

Spatial Analysis of Fine Particulate Matter (PM_{2.5}) in South St. Boniface and Mission Industrial Area, Winnipeg, Manitoba, Canada

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How to cite this paper: Solademi, F., & Thompson, S. (2023). Spatial Analysis of Fine Particulate Matter (PM_{2.5}) in South St. Boniface and Mission Industrial Area, Winnipeg, Manitoba, Canada. *Journal of Geoscience and Environment Protection*, 11, 176-196. <https://doi.org/10.4236/gep.2023.118011>

Received: August 10, 2023

Accepted: August 28, 2023

Published: August 31, 2023

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Abstract

Particulate matter smaller than 2.5 microns (PM_{2.5}) stays airborne for long periods and can enter the lungs, increasing respiratory and cardiovascular risks. Metal shredders are known sources of PM_{2.5}, lead and other heavy metals. Winnipeg residents of South Saint Boniface (SSB) in Manitoba, Canada, live downwind of the Mission Industrial Area (MIA), which includes a metal shredder, train tracks and other industries. Residents are concerned about the MIA air and noise pollution and wanted ambient air quality monitoring in their mixed land-use area to understand its impact on their health. We measured and mapped the daytime PM_{2.5}, from the MIA and South St. Boniface (SSB) neighborhoods using the Dyllos DC 1700 PM over seven months. The Dyllos air quality data for PM_{2.5} was validated by the two federal reference monitors in the city, finding a moderate to very strong correlation ($r = 0.52$ to 0.83 ; p -value < 0.001), confirming good accuracy. A spatial analysis of the emission data showed that the highest pollution concentration was downwind of the scrap metal shredder in MIA. One-way ANOVA and Pearson correlation analysis revealed significantly higher levels of PM_{2.5} at MIA and SSB than at the reference sites, which are away from pollution sources. The PM_{2.5} Canadian Ambient Air Quality Standard (CAAQS) of 27 $\mu\text{g}/\text{m}^3$ was exceeded downwind of the property line of the scrap metal shredder in the MIA for five of the 35 monitoring days averaging between 28.9 $\mu\text{g}/\text{m}^3$ to 38.1 $\mu\text{g}/\text{m}^3$ over eight hours. The standard was not exceeded in the residential area, although PM_{2.5} levels higher than background levels increased SSB residents exposure levels. This exceedance of regulatory standards requires action to reduce emissions.

Keywords

Particulate Matter, Air Monitor, CAAQS, ArcGIS, Scrap Metal Shredder, Kriging, and Mapping, Citizen Science

1. Introduction

Scrap metal recycling has positive and negative environmental impacts (Foulke, 2008). Positively, recycling metals can replace virgin ore from mining the earth, which is less energy intensive. Scrap metal recycling facilities salvage valuable metals from automobiles, aluminum sheets and copper parts in buildings. Negatively, heavy metal and particulate emission from scrap metal recycling pose a risk to human health and the environment (Owoade et al., 2015; Ogundele et al., 2017). Scrap metal shredders emit lead, zinc, mercury, chromium, and other metals (Foulke, 2008). Studies of scrap metal recycling facilities in Nigeria and the USA measured high levels of fine particulate matter (PM_{2.5}) emissions exceeding the World Health Organization's (WHO) guidelines (Owoade et al., 2015; Raun et al., 2013; World Health Organization, 2000; 2006).

Significant health risks are posed by fine particulate matter less than 2.5 microns in size (PM_{2.5}) (World Health Organization, 2021). This PM_{2.5} penetrates deep into the respiratory airways, thoracic region, lungs, and bloodstream to cause damage (World Health Organization, 2013). The WHO air quality guideline has no safe exposure level to PM_{2.5}, with increasing levels resulting in higher rates of cardiopulmonary and respiratory diseases (Xing et al., 2016). The small size of 2.5 microns allows the particle to remain airborne to travel large distances from its industrial or fire source (Brauer et al., 2018; Sofowote & Dempsey 2015).

Numerous epidemiological studies identify health risks and increased hospitalization rates from short-term exposure to fine respirable particles, especially among the elderly and people with pre-existing lung and heart diseases (Rückerl et al., 2011; Le et al., 2014). Exposure to PM_{2.5} damages the lungs and respiratory airways, worsening asthma symptoms, causing breathing difficulties and irritating the throat (D'Amato et al., 2015; Jung et al., 2019). Exposure to PM_{2.5} is associated with respiratory and cardiovascular risks, including chronic obstructive pulmonary disease (COPD), asthma, chest pain and bronchitis (Sutherland et al., 2005; Ovadnevaite et al., 2006). Many industries cause particulate emissions, noise, increased traffic, and toxic substances pollution posing health risks (Ostrowski et al., 1999; Koranteng et al., 2007). PM_{2.5} pollution risks both the health of workers with exposure on the job and nearby residents to industrial pollution sources in mixed land-use neighborhoods (Taylor, 2014). Mixed land-use areas often attract hazardous industrial facilities near racialized and lower-income neighborhoods, increasing their health risks (Hamilton, 2013). Long-term exposure to PM_{2.5} is correlated significantly with respiratory-related diseases and death (Brunekreef & Holgate, 2002). As well as particulate, other hazards from industrial facilities include noise, increased traffic, and toxic substances posing health risks (Ostrowski et al., 1999; Koranteng et al., 2007). Thus, concentrating on polluting industrial facilities near low-income and racialized residential areas constitutes environmental injustice and greater health risks (Mohai & Saha, 2015; Whittemore, 2017).

To understand and manage air quality in mixed land-use areas requires regulatory urban air monitors to measure ambient levels of PM_{2.5} (Canadian Council

Ministers of Environment (CCME, 2022). However, regulatory analysis of local sources of PM_{2.5} is limited due to its expensive cost to deploy monitoring equipment and the inability of monitors to assess both upstream and downstream sources simultaneously to pinpoint emission sources (Han & Stock, 2017; Oluwadairo et al., 2022). The PM_{2.5} levels in ambient air vary spatially for different land-uses, industrial, residential, commercial, and agricultural activities and with mixed land-uses can be difficult to pinpoint pollution sources. The spatial variability of PM_{2.5} is due to local sources, not regional sources (Pinto et al., 2004; Anastopoulos et al., 2022).

This study discusses the levels and sources of pollution impacting the low-income residential area of South St. Boniface next to the Mission Industrial Area (MIA), which includes a metal shredder (Winnipeg Regional Health Authority, 2015). This paper studies the PM_{2.5} levels at different distances and directions from the metal shredder. In this paper we first discuss the study areas. Then we discuss the equipment used in the method and its validity to show how we arrived at our sampling strategy, considering wind direction and distance from the shredder. In the findings, we quantify PM_{2.5} levels downwind of the shredder to compare to upwind levels and background levels away from pollution sources. In the findings, we show graphs and maps of the pollution levels in different seasons to reveal the pollution sources. We then discuss the findings considering health and environmental risks and make recommendations to safeguard health and the environment.

