RED DEER FINE PARTICULATE MATTER RESPONSE

SCIENCE REPORT

APRIL 2016

Alberta Government

ISBN No. 978-1-4601-2542-7 (Printed)
ISSN No. 978-1-4601-2543-4 (Online)

Red Deer Fine Particulate Matter Science Report

<u>Note from the Secretariat:</u>

Management Approach of the Red Deer Fine Particulate Matter Response and Science Report

The Red Deer Fine Particulate Matter Science Report (herein: the science report) was developed in response to the exceedance of the Canada-wide Standard for fine particulate matter at Red Deer Riverside monitoring station. Following an exceedance, a management response is mandatory. The goal of the management response is to use scientific investigation to inform the development of actions to reduce observed fine particulate matter concentrations. The science report represents a compendium of the shared understanding of the influences, both natural and anthropogenic, affecting fine particulate matter concentrations at Red Deer Riverside monitoring station. A shared understanding rooted with scientific investigation is essential for multi-stakeholder collaboration to identify, develop and implement management actions to ultimately address the issue. The collective scientific understanding also includes the acknowledgement of gaps in knowledge. The science report highlights these gaps as recommendations for future scientific investigation. Continued development of management actions requires the aggressive perusal of these gaps.

The Science Report is an accompanying document to the Red Deer Fine Particulate Matter Response and was developed in context of the goal of the Response.

Mandate

The science report was developed to provide a resource of scientific knowledge to inform the development of the management response. The science report attempts to balance the need for scientific input in three key areas:

- Understanding of ambient fine particulate matter observations
- Addressing stakeholder questions that arose during the science investigation
- Informing the management response, including the selection of the boundary of focus and the identification of management actions.

Building an understanding of observations at Red Deer Riverside monitoring station is critical in determining the focus, priority, and urgency of management actions. The objective of the science report is to provide as complete an analysis as possible, of available information, in order to best characterize sources and phenomenon affecting fine particulate matter concentrations at Red Deer Riverside monitoring station. Gaps exist in the current state of knowledge and there is a need to complete additional monitoring and analysis exercises in order to better inform the understanding of the observations at Red Deer Riverside monitoring station. To this end, a list of recommendations has been included in the science report for future investigation.

Also, addressing stakeholder concerns is an essential component of the science report. Stakeholder input and feedback was incorporated throughout the development of the science report, with this information informing the types of investigations included in the science report. Addressing stakeholder concerns with scientific investigation enabled a collective understanding of the fine particulate matter issue.

The building of a shared, science-based understanding of the fine particulate matter exceedance at Red Deer Riverside monitoring station enabled the investigations documented in the science report to inform the development of the response and associated management actions.

Key Findings

These findings form the basis of the shared understanding of the fine particulate matter issue to date. The assumptions that these findings are based on, are detailed within the report:

- Newer monitoring technologies have improved our observations of fine particulate matter. These improved observations have enabled the identification that fine particulate matter concentrations at Red Deer Riverside monitoring station are exceeding national standards.
- Meteorological phenomenon influence the occurrence of high concentrations of fine particulate matter. Common conditions exacerbate the dispersion of pollutants and result in high fine particulate matter concentrations, thereby highlighting a need for management action to reduce emissions.
- Fine particulate matter observed at Red Deer Riverside monitoring station is most likely dominated by secondary fine particulate matter species. Many source sectors are likely contributing precursor gasses which participate in the formation of secondary fine particulate matter.

Recommendations for future investigation

In order to confirm any assumptions used to build the shared understanding of the fine particulate matter issue several key areas of scientific investigation are recommended. Each of these scientific investigations are anticipated to fill current knowledge gaps and result in an improved shared understanding of the scientific information.

- Increase understanding of the species composition of particulate matter in the Red Deer air quality management area
- Apportion fine particulate matter to sources in the Red Deer air quality management area
- Broaden the understanding of spatial and temporal variations of fine particulate matter and its precursors

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Acknowledgements

The Red Deer fine particulate matter science report was developed by the Alberta Environment and Parks secretariat. The secretariat undertook a rigorous scientific investigation of the data available to date in order to inform the Red Deer Fine Particulate Matter Response and the development of management actions for fine particulate matter. The secretariat would like to thank the Parkland Airshed Management Zone for their contributions of scientific information to this report. In addition, the secretariat would also like to thank the Parkland Airshed Management Zone Technical Working Group whose technical feedback was utilized to develop a shared understanding of fine particulate matter science in the Red Deer area. The balance of government, industry and public members participating in the Technical Working Group ensured that the conclusions reached herein were robust and represent the collective knowledge of stakeholders in the Red Deer area.

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Executive Summary

Alberta committed to achieving the Canada-wide Standard for fine particulate matter in 2003 (CASA, 2003). Measurements of fine particulate matter at Red Deer Riverside monitoring station have been used to assess achievement of the Canada-wide Standard under the Clean Air Strategic Alliance Particulate Matter and Ozone Management Framework (CASA, 2003; Alberta's implementation of the Canada-wide standards for particulate matter and ozone). In the 2009-2011 assessment (AESRD, 2012b), Red Deer Riverside monitoring station was found to have exceeded the Canada-wide Standard for particulate matter and as a result, the development of a mandatory plan to reduced fine particulate matter concentrations to below the Canada-wide Standard was initiated. The Red Deer Fine Particulate Matter Science Report represents a compendium of the current state of knowledge regarding the causes of the exceedance at Red Deer Riverside monitoring station.

The Red Deer Fine Particulate Matter Science report was developed in conjunction with the Red Deer Fine Particulate Matter response. The response outlines the management actions identified by a multi-stakeholder advisory committee, to address the exceedance of the Canada-wide Standard. The advisory committee utilized the science summarized herein to develop effective management actions to be degree to which current knowledge could support. Stakeholders selected for the advisory committee comprised those most likely to have a significant role in affecting fine particulate matter concentrations in Red Deer. Scientific evidence (summarized herein) indicates that secondary fine particulate matter species are expected to be a large contributor to the high fine particulate matter concentrations observed in Red Deer. Of secondary fine particulate matter species, those formed through reactions with nitrogen dioxide are anticipated to be significant. Therefore, an area encompassing Lacombe County and Red Deer County was delineated as an area of high source contributions of nitrogen dioxide; through an analysis of passive nitrogen dioxide monitoring. The Red Deer Fine Particulate Matter Science report and the Red Deer Fine Particulate Matter response delineate these and the immediately surrounding counties as the "Red Deer air quality management area." Investigations and conclusions described herein are limited to the areas within these boundaries.

Red Deer Riverside monitoring station is located within an urban center, the City of Red Deer, which includes and is surrounded by varied emission sources of fine particulate matter and fine particulate matter precursor gasses. Observations of fine particulate matter concentrations at Red Deer Riverside monitoring station are somewhat limited in fully characterizing the cause of the exceedance. A major limitation is the fact that high temporal resolution fine particulate matter monitoring data cannot distinguish between different types of particulate matter species. Additionally, as monitoring technology has improved, Red Deer Riverside monitoring station has been upgraded over-time, resulting in a dataset measured using three separate methodologies. Therefore several additional sources of information were analyzed in conjunction. These sources of information included emissions inventory information for the City of Red Deer and surrounding areas, data from other monitoring stations in Red Deer and in other areas of the province, and information obtained as part of the Capital Region Fine Particulate Matter Science Report. The analysis of the fine particulate matter concentrations measured at Red Deer Riverside monitoring station, in conjunction with the other data, revolved around three key topics, which helped to characterize the cause of the exceedance. The key findings related to each topic were:

Measurement of particulate matter:

Secondary fine particulate matter species are expected to comprise a significant portion of the total fine particulate matter mass during wintertime days with high concentrations of fine particulate matter. The upgrading of fine particulate matter monitoring technology to Federal Equivalency Method standards at Red Deer Riverside monitoring station was likely a large factor behind observation of the exceedance. Federal Equivalency Method compliant instruments provide a more accurate measurement of fine particulate matter concentrations due to their improved ability to measure secondary fine particulate matter species; a large positive step change in concentrations was observed after the upgrade. Therefore, the switch to the new standard in monitoring technology enabled the detection of fine particulate matter concentrations that had previously gone unmeasured and enabled the determination that secondary fine particulate matter was present in Red Deer.

Influence of meteorology:

Fine particulate matter events occur most frequently during the colder months (October-March), but were observed to occur in all months. Seasonal and diurnal meteorological fluctuations influence fine particulate matter concentrations to a great degree. Generally, meteorological phenomenon that affect the dispersion of pollutants have the biggest impact on fine particulate matter concentrations; low wind speeds characterize these phenomenon. Temperature inversions are a major meteorological phenomenon, characterized by low wind speeds, which trap cold air near the surface of the earth and prevent the mixing of pollutants. Throughout the year, nocturnal temperature inversions have a diurnal influence on fine particulate matter concentrations and during the colder months temperature inversions driven by large-scale weather systems are frequent and may limit dispersion for several days at a time. Fine particulate matter event days were associated with southerly winds at Red Deer Riverside monitoring station, an association that is likely driven in large part by the alignment of the Red Deer river valley relative to the monitoring station.

Evidence of secondary particulate matter and potential sources:

As a consequence of similar meteorological conditions, due to large-scale weather systems in Alberta, Edmonton, Red Deer and Calgary can experience high particulate matter concentrations concurrently. With similar emissions sources in these urban locations, the observation of coincident high particulate matter concentration enables comparisons, particularly between the more detailed measurements of fine particulate matter outside of the Red Deer area. In Edmonton, nitrogen dioxide driven species of secondary fine particulate matter were observed to be dominant in the formation of fine particulate matter events in the colder months. The implications of the observations in Edmonton suggest that Red Deer, with an abundance of nitrogen dioxide sources, as demonstrated through emissions inventories and monitoring, is likely to be impacted significantly by secondary fine particulate matter species formed through reactions with nitrogen dioxide. A major source of nitrogen dioxide in Red Deer, and nearby Red Deer Riverside monitoring station is from transportation. Although some fine particulate matter (expected as primary fine particulate matter) emitted from nearby transportation related sources is expected to influence the concentrations at Red Deer Riverside monitoring station, these impacts are not significant enough to be the sole cause of the observed exceedance. Therefore transportation emissions from other major transportation corridors in Red Deer are more likely to be influencing concentrations of fine particulate matter (as secondary fine particulate matter) measured at Red Deer Riverside monitoring station. These conclusions are similar to those reached in Edmonton. The degree of impact of transportation related emissions on observed fine particulate matter concentrations, however cannot be fully quantified without further data collection and analysis. Therefore, with the current state of knowledge, other emissions sources capable of participating in the formation of secondary fine particulate matter (e.g. industrial emissions), cannot be ruled out for influencing the observation of high concentrations of fine particulate matter.

Recommendations for future investigation

The science report is intended to represent a snapshot of the current state of knowledge regarding fine particulate matter at the time of the development of the fine particulate matter response. It is intended to document the understanding of the exceedance of the fine particulate matter Canada-wide Standard to date and inform the development of management actions included in the fine particulate matter response. Several knowledge gaps have been identified within the science report and in order to continue to make progress on the development and implementation of new management actions, continued scientific investigation is necessary. The following recommendations are prioritized based on the scope of the knowledge gaps identified and the relative need of the scientific investigation to develop future management actions.

Recommendation	
Description	Rationale
Increase understanding of the species composition of particulate matter in the Red Deer air quality management area	
• Commence a sampling study in the Red Deer air quality management area to identify the species composition of particulate matter during event and non-event days.	Rationale: Speciation has not been measured in Red Deer. In order to confirm assumptions made in the science report, this assessment is essential.

Apportion fine particulate matter to sources in the Red Deer air quality management area	

• Undertake source apportionment modelling using CMAQ, separate from or in conjunction with ongoing work in the Capital Region. Additional specific investigations may include:
  ○ Investigate home heating emissions (including emissions impacts from different fuel types). Understand diurnal variations in home heating emissions with respect to fine particulate matter concentration variations.
  ○ Undertake a detailed analysis to determine whether variations in vehicle traffic due to changes in the local economy of Red Deer may impact fine particulate matter concentrations
	Rationale: The relationship between fine particulate matter concentrations and specific emissions sources in Red Deer is poorly understood. A sector based source apportionment would fill this gap by identifying key source sectors which have the most significant impacts on fine particulate matter concentrations. This initiative will help to implement current management actions and develop new management actions if gaps exist.

• Investigate NO to NO_2 conversion in order to contextualize the locality of emissions impacting Red Deer Riverside station. Understanding the degree of transport to which NO_x has undergone may allow for determining source contribution regions affecting Red Deer Riverside.	Rationale: The relationship between fine particulate matter concentrations and specific emissions sources in Red Deer is poorly understood. Contextualizing the measured NO_x emissions in terms of their NO and NO_2 components will help localize potential emission sources and aide in source apportionment.
Broaden the understanding of spatial and temporal variations of fine particulate matter and its precursors	
• Continue to investigate the suitability of using RDPS (Regional Deterministic Prediction System) Output (a meteorological model capable of predicting atmospheric stability) to identify temperature inversions over Red Deer and integrate these results into future investigations if determined to be suitable.	Rationale: Upper air soundings are not available in Red Deer therefore determining the impact of inversions is reliant on other meteorological information. Characterization of the suitability of the RDPS meteorological model output to the Red Deer area will help provide more confidence in establishing the link between fine particulate matter event days and atmospheric temperature inversions.

Broaden the understanding of spatial and temporal variations of fine particulate matter and its precursors	
• Investigate influence of large scale (100s of km) meteorological systems on multi-station fine particulate matter events in order to better understand conditions favorable for fine particulate matter event days.	Rationale: Multi-station fine particulate matter events were observed across the Edmonton-Calgary corridor. Observations from monitoring stations suggest similar meteorological phenomena are driving these events. However, no investigation of large-scale phenomena have been performed to date, leaving a gap in knowledge.
• Investigate the potential for terrain to influence meteorology in the Red Deer area and determine what influence this may have on fine particulate matter concentrations. A modelling investigation may be most suited to this question.	Rationale: Terrain effects are recognized in meteorology and air quality science and the City of Red Deer, along with associated air quality monitoring stations, sit below two large ridges and within a substantial river valley. The effect of these terrain features has not been characterized.

1. Introduction

1.1. Purpose

In 2003, Alberta committed to achieving the Canada-wide Standard for fine particulate matter ($PM_{2.5}$) (established by the Canadian Council of Ministers of the Environment in 2000; CCME, 2000) through implementation of the Clean Air Strategic Alliance Particulate Matter and Ozone Management Framework (CASA, 2003). Implementation of this framework involved performing annual assessments on all air quality monitoring stations in the province measuring fine particulate matter or ozone. Fine particulate matter concentrations were assessed at each station with sufficient data. Action levels were then assigned to each station with respect to the assessed fine particulate matter concentration. The action levels in the Clean Air Strategic Alliance Fine Particulate Matter and Ozone Management Framework are listed in Figure 1.

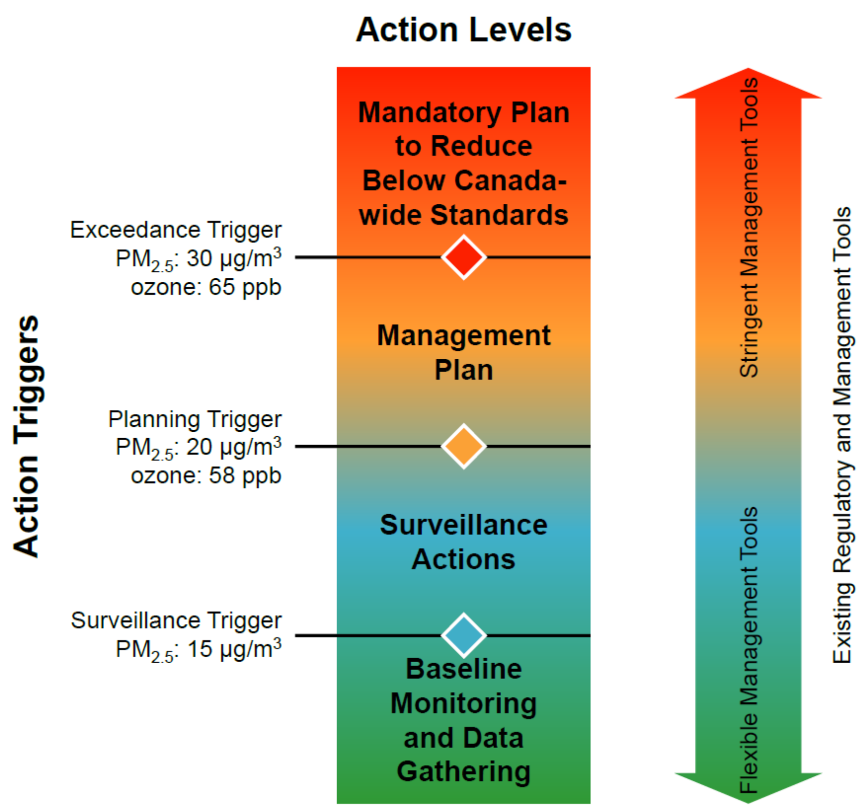

Figure 1: Action triggers and levels of the Clean Air Strategic Alliance Fine Particulate Matter and Ozone Management Framework (CASA, 2003). The exceedance trigger is equivalent to the Canada-wide standard.

Red Deer Riverside monitoring station has been assessed as part of the Clean Air Strategic Alliance Fine Particulate Matter and Ozone Management Framework since its inception, and in 2009-2011 assessment (AESRD, 2013b), released in January 2013, the station was placed into the "Mandatory Plan to Reduce Below Canada-wide Standards" action level under the framework. Assignment to this action level indicates that Red Deer Riverside monitoring station exceeded the Canada-wide standard of 30 $\mu g/m^3$ and that a plan to reduce the observed concentrations at this station must be developed. The Red

Deer Fine Particulate Matter Response documents the plan developed in conjunction with stakeholders, to reduce concentrations to below the Canada-wide Standard.

The Red Deer Fine Particulate Matter Science Report (herein: “the science report”) was developed in an effort to characterize the cause of the exceedance of the Canada-wide Standards at Red Deer Riverside monitoring station. The science report was developed internally by Alberta Environment and Parks with external consultation with the Parkland Airshed Management Zone Technical Working Group. The intent of the science report was to investigate the cause of the exceedance of the Canada-wide Standards, to the highest degree that available data can support. To guide the development of the Red Deer Fine Particulate Matter Response, strong science support was determined to be essential. The science report focuses on Red Deer Riverside monitoring station. At the time of the exceedance the only other permanent continuous air quality monitoring station in the vicinity of the City of Red Deer was Caroline monitoring station. For the 2009-2011 Clean Air Strategic Alliance Particulate Matter and Ozone Management Framework assessment (AESRD, 2013b), Caroline monitoring station was reported to be in the “Baseline Monitoring and Data Gathering” action level. The “Baseline Monitoring and Data Gathering” action level is the lowest of the four levels under the Clean Air Strategic Alliance Particulate Matter and Ozone Management Framework (CASA, 2003). For this reason, investigating the observed fine particulate matter concentrations at Caroline monitoring station was not a focus of the science report.

Red Deer Riverside monitoring station continued to exceed the Canada-wide standard in the 2010-2012 Clean Air Strategic Alliance Fine Particulate Matter and Ozone Management Framework assessment (released in April 2014; AESRD, 2014), therefore work to manage fine particulate matter concentrations in the vicinity of Red Deer River monitoring station, and to further characterize the cause of these exceedances, remains important. Starting in 2015, the Canadian Amibient Air Quality Standards have been implemented, replacing the Canada-wide Standards for the assessment of fine particulate matter and ozone in Canada. The implementation of the Canadian Ambient Air Quality Standards is important as it they replace the Canada-wide Standard for fine particulate matter with a new, more stringent limit. The new limit for fine particulate matter is 28 $\mu g/m^3$; it is based on the three year average of the annual 98^{th} percentile 24-hour average concentration. Additionally, a new assessment metric and associated limit, based on the annual average of fine particulate matter concentrations is being introduced. The new annual average Canadian Ambient Air Quality Standard for fine particulate matter is based on a three year average of annual fine particulate matter concentrations averages. The Canadian Ambient Air Quality Standards are based on the Population Improvement Approach (which strives for improvements in air quality for more Canadians over time), therefore they are set to become more stringent in 2020. With new, more stringent standards being implemented a focus on reducing fine particulate matter concentrations to below these standards is important.

1.2. Particulate Matter

Particulate matter is comprised of liquid or solid particles suspended in the atmosphere. These particles can range across several orders of magnitude in size (10^{-3} – 100 µm in diameter) and may originate from a wide variety of sources. For the purposes of measurement, particulate matter can be classified into a number of size fractions. Fine particulate matter is composed of particles less than or equal to 2.5

micrometres in diameter, and is the focus of the science report. The fine particulate matter size fraction is of interest as particles of this diameter or less are able pass through the respiratory tract of the human body and enter the lungs.

Particulate matter can be broadly categorized into two categories determined by emission source. Primary particulate matter is defined as any particulates that are emitted directly to the atmosphere as liquid or solid particles from their source. Examples of primary particulate matter sources include unpaved roads (which emit primary particulate matter as dust; as particles of crustal (rock) matter) and the combustion of fossil fuels (which emit primary particulate matter as soot; as particles of elemental carbon).

Secondary particulate matter is defined as any particulates that form within the atmosphere as a result of reactions involving precursor compounds. The exact nature of these reactions varies depending on the atmospheric concentration of various precursor compounds, however the products can be easily categorized into organic and inorganic products. Inorganic secondary particulate matter includes species such as ammonium nitrate and ammonium sulphate, which form through atmospheric reactions of the precursor gases: ammonia, oxides of nitrogen and sulphur dioxide. The precursor gases involved in the formation of inorganic secondary fine particulate matter are emitted from a wide variety of point and non-point sources ranging from agricultural emissions to an assortment of combustion related emissions. Reactions forming ammonium nitrate and ammonium sulphate occur in equilibrium, therefore the concentrations of the reactants are key in limiting the production of these compounds. An investigation carried out as part of the Capital Region Fine Particulate Matter Science Report (AESRD, 2015) indicated that within the Capital Region, ammonia appears to be non-limiting, indicating that concentrations of oxides of nitrogen and sulphur dioxide are key in determining the formation of ammonium nitrate and ammonium sulphate, respectively. The formation of organic secondary fine particulate matter is more complex than the formation of inorganic species due to the large assortment of potential precursor compounds in the atmosphere as well as the potential for these compounds to undergo phase changes in order to form secondary fine particulate matter. The vast majority of organic secondary fine particulate matter forms through reactions involving volatile organic compounds as precursors. Volatile organic compounds can be emitted from natural non-point sources or from a range of anthropogenic point and non-point sources.

