Elevated $PM_{2.5}$ Concentrations from a Wood-Burning Community Event in Providence, RI

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Table of Contents

Abstract

WaterFire is a recurring community and arts event in Providence, RI that involves igniting small bonfires along the Providence River. Increases in fine particulate matter ($PM_{2.5}$), a common air pollutant, have been linked to wood-burning events. This study investigates the effect of WaterFire events on Providence's air quality. Hourly concentrations of $PM_{2.5}$ and WaterFire dates for 2023 were obtained from the Breathe Providence network—a network of 25 low-cost air pollution sensors—and the WaterFire website, respectively. WaterFire "Control" and "Test" periods, defined as the night before and the night of each event, were isolated from the $PM_{2.5}$ data. Data was analyzed daily, weekly, monthly, and on a sensor-to-sensor basis. The Test period was also compared to the coldest days in 2023, the Fourth of July fireworks, and the 2023 Canadian wildfires, which were hypothesized to have elevated $PM_{2.5}$ concentrations. Results show that WaterFire generates higher average $PM_{2.5}$ values across Providence when compared to the Control period, particularly in winter months. Sensors surrounding WaterFire locations in Downtown Providence show the greatest enhancement, while peripheral sensors were minimally impacted. WaterFire days show higher average $PM_{2.5}$ values than the coldest days from 2023, but lower $PM_{2.5}$ concentrations than the Fourth of July fireworks and the 2023 Canadian wildfires. WaterFire increases $PM_{2.5}$ concentrations in Providence, which appears to increase emergency department visits for asthma in children and COPD in adults in southern Providence. Given the high rates of chronic respiratory conditions in this area, intervention steps to protect vulnerable populations should be taken.

1. Introduction

1.1 Particulate Matter

The health impact of fine particulate matter ($PM_{2.5}$) has been well documented over the past few years, with the pollutant being linked to the induction or aggravation of respiratory diseases (asthma, chronic obstructive pulmonary disease – COPD), cardiovascular diseases, and chronic diseases (type 2 diabetes mellitus, hypertension), among others.[1] This paired with the relatively high prevalence of asthma in Rhode Island[2] stresses the importance of understanding sources of $PM_{2.5}$ in the state and mitigating the increase of ambient and indoor concentrations of the pollutant.

Particulate matter (PM) is defined as tiny solid or liquid droplet inhalable particles, which could be classified in different size classes, including PM_{10}, $PM_{2.5}$, and $PM_{0.1}$.[3] $PM_{2.5}$ is fine particulate matter of size 2.5 micrometers (μm) or less, which can include a combination of smoke, dirt, and dust particles suspended in the air.[4,5] $PM_{2.5}$ pollution can either be produced indoors or outdoors and enter a building through infiltration or ventilation.[6] Indoor sources include common household practices, such as cooking, smoking, fuel combustion for heating, and burning incense,[6] while outdoor sources include vehicle emissions, sea salt, road dust, and biomass/wood-burning.[7] In addition to these primary sources, $PM_{2.5}$ is created through secondary sources, which include atmospheric reactions of nitrate and sulfate that contribute to haze formation.[8] $PM_{2.5}$ is listed by the Environmental Protection Agency (EPA) as a criteria pollutant, as defined by the Clean Air Act,[9] meaning its ambient atmospheric concentrations are regulated.[4] In February of 2024, the EPA reduced the primary annual standard of $PM_{2.5}$ from 12.0 $\mu g/m^3$ to 9.0 $\mu g/m^3$,[10] recognizing the impact of $PM_{2.5}$ on human health.

