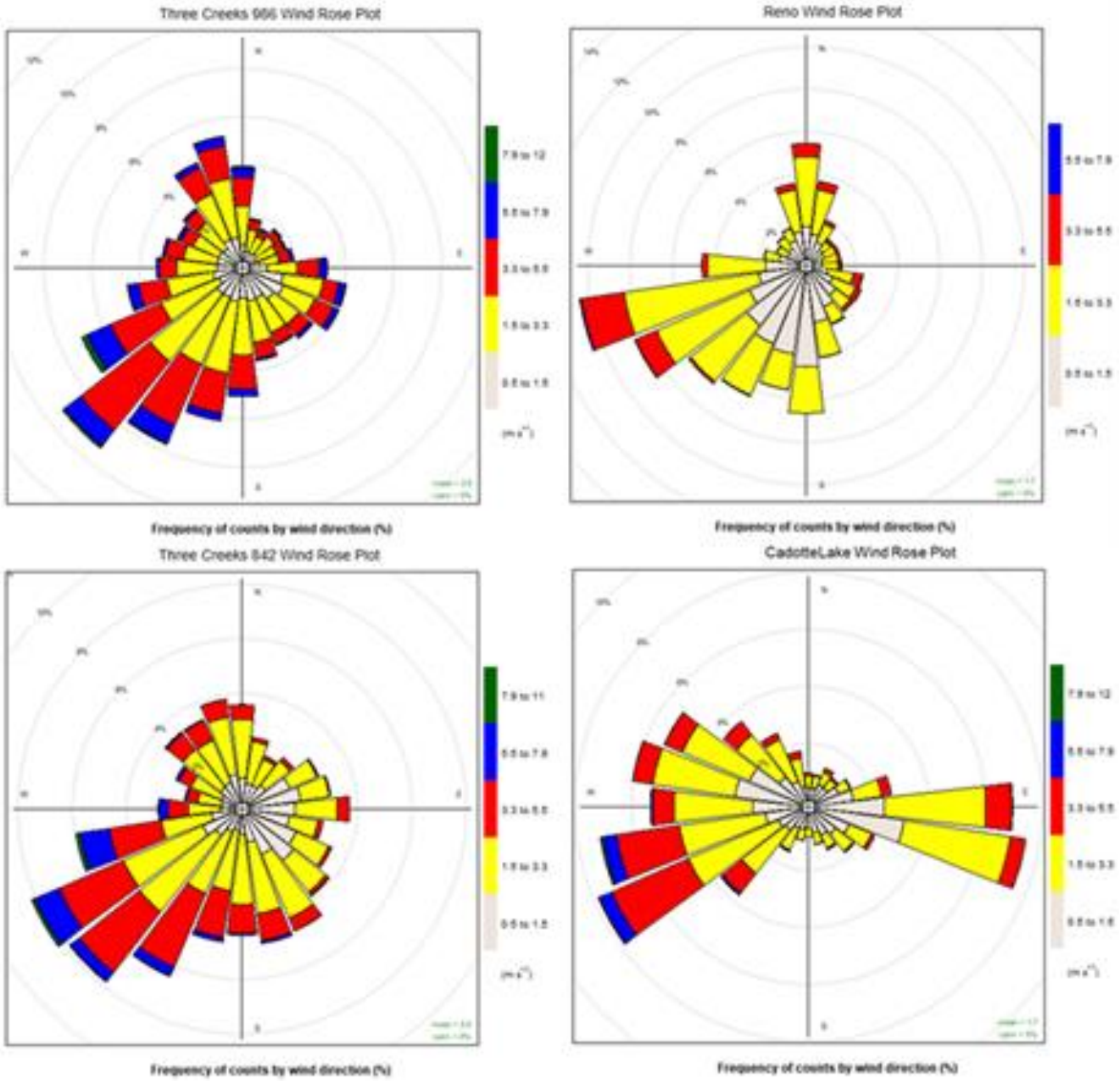
- 2012-2021: Ten-year comparison of wind and pollution roses between the two Three Creeks stations (986 and 842)
- 2015-2021: Seven-year comparison of wind and pollution roses between Three Creeks stations (986 and 842) and Reno station
- 2019-2021: Three-year comparison of wind and pollution roses between Three Creeks stations (986 and 842), Reno and Cadotte Lake stations.

The wind and pollution roses did not differ much for the long, medium and short terms, suggesting that the prevailing winds and their controls on pollutant concentrations were relatively constant over time at each station. Therefore, the emphasis is on the short-term scenario (2019-2021) which allow for comparisons between all four continuous monitoring PRAMP stations (**Figure 49** to **Figure 55**).

Representativeness of Wind Conditions in the PRAMP Network

The Three Creek stations are relatively similar in terms of prevailing wind direction (**Figure 49** shows that most frequent winds are from southwest at both stations) but also in terms of wind speed when winds are from southwest (5.5-7.9 ms^{-1}). Three Creeks 986 is additionally influenced by faster winds from northwest, north, northeast and southeast compared to Three Creeks 842; this is because 986 is located north-northeast from 842. The Reno station is relatively similar to the two Three Creeks stations; however, because it is located south of the Three Creeks stations, the Reno station is even more influenced by winds from southwest (frequency > 10 %) but of lower speed (3.3-5.5 ms^{-1}). The Cadotte Lake station also experienced southwest winds more frequently but also experienced eastern winds due to its northeastern location from Three Creeks 986. Therefore, if a choice needs to be made between these four stations to optimize the PRAMP network, one of the two Three Creeks stations may be a good candidate for elimination considering wind direction and speed only.

