2016

Spatiotemporal Variation of PM2.5 in the Central Okanagan Region

Final Report

November 30, 2016

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Executive Summary

Based on long-term monitoring data, air quality in the Central Okanagan is generally good. However, research indicates that, although ambient air quality is meeting standards, specific neighbourhoods may reach unhealthy levels due to wood stoves and proximity to major roads. This study was designed to identify possible hot spots of $PM_{2.5}$ in the region, and to further investigate whether $PM_{2.5}$ measurements from a single monitoring station at Okanagan Collage in Kelowna can adequately represent the entire Central Okanagan region. The project design and data collection involved both mobile and fixed-site monitoring.

Mobile monitoring was conducted by running DustTrak and GPS instruments inside a vehicle. The vehicle was driven 26 times along predetermined routes under a range of venting conditions and times of day, from November 2015 to April 2016. The route was designed considering the density of wood stoves in the region, land use, arterial and major roads, and a previous 2005 CRUISER study. The route was 213 km in length and covered the City of Kelowna, District of Peachland, City of West Kelowna, Westbank First Nation, District of Lake Country and the Regional District of Central Okanagan (RDCO) East rural area. More than 106,000 individual measurements were collected.

Results indicate that the $PM_{2.5}$ spatial distribution varies seasonally and diurnally. There were several areas that consistently had higher $PM_{2.5}$ values than surrounding areas. These areas were defined as both major and minor hot spots. The biggest hotspot was found in the Rutland area from data collected on Highway 33, Hollywood and Rutland road, followed by the Mission (Okanagan view) and Lake Country (Woodsdale) areas.

Stationary monitoring was conducted by alternating an E-BAM instrument between two locations: Johnson Bentley Memorial Aquatic Centre in West Kelowna and City Hall in downtown Kelowna from October 2015 to April 2016. Hourly measurements provided 92 and 86 $PM_{2.5}$ daily averages from the temporary sites in West Kelowna and Downtown Kelowna, respectively. Comparing paired $PM_{2.5}$ daily averages, regression analysis shows good correlation between the Downtown Kelowna site and Kelowna College station, whereas the West Kelowna site shows a moderate correlation. Furthermore, the trends in $PM_{2.5}$ daily averages are found to be fairly similar between the temporary sites and Kelowna College throughout the stationary monitoring periods.

In addition to temporal similarity, further statistical analysis was incorporated to explore spatial uniformity in $PM_{2.5}$ concentrations: the coefficient of divergence (COD) as a relative measure of homogeneity, and the 90th percentile (P_{90}) of the differences between the sites' 24-hr concentrations as an absolute measure of homogeneity. Such analysis reveals spatial uniformity in $PM_{2.5}$ between Kelowna College station and the Downtown site, based on a COD value of 0.156 and a P_{90} value of 3.5 µg/m^3. However, with higher COD of 0.202 and P_{90} of 4.6 µg/m^3, $PM_{2.5}$ tends toward non-uniformity between West Kelowna and Kelowna College.

Over the duration of the stationary monitoring, whereas the 24-hour Provincial Objective for $PM_{2.5}$ of 25 µg/m^3 was never exceeded at Okanagan College station, measurements at the temporary monitoring sites revealed two exceedance events. On January 6^{th}–7^{th} of 2016, the $PM_{2.5}$ 24-hour rolling average exceeded the provincial objective for a total of 35 consecutive hours in Downtown Kelowna, and on February 12^{th} an exceedance lasted for 20 consecutive hours in West Kelowna. While the latter event was likely triggered by a nearby open-burning activity, the Downtown event may possibly be attributed to local sources as well as differences in local meteorological conditions.

Based on this study, longer-term, continuous monitoring at stationary locations would be recommended, especially within the identified major hot spots. Consideration can be made to the development and implementation of stringent policy for wood appliances in the region. Furthermore, educational efforts on wood burning practices could be redirected to neighborhoods with potentially high $PM_{2.5}$ exposure, such as the Rutland area.

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Introduction

The air quality in the Central Okanagan is generally good, as measured levels of pollutants rarely exceed provincial and national standards and objectives for ambient air quality. However, specific events can lead to levels of pollutants that can exceed those levels – particularly when smoke from forest fires gets trapped, as shown in Figure 1. Furthermore, emerging research indicates that although ambient air quality may be meeting all standards and objectives, specific neighbourhoods may reach unhealthy levels (e.g. neighbourhoods with higher concentrations of wood stoves, or residences along major traffic corridors). With continued population growth in the region, these pressures are expected to increase, unless appropriate measures are put into place to mitigate the effects of this growth.

Figure 1. Smoke from a forest fire, Kelowna, June 2015

The Central Okanagan has a large population that is served by one air monitoring station, located in the Okanagan College. An assessment of the BC air quality monitoring network identified that the Thompson/Okanagan region appears under-represented in monitoring particulate matter that is 2.5 microns or less in diameter, called $PM_{2.5}$, and PM_{10} relative to other regions and the total emissions (Hafner & Penfold, 2007). The same report also identified Kelowna as under-represented for the number of air quality monitoring stations based on its population. Figure 2 illustrates the urban populations of communities across BC (outside the lower mainland) and the number of air quality monitors they are served by, demonstrating the Kelowna has a low number of stations relative to its population.

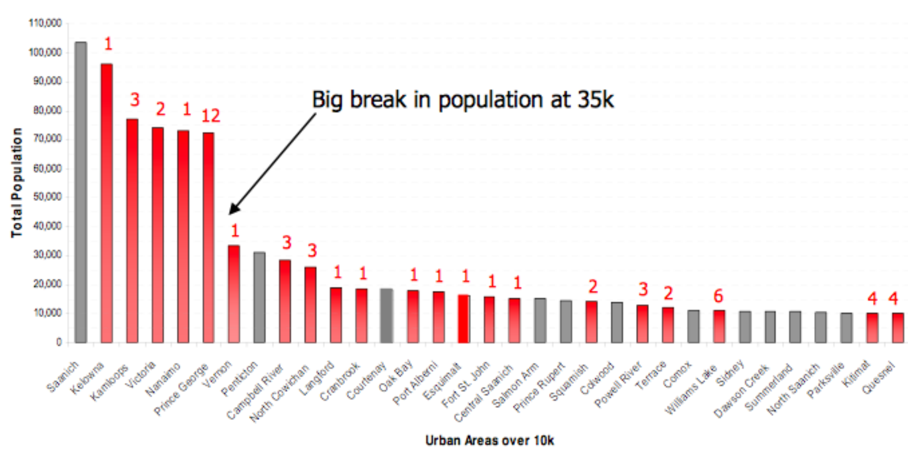

Figure 2. Community (urban) population annotated with monitor coverage. Red—monitor present (number represents count of monitors); grey—no monitor within community. There are 74 monitors in areas under 10,000 (small towns, rural areas).

The first comprehensive air monitoring station was officially opened in Kelowna in 1994. The pollutants measured in the Central Okanagan airshed, are H_2S Hydrogen sulfide, $PM_{2.5}$, PM_{10}, sulphur dioxide (SO_2), nitrogen oxides (NO_X), ozone (O_3), and carbon monoxide (CO). This station has been upgraded through the years. A Tapered Element Oscillating Microbalance (TEOM) monitor for PM_{10} was installed in the Kelowna College since 1998. Ministry of the Environment (MoE) installed a number of different Synchronized Hybrid Ambient Real-time Particulate monitor (SHARP) units at the Kelowna Station, which were discontinued due to technical difficulties. For the current unit in operation at the Kelowna Station, $PM_{2.5}$ monitoring and reporting was officially switched over from the TEOM to the SHARP in April 2014. The ambient air pollutants of greatest concern in relation to human and environmental health in the Central Okanagan are particulate matter and ozone.

Figure 3. Air Monitoring Station- Roof view Okanagan College

Figure 4. TEOM, NO_X, SO_2, O_3 equipment- Okanagan College

Particulate matter is linked with a broad range of health effects, primarily affecting the respiratory and cardiovascular systems, and impacts may occur from both short-term and long-term exposure. Recent reports from the World Health Organization (WHO) released in 2013, the International Agency for Research on Cancer, part of WHO, announced that it classified outdoor air pollution as carcinogenic to humans**.** Particulate matter was separately evaluated by WHO and was also classified as carcinogenic to humans (WHO, 2013).

Ozone primarily affects the respiratory system causing shortness of breath, coughing, inflammation, and can trigger conditions such as asthma and bronchitis when it is present at ground-level (as opposed to the “ozone layer” in the stratosphere that protects us from ultra-violet radiation). People with respiratory problems are particularly vulnerable to negative effects of ozone, and are advised to limit outdoor exercise and exposure during periods of elevated ozone. Elevated ozone can also adversely impact plant growth and ecosystem health.

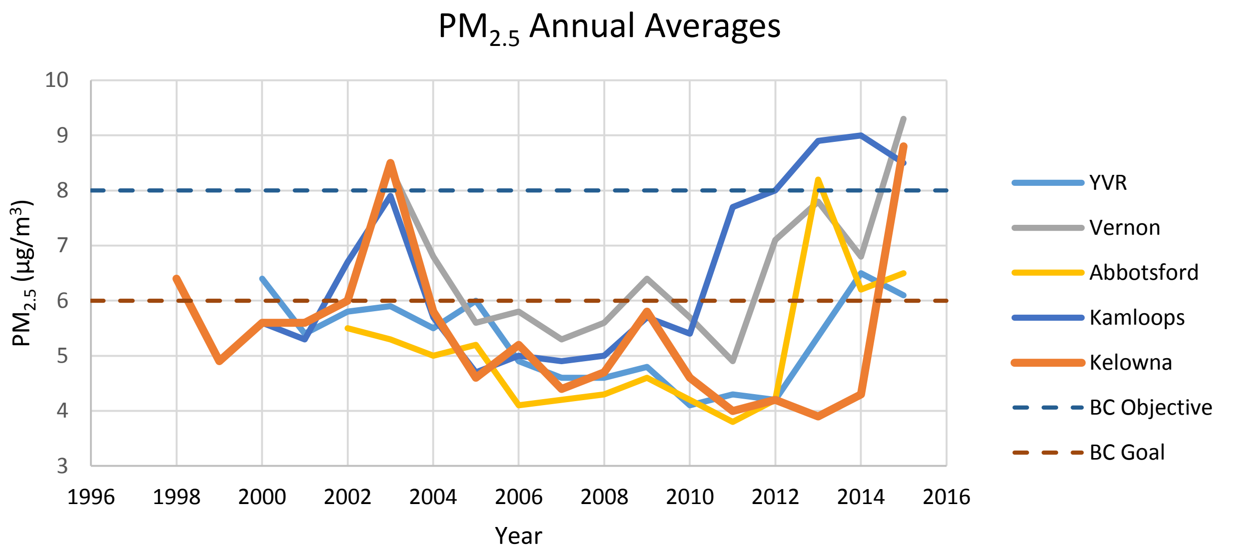

Figure 5. Fine Particulate matter ($PM_{2.5}$) levels at select BC locations (1998-2015) using Annual Averages

Figure 5 and Figure 6 show levels of fine particulate matter in Kelowna compared to select BC municipalities. The highest levels of particulate matter were recorded during years with extensive forest fires; the $PM_{2.5}$ Annual Average values exceeded the BC objectives and goals in Kelowna in 2003, 2004 and 2015. Note that although the Canada Wide Standard is not exceeded, levels of $PM_{2.5}$ do occasionally measure in above that pollution level. During the 2003 forest fire, there were 17 24-hour periods that measured above the Canada Wide Standard. More recently in 2015, there were high values recorded in Kamloops and YVR (Vancouver International Airport).

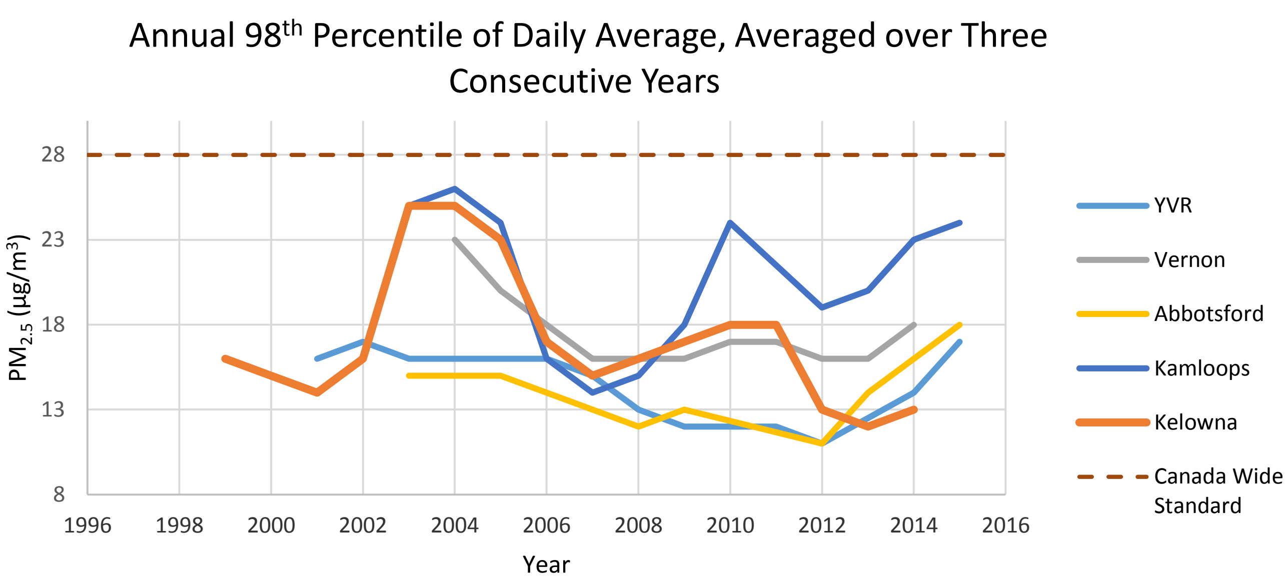

Figure 6. Fine Particulate matter ($PM_{2.5}$) at select BC locations (1999-2015) using 24-hour Canada Wide Standard*

*The Canada Wide Standard for Particle matter is 28 $\mu g/m^3$-Achievement based on annual 98th percentile of daily average, averaged over three consecutive years.

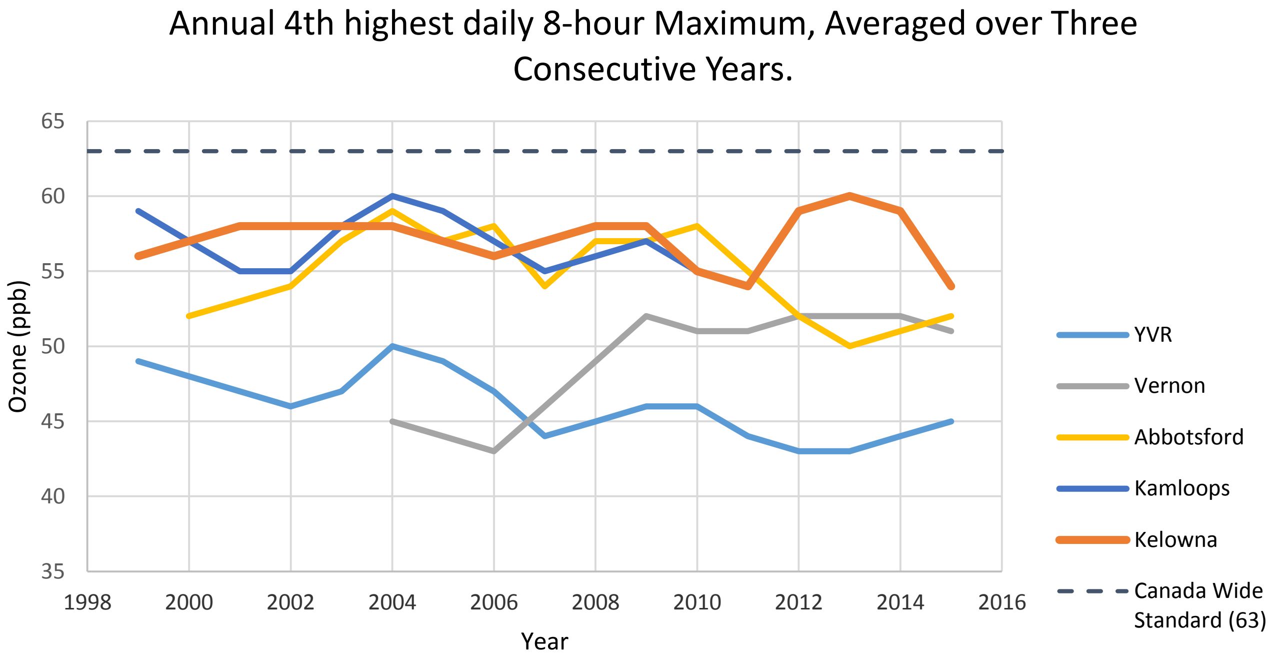

Figure 7. Ozone levels at select BC locations (1999-2015) using the 8-hour Canada Wide Standard*

* Canada Wide Standard for Ozone is 63ppb- Achievement based on annual 4th highest daily 8-hour maximum, averaged over three consecutive years.

Air quality advisories in the Central Okanagan are issued by the Ministry of Environment (MoE) when levels exceed and are expected to continue exceeding the BC ambient air quality objective of 25µg/m^3 or 50µg/m^3 (based on a 24 hour rolling average) for $PM_{2.5}$ and PM_{10} respectively. However, over the past 10 years, no Air Quality advisories have been issued for the Central Okanagan in the months excluding the wildfire season.

For the summer months around the wildfire season, it is difficult to discern those advisories that would specifically apply to the Central Okanagan, as Smoky Skies (and previously Smoke) advisories usually apply to large geographical areas that might include a certain region. There was a single Air Quality advisory issued on July 12, 2012 due to high Ozone levels in Kelowna.

Background

Airshed Management in Central Okanagan

In 2006 a study by Environment Canada stated that sustained air quality improvements will yield substantial cumulative benefits associated with avoided health effects occurring over multiple years. For the Central Okanagan the quantifiable annual benefits estimates associated with a 10% improvement in $PM_{2.5}$ are $16,646,630 with additional unquantifiable benefits- including impacts in tourism and on local area residents associated with visibility improvements, adverse effects on important local agricultural crop yield, impacts in forestry, wildlife health, and other effects that are difficult to quantify but which may be substantial (Parker, 2006). In 2007, the Regional District of Central Okanagan created an Airshed Management Plan with the aim of reducing the impact of air pollutants in the region. Several actions were implemented through the following years:

- smartTRIPS neighborhood program, engaged Pandosy and Spring Valley neighborhoods in sustainable transportation initiatives, with the goal of increasing biking, walking, transit ridership, carpooling, and other smart options.
- Anti-idling program including anti-idling street signs and decals, school based and corporate based campaigns (2011).
- Community Energy and Emissions Plans / Climate Action Plans developed in Kelowna, Peachland and Lake County (draft) that include goals to reduce emissions from transportation and improve transit and active transportation within their respective jurisdictions.
- Agricultural Wood Waste Chipping Program: Since 2004 the RDCO has offered a free program for orchardists who choose to chip wood waste into mulch as an alternative to burning it. Since the program started, over 70,000 cubic meters of wood have been composted instead of being burned, resulting in almost 1,000 tonnes of avoided particulate matter emissions, and avoiding the health-related repercussions of these emissions per year.
- In 2010, the Regional Waste Reduction Office and the City of Kelowna set up a Commercial Diversion Program in response to a study that indicator approximately 50% of solid waste from local businesses, institutions and multi-family properties could have been diverted. Education was followed up with increased monitoring and scrutiny of loads and surcharges at the landfill.
- Open Burning Information Line (September 2011)
- RDCO Bylaw No. 1066 now requires a venting index of 65 or greater and particulate matter ($PM_{2.5}$) concentration less than 15 $\mu g/m^3$ for outdoor burning (August 2011). RDCO Regional Smoke Control Bylaw No. 773 (created 1998, amended 2011)
- Municipal open burning bylaws:
    - City of Kelowna, bylaw 10760
    - District of Lake Country, bylaw 612
    - District of Peachland, bylaw 1718
    - District of West Kelowna, bylaw 0114

- WFN Fire Protection Law No. 2005-11
- Outdoor Power Equipment Institute of Canada (OPEIC) Recycling Program drop off locations in Kelowna
- Woodstove Exchange Program for RDCO residents (2001 to present). The Province provided funding to the region through the Woodstove Exchange program from 2001 to 2016 that resulted in the removal of 687 inefficient wood stoves from the Central Okanagan.

After five years of implementation, an assessment of the progress made in managing activities that impact local air quality was performed and a new Clean Air Strategy was updated in 2015. Sixteen main strategies were identified, as shown in Table 1.

Table 1. 2015 Clean Air Strategies

Sustainable Transportation	
Walking, cycling, public transit, carpooling and clean vehicles are the most accessible, affordable and efficient ways to get around.	
1	Integrate air quality requirements and targets into transportation and land use plans
2	Develop and deliver programs to encourage sustainable modes of transportation
3	Reduce emissions from vehicles on the road
Green Industry	
Commercial, forestry, agricultural and other industrial operations across the region make decisions that keep our air clean and clear.	
4	Reduce emissions from commercial fleets and diesel equipment
5	Aim to eliminate smoke from burning (agriculture, forestry & land clearing)
6	Manage pollutants from commercial operations
7	Regional coordination with industry
Clean Outdoor Activities	
Community members minimize air pollution from outdoor maintenance and recreation activities.	
8	Aim to eliminate backyard burning in residential neighbourhoods
9	Minimize pollutant emissions from yard maintenance activities
10	Minimize pollutants from recreation activities (ATVs, boats, etc.)
Green Buildings	
Buildings are energy efficient, use green energy, and keep our air clean and clear.	
11	Reduce and/or eliminate smoke emissions from home fireplaces and wood stoves
12	Address emissions from household products (e.g. cleaning and painting)
13	Support green building, renovations and renewable energy in homes
Better Information and Awareness	
Community decision makers, businesses and citizens have access to clear, accurate information to help us make the best decisions to keep our air clean and clear.	
14	Improve local air quality data and information
15	Make local air quality information accessible to decision makers
16	Make air information available to all citizens and businesses

This project supports the 2015 Central Okanagan Clean Air Strategy “14.2 Participate in research to improve understanding of key pollution sources”. Regional Services will encourage and participate in provincial, federal, and university-led research programs that increase local knowledge of key pollution sources in the valley.

Woodstove Inventory: Residential Wood Heating

Wood smoke can be a significant source of localized pollution. As shown in Figure 9, 30% of particulate matter ($PM_{2.5}$) in the Central Okanagan comes from residential wood burning. Sources of $PM_{2.5}$ are, based on the most recent air emissions inventory called the *Okanagan High Resolution Emission Inventory* conducted by RWDI for Environment Canada in 2010, and are largely based on Environment Canada data from 2006 (Garrat, 2014). Based on the 2003 provincial inventory MoE estimated 115,000 uncertified wood stoves in BC. In a 2012 survey MoE estimated 70,000 uncertified remaining. The decrease represents the passage of time (9 years) plus the effect of the Provincial Woodstove Exchange Program. According to MoE's survey there are 53,000 households in Kelowna and 29,000 more in the rest of the RDCO. Within Kelowna there would be about 5,300 in-use wood appliances 1,900 stoves, 3400 fireplaces and inserts. Within the rest of the Regional District 9,800 in-use wood appliances 5,400 stoves, 4,400 fireplaces and inserts. Total 7,300 stoves and 7,800 fireplaces and inserts in use – Total 15,100.

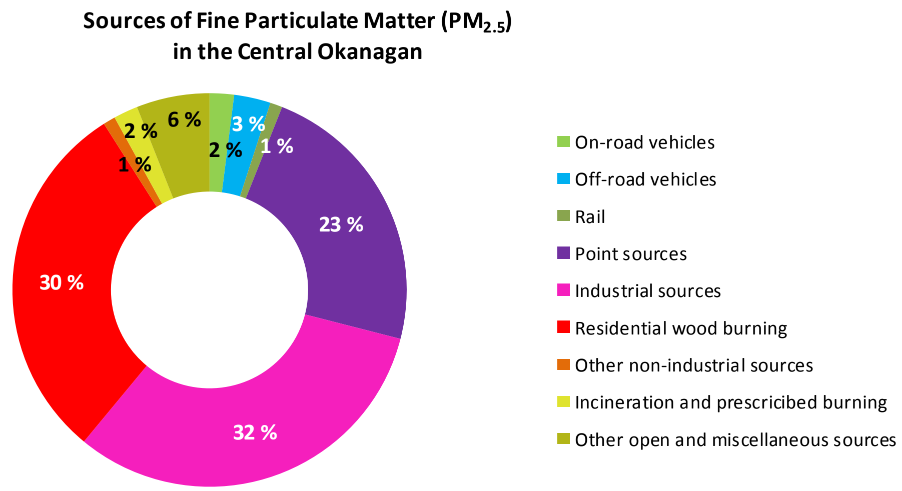

Figure 9. Sources of fine particulate matter ($PM_{2.5}$) in the Central Okanagan, Environment Canada data from 2006

Roughly there are 14,800 appliances in households that don't use them at all. Of the in-use fireplace/inserts, MoE personnel estimates 3,000 certified, 4,800 uncertified. Of the stoves, it is estimated 4,400 certified and 2900 uncertified. These percentages are based on the survey results. However, people do tend to over report stoves being "certified" as they like to think they are doing the right thing. MoE estimates that the true number could range between 4,000-12,000.

Figure 8. Wood stoves and Inserts in-use in the Okanagan, Source- Ministry od the Environment

The location of those appliances is difficult to determine. Data available is very limited per municipality. For example, Kelowna keeps electronic records of building permits (legal wood stoves installations) since 1995, but the other municipalities do not have the same capabilities. The availability of electronic records is variable in the other municipalities. The available database for the Central Okanagan region accounts for 1,674 (as of Dec 2015). The distribution per municipality of those appliances is shown in Figure 10.

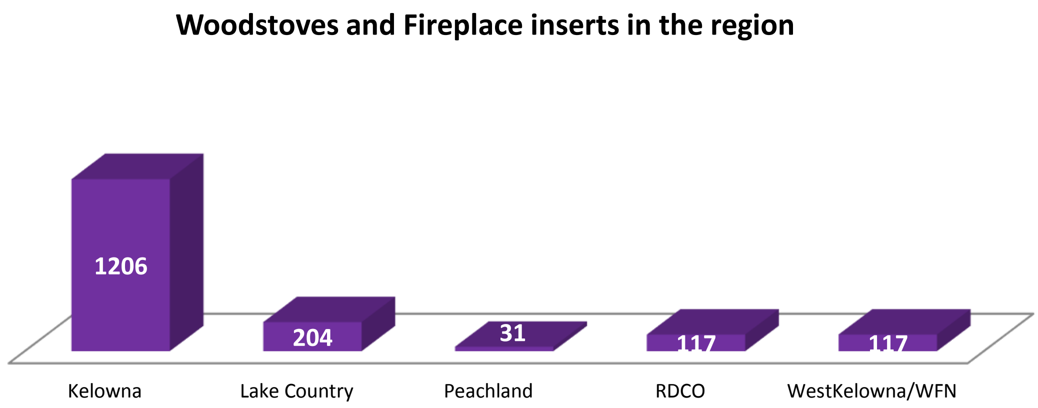

Figure 10. Wood stoves and Fireplace inserts by municipality

Since 2001, through precursor initiatives of the actual Woodstove Exchange Program, the Regional District of Central Okanagan has exchanged 687 old wood stoves in the region avoiding 44.2 tonnes of particulate matter getting into the local air shed every year. During 2012-2015, 28% of the complaints received were due to smoke from indoor appliances and 20% for open burning.

Open Burning

According to Bylaw 773[1] and Bylaw 1066[2], within the Regional District of the Central Okanagan, open burning requires a valid permit and is only allowed between October 1 and April 30. Open burning is only permitted when the Venting Index_is 65 or greater and particulate matter ($PM_{2.5}$) concentration is less than 15 µg/m^3. An average of 1,600 open burning permits is issued during Open burning season in the Central Okanagan.

Also, fuel modification projects are usually approved by local Fire departments. Fuel modification is the practice of a controlled burn of dead trees and other vegetation that has potential of becoming wild fire fuel in the hot summer season.

[1] Central Okanagan Smoke Control Bylaw 773
[2] Prevention of Fires Bylaw 1066

Vehicles in the Okanagan

Sources of fine particles include all types of combustion activities (e.g. motor vehicles, power plants, wood burning, etc.) An operating vehicle emits a range of gases from its tailpipe into the atmosphere, such as volatile organic compounds (VOCs), carbon monoxide (CO), and oxides of nitrogen (NO_X). All these emissions are known to contribute toward air pollution and smog (a combination of fine particulate matter, nitrogen oxides, sulfur oxides, volatile organic compounds and ammonia, which react in the presence of sunlight to form ozone, vapors and particles). Based on information provided by the Insurance Corporation of British Columbia (ICBC) and the 2013 Central Okanagan Household Travel Survey, it was estimated that the total number of vehicles (including passenger, commercial, motor homes, motorcycle, hybrids and electric vehicles) in the Central Okanagan was 142,112. Kelowna has the highest per capita vehicle ownership of 33 Canadian municipalities (Hollingworth, Mori, Cham, Passmore, & Irwin, 2010). Transportation modal share data indicates that private automobiles accounts for about 67% of all trips in the region. This percentage yields approximately 123,000 drivers on the road on a typical weekday (Villarreal, 2013).

Research has shown that there is no threshold below which $PM_{2.5}$ has zero health effects. This means that is important to minimize the amount of $PM_{2.5}$ sources produced and humans' exposure to it. The majority of health impacts from $PM_{2.5}$ result from extended exposure to concentrations below the level at which a public advisory would be issued (Kendall, 2003). The air quality in the Central Okanagan is generally good, as measured levels of pollutants rarely exceed provincial and national standards and objectives for ambient air quality. However, in recognition of the lack of a threshold for $PM_{2.5}$ levels, the Canadian Wide Standards contain a stipulation to "keeping clean areas clean" and "continuous improvements" in areas that are already meeting the standards, like the Central Okanagan.

Considering the amount of uncertified appliances still in-use and the increasing number of vehicles in the region, the RDCO wanted to take further steps to analyse if possible unhealthy levels of $PM_{2.5}$ could be found in specific areas thorough the region. This study will help the region to redirect its efforts to accomplish further air pollution reductions.

Population density

Numerous studies have linked elevated particle levels in the air to increased hospital admissions, emergency room visits, asthma attacks and premature deaths among those suffering from respiratory problems. Since children's lungs and respiratory systems are still developing, they are also more susceptible than healthy adults to fine particles (Etzel, 2009). Exposure to fine particles is associated with increased frequency of childhood illnesses and can also reduce lung function in children. In British Columbia, an estimated 25 to 250 deaths each year result from the short-term health impacts of degraded air quality. An estimated 130 to 1,300 hospitalizations, and 170 to 1,700 emergency room visits are also attributed to short-term degraded air quality in British Columbia. Nationally, an estimated 2,500 deaths occur annually due to short-term exposure to degraded air quality. In contrast, it is now estimated that up to 17,500 excess deaths occur due to long-term exposure.

This study does not attempt to describe how an individual or population comes in contact with a contaminant, or quantify the amount of contact of those pollutants across space and time, but to identify if there are possible hot spots of $PM_{2.5}$ to redirect air pollution reductions efforts in the region. As approximately 10% (11,485) of persons aged 5-54 years in the Central Okanagan have asthma and approximately 8% (7,272) of persons aged 45 years and older have Chronic Obstructive Pulmonary Disease (COPD)[3], according to the provincial Chronic Disease Registry (Watt, 2014). Such estimates highlight the value of not only reducing the extreme air quality events, but also focusing on ensuring air quality remains at the highest possible level at all times[4] for the benefit of the general public, but specially the vulnerable people in the region (Hassleback & Taylor, 2010). Through this study, several maps were prepared. The population distribution is displayed with wood stove density as well as $PM_{2.5}$ concentrations in Appendix 5. These maps show the individual wood stoves and a population density layer. No in depth analysis has been done, but these maps can be used for further analysis.

Speciation Study Results 2005

In 2009, a study was completed in Kelowna that used Positive Matrix Factorization (PMF) Model to identify the sources contributing most significantly to both the fine and coarse fraction of airborne particulate matter in the city of Kelowna (Allen & Jackson, 2009). One hundred and six 24-hour samples were collected on a one-in-three-day sampling schedule, between October, 2005 and September, 2006. Speciation of the samples was performed using X-ray fluorescence and ion chromatography, as well as a thermal/optical carbon analyzer. Source apportionment was conducted using the software package EPAPMF2. Six sources were identified for the fine fraction, as shown in Figure 11.

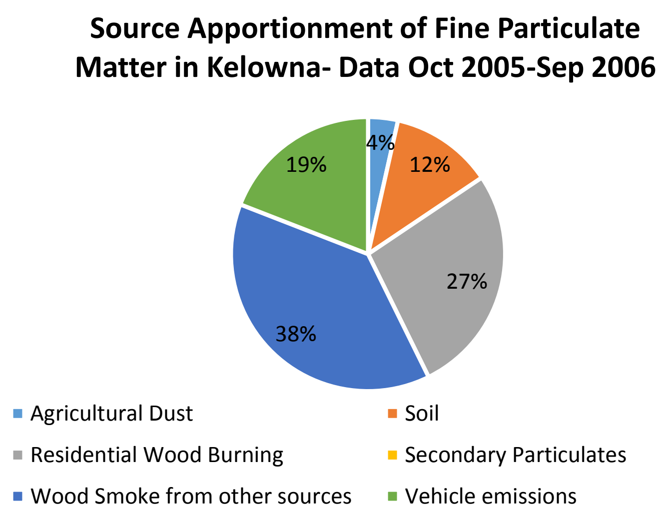

Figure 11. Source Apportionment of Fine Particulate-Data collected from Oct 2005-Sep 2006

Over the entire sampling period, the modeled mass of fine fraction particulate matter was influenced most substantially by wood smoke and vehicle emissions. Residential wood burning was the dominant contributor to fine fraction particulate during the winter, though other wood smoke and vehicle emissions also made notable contributions. Five sources were identified for the coarse fraction: soil (contributing 32% of modeled concentration), road salt (15 %), secondary particles (11 %), agricultural dust (29 %), and residential wood burning (13 %). Soil and agricultural dust were found to contribute most substantially to the total concentration of coarse fraction particulate matter. When the highest concentration days are isolated, soil, road salt, and agricultural dust contributed most notably to the coarse fraction concentration, while wood burning accounted for the majority of the modeled fine fraction concentration. (Allen & Jackson, 2009).

[3] Local Health Area Profile 2014
[4] Air Quality Health Index Variation Across British Columbia

Environment Canada's CRUISER data

In 2005, Environment Canada's unique CRUISER (Canadian Regional and Urban Investigation System for Environmental Research) mobile laboratory performed a mobile study in the Central Okanagan. Data was collected from October to November 2005 and was used to provide initial insight into the spatial variations in pollutants.

CRUISER also obtained mobile measurements driving in Kelowna and throughout the Okanagan Valley, as far south as the US. Border. These were obtained on multiple days. Through this project, the 2005 data was processed and mapped focusing on both the local variations in Kelowna and differences between Kelowna and the surrounding region. Initial data provided was in the form of excel files containing the information of GPS coordinates and concentration of different pollutants. However, direct measurement of $PM_{2.5}$ was not taken back in 2005 but different species that can give a good estimate of $PM_{2.5}$ were measured.

Project Objectives

With a single monitoring station, the variation of key air pollutants within the region remains largely unknown. $PM_{2.5}$ is one such key pollutant, and its levels are known to exhibit large variations throughout the complex terrain that characterizes the region. The objectives of this project are:

- To assess neighborhood exposure of $PM_{2.5}$ by identifying hotspot areas that could be affected by transportation and residential wood smoke. Mapping the $PM_{2.5}$ concentrations will support the airshed management planning. Data generated will provide a rich foundation for other related research.

- To assess if $PM_{2.5}$ concentrations differ from the operational monitoring station located at Okanagan College when continuous monitoring is performed in different locations. Comparing and analyzing this data could guide future planning, management and monitoring in the region.

- To enhance the knowledge obtained from the proposed mobile monitoring, a spatial analysis of relevant 2005 data from Environment Canada mobile lab (CRUISER) will be included along with interpretation of source apportionment of CRUISER data focusing on organic PM and black carbon (BC) due to this fraction's link to wood smoke and traffic emissions.

Project Design and Methodology

Study Area

The mobile monitoring project was designed to identify areas that could be affected by fine particulate matter from wood stove emissions and transportation sources. The route was designed considering the density of wood stoves in the region and the previous 2005 CRUISER route. The mobile monitoring route covers the City of Kelowna, Peachland, City of West Kelowna, Westbank First Nation, Lake Country and East RDCO rural area.