The inhalable nature of fine particulate matter allows its particles to enter the body through the nasal and oral cavities, where it is transported into the lungs and causes an inflammatory response.[5] For this reason, $PM_{2.5}$ pollution has been linked to respiratory diseases, aggravations of existing asthma conditions – especially in children – and allergic reactions in non-pollen seasons.[5] Once introduced into the lungs, $PM_{2.5}$ particles can also enter the bloodstream and be transported to other organs, where they can cause diseases. In addition to the aforementioned health conditions, $PM_{2.5}$ has been linked to stroke, tuberculosis, ischemic heart disease, and obesity.[5] These health conditions impact vulnerable communities – children, older adults, and individuals of low socioeconomic status – at a greater rate.[11]

According to the Centers for Disease Control and Prevention (CDC), Rhode Island has some of the highest asthma rates in all age demographics in the United States.[12] In Providence, RI, communities most affected by asthma tend to be those with the greatest social vulnerability: low-income neighborhoods, communities with a majority of people of color, and neighborhoods located adjacent to environmental hazards (Figure 1). Furthermore, student absenteeism in Providence is commonly associated with asthma or respiratory conditions, revealing the damaging effects of poor air quality on students' academic performance.[13] This contributes to the rise in social inequalities, as these students will have a decreased potential for human capital formation.[14]

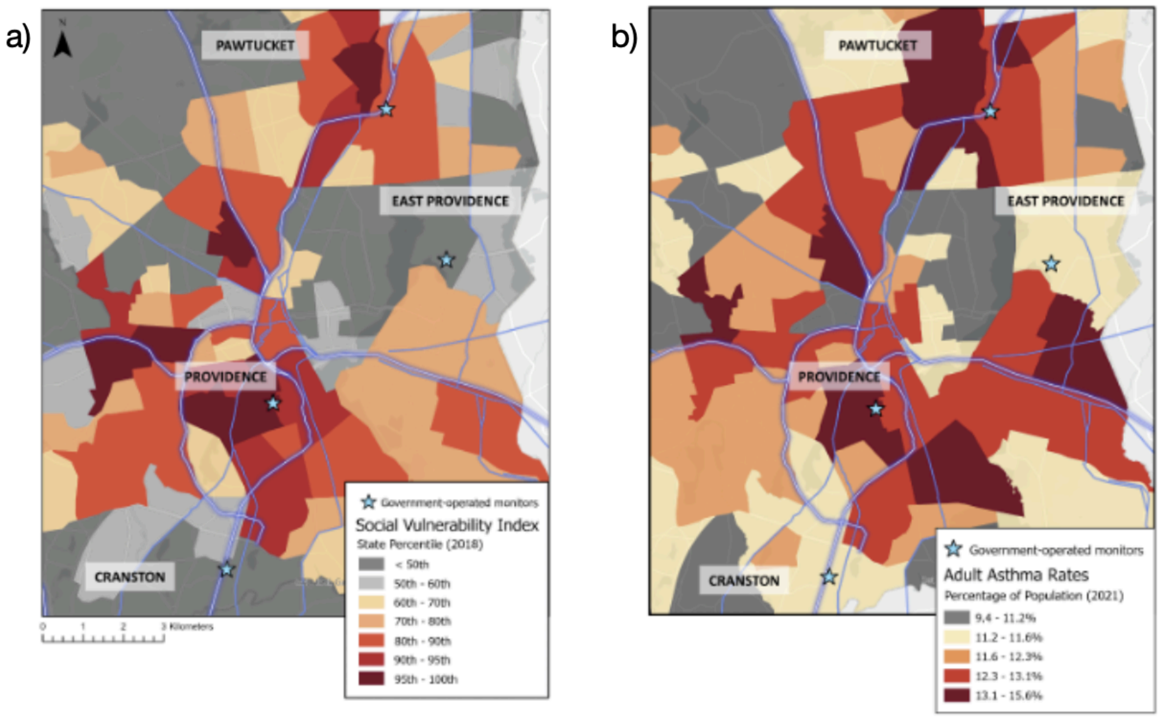

Figure 1: a) Map of Providence, showing the Center for Disease Control (CDC) Agency for Toxic Substances and Disease Registry's Social Vulnerability Index — darker colors represent greater vulnerability. b) Map of Providence, showing adult asthma rates — darker colors represent greater asthma rates. For both graphs, blue stars represent government-operated sensors.
(CDC, 2024)