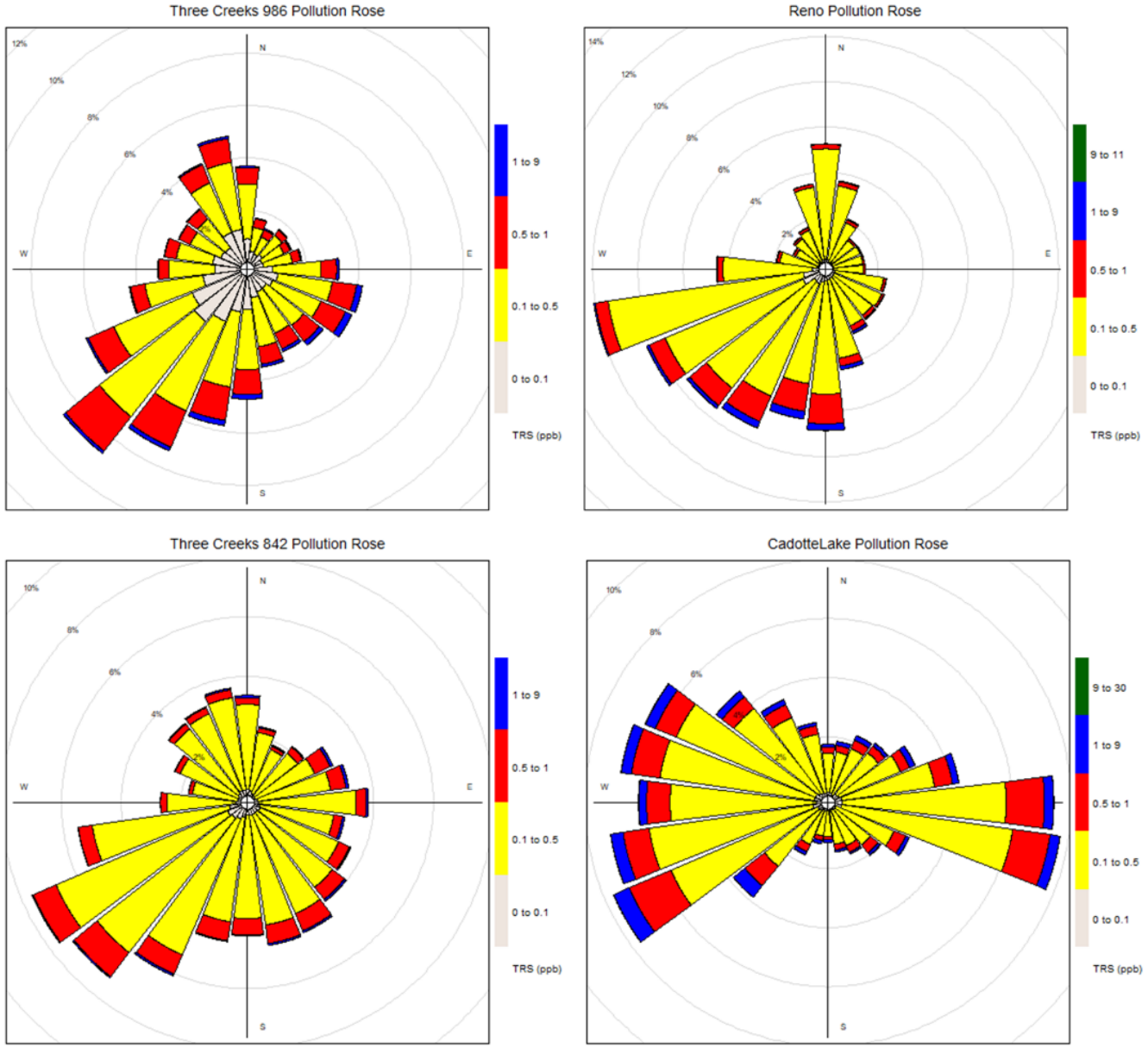
Figure 49: Prevailing Wind Direction and Speed at Continuous Monitoring PRAMP Stations (Three Creeks 986 and 842, Reno and Cadotte Lake) during 2019-2021



Wind influence on TRS Concentration

The similarity between the two Three Creeks stations observed regarding wind direction is preserved in the TRS pollution roses (**Figure 50**). Although less frequent, the highest concentrations were from east-southeast-south-southwest (Three Creeks 986) and northeast-east-southeast (Three Creeks 842), where many wells are located (see **Figure 3**), pointing out that the wind influence was stronger than that of the emissions source. The weaker influence of wells from other locations (e.g., TRS concentration of up to 9-11 ppb) is also picked up by the Cadotte Lake station (most frequently from southwest-west-northwest and east-southeast directions) and the Reno station (higher frequency from south and southwest).

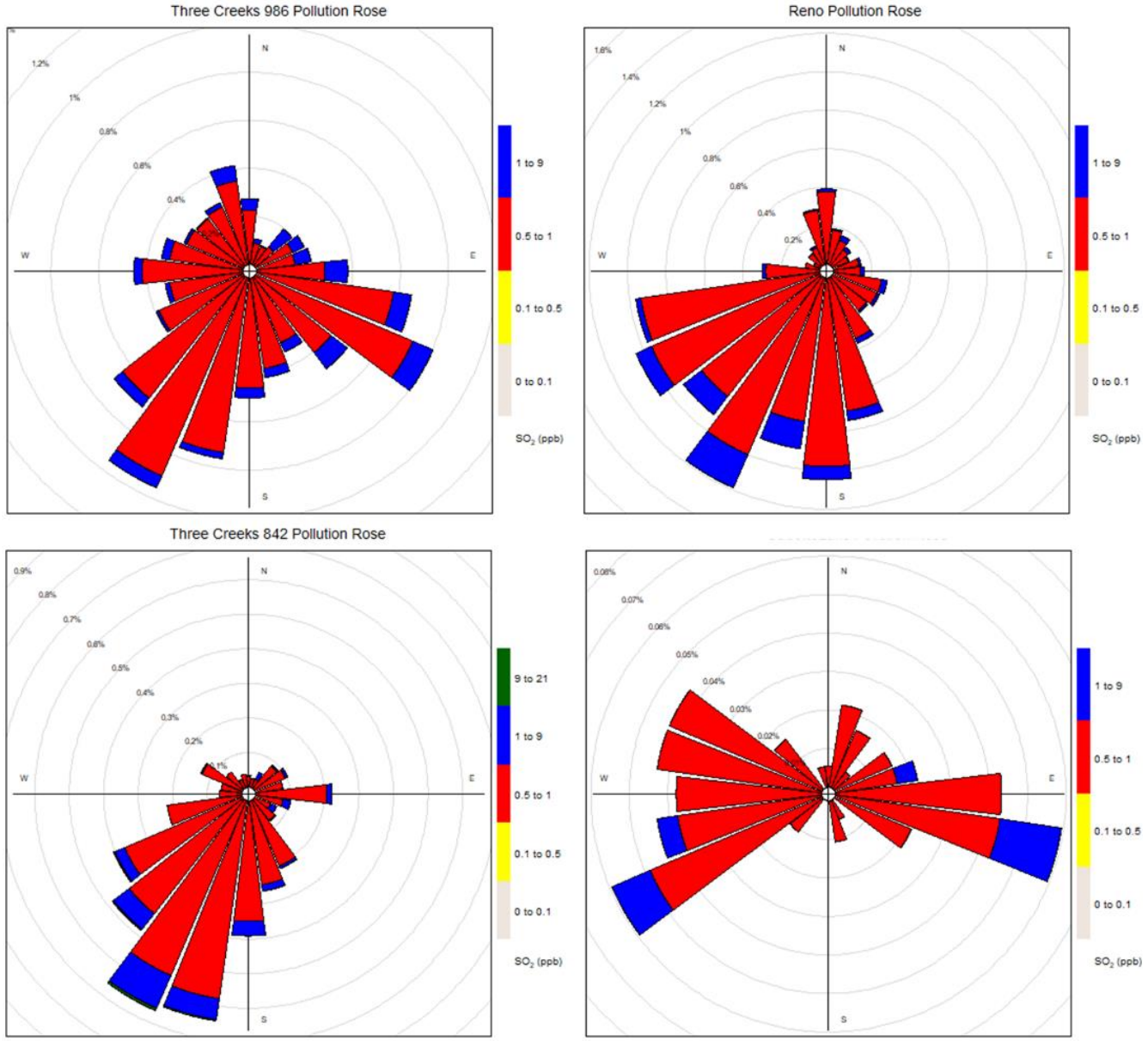
Figure 50: Wind Influences on TRS Concentrations at Continuous Monitoring PRAMP Stations (Three Creeks 986 and 842, Reno and Cadotte Lake) during 2019-2021



Wind Influence on SO_2 Concentration

The frequency of SO_2 observations per wind direction bin is very low at all stations (**Figure 51**). Again, the similarity between the Three Creeks stations is obvious as observed with the TRS and wind roses. The most frequent observations associated with southwest winds (at both stations) and with southeast winds (at Three Creeks 986). Largest concentrations (up to 9 ppb), however, occurred from all wind directions at Three Creeks stations. Reno picked up largest SO_2 concentrations from southwest and south, while Cadotte Lake picked those from southwest and southeast. In summary, SO_2 also supports the elimination from the network of one of the Three Creeks stations but this interpretation is biased due to very low frequency of SO_2 data per wind bins (≤ 1.2% overall).