2. Materials and Methods

2.1. Study Area

This pollution study focuses on the MIA and SSB neighborhoods on the north and east side (see **Figure 1**) of the St. Boniface area. The St. Boniface and St. Vital districts of Winnipeg, Manitoba, with a population of 95,514 (Statistics Canada, 2021). The SSB neighborhood is located within one km of a scrap metal shredder, a railway, and many other manufacturing facilities in the MIA area. This area has a large population of low-income people, Indigenous people and people of colour (Statistics Canada, 2021). The scrap metal shredding and processing operations have caused fires, explosions, noise and emissions, raising deep concerns from the residents and business owners in SSB (Canadian Broadcasting Corporation, 2015; Larsen, 2017). Residential areas in central St. Boniface, SSB and Southdale are located nearby MIA on the south side.

2.2. Monitoring Approach, Instrument Selection, and Validation

The first author monitored Winnipeg's MIA in the SSB neighborhood for over 500 daytime hours for PM_{2.5} from June 2018 to December 2018. The MIA has many diverse industries within a 24.5 km² area of the Red River and Seine River junction, including a scrap metal recycling plant with a metal shredder (Manitoba Environment and Climate, 2017). The scrap metal shredder is located less

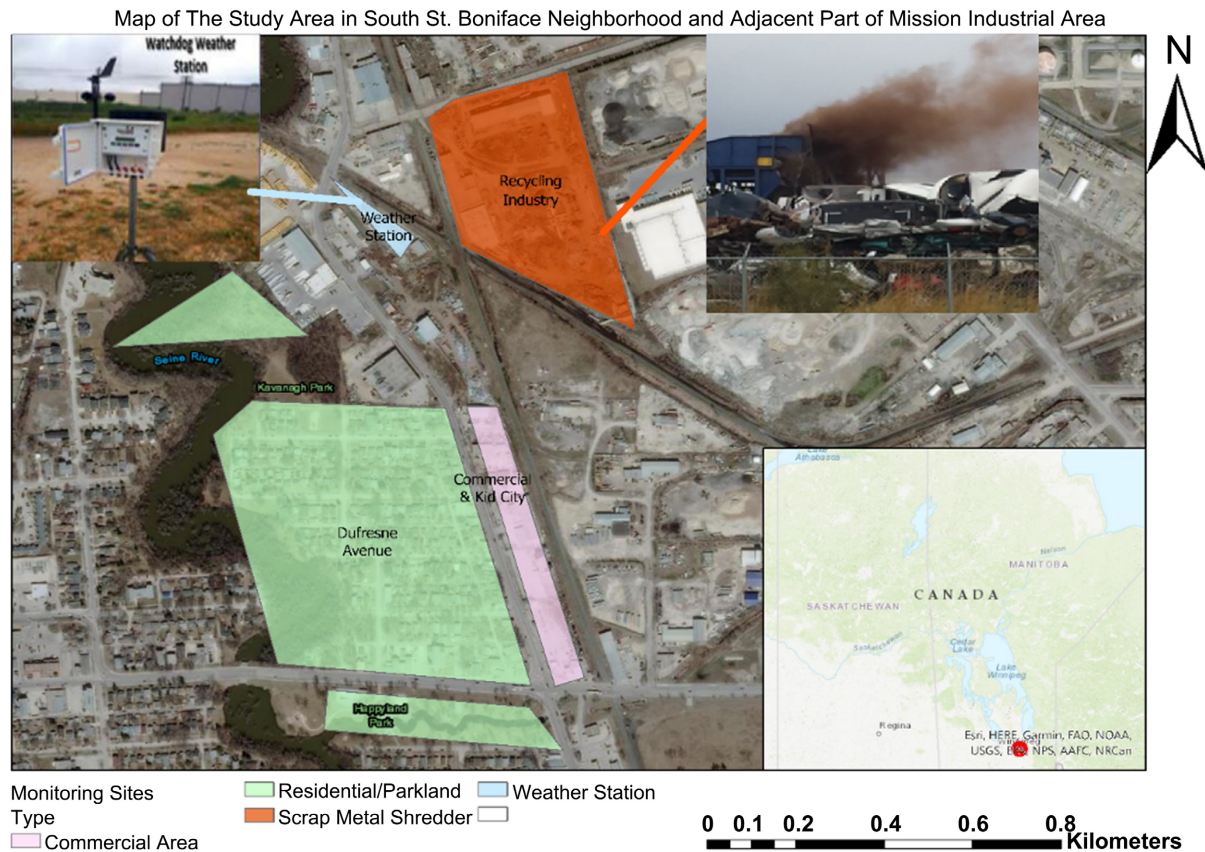


Figure 1. Map of St. Boniface, Winnipeg, showing the locations of residential neighborhoods and the recycling industry with inset of Canada.

than one kilometers from the closest residential street in the SSB neighborhood. The scrap metal recycling facility received a license to operate a scrap metal shredder on January 16th, 2017 (Manitoba Environment and Climate, 2017).

2.2.1. Equipment to Monitor $PM_{2.5}$ Levels

The regulatory method to monitor $PM_{2.5}$ compliance requires designated Environmental Protection Agency (EPA) Federal Reference Methods (FRM) or Federal Equivalent Methods (FEM) using manual gravimetric pre-weighed filter paper and non-filter-based techniques (Noble et al., 2001; CCME, 2011). These high-volume air samplers have a suction fan at a precise airflow. Government and regulatory agencies deploy these methods (FRM and FEM) to report city or regional air quality levels for $PM_{2.5}$. The FRM regulatory approach costs thousands daily, which is unaffordable for citizens or most universities.

To regularly monitor emissions over the many pollution events is required, which requires more than one day per year (Carvlin et al., 2017). The FRM/FEM monitors are expensive equipment and require trained staff with technical expertise to operate and maintain, which is costly. The many thousands of dollars required for long-term FRM monitoring meant this method could not be used. Other validated methods had to be used for long-term monitoring to be affordable. Commercially available low-cost particulate monitoring technologies have

shown accurate results for PM concentrations (Northcross et al., 2013; Wang & Ogawa, 2015; Jiao et al., 2016). We chose the rechargeable battery-operated Dylos DC 1700-PM laser particle counter to monitor air quality for citizen science purposes rather than regulatory purposes, due to its good accuracy for indoor and outdoor PM_{2.5} concentrations (Northcross et al., 2013; Dylos Corporation, 2019; Arling et al., 2010; Semple et al., 2013; Steinle et al., 2015). This monitor is low-cost compared to traditional gravimetric and continuous designated EPA particulate matter monitors in industrial and residential areas (Steinle et al., 2015). This awareness and advocacy tool has allowed monitoring networks for citizens to advocate for better air quality (Clements et al., 2017).