1.2 Breathe Providence Project

Research for this study was conducted under the Breathe Providence project,[15] which is a community-focused network of low-cost air quality monitors in Providence, RI based at Brown University and led by primary investigator Dr. Meredith Hastings. With the aim of producing relevant data for residents, scientists, and policymakers, the network was built around community priorities. With support from the Clean Air Fund,[16] Breathe Providence continuously measures carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxides (NO_x), fine particulate matter ($PM_{2.5}$), ozone (O_3), and meteorological conditions at 25 locations preferentially distributed throughout neighborhoods in Providence (24 sensors were active at the time of this research) (Figure 2). Breathe Providence seeks to (1) advance the science and policy utility of lower-cost air quality monitoring data, (2) understand the landscape of air pollution and climate-related emissions in Providence, and (3) raise awareness of local air quality and support improved policy and local environmental and sustainability initiatives.

In line with the project's community-focused nature, the project has undertaken "responsive analyses" that address community partners' requests and questions. One of those partnerships is with the South Providence Health Equity Zone (SPHEZ). In Rhode Island, the Health Equity Zones initiative builds resilient communities by bringing people together to challenge systems that propagate health inequalities.[17] During a discussion of general patterns of major pollutants in their area, members of the SPHEZ Chronic Health Conditions Subcommittee expressed concerns about pollution generated from local wood-burning "WaterFire" events.