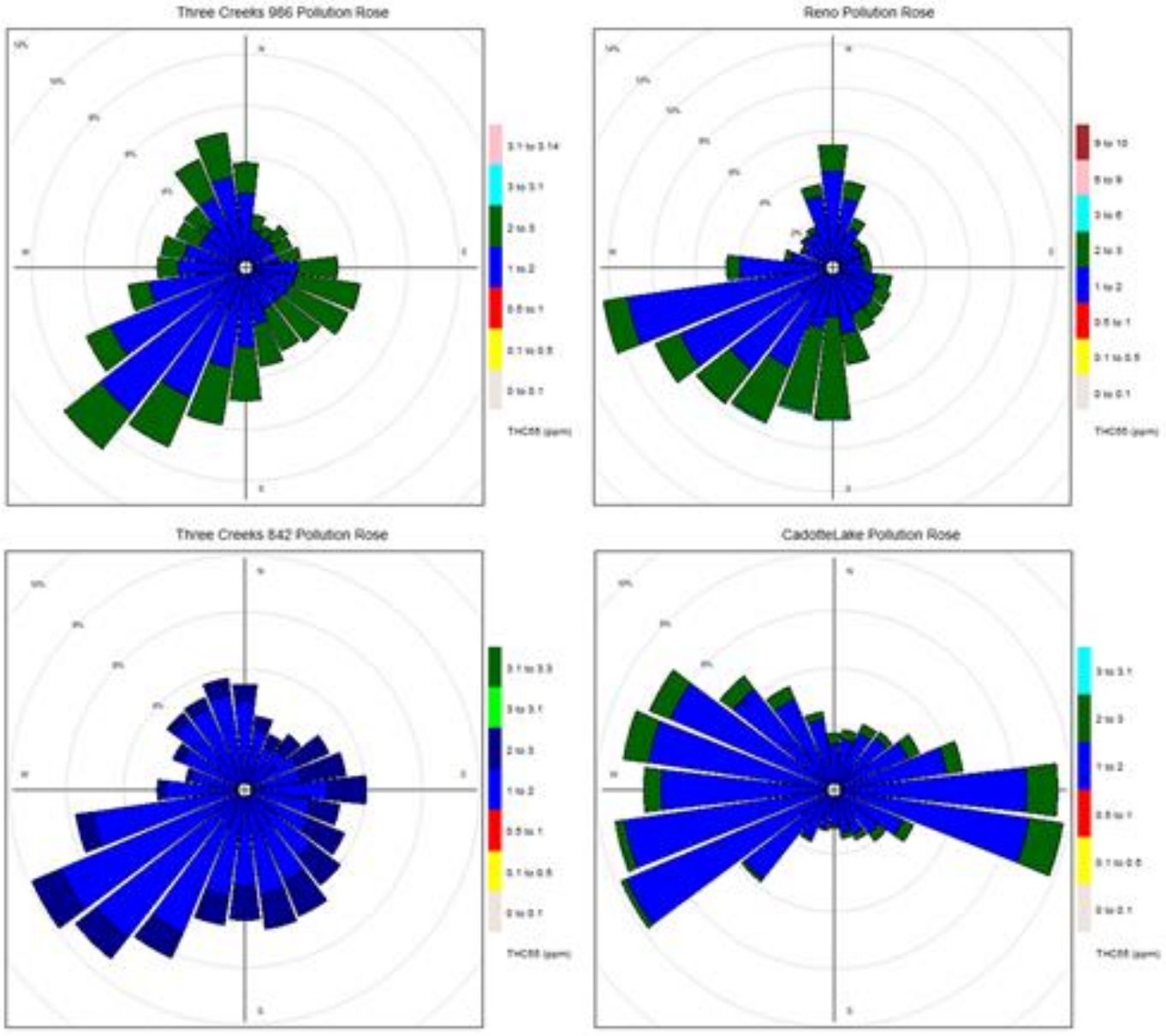
Figure 51: Winds influences on SO_2 concentration at continuous monitoring PRAMP stations (Three Creeks 986 and 842, Reno and Cadotte Lake) during 2019-2021



Wind Influence on THC Concentration

THC roses are consistent with wind roses at all stations in terms of direction and frequency. The largest concentrations associated with prevailing winds from southwest (Three Creeks 986 and 842), south-southwest (Reno) and east-west (Cadotte Lake). The agreement between wind and pollution roses for THC at any station clearly indicates that the stations are not uniquely located. However, the two Three Creeks stations appear to be very correlated due to similar wind influences.

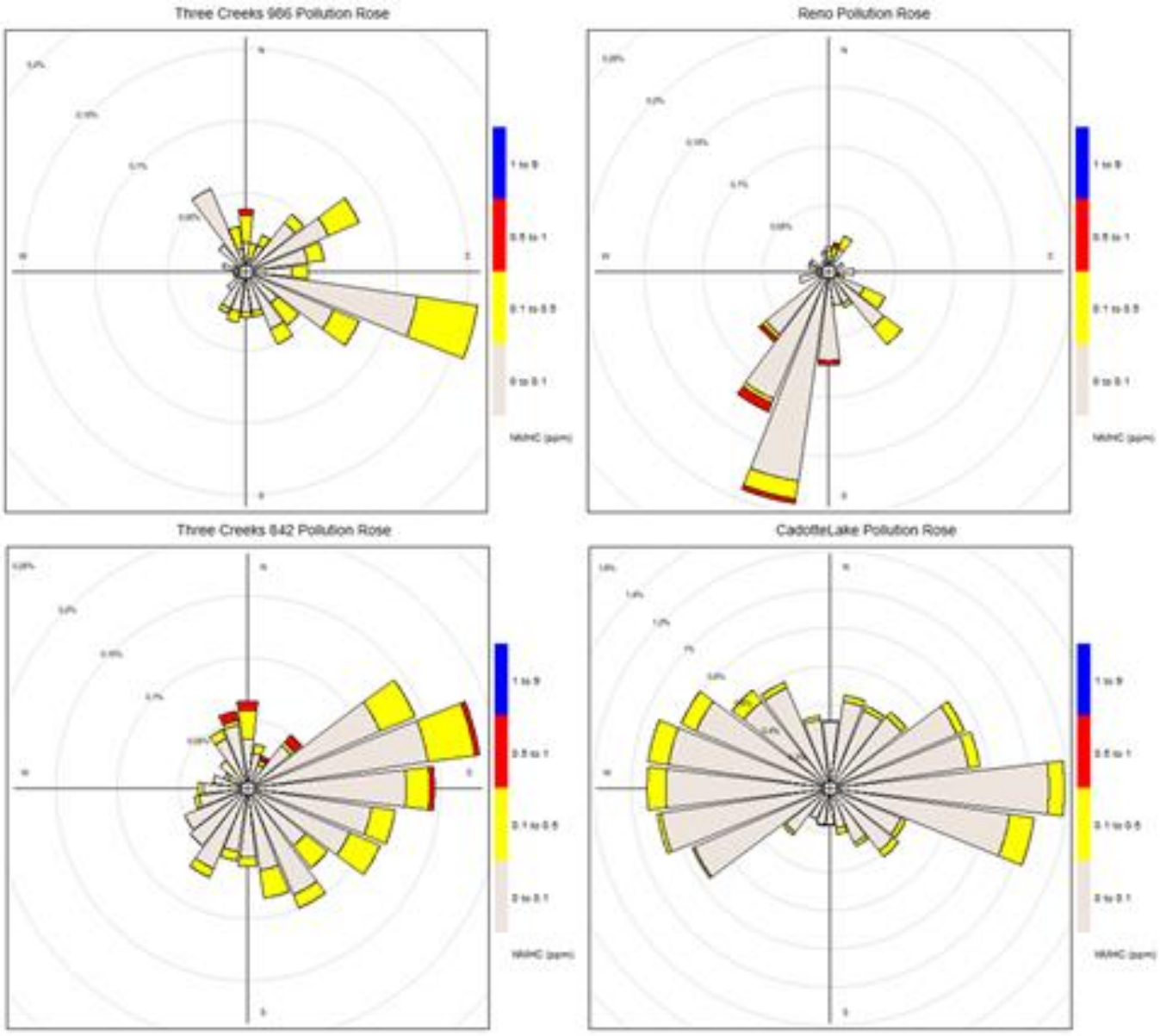
Figure 52: Wind influences on THC concentration at continuous monitoring PRAMP stations (Three Creeks 986 and 842, Reno and Cadotte Lake) during 2019-2021