The project design and data collection methods are based in part on previous studies of wood stove emissions that involve both mobile monitoring and fixed-site monitoring (Hayek, 2011). Sampling was conducted in a manner to ensure the collection of $PM_{2.5}$ measurements, which would result in adequate datasets that are representative in both space and time. The desired datasets would be sufficiently large in sample size, span over all seasonal and diurnal variations, and reflect proper geographic representation and good spatial coverage. To meet such expectations, sampling was taken in two forms: mobile and stationary monitoring. Mobile monitoring was conducted by positioning DustTrak and GPS instruments inside a vehicle. The vehicle was driven along predetermined routes and times of day and, at the end of each run, the resulting DustTrak and GPS data was downloaded into a computer using proper software and merged by measurement time. On the other hand, stationary monitoring was achieved by positioning an E-BAM at two locations: Johnson Bentley Memorial Aquatic Centre in West Kelowna and City Hall in downtown Kelowna and all data was compare to the operational monitor at the KLO Okanagan Collage. A co-location of the E-BAM was also performed previous to this study.

Route Design

The route was designed by identifying areas that could be affected by fine particulate matter from wood stove emissions and transportation sources. Using ArcGIS, the $PM_{2.5}$ monitoring route was designed considering:

- Wood stoves installed in the region: through the building permits of the wood stoves and fireplaces inserts legally installed, the postal codes were geocoded (i.e. converted to GPS coordinates using GPS Visualizer) (Schneider, 2003-2016)[5].
- Industry locations: MoE provided a list of all the facilities in the Central Okanagan authorized for air discharges by the Ministry of Environment. The postal codes of 23 industrial facilities were converted to GPS coordinates.
- Land use (agricultural and industrial areas), arterial and major roads: database provided by the City of Kelowna.

A route was designed avoiding industry locations and considering wood stove density and major roads. The final route shown in Figure 12 covers all municipalities in RDCO and showcases the most time efficient route that maximizes wood stove coverage.

[5] http://www.gpsvisualizer.com/geocoder/

Route 1:

- Starting at UBC Okanagan and ending at Orchard Park Mall in order to provide researchers with the possibility of a break for food, washroom, etc.
- At 105 km in length, the route takes approximately 2 hours and 6 minutes at 50 km/h throughout
- The route spans from UBCO to Lake Country and RDCO before arriving at Orchard Park Mall

Route 2:

- After the break at Orchard Park Mall, route 2 proceeds till it reaches its end at downtown Kelowna
- At 108 km in length, the route takes approximately 2 hours and 10 minutes at 50 km/h throughout.
- The route spans from Orchard Park Mall, to South Kelowna (Mission), to West Kelowna and Westbank First Nation into Peachland before ending back in downtown Kelowna.

The route was driven forward/backward to give variance in time sampled at specific locations. The route in Figure 12 was designed considering the woodstove counts by postal codes, trying to avoid industry locations that could impact the $PM_{2.5}$ measurements. The route was also initially compared with the estimated $PM_{2.5}$ concentrations from the 2005 CRUISER data for reference and possible data comparison with the 2015 data collection.

The mobile monitoring routes and driving directions are included in Appendix 9.

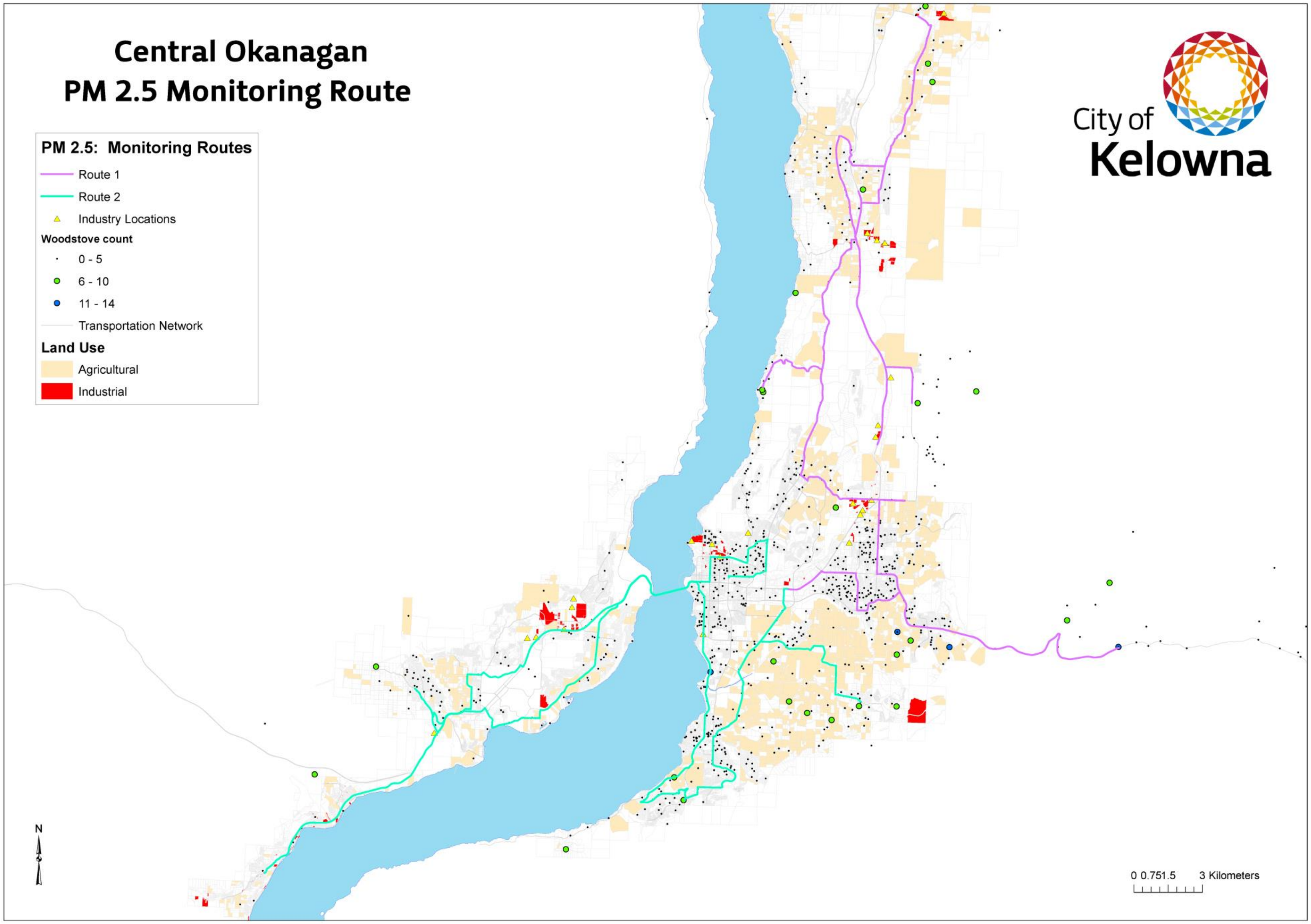

Figure 12. Central Okanagan $PM_{2.5}$ Monitoring Route- Woodstove count by postal code through building permits, Data Dec 2015

Instrumentation

Three units were provided by the Ministry of Environment to performed this study; a DustTrak, an EBAM and a GPS. The researchers were trained by Ministry of the Environment staff on November 25th 2015 to proper manage, use and set the DustTrak and GPS. Researchers were instructed to be careful that the monitors were functioning properly and giving reasonable data. The setup in terms of vehicle / outside temperature, length and straightness of sampling pipe, etc. were also important to check so that these factors don't affect the measurements. A $PM_{2.5}$ monitoring protocol was drafted and the sampling sheet to record data collection was developed and provided. All the equipment was located in an available building owned by the City of Kelowna and access was granted to the researchers.

DustTrak II Aerosol Monitor

The DustTrak Aerosol Monitor, model 8532, is a lightweight portable hand held light scattering photometer that produces real-time aerosol mass readings. It is capable of collecting all particulate matter in a range from 0.001 to 150 µg/m^3 in both indoor and outdoor environments (TSI, 2016)[6]. These properties made the DustTrak II monitor the best choice for collecting mobile measurements of $PM_{2.5}$. Prior to each mobile monitoring trip, the DustTrak was calibrated by performing zero reading, the oil impactor was properly clean, the test length was set for 7 hours and the log interval was set to be every 5 seconds. Then DustTrak time and GPS were synchronized to be within 3 seconds and a test run was always performed before start the sampling.

Figure 13. DustTrak Handheld Device

GPS

The Global Positioning System (GPS) is a space-based navigation system that provides location and time information in all weather conditions, anywhere on or near the earth where there is an unobstructed line of sight to four or more GPS satellites. For the mobile monitoring, a GPS unit was needed to geo-reference the DustTrak data and map the sample routes. The GPS used in this study was a GARMIN 16 X. For every trip, the GPS was set up and the time synchronized with the DustTrak. The GPS setup and all the equipment protocols are included in Appendix 1.

Figure 14. GPS- GARMIN 16X

[6] http://www.tsi.com/dusttrak-ii-aerosol-monitor-8532/

E-BAM

The E-BAM, which stands for Environmental Beta Attenuation Monitor, is a complete measurement system that provides truly accurate, precise, real time measurement of fine particulate matter automatically at low cost. It is for these reasons that it was the preferred monitor to move from location to location (Met One Instruments, 2013). The E-BAM monitor works by emitting high energy beta ray through filter tape that is detected by a scintillation counter to produce a zero reading. Throughout the one-hour detection period, a controlled amount of outside air is brought through the filter tape which can be measured for the amount of particulate matter in the ambient air. This process is repeated each hour and logged for data analysis (Met One Instruments, Inc, 2009).

$PM_{2.5}$ E-BAM location

The equipment was set to continuously measure and log average concentrations for at least one-month period at two different locations. Stationary monitoring location was designed taking into account local emission sources, land use, terrain and population density, also having access to a secure building that meets Ministry of the Environment monitor sitting criteria. The two locations chosen were Johnson Bentley Memorial Aquatic Centre in West Kelowna and City Hall in downtown Kelowna and are shown in Figure 16. The monitoring schedule is shown in Table 2.

Figure 15. E-BAM installed at Johnson Bentley in West Kelowna

An agreement with the property managers of those buildings were made to install the equipment for a set period of time. Ideally, and pending on the monitoring results, such locations could also match potential sites of continuous monitoring that are aligned with the District's present and long-term development goals. To avoid unnecessary risks accessing the roof at any of those locations, a modem and cellular data were needed to retrieve all information via wireless connection.

Table 2. E-BAM Monitoring Schedule

E-BAM Stationary Equipment			
Date	**Event**	**Location**	**Address**
9 October 2015	Installation and running at West Kelowna	Johnson Bentley Memorial Aquatic Center	3737 Old Okanagan Hwy, Westbank, BC, V4T 2H6
1 December 2015	Move to Downtown Kelowna	City Hall	
19 January 2016	Move to West Kelowna	Johnson Bentley Memorial Aquatic Center	
3 March 2016	Move to Downtown Kelowna	City Hall	1435 Water St, Kelowna, BC, V1Y 1J4
8 April 2016	Measurement stopped due to pump failure	City Hall	

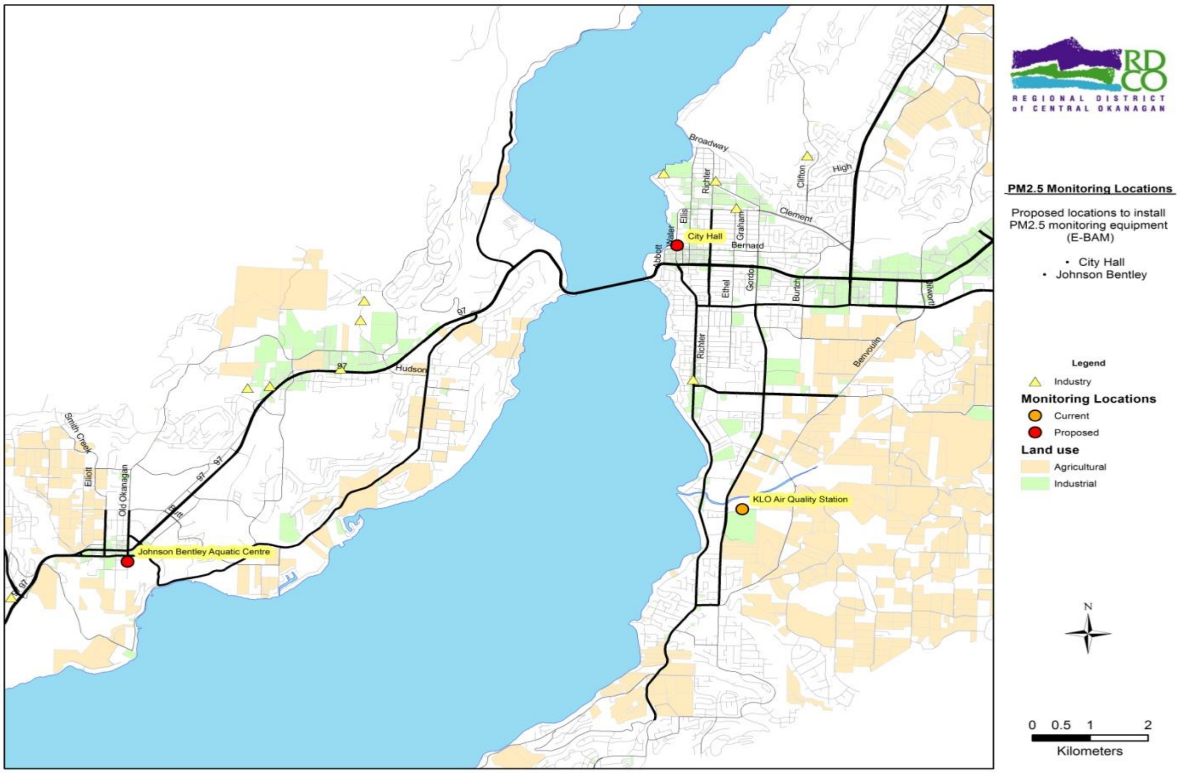

Figure 16. Stationary equipment locations- current (SHARP) and experimental (E-BAM)

SHARP

The SHARP (Synchronized Hybrid Ambient Real-time Particulate) is a continuous ambient particulate matter monitor that uses a Carbon-14 source, detector and a light scattering nephelometer inside an enclosure. What makes it different from the EBAM is that it uses both mass deposits and a light scattering nephelometer. This allows for accurate measurements as both are widely accepted for PM measurement. The SHARP monitor also logs data without being attended for long periods of time, as it automatically advances its filter tape on a frequency programmed by the user (Thermo Fisher Scientific, 2016)[7]. The SHARP is one of the newest and most reliable air quality monitors available and meets U.S. and international particulate matter monitoring regulations (Thermo Fisher Scientific, 2016).

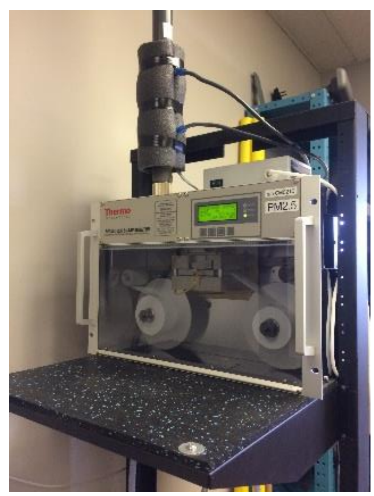

Figure 17. SHARP equipment - Okanagan College

The new SHARP monitor was installed in 2014 at the KLO Okanagan College monitoring station and the first values were recorded on May 22, 2014. The SHARP monitor was a much needed upgrade from the previous TEOM (Tapered Element Oscillating Microbalance) monitor, which had the tendency to underestimate fine particulate concentrations due to sample air heating.

[7] https://www.thermofisher.com/order/catalog/product/5030SHARP

Sampling procedure

Sampling schedule

Mobile monitoring was conducted between November 26, 2015 and April 14, 2016. Data collection was planned and performed under a range of venting conditions; priority was given for sampling on days under worst-case venting scenarios (evenings that were calm, clear and anticyclonic) that will most likely have the highest concentrations of $PM_{2.5}$ revealing possible hot spots. Also sampling was performed under good venting conditions to compare the range of results. Sampling was conducted along the predetermined routes that focused on residential areas with greater woodstove's density but also aimed to capture $PM_{2.5}$ from transportation at different traffic peaks. In addition to the publicly available tools for venting and meteorological forecasts, Environment Canada and MoE experienced meteorologists provided support to determine the days with ideal meteorological conditions for sampling; the project manager and researcher were added to the Ministry's Stagnation Forecast distribution list. Also during the sampling period, all the Regional District of Central Okanagan controlled burning news releases were emailed directly to the researcher. The estimated and planned total samples schedule is shown in Table 3.

Table 3. Planned Total Mobile Sampling

	Nov	Dec	Jan	Feb	Mar	Total sampling	Time (6hrs/sampling)
Morning (M)	1	1	1	1	1	5	30
Afternoon (A)	1	1	1	1	1	5	30
Evening (E)	1	4	4	4	4	17	102
Total	3	4	6	4	6	27	162

Trips were taken in the morning, afternoon and the evening. The actual number of trips differed by one as originally planned, and the monthly distributions and time required to perform the sampling differed as shown in Table 4.

Table 4. Actual Total Mobile Sampling

	Nov	Dec	Jan	Feb	Mar	Apr	Total sampling	Time (7hrs/sampling)
Morning (M)	1	1	1	1	0	1	5	35
Afternoon (A)	0	1	0	0	3	1	5	35
Evening (E)	1	4	2	5	4	0	16	112
Total	2	6	3	6	7	2	26	182

The $PM_{2.5}$ Mobile Monitoring Protocol was based in similar studies and as recommended by Ministry of the Environment staff. The mobile sampling protocol is described in Appendix 1.

Mobile equipment setup

The mobile monitoring equipment was provided by the Ministry of Environment and consisted of one computer, a DustTrak Aerosol Monitor, model 8532 for measuring $PM_{2.5}$ and a GPS GARMIN 16X to ensure all sampling could be assigned to a geographic location. The GPS and DustTrak were powered using a 12V power inverter that was connected to the vehicle's cigarette lighter receptacle. The GPS was programmed to log the date, time, latitude, longitude, and elevation in one second intervals. The GPS and DustTrak remained in operation until the mobile monitoring was completed.

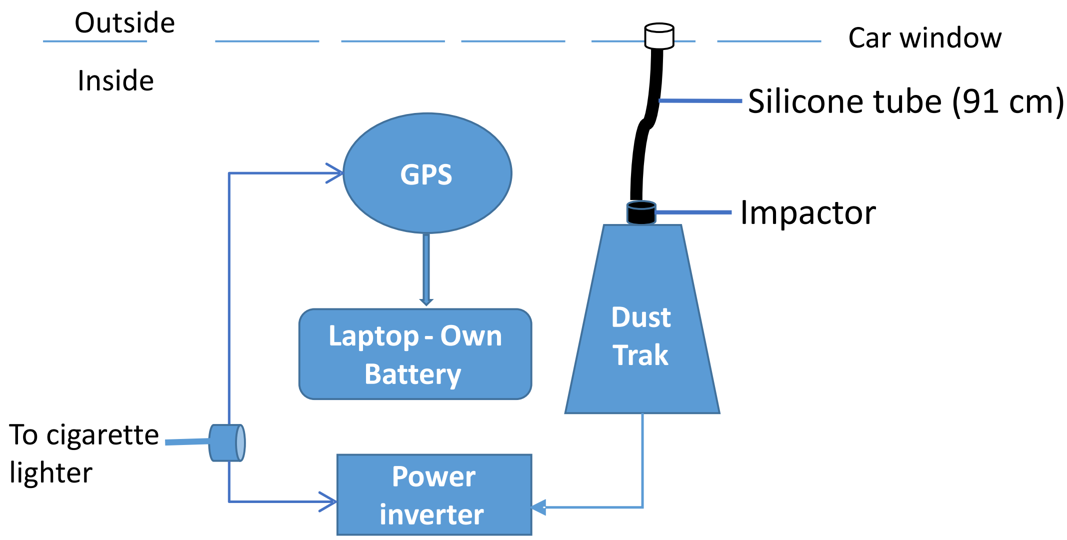

Figure 18. Schematic of mobile monitoring setup

At the beginning of each trip, the setup between the DustTrak time and the GPS time was done manually. The protocol indicates they should be synchronized within 3 seconds and therefore a small time delay could exist between the GPS and the DustTrak. Differences between GPS coordinates and $PM_{2.5}$ measurements can make a difference when collecting mobile data, especially at high speeds. If we consider the maximum delay of three seconds, and the maximum speed of 70km/h, the highest error that could have been experienced would be a difference of 58 meters, this would be significant if this study was on a much smaller scale, but due the large area of study, this was determined to be negligible in relative to the total area of the Central Okanagan.

DustTrak Response Time

Given that the DustTrak was fitted with a silicone tube to reach the car window, as shown in Figure 18, a time lag would result from the air sample's intake through the tube. The time lag will depend on the diameter and the length of the tube and the flow rate of the DustTrak. The Material of the tube is also important, as it could be static and hinder the air flow along its sides. However, the material of the tube used is black conductive silicone, which prevents static losses. The flow rate and dimensions are outlined in the table below.

Table 5. DustTrak inflow tube measurements

	Measurement	Metric Conversion
Tube Diameter (D)	0.19 Inches	0.4826 cm
Tube Length (l)	3 Feet	91.44 cm
Flow Rate (FR)	3 L/min	50 cm^3/s

Based on the tube and flow specifications, we are able to calculate the volume (V) in the tube and the time (t) it takes an equivalent volume of air to flow through the tube by the flow rate (FR).

Equation 1. Volume of DustTrak tube

$$V = \pi\left(\frac{D}{2}\right)^2 l = 16.73\ cm^3$$

Equation 2. Time to reach the impactor

$$t = \frac{V}{FR} = 0.33\ seconds$$

Therefore, it would only take about 0.33 seconds for an air sample to travel through the tube, which is fairly negligible considering that, if the car was traveling at a maximum of 70km/h, it would only cause a shift of 6.5 meters. Based on this analysis, the time lag was not incorporated into the mobile monitoring analysis, as the resulting spatial displacement is relatively negligible.

Sampling times

DustTrak doesn't provide data for specific sources, and supplementary data is needed to determinate possible sources. Considering data from a previous study of source apportionment, is expected measurements collected during the evenings under stable atmospheric conditions would provide information mainly on $PM_{2.5}$ concentrations due to wood smoke. Sampling collected during mornings and afternoons could provide information mainly due to traffic, a summary is shown in Table 6.

Table 6. General Sampling Schedule

General Sampling	Time	To capture $PM_{2.5}$ mainly from	Season
Morning (M)	5-11 am	Woodstove smoke /Traffic	Fall-winter-spring
Afternoon (A)	12-6 pm	Traffic	Fall-winter-spring
Evening (E)	6-12 am	Woodstove smoke	Fall-winter-spring

However, during the months of November to April is Open Burning season in the Central Okanagan and those days and any unusual event (fires, vehicles idling, etc.) were registered in the monitoring sampling sheet, included in Appendix 2. All sampling notes are included in Appendix 8. The conditions to allow open burning in the Central Okanagan are: Venting Index of 65 or greater and $PM_{2.5}$ of 15 µg/m^3 or less. Windy and stormy days were avoided as natural dispersion would likely lower the smoke levels to below detection limits.

Researchers and Vehicle's availability

A couple of researchers with science background were hired by the City of Kelowna and trained by MoE staff and through OGO Car Share one vehicle was always available to conduct the sampling, (OGO, 2016). The vehicles that were available for this project were:

- 2010 Toyota Prius Hybrid (866 MTK)
- 2009 Honda Civic Hybrid (865 MTK)
- 2007 Toyota Prius Hybrid (CE2 57K)

A memorandum was sent to the RCMP to let them know about the study and to provide the license plate of the vehicles involved in data collection, addressing beforehand possible neighbours' concerns for suspicious driving along the neighborhoods. The memo is included in Appendix 3.

Considering the route was approximately 213km in length, and the researchers attempt to drive approximately 10km/h under the speed limit (i.e. 40 km/hr or less in residential areas, 70km/hr on the highways), it was estimated it could take them 5.3 hrs to complete the route. Allowing for another 30 min to setting and loading equipment, the total estimated time to complete the route was 6 hrs. However, the actual sampling time was 7 hours. The vehicle was driven at a speed of 40km/h in residential areas, and the DustTrak was set to take samples every 5 seconds; that means samples were taken approximately every 55 meters along the route. After the route was completed the DustTrak data was downloaded with a USB into a computer. Based on the sample and location times, the DustTrak and GPS data were merged using an "R" Script developed by Ministry of the Environment staff. "R" is a programming language and environment for statistical computing and graphics. The data merger script is included in Appendix 6.

Data Analysis

A researcher with strong atmospheric background analyzed the resulting datasets using the statistical computation tool "R" programming platform, and following recognized procedures. Furthermore, quality assurance and control of the datasets were accounted for, aided by the expertise and guidance of other Ministry and Environment Canada staff. The R scripts are included in Appendix 6.

In addition to investigating the regional variations in $PM_{2.5}$ levels, the analysis was focused on answering a fundamental question: how much do these levels differ from the measurements of a single station in Kelowna? As such, data collection and analysis were geared towards quantitative measures and averaging times that can yield meaningful results. Ultimately, the results of mobile monitoring would shed some light on the intra-urban variations in $PM_{2.5}$ levels within the Central Okanagan, and are expected to reveal potential "hot spots" that may warrant further investigation.

Quality Assurance of DustTrak data

The DustTrak monitor uses light scattering to collect $PM_{2.5}$ concentrations. This technique is effective, but is very different from the techniques of the E-BAM and SHARP and can be altered by the relative humidity in the air and produce some suspected outliers (Zieger, et al., 2010). The total amount of data points collected through the predetermined route were 106,526. Some measurements were extremely high, sometimes reaching up to a thousand micro grams per cubic meter. These high values were dealt with by inspecting adjacent values; if values before and after were high as well, then the value was kept, otherwise it was removed. There were not too many high values of $PM_{2.5}$ recorded, there were 2,935 values above 50, 225 values above 100 and 97 values above 150. Such numbers are reasonable considering that there were 106,526 total data points. Once all these abnormally high values were inspected, the remaining values were put through a spatial averaging algorithm described in the section Displaying Mobile Results and Figure 47. Any values that were below zero were excluded when processed through ArcGIS.

Quality Assurance of E-BAM data

The hourly $PM_{2.5}$ data collected by the E-BAM monitor were generally good, but there were some suspicious values that needed to be adjusted before analyzing the data. The main adjustment made was to values that fell below zero. In total there were 778 values below zero and 374 values below -3.5 out of a total of 4,391. In order to correct for these negative values and as per MoE's staff recommendation, any $PM_{2.5}$ concentrations between 0 and -3.5 were changed to 0, and any concentrations below -3.5 were changed to a NA placeholder. An NA value does not affect any calculations such as mean, standard deviation, etc. Very high $PM_{2.5}$ concentrations were flagged, but were kept due to the nature of adjacent values and possible sources that could have resulted in "spikes" in the data.

E-BAM Co-location and maintenance

This study used different air quality monitors, the E-BAM and the SHARP, which could lead to differences in measured $PM_{2.5}$ concentrations. Therefore, the question arises as to whether different concentrations are due to the differences in location or monitoring technologies. In order to investigate the relationship between the E-BAM and SHARP measurements, both monitors were co-located in August 2015 at the KLO Okanagan College monitoring station. Fortunately, for the purpose of this analysis, during the time when the monitors were co-located, there was an intense forest-fire event that provided an opportunity to see how similarly the monitors work over a large range of $PM_{2.5}$ concentrations. In Figure 20, the time series shows the 24-hour rolling mean from August 14th till September 4th, spanning $PM_{2.5}$ concentrations from 0 to over 300 µg/m^3.

Figure 19. E-BAM co-location at the Kelowna College Station, August 2015

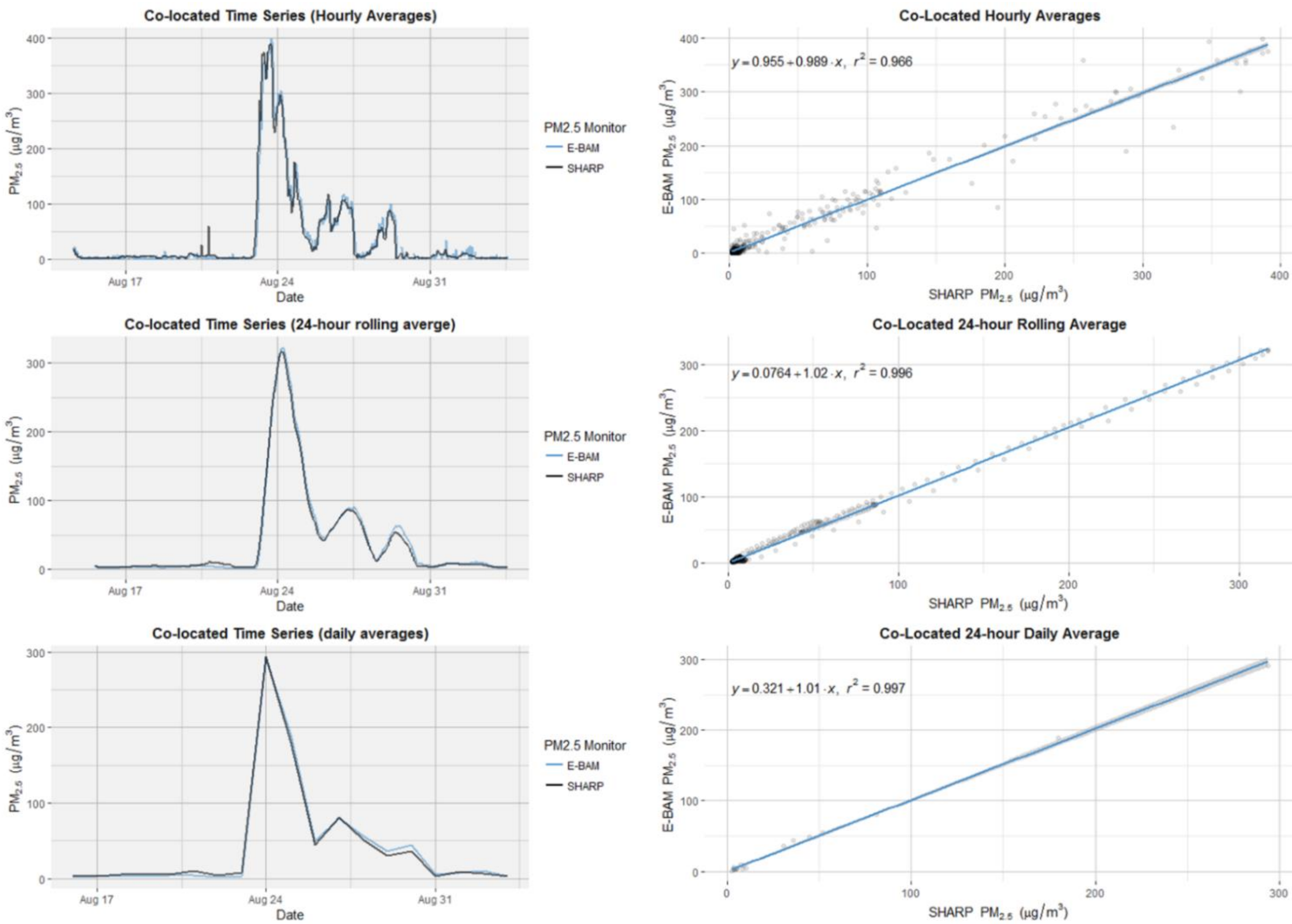

Figure 20. Co-location time series and regression E-BAM and SHARP

A time series and regression analysis are considered for hourly, 24-hour rolling, and daily averages. The time series on the left show close similarity between the two monitors, especially in the 24-hour rolling average and daily averages. On the right-hand side of Figure 20, a regression analysis shows how datasets compare with each other. The regression plots show a very good correlation for each of the three averaging times. First, the R^2 value is very close to one, which is a measure of how close one variable represents the other. Secondly, the slope of the line is close to one, which indicates a one-to-one ratio of measured particulate matter between both monitors. Finally, the intercept on all three plots is close to zero, which suggests that both monitors have fairly close baseline measurements. After the co-location was performed in August 2015, the E-BAM was deployed in West Kelowna to begin taking measurements for this study. During the time when the E-BAM was deployed, routine maintenance was performed; every two weeks the monitor was inspected for computed errors as well as mechanical errors with the pump and filter tape. In addition, the filter tape lasts for 60 days when taking one-hour measurements, and had to be changed on a routine basis.

Quality Assurance of GPS data

A GPS quality assurance was performed at least once per month. Identifying a few positions/ intersections along the beginning, middle and end of the predetermined route to validate the exact time and locations were accurate. A procedure on how the DustTrak and GPS times were synchronized to assure all data could be georeferenced is included in Appendix 1.

CRUISER Data - Assumptions & Procedure

Environment Canada provided the 2005 data. As the GPS coordinates were at the interval of 1 minute and the concentration of components that were measured by Aerosol Mass Spectrometry (AMS) ("NH4, ug/m^3", "SO4, ug/m^3", "NO_3, ug/m^3", "Cl, ug/m^3", "Org, ug/m^3") were at the interval of 5 minutes; the 1-minute scale was converted to a 5-minute scale. It was done by taking the position of cruiser at the end of 5-minute time period of the AMS. It was suggested to take the 5-minute average of the GPS but then it would not lie on the road.

In order to get an estimate of $PM_{2.5}$ the AMS ("NH4, ug/m^3", "SO4, ug/m^3", "NO_3, ug/m^3", "Cl, ug/m^3", "Org, ug/m^3") mass was added to the Black Carbon (BC) mass. The average of starting to end point of AMS interval was taken to measure the average concentration of BC during that interval. BC was also measured in 1-minute interval. Different maps were generated to see the spatial variation of $PM_{2.5}$ estimates throughout the 2005 route. Hotspot analysis and interpolation with inverse distance is used to see the overall variation. All of this was done in ArcGIS. Data from 2005 served as guidance to plan the mobile deployment strategy, analysis of 2005 CRUISER data and new mobile measurements occurred in parallel. Thus, the CRUISER data served to having a first look at the spatial distribution of multiple pollutants, within-city and outside of city levels and insight on PM speciation, which will help support the analysis in terms of the relative contributions of sources in Kelowna. Furthermore, the CRUISER data also represent a 'snapshot' from ten years prior to the new measurement study. Some insight into how growth in the region has impacted air pollutants is expected to be derived from the analyses.

Result Analysis

Cruiser 2005

The Estimated CRUISER $PM_{2.5}$ data in Figure 21 shows the Inverse Distance Weighed (IDW) representation of $PM_{2.5}$ from the Aerosol Mass Spectrometer (AMS). The IDW is an interpolation method that outputs a surface by using an internally weighted combination of set sample points, where the weight is a function of inverse distance (Esri, 2012). Although the IDW is used to have a clearer picture of the distribution of $PM_{2.5}$, it is not exact as it estimates based on the input points. The estimated $PM_{2.5}$ concentrations from the 2005 CRUISER and the $PM_{2.5}$ concentrations measured in 2015-2016 are different, but they do have some similar aspects that can be compared. The 2005 CRUISER data will be referred to as CRUISER $PM_{2.5}$ and the 2015–2016 study will be referred to as Measured $PM_{2.5}$.