2.2.2. Validation of Dylos Laser Particle Counter for PM_{2.5} Measurement

The Dylos DC 1700 is a laser particle counter of light scattering, detecting and counting particles (cubic foot) in two size ranges: coarse particulate matter larger than 2.5 µg (PM_{2.5}) to 10 µg (PM₁₀) and fine particulate matter, small from 2.5 to 0.5 µg (Dylos Corporation, 2019). We measured only fine particulate matter in this study (Figure 2). Particles smaller than 0.5 µg are nanoparticles not measured by the Dylos 1700. The DC 1700 draws the airstream at 28.32 litres/minute with an inbuilt computerized fan to monitor the particles in the measurement chamber with a laser beam operating at a 650 nm wavelength (Northcross et al., 2013). The airstream particles pass through a laser light, which causes scattering effects. Dylos logged the number of particles detected for each particle size by the scattering effect on an inbuilt memory, storing up to a week's time-stamped data recorded every minute (about 10,000 samples). Dylos particle count per cubic foot to microgram per meter cube (µg/m³) unit measurement of PM_{2.5} by FRM and FEM using validated statistical and algorithmic models (Arling et al., 2010) considering relative humidity factor in SSB and MIA.

Many studies validate the Dylos' accuracy. Validation was done when the Dylos is collocated with designated EPA FRM and FEM PM_{2.5} air monitors



Figure 2. The rechargeable battery-operated Dylos DC 1700-PM laser particle counter.

(Carvlin et al., 2017; Northcross et al., 2013; Arling et al., 2010; Semple et al., 2013; Steinle et al., 2015). According to Steinle et al. (2015), Dyls and a FEM national PM_{2.5} air monitoring network showed a correlation of 0.9 and 0.7 at urban and rural background sites, respectively. Similarly, field tests of wood smoke by Dyls 1700 and FEM were highly correlated at 0.81 and 0.99 (Carvlin et al., 2017).

2.2.3. The Sampling Method

We calibrated the settings of the Dyls counter to measure the PM_{2.5} concentration of suspended particulate matter below 2.5 µg, specifically PM_{2.5}. We monitored for PM_{2.5} at the fence line or property's edge of the recycling industry, close to the emission source (Owoade et al., 2015; Raun et al., 2013). This sampling point was the best place to measure emissions available, as the outdoor metal shredder lacked an exhaust stack and we were not allowed on the industrial property.

We followed a daily schedule routine for monitoring MIA and SSB. At MIA, we recorded the upwind PM_{2.5} for one hour in the morning and one hour in the afternoon with the Dyls 1700 Air Quality Monitor before scrap metal recycling in the MIA commenced. Our schedule of monitoring SSB and MIA is summarized in **Table 1**.

2.3. Method of Data Analysis

We obtained the mean, median and standard deviation for the PM_{2.5} from the Dyls and the FRM stations. We corrected the PM_{2.5} using the relative humidity factor from the nearby Environment Canada weather station. We installed a Watchdog weather station downwind of the MIA to obtain more localized data for temperature, humidity, wind speed and direction. We determined the statistical significance of the Dyls PM_{2.5} levels in SSB and the PM_{2.5} levels by Pearson correlation to Manitoba's FRM/FEM monitors. The hourly data met the assumptions of Pearson correlation of related pairs, continuous data, and linearity. The statistical significance was defined at a level of $p < 0.05$ (Pei et al., 2016). Using Pearson correlation, we tested the hypothesis that the hourly upwind PM_{2.5} measured by the Dyls and corresponding FRM monitors data using statistical software SPSS version 23 and Microsoft Excel 2016.

Table 1. PM_{2.5} monitoring schedule in mission industrial area (MIA) and South St. Boniface (SSB).

Monitoring Sites for PM _{2.5}	Monitoring Times	No. of Days
Upwind MIA	7:30 AM-8:30 AM and 4:00 PM-5:00 PM	2 - 3 weekdays
Downwind MIA	8:30 AM-4:00PM	2 - 3 weekdays
Residential SSB (Archibald roadside)	7:40 AM-8:40 AM and 4:00 PM-5:00 PM	2 - 3 weekdays
Residential SSB (Dufresne Avenue streets)	9:00 AM-4:00 PM	2 - 3 weekdays

The statistical hypothesis test for this p -value is H0: No statistically significant relationship exists between the upwind PM_{2.5} in MIA and ambient levels measured by regional regulatory monitors (PM_{2.5}) in Winnipeg. H1: A statistically significant relationship exists between MIA's upwind (PM_{2.5}) and Winnipeg's ambient level measured by regional regulatory monitors (PM_{2.5}). We performed a statistical hypothesis test for the p -value and variability (r) test, with the hypothesis (H) for H0 being the null hypothesis. H0: There is no statistically significant relationship between the tested instruments, the Dylos (residential monitor) and FRM monitors.

The descriptive statistics for downwind mass concentration of PM_{2.5} during scrap metal recycling operations for monitoring hours were analyzed with SPSS and Microsoft Excel. We compared the daily mean values of downwind respirable fine particulate matter (PM_{2.5}), upwind values, and regulatory monitors with the Canadian Ambient Air Quality Standards (CAAQS) threshold values of 27 µg/m³. We applied regulatory guidelines/standards to compare levels. We also compared the PM_{2.5} levels in MIA and SSB to the background PM_{2.5} levels in FRM stations. Then we statistically analyzed the one-way analysis of variance (ANOVA) and posthoc test on SPSS version 23. We analyzed the hourly mean differences of PM_{2.5} values measured at the downwind fence line scrap metal shredding emission monitoring points with a one-way ANOVA (PM_{2.5}). We compared if statistically different then the downwind cardinal points as group factors. We also statically analyzed Tukey's HSD multiple comparisons of means. We determined summary statistics of PM_{2.5} for the different streets in Dufresne Avenue of SSB, including daily mean and standard deviation of PM_{2.5} measured in St. Boniface, hourly minimum, and maximum values of daily PM_{2.5}, CAAQS 2015 24-hours value (27 µg/m³) for poor air quality.

Also, we mapped spatial and temporal variation of PM_{2.5} in the MIA and SSB neighborhoods using ArcMap on the ArcGIS desktop. Variations in PM_{2.5} are mapped over the months through time-series data (Liu et al., 2017). Mapping of air pollutants provides a visual of the local and regional levels of air pollutants, revealing hotspots with higher pollution levels (Bari & Kindzierski, 2018). Thus, ArcGIS software was applied to conduct a spatial analysis of PM_{2.5} hourly data measured at the scrap metal recycling fence line areas and the residential sampling points. In our study, PM_{2.5} values were interpolated using geostatistical kriging analysis and the color-coding of Canadian Ambient Air Quality Standard (CAAQS) for management action level for achieving air quality zone (see CAAQS in Table 2). Monthly visualized patterns of respirable particulate matter emission trends at the scrap metal shredder sampling points and ambient levels in SSB are presented.

3. Result and Discussion of Particulate Matter (PM_{2.5}) in Mission Industrial Area and South St. Boniface

The summary statistics for the PM_{2.5} monitored in the upwind and downwind

Table 2. Canadian ambient air quality standards (CAAQS) for PM_{2.5}.

	PM _{2.5} annual (µg/m ³)		PM _{2.5} 24-hour (µg/m ³)		Management Level & Action
	2015	2020	2015	2020	
	Threshold Values	10	8.8	28	
		6.4		19	Action for Preventing CAAQS Exceedance
		4		10	Action Preventing Deterioration of Air Quality
		<4		<10	Actions for Maintaining and Keeping Clean Air Zones

directions of the scrap metal shredder in Mission Industrial Area are presented in **Chart 1**.