Wind Influence on NMHC Concentration

NMHC roses are different than the wind roses at all stations but Cadotte Lake and, in particular, at the Three Creek stations (**Figure 53**). Most frequent NMHC concentrations arrived from southeast and northeast at 986 and from northeast-east at 842 (prevailing winds though were from southwest at both stations), while the largest concentrations associated with a northern direction at both 986 and north-northeastern direction at 842. At Reno, most frequent and largest NMHC concentrations were from southwest. The Three Creeks and Reno stations reflect stronger influences from nearby emissions sources and therefore none can be removed from the network.

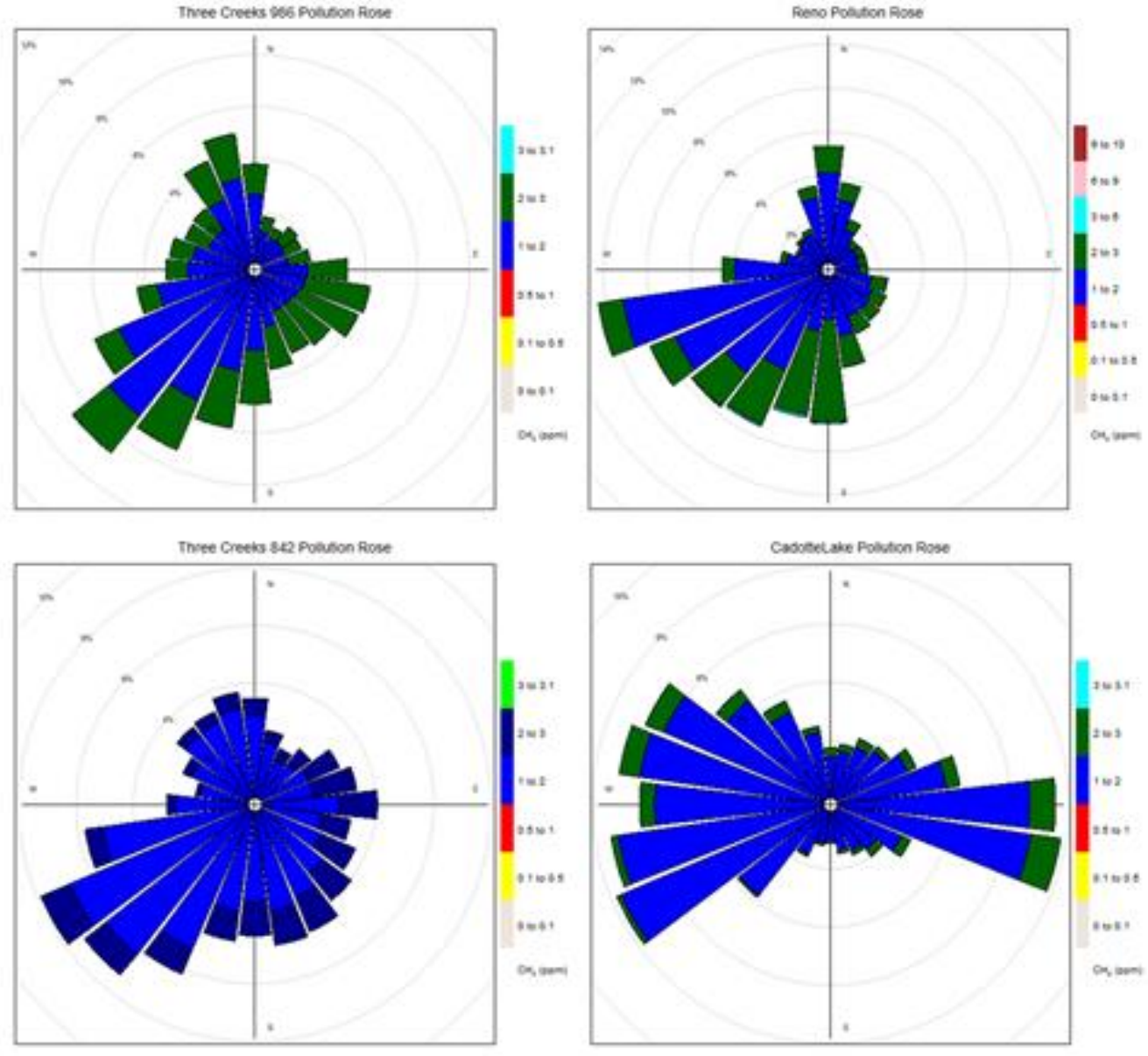
Figure 53: Winds Influences on NMHC Concentration at Continuous Monitoring PRAMP stations (Three Creeks 986 and 842, Reno and Cadotte Lake) during 2019-2021



Wind Influence on CH_4 Concentration

Like THC roses, the CH_4 roses also are consistent with wind roses at all stations. The largest concentrations associated with prevailing winds from southwest (Three Creeks 986 and 842), south-southwest (Reno) and east-west (Cadotte Lake). The lack of disagreement between wind and THC roses clearly indicates that the stations are not uniquely located. However, the Three Creeks stations are correlated due to similar wind influences and so one may be redundant.