The differences of both studies are:

CRUISER Estimated $PM_{2.5}$

- $PM_{2.5}$ was estimated as the sum of NH_4, SO_4, NO_3, Cl, Org, Black Carbon (BC)
- There were a total of 4 trips taken that covered the entire Okanagan
- Each day a new route was taken, so concentrations are represented in point data rather than by a line.
- Data was collected in October 2005

Measured $PM_{2.5}$

- $PM_{2.5}$ was measured directly with the DustTrak monitor.
- There were a total of 26 trips taken, all of which were along the same route.
- Data is represented in line that is the average of all trips taken.
- Data was collected from November 2015 to April 2016

The similarities of both studies are:

- Both have the same scale of $PM_{2.5}$
- Both show the spatial distribution over the Central Okanagan

The 2005 CRUISER data provides a basic understanding of the dispersion of pollutants over the four trips taken in the Central Okanagan. A benefit of the 2005 CRUISER data is that it contained the several species that can contribute to poor air quality. These species were Black Carbon, SO_2, O_3, CO, Cl, NO and NO_2. It should be noted that these major ambient pollutants are different than the ones used to estimate $PM_{2.5}$ (NH_4, SO_4, NO_3, Cl, Org and Black Carbon). The chemical pollutants NO_x, SO_2, CO, O_3 are important to understand as they behave differently than the estimated $PM_{2.5}$, which is the focus of the 2015–2016 study. Although the two sets of data differ by ten years, a general sense of these other pollutants behavior can be considered when looking at the distribution of $PM_{2.5}$. Figure 21 shows the spatial distributions of the pollutants measured in 2005:

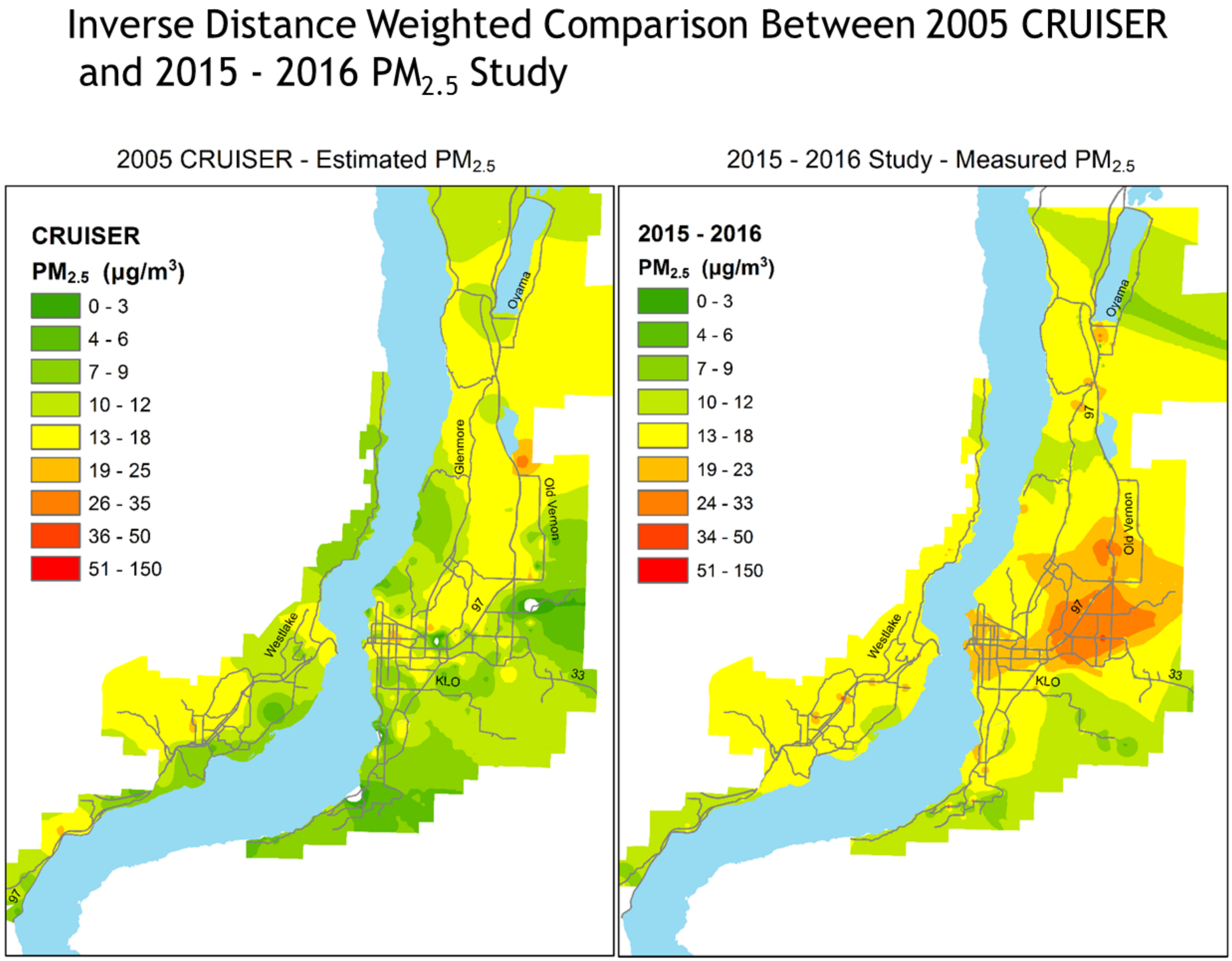

Figure 21. Inverse Distance Weighted comparison between estimated 2005 $PM_{2.5}$ (4 trips) and 2015-2016 measured $PM_{2.5}$ (26 trips) along predetermined routes in the Central Okanagan

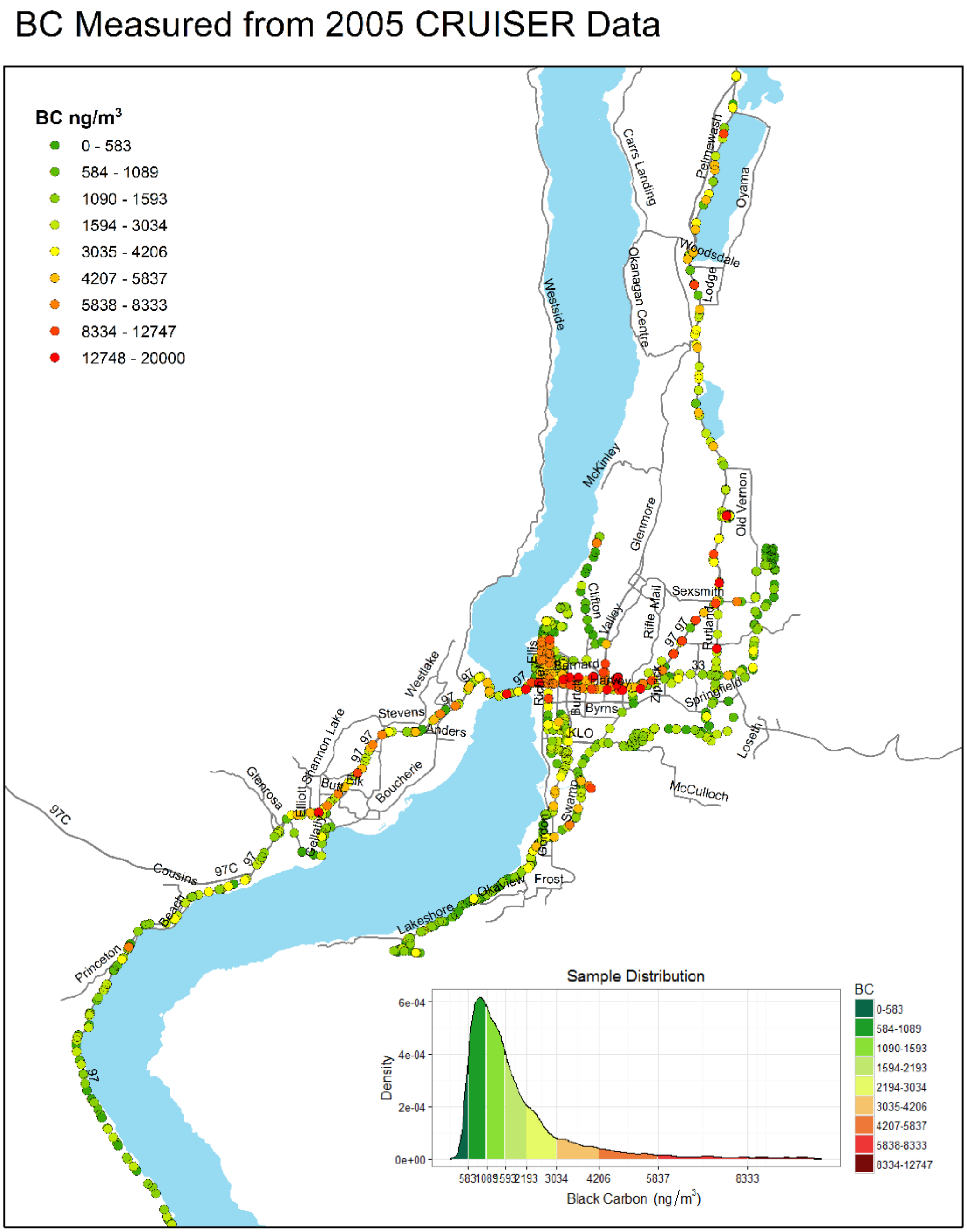

Figure 22. Black Carbon measured from 2005 data in the Central Okanagan

Black carbon (BC) is a product of incomplete combustion of fossil fuels, biofuels, biomass and is a subset of particulate matter that consists of pure carbon. Out of all particulate matter, BC absorbs most light and is very effective in converting light energy into heat in the same way as greenhouse gas does, only BC is more effective at doing this. BC has been linked to premature mortality and is considered hazardous by a number of studies (EPA, 2016). As BC is a product of incomplete combustion, it makes sense that the highest values are located along Highway 97, especially in the center of Kelowna and West Kelowna where most traffic is found.

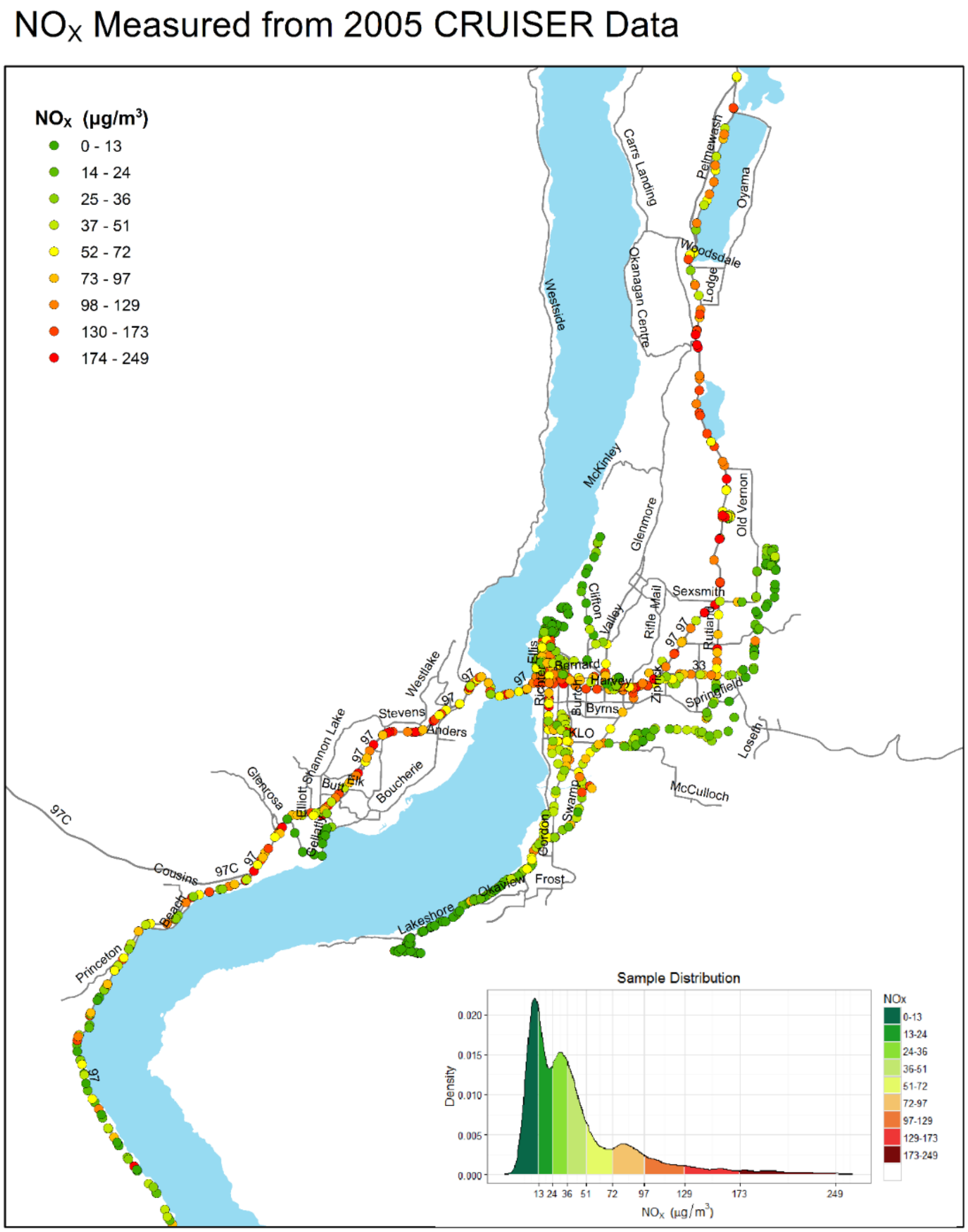

Figure 23. NOx measured from 2005 data in the Central Okanagan

NO_X is the combination of NO and NO_2. Both of these gasses are products of a combustion reaction that include nitrogen, oxygen and hydrocarbons. The majority of NO_X comes from vehicle emissions, and tends to be higher on major roads. High levels of both NO and NO_2 have been linked to respiratory issues and other adverse health effects. Also NO_X is a product for ozone and particulate matter, the two other major factors that contribute to air quality (WHO, 2003). The CRUISER data shows the distribution of NO_X in the Central Okanagan for October 2005. The spatial distribution shows that higher NO_X values are observed along major roads were traffic is more congested. The highest values are seen along Highway 97 and in the downtown core.

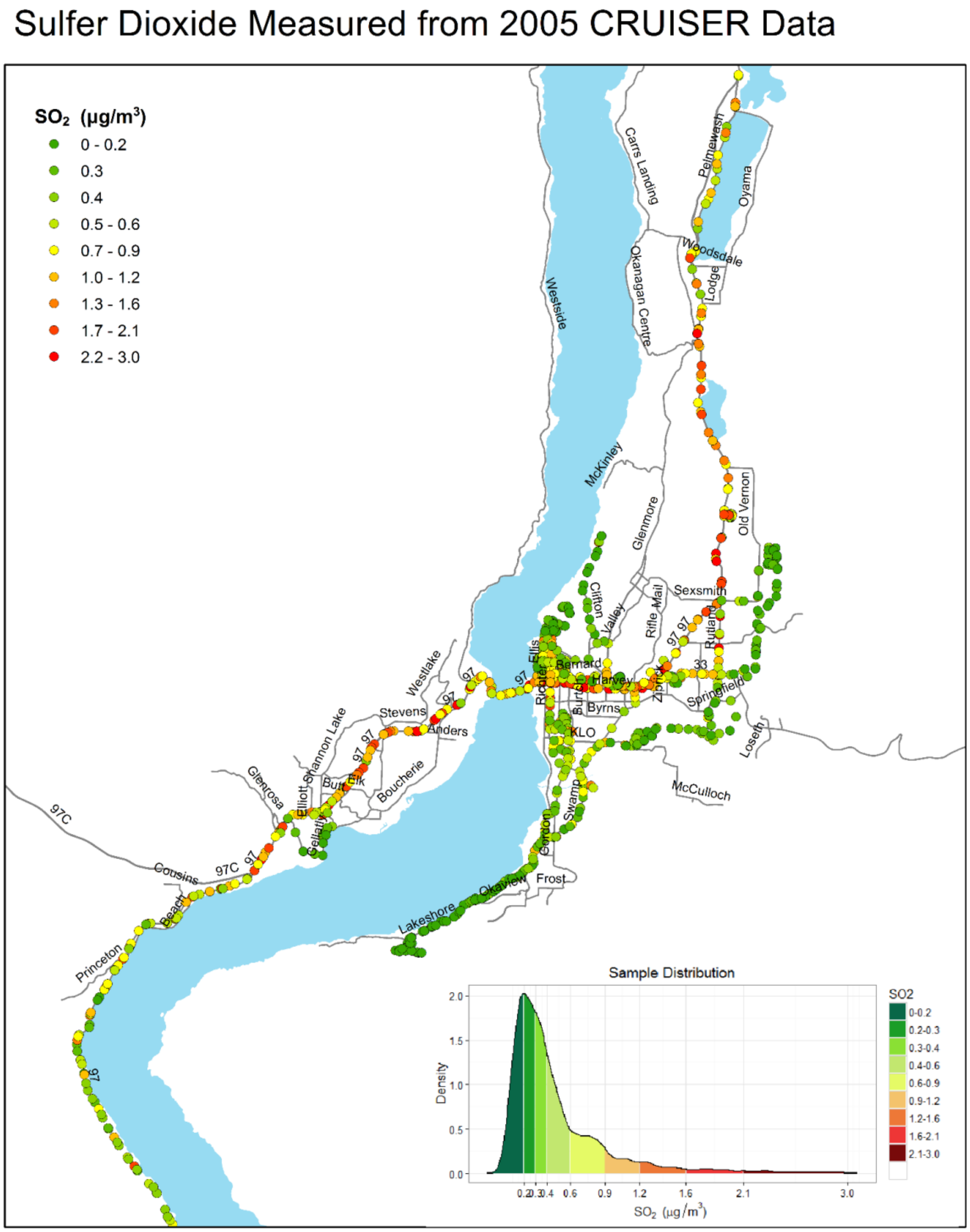

Figure 24. SO_2 measured from 2005 data in the Central Okanagan

SO_2 is a pungent gas that is created from the generation of electricity form coal, oil and gas. Sulfur dioxide is a product of vehicle combustion at small quantities and is in high enough quantities it can lead to irritation of the throat, coughing and shortness of breath (CCOHS, 2016). In the SO_2 map, it is shown that the highest concentrations were along major roads, similar to the distribution of NO_X.

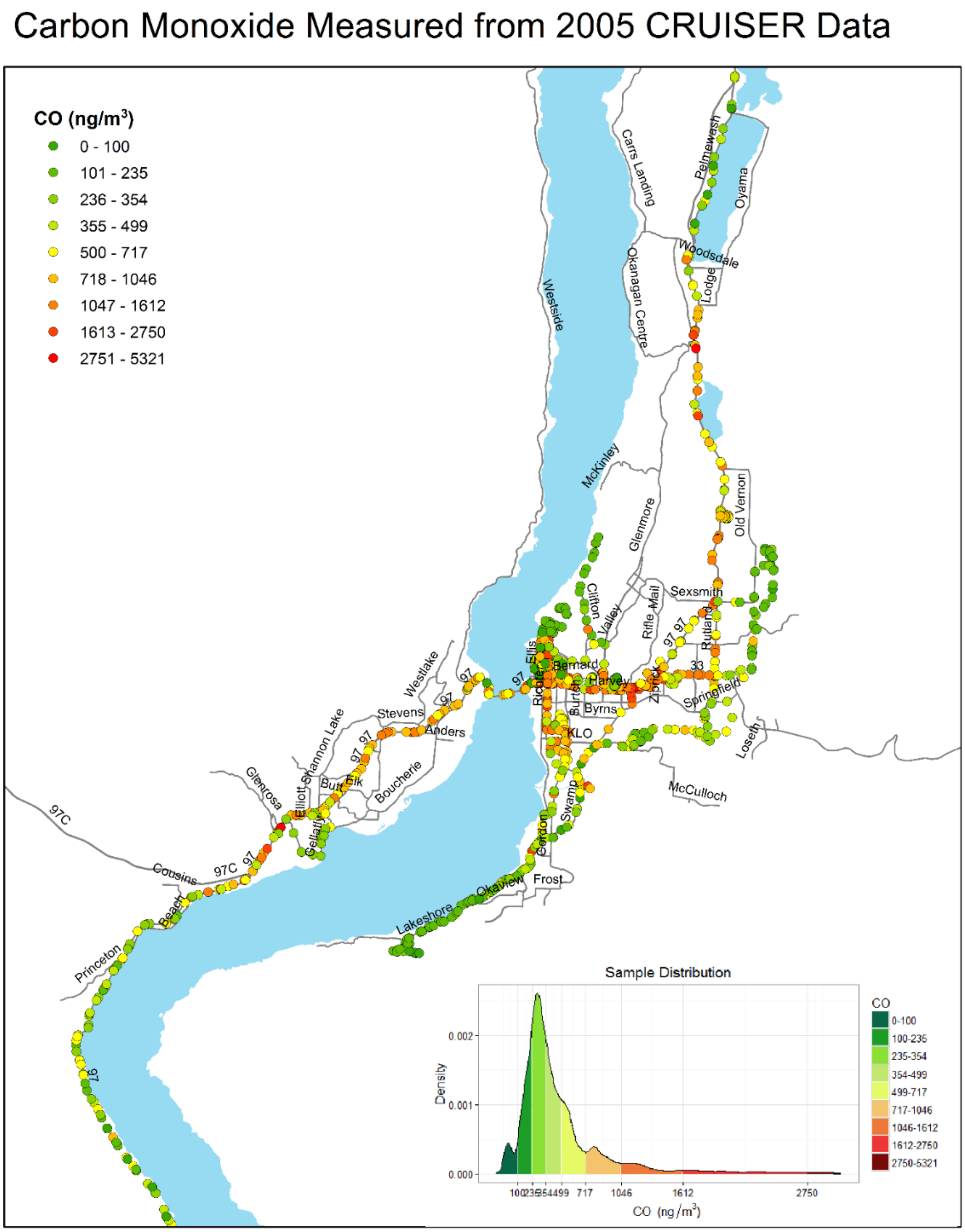

Figure 25. CO measured from 2005 data in the Central Okanagan

Carbon monoxide (CO) is the result of a combustion reaction that is partial or incomplete. Almost all combustion from vehicles are somewhat incomplete and result in the production of carbon monoxide and carbon dioxide rather than just carbon dioxide. Low concentrations are common, but when CO becomes higher than 35 ppb, it can cause harmful effects to humans and animals (EPA, 2016). As CO is a product of incomplete combustion from vehicles, it is no surprise that the highest concentrations were found along the busiest roads in the Central Okanagan as shown in Figure 25.

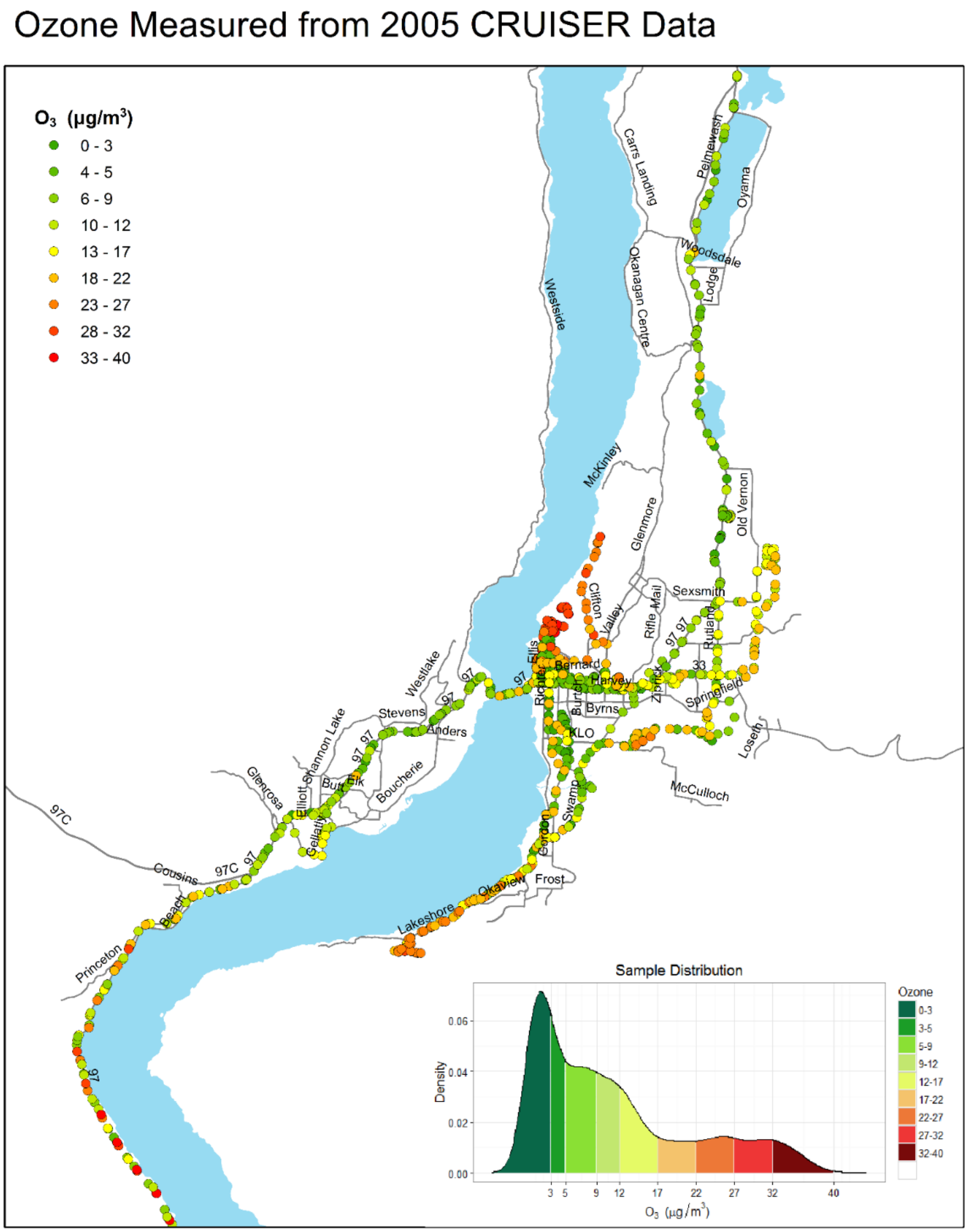

Figure 26. O_3 measured from 2005 data in the Central Okanagan

O_3 is a secondary pollutant that is generated from volatile organic compounds (VOC's), NO_X and ultra violet light. Unlike stratospheric ozone that protects us from the sun's ultraviolet radiation, ground level ozone is harmful to plants and animals and causes negative effects on the respiratory system (WHO, 2003). The distribution of ozone is different than the other pollutants as its highest values do not lie on busy highways. The highest values were located at the wood mill, in the upper mission, and on the southern part of the highway towards Penticton. These high areas could be to the level of VOC's in those areas that contribute to the production of ozone.

Stationary Monitoring

British Columbia has some of the most complex terrain, topography and meteorology in Canada due to all the valleys, lakes and mountains that span most of the province. The Okanagan is no exception, and contains many micro-climates within a small area that can be more difficult to produce a weather forecast or an air quality advisory due to varying local meteorological conditions. Considering this, the E-BAM monitor was placed in the two locations that are not only affected by wood stoves and traffic, but differ in local conditions. These conditions are mainly due to valley lake effects such as lake breeze, katabatic drainage and cold air ponding, all of which can affect each areas' ability to disperse pollutants. Factors such as $PM_{2.5}$ concentrations, wind speed and direction were looked at to explore possible air quality variations in their local climates.

The West Kelowna location was chosen to be at the Johnson Bentley Memorial Aquatic Center and the Downtown Kelowna location was stationed at City Hall. Both of these locations are located in areas of high traffic flow. The West Kelowna location is close to Highway 97, which is the primary way to get to and from the South Okanagan from Kelowna. The BC Ministry of Transportation reported in 2009 that there was an average of 52,000 vehicles passing between Kelowna and West Kelowna daily (BC billboards 2009.) In addition, the City Hall E-BAM location is located on Water Street, which is one of the busiest streets in Kelowna's downtown with many residences and businesses nearby. As well as a great deal of traffic, both locations have a number of registered wood burning stoves in a relatively short distance as shown in Figure 12. The combustion of these wood stoves is a common source of $PM_{2.5}$ (Wilson et al., 2005).

It will be important to understand that there will be some similarities as well as differences in the pollution sources, topography, and meteorology at all three locations as well as the different monitoring techniques provided by the E-BAM and SHARP monitors. These similarities and differences will be shown through a number of figures and statistics in this section of the report. The raw data will be displayed along with the daily mean and the 24-hour rolling averages of fine particulate matter readings to show how the $PM_{2.5}$ varies throughout this time period. Since the E-BAM monitor can only be in one place at a time, this temporary monitor was compared to the operational SHARP $PM_{2.5}$ monitor that is permanently stationed at the Okanagan College. Since two different monitors were used, and although their co-located measurements were shown to be well correlated, it is expected that these monitors can still produce different results even at the same location (Thermo Fisher Scientific, 2016).

Stationary Monitoring Analysis

As a first step, data analysis was done to see the trends of $PM_{2.5}$ in all three locations. Figure 27 shows the raw hourly data collected by both monitors for the duration of the collection period. From October 9th till April 8th the SHARP monitor was at a fixed location at KLO Okanagan College, whereas the E-BAM was moved back and forth between the dates listed in Table 2.

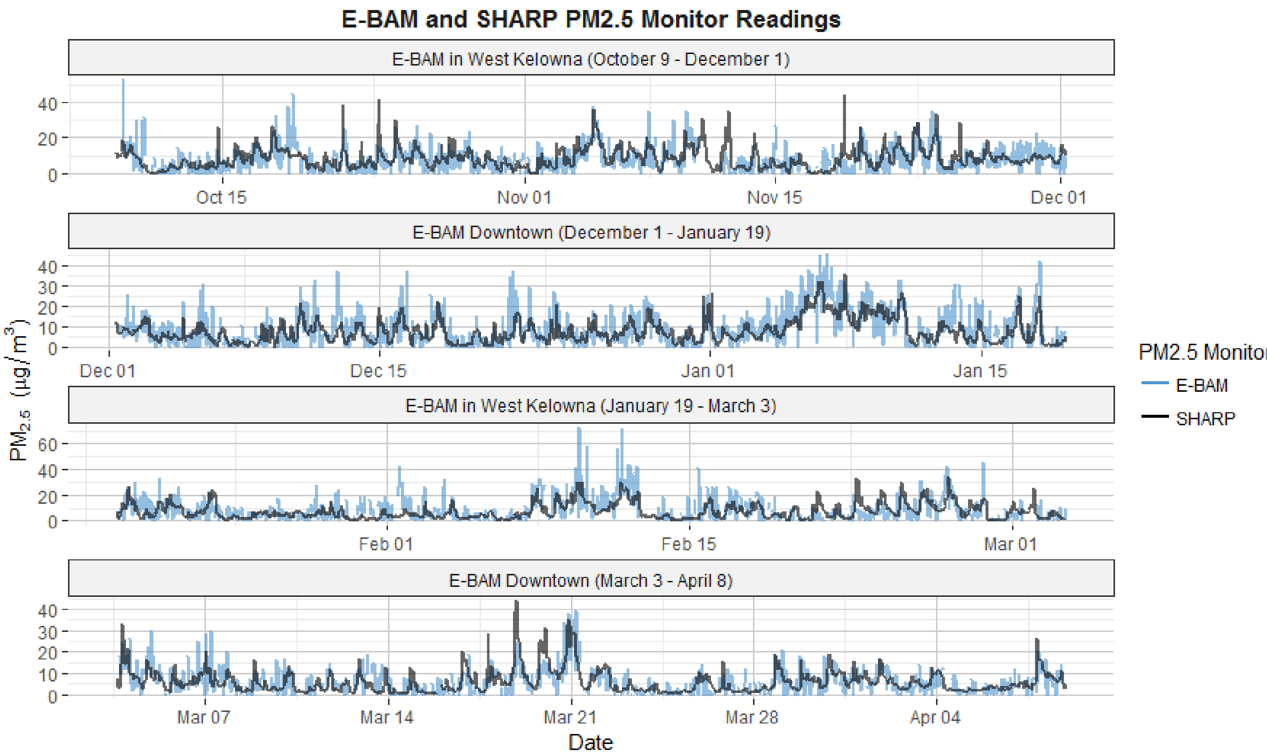

Figure 27. $PM_{2.5}$ Hourly Averages from E-BAM at selected locations and SHARP at the KLO Okanagan College

Overall, the hourly measurements from both monitors exhibit significant variability over relatively short periods of time. The measured $PM_{2.5}$ concentrations at all sites were higher during the first half of January, and noticeably lower towards the end of January, early February and late March. The E-BAM monitor, displayed in blue, had more variability throughout the time collected, whereas the SHARP readings, displayed in black, were smoother with less hourly variations. These differences may be attributed to differences in monitoring technologies.

For the purposes of air quality characterization and management, the 24-hour running mean (24-hour rolling average) and daily (midnight to midnight) averages are typically reported and examined. The 24-hour running mean was calculated for each hour as the mean of the past consecutive 24 hourly data. For example, the rolling mean data point plotted for January 8th at 5am will be the average of the data points between 6am January 7th and 5am January 8th. Since this is a rolling average, it moves along the entire data set and produces a continuous hour by hour average. The 24-hour rolling mean is useful for several purposes. In addition to being smoother with less noisy variations, the 24-hour rolling average is primarily used in issuing and lifting air quality advisories by the Ministry of Environment, in reference to the 24-hour provincial air quality objective for the $PM_{2.5}$ of 25 µg/m^3. The E-BAM and SHARP 24-hour rolling averages are shown in Figure 28.

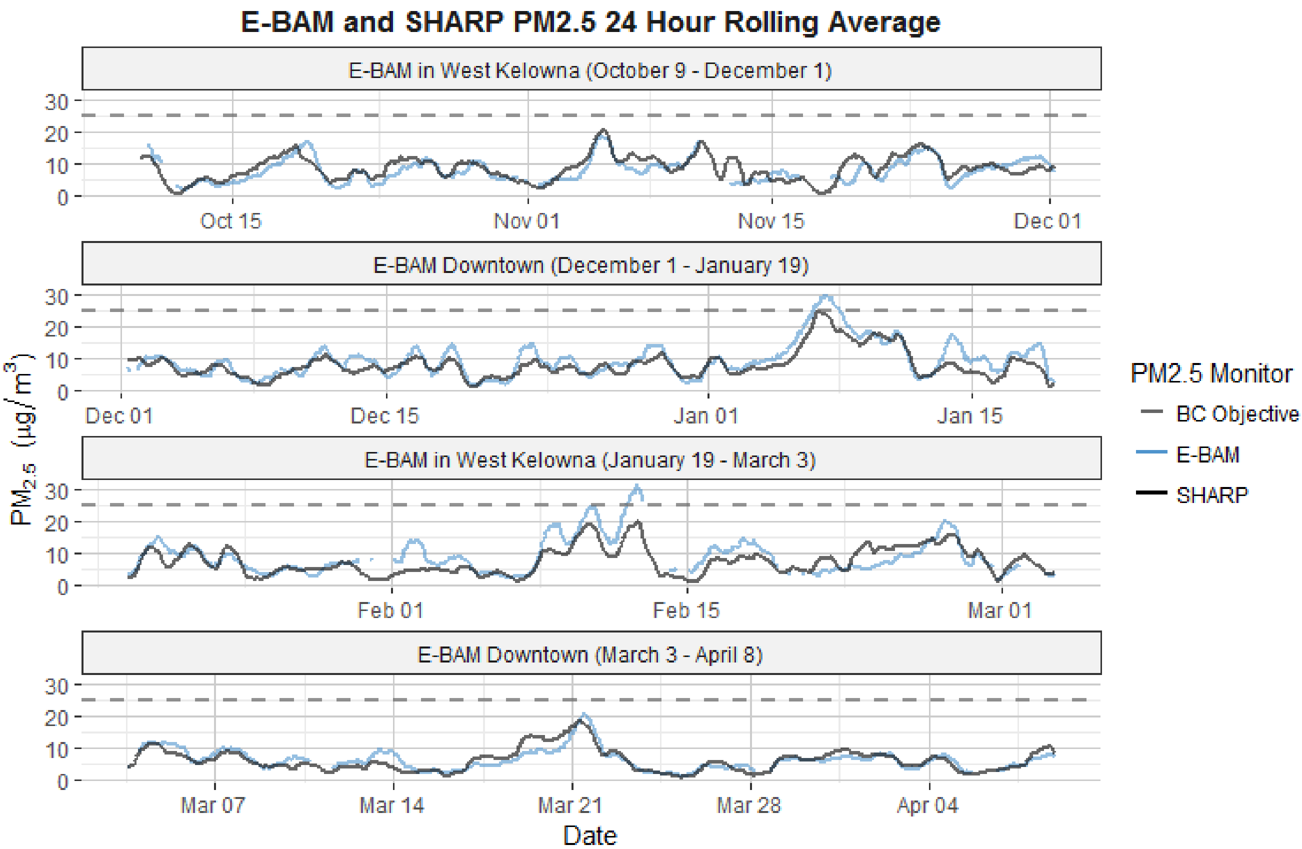

Figure 28. $PM_{2.5}$ 24-hour Rolling Average from E-BAM at selected locations and SHARP at the KLO Okanagan College

Compared to the hourly measurements, the rolling averages from both monitors exhibit much smoother time variations. Overall, results from the different monitoring sites show mostly similar temporal trends throughout the measurement periods. Based on the 24-hour rolling average, whereas the BC objective was never exceeded by the SHARP monitor at KLO Okanagan College, the E-BAM measurements show exceedances at downtown Kelowna during January 6th – 7th and at West Kelowna on February 12th. These two events are particularly important because they suggest that an advisory would have been considered at those locations. In order to understand the conditions that contributed to the aforementioned events of BC objective exceedances, an in-depth analysis for both cases is presented further in this section.

The daily averages are plotted in Figure 29. This shows the average for each day taken from midnight to midnight for each period, which smooths out the smaller diurnal variations and leaves only the changes in $PM_{2.5}$ that occur from day to day. These are important for policy making as they follow trends on a macro scale. The daily trends look similar to the 24-hour rolling averages, but highlight the days where the different monitoring locations reported markedly different results.