1.3. Description of Region

1.3.1. Sensitive receptors and natural landscape

The City of Red Deer is located in central Alberta. The city is home to 100 807 people (2015 municipal census). Other major population centers within the vicinity of the City of Red Deer include the Town of Sylvan Lake (population: 13 015 (2013 municipal census)), the City of Lacombe (population: 12 728 (2014 municipal census)), the Town of Innisfail (population 7 922 (2013 municipal census)), Town of Blackfalds (population: 7 858 (2014 municipal census)) and the Town of Penhold (population: 2 476 (2012 municipal census)). Outside of these populated areas, land immediately adjacent to the City of Red Deer supports a mix of land uses, from unincorporated residential areas (approximate population of 2600 within 10 kilometres of the City of Red Deer border) to light industrial and agriculture. Beyond this distance, Red Deer and Lacombe counties, with the exception of the noted major population centers, are predominantly rural and land use is mostly agricultural with sporadic industrial use. Two counties, Red Deer County (population: 18,351 (2011 Federal census)) and Lacombe County (population: 10 312 (2011 Federal Census)) encompass these lands. Figure 2 shows a map of the sensitive receptors in the vicinity of the City of Red Deer.

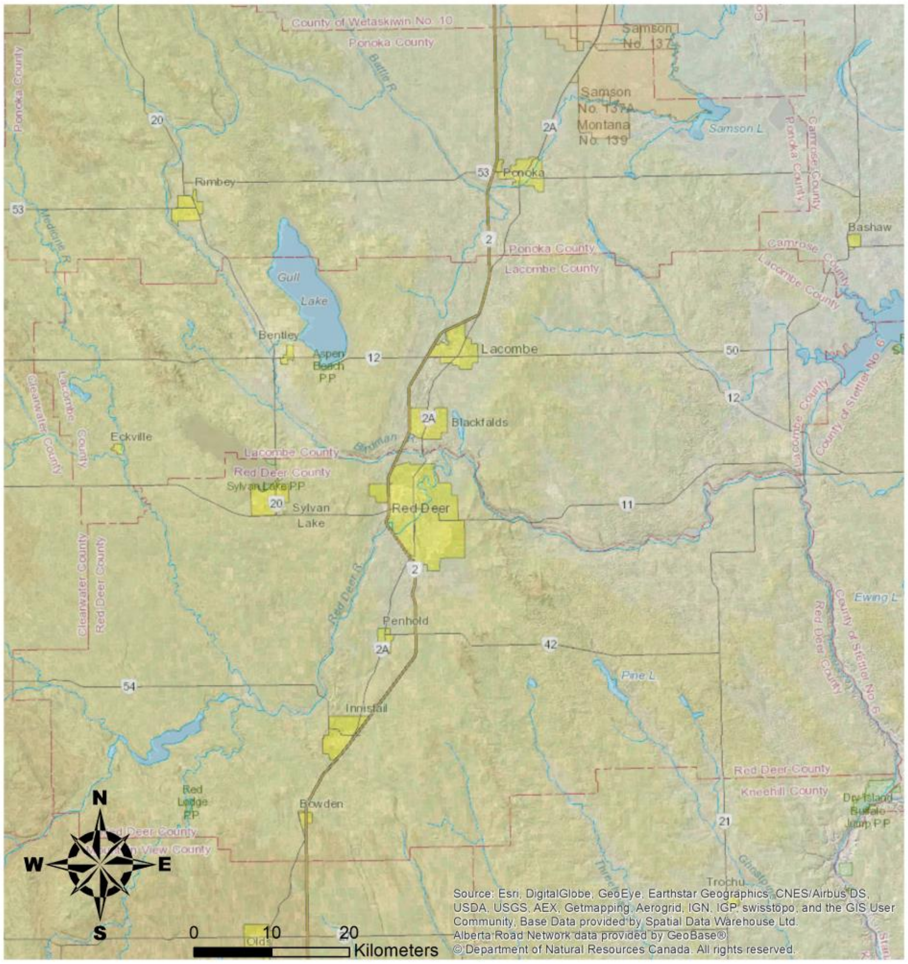

Figure 2: Map of sensitive receptors in the vicinity of the City of Red Deer.

The natural landscape in the Red Deer area is comprised of parkland with rolling terrain. Drainage features ranging from broad shallow valleys to deeply incised canyons dominate topographical relief. The City of Red Deer is located on relatively flat land centered around the Red Deer River valley (Figure 3). The Red Deer River valley walls range in size from 20-60 metres deep and the river travels in a north-easterly direction through the city (Figure 3). The city and river valley, where the river runs through the city, are located in a broad valley demarcated by broad north-south oriented ridges which rise 100-150 metres above the Red Deer River and are spaced approximately 20 km apart.

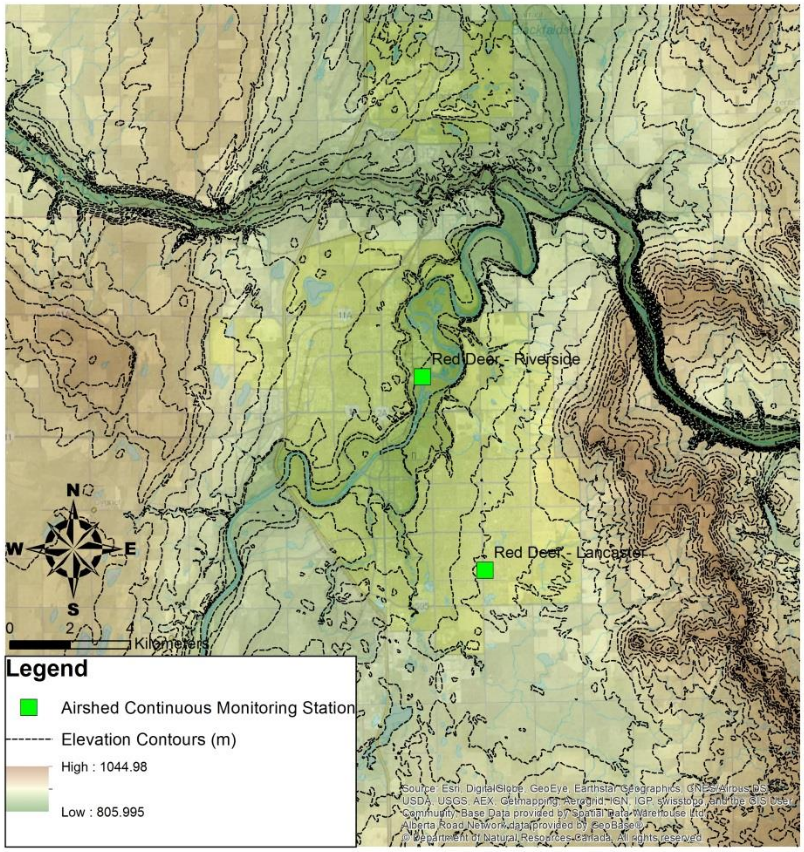

Figure 3: Topographical relief in the vicinity of the City of Red Deer. Contour lines are at 10 metre intervals. The locations of Red Deer Riverside and Red Deer Lancaster monitoring stations are indicated.

1.3.2. Regional Emissions Profile

Emission sources within the Red Deer area range from large point sources to collectively significant non-point sources. In order to characterize the distribution of emissions from various source sectors, three pollutants of concern were identified; Nitrogen dioxide and sulphur dioxide – known precursors to the formation of secondary fine particulate matter, and fine particulate matter ($PM_{2.5}$) – measured/estimated emissions of primary fine particulate matter. Emissions sources in the Red Deer area were determined from the 2008 Alberta Air Emissions Inventory. Point sources were classified into three key sectors: upstream oil and gas, chemicals industry and other industrial. Other industrial emissions included emissions from petroleum product transportation, electrical power generation, the grain industry and the cement, concrete and asphalt industry. Non-point source data were only available by census subdivision (representing incorporated municipalities such as cities, towns, villages and summer villages), therefore the emissions profile for the Red Deer area was generated using emissions data from all point and non-point sources from census subdivisions contained within census division 8. The boundaries of Census division 8 are defined by the boundaries of its three constituent counties, Red Deer county, Lacombe county and Ponoka county. Non-point sources were classified into several key sectors: On-road transportation, off-road transportation, residential and commercial heating, open area sources, and miscellaneous sources. Open area sources include emissions from agricultural operations, construction operations, dust from roads (paved and unpaved), prescribed burning and waste processing. Miscellaneous non-point sources include incineration sources (e.g. cremation), industrial sources, air transportation, rail transportation, emissions from structural fires and miscellaneous emissions from cigarette smoking and meat cooking.

1.3.2.1. Nitrogen dioxide

Industrial point sources account for 65% of nitrogen dioxide emissions in census division 8 (Figure 4 and Figure 5). The vast majority of point source emissions (and more than half of all emissions) of nitrogen dioxide are from upstream oil and gas facilities (Figure 5). These facilities are for the most part distributed throughout census division 8 and are largely located outside of population centers (Figure 6). Other industrial point sources include emissions from chemicals manufacturing and other industrial activities (Figure 5). Point source emissions do not undergo substantial seasonal fluctuations. The balance of nitrogen dioxide emissions in census division 8 (35%) are associated with non-point source emissions from a number of sectors (Figure 5). Non-point source emissions are highest in the City of Red Deer, Red Deer, Lacombe and Ponoka counties. Of the sectors contributing to non-point source emissions, transportation related emissions are predominant, accouting for 84% of non-point source emissions of nitrogen dioxide and 30% of nitrogen dioxide from all sources (point and non-point) in census division 8 (Figure 5). Transportation related emissions are approximately evenly split between off-road and on-road sources (Figure 5). On-road emissions are highest from those sub-divisions with the greatest populations and therefore the highest road usage (Figure 7). On-road sources do not undergo significant seasonal variation and are expected to be consistent year round. Off-road emissions sources are dominated by diesel-fueled vehicles such as construction and agricultural equipment. Smaller contributions come from off-road vehicles and devices with small engines, such as all-terrain vehicles, yard equipment and aquatic vessels. Contributions of off-road transportation emissions are concentrated near population centers (Figure 8). These activities are largely season dependent and therefore it is expected that off-road emissions are largest in the warmer months. Other significant non-point source emissions of nitrogen dioxide are from residential and commercial heating and other miscellaneous sources.

1.3.2.2. Sulphur dioxide

Emissions of sulphur dioxide in census division 8 are approximately 20 times less than nitrogen dioxide emissions (Figure 4) and are dominated by upstream oil and gas point sources (accounting for nearly 90% of all emissions of sulphur dioxide; Figure 5). Sulphur dioxide emitting point sources are distributed sparsely throughout census division 8 and are located outside of population centers (Figure 9). One large industrial point source emitting just over 200 tonnes per year of SO_2 is located near the City Red Deer. Non-point source emissions of sulphur dioxide are predominantly from residential and commercial heating and off-road transportation (Figure 5). The City of Red Deer and Red Deer County have the highest emissions of non-point source SO_2 emissions. Sulphur dioxide releasing non-point sources include emissions from the heating of buildings as well as emission from heavy duty diesel engines, both of which are concentrated near populated areas (Figure 9).

1.3.2.3. Fine particulate matter

Nearly the entirety (97%) of fine particulate matter (attributed as primary fine particulate matter) that is emitted in census division 8 is from non-point sources (Figure 4). Open area sources dominate the non-point source emission of primary fine particulate matter (96% of the non-point source emitted fine particulate matter; Figure 5) which is largely emitted as dust from unpaved roads and in smaller quantities from construction operations and agriculture. Red Deer County is the largest source of non-point source emitter of primary fine particulate matter (Figure 10). While Un-paved roads are found within Red Deer, Lacombe and Ponoka counties, Red Deer County's location, encompassing the City of Red Deer, means that traffic loads on rural un-paved roads are higher than in the other counties, and subsequently result in more emissions of fine particulate matter. Significant non-point source construction operations may occur anywhere within census division 8, however these emissions can be expected to be concentrated around population centers. In addition, these emissions are expected to be focused throughout the warmer snow-free months (April-September) as construction operations are limited in the wintertime as snow-cover and ground freeze-up makes construction difficult. These same natural processes also act to limit the emission of fine particulate matter from un-paved roads. Point source emissions of fine particulate matter are collectively small, with the largest contributions coming from the chemicals manufacturing industry (Figure 10).

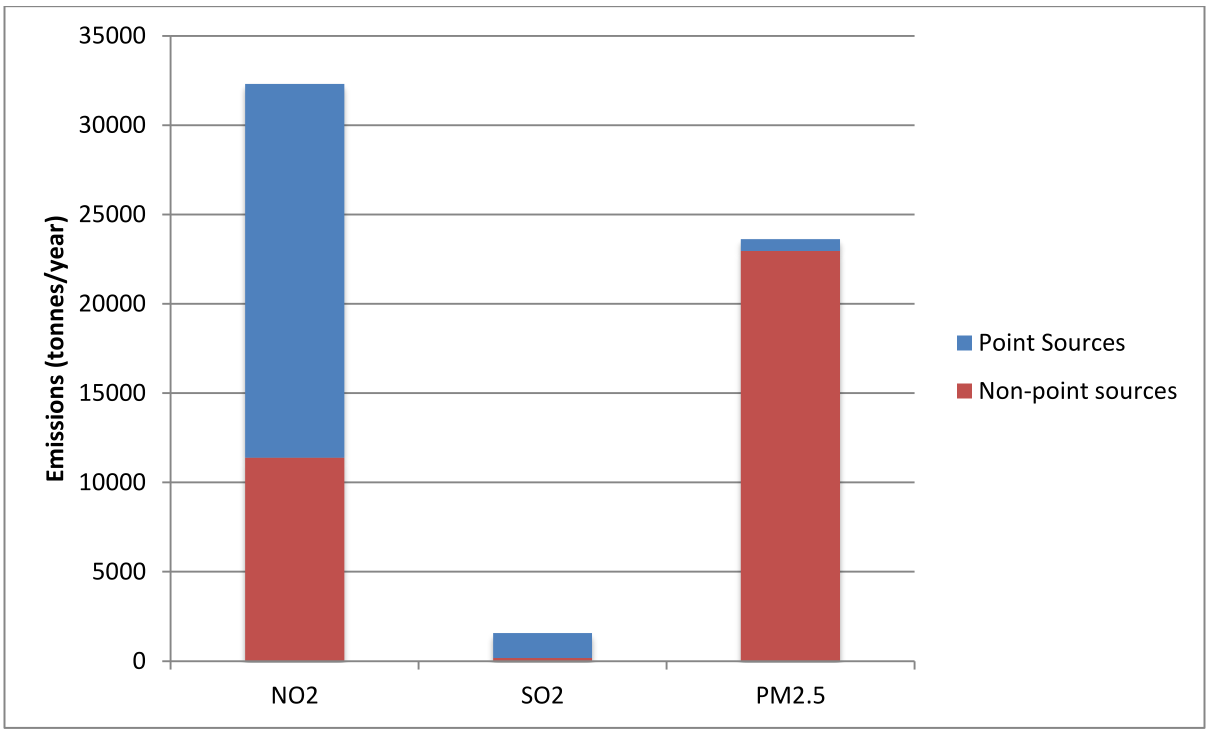

Figure 4: Yearly emissions of fine particulate matter precursors and primary fine particulate matter by point sources and non-point sources in census division 8

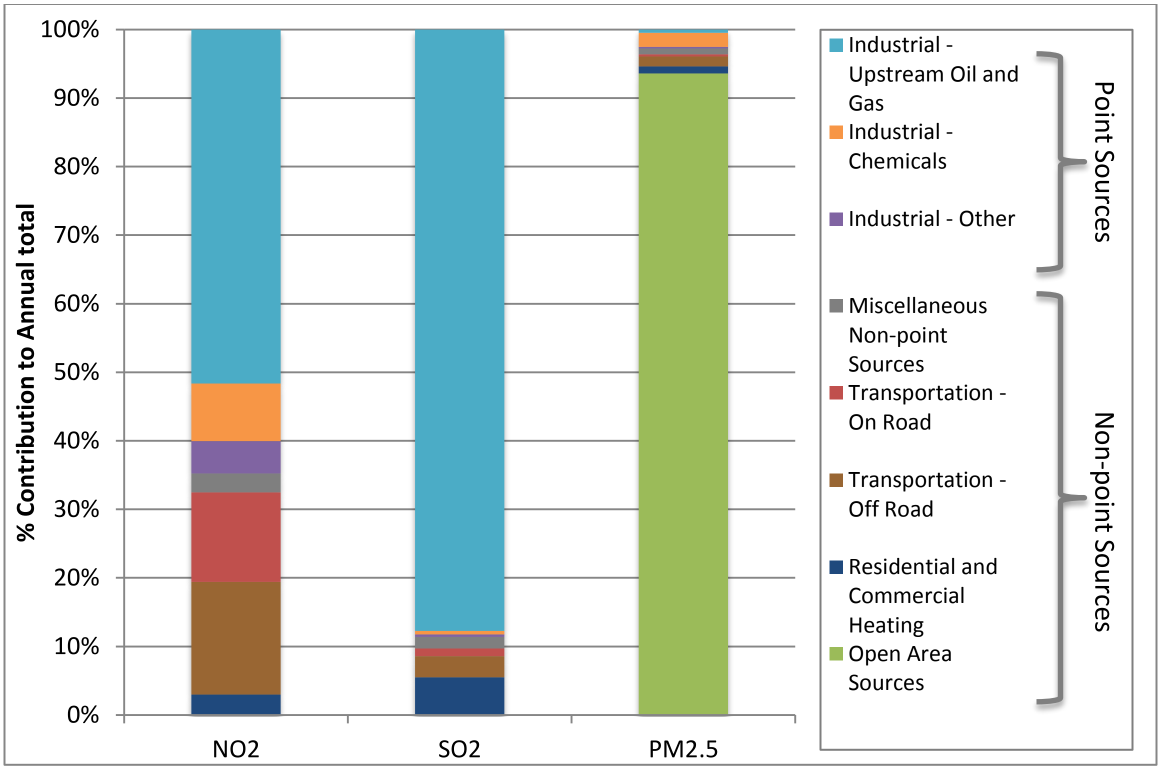

Figure 5: Sector-based breakdown of yearly fine particulate matter precursor and primary fine particulate matter emissions in census division 8.

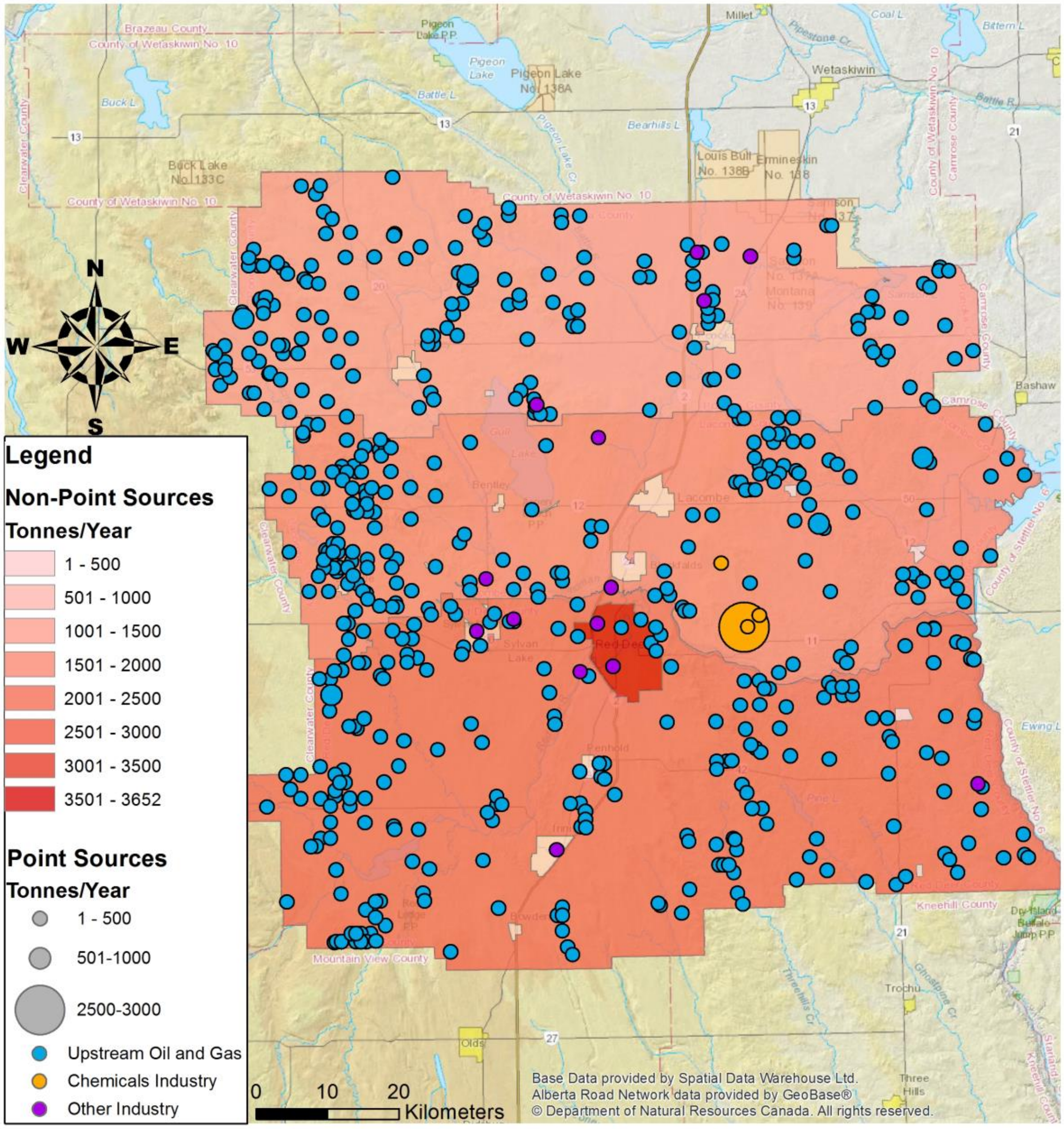

Figure 6: Yearly Nitrogen dioxide emissions from point (circles) and non-point (area colour) sources in Census Division 8. Emissions were derived from the 2008 Alberta Air Emissions Inventory. Point sources are divided into three key sectors and are identified by their total annual emissions. Non-point source emissions are identified as annual totals from each of 25 census subdivisions (e.g. cities, towns, etc.) in Census Division 8.