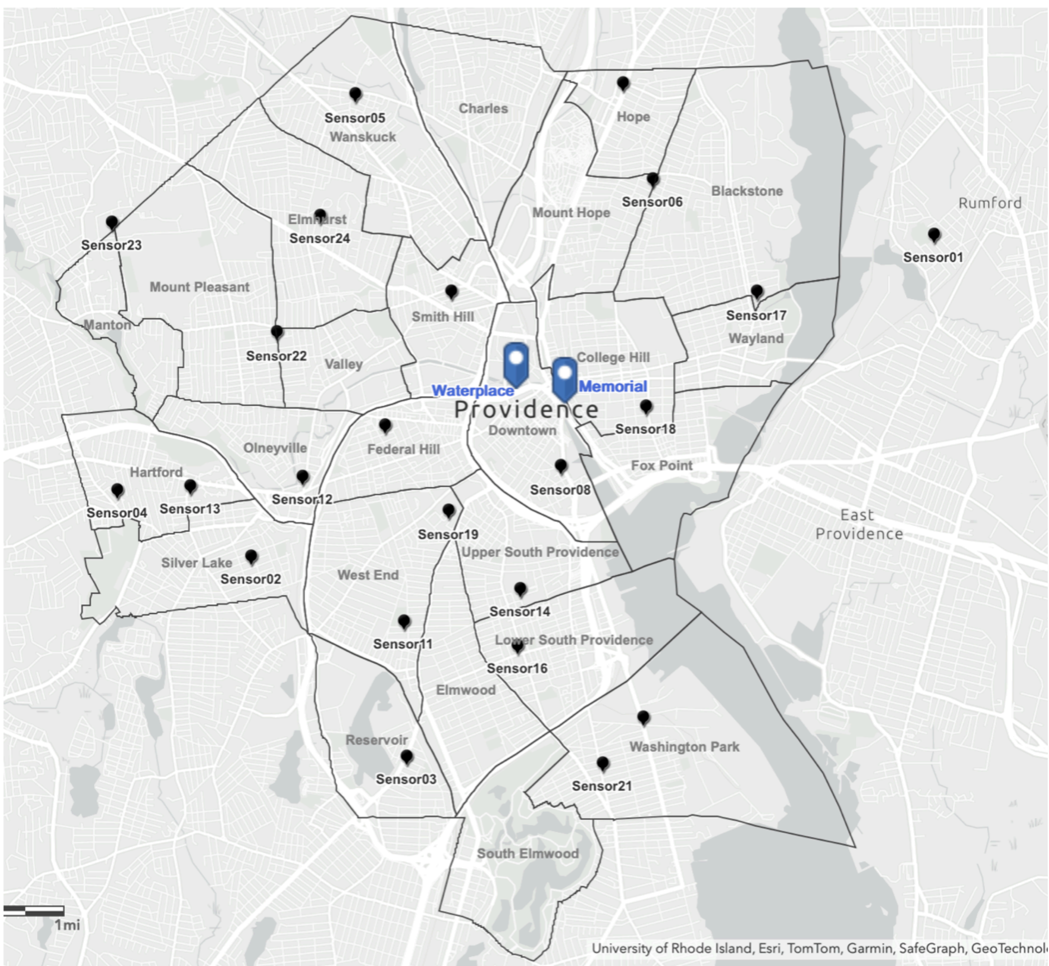

Figure 2: Map of Providence with Breathe Providence sensor locations (black symbols) and WaterFire locations (blue symbols).

1.3 WaterFire: A Community Wood-Burning Event

Created in 1994 by Barnaby Evans, WaterFire is a recurring community and arts event in Providence, RI that involves igniting small wood-burning fires along the Providence River in Downtown Providence.[18] The event has attracted millions of visitors to Providence to experience the captivating displays organized about 16 times a year from March to December. Besides the wood-burning fires ignited along the Providence River, WaterFire entertains its audience through performances by fire dancers and with music from all over the world, while providing food from various vendors. With opportunities for boat rides, wedding proposals, birthday celebrations, and memorials,[19] WaterFire promises a memorable night to its attendees.[20] WaterFire events have also been organized to celebrate events such as the Fourth of July and New Year's Eve.

WaterFire events are hypothesized to increase local fine particulate matter ($PM_{2.5}$) concentrations. Previous work has shown that burning wood, such as that occurring during wildfires[21] and prescribed burning events,[22] increases $PM_{2.5}$ concentrations, occasionally at a regional scale. In an effort to address the SPHEZ's concern, this study focuses on WaterFire and its influence on local $PM_{2.5}$ pollution patterns and hospital emergency department visits related to respiratory health. Potential interventions are suggested to mitigate the impact of $PM_{2.5}$ pollution on human health.

1.4 Case Studies

The impact of WaterFire is also considered in the context of other known local $PM_{2.5}$ sources, including winter heating, fireworks, and wildfires. Firstly, for the winter heating period, about a third of the homes in Rhode Island use petroleum products, primarily heating oils, to generate heat.[39] As temperatures drop for the winter, demand for heating increases, which would cause an increase in $PM_{2.5}$ concentrations in the city, as wood-burning is a particulate matter source.[7] Secondly, fireworks utilize gunpowder and other chemicals to create explosions of color when ignited,[40] emitting pollutants such as sulfur dioxide, particulate matter, and hazardous trace elements.[42] Thus, fireworks are classified as hazardous under the Federal Hazardous Substances Act (FHSA).[41] Displays large enough to attract community gatherings occur infrequently in Providence, for celebrations such as the Fourth of July and New Year's Eve.[43] Lastly, Wildfires are a natural event that could arise from the spontaneous combustion of wood in regions of high tree density, allowing for the spread of the fires,[37] but also from triggers such as lightning and cigarette butts without the need for high tree density. Uncontrolled wildfires can burn large amounts of vegetation and contribute to the long-distance transport of $PM_{2.5}$. In 2023, wildfires across Canada from April to October caused worsened air quality over the Northeastern United States.[38] Together, these case studies provide the opportunity to compare WaterFire events to a spectrum of other anthropogenic and natural sources of $PM_{2.5}$.