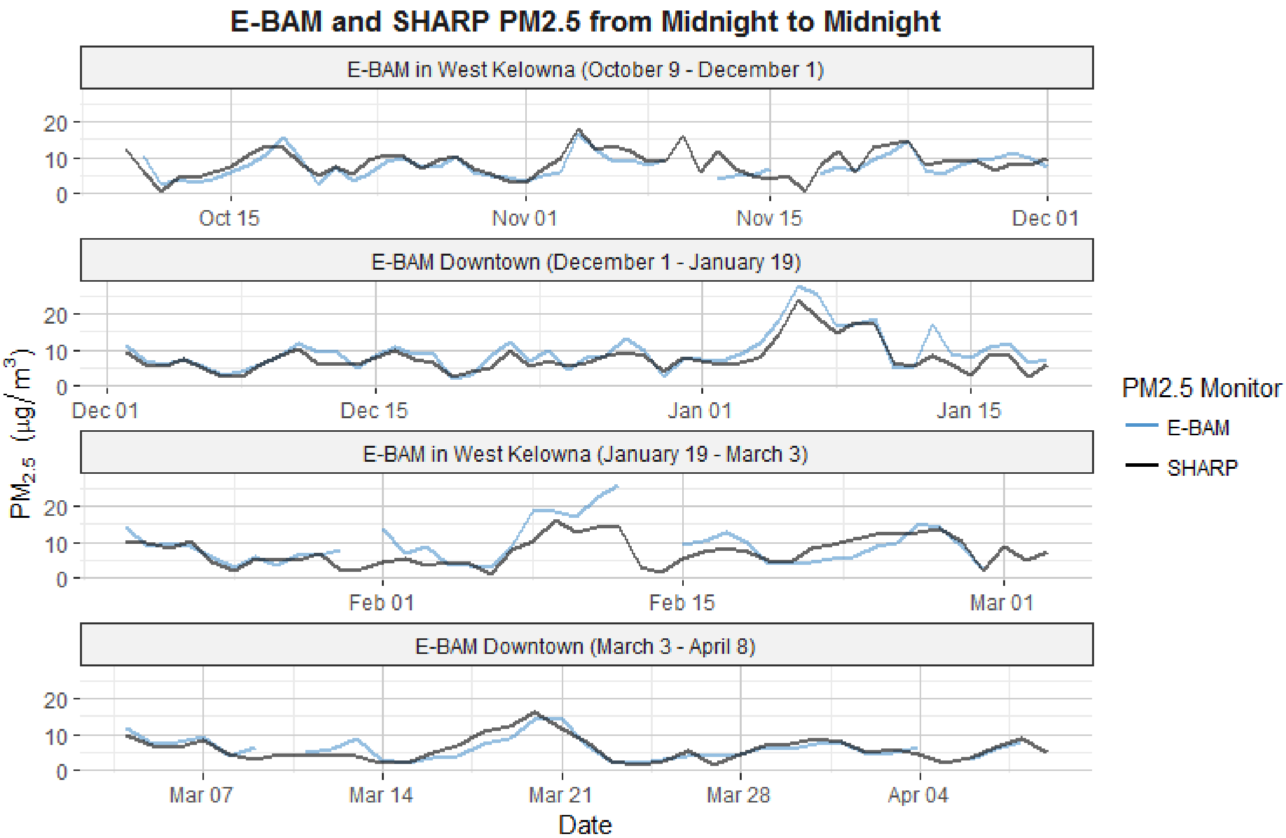

Figure 29. $PM_{2.5}$ Daily Average from E-BAM at selected locations and SHARP at the KLO Okanagan College

A summary of data capture, essential statistics and exceedances for each monitoring location and period are presented in Table 7. For all the data periods, the SHARP yielded more valid hours than the E-BAM and with near-complete data capture rates. Nevertheless, the E-BAM provided good capture rates, ranging from 84.8% to 94.6%, considering the E-BAM's instrumentation purpose and that capture rates of at least 75% are deemed acceptable for the purpose of air quality reporting.

Regarding the mean and the hourly-daily maximum values, Table 7 shows mixed results between the different monitoring periods and locations. Whereas the mean and maximum values are relatively comparable between the SHARP and E-BAM locations for the 1st (West Kelowna) and 4th (Downtown) periods, the E-BAM locations yielded noticeably higher values for the 2nd (Downtown) and 3rd (West Kelowna) periods. The E-BAM measurements yielded the highest mean value of 9.6 µg/m^3 during the 2nd period. The E-BAM also resulted in the highest hourly maximum of 73 µg/m^3 during the 3rd period in West Kelowna, as well as the highest daily maximum of 27.7 µg/m^3 during the 2nd period in Downtown Kelowna.

Over all the measurement periods, the SHARP monitor at the Kelowna College station did not yield any daily or running-mean averages above the 24-hour Provincial Objective for $PM_{2.5}$ of 25 µg/m^3. On the other hand, the E-BAM resulted in two days and 35 running-mean hours that exceeded the Provincial Objective during the 2nd monitoring period (Downtown), and further yielded one day and 20 hours above the Objective during the 3rd period (West Kelowna).

Table 7. Data capture and statistical summary of $PM_{2.5}$ measurements by E-BAM and SHARP from October 9, 2015-April 8, 2016

E-BAM Location / Data Period	Monitor	Valid Hours	Complete Data [%]	Mean*	Hourly Max.*	Daily Max.*	Days > 25*	Hours Run. Mean > 25*
West Kelowna 1. Oct 9 – Dec 1	*SHARP*	1224	100	8.3	43.9	18.0	0	0
	E-BAM	1094	89.4	7.7	45.0	16.7	0	0
Downtown 2. Dec 1 – Jan 19	*SHARP*	1127	99.9	7.8	35.7	24.1	0	0
	E-BAM	1068	94.6	9.6	46.0	27.7	2	35
West Kelowna 3. Jan 19 – Mar 3	*SHARP*	1007	99.9	7.3	34.5	16.2	0	0
	E-BAM	855	84.8	8.9	73.0	26.1	1	20
Downtown 4. Mar 3 – Apr 8	*SHARP*	836	99.5	5.9	43.8	16.2	0	0
	E-BAM	733	87.2	6.1	39.0	14.4	0	0

*Units in µg/m³

Statistical summaries of each period are shown in the box plots in Figure 30. The blue boxes refer to data collected from the E-BAM and the grey boxes refer to data collected from the SHARP monitor. The box plot shows the median value, represented by the horizontal line in the box as well as the distribution of data in each two-month category. The sections above and below the median are called the upper and lower quartiles. These quartiles contain 25% of the data above and below the median. The solid lines indicate the range of all the data, except for the outliers that are far from the median and represented by dots.

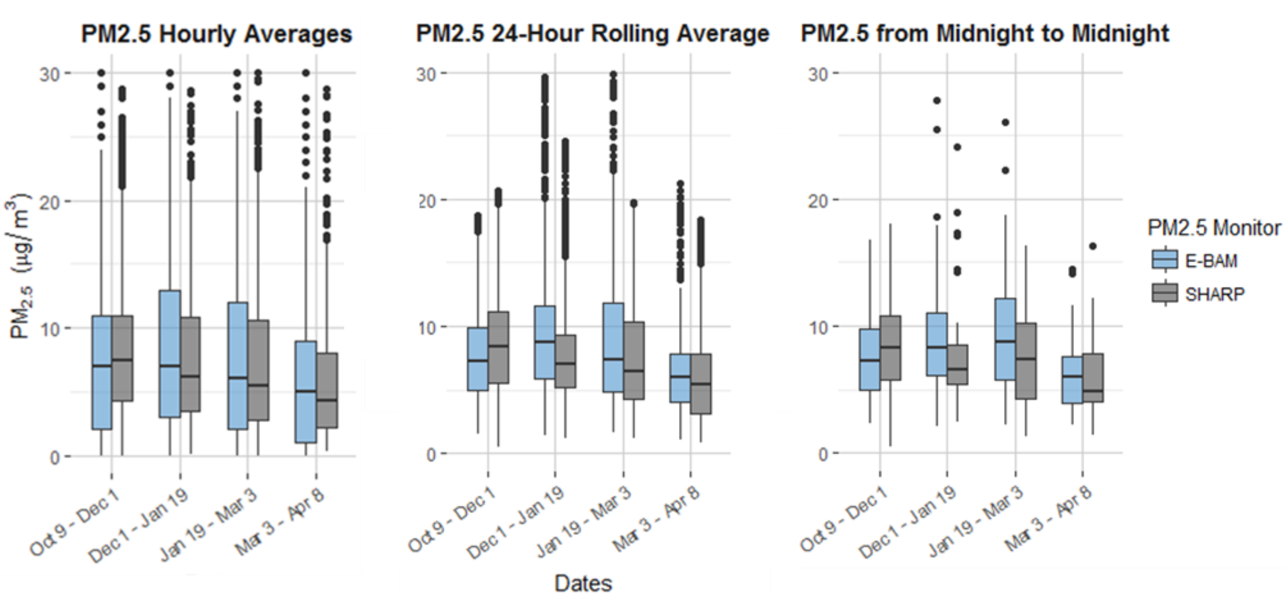

Figure 30. E-BAM and SHARP Boxplots from Oct 9, 2015 to Apr 8, 2016

In Figure 30, there are three separate box plots, one for hourly averages, 24-hour rolling averages and the daily averages. The hourly averages box plot contains the most data points, had more spread and more outliers than the other two. In the first period, the E-BAM had a higher spread and had a slightly lower median. For the three next periods the E-BAM still had a higher spread but had a slightly higher median than the SHARP monitor. The higher spread of the E-BAM reflects the hourly variability that was shown in Figure 27. For the 24-hour rolling averages, the SHARP monitor had a higher median value for three out of the four time periods. The period of December 1st to January 9th when the EBAM was located at downtown Kelowna was the only time when the SHARP had a lower median then the E- BAM. The spread of $PM_{2.5}$ concentrations was highest in the January-March period, and lowest in the March-April period. The daily average boxplot displays results that were quite similar to the 24-hour rolling averages, with only a few minor differences; the second period has slightly lower median and there is a reduction of outliers.

The differences between the monitoring sites can also be investigated in terms of the differences in their daily-average concentrations. This shows how results differ for each day (midnight to midnight) of the study. The difference is calculated by subtracting the daily averages of the E-BAM from the SHARP. This means that positive values represent the E-BAM monitor recording higher values and negative values represents SHARP recording higher values. In Figure 31, the blue areas represent when the E-BAM was placed in West Kelowna and the pink areas when the E-BAM was placed downtown.

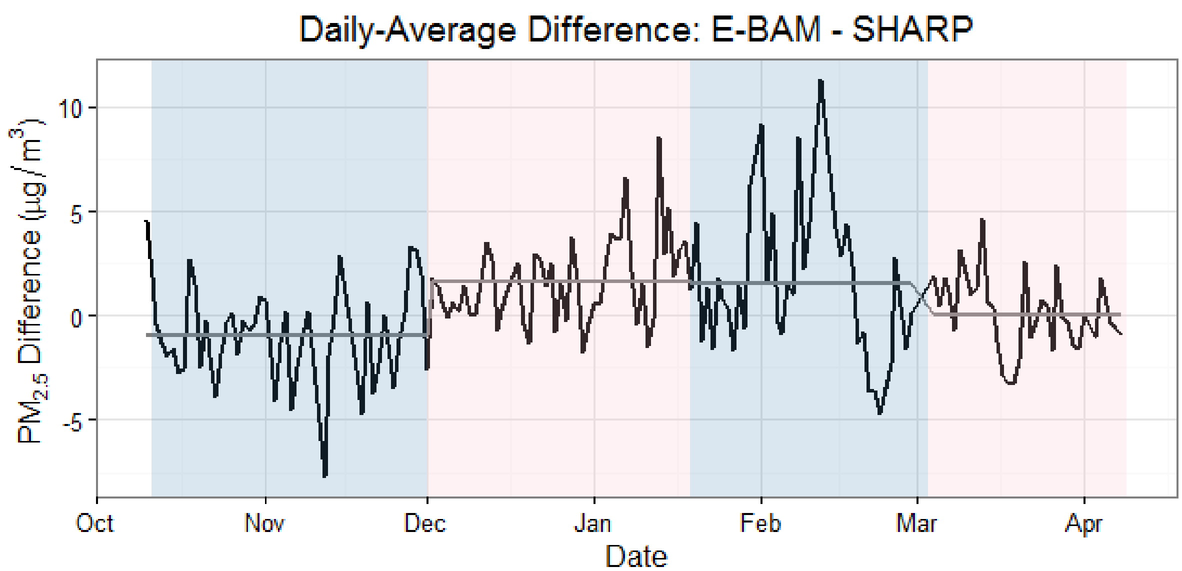

Figure 31. Difference in $PM_{2.5}$ daily-average concentrations between the E-BAM and SHARP monitors

There are a few peaks, positive or negative, that surpass a difference of ±5 micro grams per cubic meter, but the differences generally remained relatively low. The average difference in each period is shown by a grey line. The first and last periods had lower average differences within 1 µg/m^3, whereas the average differences for the second and third periods were higher around 2 µg/m^3. In addition to these differences, the 90th percentile (P_{90}) of the absolute differences between the sites' 24-hour averages provides a comprehensive measure of the variations in $PM_{2.5}$ concentrations within urban areas (Pinto et al., 2004). Considering the total combined measurements for each location, the P_{90} value for West Kelowna is determined to be 4.6 µg/m^3, higher than the value for Downtown Kelowna of 3.5 µg/m^3, as shown in Table 8.

Table 8. 90th Percentile of absolute differences in $PM_{2.5}$ daily-average concentrations between the E-BAM and SHARP monitors

Location of E-BAM	Number of Observations	P_{90} (μg/m³)
West Kelowna	92	4.6
Downtown Kelowna	86	3.5

Downtown Kelowna exceedance from January 6th – 7th.

The larger of the two exceedance events was in the second period when the E-BAM was recording particulate matter downtown Kelowna. The exceedance during this period started at 2pm January 6th and lasted until 12am on January 8th for a total of 35 consecutive hours. During this exceedance, there were meteorological conditions that could have contributed to the high values of $PM_{2.5}$ measured downtown:

- Temperatures were seasonal between 0 and 4 degrees Celsius, which are typical temperatures for wood stove use.
- The venting index for both days was low with values of 12 on January 6th and 17 on January 7th
- Wind speeds were low at both locations, but much lower at the downtown location. Wind speeds measured downtown were quite stagnant with values less than 1 m/s for the two-day period. For the same time period at the Kelowna College station, wind speeds reached 3 m/s.

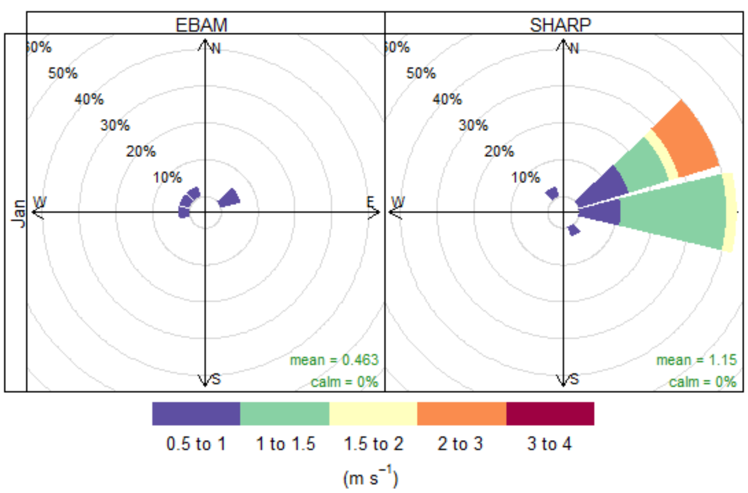

Figure 32 Wind Rose for E-BAM at Downtown Kelowna Vs SHARP when BC objective exceedance was recorded, January 6, 2016 – 35 consecutive hours

- The Environmental sounding indicated a temperature inversion at 4pm on both days. A temperature inversion is when temperature increases with increasing altitude, which prevents air from staying buoyant rising any further. These temperature inversions show a stable boundary layer close to the surface on both days, but is more prominent on January 6th. On the left side of Figure 33, an inversion layer from about 925-875 hPa can be seen for 6 of January and the right side shows a much smaller inversion for 7 January. Both days have some stable layers in the bottom part of the profile as shown in the environmental soundings (Olman, 2016).

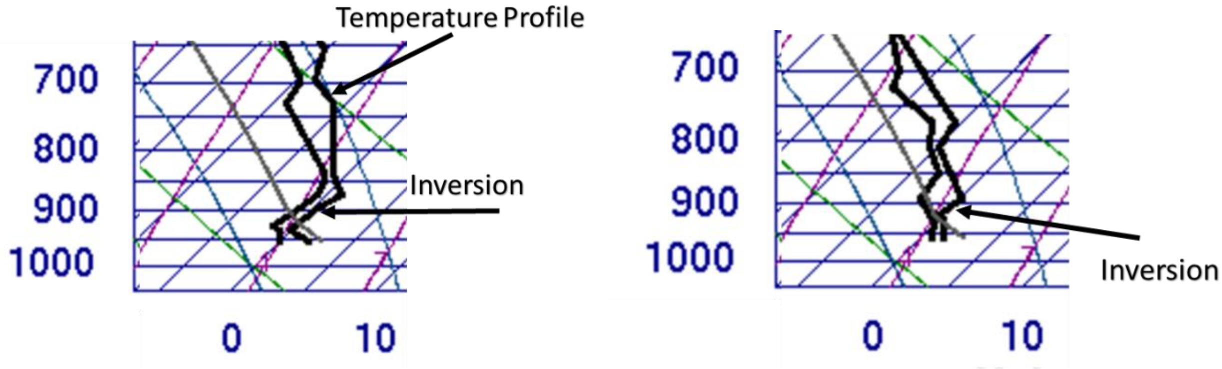

Figure 33. Temperature Inversion- 4:00 pm PST January 6 and 4:00 pm PST 7 Jan 2016 respectively

These stagnation conditions have gradually built up concentrations of $PM_{2.5}$, and eventually resulted in the BC objective exceedances at downtown Kelowna. The wind speed differences shown in Figure 32 illustrate how local conditions vary throughout the Central Okanagan, which might possibly be a factor in the different $PM_{2.5}$ concentrations.

West Kelowna exceedance on February 12th

The exceedance on February 12th lasted for a total of 20 consecutive hours, and the meteorological conditions that could have contributed to the high values of $PM_{2.5}$ were:

- Temperatures were seasonal between 1 and 5 degrees Celsius, which are still cool enough for wood stove use.
- The venting index was 27, well below good venting conditions.
- Wind speeds in both locations were low, but were blowing in different directions. In West Kelowna, winds were primarily coming from the south with a mean of 0.97 m/s and the winds at KLO Okanagan College varied from east to west with a mean of 0.98 m/s. Contrary to the first exceedance, the wind speeds at both sites had a similar magnitude. Therefore, it is possible that local sources and topography were conducive to high $PM_{2.5}$ at the EBAM site.

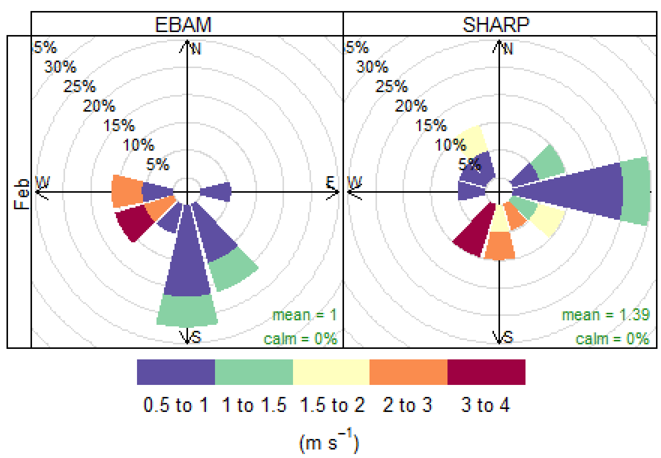

Figure 34. Wind Rose for E-BAM at West Kelowna Vs SHARP at Okanagan Collage when BC objective exceedance was recorded, February 12, 2016 - 20 consecutive hours

The discrepancies in $PM_{2.5}$ concentrations on February 12 could have been the result of factors other than differences in local meteorological conditions. A possible cause could be a fuel modification project that was performed on February 6th in the Glen Canyon Regional Park located in West Kelowna, as shown in Figure 35. The approximate distance between the E-BAM and the park is 800-1000m, which is much closer than the SHARP on the other side of the lake - 11.13 km away.

Figure 35. Glen Canyon Regional Park

This particular fuel modification was performed when the venting index was only 42, which is rated as FAIR. Normally, open burning is not allowed unless the venting index is above 65 in the Okanagan, but a custom venting index was issued for Glen Canyon Park on February 6th.

Crews disposed of fire hazard debris collected as part of a large fuel modification project on just over 15-hectares in the regional park between the trail entrances at Hebert and Brown Roads and Westbank Centre Park, south to the Gellatly Road parking area. After the fuel modification was performed there were poor venting conditions in the days prior to the BC exceedance in West Kelowna on February 12th. The gradual increase in $PM_{2.5}$ 24-hour rolling average over this period is shown in Figure 36.

Table 9. Venting Indices at 4:00 pm on February 6 to 12, 2016

Date	VI	Category
February 6	42	Fair
February 7	11	Poor
February 8	10	Poor
February 9	25	Poor
February 10	12	Poor
February 11	11	Poor
February 12	27	Poor

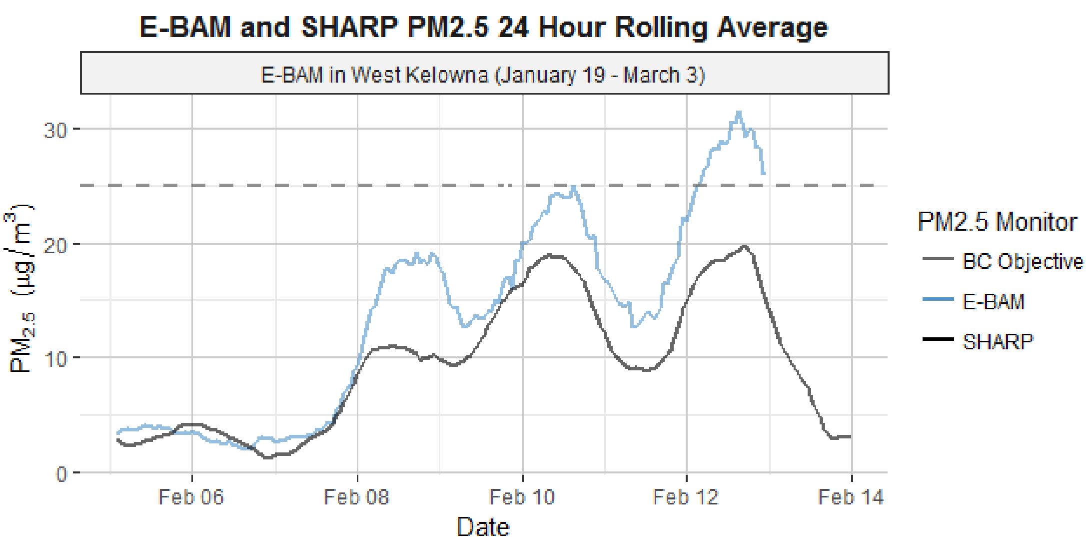

Figure 36. $PM_{2.5}$ 24 Hour Rolling Average for E-BAM at West Kelowna Vs SHARP at Okanagan Collage when BC Objective exceedance occurred in West Kelowna, February 12, 2016 - 20 consecutive hours

Regression analysis

A regression analysis was done for each location of the E-BAM. The 24-hour rolling average and the daily averages are used for the regression analysis to get a sensible correlation between both monitors since the hourly data would naturally be quite different and yield noisy regression.

In Figure 37, the SHARP $PM_{2.5}$ 24-hour rolling average is plotted against the E-BAM for each location, West Kelowna and downtown Kelowna. When looking at the correlation between data points, it will be important to factor in the distances between Kelowna College and the other two locations. The distance from the Kelowna College to City hall is 3.17 km and the distance from Kelowna College to Johnson Bentley Aquatic center in West Kelowna is 11.13 km. Taking this into consideration, it is no surprise that the correlation in Figure 37, between the two is higher when the E-BAM was placed in downtown Kelowna rather than in West Kelowna.

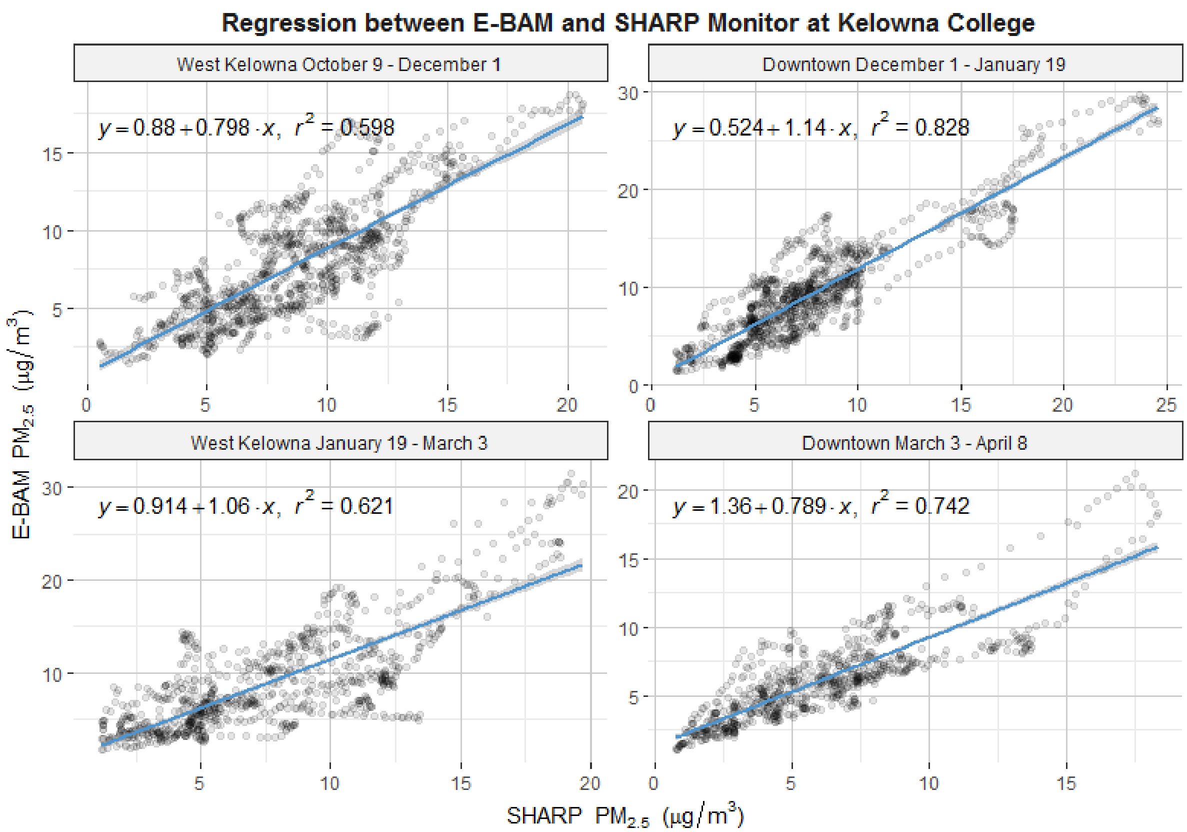

Figure 37. Regression Analysis- 24-Hour Rolling Average between E-BAM and SHARP

The equations included in Figure 37 represent the line of best fit shown in blue. This line is a basic linear model that can return an estimate of West Kelowna or downtown Kelowna $PM_{2.5}$ based on the reading at the KLO Okanagan College. The R^2 values are a measure of how well one variable represents another by the percent of data that is closest to the line of best fit. The slope of the line would indicate if there is any skew to one monitor over another. For instance, if the slope is greater than 1, than the E-BAM would overall be reading higher values. The slopes tended to be higher in the winter months regardless of location and lower in fall and spring.

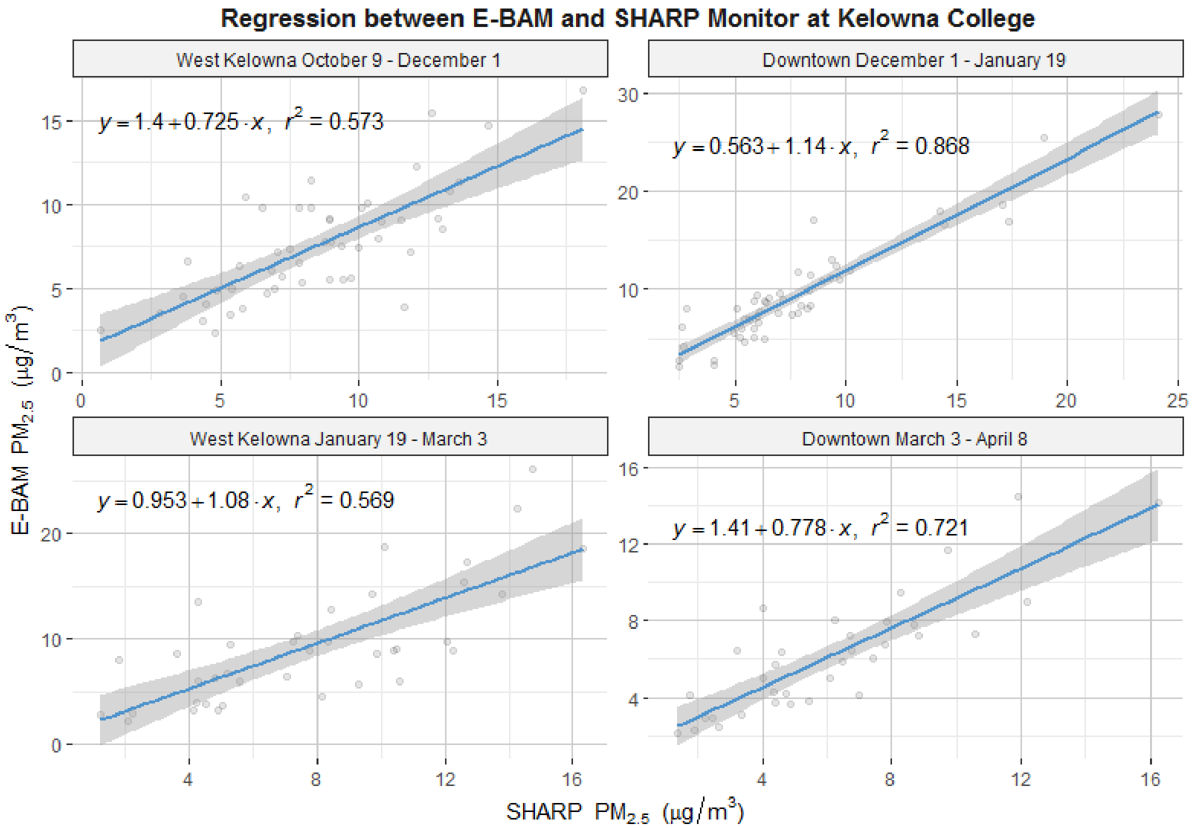

Figure 38. Regression analysis - Daily Averages

The regression analysis for the daily averages in Figure 38 show results similar to the 24-hour rolling averages. Higher correlation was found for downtown than West Kelowna. This further supports that the Kelowna College station is more representative for areas as close as downtown, and less representative for areas as far as West Kelowna. The slopes of the lines were also similar to the corresponding 24-hour rolling averages. The results suggest that the E-BAM recorded overall higher $PM_{2.5}$ concentrations in the winter at Downtown Kelowna, and the SHARP recorded higher $PM_{2.5}$ concentrations than West Kelowna in the Fall and higher than Downtown in the Spring.

Further to the above regression analysis, commonly used measures of correlation are the covariance and Pearson's r correlation. An overall summary of these measures is shown in Table 10.

Table 10. Measures of Correlation between E-BAM and SHARP

Date and Location of EBAM	Data type	R^2	Pearson's r correlation
Co-Located August 14 – September 3	*Hourly Average*	0.965	0.983
	24-hour Rolling Average	0.996	0.998
	Daily Average	0.997	0.999
West Kelowna October 9 – December 1	*Hourly Average*	0.178	0.426
	24-hour Rolling Average	0.598	0.777
	Daily Average	0.564	0.759
Downtown December 1 – January 19	*Hourly Average*	0.409	0.639
	24-hour Rolling Average	0.827	0.912
	Daily Average	0.865	0.931
West Kelowna January 19 – March 3	*Hourly Average*	0.218	0.467
	24-hour Rolling Average	0.621	0.781
	Daily Average	0.557	0.755
Downtown March 3 – April 8	*Hourly Average*	0.309	0.549
	24-hour Rolling Average	0.742	0.855
	Daily Average	0.721	0.849

More information on how these correlation parameters are calculated is provided in Appendix 4. The r and R^2 values are shown in Table 10 for each location and measurement period of the E-BAM against the SHARP at the KLO Okanagan College. For each period and location, correlation measures are provided for the hourly, 24-hour rolling, and the daily averages. Given the different locations, and considering that the E-BAM tended to produce rather noisy hourly data, the correlation for the 24-hour running and daily means are naturally higher than for the hourly data.

An important result is that each measure of correlation relative to Okanagan College was significantly higher for the Downtown location rather than West Kelowna. For example, the Downtown R^2 values for the daily averages were 0.865 and 0.721, while the West Kelowna R^2 values for the daily averages were 0.564 and 0.557. Therefore, the differences observed between these two sites indicate that the downtown measurements were fairly correlated to the Okanagan College measurements, while those at West Kelowna were less correlated.

Coefficient of Divergence

The regression analysis is a comprehensive way of showing how similar the $PM_{2.5}$ readings were between different locations. However, what this analysis does not provide is a standard measure that would indicate whether or not measurements exhibit spatial variability. One common measure of spatial variability in air quality measurements is the coefficient of divergence (Krudysz et al. 2009).

Equation 3. Coefficient of Divergence

$$COD_{es} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(\frac{x_{ie} - x_{is}}{x_{ie} + x_{is}}\right)^2}$$

Where e,s represents the monitors EBAM and SHARP respectively, n represents the number of observations and x is the $PM_{2.5}$ observations. The COD yields a fraction between 0 and 1, where 0 indicates observations that are exactly the same and 1 indicates no similarity. The threshold number typically used to determine similarity is 0.20 or 20% (Krudysz et al. 2009). The COD was calculated for the daily averages of the co-located data and data collected at each site. The COD results are shown in Table 11.

Table 11. Similarity of E-BAM and SHARP by Coefficient of Divergence

Daily Average		
Time and Location of E-BAM	**Number of Observations**	**COD**
West Kelowna October 9 – December 1, 2015	50	0.185
Downtown Kelowna December 1 – January 19, 2015 – 2016	49	0.158
West Kelowna January 19 – March 3, 2016	42	0.224
Downtown Kelowna March 3 – April 8, 2016	37	0.155
West Kelowna, combined	92	0.202
Downtown Kelowna, combined	86	0.156

Defining two sets of $PM_{2.5}$ concentrations as homogeneous when the COD is below 20% and heterogeneous when the COD is above 20% is a good measure to classify uniformity of the two sites (Wilson et al., 2005). The COD calculated for each period shows the highest similarity for the last period when the E-BAM was downtown, with a lowest COD value of 0.155. Both periods in West Kelowna had noticeably higher COD values, and the highest COD was for the third period. In reference to the COD threshold of 0.2, only for the period of January 19th to March 3rd when the E-BAM was in West Kelowna does the COD exceed the 0.2 threshold with a value of 0.224. Combining the monitoring periods' data for each location, the overall COD for West Kelowna of 0.202 is found to be higher than the value for Downtown Kelowna of 0.156. In order to provide context to the differences observed in Kelowna an additional analysis with SHARPs in the greater Vancouver area was performed.

Coefficient of Divergence and regression analysis in the Greater Vancouver Area

The correlation between the E-BAM and SHARP monitors has been variable for different monitoring times and locations. It can be hard to say whether these differences are influenced more by the distance between monitors or the $PM_{2.5}$ monitoring technology. One way to clarify this was to compare $PM_{2.5}$ readings between several SHARP monitors. Currently there is only one SHARP monitor in the Central Okanagan, but there are several operational SHARP monitors in the Greater Vancouver area and the Lower Fraser Valley. Comparing these SHARP monitors will allow for a better understanding of $PM_{2.5}$ concentration differences that is based purely on location rather than the monitoring technology. A map of the air quality monitoring locations in the Lower Mainland are shown in Figure 39.