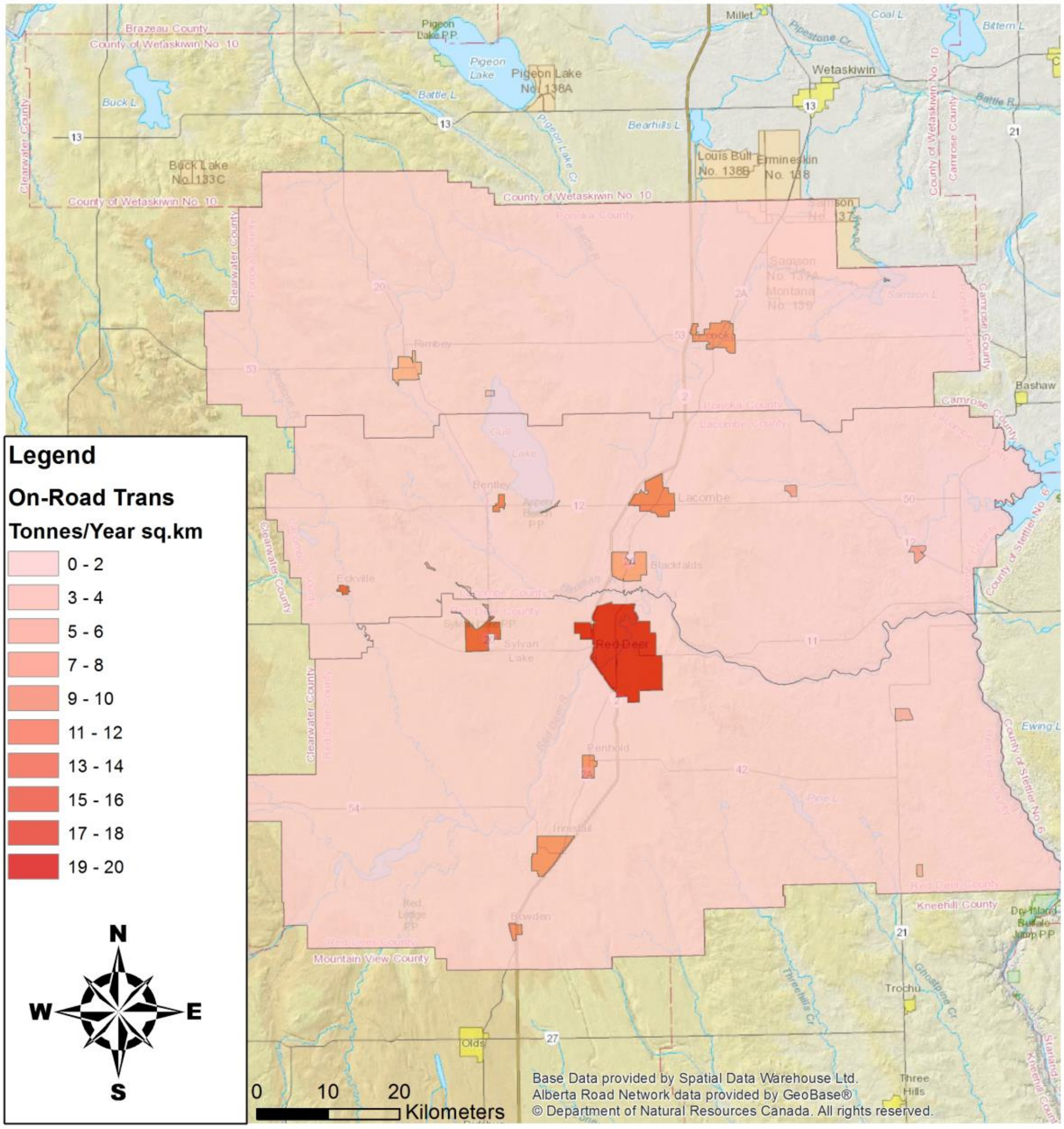

Figure 7: Yearly emissions of Nitrogen dioxide per unit area (tonnes per year squared kilometre) from on-road transportation related non-point sources in Census Division 8. Emissions were derived from the 2008 Alberta Air Emissions Inventory. Emissions per unit area were derived from the total on-road transportation related non-point source emission in each census subdivision divided by the area of each subdivision.

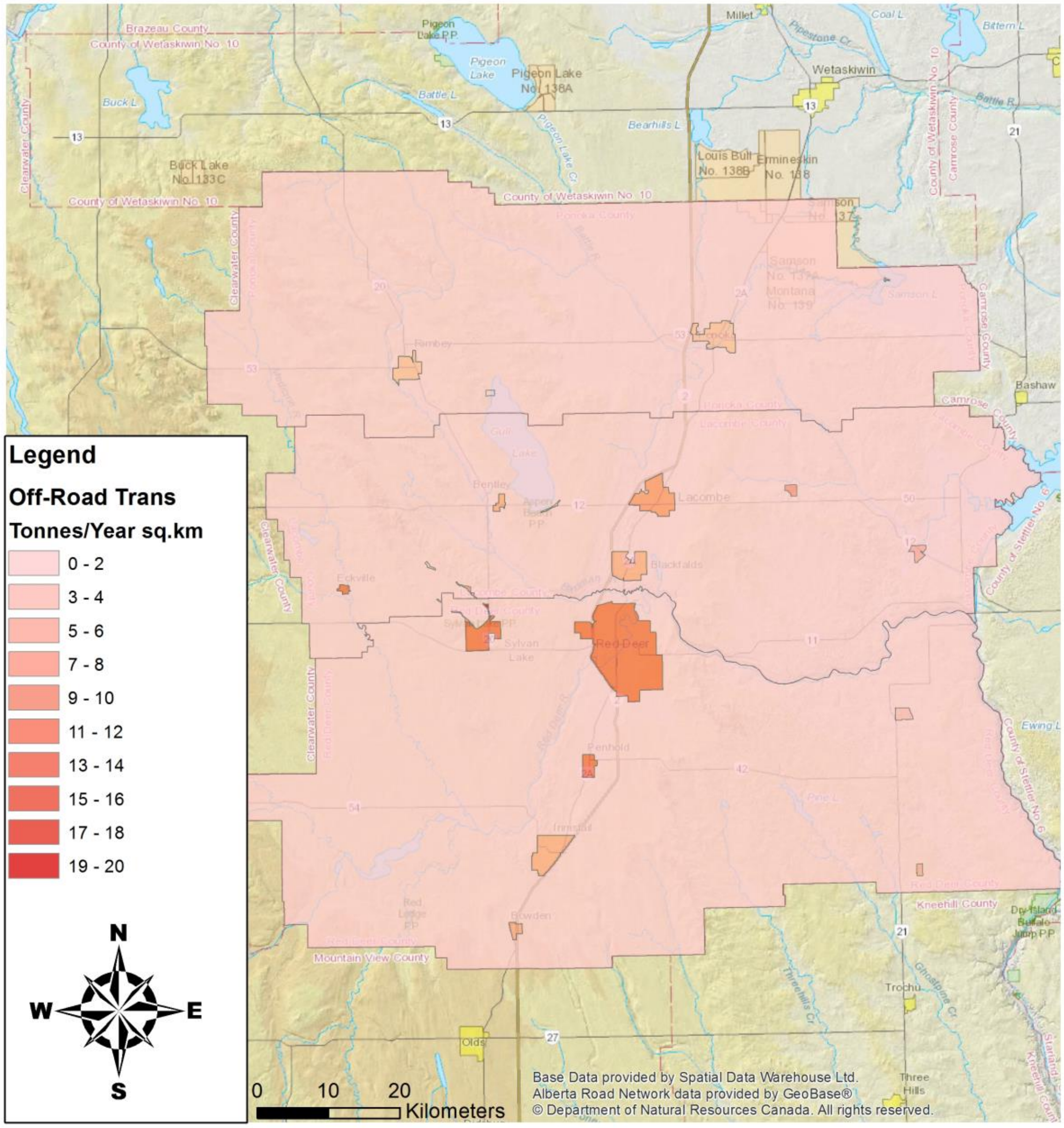

Figure 8: Yearly emissions of Nitrogen dioxide per unit area (tonnes per year squared kilometre) from off-road transportation related non-point sources in Census Division 8. Emissions were derived from the 2008 Alberta Air Emissions Inventory. Emissions per unit area were derived from the total off-road transportation related non-point source emission in each census subdivision divided by the area of each subdivision.

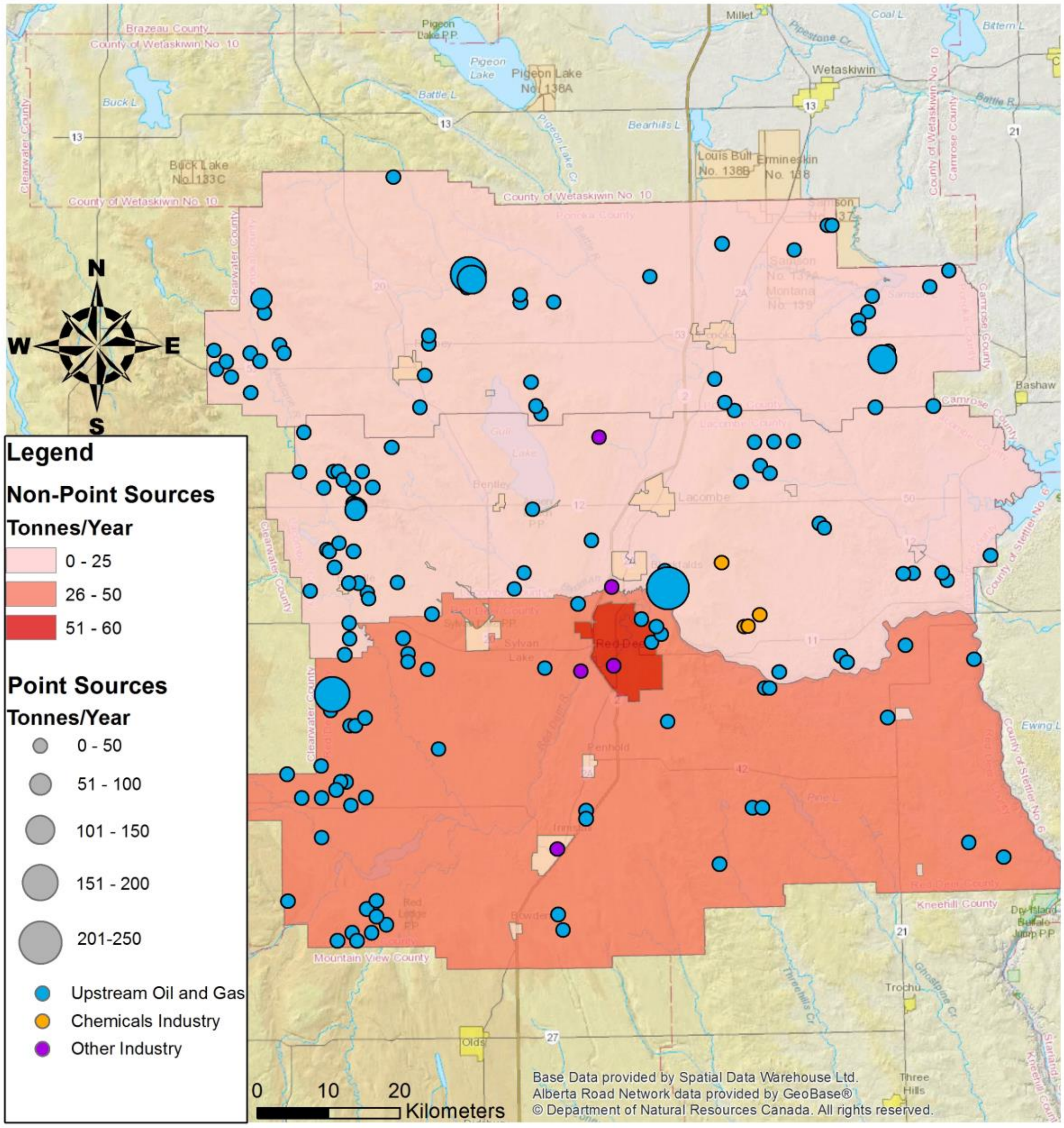

Figure 9: Yearly Sulphur dioxide emissions from point and non-point sources in Census Division 8. Emissions were derived from the 2008 Alberta Air Emissions Inventory. Point sources are divided into three key sectors and are identified by their total annual emissions. Non-point source emissions are identified as annual totals from each of 25 census subdivisions (e.g. cities, towns, etc.) in Census Division 8.

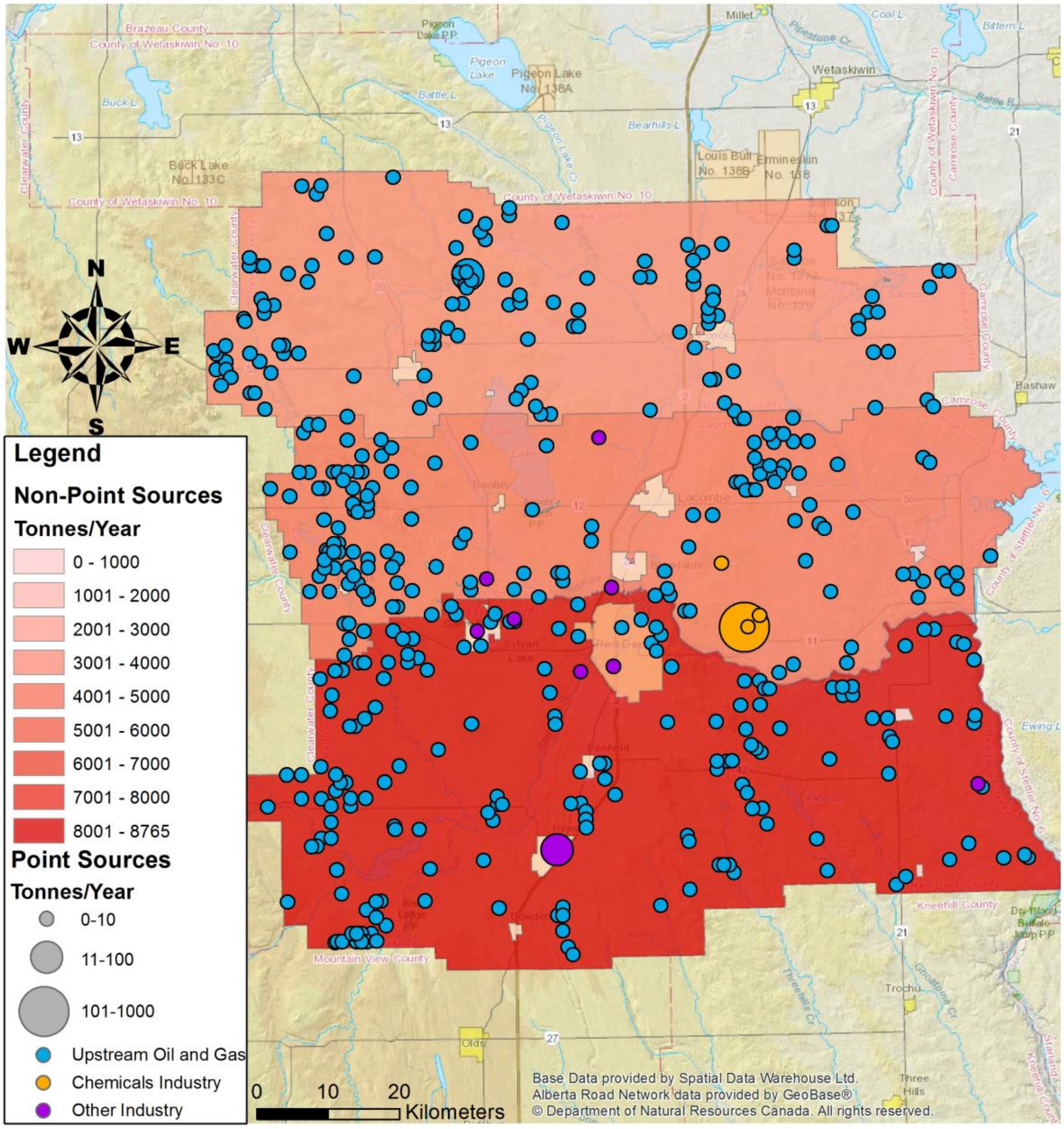

Figure 10: Yearly fine particulate matter (as primary fine particulate matter) emissions from point and non-point sources in Census Division 8. Emissions were derived from the 2008 Alberta Air Emissions Inventory. Point sources are divided into three key sectors and are identified by their total annual emissions. Non-point source emissions are identified as annual totals from each of 25 census subdivisions (e.g. cities, towns, etc.) in Census Division 8.

1.4. Description of Monitoring Stations

Monitoring of the ambient air in the Red Deer area is undertaken by the Parkland Airshed Management Zone. The Parkland Airshed Management Zone currently has a total of three permanent continuous ambient monitoring stations: two within the City of Red Deer (Red Deer Riverside monitoring station and Red Deer Lancaster monitoring station) and one near the Village of Caroline (Caroline monitoring station). The Parkland Airshed Management Zone also operates one portable continuous ambient monitoring station (David McCoy portable station; which is deployed in response to localized air quality issues, or for research purposes) and a network of 32 passive ambient monitoring stations (passive monitoring stations are co-located with Red Deer Riverside, Red Deer Lancaster and the David McCoy portable monitoring station). Passive monitoring stations are equipped to measure sulphur dioxide, nitrogen dioxide, and ozone concentrations. Additional details about the entire Parkland Airshed Management Zone network of monitoring stations can be found in the Parkland Airshed Management Zone Ambient Air Monitoring Plan (PAMZ, 2015).

Ambient air monitoring in the City of Red Deer has occurred since 1999 at the Red Deer Riverside monitoring station. The Red Deer Riverside monitoring station is located within the Red Deer River valley in the industrialized portion of northeast Red Deer (Figure 3 and Figure 11). The monitoring station is adjacent to a collector roadway, Riverside Drive, and is nearby the City of Red Deer civic yards (Figure 11). Red Deer Riverside monitoring station was established by Alberta Environment and Parks, who also operated the station until 2005, when operation of the station was assumed by the Parkland Airshed Mangement Zone. Red Deer Riverside monitors ambient concentrations of sulphur dioxide, hydrogen sulphide, oxides of nitrogen, fine particulate matter, ozone, carbon monoxide, non-methane hydrocarbons, methane, total hydrocarbons and meteorological parameters.

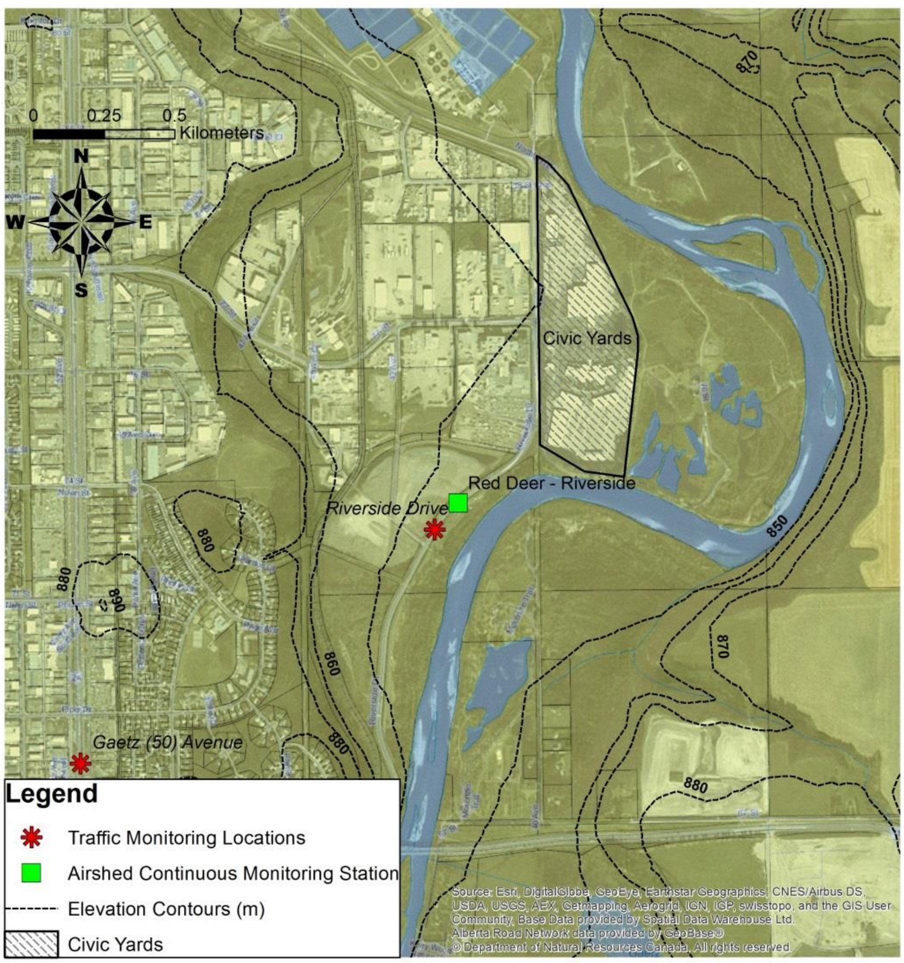

Figure 11: Location of Red Deer Riverside monitoring station with respect to the Red Deer River, Red Deer River valley, City of Red Deer civic yards and nearby roadways. Elevation contours are at 10m intervals. Traffic volume measurement locations on nearby roadways are indicated.