3.1. Upwind Values of PM_{2.5} near Fence-line of Scrap Metal Recycling Activities

Chart 1 shows the upwind PM_{2.5} level for the MIA follows the trend of the FRM1 monitor located on Ellen Street, five kilometres away. Both the Dylos and the FRM1 range from 1.7 µg/m³ to 25.3 µg/m³ in the morning and 1.8 µg/m³ to 22.3 µg/m³ in the afternoon. A similar trend in farther FRM2 on Scotia Street, sited eight kilometres from MIA, also recorded 0.4 µg/m³ to 36.9 µg/m³ for the morning and hourly afternoon readings ranged between 1.3 µg/m³ and 24.4 µg/m³.

The average (PM_{2.5}) upwind measurements taken by the Dylos instrument and ambient (PM_{2.5}) level measurement FRM1 monitor showed a significant, very strong linear relationship ($r = 0.83$, $p < 0.01$). Similarly, average (PM_{2.5}) upwind measurements for the Dylos and FRM2 monitor had a significantly strong relationship ($r = 0.83$, $p < 0.01$). FRM1 and FRM2 monitors showed a significant, strong linear relationship and a very high positive correlation ($r = 0.73$, $p < 0.01$) (see **Table 3** for Correlation Analysis).

The monitored high upwind and the ambient PM_{2.5} exceeded 27 µg/m³ for CAAQS and 24-hour mean 15 µg/m³ by the World Health Organization (WHO) in MIA on 8th, 17th and 23rd August 2018. During these dates, hourly upwind levels measured by the Dylos ranged between 19.2 µg/m³ to 24.6 µg/m³, similar to the values at Ellen 20.1 µg/m³ to 25.3 µg/m³. Scotia recorded 24.4 µg/m³ to 36.9 µg/m³ [45], respectively, the city-wide wildfire smoke impact on ambient air quality. Except on wildfire days, the upwind Dylos PM_{2.5} levels in MIA ranged from 0.3 µg/m³ to 11.7 µg/m³. These upwind levels were slightly lower than the FRM/FEM monitors, ranging from 0.4 µg/m³ to 15.5 µg/m³. By comparing downwind with the upwind, we could isolate the source of the pollution to the shredder. The downwind levels were significantly higher than the upwind Dylos and FRM/FEM monitors.

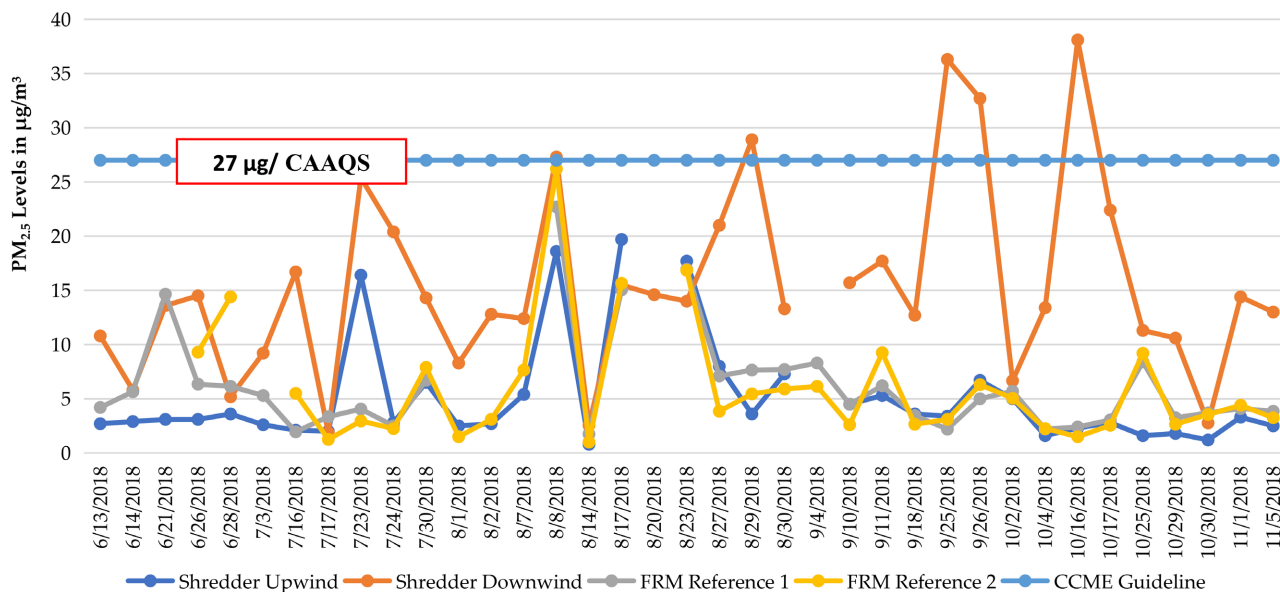


Chart 1. PM_{2.5} levels in up/downwind scrap metal shredder and ambient PM_{2.5} levels in reference monitors, Winnipeg.

Table 3. Pearson correlation of PM_{2.5} levels monitored at upwind scrap metal shredder and FRM1 and FRM2 regulatory monitors.

Correlations		Dylos (Low-cost)	FRM1 (Regulatory)	FRM2 (Regulatory)
Dylos (Upwind)	Pearson Correlation	1	0.826**	0.831**
	Sig. (2-tailed)		0.001*	0.001*
	N	34	34	36
FRM1 (Regulatory)	Pearson Correlation	0.826**	1	0.789**
	Sig. (2-tailed)	0.001*		0.001*
	N	34	36	36
FRM2 (Regulatory)	Pearson Correlation	0.831**	0.789**	1
	Sig. (2-tailed)	0.001*	0.001*	
	N	34	36	36

*Significant at $p \leq 0.05$ level; **Correlation is significant at the 0.01 level (2-tailed).

3.2. PM_{2.5} Downwind Fence-Line Measurement near Scrap Metal Recycling Operations

The daily mean values of PM_{2.5} measured at the downwind north, south, west, and east fence line of the scrap metal recycling operations range between $1.9 \pm 0.85 \mu\text{g}/\text{m}^3$ and $38.1 \pm 20 \mu\text{g}/\text{m}^3$ between June 13th and December 18th, 2018. The PM_{2.5} air monitoring at the fence line sampling points of the recycling facility had significant variation. In June 2018, the fine respirable particulate matter ranged between $5.2 \pm 2.03 \mu\text{g}/\text{m}^3$ and $14.5 \pm 6.7 \mu\text{g}/\text{m}^3$, below the $27 \mu\text{g}/\text{m}^3$ limit of CAAQS. For June, the daily hourly minimum and maximum values ranged from 3.3 to $8.4 \mu\text{g}/\text{m}^3$ and 7.6 to $25.6 \mu\text{g}/\text{m}^3$. This was below the threshold values

limit for management action.