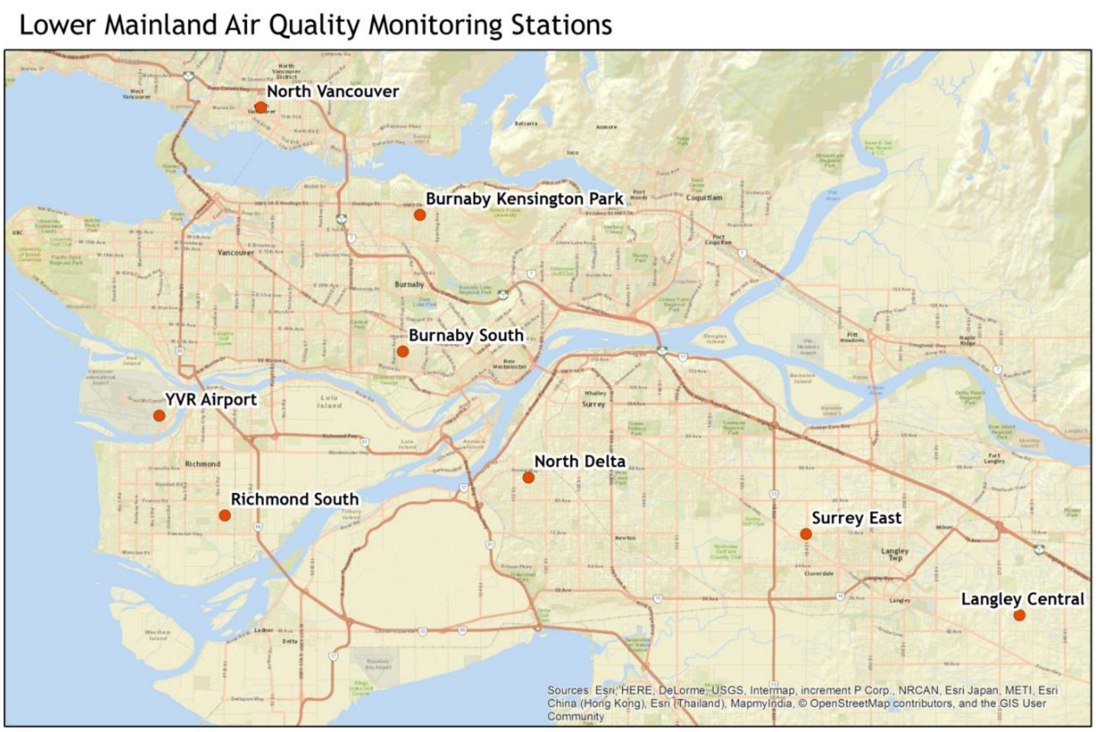

Figure 39. Air Quality Monitoring Stations in the Greater Vancouver Area

This comparison will be referenced by the Burnaby South air quality station, as it is a central location relative to the other monitoring sites. From the Burnaby South station, four surrounding air quality monitoring locations will be analyzed in pairwise comparisons using the coefficient of divergence (COD). The four neighboring monitoring stations that we will be comparing are Burnaby Kensington Park, North Vancouver Monahan Park, Richmond South and YVR Airport. These stations were chosen because they all use SHARP monitors and they have comparable distances to the E-BAM and SHARP in the Central Okanagan. The distances between Burnaby South and the four monitoring locations are as shown in Table 12.

Table 12. Station distances from Burnaby South

Monitoring Station	Distance from Burnaby South
Burnaby Kensington Park	6.8 km
Richmond South	12.0 km
YVR Airport	12.5 km
North Vancouver	14.0 km

In order to derive COD results in reference to the E-BAM/SHARP COD analysis, we compute the COD between Burnaby South and the four chosen locations for the same E-BAM measurement periods.

Table 13. COD between Burnaby South and four chosen locations

Monitoring Station	October 9th 2015 – December 1st 2015	December 1st 2015 – January 19th 2016	January 19th 2016 – March 3rd 2016	March 3rd 2016– April 8th 2016
Burnaby Kensington Park	0.187	0.208	0.162	0.149
Richmond South	0.236	0.242	0.235	0.190
YVR Airport	0.233	0.220	0.212	0.168
North Vancouver	0.247	0.184	0.176	0.209

The COD of Burnaby South against each neighboring location were all close to what was observed between the E-BAM and SHARP in the Central Okanagan. This is an indication that the two $PM_{2.5}$ monitoring technologies, E-BAM and SHARP, are adequate for the study as their differences were very similar to those found in several SHARP monitors in the Lower Mainland.

The regression analysis for the daily averages shown in Figure 40 shows $PM_{2.5}$ concentrations during the period between October 2015 and April 2016. In the regression plot there is a surprisingly high amount of scatter between Burnaby South and the other four monitoring locations. The R^2 values were relatively low, ranging from 0.504 to 0.542, and each slope was below 1 indicating that the reference station was commonly higher that Burnaby south. This result was notably different than what might have been suspected when the $PM_{2.5}$ monitoring stations are relatively close and all use the same SHARP monitor. However, Greater Vancouver is made up of a network of cities and has complex meteorology which can cause each of these stations to have varied results from one another.

The COD and the linear regression comparison in the Lower Mainland shows that even between the same SHARP monitors there can be marked differences between $PM_{2.5}$ concentrations measured at neighboring locations. This allows us to understand why there were significant differences between the E-BAM and SHARP monitoring during the study done in the Central Okanagan.

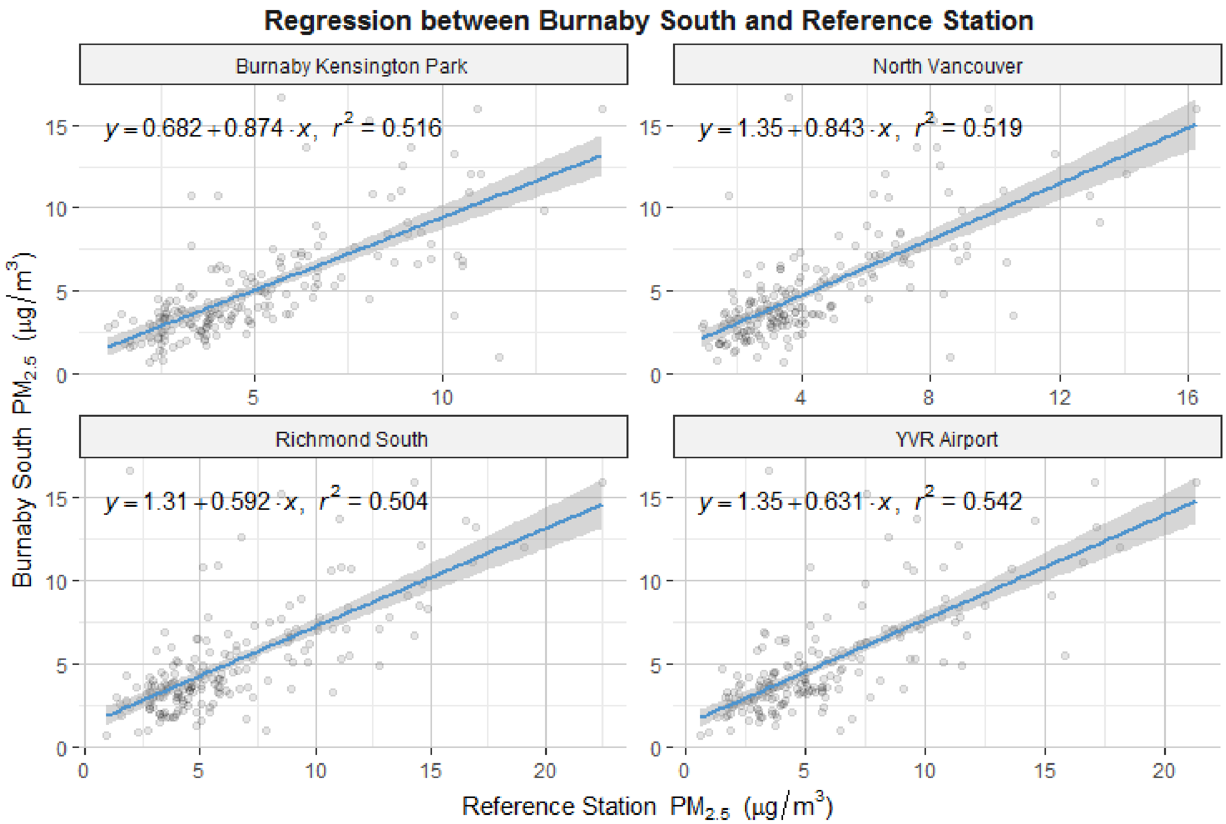

Figure 40. Burnaby South Regression between October 2015 and April 2016

Meteorology

General weather forecasts are based on large scale synoptic events. Another important factor of weather forecasts is the medium and small scale weather called mesoscale and microscale. Essentially every location has different micro meteorology, but this is especially prominent in the Okanagan due to valley, mountain and lake effects. These effects can cause localized stagnation in some areas while others are able to disperse pollutants into the atmosphere. There are a few ways in which the atmosphere can be measured for its ability to disperse pollutants such as particulate matter. The most useful is an environmental sounding which is a vertical profile of the atmosphere that records temperature, dewpoint, wind speed and direction with increasing height. When the temperature within a rising parcel of air is cooler than the air surrounding the parcel, the parcel is negatively buoyant and cannot rise further. This prevents air from dispersing higher in the atmosphere and contributes to higher concentrations of pollutants such as $PM_{2.5}$ in the air. Environment Canada and the BC Ministry of Environment takes the maximum height pollutants can reach if dispersed vertically, called the mixing height, and factors in the wind speed to create a venting index (VI.) The venting index is an easy way of communicating that information with a value from 0 – 100 (MoE, 2016).

Table 14. Venting Index values in BC

Venting Index	Ventilation Category
0-33	Poor ventilation
33-54	Fair ventilation
55-100	Good ventilation
65-100	Good ventilation for the Central Okanagan

The standard venting categories in BC are shown above in Table 14, which are classified as: good, fair and poor ventilation. However, in the Central Okanagan, a good venting index to allow any open burning is considered to be 65 or higher due to the stable boundary layer that is mostly present in valley conditions (MoE, 2016). The downside to the Venting Index is that it is produced for a large area, in this case the entire Okanagan, based on both mean wind speed and mixing height. These two variables that make up the Venting Index are calculated through a model, but can also be measured. Mixing height is rather difficult to measure as it requires data from an environmental sounding, which are launched twice a day and would represent the entire Okanagan. However, wind speed is easier to measure and analyze. Using the wind speed from each location can offer some indication on how pollutants may disperse locally.

Wind roses are plotted in Figure 41 for each period and for both E-BAM and SHARP monitoring sites. Wind rose is a graphical tool that summarises wind speed and direction data. Each pie-shaped sector shows the percentage of time that the wind blows from any given direction. The different colours within each sector show the percentage of time that winds of different speeds blew from that direction. The wind-rose also shows the mean wind speed and the percentage of calm winds, where calms are defined as hours with mean wind speed of zero.

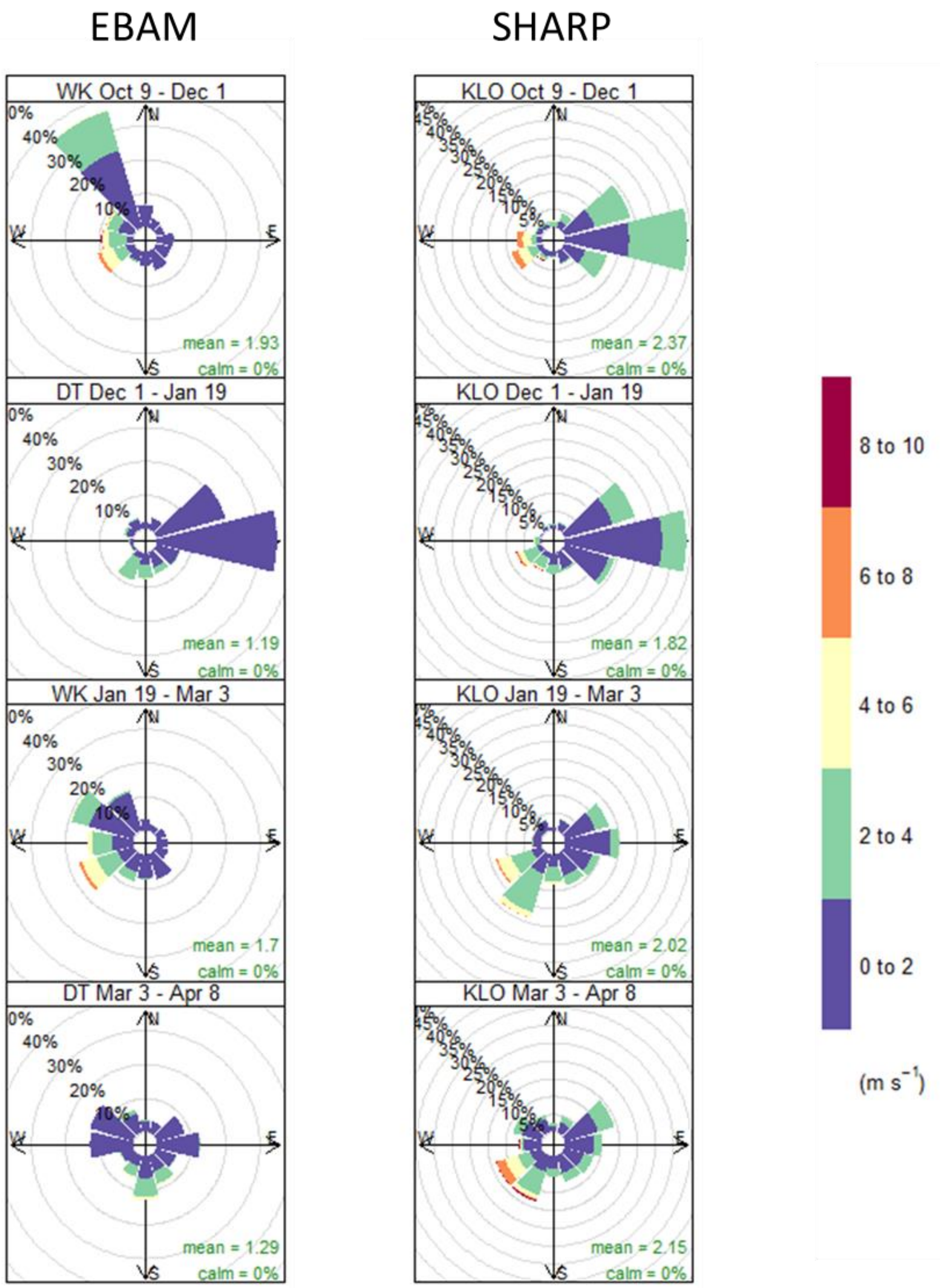

Figure 41. Wind Rose Analysis of E-BAM at selected locations and SHARP at KLO Okanagan College

The E-BAM wind roses in the left of Figure 41 show the local winds at both West Kelowna and Downtown Kelowna marked by WK and DT respectively. The SHARP wind roses, on the right of Figure 41, show the wind conditions for the same periods at Kelowna College marked by KLO. In the first period from October 9th – December 1st wind directions were quite different between the sites even though the wind speeds were comparable. In West Kelowna, wind was primarly coming from the northwest and had some wind gusts coming from the southwest. At Kelowna College, wind was primarily coming from east, but gusts were similarly coming from the southwest.

In the second period from December 1st to January 19th, the two wind roses had similar wind direcions when the E-BAM was located downtown Kelowna, with higher wind speeds measured at Kelowna College. In the last two periods, the measured wind speeds were overall higher at Kelowna College. Given that wind speed, as a component of the Venting Index, is a useful measure of how well pollutants can be dispersed in the atmosphere, the differences in wind speed between the monitoring locations are investigated in terms of mesurment period and time of day. To that end, wind speeds were only included if both the E-BAM and SHARP wind speeds were available for a given hour to ensure equal counts.

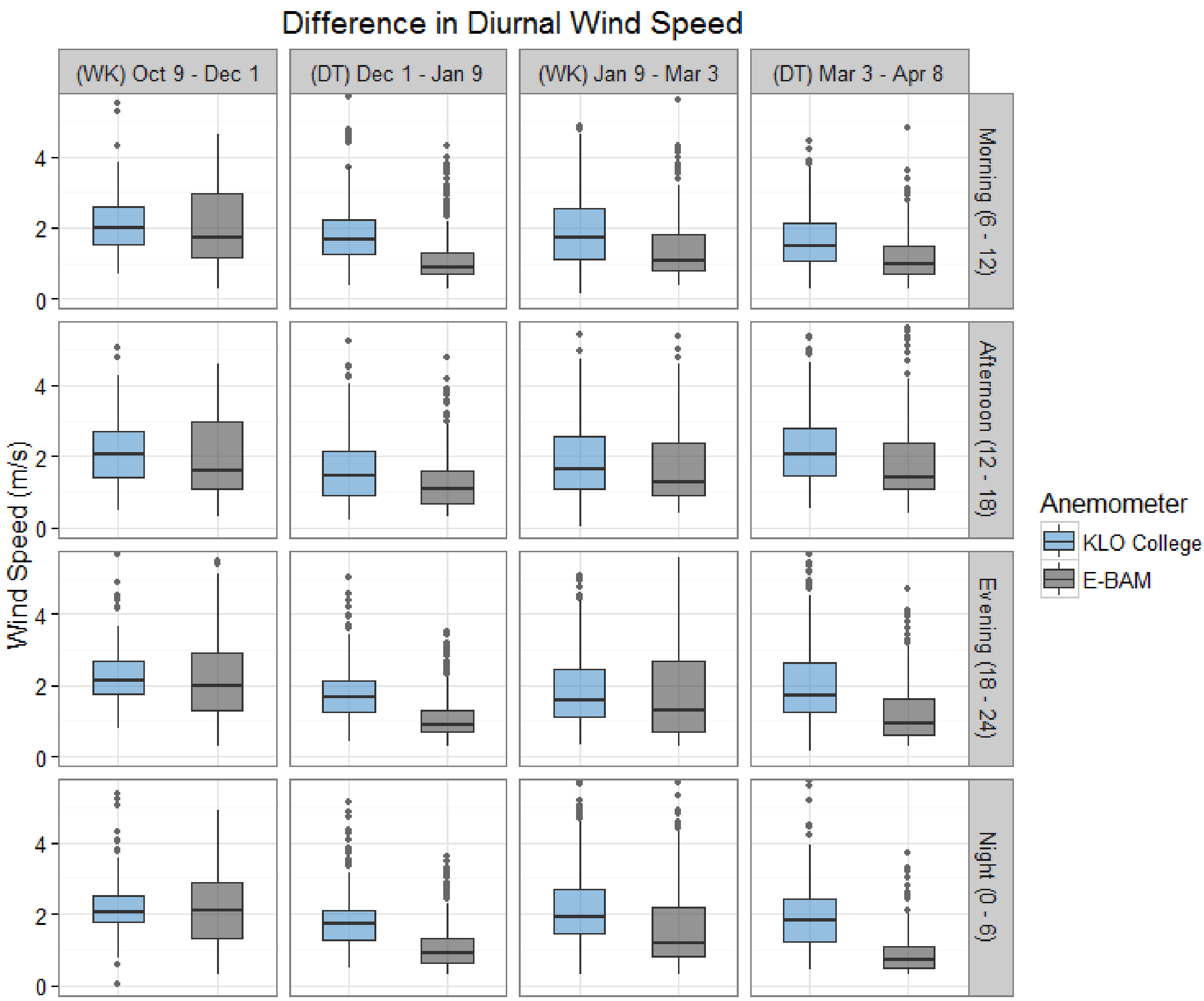

Figure 42. Diurnal Wind Speed from E-BAM's anemometer at selected locations and KLO Okanagan College

Figure 42 shows how much wind speeds can differ by time of day and by location. The columns represent the date and location of the E-BAM and the rows represent the time of day. The differences in some categories are significant; for example, the wind speeds recorded between December 1st and January 9th are markedly different. The tower anemometer at KLO Okanagan College reported higher wind speeds than the E-BAM located at City Hall for each time of day. Having lower wind speeds consistently at the downtown location suggests that, during the fall and winter season, there could be local stagnation that may contribute to higher concentrations of pollutants.

Mobile Monitoring

The E-BAM was useful in detecting varying particulate matter concentrations from the selected locations in West Kelowna and downtown Kelowna; however, there are likely areas and neighborhoods throughout the Central Okanagan that experience much higher values of particulate matter that could not be well represented by these stationary monitoring stations. These high exposure neighborhoods can be produced by transportation emissions, open burning, wood stove use and other activities throughout the valley. The $PM_{2.5}$ released into the air from these activities can vary from month to month and morning to night. In addition, seasonality could affect how much particulate matter is released in the atmosphere, while local meteorological conditions affect how well pollutants are dispersed. For example, in the colder months, wood burning stoves are used more frequently to heat homes for warmth and for aesthetic purposes, which markedly increases fine particulate matter. In addition, during these times of cooler temperatures, a stable boundary layer that restricts air from mixing into the upper atmosphere is commonly observed. These effects cause higher $PM_{2.5}$ concentrations, and contribute to compromised air quality, which are experienced mostly near areas of higher population density. Mobile monitoring captures these variations in $PM_{2.5}$ due many factors including population density, wood stove use, diurnal and seasonal variations.

The spatial representativeness of mobile monitoring can explain many factors that stationary monitoring cannot. The mobile monitoring was conducted for over six months and covered mornings, afternoons, and evenings for a wide representation of ambient conditions.

Mobile Monitoring Analysis

The mobile monitoring of $PM_{2.5}$ was conducted between November 2015 and April 2016. Over this time period there were a total of 26 trips that included a wide range of conditions. This captured a variety of dispersion produced by diurnal cycles such as convective mixed layers that happen during the day and stable nocturnal boundary layers that occur during the night and early morning. In addition, days with various venting indices were chosen to get a diverse set of sampling days. The date, time, venting index (VI), and various $PM_{2.5}$ values are shown for each trip in Table 15.

Table 15. Mobile monitoring trips

Mobile Sampling Trips									
Sampling Morning (M) Afternoon (A) Evening (E)	Date M/D/Y	Start Time H:M:S	End Time H:M:S	VI at 4:00 pm	Mean $PM_{2.5}$ µg/m³	Max $PM_{2.5}$ µg/m³	Standard Deviation	SHARP mean $PM_{2.5}$ µg/m³	SHARP max $PM_{2.5}$ µg/m³
E	11/26/2015	18:01:00	00:48:58	13	30.93	168	13.77	13.2	18.4
M	11/28/2015	05:29:11	08:26:46	11	21.03	53	3.27	6.3	6.5
M	11/29/2015	05:27:08	08:26:33	17	23.17	61	4.91	6.5	7.8
E	12/15/2015	18:15:27	00:03:22	16	21.19	108	7.03	11.0	14.1
M	12/22/2015	05:15:54	10:42:24	13	18.57	168	11.67	4.3	8.5
E	12/23/2015	17:45:27	23:16:32	11	14.35	129	12.27	8.9	13.8
A	12/28/2015	12:12:00	17:53:00	25	20.99	319	11.14	7.4	12.5
E	12/29/2015	18:02:39	23:47:14	30	11.63	315	10.74	5.4	6.6
E	12/30/2015	18:02:12	23:41:37	20	9.53	135	8.09	6.8	10.2
M	1/8/2016	05:03:23	10:32:33	11	31.58	146	11.32	12.7	17.1
E	1/18/2016	17:56:19	23:41:19	26	8.33	93	7.17	1.4	3.9
E	1/24/2016	18:06:19	23:36:59	22	13.13	79	5.89	2.7	4
E	2/2/2016	17:58:18	23:31:03	24	21.62	196	13.98	8.2	15
E	2/9/2016	18:26:12	23:53:02	25	37.71	229	20.05	24.2	29.6
M	2/16/2016	05:02:26	10:19:06	41	8.83	135	7.08	4.6	7.9
E	2/20/2016	17:37:19	23:12:54	79	14.28	317	14.29	8.4	20.2
E	2/24/2016	17:56:36	23:18:46	17	28.04	1380	29.63	17.6	29.4
E	2/25/2016	17:47:27	23:33:27	17	27.94	254	17.54	17.0	23.8
E	3/8/2016	18:22:42	01:22:37	98	10.38	116	10.14	7.8	16
E	3/16/2016	17:52:26	22:40:56	99	9.70	139	9.19	9.1	20
A	3/17/2016	12:25:00	17:21:00	99	7.83	1020	22.03	1.6	2.9
E	3/22/2016	17:55:38	22:44:08	82	6.48	229	6.46	2.3	4.3
A	3/23/2016	11:59:16	16:52:41	78	7.32	1280	26.63	2.1	3.2
A	3/25/2016	11:54:48	16:43:23	99	6.48	1290	37.44	1.5	2.3
E	3/26/2016	18:05:26	23:21:06	99	10.59	278	12.00	6.1	15.7
M	4/12/2016	05:53:49	11:24:14	99	13.64	517	15.25	6.3	8.8
A	4/14/2016	12:00:00	17:57:00	91	8.80	710	18.29	3.4	4.1

The variety of seasonal venting conditions is captured by grouping the data into three two-month periods. These periods are November to December, January to February and March to April. Using these periods, it can be demonstrated how $PM_{2.5}$ concentrations will change as the winter season transitions into spring. Within these two-month subsets, days were captured that had poor venting conditions (evenings that are calm, clear and anticyclonic), and days where venting conditions were more favorable for dispersion (cyclonic low pressure systems). Combining a variety of days for each period gives a general sense of where the areas with highest average $PM_{2.5}$ concentrations are located. In addition to varying day-to-day conditions, there were also diurnal variations to be considered. The stable boundary layer that is present in the early morning and late evening will typically result in higher $PM_{2.5}$ values than during the middle of the day. As this diurnal variation will alter the potential hot spots, the $PM_{2.5}$ observations were adjusted to remove the daily trend, as described in the following section.

Adjusting Temporal Trends

The route was designed by identifying areas that could be affected by fine particulate matter from wood stove emissions and transportation sources as described in the Route Design on page 21. Routes one and two each took about three hours to be completed from start to finish, and most of the time they were driven back to back for a total of six hours driving time in one consecutive trip. Regardless of whether the trip was taken in the morning, afternoon or evening there are trends in $PM_{2.5}$ that occur throughout a typical day that affect measurements in a six-hour period. During the cold season, these trends usually cause particulate concentrations to be lowest during the middle of the day when the air is buoyant and well mixed and highest during the night and early morning when a nocturnal inversion is present. This natural temporal trend in $PM_{2.5}$ raises the question of whether concentrations were more affected by the time of day or by location. Such a question needs to be addressed in order to determine the effect of location on $PM_{2.5}$ concentrations.

The mobile data were de-trended by finding the average diurnal trend at the stationary SHARP monitoring station and applying that trend to the mobile measurements. Since the two monitors, SHARP and DustTrak, record $PM_{2.5}$ concentrations on different scales, the results from each monitor were transformed into z-scores. Z-scores are a way of showing how far any given point is from the mean. This distance from the mean is measured in standard deviation, a universal standard of how far a quantity deviates from the mean, which is calculated by Equation 4.

Equation 4. Standard deviation

$$\sigma = \sqrt{\frac{\sum(x-\mu)^2}{N}}$$

Where the Greek letter sigma (σ) is standard deviation, the Greek letter mu (μ) is the mean and N is the number of points.

The z-scores were calculated from the stationary SHARP monitor for each hour in the 24-hour period for the same days mobile trips were taken to see the natural variations in $PM_{2.5}$ for those days. As expected, the highest values were during the night and the lowest values were observed during the middle of the day. The z-scores are calculated by subtracting each point from the mean and dividing that by the standard deviation.

Equation 5. Z-score equation

$$z - \frac{x-\mu}{\sigma}$$

Where the x is the $PM_{2.5}$ concentration from the SHARP for a specific hour, while mu (μ) and sigma (σ) are the mean and standard deviation of the SHARP concentrations over a corresponding 24-hour period.

From these Z-scores, a polynomial equation was determined to best fit the average 24-hour trend of the SHARP readings. Using the polynomial equation, which takes in the time of day and outputs the average Z-score, the data could be de-trended for temporal oscillations as shown in the following two figures.

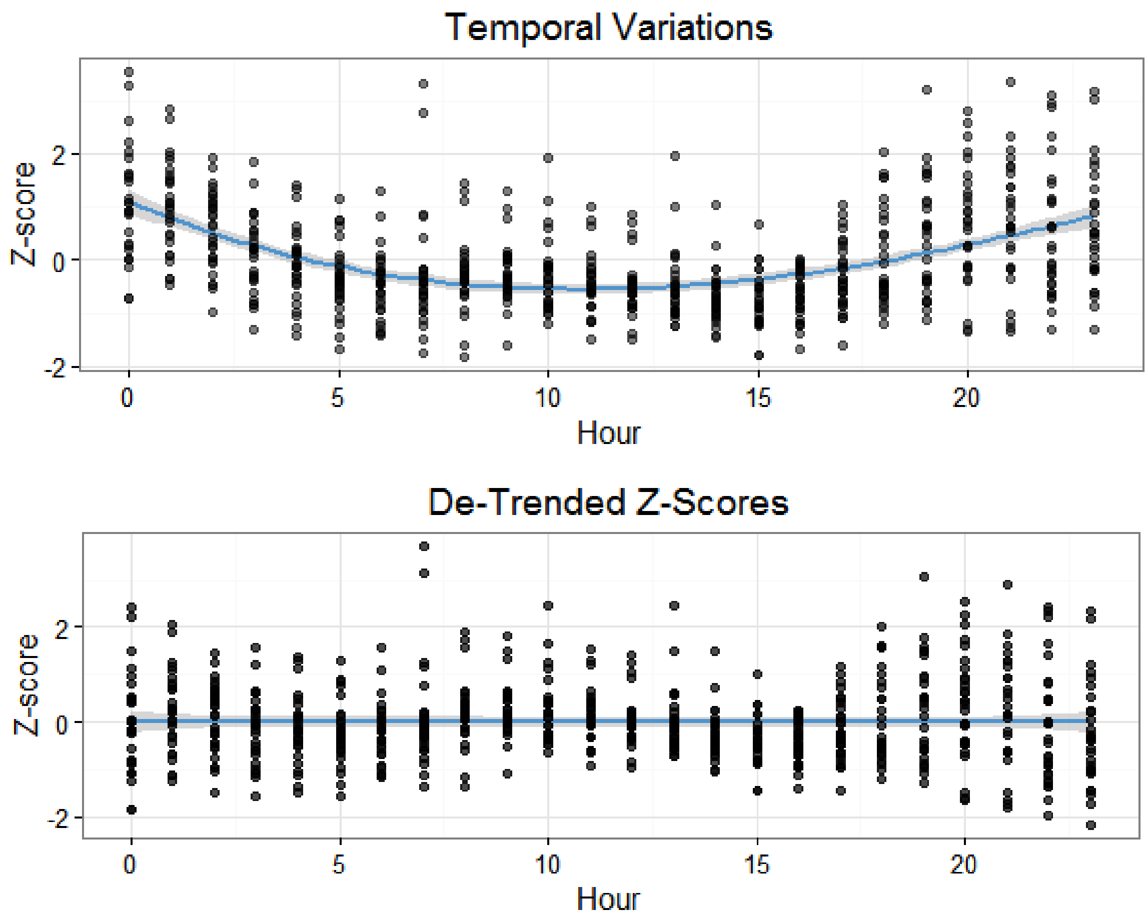

Figure 43. De trended SHARP Temporal variations

The derived polynomial equation works to counter act the daily variations. This is shown in the two figures above, where the trend is straightened to eliminate the daily peaks and troughs of $PM_{2.5}$. This equation derived from the SHARP data is then applied to the DustTrak z-score values to eliminate the temporal trend affecting the $PM_{2.5}$ concentrations. This generally means that values recorded at later hours in the day are slightly lowered and values recorded in the middle of the day are slightly raised. This was accomplished via the following equations.

Equation 6. Z-score equation adjustment

$$z = \frac{x - \mu}{\sigma}$$

$$z' = -1.09 + (0.33)h - (1.91 * 10^{-2})h^2 + (2.21 * 10^{-4})h^3$$

$$z'' = z + z'$$

$x = PM_{2.5}$ data point
$\mu =$ mean
$\sigma =$ standard deviation
$z' =$ z-score adjustmet
$h =$ hour
$z'' =$ normailzed z-score

Where the z-score adjustment equation is derived from the SHARP data, and all the input values are from the DustTrak data. Using a normalizing method does come with some error, as values are adjusted based on a polynomial equation. Nevertheless, such a method still provides a good estimate for eliminating false hot spots due to temporal trends.

Mobile Results

The distribution of $PM_{2.5}$ concentrations varied for each trip taken. There were some days that had high and low average values, but there is much more to look at than just the mean or median. A breakdown of each trip in a boxplot shows what the median values were, the spread of each trip's data, and the minimum and maximum values. The first nine trips in November and December had a variety of results. In this period, trips were taken in the morning, afternoon, and evening, which did not seem to have any noticeable influence on the results. Over these days, the sampling results resembled a near- downward trend until December 30th. In the period of January to February, trips were mostly taken in the evening and a couple in the morning. In this period both the spread of the data and the medians display a significant variation. As $PM_{2.5}$ values are affected by stagnation conditions and increased emissions, it was expected to have higher $PM_{2.5}$ concentrations during this period, as most wood stoves are actively in use and venting is mostly poor. The last period from March to April exhibits near-uniformity, as the medians were relatively low and the spreads of data were generally similar. This is likely due to the atmosphere's enhanced ability to disperse pollutants, as well as the decrease in emission sources – namely wood stoves. It is shown in Figure 45 that most of the days during this period have high venting indices, all of which are well into the "Good" category outlined in Table 14.

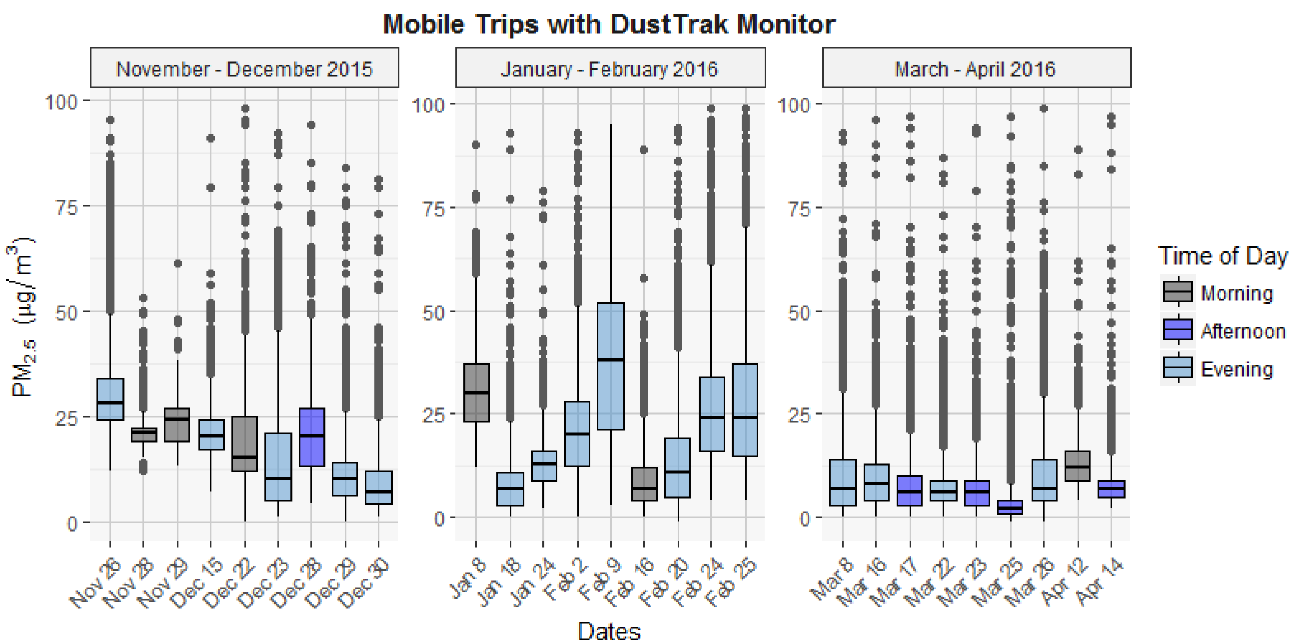

Figure 44. De-Trended Mobile Monitoring Summary

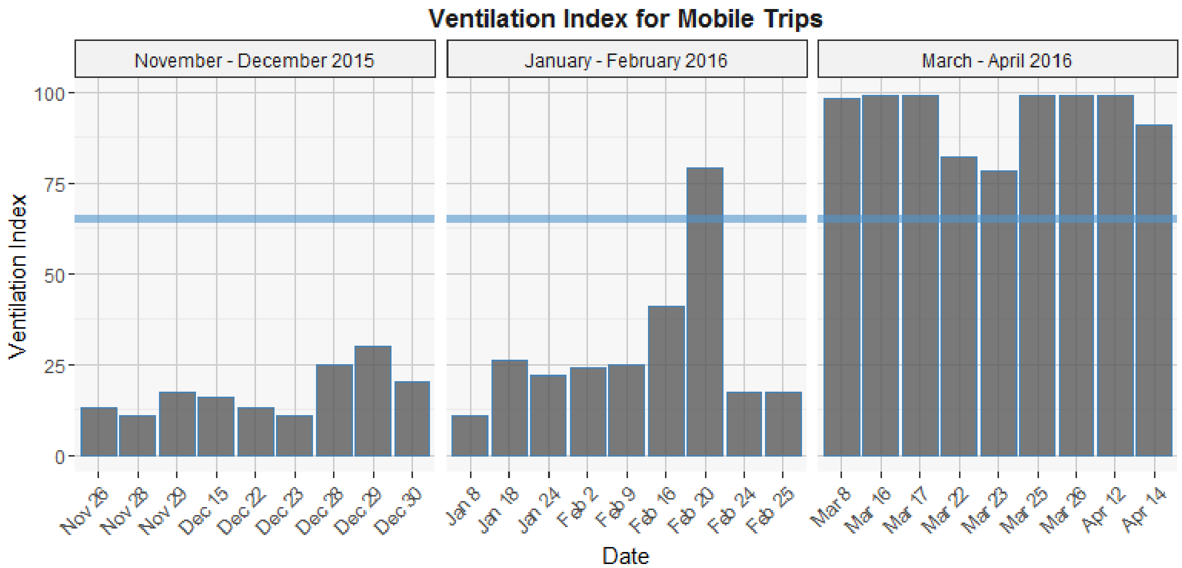

Figure 45. Ventilation Index during Mobile Trips

Figure 45 shows the ventilation index for each trip taken, where the horizontal blue line represents the threshold for good venting days in the Central Okanagan (VI 65). Comparing Figure 44 and Figure 45, we see that higher venting indices typically match up to days with low $PM_{2.5}$ concentrations. Also, the Venting Index and median $PM_{2.5}$ concentrations for each trip were compared by the scatter plot in Figure 46. The median $PM_{2.5}$ value was used in line with the boxplots in Figure 43. The colours indicate poor, fair and good venting categories. $PM_{2.5}$ concentrations within the poor and fair venting categories depict fairly scattered values, with little to no correlation to the Venting Index. On the other hand, the $PM_{2.5}$ concentrations falling within the good category have much lower values than the other categories.