In the late fall of 2014, the Parkland Airshed Management Zone re-purposed one of its two portable monitoring stations into a permanent monitoring station located within the Lancaster neighborhood of southeast Red Deer (Figure 3). The rationale for adding Red Deer Lancaster monitoring station to the Parkland Airshed Management Zone network was to provide a monitoring location within the City of Red Deer more representative of the ambient conditions experienced by the majority of residents. Red Deer Lancaster station is located within a large residential area, outside of the Red Deer River valley (approximately 50 metres higher in elevation than Red Deer Riverside station; Figure 3) and near an arterial roadway (30th Avenue). The site occupied by the permanent Red Deer Lancaster station was first established in late 2012 and was used by one of the Parkland Airshed Management Zone portable monitoring stations during the winters of 2012-2013 and 2013-2014. Red Deer Lancaster monitors ambient concentrations of sulphur dioxide, total reduced sulphur, oxides of nitrogen, fine particulate matter, ozone, non-methane hydrocarbons, methane, total hydrocarbons and meteorological parameters.

Caroline monitoring station is located in a rural/agricultural setting approximately 70 kilometres southwest of the City of Red Deer. Caroline monitoring station was established as a compliance monitoring station for the upstream oil and gas industry and was subsequently transitioned into Parkland Airshed Management Zone network in 1999. Caroline monitors sulphur dioxide, total reduced sulphur, oxides of nitrogen, fine particulate matter, ozone, total hydrocarbons and meteorological parameters.

2. Observations

Continuous fine particulate matter concentrations encompassing the period of October 2007 through to May 2014 were obtained from the Clean Air Strategic Alliance Data Warehouse (CASA, 2015) for Red Deer Riverside, Red Deer Lancaster and Caroline monitoring stations. This period was selected as it represents the span of time from which Red Deer Riverside was recognized as entering into the "Surveillance actions" action level (2007-2009) under the Clean Air Strategic Alliance Particulate Matter and Ozone Management Framework (AESRD, 2012) through to the present. Data available through the Clean Air Strategic Alliance are rigorously quality controlled.

Figure 12, Figure 13 and Figure 14 show hourly averaged fine particulate matter concentration measurements at Red Deer Riverside, Red Deer Lancaster and Caroline monitoring stations, respectively. Dates with fine particulate matter concentrations associated with forest fires, as identified at Red Deer Riverside monitoring station, have been removed (as occurs with the assessment fine particulate matter under the Clean Air Strategic Alliance Particulate Matter and Ozone Management Framework (CASA, 2003b). Monthly averages were calculated and displayed to aid in the identification of trends. In order to identify differences in monitoring technologies between stations and over time, monitoring technologies were annotated in the figures by colour: Blue for TEOM-SES, Red for TEOM-FDMS, Green for SHARP 5030 and Purple for BAM. A detailed discussion of these monitoring technologies and the implications of these technologies on the measured fine particulate matter concentrations can be found in section 3.1.

2.1.Red Deer Riverside

Observations of fine particulate matter concentrations at Red Deer Riverside monitoring station were variable throughout the period of October 2007 to May 2014 (Figure 12). Concentrations were generally low and stable from October 2007 to May 2009 (Figure 12). A notable step change in observed concentrations occurred following the change from TEOM-SES to TEOM-FDMS monitoring technology in May 2009 (Figure 12). A detailed discussion on the changes in monitoring technologies at Red Deer Riverside monitoring station can be found in section 3.1. Following the switch in monitoring technologies observed concentrations were overall higher and more variable, with significant increases in concentrations during the winters of 2009-2010, 2010-2011 and 2012-2013 (Figure 12). A discussion on the seasonal variation of fine particulate matter can be found in section 3.2. No step change was observed following the switch from TEOM-FDMS to SHARP monitoring technology in August 2013. A discussion around this monitoring technology change can be found in section 3.1.

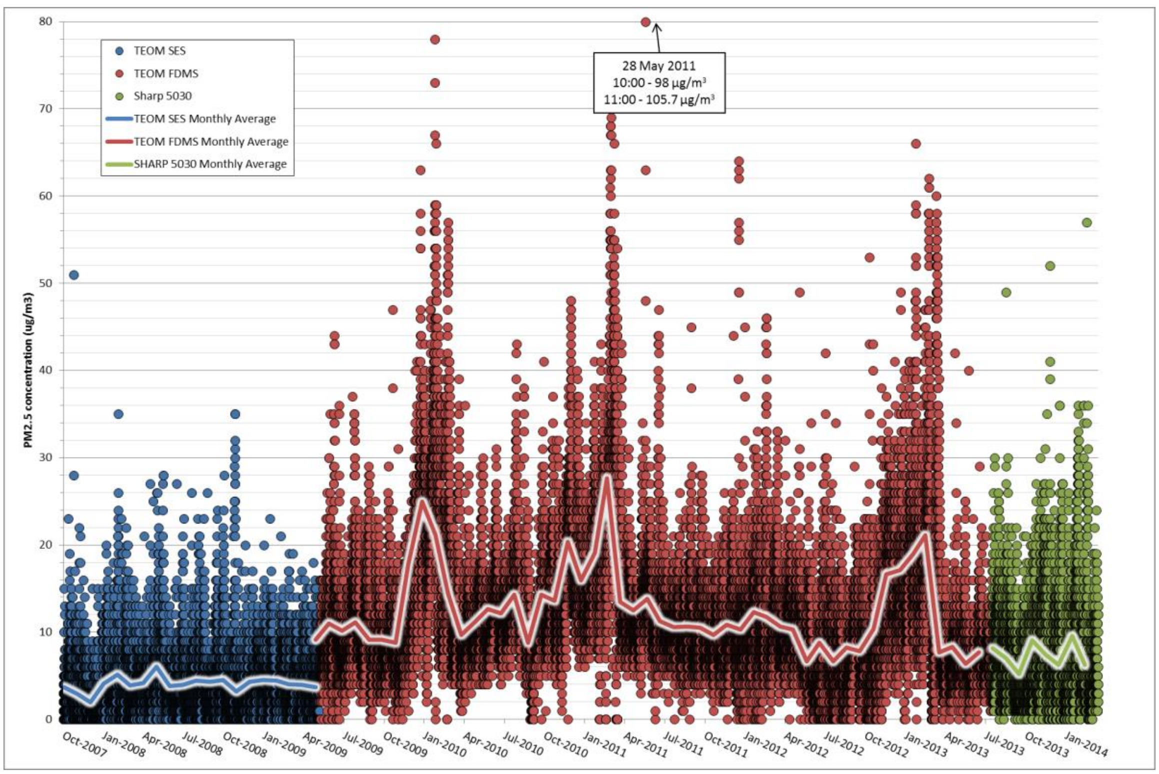

Figure 12: Time series of hourly and monthly average fine particulate matter concentrations as measured at Red Deer Riverside station from October 2007 to May 2014. Note: Data presented between September 2009 and July 2013 were rounded to the nearest integer to match the rounding methods used throughout the rest of the period.

2.2.Red Deer Lancaster

Observations of fine particulate matter concentrations at Red Deer Lancaster station were limited to a small portion of the period between October 2007 to May 2014. Monitoring at the Red Deer Lancaster site was undertaken starting in October 2012 through to March 2013 and again from June 2013 to May 2014 (Figure 13). During the period with observations available, despite utilizing a different monitoring technology than Red Deer Riverside monitoring station, observed fine particulate matter concentrations were similar; in terms of overall trend and magnitude. Due to limited availability of data, particularly, the lack of at least one continuous year of data, fine particulate matter concentrations at Red Deer Lancaster will not be discussed in further detail in the science report.

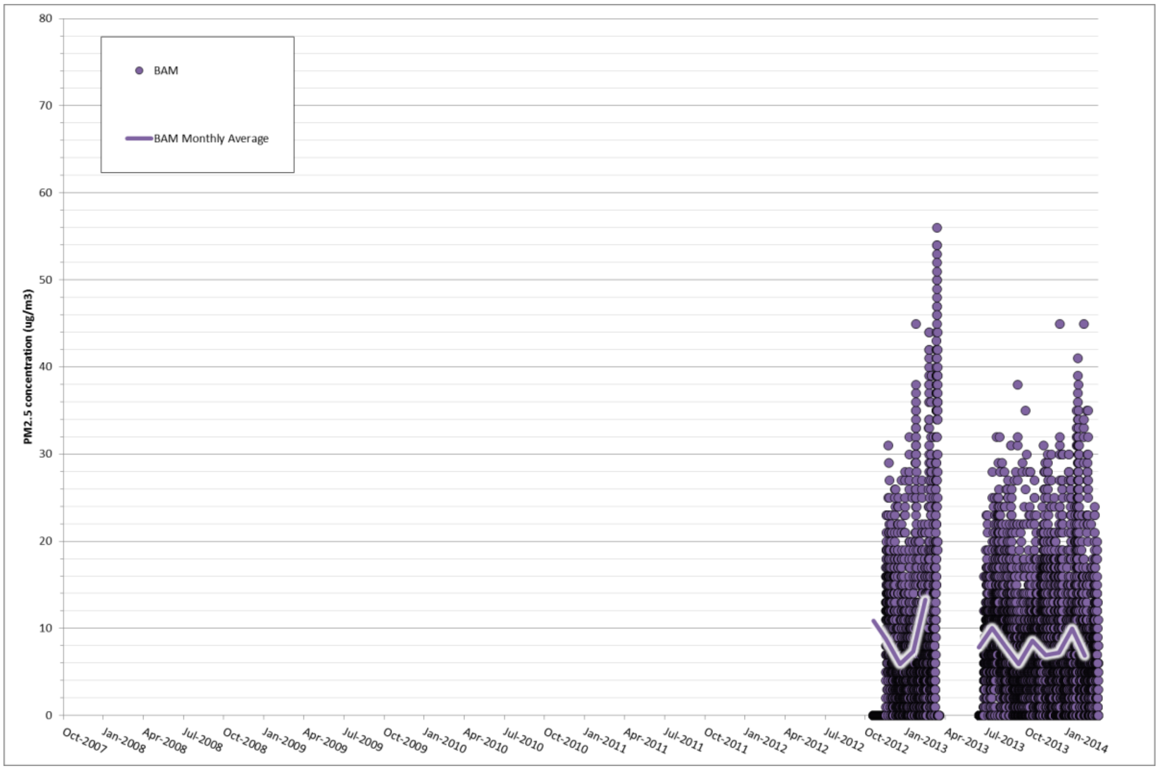

Figure 13: Time series of hourly and monthly average fine particulate matter concentrations as measured at Red Deer Lancaster station from October 2007 to May 2014.

2.3. Caroline

Observed concentrations of fine particulate matter at Caroline monitoring station were somewhat variable through the period of October 2007 to May 2014 (Figure 14). In general, observed concentrations were much lower at Caroline monitoring station than at Red Deer Riverside (Figure 14). Periodic increases in fine particulate matter concentrations were observed to occur during the summer months and can largely be attributed to forest fires. Wintertime concentrations were typically very low. Due to the overall low concentrations of fine particulate matter observed at Caroline monitoring station, particularly during the wintertime when concentrations at Red Deer Riverside monitoring station are high, no further discussion of the observations from this station will be included in the science report.

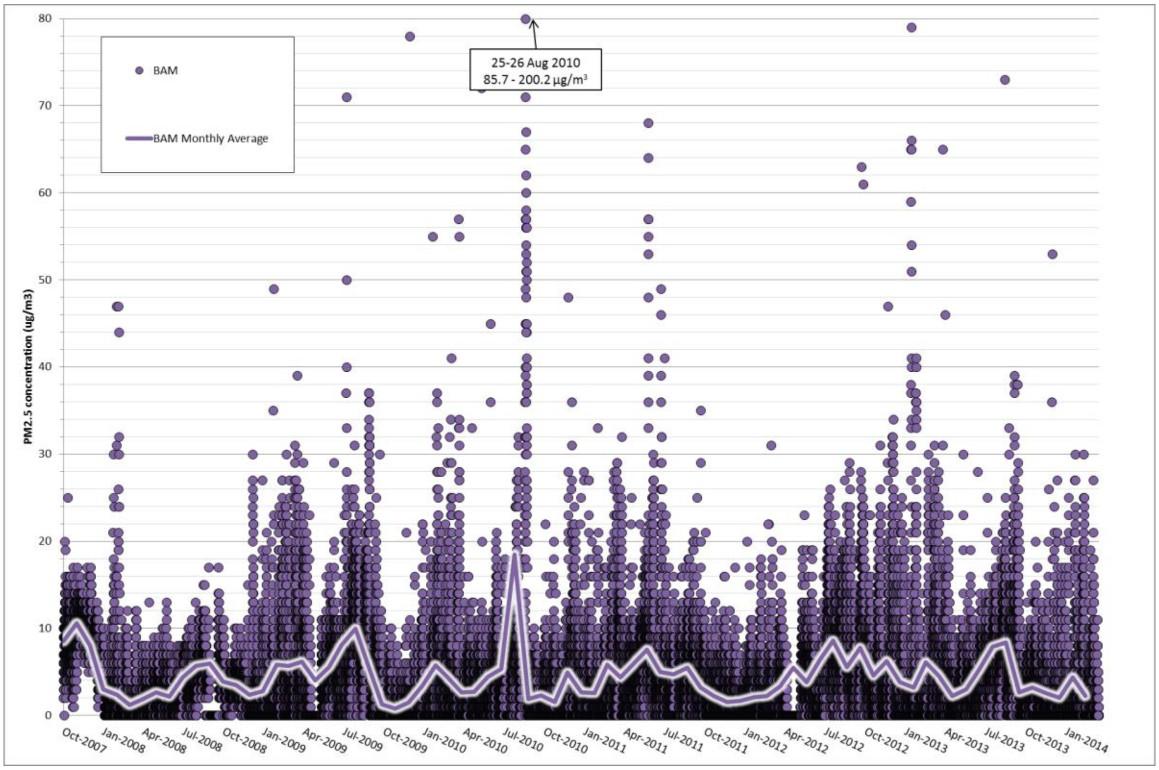

Figure 14: Time series of hourly and monthly average fine particulate matter concentrations as measured at Caroline monitoring station from October 2007 to May 2014. Note: Data presented between September 2009 and July 2013 were rounded to the nearest integer to match the rounding methods used throughout the rest of the period.

3. Discussion

The following discussion attempts to characterize the circumstances driving the exceedance of the Canada-wide Standards at Red Deer Riverside monitoring station. Three main discussion topics were derived from a series of investigative questions developed internally by Alberta Environment and Parks. The development of investigative questions was informed by an interest in exploring variables expected to impact fine particulate matter concentrations as well as to address specific questions raised by stakeholders. These discussions focus primarily on the observations from Red Deer Riverside monitoring station but also draw upon other data where appropriate. The following three topics form the body of the discussion:

Measurement of Particulate Matter (Section 3.1)

This discussion focuses on the methodologies used in the continuous measurement of fine particulate matter in the ambient atmosphere. Different technologies have been used at Red Deer Riverside monitoring station over time and the associated methods used may have implications on the measured concentrations.

Influence of Meteorology (Section 3.2)

This discussion focuses on the influence of meteorological variables on the observed fine particulate matter concentrations at Red Deer Riverside monitoring station.

Evidence of secondary particulate matter and potential sources (Section 3.3)

This discussion focuses on the fact that with currently available information is not possible to confirm whether the observed fine particulate matter concentrations are predominantly primary or secondary fine particulate matter. Without this information, the determination of which source sectors are contributing most strongly to the observed fine particulate matter concentrations is impaired. Discussions of a number of smaller investigations form the body of this section. These topics include the exploration of multi-station fine particulate matter events and the impact of traffic from nearby roadways. The evidence presented points to the formation of secondary fine particulate matter as a key driver of fine particulate matter concentrations in the Red Deer area.

3.1.Measurement of Particulate Matter

Red Deer Riverside monitoring station has been measuring fine particulate matter concentrations since 2001. During the period of time spanning its operation to date, monitoring technology for fine particulate matter has improved and as such, instrumentation changes have been made twice at Red Deer Riverside monitoring station, once in 2009 and again in 2013. As noted in section 1.1, Red Deer Riverside monitoring station was identified as having exceeded the Canada-wide standard for fine particulate matter in the 2009-2011 Clean Air Strategic Alliance Particulate Matter and Ozone Management Framework assessment (AESRD, 2013). This assessment coincides with the adoption of a new monitoring method and instrument at Red Deer Riverside monitoring station as well as the previously identified step-change in fine particulate matter concentrations observed in May 2009. It is important to characterize the differences between the monitoring technologies that have been used at Red Deer Riverside monitoring station in order to understand their potential contribution to variations in observed fine particulate matter concentrations over time.

Table 1: History and technical details of fine particulate matter monitoring equipment at Red Deer Riverside station.

Instrument	Measurement Method	Monitoring period
TEOM SES	Tapered Element Oscillating Micro-balance with Sample Equilibrium System *Inlet temperature:* 40°C	2001 – May 12 2009
TEOM FDMS	Tapered Element Oscillating Micro-balance with Filter Dynamics Measurement System	*Used for reporting:* May 12 2009 – August 13 2013 *Co-located measurement:* August 13 2013 – April 2015
SHARP 5030	Nephelometry calibrated via Beta Attenuation *Inlet temperature:* Variable according to Relative Humidity	August 13 2013 - Present

3.1.1. Monitoring Principles of Operation and Rationale for Analayzer Upgrades at Red Deer Riverside Station

Until 2009 the Tapered Element Oscillating Microbalance Sample Equivalent System (TEOM-SES) fine particulate matter monitor operated at the Red Deer Riverside monitoring station. This technology utilizes an oscillating microbalance to continuously measure particulate matter mass accumulation while known quantities of air are drawn over the microbalance; particulate matter concentration is then calculated from the particulate mass and volume of air collected during each sample interval. Particulate bound water is driven off with a heated inlet prior to measurement to enable characterization of the true “dry” particulate mass and to reduce instrument maintenance associated with excess moisture. Research conducted by the instrument manufacturer and others, intended to determine the efficacy and representativeness with which the instrument measures the sum of the various fine particulate matter species, concluded that the heated inlet was affecting measurements. The heated inlet, intended to drive off only particulate bound water, was also determined to be systematically volatilizing some of the fine particulate matter species present in the atmosphere, resulting in a lower measured particulate mass than is actually present in the ambient atmosphere. The species most easily volatilized as a result of the heated inlet were found to be the relatively volatile ammonium nitrate and organic matter species; both common secondary fine particulate matter species. Various adjustments have been attempted by the instrument manufacturer, over time, to lower the inlet temperature to a level that would avoid volatilizing the volatile fine particulate matter species. However, regardless of temperature (temperatures were lowered from the original design of the instrument at 50°C to 40°C and ultimately 30°C) some degree of losses were still apparent. The TEOM SES instrument at Red Deer Riverside was operated with an inlet temperature of 40°C. In order to better account for the volatile species lost to the older TEOM-SES technology, a new inlet heating methodology, titled the Filter Dynamics Measurement System (FDMS), was integrated into the TEOM analyzer giving rise to the TEOM-FDMS fine particulate matter monitor. In short, the problem of lost volatile species was solved by the FDMS. Two different particle mass concentration measurements are performed by the Tapered Element Oscillating Microbalance sensor: a base measurement of the incoming ambient air heated to 30°C as would occur in a TEOM-SES instrument and a reference measurement of the ambient air stripped of volatile particulates by a filter chilled to 4°C. The difference in masses measured by the Tapered Element Oscillating Microbalance is therefore equivalent to total mass of volatile and non-volatile particulates in the ambient atmosphere. On May 12, 2009, a Tapered Element Oscillating Microbalance Filer Dynamics Measurement System (TEOM-FDMS) instrument was installed at Red Deer Riverside to replace the outdated TEOM-SES instrument that had been in operation at the station since 2001. No subsequent measurements were made with the TEOM-SES at Red Deer Riverside

Difficulties maintaining reliable operation of TEOM-FMDS instruments has led to the adoption of more reliable particulate matter monitoring instruments within the Province of Alberta since 2009. Challenges with TEOM-FDMS instruments include large hour-to-hour swings in reported concentrations, substantial numbers of hours lost due to negative values, high maintenance hours (affecting overall station up-time), and high cost of replacement and consumable parts. The US EPA has recognized a number of fine particulate matter instruments that are able to account for volatile species of fine particulate matter as being Federal Equivalency Method equivalent (US EPA 2014). One of the recognized instruments, the Synchronized Hybrid Ambient Real-time Particulate (SHARP) 5030 instrument was selected to replace the TEOM-FDMS at Red Deer Riverside station in 2013. In brief, the SHARP 5030 instrument utilizes nephelometry (a type of photometry method which measures light scatter from particulates) to measure particulate concentration in real time. The nephelometric measurements are continuously calibrated with a synchronized beta attenuation sensor (this method uses a filter tape to collect particulates over a given period of time; the degree to which particulates attenuate (block) beta rays from a radioactive source is strongly correlated to ambient concentration). The SHARP 5030 instrument began operation on August 1, 2013 and continues in operation to present. While no longer used for ambient concentration reporting the TEOM-FDMS remained in operation at Red Deer Riverside monitoring station until April 2015. This was implemented in an effort to determine whether there are notable differences between the concentrations reported by the TEOM-FDMS and the SHARP 5030 instruments at Red Deer Riverside monitoring station. The availability of a substantial set of co-located measurements allows for the characterization of the comparability of the two measurement techniques (TEOM-FDMS vs SHARP 5030) with respect to the concentrations measured at Red Deer Riverside monitoring station.

3.1.2. Comparability of Fine Particulate Matter Monitoring Technologies Used at Red Deer Riverside

Differences in the analytical methods of various fine particulate matter monitoring instruments are known (e.g. TEOM-SES vs TEOM FDMS) to have an effect on the concentrations measured by these instruments. For this reason detailed investigations into the impact of changes in instrumentation on the measured fine particulate matter concentrations at Red Deer Riverside monitoring station have been conducted by the Parkland Airshed Management Zone and Alberta Environment and Parks. The Parkland Airshed Management Zone tasked NOVUS Environmental in 2012 to examine observed fine particulate matter concentrations at Red Deer Riverside monitoring station during the period of 2008-2011 and characterize the effect that instrument changes, among other factors, may have had on the data (NOVUS Environmental, 2012). Alberta Environment and Parks further explored the fine particulate matter data from Red Deer Riverside monitoring station (including co-located TEOM-FDMS and SHARP 5030 measurements) as well as additional co-located measurements made at Edmonton McIntyre monitoring station (co-located measurements between a TEOM-SES and TEOM-FDMS instrument.