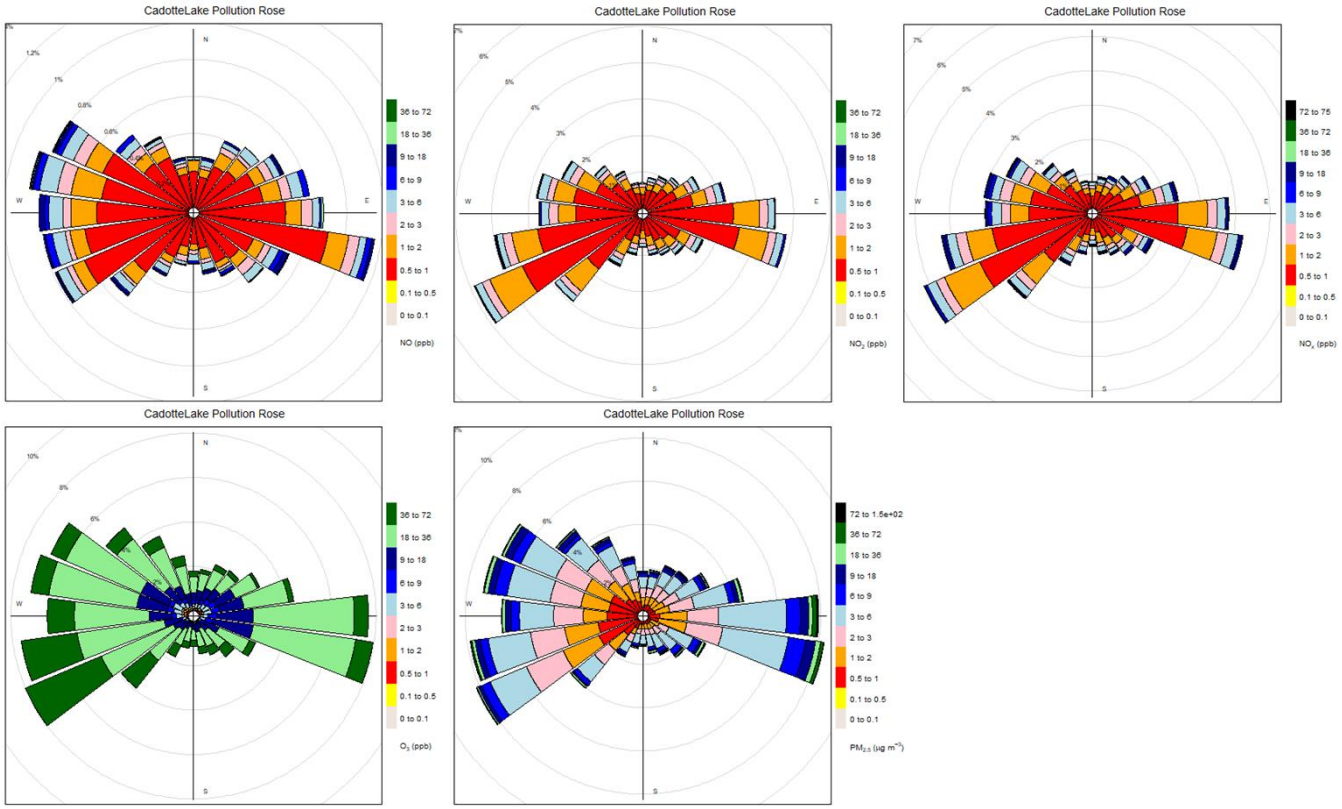
Figure 54: Winds Influences on CH_4 Concentration at Continuous Monitoring PRAMP Stations (Three Creeks 986 and 842, Reno and Cadotte Lake) during 2019-2021



Wind influence on NO, NO_2, NO_x, O_3 and $PM_{2.5}$

The effect of wind on other pollutants measured in the PRAMP area (Cadotte Lake station only) also were investigated (**Figure 55**). Pollution roses of NO, NO_2, NO_x, O_3 and $PM_{2.5}$ all agreed with the wind roses at this station. The largest concentrations also were consistent with the most frequent wind directions. Given these results, the elimination of Cadotte Lake stations from the monitoring network is not supported.

Figure 55: Wind Influences on NO, NO_2, NO_x, O_3 and $PM_{2.5}$ at Cadotte Lake during 2019-2021



Appendix B. Low-Cost Sensor Comparison

Table B.1 U.S. EPA $PM_{2.5}$ Sensor Evaluation

Sensor Model	Detection Approach	Operating Details	Test Environment	Reference Monitor Used	Avg Time; Testing Period	R^2
Alphasense OPC N2	Optical particle counting (0.38 to 17 microns). The cumulative particle counts across various size designations are converted to estimates of PM2.5 and PM10 particle mass concentrations.	Unit was integrated into a prototype United Nations multi-pollutant sensor pod. Designed as a stationary monitor; it recorded data as 1-minute averages in units of µg/m^3.	One month (November 2016) of continuous testing at an EPA testing platform in Research Triangle Park, NC	GRIMM EDM 180 FEM PM2.5 Monitor	1 h averaging period; Approximately 1 month of continuous data collection	0.007 (PM2.5) 0.01 (PM10)
Shinyei	Volume scattering – particles (possibly including particles larger than 2.5 µm) entering the sensor scatter light from an internal light source. The scattered light signal is converted to an estimated particle mass concentration.	Designed as a stationary miniaturized monitor; can record data as fast as 1 second; data units in µg/m3.	Minimum 30-day testing period of duplicate or triplicate monitors at a state regulatory monitoring site in hot and humid conditions in Decatur, GA.	MetOne BAM 1020 FEM PM2.5 Monitor	12 h averaging period; minimum 30 days	0.45 to 0.60
Dylos	Optical particle counter – particles entering sensor are individually sized and counted based on how they scatter light. The sensor outputs particle counts in two size ranges (>0.5 µm; >2.5 µm).	Designed for indoor use; can record data as fast as 1 minute; data output units in particle counts.	Minimum 30-day testing period of duplicate or triplicate monitors at a state regulatory monitoring site in hot and humid conditions in Decatur, GA.	MetOne BAM 1020 FEM PM2.5 Monitor	12 h averaging period; minimum 30 days	0.63 to 0.67 (pro); 0.58 (DC1100)
AirBeam	Volume scattering – particles (possibly including particles larger than 2.5 µm) entering the sensor scatter light from an internal light source. The scattered light signal is converted to an estimated particle mass concentration.	Designed as a highly portable handheld monitor; data are reported in units of µg/m3.	Minimum 30-day testing period of duplicate or triplicate monitors at a state regulatory monitoring site in hot and humid conditions in Decatur, GA.	MetOne BAM 1020 FEM PM2.5 Monitor	12 h averaging period; minimum 30 days	0.65 to 0.66
MetOne	Optical particle counter – particles entering sensor are individually sized and counted based on how they scatter light. The sensor outputs estimated mass concentrations in four size fractions (PM1, PM2.5, PM4, and PM10).	Designed as a handheld monitor; can record data as fast as 1 minute; data output units in micrograms per cubic meter (µg/m3).	Minimum 30-day testing period of duplicate or triplicate monitors at a state regulatory monitoring site in hot and humid conditions in Decatur, GA.	MetOne BAM 1020 FEM PM2.5 Monitor	12 h averaging period; minimum 30 days	0.32 to 0.41