Our study found higher daytime downwind $PM_{2.5}$ between July and October 2018. In July, the daily mean value ranged from 1.86 ± 0.85 to $25.4 \pm 9.71 \mu\text{g}/\text{m}^3$, below CAAQS (see **Chart 2**). Daily mean values of $PM_{2.5}$ observed in August ranged from 2.55 ± 0.82 to $28.9 \pm 15.4 \mu\text{g}/\text{m}^3$. Scrap metal shredding and other activities sporadically operated during August 2018 due to the annual maintenance of the automobile shredder. Daily means for three out of 11 monitoring days in August, at 27.2, and $28.9 \mu\text{g}/\text{m}^3$, respectively, exceeded the $27 \mu\text{g}/\text{m}^3$ CAAQS. In September and October 2018, four monitoring days out of 13 exceeded CAAQS. Daily mean values of $PM_{2.5}$ during the scrap metal recycling operation hours ranged between $28.1 \pm 10.1 \mu\text{g}/\text{m}^3$ and $38.1 \pm 20.7 \mu\text{g}/\text{m}^3$ (see **Chart 2**).

3.3. Result of One-Way ANOVA for $PM_{2.5}$ Downwind Emissions from Scrap Metal Shredding

The one-way ANOVA in **Table 4** shows a statistically significant difference between the 243-hourly means of $PM_{2.5}$ for the four downwind monitoring points of scrap metal shredder, $F(3, 40) = 14.66$, $p \leq 0.001$. Furthermore, the Tukey HSD multiple comparisons of means showed a statistically significant difference between $PM_{2.5}$ levels for the four grouped downwind monitoring points: Northwesterly, Northeast, Southwest, and Southeast ($p \leq 0.001$).

3.4. Result and Discussion of Respirable Fine Particulate Matter ($PM_{2.5}$) in South St. Boniface

In the residential areas, the daytime $PM_{2.5}$ means ranged between $0.79 \pm 0.14 \mu\text{g}/\text{m}^3$ and $27.9 \pm 6.45 \mu\text{g}/\text{m}^3$ between June 15th and December 13th, 2018 (see **Chart 3**). The highest daily mean values occurred on three out of the eight monitoring days on the 10th, 16th, and 24th of August, which measured $21.9 \pm 1.1 \mu\text{g}/\text{m}^3$,

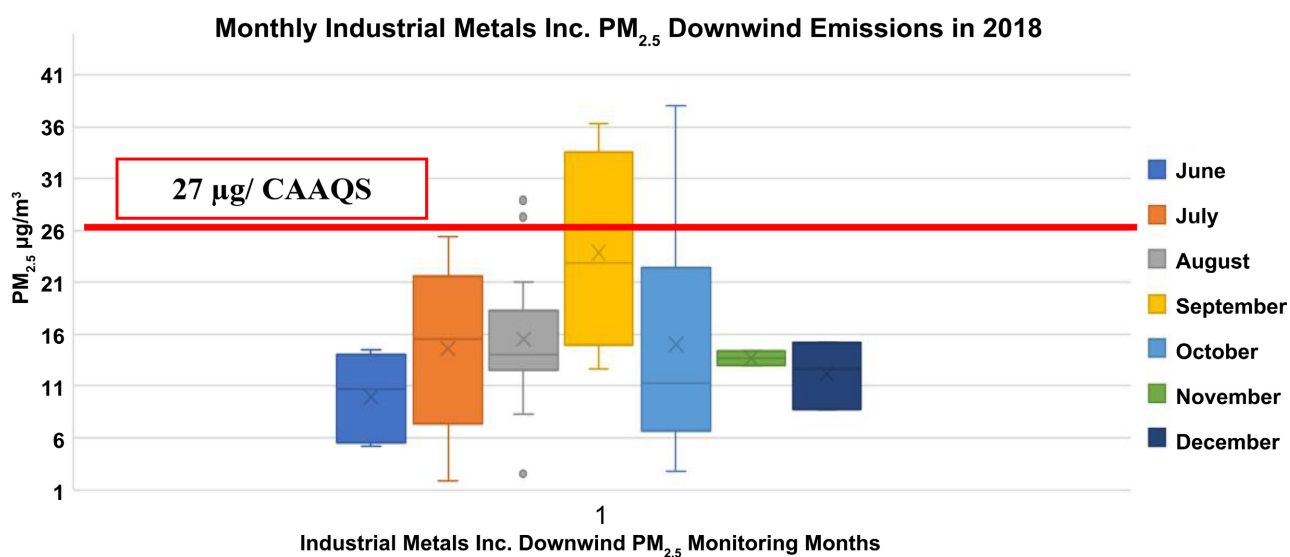


Chart 2. Emissions of fine respirable particulate downwind from scrap metal shredder for seven months.

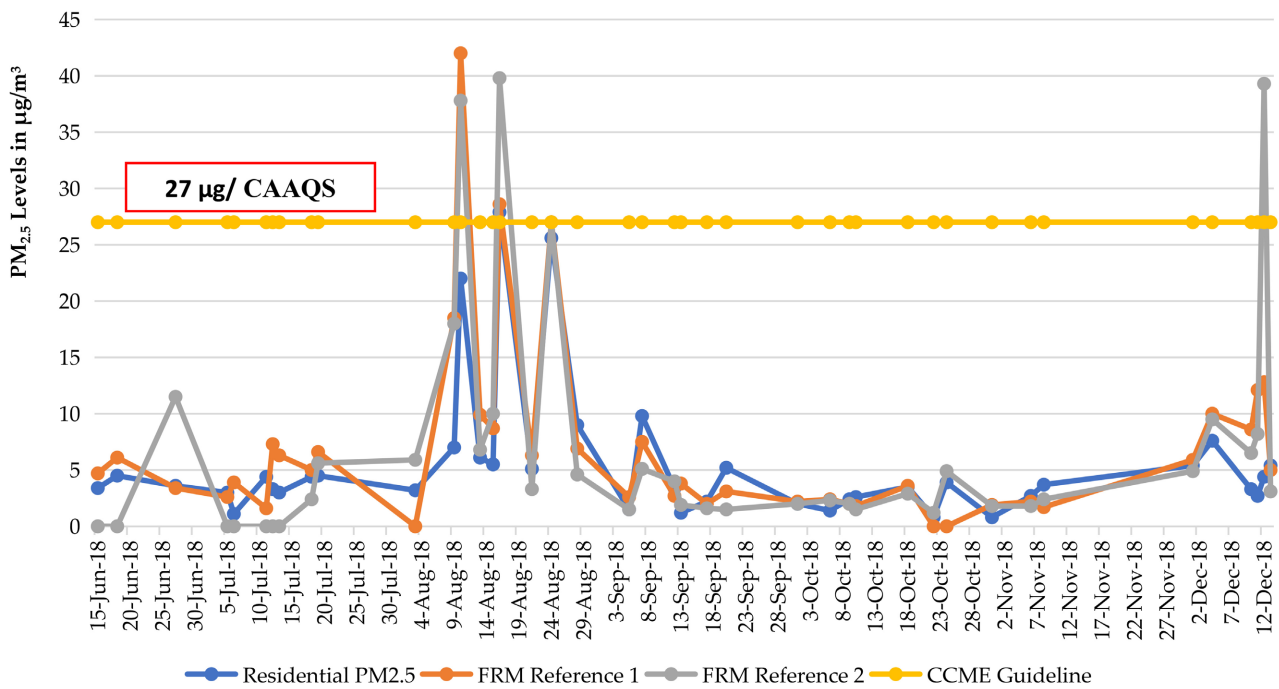


Chart 3. PM_{2.5} levels in Up/downwind scrap metal shredder and ambient PM_{2.5} levels in reference monitors, Winnipeg.