3.1.2.1. Parkland Airshed Management Zone NOVUS Environmental Report

NOVUS Environmental compiled fine particulate matter concentration data from 2008 to 2011 at Red Deer Riverside monitoring station (NOVUS Environmenta, 2012). They analyzed the data utilizing hourly, daily, monthly, and annual averaged concentrations by comparing measurements prior to the adoption of TEOM-FDMS to the measurements after the adoption of TEOM-FDMS. Other pollutants such as oxides of nitrogen, volatile organic compounds, and carbon monoxide were also analyzed to understand any trends in the historical data.

Figure 15 shows a normalized comparison (all measurements scaled relative to the 2008 annual average of each respective pollutant) of monthly fine particulate matter concentrations during the periods before and after the 2009 switch in analyzer technologies. Following the adoption of TEOM-FDMS, fine particulate matter concentrations increased drastically, by an approximate factor of 2.5 greater than 2008 measurements (Figure 15). Additionally, following the adoption of TEOM-FDMS observed concentrations underwent strong seasonal variations to as much as 6.5 times greater than peak 2008 measurements (Figure 15). Seasonal patterns as observed with TEOM-FDMS measured concentrations, indicated that concentrations are highest, and most different from TEOM-SES measured concentrations, in the wintertime (approximately from October to March; Figure 15). During the rest of the year concentrations are lower and the difference between TEOM-SES and TEOM-FDMS measurements are smaller, however TEOM-FDMS measured concentrations remain a factor of 2 greater (Figure 15). There was no significant seasonal pattern observed for fine particulate matter concentrations as measured by TEOM-SES prior to 2009, suggesting that the concentrations measured by TEOM-SES did not vary significantly between seasons (NOVUS Environmental, 2012).

The NOVUS Environmental report also compared the seasonal variation for other pollutants (NOVUS Environmental, 2012). Carbon monoxide and oxides of nitrogen were selected due to their association with emission sources in the City of Red Deer (e.g. transportation emissions from the nearby Riverside Drive) and both showed strong seasonal patterns (Figure 15). Higher concentrations were observed in the winter and lower concentrations were observed throughout the rest of the year (Figure 15). These seasonal variations were similar to the seasonal trend observed for fine particulate matter measured with TEOM-FDMS, however there was no appreciable difference in the magnitude of the variations of the other pollutants during the period before or after May 2009 (Figure 15). Seasonal variations in volatile organic compound concentrations were also consistent year to year (Figure 15). The fact that seasonal variations for carbon monoxide, oxides of nitrogen and volatile organic compounds, did not differ substantially from before 2009 to the period after suggests that a systematic difference in measured concentrations was limited to fine particulate matter measurements; only fine particulate matter underwent a change in instrumentation during this period. Therefore the report concluded that fine particulate matter concentrations were affected by the change in monitoring technology (NOVUS Environmental, 2012). Whether the entire increase in measured concentrations was associated with the instrumentation change or due to other factors is also discussed within this report and is detailed in section 3.3.

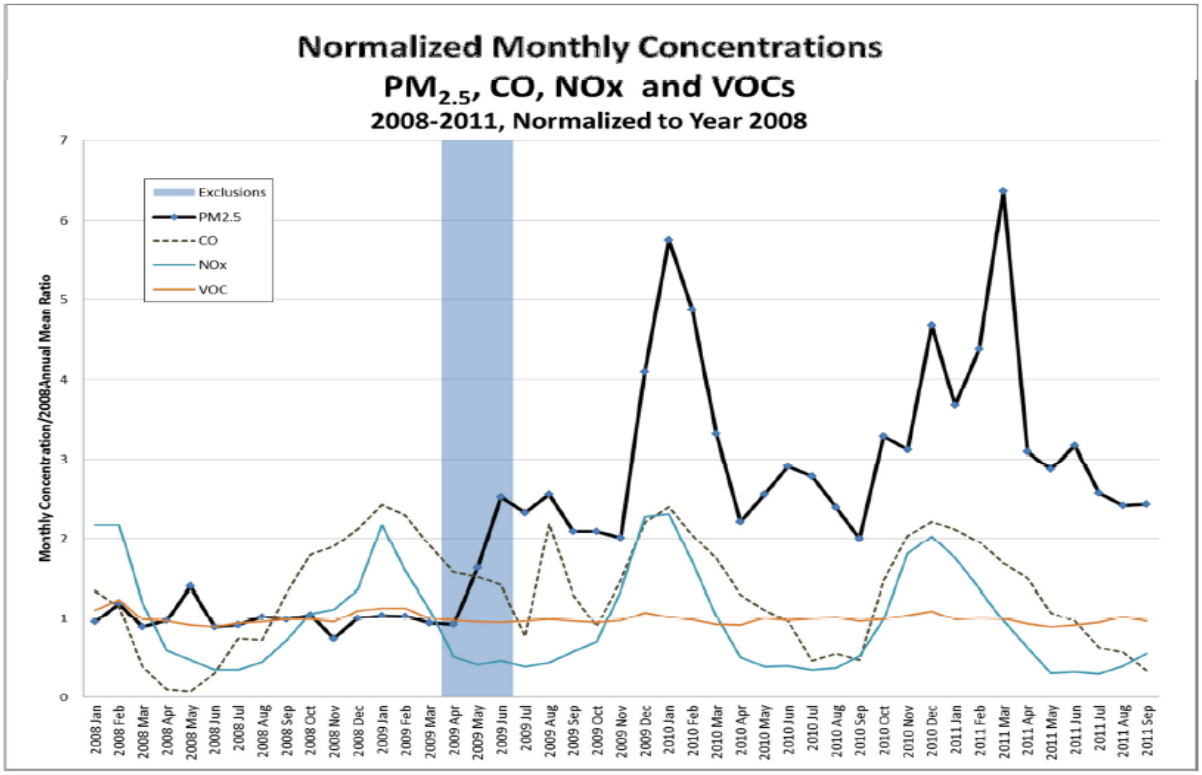

Figure 15: Normalized monthly concentrations for PM2.5, CO, NOx, and VOCs. The normalization is based on 2008 annual concentrations. For example, if the normalized concentration equals 1, the real monthly concentration is the same as the 2008 annual mean concentration. Forest fire related particulate matter spike values were removed in August 2010. The blue section indicates the period the TEOM FDMS was installed and the Civic Yard was phased in.

3.1.2.2. Alberta Environment and Parks Investigation

The results of the NOVUS report, identifying the presence of previously unobserved seasonal patterns after the adoption of TEOM-FDMS, in addition to the substantial step-change in hourly concentrations noted in May 2009, highlighted the need for an investigation comparing the measurement technologies utilized at Red Deer Riverside monitoring station. Specifically higher fine particulate matter concentrations observed via TEOM-FDMS in the winter, as compared to TEOM-SES, suggests that this technology better characterizes some aspect of the particulate matter speciation that was previously not measured by TEOM-SES; a species likely comprising a large portion of wintertime fine particulate matter.

Unfortunately there were no collocated measurements (measurements taken by both instruments at the same location at the same time) available from Red Deer Riverside monitoring station for TEOM-SES and TEOM-FDMS, making it difficult to characterize any systematic impacts that the analyzer change may have had on the observed concentrations. However, co-located measurements with TEOM-SES and TEOM-FDMS are available from Edmonton McIntyre monitoring station. Edmonton McIntyre station is located in South Edmonton and has operated co-located TEOM-SES and TEOM-FDMS instruments since

November 2006. The TEOM-FDMS is identical to that used at Red Deer Riverside monitoring station, however the TEOM-SES utilizes an inlet temperature of 30°C, lower than the inlet temperature of 40°C utilized by the TEOM-SES at Red Deer Riverside monitoring station. These data were explored in detail to contextualize the impacts expected from the instrument change at Red Deer Riverside monitoring station.

As noted in section 3.1.1, approximately a year and a half of co-located SHARP-5030 and TEOM-FDMS measured concentrations were made at Red Deer Riverside monitoring station. These data were utilized to contextualize the differences in these two Federal Equivalency Method recognized instruments and discuss the potential systematic impacts on the data resulting from the instrument change to SHARP-5030 in August 2013.

In order to determine the comparability of monitoring methods and characterize any systematic changes as a result (specifically between TEOM-SES vs TEOM-FDMS, and TEOM-FDMS vs SHARP-5030) both sets of co-located data were compared in an identical manor. Linear regressions (a slope of 1 and y-intercept of 0 indicating representative monitoring techniques) were used to compare each set of co-located data using three metrics. Hourly concentrations were compared to characterize instantaneous instrument response to fine particulate matter concentrations. Twenty four hour averaged concentrations were also compared to characterize broad comparability between methods by averaging over hour to hour differences. Lastly data above the 98th percentile of twenty four hour averages were compared in an effort to characterize the events with the highest fine particulate matter concentrations; the 98th percentile of twenty four hour averages was used in reporting for against the Canada-wide standards and will be used in reporting for the Canadian Ambient Air Quality Standards.

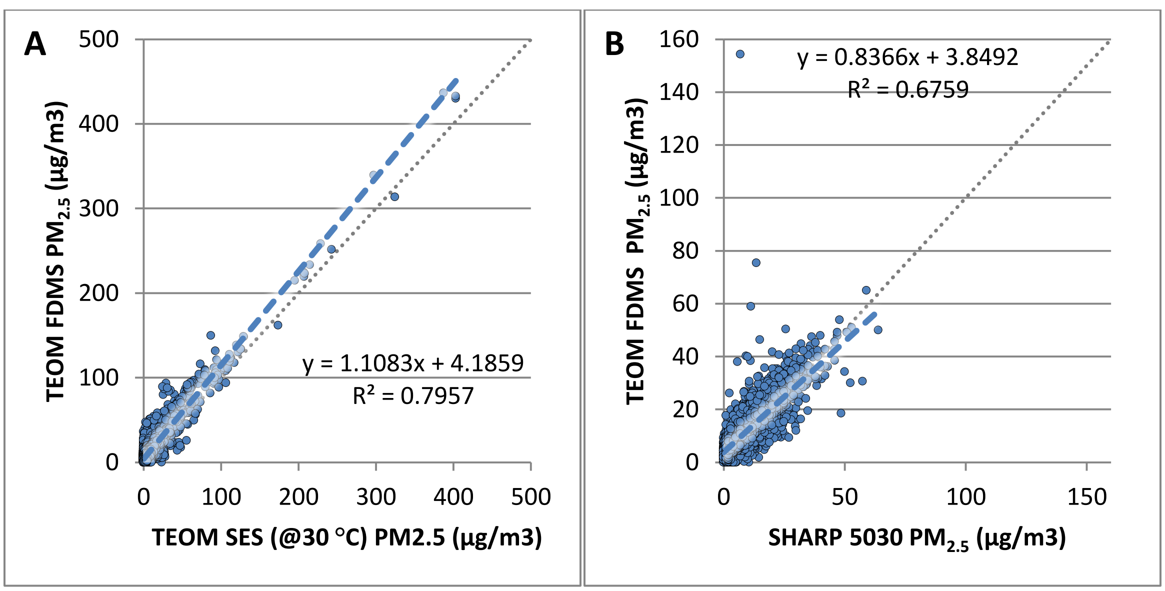

Figure 16: A) Comparison of TEOM-FDMS versus TEOM-SES @ 30 Celsius hourly $PM_{2.5}$ concentration measurements at Edmonton McIntyre monitoring station during 2008-2011. B) Comparison of SHARP-5030 versus TEOM-FDMS hourly $PM_{2.5}$ concentration measurements at Red Deer Riverside monitoring station during 2013-2015

Linear regressions of hourly fine particulate matter concentrations as measured by TEOM-SES versus TEOM-FDMS (Figure 16A) and SHARP-5030 versus TEOM-FDMS (Figure 16B) indicate that these instruments respond slightly differently to concentrations in the ambient air. These differences are distinct and the relationship between the instrument pairs can be used to indicate what systematic effects may expected from changes between analyzers. Both co-located pairings failed, to some degree, to respond to the same ambient concentrations with identical measured concentrations (as indicated by an R^2 value less than 1). The SHARP-5030 versus TEOM-FDMS (Figure 16B) had a somewhat poorer reproduction of ambient concentrations than the TEOM-SES versus TEOM-FDMS pairing (Figure 16A). The poorer apparent performance of the SHARP-5030, as determined by R^2 value may be exacerbated by the measurement technique used by this instrument which is entirely different than that used in the TEOM-FDMS; the TEOM-SES and TEOM-FDMS share the same basic analysis method with different sample pre-treatments.

Both co-located pairings have linear regressions with slopes that trend away from 1, indicating a systematic bias in concentrations with one measurement method consistently either under-reporting or over-reporting the ambient concentration. However, the slope cannot be discussed in isolation, because at y-intercept is significant at the typical concentrations measured at Red Deer Riverside monitoring station. With respect to the TEOM-SES versus TEOM-FDMS (Figure 16A), the slope of 1.1 indicates that TEOM-FDMS measurements are consistently larger than the equivalent TEOM-SES measurements and that the difference in reported concentrations between these two instruments is larger at higher ambient concentrations. Additionally the y-intercept of 4.2 indicates that there is a systematic bias between measurements, with the TEOM-FDMS reading, on average 4.2 µg/m^3, higher than the TEOM-SES. These observations are consistent with the methodological differences between the two instruments; that is that the TEOM-FDMS captures more volatile species than the TEOM-SES, and that these volatile species make up a higher composition of fine particulate matter on days with the highest total concentrations of fine particulate matter. This observation is also similar in magnitude to the step-change observed at Red Deer Riverside monitoring station between the reporting of fine particulate matter concentrations by TEOM-SES to the reporting by TEOM-FDMS. Therefore, the observed change in fine particulate matter concentrations during the change in analyzers at Red Deer Riverside monitoring station may have been almost entirely driven by the systematic change in analyzers.

With respect to the SHARP-5030 versus TEOM-FDMS comparison (Figure 16B), the slope of 0.84 indicates that TEOM-FDMS measurements are consistently smaller than the equivalent SHARP-5030 measurements. It also indicates that the difference in reported concentrations between these two instruments is larger at higher ambient concentrations. However, the magnitude of the y-intercept, of 3.8, places the linear regression in an interesting position with respect to ambient concentrations. The linear regression suggests that ambient concentrations of 23.6 µg/m^3 will be measured identically by both instruments. Higher concentrations would be reported via SHARP-5030 above this value and higher concentrations would be reported via TEOM-FDMS below this value. While the concentration differences are substantial, the overall positioning of the linear regression suggests that at higher concentrations the SHARP-5030 reports equivalent or slightly larger fine particulate matter concentrations than the TEOM-FDMS, indicating equivalent, or perhaps better, capture of volatiles.

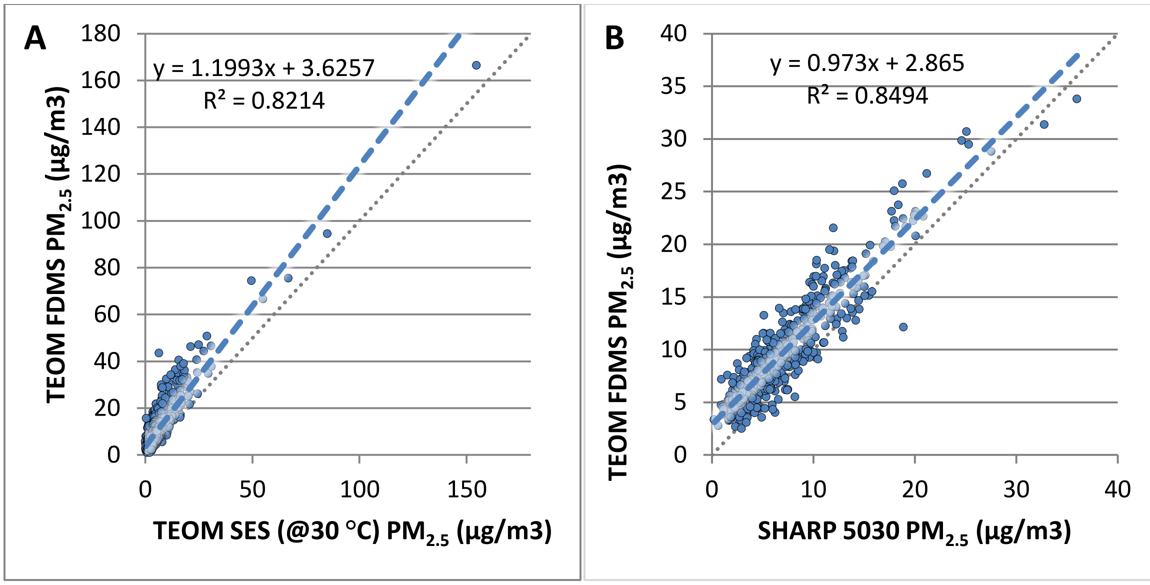

Figure 17: A) Comparison of TEOM-FDMS versus TEOM @ 30 Celsius twenty hour average $PM_{2.5}$ concentration measurements at Edmonton McIntyre monitoring station during 2008-2011. B) Comparison of SHARP-5030 versus TEOM-FDMS twenty hour average $PM_{2.5}$ concentration measurements at Red Deer Riverside monitoring station during 2013-2015

Linear regressions of twenty four hour averaged TEOM-SES versus TEOM-FDMS (Figure 17A) and SHARP-5030 versus TEOM-FDMS (Figure 17B) measurements indicate that the averaged measurements reported by these instruments systematically differ from the regressions of the hourly data, indicating that averaging has a significant effect on the data. Both twenty four hour averaged co-located pairings had similar R^2 values that were larger than the equivalent hourly comparisons. Part of this improvement is most likely related to the fact that averaging removes some of the hour to hour variation between instruments.

The linear regression for the twenty four hour TEOM-SES versus TEOM-FDMS (Figure 17A) pairing was similar to the linear regression for the hourly data, with a slope greater than 1 and a positive intercept. Most importantly however, the slope for the twenty four hour data was 1.2, which is steeper than that for the hourly data indicating that on days with higher concentrations the TEOM-FDMS reported concentrations are 20% larger than those measured by TEOM-SES.

The linear regression for the twenty four hour SHARP-5030 versus TEOM-FDMS (Figure 17A) pairing was different in comparison to the linear regression for the hourly data, with a slope very close to 1 and a smaller positive intercept. This indicates that on a twenty four hour average basis, the SHARP-5030 responds nearly equivalently to the TEOM-FDMS across all ambient concentrations. However the magnitude of the y-intercept suggests that the resultant concentrations as measured by the SHARP-5030 are typically 2.9 $\mu g/m^3$ smaller than those measured by the TEOM-FDMS. This apparent systematic bias towards smaller concentrations as measured by SHARP-5030 on a twenty four hour basis could be the result of the higher measurement of fine particulate matter by TEOM-FDMS at lower concentrations; hourly concentrations below 23.6 ug/m^3 comprising the vast majority of the dataset. Therefore, as the new annual average Canadian Ambient Air Quality Standard takes these lower concentrations into account, it is expected that the bias observed between the TEOM-FDMS and the

SHARP-5030 via the twenty four hour regression will be similar for the annual averages calculated. It is likely that there will be some systematic bias between the annual average Canadian Ambient Air Quality Standards calculated with TEOM-FDMS observations versus SHARP-5030 observations, with the expected tendency for SHARP-5030 derived calculations to be less than those calculated with TEOM-FDMS.

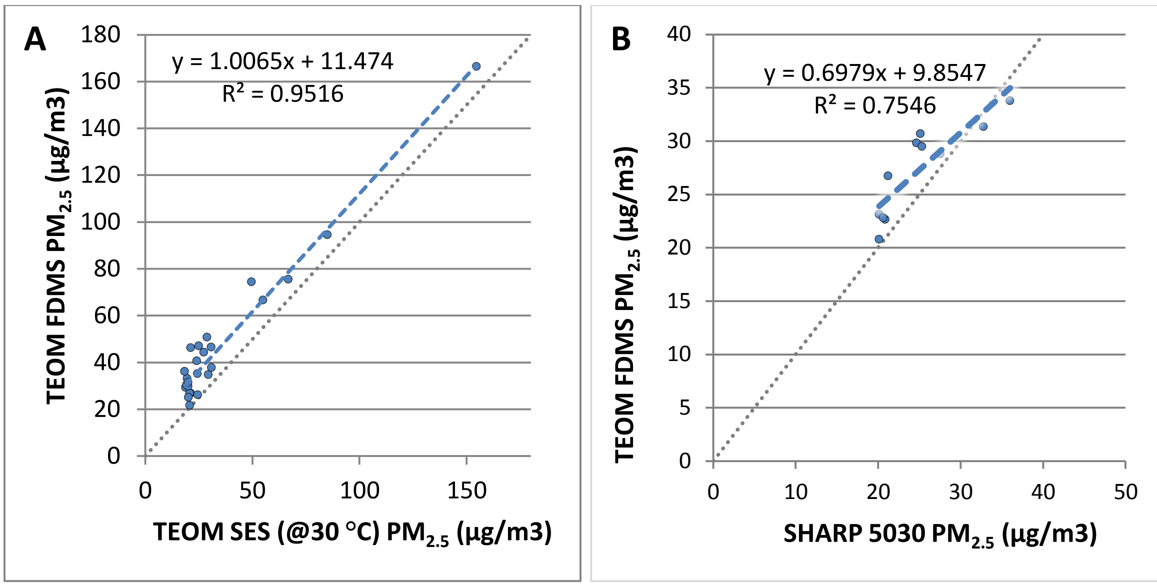

Figure 18: A) Comparison of 24 hour average $PM_{2.5}$ measurements greater than the 98th percentile as measured by collocated TEOM-FDMS and TEOM-SES (@ 30 Celsius) instruments at Edmonton McIntyre monitoring station during 2008-2011. B) Comparison of 24 hour average $PM_{2.5}$ measurements greater than the 98th percentile as measured by collocated SHARP-5030 and TEOM-FDMS instruments at Red Deer Riverside monitoring station during 2013-2015.

Linear regressions of twenty four hour averaged TEOM-SES versus TEOM-FDMS (Figure 18A) and SHARP-5030 versus TEOM-FDMS (Figure 18B) measurements above the 98th percentile indicate that the highest averaged measurements reported by these instruments systematically differ from the remainder of the averaged concentrations.

The twenty four hour averaged concentrations greater than the 98th percentile comparison of co-located TEOM-SES versus TEOM-FDMS (Figure 18A) was highly linear with a slope of 1 and R^2 of 0.95. Therefore the response between these instruments on an averaged basis is very similar across all high concentration days. However a substantial y-intercept suggests that on average days with high fine particulate matter concentrations are measured 11.5 µg/m^3 less by the TEOM-SES than the TEOM-FDMS. The implication of this difference is that on the days with the highest fine particulate matter concentrations (greater or equal to the 98th percentile) the TEOM-SES measurements are not accounting for approximately 30% of the particulate mass measured by the TEOM-FDMS.