Sensor Model	Detection Approach	Operating Details	Test Environment	Reference Monitor Used	Avg Time; Testing Period	R^2
Air Quality Egg	Volume scattering – particles (possibly including particles larger than 2.5 µm) entering the sensor scatter light from an internal light source. The scattered light signal is converted to an estimated particle mass concentration.	Designed for indoor use or outdoor use with proper weather shielding. Data are reported in units of µg/m^3.	Minimum 30-day testing period of duplicate or triplicate monitors at a state regulatory monitoring site in hot and humid conditions in Decatur, GA.	MetOne BAM 1020 FEM PM2.5 Monitor	12 h averaging period; minimum 30 days	-0.06 to 0.40
Cairpol CairClip PM - prototype	Volume scattering – particles (possibly including particles larger than 2.5 microns (µm) entering the sensor scatter light from an internal light source. The scattered light signal is converted to an estimated particle count concentration.	Lightweight and miniature; can record data as fast as 1 minute; data output in µg/m^3.	Wintertime outdoors in Durham, North Carolina; Reference monitor $PM_{2.5}$ ranged ~2-45 µg/m^3.	Grimm Model EDM180 $PM_{2.5}$ monitor	5 min; ~1.5 months	0.06
Airviz Speck v2	Volume scattering – particles (possibly including particles larger than 2.5 µm) entering the sensor scatter light from an internal light source. The scattered light signal is converted to an estimated particle count concentration.	Designed for indoor use; can record data as fast as 5 seconds; data output in particle counts.	Wintertime outdoors in Durham, North Carolina; Reference monitor $PM_{2.5}$ ranged ~2-23 µg/m^3.	Grimm Model EDM180 $PM_{2.5}$ monitor	5 min; ~1.5 months	0.01
Dylos DC1100	Optical particle counter – particles entering sensor are individually sized and counted based on how they scatter light. The sensor outputs particle counts in two size ranges (>0.5 µm; >2.5 µm).	Designed for indoor use; can record data as fast as 1 minute; data output units in particle counts.	Wintertime outdoors in Durham, North Carolina; Reference monitor $PM_{2.5}$ ranged ~2-45 µg/m^3.	Grimm Model EDM180 $PM_{2.5}$ monitor	5 min; ~1.5 months	0.55[a]
Met One Model 831	Optical particle counter – particles entering sensor are individually sized and counted based on how they scatter light. The sensor outputs estimated mass concentrations in four size fractions (PM1, $PM_{2.5}$, PM4, and PM10).	Designed as a handheld monitor; can record data as fast as 1 minute; data output units in micrograms per cubic meter (µg/m^3).	Wintertime outdoors in Durham, North Carolina; Reference monitor $PM_{2.5}$ ranged ~2-45 µg/m^3.	Grimm Model EDM180 $PM_{2.5}$ monitor	5 min; ~1.5 months	0.77[b]
RTI MicroPEM	Particles enter through size-selective inlet that removes particles >2.5 µm, then the remaining particles scatter light from a light source. An integrated filter collects all the particles, which can be optionally weighed in a laboratory after a period of use.	Designed as a wearable monitor for indoor or outdoor environments; can record data as fast as 10 seconds; data units in µg/m^3.	Summertime outdoors in Durham, North Carolina; Reference monitor $PM_{2.5}$ ranged ~4-33 µg/m^3.	Grimm Model EDM180 $PM_{2.5}$ monitor	5 min; ~1 month	0.72

Sensor Model	Detection Approach	Operating Details	Test Environment	Reference Monitor Used	Avg Time; Testing Period	R^2
Shinyei PMS-SYS-1	Volume scattering – particles (possibly including particles larger than 2.5 µm) entering the sensor scatter light from an internal light source. The scattered light signal is converted to an estimated particle count concentration.	Designed as a stationary miniaturized monitor; can record data as fast as 1 second; data units in µg/m^3.	Fall outdoors in Durham, North Carolina; Reference monitor $PM_{2.5}$ ranged ~2-26 µg/m^3.	Grimm Model EDM180 $PM_{2.5}$ monitor	5 min; ~1 month	0.15
Perkin-Elmer Elm	Volume scattering – particles (possibly including particles larger than 2.5 µm) entering the sensor scatter light from an internal light source. The scattered light signal is converted to an estimated particle mass concentration.	Designed as a stationary outdoor monitor; can record data as fast as 1 minute; data units in µg/m^3.	Wintertime outdoors in Durham, North Carolina; Reference monitor $PM_{2.5}$ ranged ~2-23 µg/m^3.	Grimm Model EDM180 $PM_{2.5}$ monitor	5 min; ~1.5 months	0.00

Notes: a Comparison results are for the small channel (>0.5 um).
b Comparison results shown are for the PM1 channel, which had the highest correlation with the reference monitor. The PM2.5 channel had significant outliers that were unexplained.

Table B.2 South Coast AQMD $PM_{2.5}$ Sensor Evaluation

Make (Model)	Indicative Cost (USD)	Pollutant(s)	*Field R^2	*Laboratory R^2	*Field MAE (µg/m^3)	*Laboratory MAE (µg/m^3)
Aeroqual (AQY v0.5) Discontinued	$3,000	$PM_{2.5}$	0.84 to 0.87	0.99		28.8 to 36.0
Aeroqual (AQY v1.0)	$4,000	$PM_{2.5}$	0.76 to 0.81	0.99	4.2 to 5.3	5.4 to 15.1
		PM_{10}	0.56 to 0.68		35.4 to 38.8	
Aeroqual (S500-PM)	$1,490	$PM_{2.5}$	0.46 to 0.67	0.99	4.4 to 6.2	11.9 to 32.4
		PM_{10}	0.15 to 0.24		13.5 to 18.0	
Airly	$1,000	$PM_{1.0}$	0.79 to 0.89		4.2 to 5.3	
		$PM_{2.5}$	0.83 to 0.89		4.5 to 5.0	
		PM_{10}	0.34 to 0.37		19.3 to 19.7	
Air Quality Egg (2018 Model)	$249	$PM_{1.0}$	0.86 to 0.88	0.99	2.1 to 2.3	7.0 to 7.3
		$PM_{2.5}$	0.84 to 0.85	0.99	4.4 to 5.3	6.1 to 6.6
		PM_{10}	0.12 to 0.13	-	16.4 to 19.2	
Air Quality Egg (Version 1)	$200	PM	~ 0.0			
Air Quality Egg (Version 2)	$240	$PM_{2.5}$	0.79 to 0.85			
		PM_{10}	0.31 to 0.40			
Air Quality Egg (2022 Model)	$671	$PM_{1.0}$	0.84 to 0.89		2.93 to 3.87	
		$PM_{2.5}$	0.88 to 0.90		6.02 to 7.12	
		PM_{10}	0.29 to 0.52		18.5 to 20.8	
AirThinx (IAQ)	$1,000	$PM_{1.0}$	0.68 to 0.70		2.4 to 2.5	
		$PM_{2.5}$	0.54 to 0.57		4.8 to 5.0	
		PM_{10}	0.03 to 0.05		19.7 to 19.8	
Airviz Inc. (Speck)	$150	$PM_{2.5}$	0.32			
Alphasense (OPC-N2)	$310	$PM_{1.0}$	0.63 to 0.82	0.99		
		$PM_{2.5}$	0.65 to 0.80	0.99		
		PM_{10}	0.45 to 0.57	0.99		
Alphasense (OPC-N3)	$338	$PM_{1.0}$	0.78 to 0.82	0.99	4.4 to 5.0	39.0 to 43.2
		$PM_{2.5}$	0.52 to 0.67	0.99	7.1 to 9.2	40.3 to 46.9
		PM_{10}	0.45 to 0.52	0.99	18.0 to 24.1	39.2 to 48.0