Table 4. One-way ANOVA for PM_{2.5} levels monitored downwind directions of the scrap metal shredder.

	PM _{2.5}				
	Sum of Squares	Df	Mean Square	F	Sig.
Between Groups	5257.195	3	1752.398	14.656	0.001*
Within Groups	28696.774	240	119.570		
Total	33953.969	243			

*Significant at $p \leq 0.05$ level.

25.6 ± 5.9 µg/m³, and 27.9 ± 6.5 µg/m³, respectively. High PM_{2.5} levels in residential areas for these three days were similarly recorded at the reference monitoring stations, 41.6 ± 8.4 µg/m³, 38.7 ± 9.5 µg/m³, and 4.8 ± 0.6 µg/m³ for FRM2 monitor, and 43.3 ± 5.1 µg/m³, 27.1 ± 5.9 µg/m³ and 6.9 ± 0.5 µg/m³ for FRM1 monitor in Winnipeg. These three-day means exceeded the CAAQS 27 µg/m³ threshold guidelines for poor air quality. The highest values occurred when wildfire smoke from British Columbia, Alberta or Ontario smoke were moving into Winnipeg in early and late August 2018 (see Chart 4).

With higher ambient PM_{2.5} levels and short-term human exposure, smoke plumes from wildfire provide risks to vulnerable and distant geographical populations. PM_{2.5} values in SSB were lower than the CAAQS for days monitored. Daily means of PM_{2.5} observed in June and July ranged from 1.1 ± 0.2 µg/m³ to 4.54 ± 0.3 µg/m³, respectively. These summer levels in SSB were lower and within the PM_{2.5} values 1.9 ± 0.6 µg/m³ to 6.6 ± 0.7 µg/m³ for FRM1 monitor station,

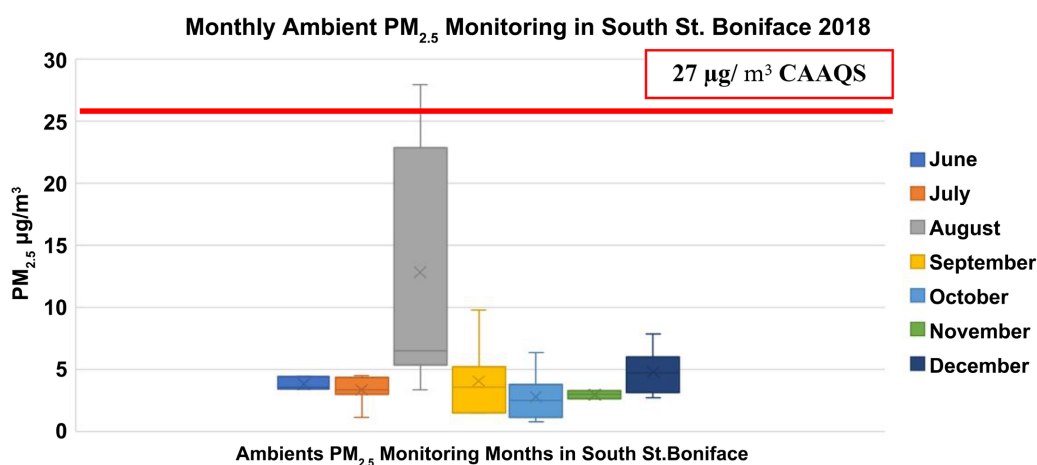


Chart 4. Monthly ambient PM_{2.5} levels monitored in South St. Boniface for seven months.

with $2.7 \pm 0.7 \mu\text{g}/\text{m}^3$ to $10.9 \pm 4.6 \mu\text{g}/\text{m}^3$ for FRM2 monitor station. Similarly, PM_{2.5} levels June and July in the residential area of SSB were lower than the MIA upwind measurements ranging from $2.0 \pm 0.2 \mu\text{g}/\text{m}^3$ to $16.4 \pm 18.5 \mu\text{g}/\text{m}^3$ (see **Chart 4**). Similarly, PM_{2.5} values for September to December monitoring months ranged from $1.5 \pm 0.53 \mu\text{g}/\text{m}^3$ to $9.81 \pm 3.87 \mu\text{g}/\text{m}^3$ (see **Chart 4**). These PM_{2.5} levels from September to December in SSB are lower than the $1.2 \pm 0.1 \mu\text{g}/\text{m}^3$ to $35.8 \pm 30.8 \mu\text{g}/\text{m}^3$ measured at the FRM2 station and $1.8 \pm 0.04 \mu\text{g}/\text{m}^3$ to $12.7 \pm 1.4 \mu\text{g}/\text{m}^3$ measured at the FRM1 station.

The observable differences in PM_{2.5} mass concentrations in the MIA and SSB are attributed to the northwesterly dominant wind direction observed and recorded by our Watchdog weather monitoring station (**Figure 3**). The SSB residential neighborhood is located southeast of the city area. The scrap metal shredder is northeast of the residential area. The northwesterly dominant wind direction will mostly disperse fugitive emissions from the scrap metal shredder downwind of the dominant wind direction (**Figure 3**). Prevailing wind direction affects industrial facilities' dispersion of PM_{2.5} concentration emission. According to the industrial air pollution dispersion study by Guerra et al. (2006), wind direction was a statistically significant factor in the local and regional dispersion of industrial emissions of PM_{2.5} concentration.

3.5. Result of One-Way ANOVA and Correlation Analysis for PM_{2.5} in Dufresne Avenue, South St. Boniface

The result of the one-way ANOVA (see **Table 5**) showed a statistically significant difference between the 256-hourly means of PM_{2.5} levels at Dufresne Avenue compared to other streets, where $F(3, 256) = 4.4$ and $p\text{-value} = 0.005$. Furthermore, the Tukey HSD multiple comparisons of means showed a statistically significant difference between PM_{2.5} levels for three out of four monitoring streets (Kavanagh-Cherrier ($p = 0.033$); Kavanagh-Doucet ($p = 0.037$)).