The twenty four hour averaged greater than the 98th percentile comparison of co-located SHARP-5030 versus TEOM-FDMS (Figure 18B) was similar to the results for hourly data, however with a shallower slope and a larger y-intercept. Similar to the hourly comparison, the slope and y-intercept places the linear regression in an interesting position with respect to ambient concentrations. The linear regression suggests that ambient concentrations of 32.6 μg/m^3 will be measured identically by these instruments with higher concentrations being reported via SHARP-5030 above this value. Fine particulate matter concentrations can be expected to me measured higher by TEOM-FDMS than by SHARP-5030 below this value. The 98^{th} percentile of twenty four hour average Canadian Ambient Air Quality Standard is set at 28 μg/m^3 between 2015 and 2020. Previous assessments of fine particulate matter at Red Deer Riverside monitoring station under the Canada-wide standards (achievement is based on the same 98^{th} percentile of twenty four hour averages metric) have placed the 3 year average of this metric at 11.7-31.4 μg/m^3. Therefore, adoption of SHARP-5030 technology may result in a systematic reduction in observed 98^{th} percentile values. It is important to note that less data were available for the comparison of SHARP-5030 versus TEOM-FDMS than for TEOM-SES versus TEOM-FDMS (10 versus 26 data points).

3.1.3. Implications of the adoption of FEM analyzers on the measurement of $PM_{2.5}$

Federal Equivalency Method fine particulate matter monitors clearly measure higher fine particulate matter concentrations than co-located non-federal equivalency method monitors. The tendency for the difference between federal equivalency method and non-federal equivalency method analyzers to vary seasonally suggests that federal equivalency method analyzers capture some species of fine particulate matter more effectively and that those species vary in concentration seasonally. The speciation of fine particulate matter concentrations in Alberta is measured at Edmonton McIntyre on a regular basis (every third day). These data were analyzed in the Capital Region Fine Particulate Matter Science Report (AESRD, 2015) for the period between 2006 and 2011, and the results are summarized below.

Significant seasonal differences in the atmospheric speciation of fine particulate matter were observed. Figure 19 shows that on average, the fine particulate matter mass was higher in the colder season (October-March) than the warmer season (April-September). A closer analysis of the cold season event days (event days were defined as twenty four hour averages > 20μg/m3), those periods with the biggest differential between non-federal equivalency method and federal equivalency method analyzers reveals that ammonium nitrate and organic matter are the two most prominent components (accounting for 66% of the total fine particulate mass; Figure 20) of the fine particulate matter mass. Volatile fine particulate matter species are liable to be volatilized in non-federal equivalency method analyzers, of which ammonium nitrate and organic matter are most susceptible (Wilson et al., 2002). Therefore it is likely that the increase in concentrations observed with federal equivalency method analyzers is directly related to the ability of these instruments to better account for the volatile fractions of secondary particulate matter which comprise the majority of fine particulate matter mass on high concentration days; this is particularly true for the most volatile specie ammonium nitrate, which, in Edmonton, accounts for nearly half of the fine particulate matter mass on high concentration days.

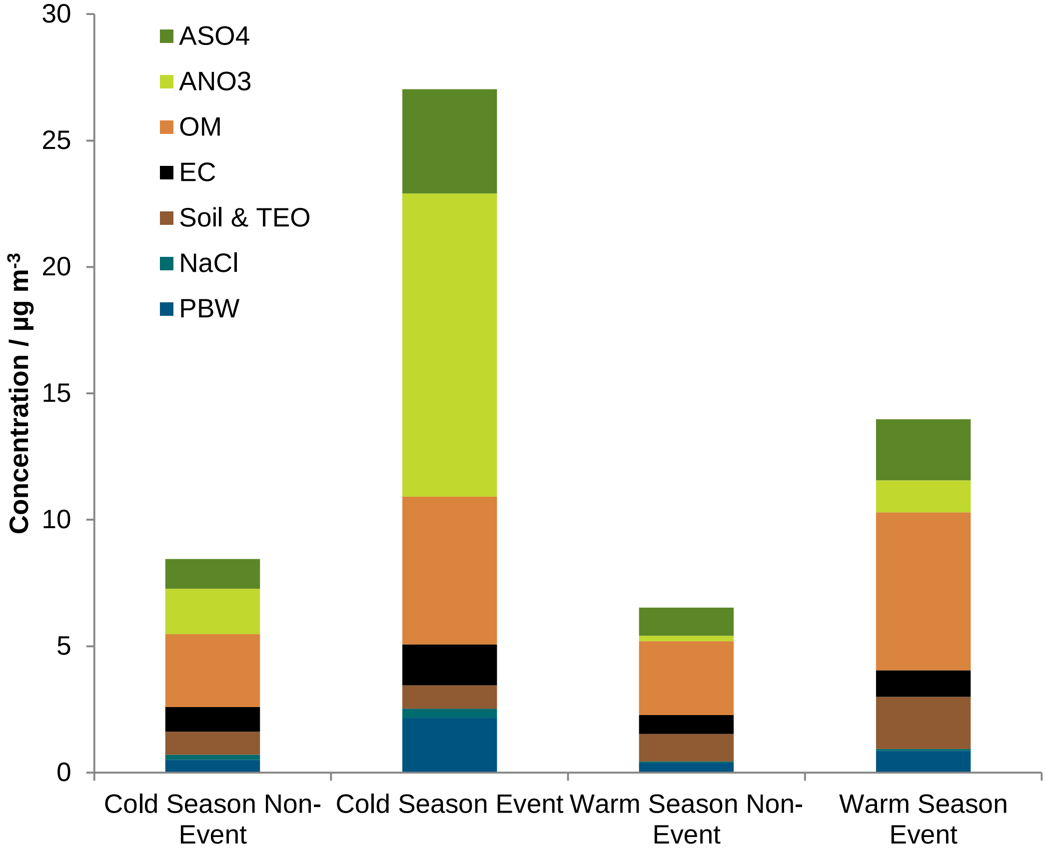

Figure 19: Speciation of $PM_{2.5}$ concentrations for non-event days (24 hour average <20 ug/m3) versus event days (24 hour average >20 ug/m3) in the cold (October-March) and warm seasons (April-September) at Edmonton McIntyre monitoring station (2006-2011). (ASO4 – Ammonium sulphate, ANO3 – Ammonium nitrate, OM – organic matter, EC – Elemental carbon, Soil & TEO – Soil particles and Trace elements, NaCl – Salt particulates, PBW – Particle bound water)

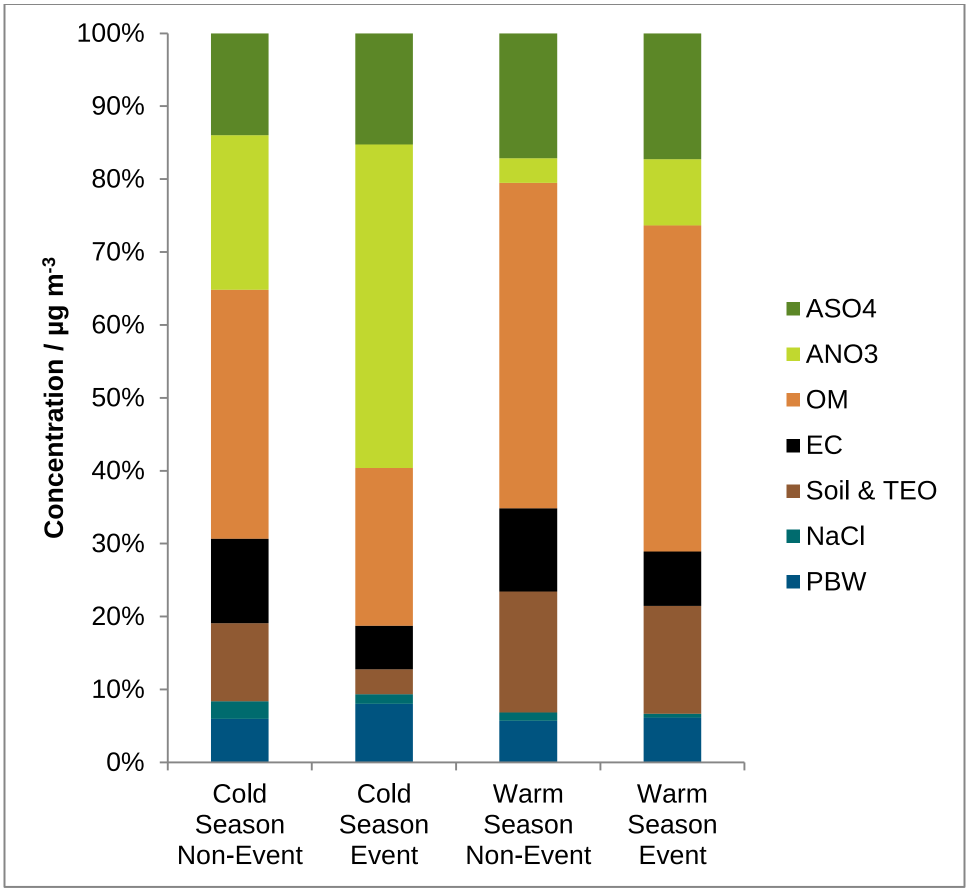

Figure 20: Speciation of $PM_{2.5}$ as a percentage of total particulate mass for non-event days (24 hour average <20 ug/m3) versus event days (24 hour average >20 ug/m3) in the cold (October-March) and warm seasons (April-September) at Edmonton McIntyre monitoring station (2006-2011). (ASO4 – Ammonium sulphate, ANO3 – Ammonium nitrate, OM – organic matter, EC – Elemental carbon, Soil & TEO – Soil particles and Trace elements, NaCl – Salt particulates, PBW – Particle bound water)Influence of meteorology

Taken in the context of Red Deer Riverside monitoring station, the similar magnitude of the step change in concentrations, after the adoption TEOM-FDMS technology, to the differences observed in the Edmonton McIntyre monitoring station co-located TEOM-SES versus TEOM-FDMS comparison, suggests that a significant component of the ambient fine particulate matter species were being lost due to volatilization. Adoption of a federal equivalency method analyzer at Red Deer Riverside monitoring station therefore had a significant impact on the observed fine particulate matter concentrations, potentially contributing almost fully to the observed step change in fine particulate matter concentrations in May 2009. With respect to the composition of fine particulate matter at Red Deer Riverside monitoring station, the observation of seasonality in the TEOM-FDMS measured concentrations suggest that volatile species are present in larger quantities in the winter than in the summer. Given the precursor emissions in the vicinity of the City of Red Deer, the volatile species likely to be present in the atmosphere are ammonium nitrate and to some extent volatile organics. This would be Similar to the speciation observed in Edmonton. The observational evidence indicates that the high wintertime fine particulate matter concentrations that impact Red Deer Riverside monitoring station are largely composed of secondary fine particulate matter.

Into the future, the use of a SHARP-5030 monitor at Red Deer Riverside monitoring station is unlikely to have as substantial an impact on observed concentrations as the previous change to TEOM-FDMS due to the relative reproducibility of these instruments at high fine particulate matter concentrations. In terms of future assessment against the CAAQS (Annual average and 3 year 98^{th} percentile 24 hour average), the relative differences in collocated measurements between TEOM-FDMS and SHARP-5030 at Red Deer Riverside monitoring station, in the range typical of ambient concentrations in the City of Red Deer (~10ug/m3 annual average, ~30 ug/m3 98^{th} percentile), may have a systematic impact on these assessments. Specifically, the SHARP-5030 analyzer was observed to record lower concentrations than the TEOM-FDMS at concentrations in the range reported in previous Clean Air Strategic Alliance Particulate Matter and Ozone Management Framework assessments, putting some degree of negative pressure on the assessed metrics. This difference is not expected to be to the same order of magnitude as the difference between assessed metrics using non-federal equivalency method analyzers.

3.2.Influence of Meteorology

Fine particulate matter concentrations at Red Deer Riverside monitoring station were observed to vary substantially throughout the year. These variations were characterized in order to determine the nature of the variations and hypothesize potential driving mechanisms. The data were analyzed by summarizing the distribution of event days with respect to time and meteorological parameters. Event days were defined as twenty four hour averaged concentrations (midnight-midnight) greater than 19 $\mu g/m^3$. Dates associated with forest fire smoke were removed from analysis (A total of 14 events were remove with an average concentration of 47 $\mu g/m^3$). The use of event days for analysis is consistent with the methodology used by the Capital Region Fine Particulate Matter Science Report (AESRD, 2015), updated from 20 $\mu g/m^3$ to 19 $\mu g/m^3$ to align with the new Canadian Ambient Air Quality Standards. The number of fine particulate matter events were compared on a monthly basis, with respect to wind speed and with respect to wind direction in order to delineate temporal patterns of fine particulate matter events and the relation of fine particulate matter events to meteorological parameters.

At Red Deer Riverside monitoring station it is evident that non-forest fire related fine particulate matter event days can occur in all seasons, however the majority of event days occur between October and March (Figure 21). There is some variability between years, as to the frequency of non-forest fire related event days, however in all years, the number of events occurring between October and March is greater than the balance of the year (Figure 21). These observations are consistent with the findings of the Capital Region Fine Particulate Matter Science Report (AESRD, 2015). The report concluded that events were more frequent during the colder months due to the seasonal variation of meteorological conditions, such as the increased frequency of temperature inversions during the wintertime.

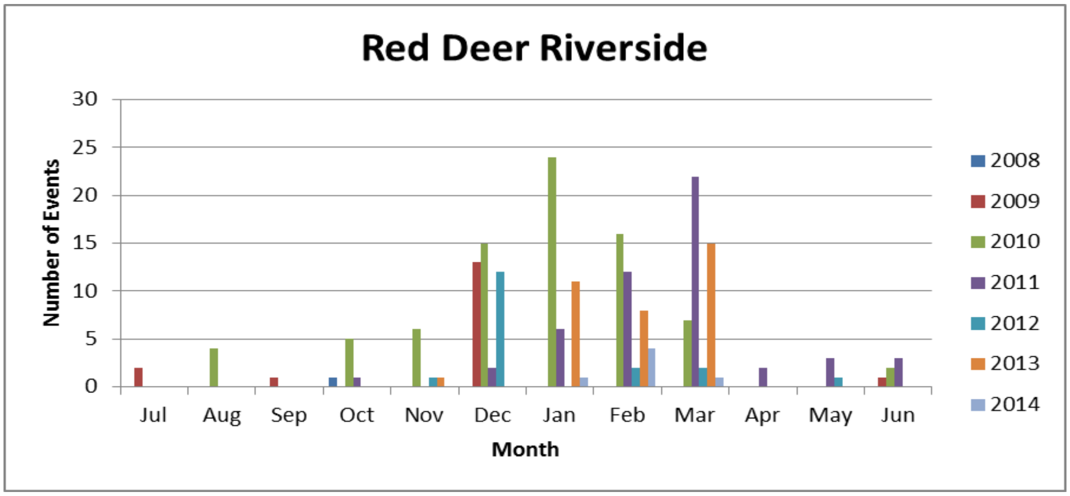

Figure 21: Seasonal distribution of fine particulate matter event days

Fine particulate matter event days are distinctly associated with low to moderate wind speeds (Figure 22). Lower wind speeds inhibit dispersion of fine particulate matter and other pollutant gases. During the wintertime, the period experiencing the highest frequency of fine particulate matter events, lower wind speeds are often associated with temperature inversions in the atmosphere. Temperature inversions occur when cold air is trapped near the surface by a layer of warmer air aloft. This condition prevents air that has been warmed due to daytime heating from rising and mixing, and dispersing pollutants. As mentioned above, the Capital Region Fine Particulate Matter Science Report investigated inversion frequencies throughout the year. It was determined that the frequency of inversions increased from October through March, an observation consistent with the occurrence of fine particulate matter event days (AESRD, 2015). Therefore, the report concluded that mechanisms affecting dispersion, of which temperature inversions are a major contributor, were a major driving force behind fine particulate matter event days in the Capital Region. This conclusion was reached through the analysis of atmospheric soundings collected twice-daily within the Capital Region in conjunction with fine particulate matter concentrations. There are no atmospheric sounding sites within a representative distance of the City of Red Deer, therefore it is not possible to confirm whether the frequency of inversions throughout the year is similar to the Capital Region. However, the seasonal variation of event days and the association of event days with lower wind speeds provides suggests that dispersion limiting mechanisms are driving fine particulate matter events at Red Deer Riverside monitoring station.

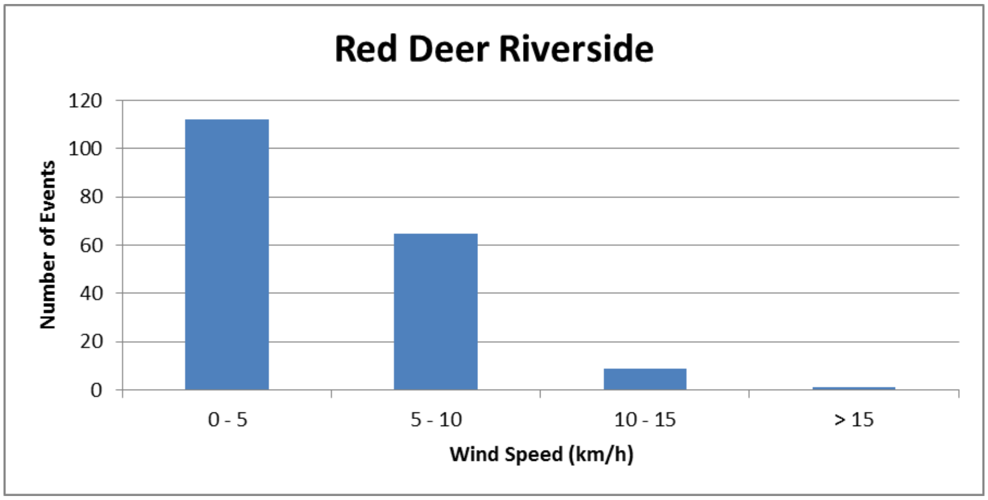

Figure 22: Distribution of fine particulate matter event days with respect to wind speed

Analysis of the wind directions associated with fine particulate matter events at Red Deer Riverside monitoring station indicates that the vast majority of events were associated with southerly wind directions (Figure 23). Often strong associations with specific wind directions may indicate strong impacts from a specific source upwind, however, upwind of Red Deer Riverside monitoring station there is no single large source of fine particulate matter. Additionally, the association of low wind speeds with fine particulate matter event days is problematic as wind direction data becomes more variable at lower wind speeds. Therefore, in the case of Red Deer Riverside monitoring station, the association of fine particulate matter with southerly wind directions is likely related to other phenomenon. One such phenomenon may be topographical channeling, where winds are funneled between prominent topographical features, resulting in a winds constrained to a narrow range of specific directions. The Red Deer River valley, where the Red Deer Riverside monitoring station is located, is a significant linear topographical feature within the City of Red Deer, and as such, some degree of topographic channeling can be expected (Figure 3). The north-south orientation of the Red Deer River valley in the vicinity of Red Deer Riverside monitoring station may be channeling the observed winds and resulting in a dominant direction observed during event days. This association may be exacerbated by other meteorological conditions, such as weather patterns which are likely to result in conditions that limit dispersion.

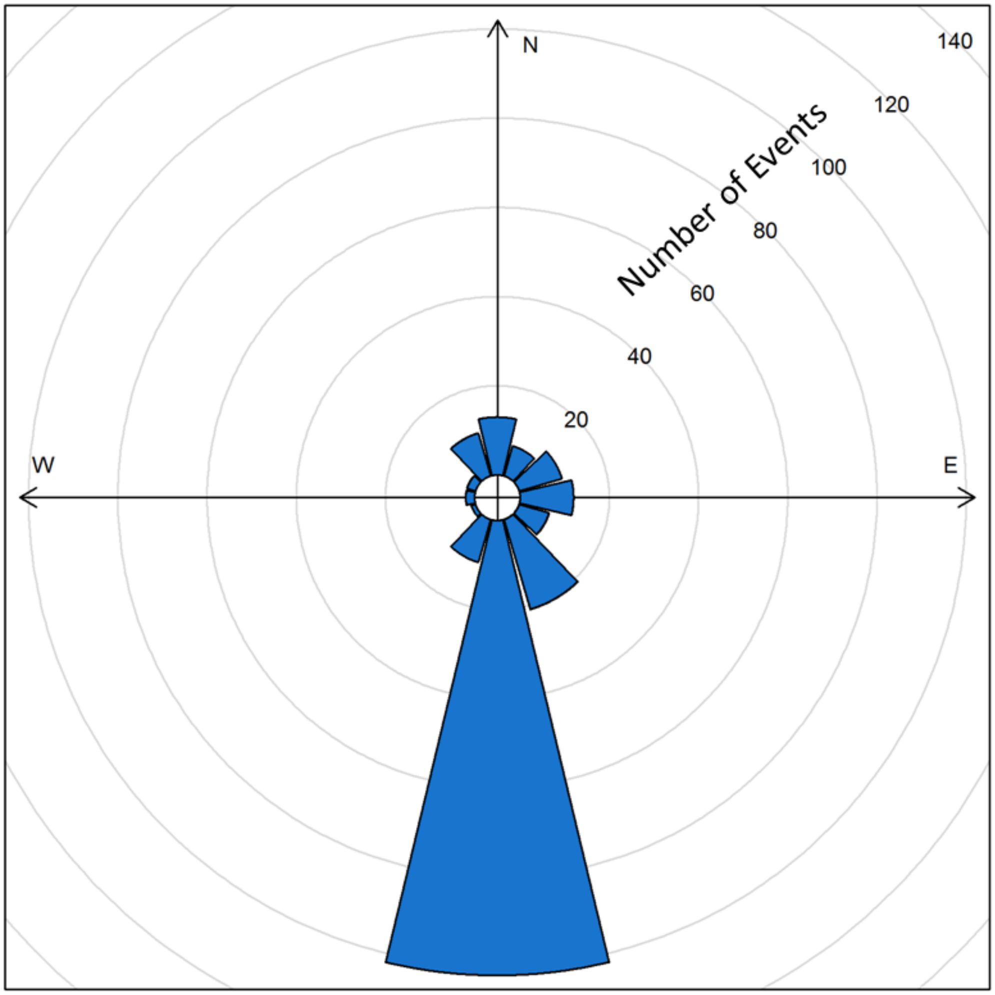

Figure 23: Distribution of event days as observed at Red Deer Riverside monitoring station with respect to wind direction.