2. Methods and Materials

2.1 Breathe Providence Data

Hourly $PM_{2.5}$ data for 2023, in μg/m^3 and local (Eastern) time, was obtained from the Breathe Providence sensor network. Each location contains a $BEACO_2N$ node, designed by the Berkeley Atmospheric CO_2 Observation Network for air quality monitoring in urban settings.[23] These low-cost sensors continuously measure multiple pollutants using a Plantower PMS5003 ($PM_{2.5}$), Vaisala CARBOCAP Carbon Dioxide Probe GMP343 (carbon dioxide, CO_2), Alphasense CO-B4 (carbon monoxide, CO), Alphasense NO-B4 and NO2-B43F (nitrogen oxides: NO_X, NO_2), and Alphasense OX-B431 (ozone, O_3).[24] The nodes also contain a Bosch Sensortec BME280 digital sensor, which provides data on temperature, pressure, and relative humidity.[24,27] The $BEACO_2N$ node design and function is described in greater detail in Shusterman et al., 2016.[25]

For $PM_{2.5}$ measurements, the Plantower (Figure 3) is a digital particle concentration sensor that determines the number of suspended particles in the air.[26] To do this, a fan sucks air and particles into the path of a laser contained in the sensor through the air intake openings (4 circular holes on Figure 3a), and the amount of light scattered by the entering particles is recorded as an electrical signal to produce a mass concentration value.[27] After this raw data is collected, it is calibrated using the CF ATM internal calibration measurements recommended for outdoor $PM_{2.5}$ concentrations.

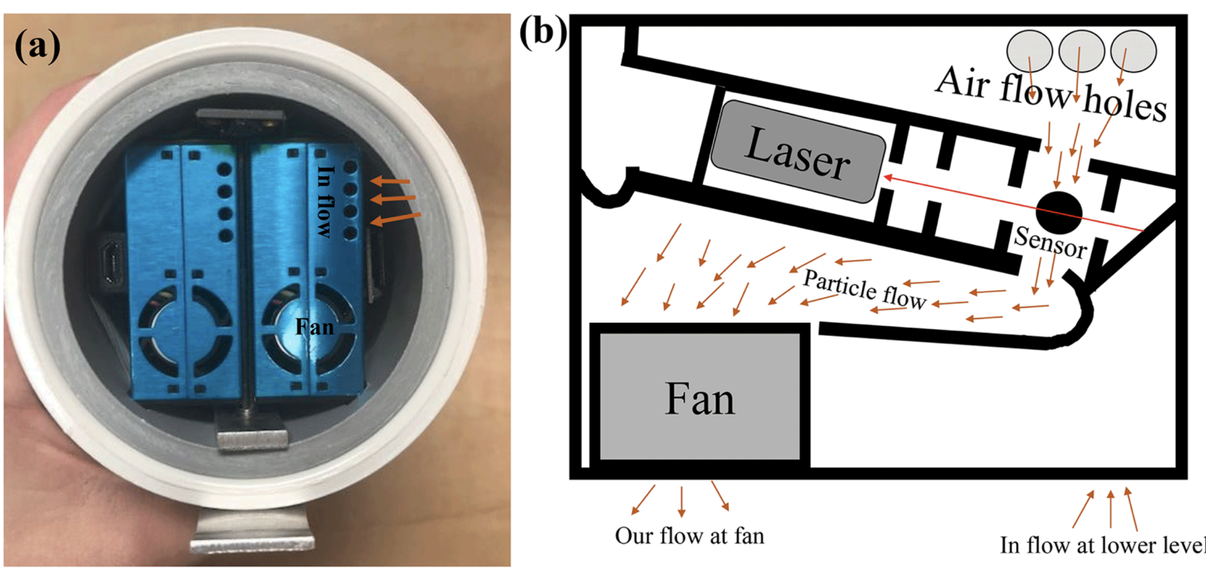

Figure 3: a) Picture of the bottom of a Purple Air sensor with 2 Plantower PMS5003 sensors (blue rectangles). b) Schematic showing the particle flow path into, within, and out of a Plantower PMS5003 sensor. (Ardon-Dryer et al., 2020)

2.2 WaterFire Data

Information about the 2023 WaterFire schedule was retrieved from the WaterFire website. This includes the date of the WaterFire event, start and end time, whether the event was a partial or full lighting of the Providence River, and the location of the lighting event along the river – Memorial Park or Waterplace Park for partial lighting, or the entire section of the river from Memorial Park to Waterplace Park for full lighting (Table 1). The locations of Memorial and WaterPlace Park are visualized in Figure 2.