PM_{2.5} concentrations vary spatially at different scales. Limited air monitoring networks in city areas or large population settlements under-report the ambient

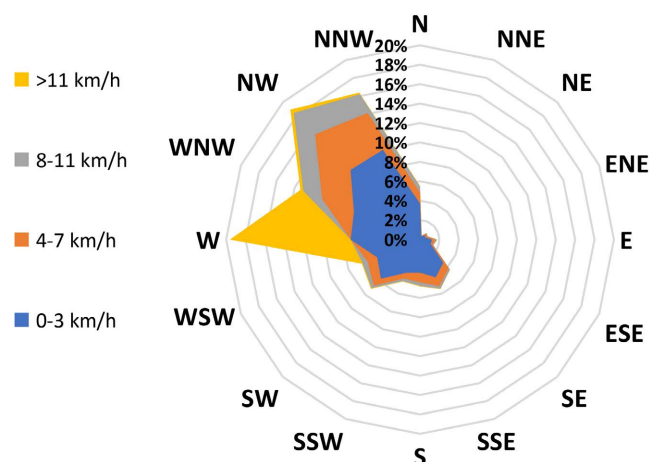


Figure 3. Wind rose for wind speed and wind direction measurement from mission industrial watchdog weather station. (6 June to 2 November 2018).

Table 5. One-way ANOVA for PM_{2.5} levels monitored downwind directions of the scrap metal shredder.

	PM _{2.5}				
	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	526.977	3	175.659	4.406	0.005*
Within Groups	10205.433	256	39.865		
Total	10732.409	259			

*Significant at $p \leq 0.01$ level.

air quality of industrial and mixed-use areas (Guerra et al., 2006). Hence, our study used the statistical analysis method, Pearson correlation, to show the relationship between the ambient PM_{2.5} concentrations monitored by the Dylos (residential) monitor at South St. Boniface with Winnipeg’s FRM monitors. We compared the 260 hours of PM_{2.5} data in SSB with 240 and 220 hours of data for FRM1 and FRM2 monitors in downtown Winnipeg. The charts above showed the increasing and decreasing trends of PM_{2.5} levels compared to the Manitoba ambient PM_{2.5} levels for Winnipeg. These two FRM monitoring stations sited five and eight kilometres from our particulate monitoring sites in SSB. Both monitoring stations in downtown Winnipeg reported Winnipeg’s general air quality, without providing local ambient air quality readings to other parts of the city.

The Dylos (residential) and FRM1 (Reference) monitors have a significant, strong linear relationship ($r = 0.67, p < 0.001$). The direction of the relationship is positive for Dylos and FRM1, meaning these variables tend to increase together (see Table 6 for Correlation Analysis). The Dylos and FRM2 have a significant relationship linear relationship ($r = 0.52, p < 0.001$), which is moderately positively correlated), meaning these variables tend to increase together. Similarly, the FRM1 and FRM2 monitors have a significant positive linear relation

Table 6. Pearson correlation of PM_{2.5} levels monitored with Dylos at South St. Boniface and FRM1 and FRM2 regulatory monitors.

Correlations		Dylos (Low-cost)	FRM1 (Regulatory)	FRM2 (Regulatory)
Dylos (Low-cost)	Pearson Correlation	1	0.673**	0.516**
	Sig. (2-tailed)		0.001	0.001
	N	260	240	220
FRM1 (Regulatory)	Pearson Correlation	0.673**	1	0.789**
	Sig. (2-tailed)	0.001*		0.001*
	N	240	240	200
FRM2 (Regulatory)	Pearson Correlation	0.516**	0.789**	1
	Sig. (2-tailed)	0.001*	0.001*	
	N	220	200	220

*Significant at $p \leq 0.01$ level; **Correlation is significant at the 0.01 level (2-tailed).

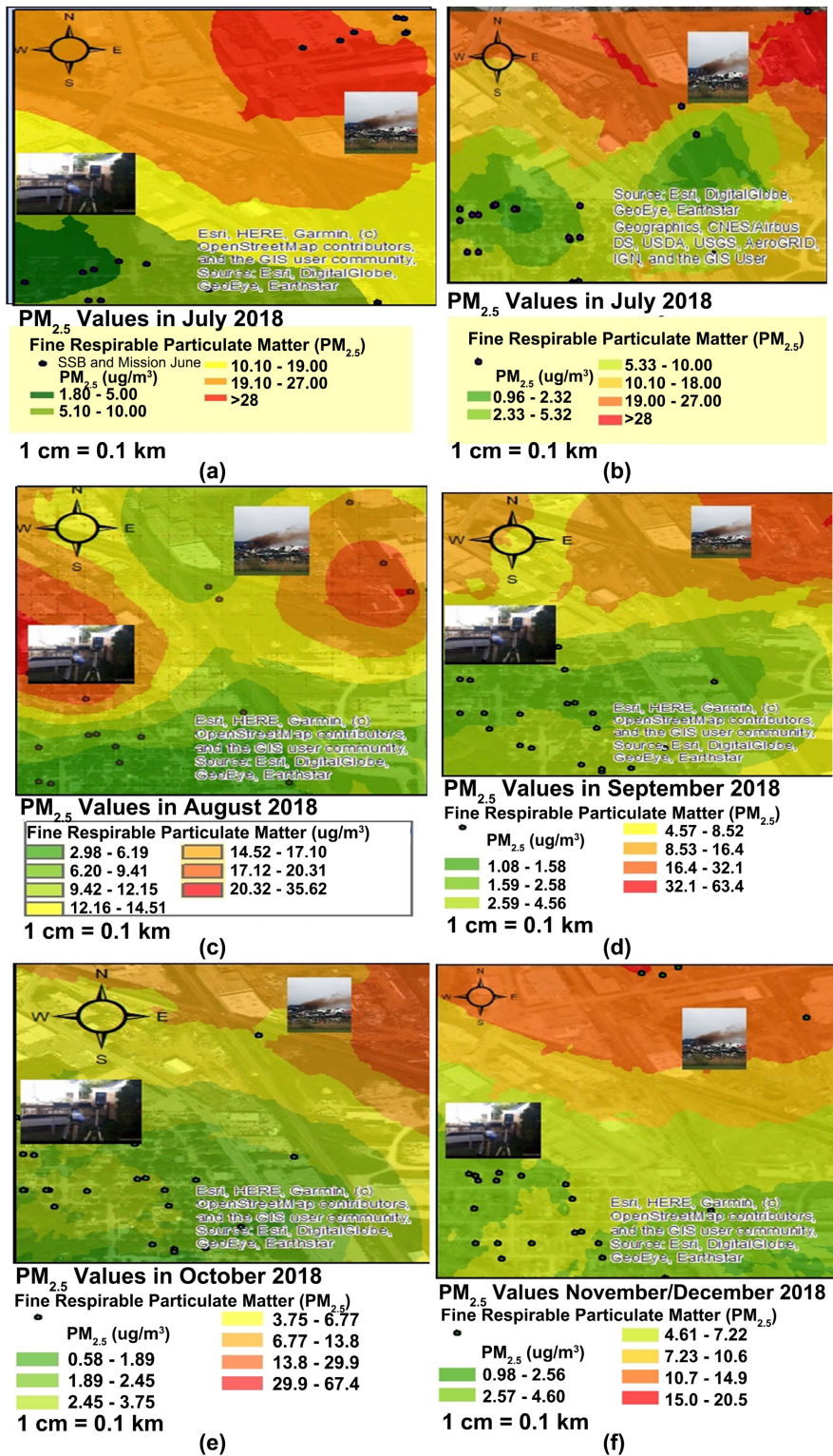
for the north and east sides. The FRM1 (Reference) and FRM2 (Reference) are very strongly positively correlated, meaning these variables tend to increase together.