The limited available data from monitoring conducted at the Lancaster monitoring station site were analyzed for comparison to the patterns observed at Red Deer Riverside monitoring station. Similar to Red Deer Riverside monitoring station, monitoring from the Lancaster monitoring station site indicated that fine particulate matter events were observed. However, as less than one full year of data are available it is not possible to comment on the seasonality of these events. More data is necessary from Lancaster monitoring station in order to confirm whether the seasonal distribution of events and the association with meteorological information is similar to Red Deer Riverside monitoring station. Lancaster monitoring station became a permanent monitoring station in December 2014, thus a comparison of measurements from all seasons at the Lancaster site will be able to be made in the near future.

3.3. Evidence of secondary particulate matter and potential sources

Since measurements of the ambient fine particulate matter species composition (used to determine the proportions of primary and secondary fine particulate matter species) have not been made at Red Deer Riverside monitoring station, the proportions of primary and/or secondary fine particulate matter measured in Red Deer cannot be confirmed. However, through specific investigations a number of inferences can be derived, ranging from the contribution of some specific sources to the observed particulate matter concentrations at Red Deer Riverside monitoring station to the potential for fine particulate matter concentrations to be driven by secondary fine particulate matter formation.

3.3.1. Multi-station events: Meteorology and source locations

Fine particulate matter events days frequently occur concurrently at air quality monitoring stations in the Edmonton, Red Deer and Calgary areas during the wintertime (October-March). An example of an extended period of correlated fine particulate matter concentrations at monitoring stations in the Edmonton, Red Deer and Calgary areas is shown in Figure 24. This event, in February-March 2011, was selected as an example of a multi-station event due to the siting of the two Parkland Airshed Management Zone portable air monitoring stations along the transportation corridor between Calgary and Red Deer. Throughout the period shown in Figure 24, changes in twenty four hour averaged fine particulate matter concentrations closely mirror each other at most stations, especially those in Edmonton and Red Deer. In order to show the spatial distribution of observed fine articulate matter concentrations during a multi-station event, observed from February 19, 2011 were mapped (February 19, 2011 marks a peak in fine particulate concentrations at stations in Edmonton, Calgary and Red Deer). In brief, mapping was carried out by plotting the twenty four hour averaged fine particulate matter concentrations, measured on February 19, 2011, from 19 air quality monitoring station within the vicinity of Edmonton, Calgary and Red Deer in ArcGIS (Figure 25). A spatial interpolation, achieved through nearest neighbour interpolation, was then completed to interpolate expected concentrations between stations (see figure caption for details; Figure 25). Similar to that identified in Figure 24, fine particulate matter concentrations were highest in areas of high population density (e.g. within Edmonton, Calgary or Red Deer) with lower concentrations measured outside of these areas (Figure 25). This finding is consistent across multi-station events, that is, fine particulate matter concentrations are highest at stations nearby high concentrations of sources. Therefore it is likely that the presence of an abundance of sources within Edmonton, Calgary and Red Deer, enable the development of events under conducive meteorological conditions. The presence of frequent multi-station events suggests that sources within Edmonton, Calgary and Red Deer are contributing to fine particulate matter events and that these multi-station events are driven by large scale meteorology which influence large areas within similar meteorological conditions.

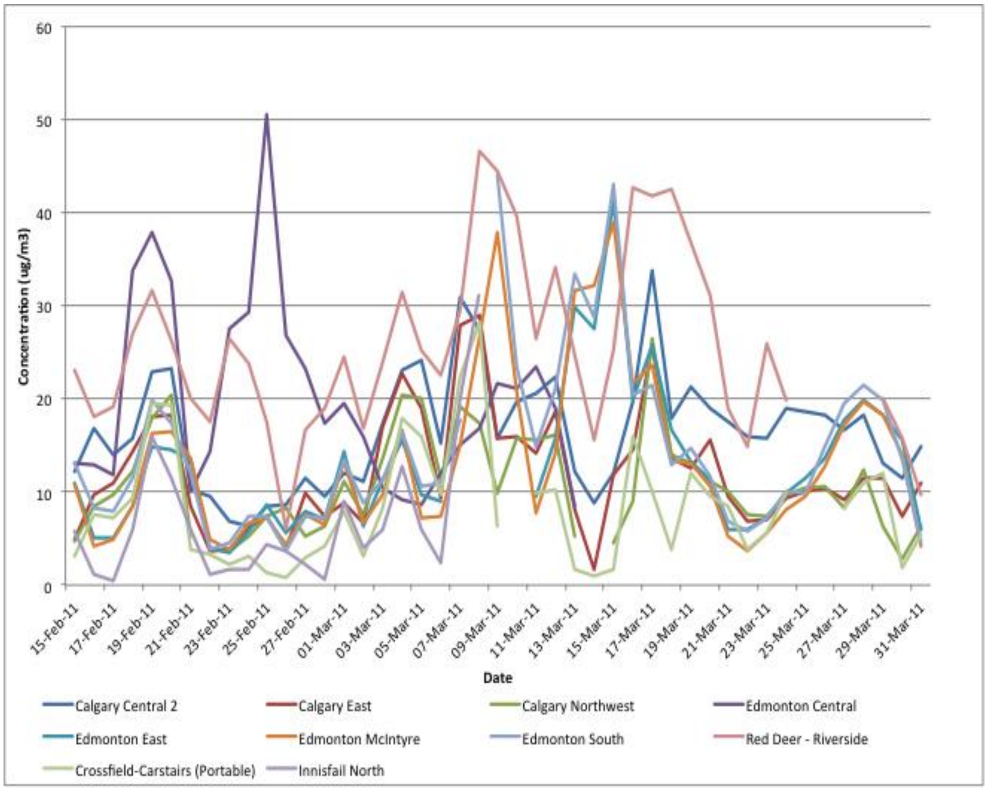

Figure 24: Twenty four hour averaged fine particulate matter concentrations between February 15, 2011 and March 31, 2011 at 10 air quality monitoring stations in Edmonton, Calgary and Red Deer.

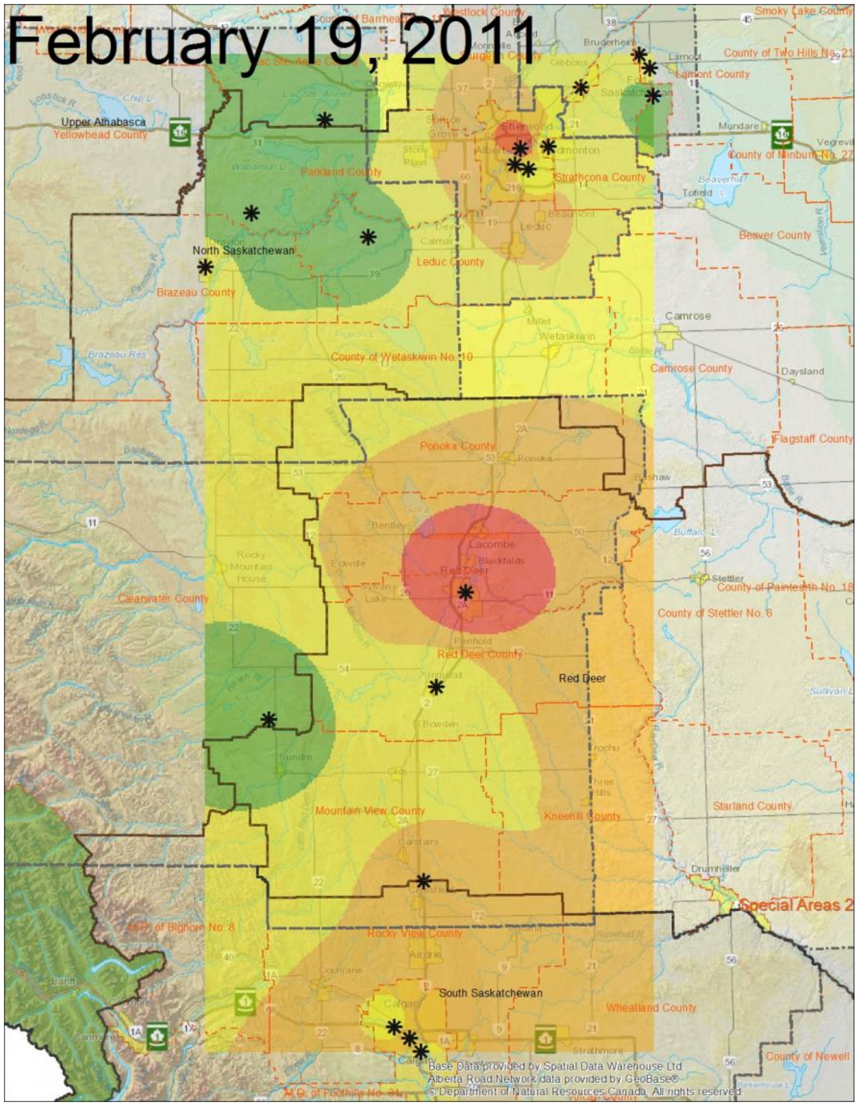

Figure 25: Spatial distribution of fine particulate matter concentrations as measured at air quality monitoring stations in the Edmonton-Calgary corridor on February 19, 2011. Spatial distribution determined by nearest neighbour interpolation, therefore distribution is most accurately defined in areas with a greater density of air quality monitoring stations. Ambient concentrations of fine particulate matter in rural areas away from air quality monitoring stations are most likely over-estimated.

Based on information presented in section 4.1 of the Capital Region Fine Particulate Matter Science Report (AESRD, 2015), regarding the speciation of fine particulate matter on event days in the Capital Region, the majority of fine particulate matter is composed of secondary species. Of the secondary species, ammonium nitrate and organic matter are dominant. An important precursor to ammonium nitrate is nitrogen dioxide. Therefore, while the species composition of fine particulate matter is unknown in Red Deer (due to the fact that it has not been assessed) investigating the distribution nitrogen dioxide emissions and observed nitrogen dioxide concentrations in the Red Deer area may inform where these precursor gases are highest and most likely to contribute to secondary particulate matter formation.

To assess the spatial distribution of nitrogen dioxide in the vicinity of the City of Red Deer, data from the Parkland Airshed Management Zone passive monitoring station network was utilized. Montly averaged nitrogen dioxide concentrations from 32 passive monitoring stations for the winters (October-March) of 2009, 2010, and 2011 (this period was selected as it coincides with the Clean Air Strategic Alliance Particulate Matter and Ozone Framework Assessment period that initiated the investigation documented within this science report) were plotted in ArcGIS (Figure 26). A spatial average using nearest neighbour interpolation was used to interpolate concentrations between the passive monitoring stations in order to characterize the spatial distribution of nitrogen dioxide in the Red Deer Area. The highest concentrations of nitrogen dioxide were found within the City of Red Deer and the immediate area (e.g. central Red Deer County, south-central Lacombe County, Town of Blackfalds, City of Lacomb; Figure 26). Concentrations quickly dropped with distance from the City of Red Deer (Figure 26). These observations are consistent with section 1.3.2.1 which identified non-point source precursor emissions to be highest within the City of Red Deer. Additionally, several point sources of varying size can be found within the City of Red Deer and immediate area.

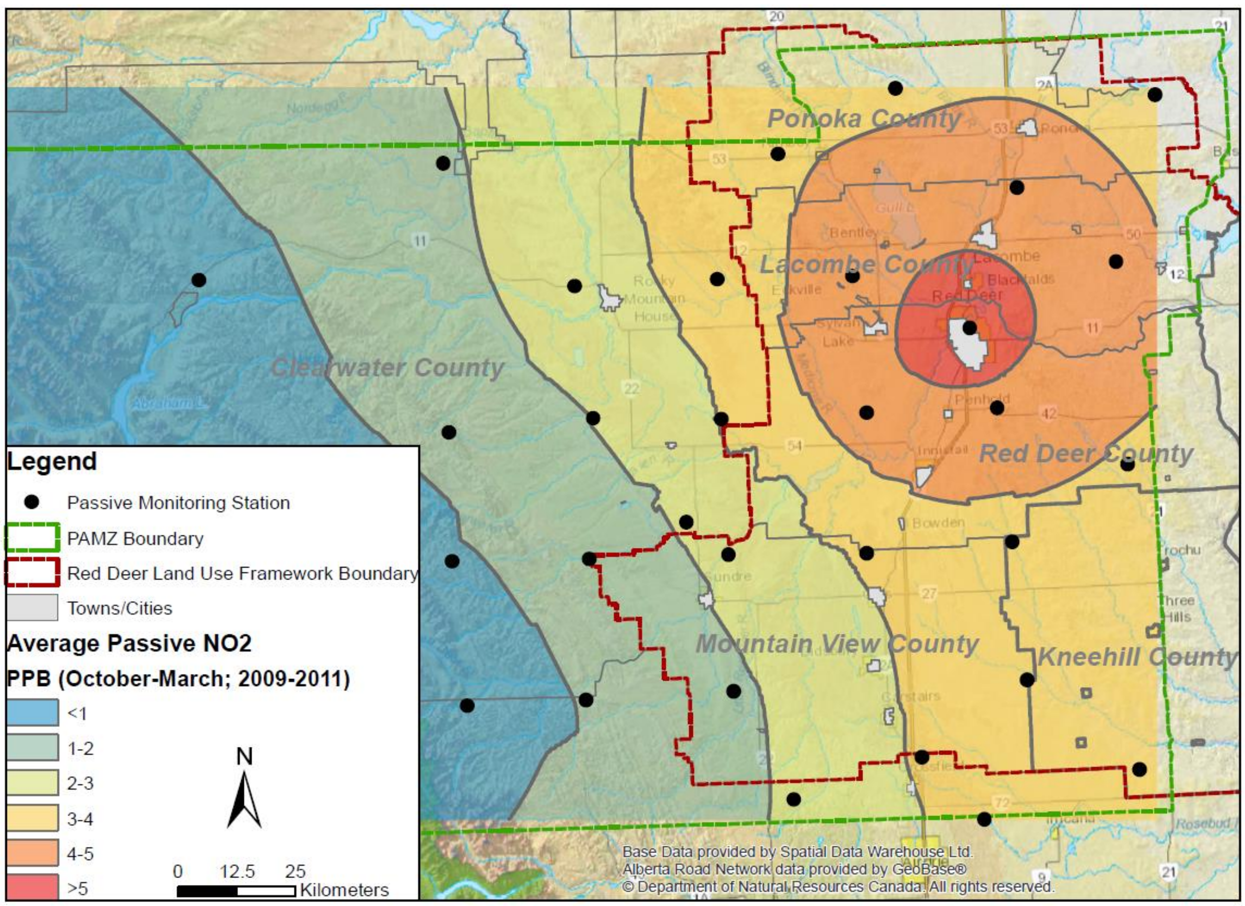

Figure 26: Spatial distribution of averaged monthly nitrogen dioxide concentrations as measured at 32 passive monitoring stations in the Parkland Airshed Management Zone. Measurements from October-March of 2009, 2010 and 2011 were averaged. Spatial distribution determined by nearest neighbour interpolation.

Red Deer Riverside monitoring station experiences fine particulate matter event days concurrent with monitoring stations in other locales known to suffer from wintertime fine particulate matter concentrations driven by secondary particulate matter species. With high concentrations of nitrogen dioxide emitters in the Red Deer area, corroborated by monitoring data, it appears likely that fine particulate matter concentrations at Red Deer Riverside monitoring station are influenced by secondary particulate matter formation. This conclusion is supported by the discussion in section 3.1 which identified monitoring based evidence suggesting the existence of volatile fine particulate matter species at Red Deer Riverside monitoring station. An assessment of secondary fine particulate matter species, through measurements at Red Deer Riverside monitoring station, is needed to confirm this assumption.

3.3.2. Transportation related emissions from nearby sources: Evidence for secondary fine particulate matter formation

Red Deer Riverside monitoring station is located approximately 20 metres away from an industrial collector road, Riverside Drive (Figure 11). This road services an industrial area and since May 2009 has acted as a conduit for traffic to and from the City of Red Deer civic yards, which was constructed 600m North of Red Deer Riverside monitoring station in 2009 (Figure 11). Primary fine particulate matter is released from motor vehicles as well as operations at the Red Deer civic yards and such emissions could have the potential to affect measurements at Riverside monitoring station considering the proximity of the station to the roadway and the City of Red Deer civic yards. The primary particulate matter emissions are in addition to the emission of known secondary particulate matter precursors from the combustion of fuels used by vehicles travelling on Riverside Drive or within the City of Red Deer civic yards. Two investigations were completed to determine the impact of transportation related emissions on the observed fine particulate matter concentrations at Red Deer Riverside monitoring station and are documented below.

3.3.2.1. Parkland Airshed Management Zone NOVUS Environmental Report

NOVUS Environmental completed a study of the Red Deer Riverside monitoring station, which in part aimed to determine whether operations at the City of Red Deer civic yards, or traffic on Riverside Drive may have resulted in the observed fine particulate matter events (NOVUS Environmental, 2012). The conclusions from this report provide insight into the potential impact these particular nearby sources may have had on the observed fine particulate matter concentrations at Red Deer Riverside monitoring station.

The report approached the investigation as a modelling exercise. NOVUS Environmental compared modelled transportation related emissions on roads nearby Red Deer Riverside monitoring station prior to the construction of the City of Red Deer civic yards and after the opening of the City of Red Deer civic yards. Fine particulate matter emissions were estimated and modelled from traffic counts on two roadways (Riverside Drive and 77 Street) in the vicinity of Red Deer Riverside monitoring station as well as estimates of emissions based on anticipated operations at the City of Red Deer civic yards (NOVUS Environmental, 2012). These emissions were modelled in CALPUFF and the resultant fine particulate matter concentrations were compared to actual observations. The model did not attempt to provide a species breakdown of fine particulate matter, therefore the results of the study only speak to the relative impact of these emission sources on the monitoring station. The results do not enable conclusions to be drawn as to whether the impact is from primary or secondary fine particulate matter produced as a result of the modelled activities.

The report determined that as a result of the construction of the City of Red Deer civic yards, traffic in the vicinity of Red Deer Riverside monitoring station increased, resulting in an estimated 13-20% increase in fine particulate matter concentrations at Red Deer Riverside monitoring station (NOVUS Environmental, 2012). The increase was found to be attributed to the increase in motor vehicle traffic along Riverside Drive, whereas the addition of bus traffic to the nearby roads was determined to not be significant. The report concluded that while a modest increase in fine particulate matter concentrations likely occurred due to increased traffic after the construction of the City of Red Deer civic yards, the increase was not of sufficient magnitude to have resulted in the high concentrations noted in the 2008-2010 Clean Air Strategic Alliance Particulate Matter and Ozone Management Framework assessment (NOVUS Environmental, 2012). Therefore the fine particulate matter mass attributable to increases in traffic along Riverside Drive corresponds to only a small fraction of that measured during event days, likely indicating that additional sources, other than just traffic emissions from Riverside Drive, 77 Street and emissions from operations at the City of Red Deer civic yards, are responsible for contributing to event day concentrations.

3.3.2.2. Environment and Parks investigation

To further explore whether the observed fine particulate matter events at Red Deer Riverside monitoring station may have been the result of the station's siting near Riverside Drive an investigation was also carried out by Alberta Environment and Parks. This investigation compared air quality and meteorological measurements at Red Deer Riverside monitoring station to traffic distributions from Riverside Drive in an effort to determine whether emissions from vehicular traffic may have resulted in the fine particulate matter events observed at Red Deer Riverside monitoring station. Traffic distributions from other nearby roads were also included in this investigation to explore the impact of traffic emissions from larger, more distant roads on Red Deer Riverside monitoring station.

Traffic data were obtained for three roads near Red Deer Riverside monitoring station (Figure 27, Table 2). This data consisted of an hourly count of vehicles travelling both ways along a given segment of each selected roadway. While not a measure of emissions produced by the vehicles travelling on the roadway, traffic count data are an appropriate proxy for transportation related emissions as they show the distribution of potential emission sources present along each roadway (i.e. individual vehicles) over time (e.g. more vehicles equates to more emissions). The road names, classifications, traffic count measurement locations and data sources for each of the three roads are contained in Table 2. The traffic count measurement locations in reference to Red Deer Riverside and Red Deer Lancaster monitoring stations are shown in Figure 27.

Table 2: Traffic count locations and metadata

Road Name	Classification	Location w/r to Riverside Monitoring Station	Traffic Count Location	Data source
Riverside Drive	Collector	Approx 20m West	Between 67th Street and Olymel Access	Novus Environmental Report (Counts data from 2009; Novus Environmental, 2012)*
Gaetz/50th Avenue	Arterial	Approx 1.6km Southwest	Between 67th and 68th Street	Stantec in October 2003 for Tues-Thurs window, and data were provided by the City of Red Deer*
Queen Elizabeth II Highway	Highway	Approx 5.1km Northwest	0.1km North of Highway 11A interchange	Alberta Transportation and an average of all Winter (Oct-Mar) weekdays from 2009-2010 were used in the investigation**

*These data sources represent the most recent data available for these roadways. Development in the area has been limited and land use patterns have not changed substantially since the measurement of this data, therefore these data are expected to representative of current traffic distribution. ** Data are available to current, however this data period was selected as it coincides with the observation of high fine particulate matter events at Red Deer Riverside monitoring station.