The 2023 WaterFire schedule contains 16 dates from April - December, with the earliest starting time for the event being at 5:30pm, and the latest ending time being 12:00am. WaterFire events mainly occur on a Saturday – 12 out of the 16 event dates are on a Saturday – but events also occurred on a Sunday, Wednesday, and two Fridays. There is almost an even split between partial and full lightings in the schedule – 9 full lightings and 7 partial lightings.

Table 1: 2023 WaterFire Schedule

	Day	Start Time	End Time	Location	Lighting	Duration
1	Saturday	2023-04-01 19:10:00	2023-04-01 21:30:00	Memorial Park	Partial	2.33
2	Wednesday	2023-04-19 19:30:00	2023-04-19 21:30:00	Memorial Park	Partial	2
3	Saturday	2023-06-03 20:15:00	2023-06-04 00:00:00	Not Indicated	Full	3.75
4	Sunday	2023-06-18 20:23:00	2023-06-18 22:00:00	Waterplace Park	Partial	1.62
5	Saturday	2023-06-24 20:24:00	2023-06-25 00:00:00	Not Indicated	Full	3.6
6	Saturday	2023-07-08 20:22:00	2023-07-09 00:00:00	Not Indicated	Full	3.63
7	Friday	2023-07-14 20:19:00	2023-07-14 22:30:00	Waterplace Park	Partial	2.18
8	Saturday	2023-07-22 20:13:00	2023-07-23 00:00:00	Not Indicated	Full	3.78
9	Saturday	2023-08-19 19:40:00	2023-08-20 00:00:00	Not Indicated	Full	4.33
10	Saturday	2023-09-02 19:17:00	2023-09-02 23:00:00	Waterplace Park	Partial	2.72
11	Saturday	2023-09-09 19:05:00	2023-09-10 00:00:00	Not Indicated	Full	4.92
12	Saturday	2023-09-30 18:29:00	2023-09-30 23:00:00	Waterplace Park	Full	4.52
13	Saturday	2023-10-14 18:06:00	2023-10-14 23:00:00	Not Indicated	Full	4.9
14	Saturday	2023-11-04 17:36:00	2023-11-04 22:00:00	Waterplace Park	Full	4.4
15	Saturday	2023-12-02 17:30:00	2023-12-02 21:00:00	Waterplace Park	Partial	3.5
16	Friday	2023-12-08 17:30:00	2023-12-08 21:00:00	Waterplace Park	Partial	3.5

Table 1: 2023 WaterFire schedule and summary of events, including the day of the week, start time, end time, location, lighting classification (full or partial), and duration of the event.

2.3 $PM_{2.5}$ Analysis

$PM_{2.5}$ statistical analyses and plotting were conducted using R version 4.3.2 and RStudio, primarily with the openair[28] and ggplot2[29] packages. Mapping and spatial analyses were conducted using ArcGIS Pro.

Hourly $PM_{2.5}$ concentrations for 2023 were first divided into 3 study periods. An **All** study period was created by filtering $PM_{2.5}$ values from sensors with 75% annual (January - December) coverage of 2023 from the complete dataset; 19 out of the 24 sensors met this threshold (Table 2). To investigate the effect of WaterFire, **Test** and **Control** study periods were generated (Table 2). The Test period consists of $PM_{2.5}$ values from only the WaterFire dates between April - December, while the Control period consists of $PM_{2.5}$ values from the night (5pm - 12am) before WaterFire dates from the last day of March - December. The time period selected represents the earliest starting time (5:30pm) and the latest ending time (12am) of WaterFire events (note that 5pm was used for the observations due to the availability of hourly $PM_{2.5}$ values in the complete dataset). Sensors with 80% coverage of both periods were used (19 out of 24 sensors used).

Focusing on the Test period, the categorization of some WaterFire events as full lightings and others as partial lightings (see Table 1) provoked interest on the amount of emitted $PM_{2.5}$ from these events. Therefore, the Test period was further divided into a partial lighting period (**Partial**), which occurred at Memorial Park or WaterPlace Park, and a full lighting period (**Full**), which did not have locations listed but are assumed to involve lightings of the Providence River from Memorial Park to WaterPlace Park (Table 2). Potential differences in $PM_{2.5}$ concentrations across the city from the different degrees of WaterFire lightings were evaluated by comparing these periods.