4. ArcGIS Mapping of PM_{2.5} in Mission Industrial Area and South St. Boniface

The interpolated maps of **Maps 1(a)-(f)** display the patterns and distribution of PM_{2.5} trends based on emissions and the prevailing wind direction of the study area. The green patterns on the interpolated maps indicate satisfactory air quality sampling areas, with PM_{2.5} levels of less than ten $\mu\text{g}/\text{m}^3$, in the residential areas in SSB. The July map shows that the green pattern displayed in the Industrial Metal Inc. scrap metal shredder indicates the inaccessible PM_{2.5} monitoring areas within the industry site where we could not measure. Please note green does not indicate zero or acceptable particulate matter levels but notes a lack of any data. The yellow shading on the interpolated maps represent areas where PM_{2.5} levels exceed 10 $\mu\text{g}/\text{m}^3$. This borderline level requires action to prevent the deterioration of air quality. The monthly orange patterns show PM_{2.5} levels of 19 to 27 $\mu\text{g}/\text{m}^3$. These high levels are mostly within 100 meters of the scrap metal industry's fence line. Last, the dark red patterns are areas where episodic hourly emissions exceeded PM_{2.5} > 27 $\mu\text{g}/\text{m}^3$. The emissions reached higher levels of 20.3 to 67.2 $\mu\text{g}/\text{m}^3$ from the scrap metal industry in the MIA and 21 to 35 $\mu\text{g}/\text{m}^3$ ambient PM_{2.5} levels in the residential area.

Discussion of Interpolated Maps for PM_{2.5} in Mission Industrial Area and South St. Boniface

The higher PM_{2.5} levels downwind of the shredder compared to those upwind indicate that the metal shredder is the source of increased particulate matter. The



Map 1. (a) June 2018 spatial distribution of particulate matter in South St. Boniface; (b) July 2018 spatial distribution of particulate matter in South St. Boniface; (c) August 2018 spatial distribution of particulate matter in South St. Boniface; (d) September 2018 spatial distribution of particulate matter in South St. Boniface; (e) October 2018 spatial distribution of particulate matter in South St. Boniface; (f) November/December 2018 spatial distribution of particulate matter in South St. Boniface.

findings show exceedances and deteriorating air quality in the downwind westerly and northwesterly areas. The interpolated maps display higher levels as red and orange patterns. The map shows the spatial and temporal patterns of variation in PM_{2.5} levels. During the fires of August 2018, Canadian Ambient Air Quality Standards exceeded 35 µg/m³ for SSB caused by the summer smoke waves that drifted into Southern Manitoba from British Columbia and Alberta. Smoke from wildfires has atmospheric residence time that often lasts for days (Andreae, 1990). According to Le et al. (2014), the elevated outdoor concentration of PM_{2.5} from wildfire smoke contributes to a 49.6% increase in respiratory and cardiovascular diagnoses compared to the absence of forest fire smoke.

Monthly kriging maps display the periodic trends of air quality patterns below CAAQS and episodic deteriorating air quality caused by summer wildfire smoke. The air quality patterns seen from the interpolation in the residential area are linked with the impact of meteorological conditions, dominantly wind direction during the sampling season (see Figure 3). During this sampling period, higher emissions were predominately dispersed downwind of the shredder, which is upwind from the SSB residential area. Thus, ambient PM_{2.5} in the SBB residential area during the summer and fall seasons was from the regional transboundary movement of smoke and particles on already higher levels than the reference in the SBB (Sapkota et al., 2005).

Our study's monitoring upwind sites and FRM/FEM monitor sites showed an increased PM_{2.5} level by ten µg/m³ caused by the wildfire smoke waves from British Columbia and the northern Manitoba-Ontario border area (Canadian Broadcasting Corporation [CBC], 2018). Studies have reported wildfire smoke waves significantly influencing summertime air quality in Canada and the Western United States, leading to a short-term exponential increase in PM_{2.5} levels (Davignon, 2014; O'Dell et al., 2019). Wildfires often cause temporary deterioration of air quality, often accompanied by regional advisories on health risks associated with exposure to PM_{2.5}.

5. Conclusion

The scrap metal shredder was identified as the source of PM_{2.5} emissions at measurable levels during its daily operations by comparing samples upwind and downwind. Most daily mean levels, downwind of the scrap metal shredder PM_{2.5}, exceed upwind levels and background sites in the air quality reference monitoring stations. Exceedances of regulatory levels occurred in the downwind air monitoring points of MIA, with upwind points in SSB residential area, during this sampling season, standards were not exceeded except during wildfire season. The exceedance of PM_{2.5} emissions levels in MIA is a public health concern and increases the risks for the proximate residential neighborhood like SSB. However, when the wind shifts in other seasons, SSB may be at risk of exceeding standards.

Zoning toxic and polluting industrial facilities near low-income communities

create poor health situations in these areas and health inequity. As SSB is low-income, with a median income of \$43,200 (Statistics Canada, 2021) compared to the federal median average of \$68,400, this low-income community suffers environmental injustice. This low-income community experiences higher pollution and risks compared to other communities, including exposures to children from contaminated air and soil. The health risks associated include asthma, and chronic respiratory conditions (WHO, 2013; Xing et al., 2016).

The PM_{2.5} emissions from the scrap metal recycling shredder had sporadic daytime exceedance levels above the CAAQS. This exceedance signals a need for regulatory monitoring and management action to prevent pollution. Ambient particulate matter monitoring in residential areas and traffic corridors averaged daytime PM_{2.5} below the poor air quality standard for CAAQS.

The ambient PM_{2.5} levels showed a moderate to very strong correlation with the PM_{2.5} values reported by Manitoba Air Monitoring Station, Ellen and Scotia Streets, Winnipeg. In Winnipeg, pollution from northern summer forest fires contributed to a significant increase in ambient PM_{2.5} values for the residential neighborhood of SSB during three days of monitoring in August 2018. The seasonal impact of wildfire smoke on ambient air quality worsens the environmental risks and burden from industrial zoning facilities proximate to residential neighborhoods and the associated health impacts on the communities.

The PM_{2.5} air sampling by Dylus DC 1700 provided a low-cost air monitoring technique for citizens to monitor risk from PM_{2.5}. However, future research for data validation using Dylus AQM in Winnipeg should be collocated with government (FRM/FEM) PM_{2.5} monitors. Using a single Dylus AQM at the monitoring locations in this study prevented the simultaneous collection of real-time upwind and downwind PM_{2.5} levels in MIA and SSB. Consequently, our PM_{2.5} monitoring study did not compare daily real-time in SSB concurrently when the scrap metal shredder operated. This research found high emissions above regulatory standards in MIA, requiring regulatory monitoring and enforcement.

Acknowledgements

We acknowledge and appreciate financial and other support provided by SSHRC and the South St. Boniface Resident Association, Winnipeg, Manitoba. They went door-to-door to fundraise to buy the Dylus DC1700 Air Quality Monitoring for data collection.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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