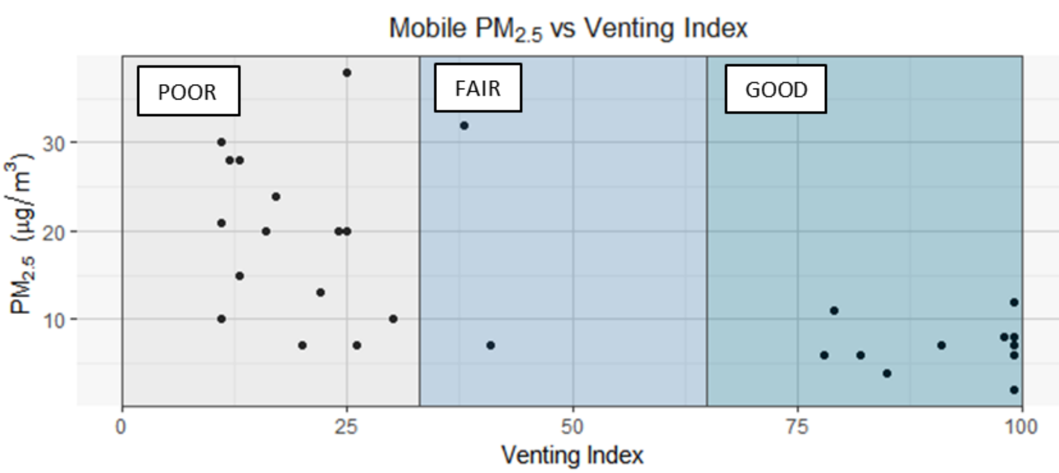

Figure 46. Venting Index vs $PM_{2.5}$ for Mobile Trips

Displaying Mobile Results

Previous mobile $PM_{2.5}$ studies done in various locations across BC provided guidance on how to analyze mobile results, but each region, including the Central Okanagan, has its own considerations due to topography and meteorology. In addition, there are other factors that could influence $PM_{2.5}$ readings, such as unexpected vehicle exhaust from trucks, construction zones and traffic jams – to name a few. Because of this, mobile monitoring has no universal standard, and there are several ways to interpret and display such information, which will be covered in this section. During the six-month period that mobile measurements were taken, there were 106,526 individual measurements made by the DustTrak monitor. This is a large amount of data to process and show on a single map. A map of each of the individual trips are shown in Appendix 7. In order to show the data in a clear way, the monitoring trips were grouped into the same three periods (November – December, January – February, March – April), as well as grouped into morning, afternoon and evenings summarized for the entire period (November 2015 – April 2016). The entire period is then shown in both $PM_{2.5}$ concentrations and also z-scores for those concentrations. The $PM_{2.5}$ values show the average spatial distribution over the entire period, which highlights the areas that had the highest combined concentrations. The z-scores are useful for showing the areas that were consistently lower and higher than the mean $PM_{2.5}$ concentrations. Both methods are beneficial to better understand the distribution over the six-month period. For each of the time periods shown, single de-trended data points were averaged by 200-meter segments along the route. This created a continuous line that represents all data points collected at a given latitude and longitude. This was done using an algorithm that selects a line segment along the route, searches in a 50-meter parameter for all the surrounding sample points, takes the average of the points and assigns the value to the route section. The process is shown in Figure 47.

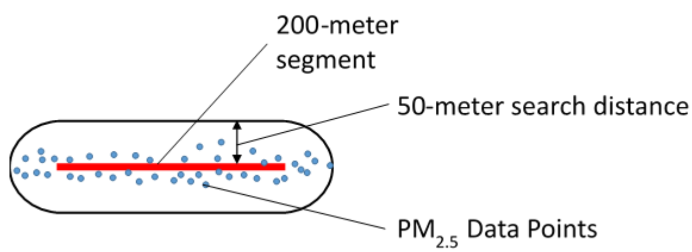

Figure 47. Route Section Average

The route section average (RSA) is the most useful way to display an average of $PM_{2.5}$ concentrations along the sampling routes. The alternative to this would be showing each individual data point which would clutter the maps and not give the full distribution of $PM_{2.5}$ concentrations. It should be noted that the RSA will average all points available for the 200-meter section. This means that maps with more measurements will be smoother and maps with less data points will be more susceptible to high and low anomalies influencing the average. Another type of interpretation is to create a continuous surface based on the data taken from the road. This would be better for displaying purposes, but can create patterns that are sometimes not present in the mobile measurements. It is for these two reasons why the RSA was chosen to display the results over the Central Okanagan. All of the maps shown in this report were created in ArcGIS software and used base layers provided by the City of Kelowna; these layers consisted of lakes, rivers, city roads and city boundaries. The maps include:

- Comparison between RSA and the wood stove density for periods between:
  - November 26, – December 30, 2015.
  - January 8 – February 25 2016.
  - March 8 – April 14 2016.
  - Morning trips (November 26, 2015 – April 14, 2016)
  - Afternoon trips (November 26, 2015 – April 14, 2016)
  - Evening trips (November 26, 2015 – April 14, 2016)
  - The entire period from November 2015 to April 2016.

All of these trips were de-trended for temporal trends.

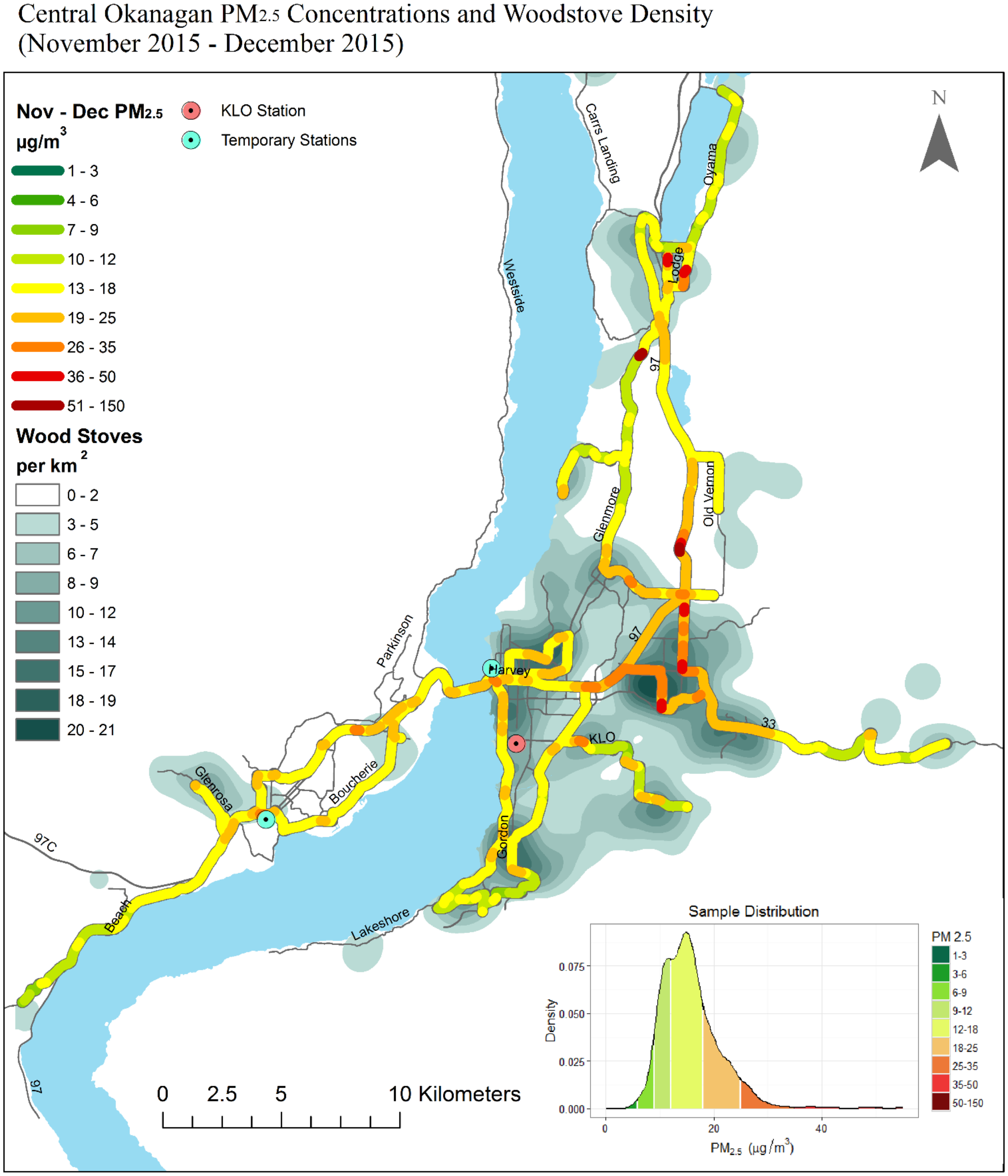

Figure 48. Mobile $PM_{2.5}$ Concentrations and Wood Stove Density-Nov to Dec 2015

During November to December 2015, nine trips with 33,210 single measurements were taken that included three mornings, one afternoon and five evening trips. The sample distribution is close to the mean of 15.0 µg/m^3 and the standard deviation was 6.1 µg/m^3. The highest values were seen along Highway 97 and Rutland.

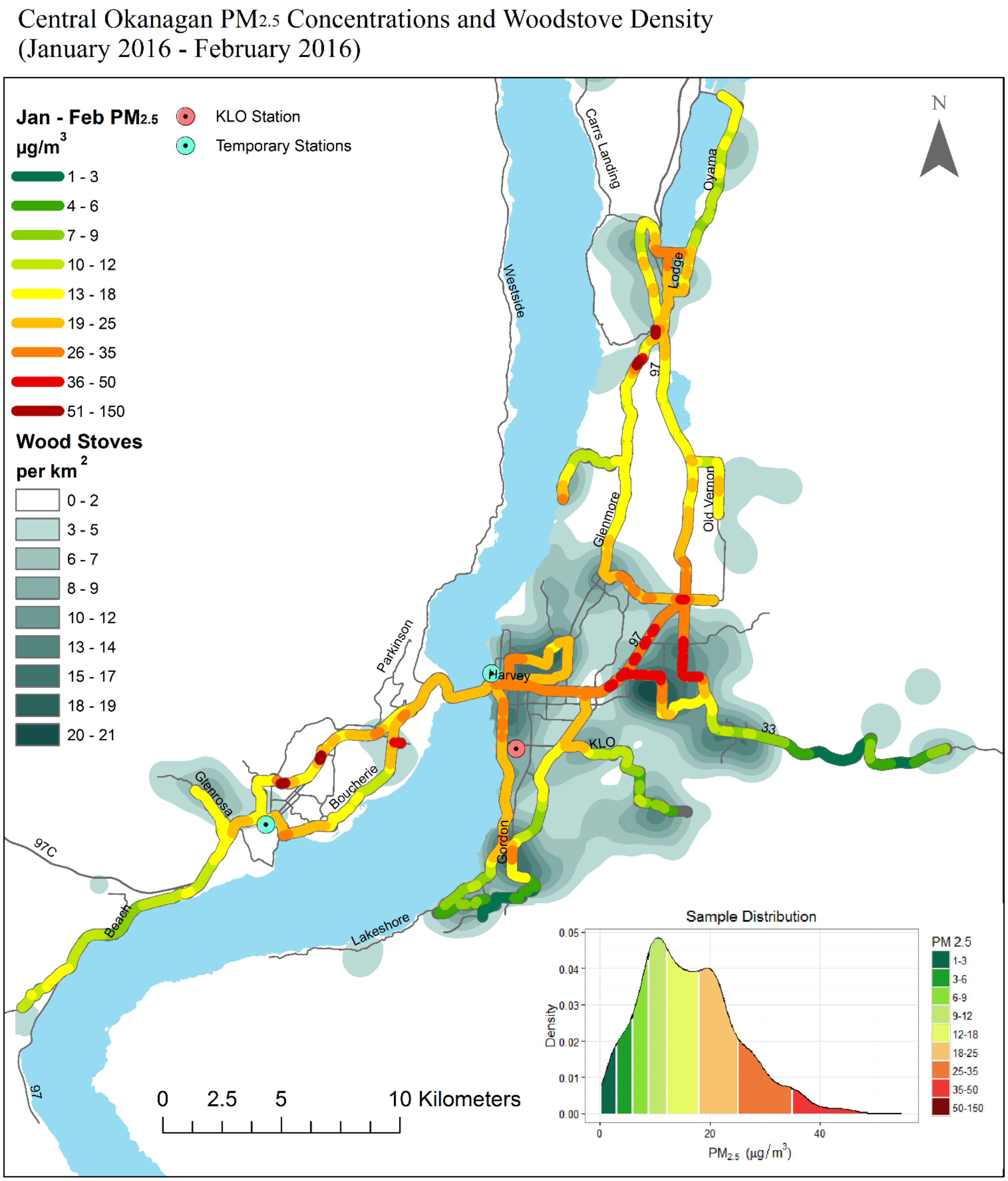

Figure 49. Mobile $PM_{2.5}$ Concentrations and Wood Stove Density-Jan to Feb 2016

During January to February, 2016 nine trips with 35,784 individual measurements were taken that included two morning and seven evening trips. The sample distribution was quite spread out in this period, with a good number of samples in each category. The mean was 16.3 µg/m^3 and the standard deviation was 9.6 µg/m^3. The highest $PM_{2.5}$ average concentrations were in Lake Country, West Kelowna and Rutland.

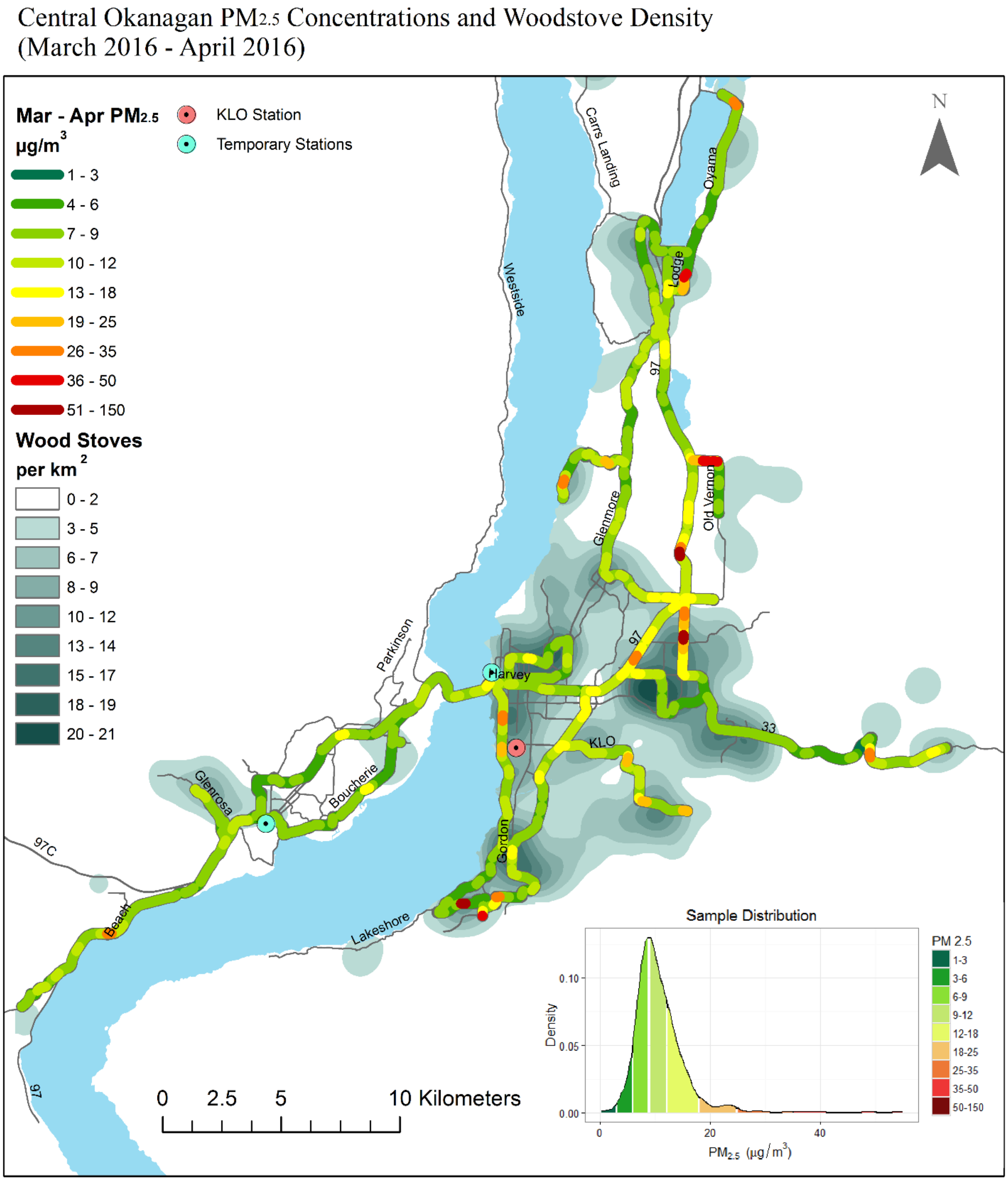

Figure 50. Mobile $PM_{2.5}$ Concentrations and Wood Stove Density-Mar to Apr 2016

From March to April, 2016 nine trips with 37,532 individual measurements were taken that included one morning, four afternoon and four evening trips. The sample distribution was relatively narrow with a mean of 11.0 µg/m^3 and a standard deviation of 7 µg/m^3. There were a few local maximum values spread out over the sampling domain, mostly in Rutland and Mission.

Central Okanagan PM2.5 Concentrations and Woodstove Density during Morning Trips (November 2015 - April 2016)

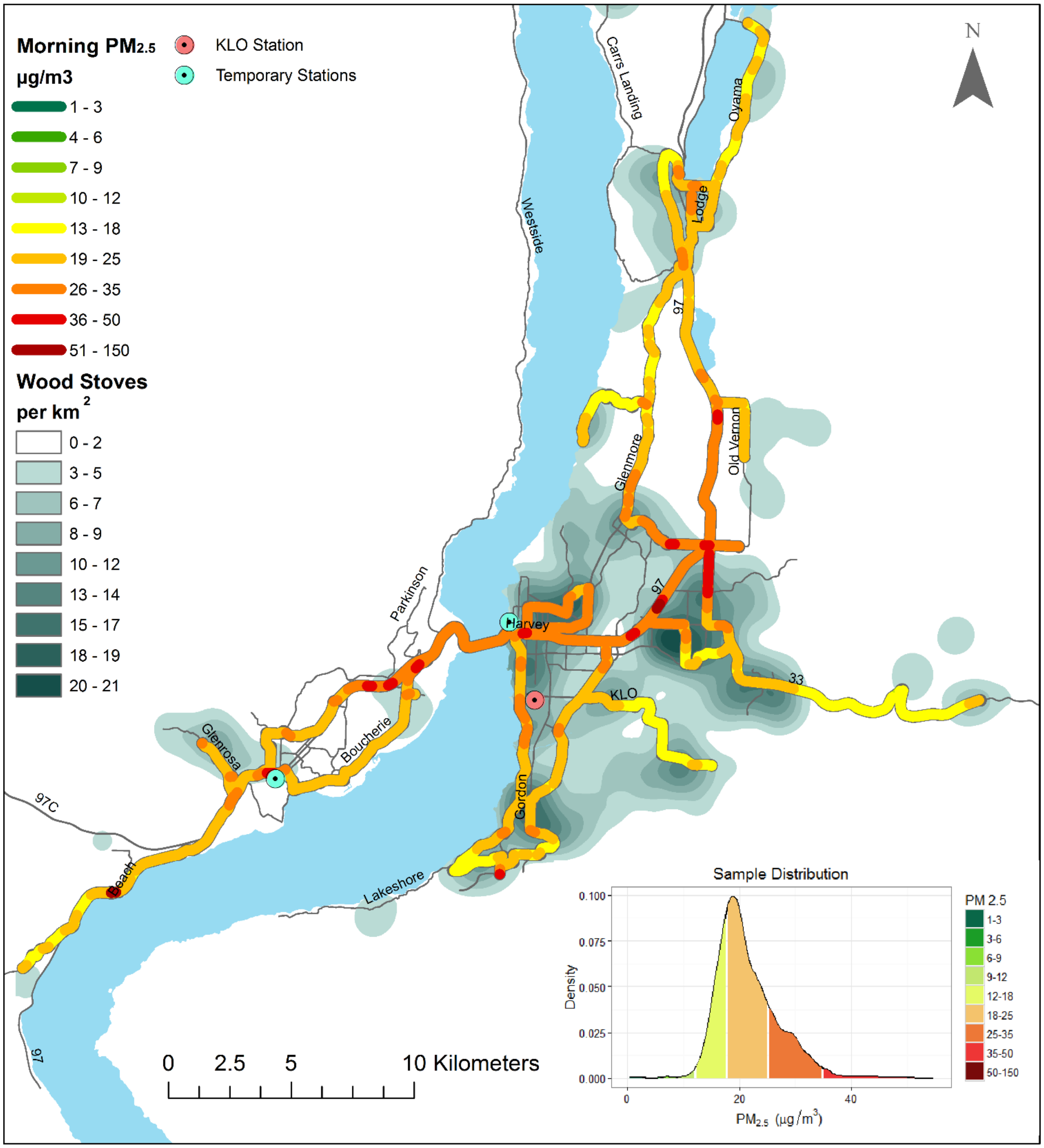

Figure 51. Morning PM2.5 Concentrations and Wood Stove Density November 2015 – April 2016

The above figure shows the $PM_{2.5}$ average concentrations for the total of five morning trips with 19,929 individual measurements taken throughout the entire sampling period. In this map we see relatively high values on average in the morning, compared to all trips combined, that are spread out over the entire area. The mean was 21.8 µg/m^3 and the standard deviation was 8.4 µg/m^3. This is possibly due to high traffic caused by the morning commute to work as well as the build up of $PM_{2.5}$ that accumulates overnight.

Central Okanagan $PM_{2.5}$ Concentrations and Woodstove Density during Afternoon Trips (November 2015 - April 2016)

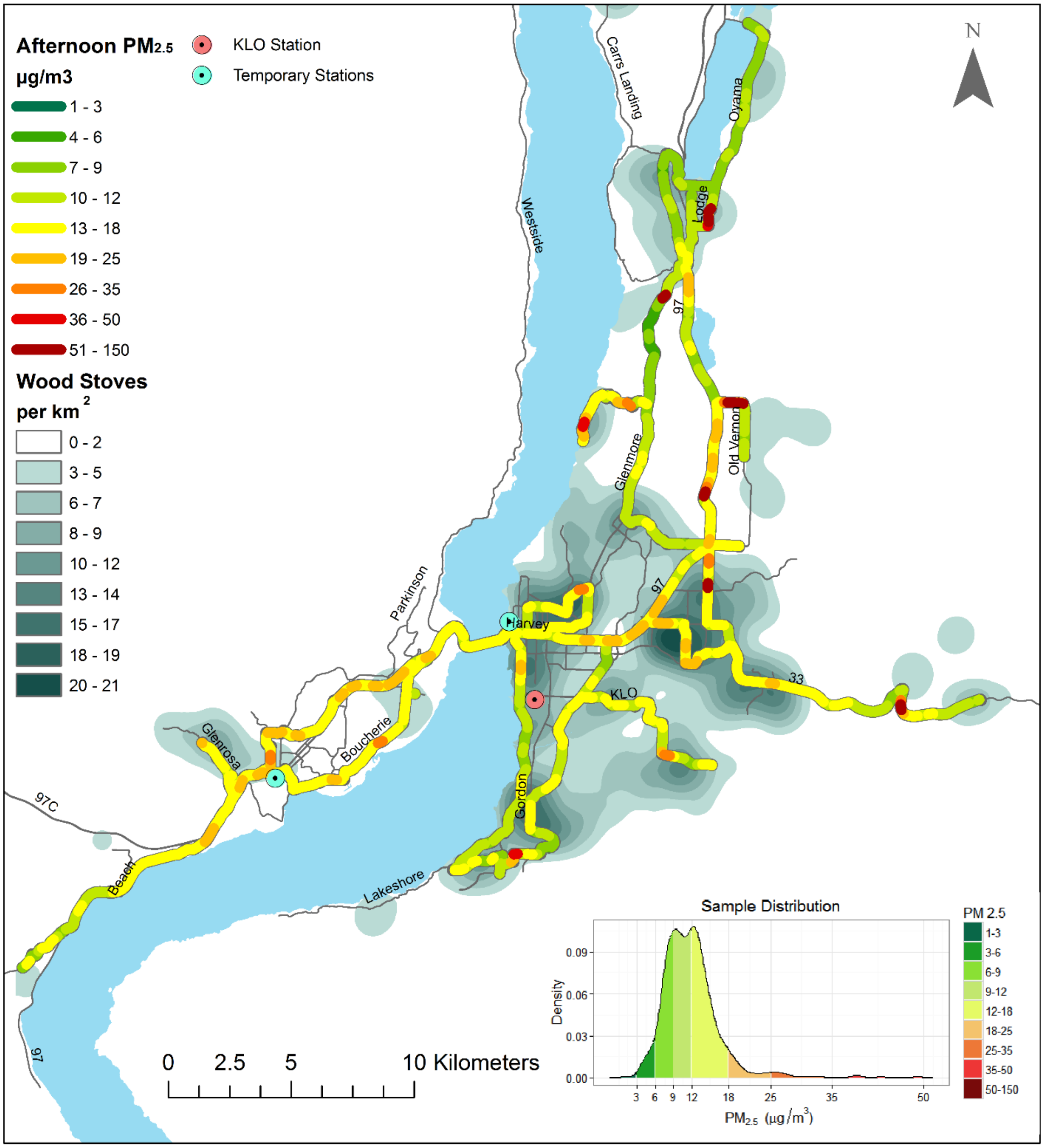

Figure 52. Afternoon $PM_{2.5}$ Concentrations and Wood Stove Density November 2015 – April 2016

Figure 52, shows the results for five afternoon trips with 21,352 individual measurements taken throughout the entire period. In this map there are hot spots spread out over major roads. This suggests that traffic emissions likely contribute to the majority of $PM_{2.5}$ in the afternoon period. The high and low concentrations were not neighborhood specific during this period and were scattered along the route. This distribution is reflected with a mean of 12.0 µg/m^3 and a standard deviation of 4.22 µg/m^3.

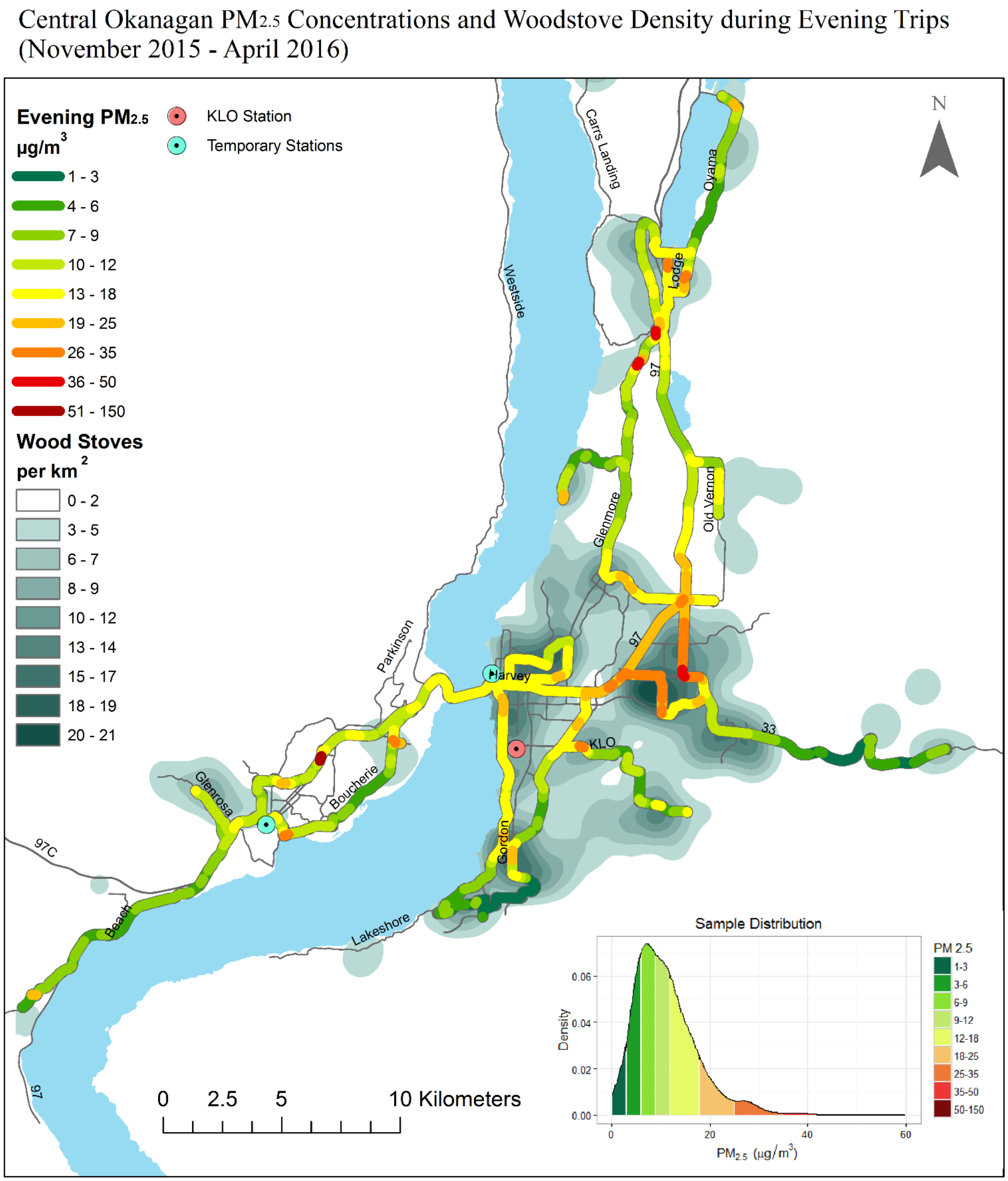

Figure 53. Evening $PM_{2.5}$ Concentrations and Wood Stove Density November 2015 – April 2016

The majority of the trips were taken in the evening, shown in Figure 53, with a total of 16 trips that included 65,245 individual measurements. The mean for the evenings was 11.0 µg/m^3 and the standard deviation was 6.6 µg/m^3. During this time of day, low and high $PM_{2.5}$ concentrations seemed to be neighborhood specific. This is shown by the low concentrations in dark green that were typically on the outer edges of the Central Okanagan, and the higher concentrations were located in areas of higher population and wood stove use. A high-exposure neighborhood was found in Rutland with some high anomalies downtown and in Lake Country.

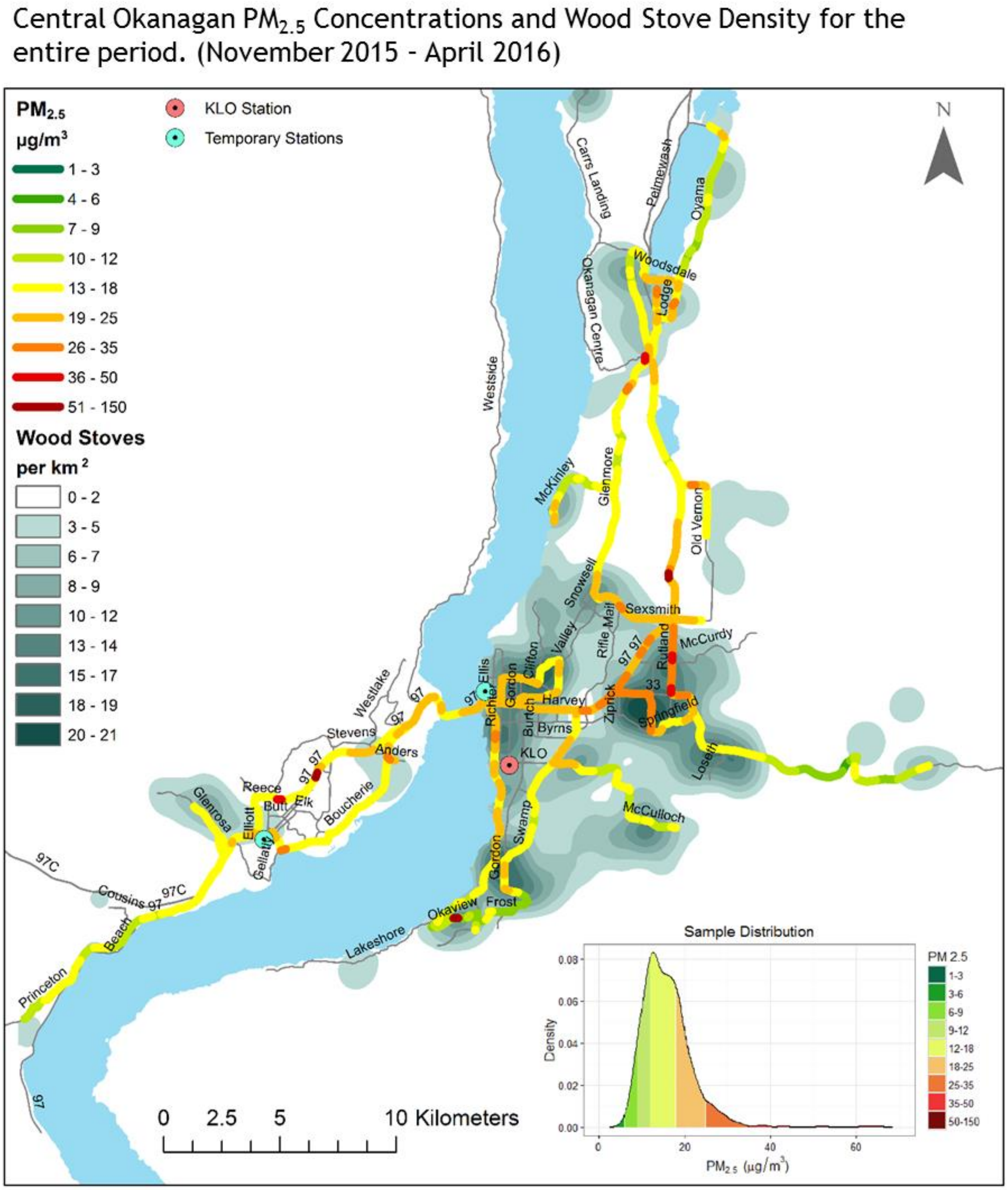

Figure 54. $PM_{2.5}$ Concentrations and Wood Stove Density for the entire sampling period November 2015 – April 2016

$PM_{2.5}$ concentrations varied from the morning to afternoon and evening periods, and over the transition of seasons from fall to spring. Nevertheless, it would be useful to analyze the spatial distribution of $PM_{2.5}$ for the entire study period. In Figure 54, a similar picture is seen as in the other maps, with higher concentrations of $PM_{2.5}$ in Rutland, Winfield and Lake Country. The mean concentration for all 26 trips is 14.7 μg/m^3, and the standard deviation is 17.8 μg/m^3. The standard deviation is considerably higher than the other averaging periods, reflecting the diversity of conditions throughout the entire sampling period.

Times and location of Highest Concentrations

- Morning
  - The particulate matter concentrations in the mornings were relatively high compared to the average of all trips taken. The mean was the highest of all diurnal periods at 21.8 $\mu g/m^3$ and the distribution was narrow, with a standard deviation of 8.4 $\mu g/m^3$. Also the spatial distribution was somewhat uniform, showing high concentrations that were spread out over the Central Okanagan. The highest values were shown to be on the busiest roads for a morning commute, such as Highway 97.
- Afternoon
  - The particulate matter concentrations in the afternoon were lower than in the morning, with a mean value of 12.0 $\mu g/m^3$, and also had a narrow distribution with a standard deviation of 4.2 $\mu g/m^3$. The spatial distribution seemed somewhat random, as low and high values were scattered across the map, with no consistent high or low anomalies. The afternoon emissions are thought to be dominated by traffic, but this does not reflect the spatial distribution shown by Figure 52. It is possible that there are other influences for these high anomalies such as open burning - four out of the five trips in the afternoon were on days when open burning was allowed.
- Evening
  - The concentrations of particulate matter in the evening had both the high and low concentrations. The mean was 11.0 $\mu g/m^3$ and the standard deviation was 6.6 $\mu g/m^3$. The spatial distribution in this period revealed high and low anomalies in a few distinct areas. It is clear, based on Figure 53 that the lowest concentrations were in the areas of lower population and wood stove density, mainly the outer edges of the Central Okanagan. The higher anomalies were in the city centers, Rutland, downtown Kelowna, Winfield, and West Kelowna. As the evenings were suspected to be primarily effected by woodstove smoke, the impact of woodstove smoke on total $PM_{2.5}$ could be significant in the development of hot-spots.