The complete $PM_{2.5}$ dataset was then divided into more study periods – **Cold**, **Fireworks**, **Wildfire** – to compare the impact on $PM_{2.5}$ from WaterFire to other events that are presumed to increase $PM_{2.5}$ concentrations (Table 2). The Cold period is made up of $PM_{2.5}$ values from the nights (5pm - 12am) of the 16 coldest days in 2023 from January - February, and November - December. These days are expected to have had the greatest emissions from home heating. Outdoor temperature data for this period was retrieved from the Environmental Protection Agency's Air Quality System (EPA AQS).[30] The dataset was filtered for sensors with 80% coverage of the Cold period (17 out of 24 sensors used). For the Fireworks period, $PM_{2.5}$ values for the nights (5pm - 12am) of 1st and 2nd July, 2023 were filtered from the complete dataset, as Fourth of July fireworks occurred on those dates around Providence for 2023. Sensors with 100% coverage of this period were used (21 out of 24 sensors used). The Wildfire period consists of $PM_{2.5}$ values from nights (5pm - 12am) in June - October on the days with the 16 highest average $PM_{2.5}$ values, as the 2023 Canadian wildfires[31] took place during those months (April - October). Sensors with 80% coverage of the period were used (21 out of 24 sensors used).

Table 2: Sensor Selection

Periods	Description	Criteria for Sensor Section	# of Sensors
All	Values from January - December in 2023	75% coverage of period	19
Test	Values from WaterFire dates and times in 2023 (see **Table 1**)	80% coverage of period	19
Control	Values from the night (5pm-12am) before WaterFire dates	80% coverage of period	19
Partial	Values from WaterFire dates categorized as 'Partial' in **Table 1**	-	19
Full	Values from WaterFire dates categorized as 'Full' in **Table 1**	-	19
Cold	Values from the nights (5pm-12am) of the 16 coldest days in 2023	80% coverage of period	17
Fireworks	Values from the nights (5pm-12am) of 1st and 2nd July 2023	100% coverage of period	21
Wildfire	Values from the nights (5pm-12am) in June - October 2023 of the days with the 16 highest average $PM_{2.5}$ values	80% coverage of period	21

Table 2: Summary of study periods with their descriptions, criteria for sensor selection, and number of sensors used (out of 24).

Trends in all study periods were characterized by generating summary statistics and time series, time variation, and calendar plot diagrams. The Control, Cold, Fireworks, and Wildfire datasets were compared to the Test dataset using an Analysis of Variance (ANOVA) test, as well as by comparing their average values across each dataset, and comparing the sensor averages across datasets. The percent enhancement in average $PM_{2.5}$ concentrations for each sensor was calculated by subtracting the Control value from the Test value, dividing by the Control value, and multiplying by 100%.

$$PercentEnhancement = \frac{Test - Control}{Control} \times 100$$

2.4 Hospital Discharge Data

Through a collaboration with the Rhode Island Department of Health (RIDOH), I was able to access the RIDOH hospital discharge database[32] to investigate the impact WaterFire has on the health of Providence residents. This database consists of daily emergency department (ED) visits for respiratory conditions from healthcare centers across Rhode Island in 2023. This includes information about patient sex, race, age, zip code, census tract number, and health condition description, among others. The database was filtered for ED visits in the city of Providence only. Emergency department visits were then grouped into six condition categories – **Asthma**, **COPD**, **Heart disease**, **Brain bleed/ tissue death**, **Hypertension**, and **Pulmonary embolism**. The "Edx1_text" column of the hospital discharge database was primarily used in the creation of these categories. This column represents the principal diagnosis of the patient, but up to 10 additional diagnoses can be reported.[32]

The asthma category was created by isolating condition descriptions with the word "asthma" included in the "Edx1_text" column of the hospital discharge database. Conditions include "unspecified asthma, uncomplicated," "mild intermittent asthma, uncomplicated," and "unspecified asthma with status asthmaticus" among others, with 15 unique asthma condition descriptions in total.