Make (Model)	Indicative Cost (USD)	Pollutant(s)	*Field R^2	*Laboratory R^2	*Field MAE (µg/m³)	*Laboratory MAE (µg/m³)
Alphasense (OPC-R2)	$435	$PM_{1.0}$	0.77 to 0.87		7.8 to 11.8	
		$PM_{2.5}$	0.67 to 0.78		7.3 to 10.0	
		PM_{10}	0.69 to 0.86		7.8 to 15.4	
Applied Particle Technology (MINIMA)	$995	$PM_{1.0}$	0.84 to 0.89	-	5.0 to 5.6	-
		$PM_{2.5}$	0.86 to 0.89	0.99	5.8 to 6.5	5.0 to 8.1
		PM_{10}	~0.37	-	39.4 to 40.3	-
AQMesh (v3.0)	$7,800	$PM_{1.0}$	0.55 to 0.73		2.4 to 3.4	
		$PM_{2.5}$	0.47 to 0.79		2.7 to 7.5	
		PM_{10}	0.24 to 0.58		11.4 to 23.1	
AS-LUNG (Air Quality Station)	$2,000	$PM_{1.0}$	0.42 to 0.88		3.2 to 7.3	
		$PM_{2.5}$	0.59 to 0.81		8.0 to 12.1	
		PM_{10}	0.15 to 0.23		18.6 to 21.2	
AS-LUNG (Portable)	$1,000	$PM_{1.0}$	0.86	0.99	3.2 to 4.3	2.6 to 3.4
		$PM_{2.5}$	0.78	0.99	6.8 to 8.2	12.8 to 13.5
		PM_{10}	0.11 to 0.14	-	18.9 to 21.6	
Atmotube (Pro)	$189	$PM_{1.0}$	0.91 to 0.93	0.99	3.6 to 4.6	1.9 to 6.4
		$PM_{2.5}$	0.88	0.99	4.9 to 5.9	2.9 to 3.8
		PM_{10}	0.22	-	20.9 to 22.9	-
Blues Wireless (Airnote)	$149	$PM_{1.0}$	0.68 to 0.86		4.3 to 6.8	
		$PM_{2.5}$	0.67 to 0.75		4.4 to 7.1	
		PM_{10}	0.04 to 0.11		20.2 to 34.8	
Cair	$200	$PM_{(1-2)}$	0.43 to 0.51			
		$PM_{(3-10)}$	0.39 to 0.51			
Clarity (Node)	$1,300	$PM_{2.5}$	0.73 to 0.76	0.99	3.0 to 3.4	9.3 to 10.6
Davis Instruments (Airlink)	$179	$PM_{1.0}$	0.85 to 0.88	-	2.2 to 2.8	-
		$PM_{2.5}$	0.74 to 0.81	0.99	4.9 to 5.9	4.3 to 6.6
		PM_{10}	0.25 to 0.31	-	12.1 to 26.0	-
Dylos (DC1100 Pro)	$300	$PM_{(0.5-2.5)}$	0.65 to 0.85	0.89	4.2	
Dylos (DC1700-PM)	$475	$PM_{2.5}$	0.58 to 0.68	0.95	24.3 to 28.5	198.3 to 209.4
		PM_{10}	0.15 to 0.18	-	43.9 to 53.8	-
Ecowitt (WH415B)	$100	$PM_{2.5}$	0.35 to 0.47		8.2 to 15.4	
Ecomesure (EcomSmart)	$4,550	PM1.0	0.61 to 0.74		5.6 to 7.9	
		$PM_{2.5}$	0.54 to 0.74		7.6 to 9.6	
		PM10	0.17 to 0.25		16.7 to 21.2	
Edimax (AirBox)	$249	$PM_{2.5}$	0.61 to 0.87		4.4 to 5.5	
Edimax (Edigreen Home)	$299	$PM_{2.5}$	0.82 to 0.83		3.3 to 4.4	
Elitech (Temtop LKC-1000S+)	$140	$PM_{2.5}$	0.91 to 0.92	0.99	3.1 to 3.6	11.1 to 21.9
		PM_{10}	0.31 to 0.35	-	11.7 to 17.9	-
Elitech (Temtop M2000 2nd Generation)	$100	$PM_{2.5}$	0.77 to 0.82	0.99	2.1 to 3.2	13.3 to 21.5
		PM_{10}	0.17 to 0.28	-	12.1 to 14.1	-
Elitech (Temtop P20)	$70	$PM_{2.5}$	0.42 to 0.87	0.99	3.8 to 6.1	5.1 to 10.7
Elitech (Temtop PMD 351)	$960	$PM_{1.0}$	0.68 to 0.75	-	2.4 to 3.8	-
		$PM_{2.5}$	0.71 to 0.74	0.99	3.8 to 5.8	26.7 to 28.8
		PM_{10}	0.27 to 0.46	-	9.1 to 18.6	-
FabLab (Smart Citizen Kit V2.1)	$119	$PM_{1.0}$	0.94	0.99	2.9 to 3.0	11.0 to 11.5
		$PM_{2.5}$	0.76 to 0.77	0.99	8.3 to 10.7	11.8 to 14.5
		PM_{10}	0.06 to 0.09	-	48.2 to 56.9	-
Foobot	$200	$PM_{2.5}$	0.55			
HabitatMap (AirBeam)	$200	$PM_{2.5}$	0.65 to 0.70	0.87	15.6 to 29.0	203.5 to 271.9
HabitatMap (AirBeam2)	$250	$PM_{1.0}$		0.99	2.9 to 3.0	16.5 to 18.1
		$PM_{2.5}$	0.63 to 0.75	0.99	3.3 to 3.7	11.3 to 13.5

Make (Model)	Indicative Cost (USD)	Pollutant(s)	*Field R^2	*Laboratory R^2	*Field MAE (µg/m³)	*Laboratory MAE (µg/m³)
		PM_{10}	~ 0.0	-	25.8 to 28.0	-
HabitatMap (AirBeam3)	$249	$PM_{1.0}$	0.95 to 0.97		1.3 to 2.6	
		$PM_{2.5}$	0.81 to 0.90		3.6 to 5.3	
		PM_{10}	0.19 to 0.25		20.4 to 26.8	
Hanvon (Hanvon N1)	$200	$PM_{2.5}$	0.52 to 0.79			
Igienair (Zaack AQI)	$3000	$PM_{1.0}$	0.78 to 0.83	-	6.3 to 6.5	-
		$PM_{2.5}$	0.80 to 0.82	0.97	3.8 to 4.2	5.3 to 23.0
		PM_{10}	0.69 to 0.71	0.99	14.4 to 23.9	6.0 to 13.1
IQAir (AirVisual Pro)	$270	$PM_{2.5}$	0.69 to 0.73	0.99	4.4 to 4.7	26.8 to 37.0
		PM_{10}	0.24 to 0.41	-	16.6 to 22.7	-
IQAir (AirVisual Pro FW1.1683)	$270	$PM_{2.5}$	0.63 to 0.81	0.99	3.5 to 5.5	1.8 to 10.8
Kaiterra (Laser Egg 2+)	$199	$PM_{2.5}$	0.81 to 0.85	0.99	3.3 to 4.0	15.2 to 23.3
		PM_{10}	0.17 to 0.25	-	8.0 to 17.3	-
Kunak (Air A10)	$3000	$PM_{1.0}$	-	0.99	-	10.4 to 17.1
		$PM_{2.5}$	0.69 to 0.75	0.99	5.4 to 6.4	4.3 to 14.4
		PM_{10}	0.60 to 0.68	0.99	18.7 to 21.9	8.9 to 23.5
Liveable Cities (SLX-PM2.5)	$954	$PM_{2.5}$	0.79 to 0.83		6.4 to 9.1	
		PM_{10}	0.71 to 0.77		11.9 to 18.1	
Lunar Outpost (Canary-S)	$1,070	$PM_{2.5}$	0.83		3.3 to 3.8	
		PM_{10}	0.14		27.4 to 28.6	
Magnasci SRL (uRADMonitor A3 HW105)	~$500	$PM_{1.0}$	0.81 to 0.85		4.0 to 5.2	
		$PM_{2.5}$	0.72 to 0.81		5.2 to 8.9	
		PM_{10}	0.15 to 0.38		20.3 to 29.1	
Magnasci SRL (uRADMonitor INDUSTRIAL HW103)	~$1,300	$PM_{1.0}$	0.74 to 0.83		2.7 to 3.7	
		$PM_{2.5}$	0.70 to 0.78		4.1 to 8.1	
		PM_{10}	0.13 to 0.34		18.1 to 25.7	
Magnasci SRL (uRADMonitor SMOGGIE-PM v1.101)	$110	$PM_{1.0}$	0.84 to 0.86	0.99	4.8 to 5.6	25.3 to 26.8
		$PM_{2.5}$	0.60 to 0.81	0.99	2.1 to 2.8	19.5 to 22.9
		PM_{10}	0.03 to 0.06	-	17.5 to 25.2	-
Met One (E-Sampler)	$5,500	$PM_{1.0}$	-			
		$PM_{2.5}$	0.55 to 0.62		10.9 to 15.2	
		PM_{10}	-			
		TSP	-			
Met One (ES-405)	$5,200	$PM_{1.0}$	0.84 to 0.91	-	2.8 to 3.6	-
		$PM_{2.5}$	0.80 to 0.92	0.99	3.5 to 4.0	19.0 to 21.2
		PM_{10}	0.78 to 0.92	0.99	4.5 to 8.9	10.4 to 24.4
Met One (Neighbourhood Monitor)	$1,900	$PM_{2.5}$	0.53 to 0.67		6.0 to 8.4	
Moji China (Airnut)	$150	$PM_{2.5}$	0.81 to 0.88			
Oizom (Polludrone Smart)	$8,000	$PM_{1.0}$	0.82 to 0.86	-	4.5 to 5.0	-
		$PM_{2.5}$	0.76 to 0.81	0.97	5.4 to 6.1	20.0 to 20.7
		PM_{10}	0.33 to 0.34	-	14.3 to 15.5	-
Origins (Laser Egg)	$200	$PM_{2.5}$	0.58			
		PM_{10}	~ 0.0			
Perkin Elmer (ELM)	$5,200	PM	~ 0.0		20.6 to 30.5	
Piera Systems (Canaree R1)	$299	$PM_{1.0}$	0.82 to 0.91		3.2 to 4.5	
		$PM_{2.5}$	0.69 to 0.90		6.3 to 7.2	
		PM_{10}	0.19 to 0.35		16.3 to 22.6	