Individual maps of the 26 trips were produced and included in Appendix 7. Those maps contain:

- Meteorological variables (temperature, mean wind speed, Relative humidity and venting index)
- Observations taken by researchers that could cause a spike in $PM_{2.5}$

Hot Spots

In order to find hot spots along the route, a z-score analysis was applied. The z-scores represent how many standard deviations a measured point is away from the mean of all measurements. This was used to define a threshold of minor and major hot spots. This procedure follows similar analysis performed by a number of studies characterizing residential wood smoke (Millar, 2006).

In accordance with the methodology described earlier in this report, the mean and standard deviation were calculated for each sampling day, from which the z-scores were derived for each 200-meter route section average on a single day. Once all the z-scores were calculated for each day, they were averaged over all trips to show areas of persistent anomalies, which will be the referred to as hot spots. These hot spots were classified as major or minor according to the following (assuming a normal distribution of pollutant concentration on a sampling run):

- Minor hot spots
  - 70 – 85th percentile of data ≈ $0.52 < \text{z-score} \leq 1.04$
- Major hot spots
  - Over 85th percentile ≈ $\text{z-score} > 1.04$

Percentiles are a way of expressing $PM_{2.5}$ concentrations in relative terms. Relatively high values were assigned to be minor hot-spots, and very high concentrations were assigned to be major hot-spots. A percentile tells how much of the data lies above and below a certain point. For example, if the 90th percentile of men's shoe sizes is 12, then a man with size 12 shoes has bigger feet than 90 percent of the male population, and 10 percent of the population have bigger feet than him. This is the same principle that is applied to the percentiles for the minor and major hot-spots.

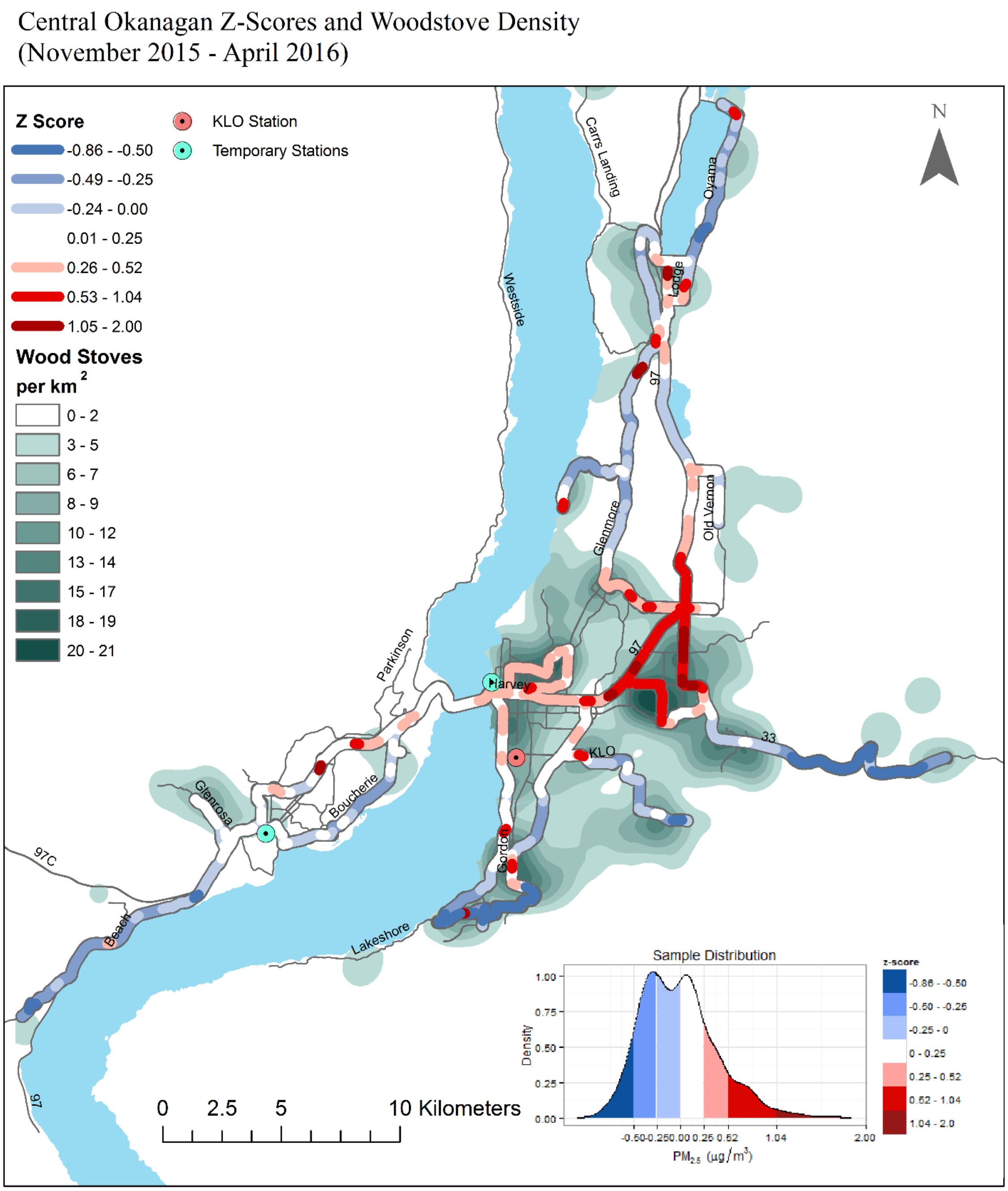

Figure 55. Z-Scores and Wood Stove Density November 2015 – April 2016

Figure 55 shows the average z-score distribution for all the 26 trips with a total of 106,526 individual measurements, which reveals consistent high-exposure neighborhoods over the Central Okanagan. The z-scores show how far a particular area deviates from the mean. Negative values are less than the mean and positive values are greater than the mean for all mobile monitoring trips.

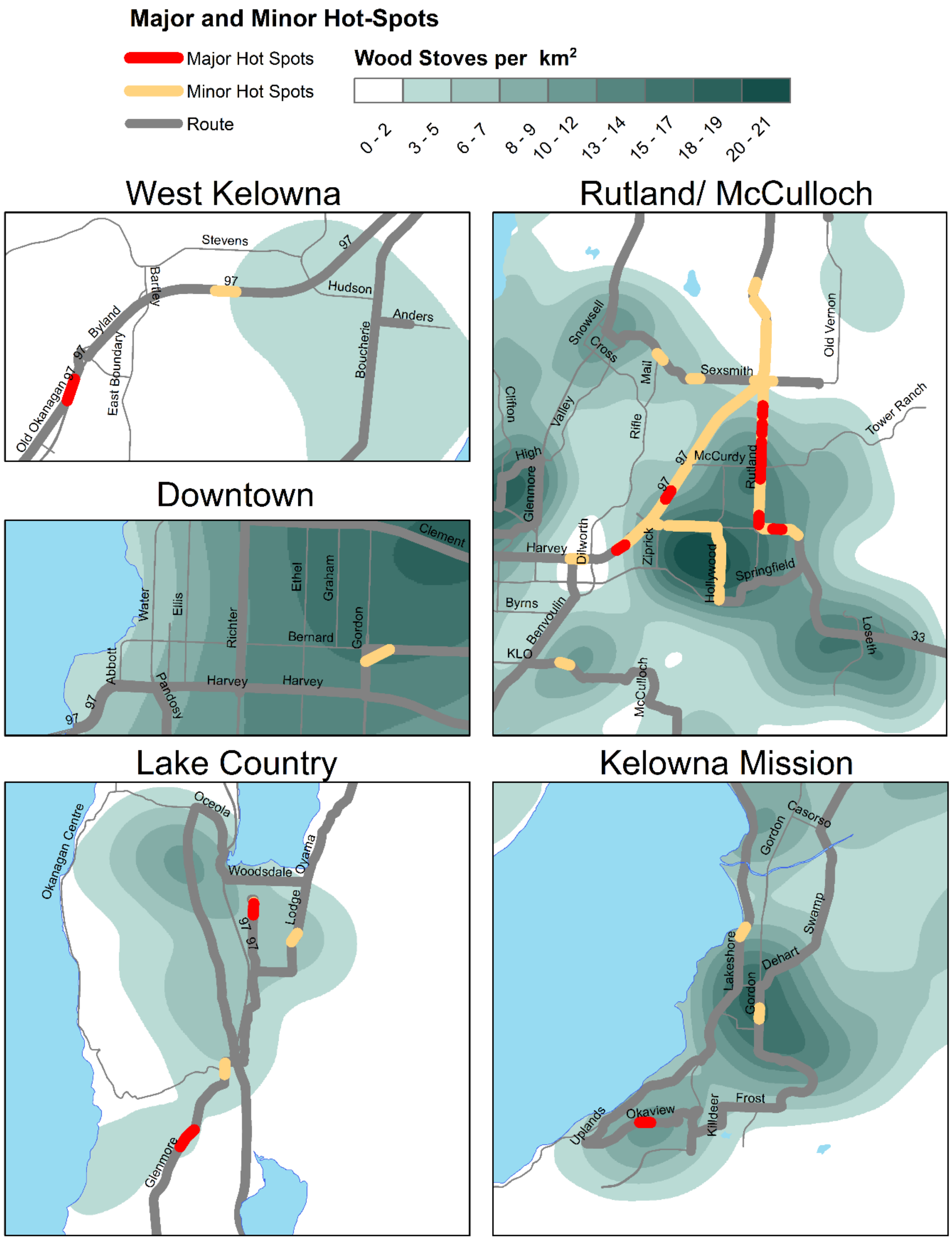

Figure 56. Major and Minor Hot spots along the predetermined Mobile monitoring route November 2015 – April 2016

The hot-spots shown in Figure 56 are for the entire sampling period using the z-score definitions of major and minor hot spots. The majority of the hot spots were located on Rutland road, Highway 33 and Highway 97. These major and minor hot spots were in line with the $PM_{2.5}$ results shown for the 2-month periods in Figure 48, Figure 49 and Figure 50. The largest and most prevalent hot-spot was in Rutland, followed by Mission and Lake Country. There are several probable causes for the hot spots, including woodstove use, traffic emissions and the local meteorology that affects pollutant dispersion.

Throughout winter and spring season, temperature inversions are experienced across the region. Without a recent speciation study, and considering only concentrations of fine particulate matter it can be difficult to identify the sources. The 2005 source apportionment study, (Allen & Jackson, 2009), found that residential wood burning was the dominant contributor to fine particulates during the winter, though other wood smoke and vehicle emissions also made notable contributions. Based on that previous study, and as described in Table 6, possible sources of $PM_{2.5}$ were identified by the time of day the mobile $PM_{2.5}$ concentrations were collected. The possible sources would differ in the morning, afternoon and the evening. Mornings would consist of woodstove smoke and traffic, afternoons would be dominated by traffic emissions and evenings would primarily consist of woodstove smoke. However, even though the mobile route was designed to avoid industry, there was reason to believe that $PM_{2.5}$ emissions from industrial sources could have an influence on the results, especially in areas that were close to industrial sources shown in Figure 12. These industrial areas were closest to the route in West Kelowna, Winfield/ Lake Country, and along Highway 97 near Sexsmith/ Old Vernon road.

Wood Stove Influence

The maps produced in the mobile monitoring section showed that in areas with higher wood stove density there was commonly high neighborhood exposure of fine particulate matter. From the diurnal maps produced, $PM_{2.5}$ concentrations had the widest distribution in the evening, with marked high exposure neighborhoods. Wood stoves are commonly in use in the evening when temperatures are cool and homes need to be heated; also in the evening the atmosphere experiences poor venting conditions, which traps particulates in the lower boundary layer. We can see the influences of woodstove smoke best during this time because there is less traffic emissions to dominate $PM_{2.5}$ concentrations across the valley. Through the evening and into the morning, we saw that $PM_{2.5}$ concentrations became higher with a narrow distribution. This could be due to wood stoves running through the night - producing smoke that gets trapped and spreads out with the nocturnal stable boundary layer when temperatures are the coolest and conditions are stagnant. This could suggest that wood stove use in the valley is a main contributor to $PM_{2.5}$ emissions. However, unlike traffic emissions, smoke from the use of wood stoves can be reduced by switching to cleaner and more efficient fuels such as natural gas or by switching to modern, more efficient wood stoves.

Challenges

The challenge with mobile data collection is that each measurement varies from the next in both time and space. Therefore, it is hard to discern whether the variability in particulate matter concentrations is the result of diurnal variations or spatial patterns. This was accounted for by de-trending the mobile measurements, which takes out some of the contribution of the diurnal variation in ventilation. All mobile maps in the previous sections were produced using de-trended data. Perhaps it even takes out a sizeable amount of that factor leaving a clearer “signature” of the temporal and spatial variations in sources. Another challenge was how to display the mobile measurements. A technique needed to be developed in order to display over 106,00 data points on a single map without compromising quality of the data. The route section average was developed in order to show averages along the route over a selected time and distance. Finally, a DustTrak co-location was planned; however, due to low levels of $PM_{2.5}$ during the co-location attempt, added to time constrains, a complete co-location analysis could not be performed.

Meteorological Conditions

This study was conducted during the winter and spring seasons from November 2015 until April 2016. In the Okanagan this time of year typically has poor venting conditions due to inversions, moderate winds, and low temperatures, all of which contribute to higher particulate matter. Cold temperatures encourage the use of wood stoves, and inversions and moderate wind speeds lead to trapping of pollutants. Although all these conditions were present, the meteorological conditions are not uniform through the Central Okanagan. It was hypothesized that micro-climates had an influence on wind speed and possibly create local areas of stagnation. This is a factor that leads to the observed variability in particulate matter concentrations. The observations are regardless of cause and they explain where people are mostly exposed to the effects of $PM_{2.5}$.

Research Assistant Availability

The initial plan was to perform all mobile sampling with the collaboration of UBCO students through a Capstone project. An application was sent to UBCO on April 2015. However, the UBCO capstone committee did not approved data collection as initially planned and rejected the project early October mainly due to safety considerations as the duration of each sampling couldn't be longer than 3 hours according to their project guidelines. In addition, sampling couldn't be conducted during December and April due to exams. Due those limitations and the nature of our project that required longer trip samplings and flexible days to perform it, a couple of researchers were hired instead, one primary and another as backup. They were trained by Ministry of Environment staff in November 2015. Therefore, data collection started three weeks later than originally planned.

Computer Issues

The researcher had some minor problems with the equipment on the first day of sampling. The computer went into "hibernation mode" about one hour into sampling. The researcher wasn't able to turn it back on, even after she changed to the spare battery. Once the researcher unplugged the DustTrak and plugged the computer into the car adapter instead to get it charged up, the computer turned back on. The GPS file was saved and the sampling continued. As a result, to avoid any battery changes during sampling and any delays, the Ministry of Environment provided a new internal notebook battery and an external battery for the computer. With the new battery further data collection was performed without any other issues.

Also during the first sampling, the USB memory stick provided to download the data off the DustTrak failed and a new USB memory stick was bought and provided to the researchers. After that, there were no other issues to access the DustTrak data.

Sampling observations and general problems encountered

A few other minor issues were reported by researchers during sampling as per the protocol described in Appendix 1:

- On December 15, the DustTrak displayed the following message: "This instrument due for calibration on 2016/01/12. Information at www.TSI.com." MoE staff recommended to not calibrate the instrument until after this sampling project was completed due to time constraints.
- Wind speed occasionally went above 10 km/h during sampling periods.
- Light rain occurred during a couple sample periods.
- One drop of oil was most often used to oil the impactor. Occasionally two drops were used, when one drop wasn't enough to absorb into the entire impactor surface.
- One time the window that holds the impactor tube in place (front passenger) was opened by accident. When safe, the research assistant pulled over, re-secured the tube, then returned to the route at the spot where the tube was dislodged, and continued.
- Accidental detours were made a few times, but always corrected
- During sampling, research assistants did their best to record on the Sampling Sheet any observations that could cause a spike in $PM_{2.5}$ (i.e. smell of wood smoke, driving through dusty conditions, etc.). However, not every single spike in $PM_{2.5}$ will be accounted for in these observation notes.

Sampling Routes Chosen

An initial route was considered covering all major postal codes with 10 or greater counts of wood stoves. However, the route length was 260 km (route 1 and 2 being 136 and 122 km in length and totaling over 5 hours of travelling). In order to have a more efficient and manageable sampling, the route was adjusted and a few areas with lesser woodstove density were taken out of from the original route. The estimated time for sampling including breaks and equipment setting was 6 hours. However, the actual sampling took longer than expected, approximately 7 hours total. The additional time was due to cleaning equipment, backing up data, and returning the OGO car to the parking lot.

Study Area

The municipalities of Kelowna, West Kelowna, Peachland, Lake Country and the East RDCO rural area were included in this project. The West RDCO rural area was not included in this project due to time and budget constraints. The route needed to be manageable for researchers to conduct all sampling and provide a general overview of possible $PM_{2.5}$ variations across the region.

Discussion

Stationary Monitoring

In addition to investigating the local and regional distributions and variations in $PM_{2.5}$, the present project aimed to answer a fundamental question: how representative measurements from a single station in Kelowna are of the Central Okanagan region? In the realm of air quality monitoring, such a question can be quite challenging to answer. Through our project design and methodology, it is hoped that our project results can shed some light and provide adequate explanations.

In urban areas, a number of factors can contribute to spatial variability in $PM_{2.5}$ concentrations, which include: local sources, meteorological conditions, topographic barriers, transient events, and monitoring differences and errors. Furthermore, an important distinction needs to be made between primary and secondary particulate matter. Local sources of primary $PM_{2.5}$, such as traffic exhaust emissions and road dust, industry and residential heating, can lead to marked variations in $PM_{2.5}$ concentrations. On the other hand, widespread formation of secondary particulate matter, coupled with the long lifetimes of $PM_{2.5}$, can lead to uniformity in $PM_{2.5}$ distributions.

When comparing air quality measurements from different sites, it is of essence to recognize the distinction between two notions: temporal similarity and spatial homogeneity. Correlation coefficients would provide a good measure of similarity between paired measurements over time, such as how well they increase and decrease together. In analyzing the $PM_{2.5}$ daily-average concentrations, whereas correlation can indicate uniformity in the day-to-day changes between two sites, it does not, however, imply uniformity in the $PM_{2.5}$ concentrations themselves. In other words, although concentrations at different sites may be highly correlated, their measured values can still differ significantly. Therefore, in addition to correlation, two other measures are incorporated to address the question of spatial uniformity in $PM_{2.5}$ concentrations: the coefficient of divergence (COD) as a relative measure of homogeneity, and the 90^{th} percentile of the differences between the sites' 24-hr concentrations as an absolute measure of homogeneity (Pinto et al., 2004).

Wilson (2005) examined a good number of studies on the subject of homogeneity in intra-urban particulate concentrations. Based on their review, studies that deduced uniformity in $PM_{2.5}$ concentrations reported Pearson's correlation coefficient (r) of at least 0.7. Pinto (2004) studied $PM_{2.5}$ spatial variability in 27 urban areas in the United States using EPA's database. Based on that study, correlation between sites was characterized as high when r exceeded 0.9, and – to certain extent – as moderate when r values ranged between 0.6 and 0.85. Based on the results of our study, and in reference to $PM_{2.5}$ measurements from the Kelowna College station, the Pearson's correlation coefficients for the paired daily-average concentrations were found to be 0.759 and 0.755 for the West Kelowna monitoring periods, and even higher values of 0.931 and 0.849 were found for the Downtown Kelowna monitoring periods. With such r values, the $PM_{2.5}$ daily averages from Downtown Kelowna can be considered well correlated with Kelowna College station, whereas values for the West Kelowna site suggest a moderate correlation with Kelowna College. Adding weight to this conclusion is our finding that, in comparing the $PM_{2.5}$ daily averages between the temporary sites and Kelowna College, their temporal trends have been fairly similar throughout the study monitoring periods.

Statistical analysis of our stationary monitoring data has revealed that, in reference to Kelowna College station, the overall COD values are 0.202 for the West Kelowna site and 0.156 for the Downtown site. Based on our literature review, a COD threshold of 0.20 is cited as a benchmark value, below which $PM_{2.5}$ concentrations from two monitoring sites are considered to be relatively homogenous (Wilson et al., 2005). While the COD value for the Downtown site is found to be below the threshold, the COD value for West Kelowna is right around that threshold. Therefore, our results indicate spatial homogeneity in $PM_{2.5}$ concentrations from the Downtown site and Kelowna College station, and seem to suggest a slight degree of $PM_{2.5}$ heterogeneity between the West Kelowna site and Kelowna College.

From our analysis, and in reference to Kelowna College station, the 90th percentile (P_{90}) of absolute differences between the $PM_{2.5}$ 24-hour averages are found to be 4.6 µg/m^3 for the West Kelowna site and 3.5 µg/m^3 for the Downtown site. Unlike the COD, there does not seem to be a well-defined P_{90} threshold for determining $PM_{2.5}$ uniformity. Based on the study by Joseph P. Pinto, 2004 their analysis suggests that $PM_{2.5}$ concentrations from a pair of monitoring sites cannot be considered spatially uniform when P_{90} values are on the order of 5 µg/m^3 or higher. Therefore, by that measure, our results for P_{90} would further favour non-uniformity in $PM_{2.5}$ between West Kelowna and Kelowna College.

In addition to the statistical measures, our study has revealed two episodes when the $PM_{2.5}$ 24-hour rolling average exceeded the provincial air quality objective at the temporary sites but not at Kelowna College station. The event on February 12th in West Kelowna lasted for 20 consecutive hours. Based on the information available from that time, that event is likely to be transient in nature, as it could have been triggered by a nearby open-burning activity. The other event, on January 6th–7th in Downtown Kelowna, lasted for a total of 35 consecutive hours and cannot be characterized as transient. Furthermore, there are no major topographic barriers between the Kelowna College and Downtown sites, and our co-location indicated a fairly good agreement between the E-BAM and SHARP measurements. Therefore, and considering the wind measurements available from our monitoring sites, it is possible that local sources as well as differences in local meteorological conditions had likely contributed to that event.

Mobile Monitoring

In the absence of co-location measurements for the DustTrak monitor in our study, it would be quite difficult to offer any interpretations on the magnitude of our mobile $PM_{2.5}$ concentrations. Nevertheless, when considered in relative terms, our mobile-monitoring results offer valuable insights into the $PM_{2.5}$ distribution throughout the Central Okanagan, help identify neighbourhoods with potentially higher exposure, as well as reveal persistent hot spots.

Our mobile monitoring has shown several areas that consistently had higher $PM_{2.5}$ concentrations than the route average, and these areas were further classified as major and minor hot spots. The most prevalent hot spot was in the Rutland area, particularly around Highway 33, Highway 97, Hollywood and Rutland Rd. There were also some minor hot spots that were noticeable in downtown Kelowna, West Kelowna, and in Lake country/Winfield. The lowest concentrations were found in Peachland, Black Mountain, Upper Mission, McCulloch and in the section of road between Kelowna and Lake Country.

There are several possible causes that can explain the high-exposure neighborhoods found in our mobile-monitoring results. The influence of temperature inversions, wind differences, and other local conditions can amplify the effects of local sources, namely woodstoves, open burnig and industrial emissions. Furthermore, seasonality seems to play a major role here. The magnitude of $PM_{2.5}$ anomalies was highest during the coldest months, which commonly had stagnant conditions and increased emissions from woodstoves, and lowest during the warmer spring months with good venting and less woodstove emissions. During the coldest period, the highest $PM_{2.5}$ anomalies were mainly found in areas with high woodstove density. Moreover, the z-score and hot-spot maps suggest a close connection between the location of woodstoves and elevated $PM_{2.5}$ concentrations.

Conclusions and Recommendations

Between October 2015 and April 2016, stationary monitoring of $PM_{2.5}$ was conducted by alternating an E-BAM monitor between two locations in the Central Okanagan. Hourly data yielded 92 daily-average concentrations from the West Kelowna site and 86 from the Downtown Kelowna site. Our analysis has shown that $PM_{2.5}$ daily averages from Downtown Kelowna are well correlated with paired measurements from Kelowna College station, whereas the West Kelowna results reveal a moderate correlation with Kelowna College. Such findings suggest that day-to-day variations in $PM_{2.5}$ tend to be largely driven by the same meteorological elements throughout the Central Okanagan. Furthermore, our findings may indicate that secondary $PM_{2.5}$ is likely to be predominant in that region. However, further analysis on the chemical composition of fine particulates would be needed to discern its origins.

Statistical analysis of our stationary monitoring results indicates spatial uniformity in $PM_{2.5}$ between Kelowna College station and the Downtown site, whereas such uniformity was not as evident between the West Kelowna site and Kelowna College. The latter finding conforms to West Kelowna's distance from Kelowna College, the complex topographic features separating the two sites, and the observed differences in local wind circulations. While our stationary monitoring yielded a relatively good number of observations, longer-term, continuous monitoring at each site could certainly add weight to more conclusive results.

Mobile monitoring was conducted to examine the spatial distribution of $PM_{2.5}$ throughout the Central Okanagan region. Data were collected during a six-month period that consisted of 26 trips along a predetermined route. More than 106,000 individual measurements were collected, which provided a thorough understanding of $PM_{2.5}$ distribution along the sampling route. All data were also de-trended and stratified by season (two-month periods), time of day (morning, afternoon, evening), and shown in terms of mass concentrations and by z-scores.

The mobile-monitoring results indicate that the $PM_{2.5}$ spatial distribution varies seasonally and diurnally. The diurnal variations provided a sense of the $PM_{2.5}$ sources and accumulations during a typical day. Without a source-apportionment study, however, it would be difficult to distinctively identify the sources of $PM_{2.5}$ along a sampling route. Based on previous studies and inventories, as well as observations made in our study, the most likely sources of $PM_{2.5}$ in the morning are lingering woodstove smoke and traffic emissions from morning commute. The main source in the afternoon was likely from traffic emissions, as indicated by the more even distribution of $PM_{2.5}$ concentrations throughout the region. In the evenings, $PM_{2.5}$ concentrations were most likely influenced by woodstoves and stagnant conditions.

Analysis of our mobile-monitoring results has revealed several areas of major and minor hot spots, most notably in the Rutland area around Highway 33, Highway 97, Hollywood and Rutland Roads. In the near future, it would be useful to conduct further stationary monitoring within the major hot spots found in this study, especially the Rutland area.

Building upon our study, population exposure and traffic related projects would be beneficial. Understanding and measuring population exposure will improve future infrastructure planning in the region (pedestrian, bike paths, bus stops, etc.). Furthermore, educational efforts on wood burning practices could be redirected to neighborhoods with potentially high $PM_{2.5}$ exposure, such as the Rutland area. Campaigns to improve vehicle efficiency and maintenance could be implemented at a regional level to bring awareness on impact of the emissions of personal vehicles.

It was shown that cold winter days in the Central Okanagan typically have low venting indices and stagnant conditions that can lead to high $PM_{2.5}$ concentrations. It is recommended to consider the development and implementation of stringent policy for wood appliances in the region; a curtailment provision that restricts the use of wood-burning appliances during poor air quality conditions or advisories, sunset provision that requires old appliances to be removed or replaced by a certain date, and ban wood appliances in new constructions, among others.

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APPENDIX 1 –Central Okanagan $PM_{2.5}$ Mobile Monitoring Protocols

1. List of Equipment

- DustTrak with power cord
- GPS (Garmin 16X)
- Lap top with power cord
- Spare external battery for lap top
- Car power converter (?) and splitter
- Map of routes
- Cleaning equipment:
  - Sonic cleaner
  - Special soap
  - Kim wipes
  - Paper towel
  - Acetone
  - Toothbrush
  - Compressed air

2. Pre-trip Preparation

- Check weather conditions using the following website to determine whether the conditions match one of the following scenarios:
  - 1. Venting Index is "poor" (under 40), wind is calm (under 10 km/h), no precipitation
  - 2. Open burning allowed, no precipitation
  - http://www.kelowna.ca/CM/Page565.aspx (open burning)
  - http://www.env.gov.bc.ca/epd/epdpa/venting/venting.html (Venting index)
  - https://weather.gc.ca/forecast/hourly/bc-48_metric_e.html (24-hour weather forecast)
  - Stagnation Forecast emails
- Email Nancy and Tarek to notify of plan to go sampling
- Reserve an OGO vehicle, selecting a hybrid whenever possible
  - 2010 Toyota Prius Hybrid (866 MTK)
  - 2009 Honda Civic Hybrid (865 MTK)
  - 2007 Toyota Prius Hybrid (CE2 57K)
- Pick up OGO vehicle and drive to Bruckal storage area to pick up equipment.
- Set up equipment in vehicle
  - See procedure notes

3. Drive routes

- Drive the pre-determined route using the navigation instructions and maps
- Aim to complete both routes (#1 and #2) during each sampling trip
- Vary between completing routes forward/backward, starting with #1 or #2 to give variance in time sampled at specific locations
- Attempt to drive appx 10km/h under the speed limit (i.e. 40 km/hr or less in residential areas, 70km/hr on the highways). Do not exceed speed limit.
- When possible, record any observations of conditions that may affect data (i.e. smell of wood smoke, drive through dust cloud, etc) on the *Mobile Monitoring Sampling Sheet*
- Check GPS and DustTrak regularly

4. GPS quality check (appx once per month)

- Identify a few points/intersections along the route (beginning/middle/end) and take note on the sampling sheet of the exact time those locations are passed by (e.g. corner of Hwy 97 and Cooper 6:32:21)
- At the end of the sampling look into the GPS file the latitude & longitude at the exact time (e.g., 6:32:21) and copy and paste the latitude and longitude into google maps to verify if the location is correct
    - i. http://www.gps-coordinates.net/
- Take notes of the coordinates confirmation

5. Post-trip

- Capture GPS Data
- End DustTrak sample and save
- Turn off all equipment, unplug, and put back into cases
- Take all equipment inside Bruckal storage area
- Copy GPS data into USB stick
- Transfer DustTrak data onto USB stick
- Clean impactor
    - i. Sonic cleaner method (used for majority of project)
        1. Fill sonic cleaner with about two inches of warm tap water
        2. Add a few drops of the special soap
        3. Place the three DustTrak impactor parts in the sonic cleaner, turn it on for 10 minutes (use a timer)
        4. Remove the parts and lightly rinse with warm running tap water
        5. Leave the parts to dry
        6. Discard the soapy water, rinse the sonic cleaner with tap water, and air dry
    - ii. Acetone method (used for the first few times sampling)
        1. Scrub the three pieces of the impactor with a toothbrush using acetone
        2. Use compressed air to dry/blow off any dust
- Put all equipment away, leave lap top charging
- Return OGO vehicle
- Download/save weather data for time of sample period
    - i. http://weather.gc.ca/past_conditions/index_e.html?station=ylw
- Transfer all data to Google Drive

6. Combine GPS and DustTrak data

- My Documents
- Data_Merger
- Open R
- File > Source R Code > Run
- Select DustTrak File
- Select GPS file
- Program will run and give diagnostics
- Fix any errors that come up
    - i. Fix GPS file errors if necessary (glitches)
    - ii. Use Ctrl+G to find line in GPS file
- Combined data file is automatically saved in Data Merger folder

- For afternoon sampling, need to switch data around in combined file due to new date in UTC time.

<u>Procedures</u>

DustTrak

1. **Zero calibration**
    a. Set up
    b. Zero cal
    c. Attach Zero Filter to DustTrak
    d. Start
    e. After 30 second when finished, remove Zero Filter
2. **Oil impactor**
    a. One/two drops on silver plate
    b. Let it absorb
    c. Place impactor face up on bottom piece of impactor, screw on top piece.
3. **Check settings**
    a. Run mode
    b. Manual
    c. Test length – 7 hours
    d. Log interval – 5 seconds
    e. Time constant (leave at 1 sec)
    f. Main
4. **Set up GPS (See instructions below)**
5. **Synchronize time with GPS**
    a. Set up
    b. Settings
    c. Date time
    d. Select time about 10 second ahead of time on GPS (ignore hour)
    e. When that time arrives, click ok
    f. Double check time is within 3 seconds when the minute changes
    g. Main
6. **Set up equipment**
    a. Connect impactor to DustTrak
    b. Connect tube to impactor
    c. White plastic end out window, secure
7. **Run test**
    a. Start (green)
    b. Screen shows name of file – record this
    c. To stop, click "Stop"
    d. Turn off equipment, disconnect tube and impactor, replace black cap on port
8. **Save data**
    a. Plug in USB stick, wait for it to load (red arrow)
    b. Data
    c. Save all → Yes
    d. When "finished saving tests", unplug USB
    e. Can delete individual files
    f. Turn off

GPS

1. **Set-up**
   a. Plug in GPS to computer using USB on left side, port on left side of computer
   b. Open Hyper terminal
   c. Cancel (to close window)
   d. File → Open → Garmin_6
   e. See “connected” in bottom left of window
   f. Transfer → Capture text
   g. Browse → Name (YYYY-MM-DD)
   h. Save in “Garmin_GPS_ runs”
   i. Save
   j. Start
   k. Will see GSP updating on screen every second and “capture” at bottom of window
   l. Synchronize time DustTrak to the GPS (within 3 seconds)
      i. Note: GPS runs on UTC time and is therefore 8 hours ahead of local time (PST)
   m. Make sure screen display brightness is turned all the way down (to conserve battery)
2. **Finish**
   a. Transfer → Capture Text → Stop
   b. Close window → Yes
3. **Save data**
   a. Plug in USB stick
   b. Transfer files to USB

APPENDIX 2 - Mobile Monitoring Sampling Sheet

Start Date and Time	
Research Assistant 1	
Research Assistant 2	
Route/Division	
Type and License Plate of Vehicle	
Starting point	
Endpoint and time	

Checklist	**X**
1 DustTrak	
1 Computer MoE	
1 GPS	
1 USB	
Download Meteorological conditions (time range of sampling) https://weather.gc.ca/trends_table/pages/ylw_metric_e.html	
Download all information on personal computer DustTrak Files and GPS.TXT	
Backup all information on USB	

Open Burning Day (Yes/No) http://www.kelowna.ca/CM/Page565.aspx	Venting Index	$PM_{2.5}$

Note taker (initials)	**Event Place**	**Event Time**	**Event Description**

APPENDIX 3- RCMP memo

REGIONAL DISTRICT of CENTRAL OKANAGAN

Regional Air Quality Program

City of Kelowna
1435 Water Street
Kelowna, B.C. V1Y 1J4

Telephone: (250) 469-8408
Fax: (250) 862-3363
www.regionaldistrict.com

RCMP
350 Doyle Avenue
Kelowna, British Columbia V1Y 6V7

November 24, 2015

As part of the 2015 Central Okanagan Clean Air Strategy, the Regional District of the Central Okanagan is performing a Mobile $PM_{2.5}$ monitoring project in the area to improve understanding of key pollution sources. A team of researchers will drive predetermined routes through the region using an OGO car vehicle. Data will be gathered from November 2015 to March 2016 and the car will be driven at a speed of 40km/h or less through several neighborhoods. The estimated time of samplings is as follows:

General Sampling	Time	To capture $PM_{2.5}$ mainly from	Season
Morning (M)	6-10 am	Traffic	Fall-winter-spring
Afternoon (A)	2-6 pm	Traffic/open burning	Fall-winter-spring
Evening (E)	6-12 am	Woodstove smoke	Fall-winter-spring

	Nov	Dec	Jan	Feb	Mar	Total sampling	Time (6hrs/sampling)
Morning (M)	1	1	1	1	1	5	30
Afternoon (A)	1	1	1	1	1	5	30
Evening (E)	1	4	4	4	4	17	102
Total	3	4	6	4	6	27	162

It is estimated to drive the complete route at least 27 times on the given timeframe. Each sampling will take up to 6 hrs to be completed. The sampling days cannot be known in advance because we will base our sampling on weather/meteorological conditions that will be forecasted one or two days in advance. The OGO cars we will use will depend on the availability for the chosen sampling day; however, the two cars we most likely we'll be using are:

- 2009 Silver Honda Civic –License Plate 865 MTK
- 2010 White Toyota Prius-License Plate 866 MTK

Attached is the $PM_{2.5}$ monitoring route for your reference. If you have any comments or concerns, please contact me.