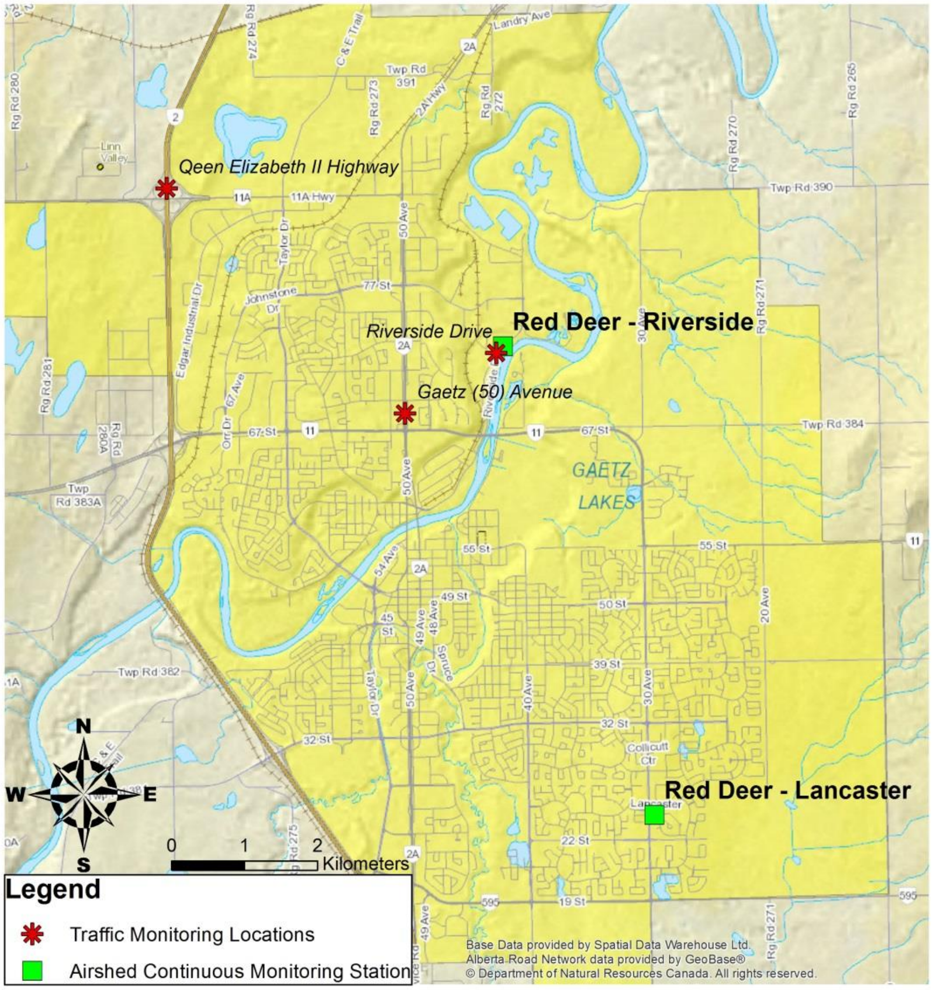

Figure 27: Locations of traffic monitoring locations in relation to Red Deer Riverside and Red Deer Lancaster air quality monitoring stations.

Riverside Drive is an industrial collector road with relatively light traffic (Figure 28 and Figure 29). The inclusion of larger, nearby roadways was to develop a comparison between Riverside Drive and other roadways in the City of Red Deer, as well as to establish the magnitude of transportation related emissions at other locations within the city. All three roads shared similar diurnal traffic distributions with peak volumes occurring around the afternoon rush hour (Figure 28 and Figure 29). Morning peak traffic volumes were somewhat more modest in comparison to the afternoon peak in all cases (Figure 28 and Figure 29). Midday traffic volumes on Riverside Drive and Queen Elizabeth II Highway initially dropped below the volume observed during the morning peak and subsequently rose back to the afternoon peak traffic volume (Figure 28 and Figure 29). Midday traffic volumes on Gaetz/50th Avenue were varied but generally increased in a linear fashion from the morning rush hour volume to that of the afternoon rush hour volume (Figure 28 and Figure 29). All three roads service zones of commercial and industrial development likely owing to the similar shape of their overall traffic volume distributions. Total traffic volume however was much greater on Gaetz/50th Avenue and Queen Elizabeth II Highway than on Riverside Drive, by a factor of five (Figure 28 and Figure 29).

Traffic volume distribution data were compared to air quality parameters at Red Deer Riverside monitoring station on event days and non-event days (137 event days and 515 non-event days were identified). Pollutants associated with transportation emissions were selected: fine particulate matter, total oxides of nitrogen, and carbon monoxide. Total oxides of nitrogen measurements were further speciated into nitric oxide and nitrogen dioxide concentrations to gain further insight into the potential sources of emissions measured at each station (oxides of nitrogen emissions from high temperature combustion, such as from internal combustion engines, are predominantly composed of nitric oxide; over time the nitric oxide is converted to nitrogen dioxide in the atmosphere). These data were also supplemented by the inclusion of wind speed data to help correlate meteorological influences on the observed concentrations. Overall, substantial differences in fine particulate matter, oxides of nitrogen and carbon monoxide concentration magnitudes were observed between event and non-event days. Specifically, concentrations of fine particulate matter, oxides of nitrogen and carbon monoxide were approximately 2.5, 1.9 and 1.5 times higher at Red Deer Riverside monitoring station on event days (Figure 28) than on non-event days (Figure 29). Additionally, wind speeds were, on average, higher on non-event days with a higher degree of variation between diurnal minimum and maximum speeds (Figure 28 and Figure 29).

At Red Deer Riverside monitoring station, two distinct peaks in fine particulate matter concentrations were evident, one morning peak (near the end of the morning rush hour) and a late evening peak, around 9-10PM on both event (Figure 28) and non-event (Figure 29) days. Strong morning peaks in oxides of nitrogen and carbon monoxide concentrations were observed at Red Deer Riverside on event (Figure 28) and non-event (Figure 29) days. Smaller, less pronounced increases in oxides of nitrogen and carbon monoxide concentrations were also observed during the evening hours. These evening increases were most pronounced on event days and remained substantially smaller than the associated morning peaks (Figure 28 and Figure 29). Of the components of oxides of nitrogen, nitric oxide comprised a significantly larger component during the morning peak than at any other time, and comprised a substantially larger fraction on event days (Figure 28) than on non-event days (Figure 29). Wind speeds were generally stable during the night-time hours with broad peaks during the daylight hours with maximums centered near solar noon. These patterns are consistent with sunlight driven mixing of the atmosphere (Figure 28 and Figure 29).

At Red Deer Riverside monitoring station, median fine particulate matter concentrations co-vary in a pattern similar to oxides of nitrogen and carbon monoxide concentrations. However this pattern is offset, resulting in peaks in fine particulate matter occurring as much as 4 hours after peaks in oxides of nitrogen and carbon monoxide (Figure 28 and Figure 29). Fine particulate matter concentrations do not co-vary with traffic. The lack of association of fine particulate matter concentrations with traffic counts suggests that primary fine particulate matter emissions from the traffic on Riverside Drive are not resulting in the fine particulate matter events at Red Deer Riverside station. Instead it is likely that emissions of precursor gasses, susceptible to producing secondary fine particulate matter, are driving fine particulate matter concentrations at Red Deer Riverside station; several observations re-enforce this assumption. Peaks of oxides of nitrogen and carbon monoxide, especially those associated with the morning rush-hour, increase nearly simultaneously with traffic volume while fine particulate matter concentrations increase after a lag of as much as four hours (Figure 28 and Figure 29). This lag may be due to the formation of secondary particulate matter from transportation related precursor gases. Due to the time of formation associated with secondary particulate matter, attribution of specific precursor emissions sources to measured fine particulate matter concentrations is difficult as even in relatively calm atmospheric conditions, some degree of transport has likely occurred. Speciation of oxides of nitrogen into its constituent components of nitric oxide and nitrogen oxides yields useful insight into the likely origin locations of these emissions. During the daytime, and especially at the morning peak, oxides of nitrogen concentrations are especially enriched in nitric oxide. Nitric oxide emitted in large quantities by transportation related sources, in addition to other combustion processes, and is oxidized by tropospheric ozone into nitrogen dioxide relatively quickly. The enrichment of the oxides of nitrogen with nitric oxide, specifically during times of elevated traffic volume likely indicates that transportation related emissions within the Red Deer area are likely a major source of precursor gases for the formation of secondary particulate matter. It is important to note that other combustion sources also exist in the Red Deer area, including industrial sources as well as those from home heating. Further investigation of the speciated oxides of nitrogen data is recommended to better characterize the potential distances of the sources emitting precursor gases. This may help identify the radius from which sources, transportation related or otherwise, may have the potential to influence the observed sine particulate matter events.

Meteorological phenomena have significant effects on the observed concentrations of fine particulate matter, oxides of nitrogen and carbon monoxide at Red Deer Riverside monitoring station. Temperature inversions are a very common meteorological phenomenon during the winter months, which typically result in calm atmospheric conditions near the surface of the earth around sunrise which give way to increased dispersion via atmospheric mixing driven by daytime heating. The increased frequency of temperature inversions during the winter months was shown by the Capital Region Fine Particulate Matter Science Report to influence the increased incidence of event days during the winter time. At Red Deer Riverside monitoring station, wind speeds are lower on event days (which are more frequent during the winter months) than on non-event days (Figure 28 and Figure 29). Additionally, stable wind speed conditions throughout the nighttime and into the morning, indicates that dispersion is being limited until wind speeds rise towards midday (Figure 28). These observations are consistent with the presence of inversions limiting dispersion to a greater degree on event days than on non-event days, resulting in higher concentrations of pollutants at Red Deer Riverside monitoring station. This process has the potential to be exacerbated in valley bottoms, where Red Deer Riverside monitoring station is located, due to atmospheric subsidence. At Red Deer Riverside station it is likely that the morning peak in fine particulate matter concentrations is related to reduced dispersion of pollutants (stable and low wind speeds) associated with a period of high transportation related emissions (morning rush-hour). The peak through the later evening hours is likely related to night-time cooling and set-up of a nocturnal temperature inversion which again limits dispersion (stable and low wind speeds) as transportation emissions begin to taper off from the evening rush-hour peak. It is evident that inversion conditions act to limit the dispersion of emissions and are likely a major contributor to the formation of secondary particulate matter. Other emission sources within the Red Deer area (ex. industry, home heating) are also likely to contribute to the formation of secondary fine particulate matter (as they release precursor gasses) and future research should be focused on determining their potential impact in conjunction with transportation emissions, especially through the understanding of the magnitude of these emissions and their diurnal variation.

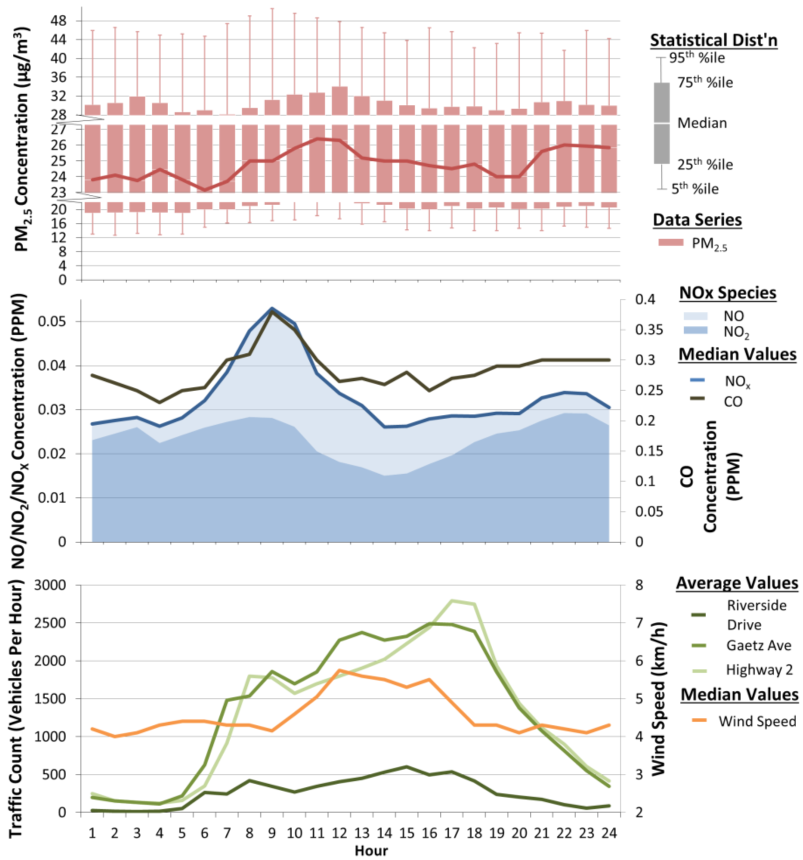

Figure 28: Event day diurnal variation of fine particulate matter, oxides of nitrogen, and carbon monoxide concentrations at Red Deer Riverside station in relation to wind speed data observed at this station and traffic counts within the city of Red Deer.

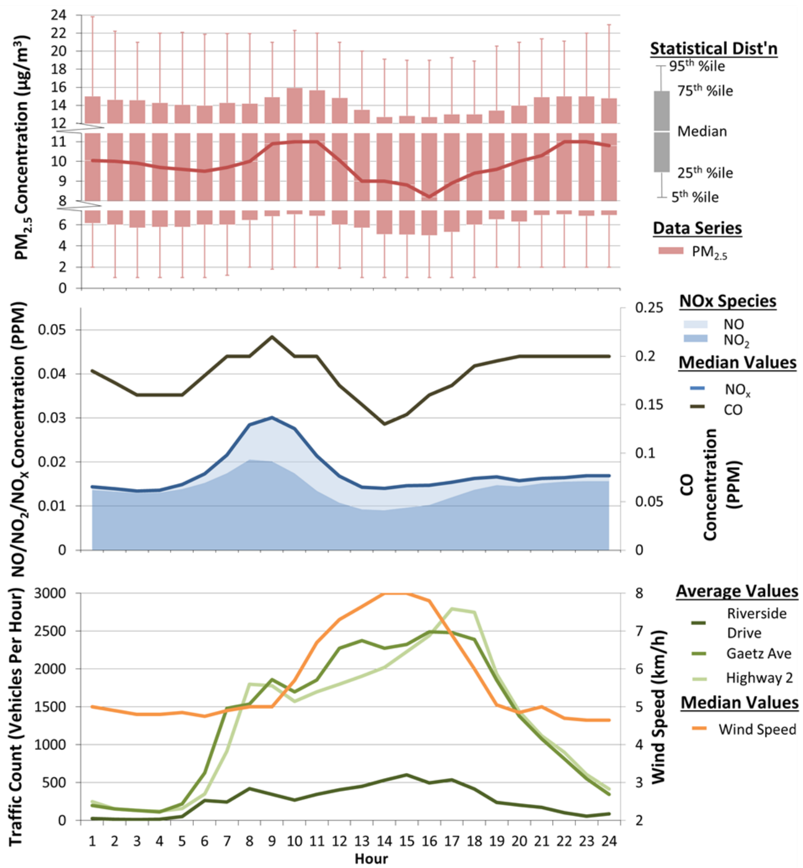

Figure 29: Non-event day diurnal variation of fine particulate matter, oxides of nitrogen, and carbon monoxide concentrations at Red Deer Riverside station in relation to wind speed data observed at this station and traffic counts within the city of Red Deer.

4. Summary

The work presented in the science report attempts to summarize the investigation, to date, in response to the exceedance of the Canada-wide Standard at Red Deer Riverside monitoring station. The science report analyzed historical data from Red Deer Riverside monitoring station, and in conjunction with supplementary information from other air monitoring stations in Alberta and the Capital Region Fine Particulate Matter Science Report, attempted to characterize the cause of the exceedance. Three main topics of discussion were identified through the investigative process and the conclusions reached, to the best that available data can support, are summarized below. Additionally, throughout the development of the science report, where knowledge gaps were identified recommendations for future investigations to address these gaps were formulated. These recommendations, prioritized to address the most significant gaps first, are summarized below.

4.1. Summarizing the three topics of discussion:

Measurement of particulate matter:

Changes in fine particulate matter monitoring technology at Red Deer Riverside monitoring station had a substantial impact on observed concentrations and a switch to newer monitoring methodologies was most likely a major contributing factor to the observation of the exceedance of the Canada-wide Standard. Newer methodologies for the measurement of fine particulate matter are more accurately able to account for volatile species, which were previously lost to volatilization prior to measurement in older instruments. Thus, the step change in concentrations of fine particulate matter after the adoption of newer analyzers is likely, in part, a reflection of the measurement of the volatile species of fine particulate matter at Red Deer Riverside for the first time. The volatile fine particulate matter species of ammonium nitrate and organic matter, both considered secondary fine particulate matter, are therefore expected to comprise a significant component the total fine particulate matter mass on events days; an observation consistent with fine particulate matter speciation measurements made in the Capital Region. Seasonal variations observed in the concentrations of fine particulate matter after the adoption of newer monitoring technologies also suggest that secondary fine particulate matter is a significant driver of fine particulate matter during the winter and comprises a much smaller component of total particulate mass during the summer.

Influence of meteorology:

Fine particulate matter concentrations vary on seasonal and diurnal temporal scales at Red Deer Riverside monitoring station. Fine particulate matter event days (concentrations greater than 19 $\mu g/m^3$) were observed to occur in all seasons but were most common during the colder months (October-March). Higher frequencies of fine particulate matter events in the colder months were also found in the Capital Region and were found to correlate with increased frequencies of meteorological phenomenon, such as temperature inversions. The correlation of event days with low wind speeds at Red Deer Riverside suggests that temperature inversions are likely important in the formation of event days as low wind speeds in the wintertime are most often associated with temperature inversions. Strong alignment of event day concentrations with southerly wind directions was likely a meteorological manifestation of wind channeling down the Red Deer River valley.

Evidence of secondary particulate matter and potential sources:

Determining the species composition of the event day fine particulate matter concentrations was not possible as speciation monitoring was not performed in Red Deer. However, specific investigations added strength to the conclusion that secondary fine particulate matter was driving event day concentrations in Red Deer. Red Deer Riverside monitoring station experiences fine particulate matter event days concurrent with other air quality monitoring stations in Edmonton, Calgary and their surrounding areas. Research from the Capital Region determined that fine particulate matter was dominantly formed through atmospheric reactions with nitrogen dioxide and volatile organic compounds to form secondary fine particulate matter species. Due to the high density of nitrogen dioxide emitting sources in Red Deer, verified through monitoring data, and the concurrent events observed along the Calgary-Edmonton corridor, secondary fine particulate matter species are expected to be driving fine particulate matter concentrations on event days. Major nitrogen dioxide emission sources in the City of Red Deer are related to transportation, thus determining the potential contribution of these sources to measured fine particulate concentrations was identified as being important to the development of appropriate management actions. A study completed for the Parkland Airshed Management Zone (NOVUS Environmental, 2012) indicated that transportation related sources in the vicinity (approximately 1-2 km from) Red Deer Riverside monitoring station had some impact on the observed measured fine particulate matter concentrations. Impacts were not large enough however to have caused the exceedance. Further analysis of fine particulate matter concentrations at Red Deer Riverside monitoring station, in conjunction with other transportation related pollutants and traffic volume measurements on major adjacent roads indicated that transportation related emissions were likely influencing secondary fine particulate matter concentrations. This conclusion was determined from the observed lag in fine particulate matter concentrations following traffic volume peaks. However, as the degree of impact of transportation related emissions on fine particulate matter concentrations was not explicitly quantifiable, other emission sources with similar potential to produce secondary fine particulate matter could not be ruled out as having an influence on observed event day concentrations.

4.2.Recommendations for future investigation

This investigations and discussions contained within the science report represent the current state of knowledge regarding fine particulate matter in the Red Deer area. Significant gaps remain, however. Specifically, many assumptions reached to date were based on corroborative evidence from other regions sharing similarities with Red Deer. In order to provide conclusive evidence, with which concrete and effective management actions for fine particulate matter can be developed, a number of recommendations for future work have been developed. These recommendation were developed in order to address significant gaps in the state of knowledge identified in the science report. Presented below is a prioritized list of recommendations anticipated to provide information to fill in knowledge gaps.

Recommendation	
Description	Rationale
Increase understanding of the species composition of particulate matter in the Red Deer air quality management area	
• Commence a sampling study in the Red Deer air quality management area to identify the species composition of particulate matter during event and non-event days.	Rationale: Speciation has not been measured in Red Deer. In order to confirm assumptions made in the science report, this assessment is essential.

Apportion fine particulate matter to sources in the Red Deer air quality management area	

• Undertake source apportionment modelling using CMAQ, separate from or in conjunction with ongoing work in the Capital Region. Additional specific investigations may include:
  ○ Investigate home heating emissions (including emissions impacts from different fuel types). Understand diurnal variations in home heating emissions with respect to fine particulate matter concentration variations.
  ○ Undertake a detailed analysis to determine whether variations in vehicle traffic due to changes in the local economy of Red Deer may impact fine particulate matter concentrations
	Rationale: The relationship between fine particulate matter concentrations and specific emissions sources in Red Deer is poorly understood. A sector based source apportionment would fill this gap by identifying key source sectors which have the most significant impacts on fine particulate matter concentrations. This initiative will help to implement current management actions and develop new management actions if gaps exist.

• Investigate NO to NO_2 conversion in order to contextualize the locality of emissions impacting Red Deer Riverside station. Understanding the degree of transport to which NO_x has undergone may allow for determining source contribution regions affecting Red Deer Riverside.	Rationale: The relationship between fine particulate matter concentrations and specific emissions sources in Red Deer is poorly understood. Contextualizing the measured NO_x emissions in terms of their NO and NO_2 components will help localize potential emission sources and aide in source apportionment.
Broaden the understanding of spatial and temporal variations of fine particulate matter and its precursors	
• Continue to investigate the suitability of using RDPS (Regional Deterministic Prediction System) Output (a meteorological model capable of predicting atmospheric stability) to identify temperature inversions over Red Deer and integrate these results into future investigations if determined to be suitable.	Rationale: Upper air soundings are not available in Red Deer therefore determining the impact of inversions is reliant on other meteorological information. Characterization of the suitability of the RDPS meteorological model output to the Red Deer area will help provide more confidence in establishing the link between fine particulate matter event days and atmospheric temperature inversions.

Broaden the understanding of spatial and temporal variations of fine particulate matter and its precursors	
• Investigate influence of large scale (100s of km) meteorological systems on multi-station fine particulate matter events in order to better understand conditions favorable for fine particulate matter event days.	Rationale: Multi-station fine particulate matter events were observed across the Edmonton-Calgary corridor. Observations from monitoring stations suggest similar meteorological phenomena are driving these events. However, no investigation of large-scale phenomena have been performed to date, leaving a gap in knowledge.
• Investigate the potential for terrain to influence meteorology in the Red Deer area and determine what influence this may have on fine particulate matter concentrations. A modelling investigation may be most suited to this question.	Rationale: Terrain effects are recognized in meteorology and air quality science and the City of Red Deer, along with associated air quality monitoring stations, sit below two large ridges and within a substantial river valley. The effect of these terrain features has not been characterized.

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