Make (Model)	Indicative Cost (USD)	Pollutant(s)	*Field R^2	*Laboratory R^2	*Field MAE (µg/m³)	*Laboratory MAE (µg/m³)
Plume Laboratorys (Flow 2)	$199	$PM_{1.0}$	0.01 to 0.14			
		$PM_{2.5}$	0.01 to 0.13		7.3 to 10.6	
		PM_{10}	0 to 0.04		19.3 to 28.3	
PM Monitor (iMonPM)	$1,995	$PM_{1.0}$	0.71 to 0.89		2.2 to 4.0	
		$PM_{2.5}$	0.65 to 0.89		3.4 to 4.9	
		PM_{10}	0.44 to 0.62		13.8 to 17.8	
PurpleAir (PA-I)	$150	$PM_{1.0}$	0.93 to 0.95	0.95		
		$PM_{2.5}$	0.90 to 0.92			
		PM_{10}	0.32 to 0.44	0.97		
PurpleAir (PA-I-Indoor)	$180	$PM_{1.0}$	-	0.99		5.1 to 9.5
		$PM_{2.5}$	0.75	0.99		18.7 to 27.7
		PM_{10}	0.36 to 0.46	0.97		4.4 to 20.4
PurpleAir (PA-II)	$200	$PM_{1.0}$	0.96 to 0.98	0.99		11.7 to 15.9
		$PM_{2.5}$	0.93 to 0.97	0.99		1.7 to 4.2
		PM_{10}	0.66 to 0.70	0.95		15.6 to 20.5
QuantAQ (MODULAIR-PM)	$1,295	PM1.0	0.87 to 0.94		4.1 to 6.8	
		$PM_{2.5}$	0.84 to 0.88		4.0 to 5.2	
		PM_{10}	0.46 to 0.78		14.7 to 21.6	
Redspira	$180	$PM_{2.5}$	0.73 to 0.87	0.99	4.7 to 7.1	11.4 to 16.2
		PM_{10}	0.31 to 0.37	-	30.8 to 33.1	-
RTI (MicroPEM)	$2,000	$PM_{2.5}$	0.65 to 0.90	0.99	6.4 to 8.3	
SainSmart (Pure Morning P3)	$170	$PM_{2.5}$	0.71 to 0.74	0.99	4.8 to 5.4	
Samyoung S&C (SY-DS-DK3)	$100	$PM_{2.5}$	0.60 to 0.62	0.98	4.8 to 11.4	36.1 to 51.8
Sensirion (Nubo) Discontinued	$2,000	$PM_{1.0}$	0.96	0.99	2.8 to 3.2	1.9 to 4.5
		$PM_{2.5}$	0.91	0.99	4.7 to 5.2	4.9 to 7.6
Sensirion (Nubo Air)	$1,700	$PM_{1.0}$	0.77 to 0.89		2.9 to 3.5	
		$PM_{2.5}$	0.73 to 0.83		5.2 to 6.5	
Sensirion (SPS30)	$100	$PM_{1.0}$	0.91	0.99	1.3 to 1.4	0.8 to 1.4
		$PM_{2.5}$	0.80 to 0.83	0.99	2.0 to 5.1	5.4 to 6.5
		PM_{10}	0.07 to 0.20	-	10.8 to 24.7	-
Shinyei (PM Evaluation Kit)	$1,000	$PM_{2.5}$	0.80 to 0.89	0.93		
Tera Sensor (NextPM)	$70	$PM_{1.0}$	0.89 to 0.94		2.1 to 4.6	
		$PM_{2.5}$	0.87 to 0.95		3.9 to 5.6	
		PM_{10}	0.34 to 0.66		26.2 to 31.6	
TSI (AirAssure)	$1,500	$PM_{2.5}$	0.81 to 0.83	0.99		32.4 to 55.0
TSI (BlueSky)	$400	$PM_{2.5}$	0.65 to 0.76	0.99	4.9 to 5.9	3.1 to 6.2
		PM_{10}	0.09 to 0.21	-	22.7 to 26.3	-
uHoo	$300	$PM_{2.5}$	~ 0.0		9.5 to 17.8	

*Notes: *The coefficient of determination (R^2) is a statistical parameter measuring the degree of relation between two variables. Here, it measures the linear relationship between the sensor and the Federal Reference Method (FRM), or Federal Equivalent Method (FEM), or Best Available Technology (BAT) reference instrument. An R^2 approaching the value of 1 reflects a near perfect correlation, whereas a value of 0 indicates a complete lack of correlation. All R^2 values reported in these reports are based either on 5-min or 1-hr average data. The Laboratory R^2 values are based on experiments conducted in the chamber, under average ambient conditions (20 degrees C and 40% RH). The mean absolute error (MAE) is a statistical parameter measuring the average of the absolute difference between the sensor and the FRM or FEM or BAT reference instruments, without considering the direction of errors. higher MAE values indicate higher sensor measurement error when compared to the reference instruments. All field MAE values are based on either 5-min or 1-hr average data; all laboratory MAE values are based on the experiments conducted in the chamber using a medium PM concentration under ambient conditions (20 degrees C and 40% RH). If a sensor has not demonstrated good performance in the field, it may not advance to the laboratory chamber test.*

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