Nancy Mora Castro, MSc, EIT
Regional Air Quality Coordinator| City of Kelowna
250-469-8408 | nmoracastro@kelowna.ca

APPENDIX 4 – Statistical Methods

The calculations performed to obtain the covariance, R^2, and pearson's r values in the regression analysis are done by performing some basic statistics. The R^2 value, which relates how well one variable represents another, is achieved by a few calculations. The first two are the the total sum of squares and the residual sum of squares. The sum of squares is the square of each point subtracted by the average of all points shown by equation 1. The residual Sum of squares is the square of the residuals (e), where the residuals are the distance between each point and the line of best fit. The R^2 is simply one minus the residual sum of squares divided by the total sum of squares shown by equation 3

$$SS_{tot} = \sum_i (y_i - \bar{y})^2 \tag{1}$$

$$SS_{res} = \sum_i e_i^2 \tag{2}$$

$$R^2 = 1 - \frac{SS_{res}}{SS_{tot}} \tag{3}$$

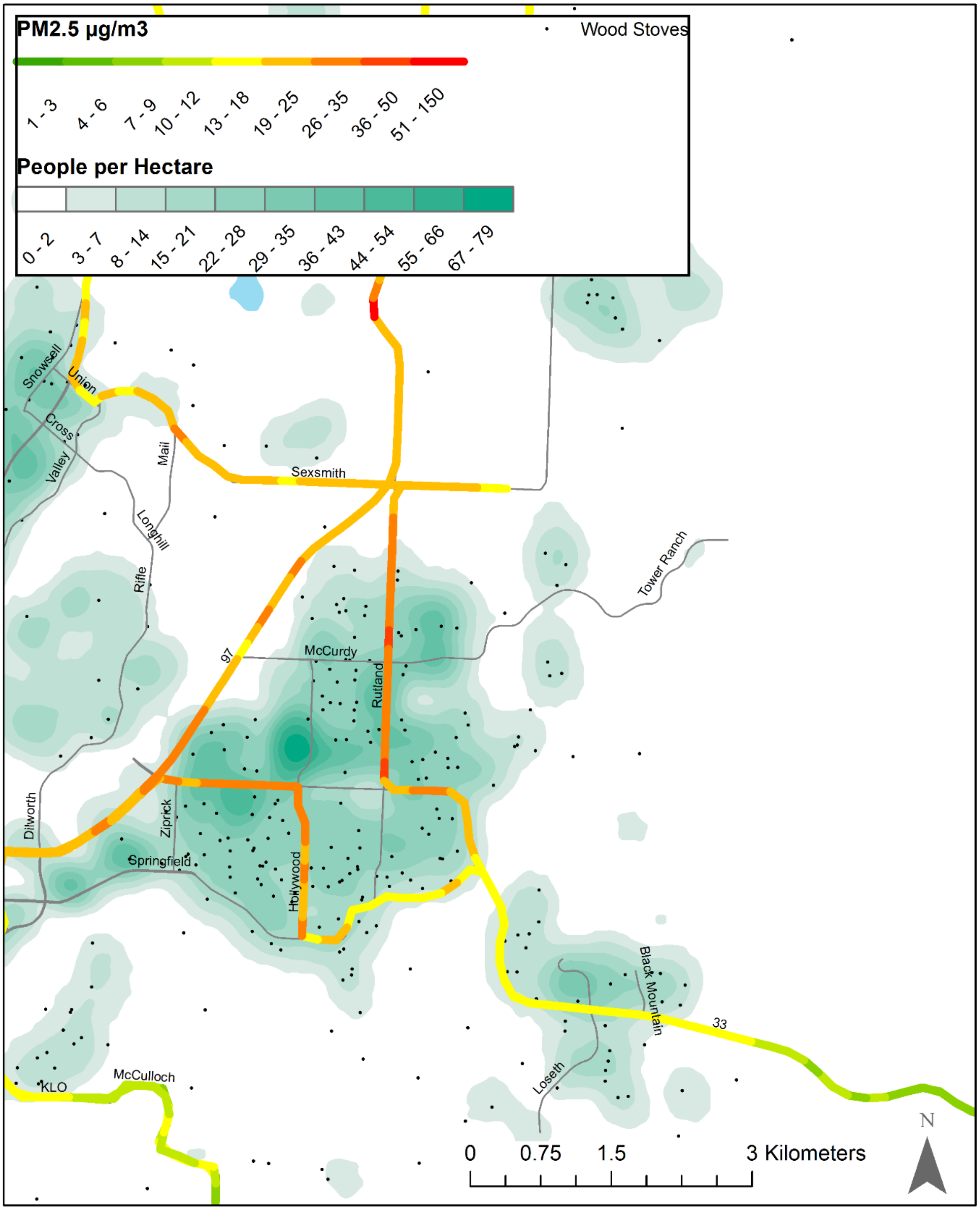
The covariance and pearson's r correlation represent the strength and direction of the two variables that are being compared. The covariance shows in particular how the two random variables change together shown in equation 5. The r correlation uses the covariance, but normalizes the result by divding by the standard deviations of each variable. The standard deviation calculation is shown in 4 and the pearson correlation is shown in 6.

$$s = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} (x_i - \bar{x})^2} \tag{4}$$

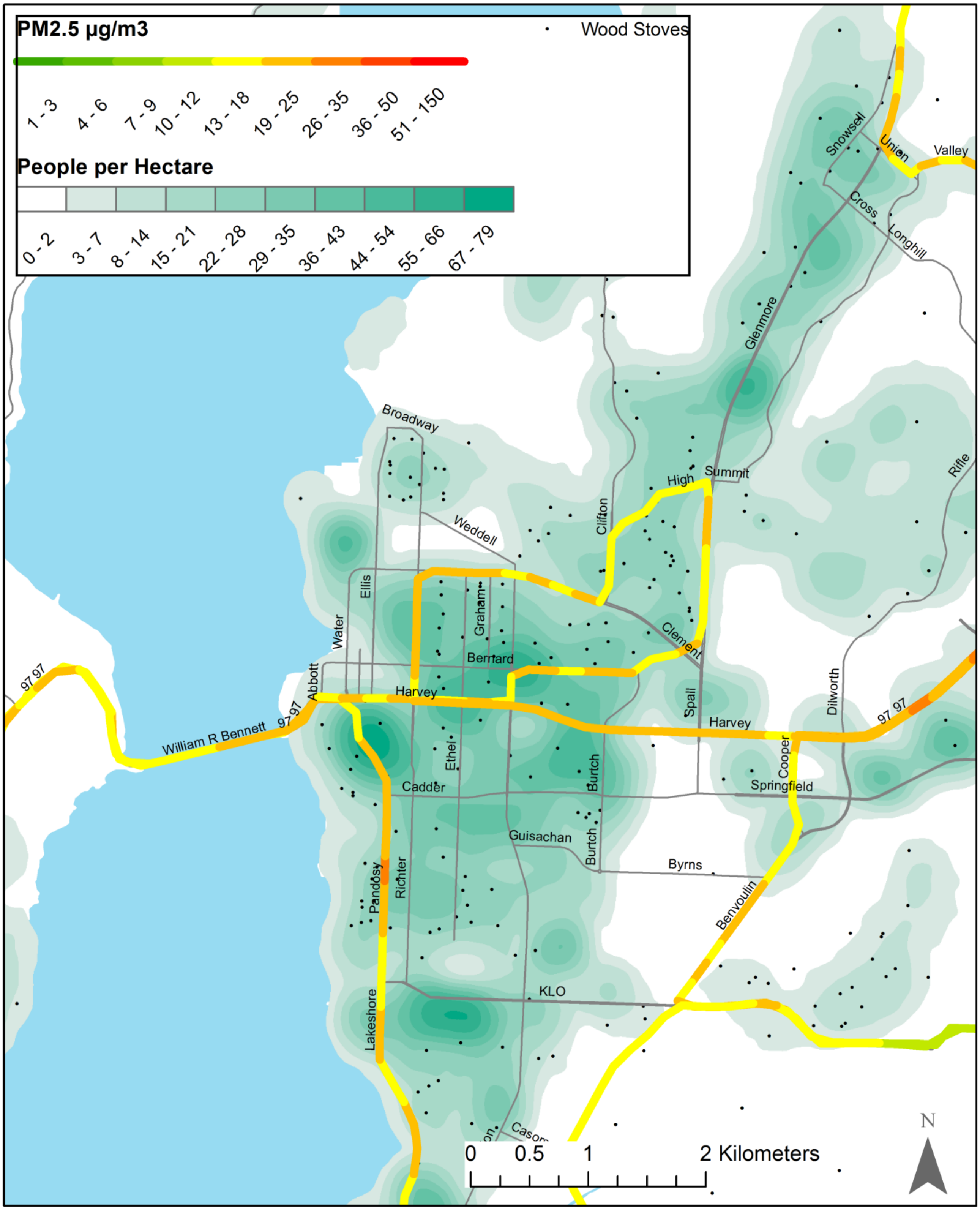
$$cov(x, y) = \frac{\sum_{i=1}^{n} (x_i - \bar{x})(y_i - \bar{y})}{n-1} \tag{5}$$

$$r(x, y) = \frac{cov(x, y)}{s_x s_y} \tag{6}$$

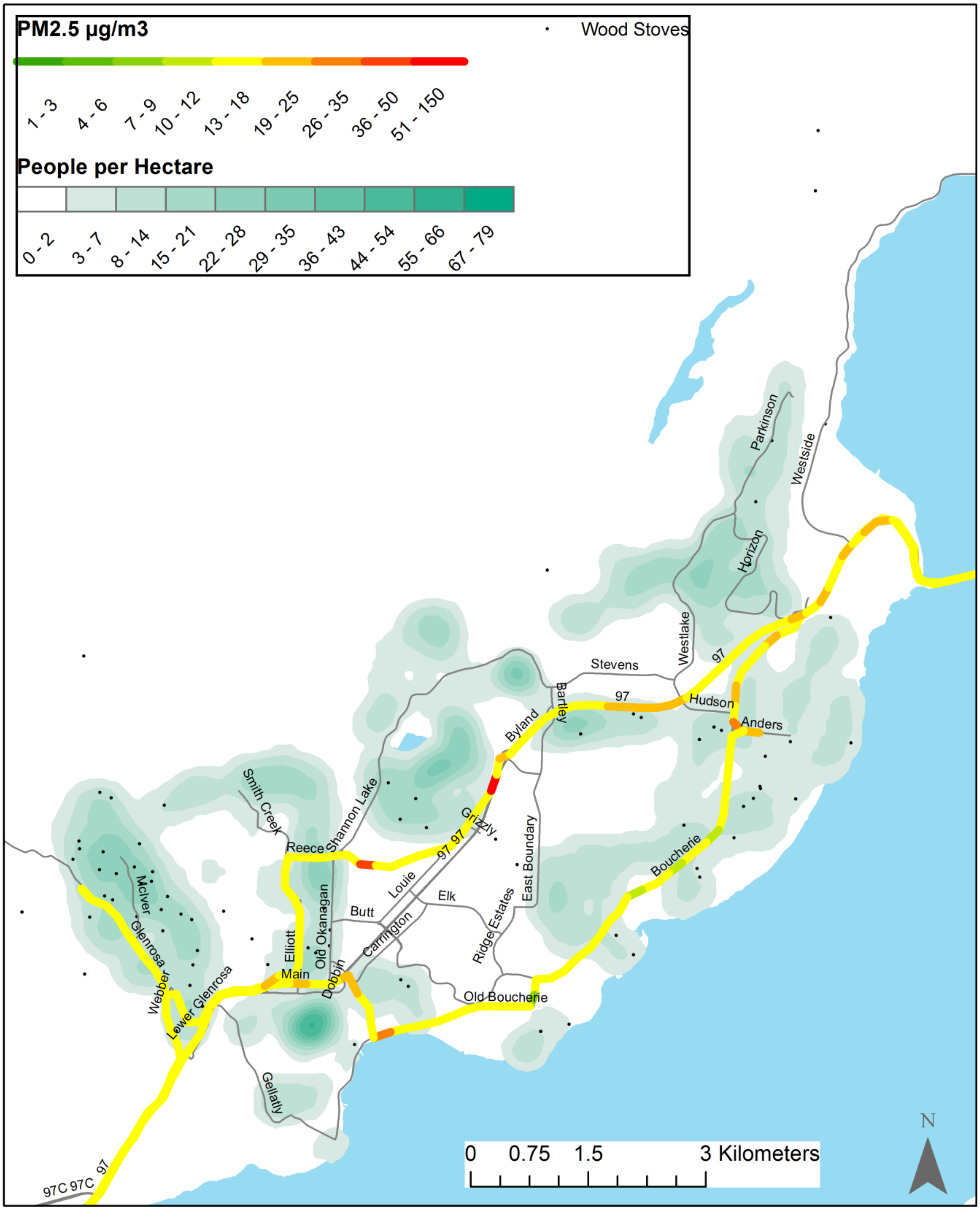
APPENDIX 5- Population distribution, IDW maps



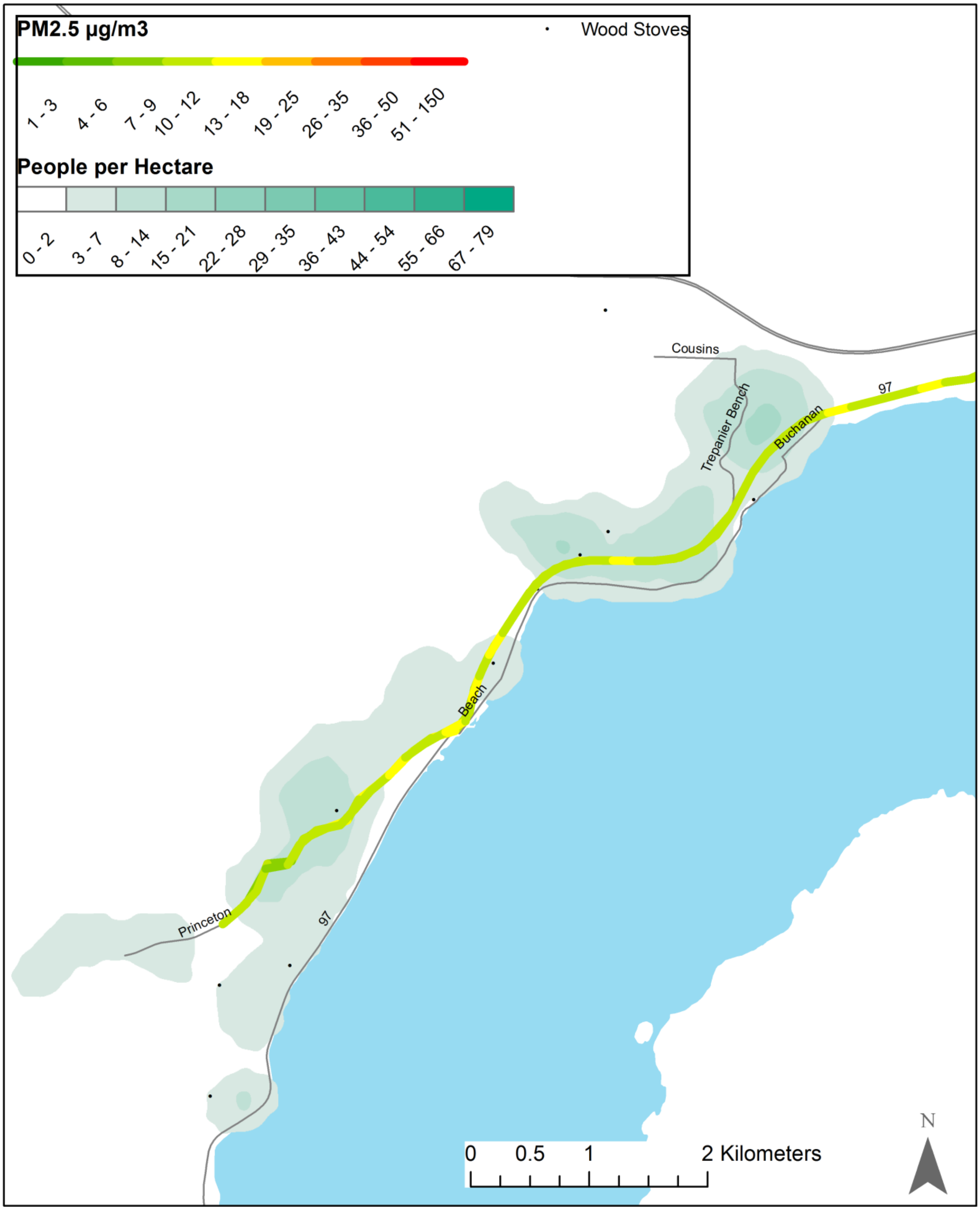
Rutland Population Distribution with Woodstoves and PM2.5 Concentrations (November - April)



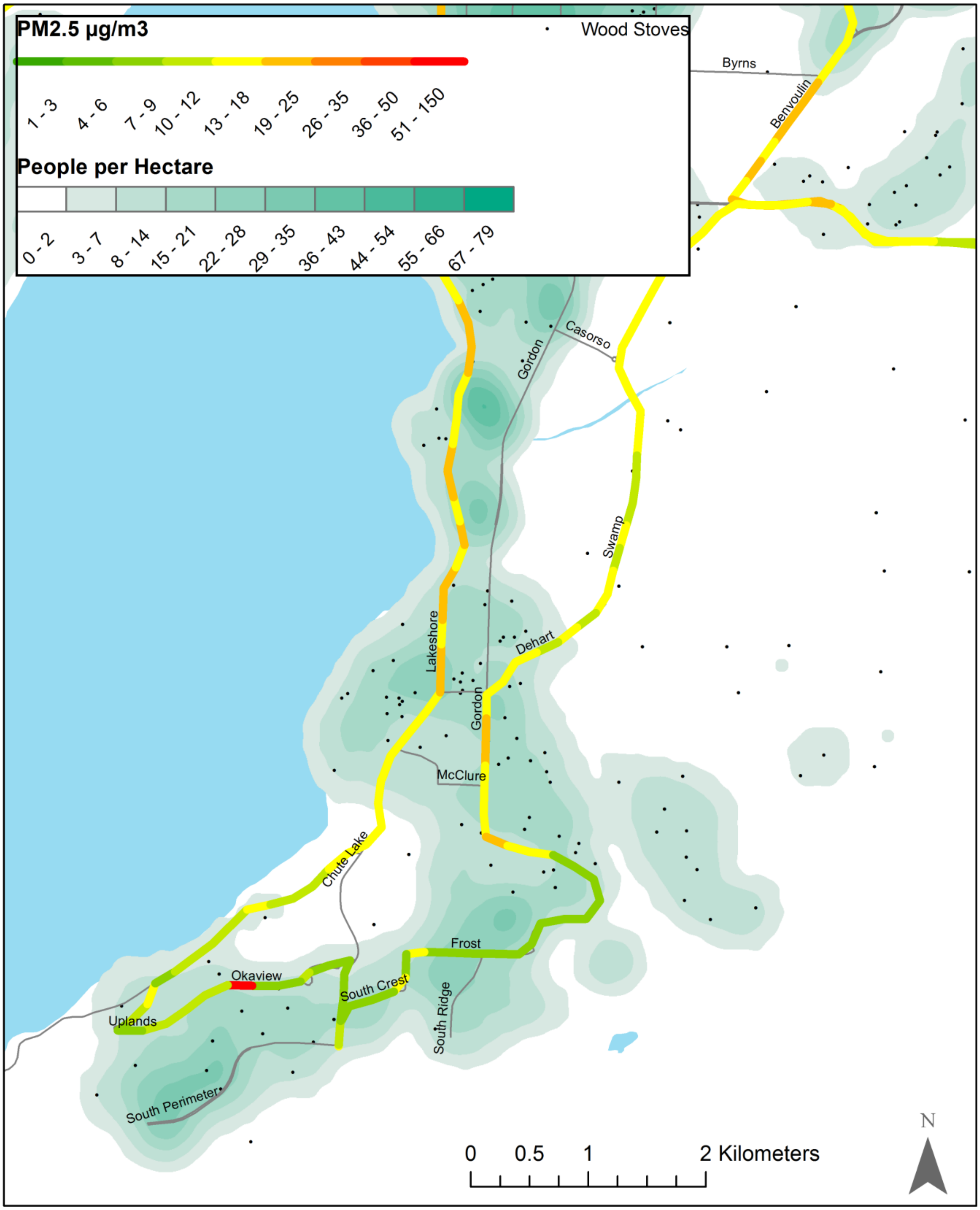
Downtown/ Genmore Population Distribution with Woodstoves and PM2.5 Concentrations (November - April)



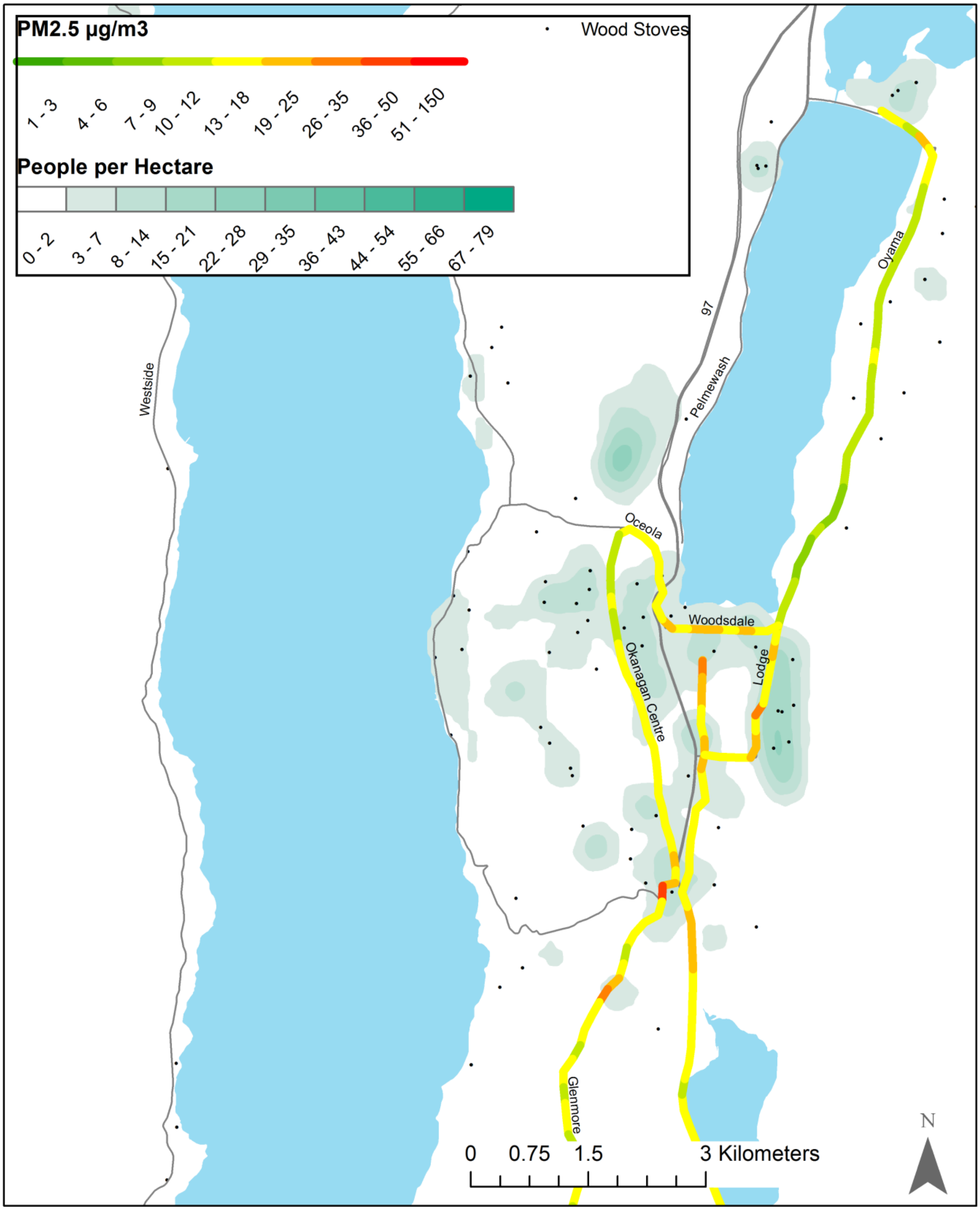
West Kelowna Population Distribution with Woodstoves and PM2.5 Concentrations (November - April)



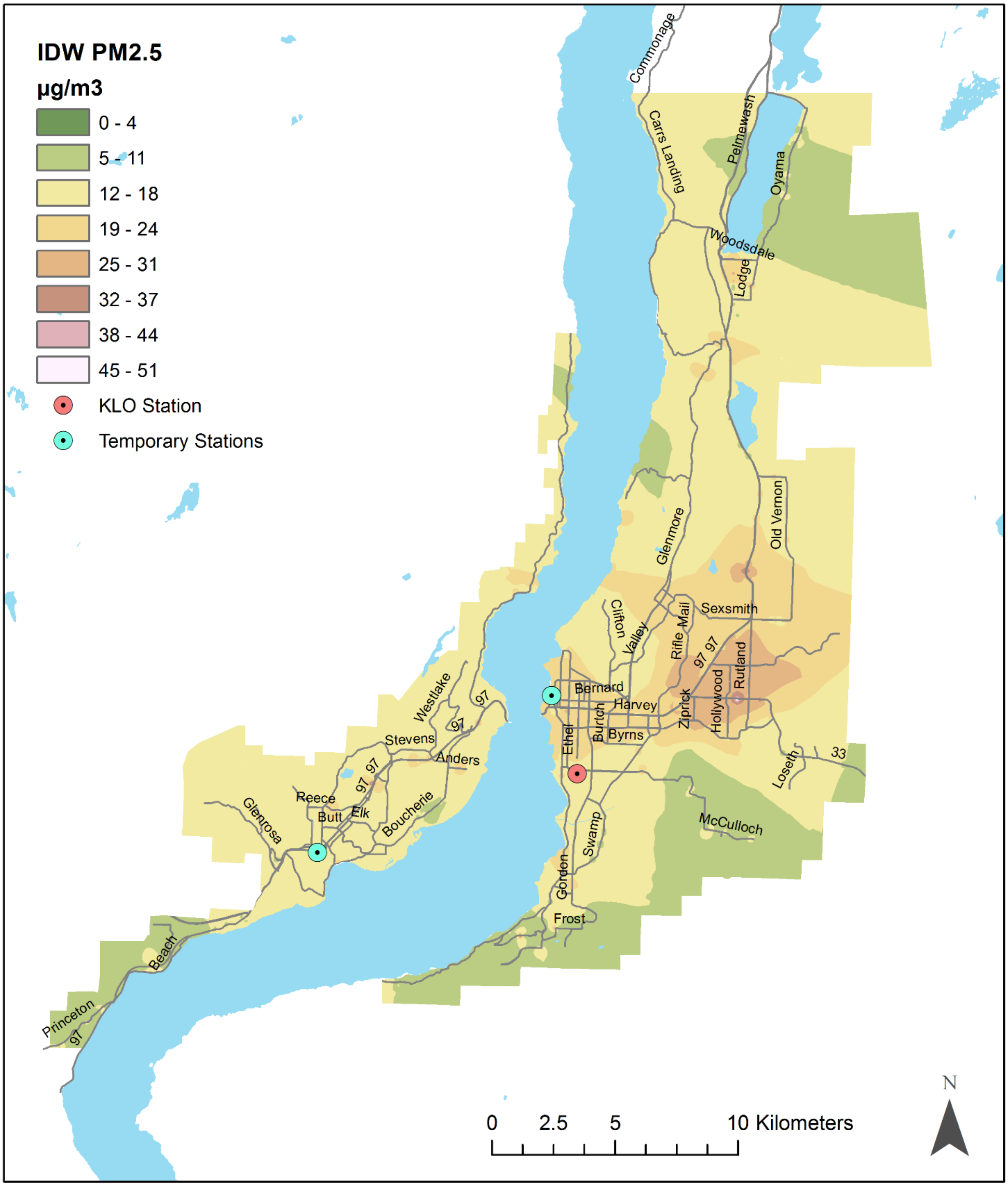
Peachland Population Distribution with Woodstoves and PM2.5 Concentrations (November - April)



Kelowna Mission Population Distribution with Woodstoves and PM2.5 Concentrations (November - April)



Lake Country Population Distribution with Woodstoves and PM2.5 Concentrations (November - April)



City of Kelowna - IDW PM2.5 Concentrations

City of Kelowna

APPENDIX 6- R Scripts

DATA MERGER

```
extract <- function(charin)
	{
	dout<-vector()
	date <-
paste(substr(charin[2],1,2),":",substr(charin[2],3,4),":",substr(charin[2],5,6),sep="")
	dout[1] <- date
	dout[2] <- substr(charin[3],1,2)
	dout[3] <- substr(charin[3],3,nchar(charin[3]))
	dout[4] <- charin[4]
	dout[5] <- substr(charin[5],1,3)
	dout[6] <- substr(charin[5],4,nchar(charin[5]))
	dout[7] <- charin[6]
	dout[8] <- charin[10]
	dout
	}

options(stringsAsFactors=FALSE)

#++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
++++++++
#++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
++++++++
#++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
++++++++

print("Please select DustTrak file")

Fdtk=file.choose()

print("Please select GPS file")

Fgps=file.choose()

DATdtk1<- read.csv(Fdtk,header=F,colClasses=c(rep("character",2)))
DATdtk2<-
read.csv(Fdtk,header=T,skip=19,colClasses=c(rep("character",4)),check.names=FALSE)

DT <- paste(DATdtk1[8,2],DATdtk1[7,2],sep=" ")
DT1dtk <- as.POSIXlt(strptime(DT,"%Y/%m/%d %H:%M:%S",tz="America/Vancouver"))

for (i in 1:2) {
	DATdtk2[,i] <- as.numeric(DATdtk2[,i])
}

print("DustTrak Start Date & Time:")
print(DT1dtk)

print("DustTrak raw data - head")
print(head(DATdtk2))
print("DustTrak raw data - tail")
print(tail(DATdtk2))

#++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
+++++
```

```
DTdtk <- character(nrow(DATdtk2))
DTdtk[1:nrow(DATdtk2)] <- DT
DTdtk <- as.POSIXlt(strptime(DTdtk,"%Y/%m/%d %H:%M:%S",tz="America/Vancouver"))
DTdtk$sec <- DTdtk$sec+DATdtk2[,1]

DATdtk <-
data.frame(date=as.POSIXct(DTdtk),GMTime=format(as.POSIXct(DTdtk),"%H:%M:%S",tz="GMT",use
tz=TRUE),PM25dtk=1000*DATdtk2[,2])

print("DustTrak data - head")
print(head(DATdtk))
print("DustTrak data - tail")
print(tail(DATdtk))

#+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
++++

DATgps1 <- read.table(Fgps,sep=",",header=F,colClasses="character")
DATgps2 <- apply(DATgps1,1,extract)
DATgps2 <- t(DATgps2)

TIMEgps <-
format(as.POSIXlt(strptime(DATgps2[,1],"%H:%M:%S",tz="GMT")),"%H:%M:%S",usetz=TRUE)
DATgps1 <-
data.frame(GMTime=TIMEgps,LatDeg=as.numeric(DATgps2[,2]),LatMin=as.numeric(DATgps2[,3]),L
atZ=DATgps2[,4],LonDeg=as.numeric(DATgps2[,5]),LonMin=as.numeric(DATgps2[,6]),LonZ=DATgps
2[,7],Elev=DATgps2[,8])

print("GPS raw data - head")
print(head(DATgps1))
print("GPS raw data - tail")
print(tail(DATgps1))

DATgps <-
data.frame(GMTime=TIMEgps,Lat=as.numeric(DATgps2[,2])+(as.numeric(DATgps2[,3])/60),Lon=-
(as.numeric(DATgps2[,5])+(as.numeric(DATgps2[,6])/60)),Elev=DATgps2[,8])

print("GPS data - head")
print(head(DATgps))
print("GPS data - tail")
print(tail(DATgps))

#+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
+++

DATout <- merge(DATdtk,DATgps,by="GMTime")
DATout <- DATout[,-1]

Fout=paste(substr(Fgps,1,nchar(Fgps)-8),"_Mobile-Sampling-Data.csv",sep="")

names<-c("Date&Time","PM2.5[micrograms/m3]","Latitude","Longitude","Elevation[m]")
colnames(DATout)<-names
write.csv(DATout,Fout,row.names=FALSE)
```

De-Trend Script

```
# Written by Tim Atkinson in 2015
```

```
# Produced for the City of Kelowna for air quality monitoring

# get the mean and standard deviation from each mobile and stationary models
# using the deviations from the mean on the stationary monitor, the mobiel monitor
# will be de-trended with the deviations from the mean

#============================
# Lower functins
# - none

# Upper functions
# - none
#============================

#====================================
# download pracma package if needed
#install.packages("pracma", lib="C:/temp")
# to load open air package
library(pracma, lib.loc="C:/temp")
#====================================

# load packages for data analysis
library(zoo)
library(plyr)
library(lubridate)
library(ggplot2)

# set working directory
dir1 <- "U:/Infrastructure/1200-40 Air Quality-PM2.5 Study/EBAM/Rdata"
setwd(dir1)

load("rawdata.Rdata")
# get only sharp data
df <- df[,c(1,4)]

dir2 <- "U:/Infrastructure/1200-40 Air Quality-PM2.5 Study/PM2.5 Mobile Monitoring
Project/Data/All combined data"
setwd(dir2)

mb <- read.csv("allSampling.csv")

# get days of sampled data
days <- substr(mb$Date.Time, 1, 10)
days <- days[!duplicated(days)]


# now subset sharp data with selected days
df$days <- substr(df$Date, 1, 10)
df <- df[df$days %in% days,]

# now get mean and standard deviation for all days that were mobile sampled
sums <- ddply(df, "days", summarize,
      mean = mean(sharp, na.rm=T),
      std  = sd(sharp, na.rm=T))



# make column in df for deviatons from the mean, sd, and amount of
# standard deviatons from the mean for each day
```

```
for(i in 1:length(df[,1])){
  dday <- df$days[i]
  for(j in 1:length(sums[,1])){
    sday <- sums$days[j]
    if(dday == sday){
      df$mean[i]  <- sums$mean[j]
      df$diff[i]  <- df$sharp[i] - sums$mean[j]
      df$std[i]   <- sums$std[j]
      df$score[i] <- df$diff[i]/df$std[i]
    }
  }
}
rm(sums)

# assign hour to data frame
df$hour <- hour(df$Date)

# create a polynomial fit for hourly data
model <- lm(df$score ~ poly(df$hour,3, raw=T))
# get t values and equation
summary(model)
model

# create function that counter acts the diurnal variation
poly1 <- function(hour){
  out <- (-1.0939789 + 0.332411*hour - 0.0190529*hour^2 + 0.0002211*hour^3)
  return(out)
}

# test results
df$norm <- poly1(df$hour) + df$score
ggplot(df, aes(x=hour, y=score)) +
  stat_smooth(method = "lm", formula = y ~ poly(x,3,raw=T)) +
  #stat_smooth(method = "lm", formula = y ~ poly(x,10,raw=T)) +
  ggtitle("De-Trended Z-Scores") +
  ylab("Z-score") +
  xlab("Hour") +
  geom_point()


#========================================================================================
======
# apply detrend from stationary data to mobile data
# rename mobile column names
names(mb)[3] <- "PM25"

mb$days <- substr(mb$Date, 1, 10)

# now get mean and standard deviation for all days that were mobile sampled
msums <- ddply(mb, "days", summarize,
              mean = mean(PM25, na.rm=T),
              std  = sd(PM25, na.rm=T))

# apply each daily mean and standard deviation to get
# how much each point deviates
for(i in 1:length(mb[,1])){
  dday <- mb$days[i]
  for(j in 1:length(msums[,1])){
```

```
    sday <- msums$days[j]
    if(dday == sday){
      mb$mean[i]  <- msums$mean[j]
      mb$diff[i]  <- mb$PM25[i] - msums$mean[j]
      mb$std[i]   <- msums$std[j]
      mb$score[i] <- mb$diff[i]/mb$std[i]
    }
  }
}
rm(msums)

# get hours in deciamls to apply to polynomial function
mins <- minute(mb$Date.Time)/60
mb$hours <- hour(mb$Date.Time) + mins
mb$hr <- hour(mb$Date.Time)

# apply normalizing polynomial function
mb$adjscore <- poly1(mb$hours) + mb$score
mb$adjdiff  <- mb$adjscore*mb$std
mb$adjPM25  <- mb$adjdiff + mb$mean

# write a data frame to export to ArcGIS
mobile <- data.frame(mb$Date.Time, mb$PM25, mb$adjPM25, mb$Latitude, mb$Longitude)
colnames(mobile) <- c("Date", "PM25", "adPM25", "Latitude", "Longitude")

# save data frame
#write.csv(mobile, file="AllAdjusted.csv")
#==============================================================================
# take z-scores for each day on adjusted PM2.5 values
mobile$days <- substr(mobile$Date, 1, 10)
msums <- ddply(mobile, "days", summarize,
               mean = mean(adPM25, na.rm=T),
               std  = sd(adPM25, na.rm=T))

for(i in 1:length(mobile[,1])){
  dday <- mobile$days[i]
  for(j in 1:length(msums[,1])){
    sday <- msums$days[j]
    if(dday == sday){
      mobile$mean[i]  <- msums$mean[j]
      mobile$diff[i]  <- mobile$adPM25[i] - msums$mean[j]
      mobile$std[i]   <- msums$std[j]
      mobile$score[i] <- mobile$diff[i]/mobile$std[i]
    }
  }
}

#write.csv(mobile, file="MBadjusted.csv")
```

Attached separately:

APPENDIX 7 – Mobile Monitoring Maps-26 Trips

APPENDIX 8- $PM_{2.5}$ Mobile Sampling Notes – 26 Trips

APPENDIX 9- Mobile Monitoring Route # 1 and # 2- Driving directions