The COPD (chronic obstructive pulmonary disease) category was created by isolating condition descriptions with the words "bronchitis," "emphysema," or "chronic obstructive pulmonary disease" in the Edx1_text column. The conditions include "chronic obstructive pulmonary disease, unspecified," "panlobular emphysema," and "unspecified chronic bronchitis" among others, with 8 unique condition descriptions in total.

The hypertension category was generated by isolating condition descriptions with the words "hypertension," or "hypertensive" in the Edx1_text column. Conditions include "essential (primary) hypertension," "hypertensive emergency," and "pulmonary hypertension, unspecified" among others, with 12 unique condition descriptions in total.

The heart disease category was created by isolating condition descriptions with the words "heart," "cardio," "cardial," "cardiac," or "angina" in the Edx1_text column of the hospital discharge database. The conditions include "acute diastolic (congestive) heart failure," "angina pectoris, unspecified," and "dilated cardiomyopathy" among others. This resulted in 31 unique condition descriptions in total.

The brain bleed/tissue death category was generated by isolating condition descriptions with the words "cerebral," "intracranial," "subarachnoid," or "subdural" included in the Edx1_text column of the dataset. The conditions include "cerebral infarction, unspecified," "nontraumatic acute subdural hemorrhage," and "nontraumatic subarachnoid hemorrhage, unspecified" among others. This resulted in 16 unique condition descriptions in total.

The pulmonary embolism category was created by isolating condition descriptions with the words “pulmonary embolism” included in the Edx1_text column of the hospital discharge database. The conditions include “chronic pulmonary embolism,” and “other pulmonary embolism without acute cor pulmonale” – 2 unique condition descriptions in total.

To analyze the data temporally, ED visits from 2 days before WaterFire to 4 days after the event – a 7 day period (Figure 4) – were isolated for the 16 WaterFire events, then grouped by health condition using the above criteria. This analysis was conducted using the hypothesis that ED visits will increase in the days following WaterFire, given an increase in $PM_{2.5}$ concentrations during the event and the knowledge that $PM_{2.5}$ exacerbates respiratory conditions.[1] Additional analyses were conducted for two age and condition subcategories, per the advice of Dr. William Goedel – an Assistant Professor of Epidemiology at Brown University – who has identified significant prevalence in the following categories in his analyses of respiratory conditions. Within the Asthma dataset, analysis was conducted for asthma in children, where children represent individuals under 18 years old. Within the COPD dataset, analysis was conducted for COPD in adults, with adults being defined as individuals 18+ years old.

Figure 4: 7 day period isolated for WaterFire health impact analysis using RIDOH’s hospital discharge data.

To analyze the data spatially across Providence, ED visits for the day of WaterFire and the day with the highest ED visits after WaterFire, from the aforementioned 7 day isolated period, were grouped by census tract number and visualized using ArcGIS Pro. The hypothesis was that on the day with the highest ED visits after WaterFire, ED visits will show a spatial shift, with increases in regions of the city with the greatest percent enhancement of $PM_{2.5}$ concentration of the sensors.

3. Results & Discussion

3.1 $PM_{2.5}$ Patterns in Providence ("All Period")

Hourly measurements of $PM_{2.5}$ across Providence, RI display distinct temporal — diurnal, day-of-week, seasonal — and spatial patterns. In analyzing the filtered All period dataset, over the course of 2023, $PM_{2.5}$ concentrations hit an hourly maximum of 213.0 μg/m^3 and a minimum of 0.0 μg/m^3, with an average of 4.8 ± a standard error of 1.4 μg/m^3.

A summary of the diurnal trends of $PM_{2.5}$ indicates that $PM_{2.5}$ concentrations peak between 5am-7am and between 8pm-12am (Figure 5a). The 5am-7am peak is characteristic of the morning traffic rush. The climb in concentrations from 2pm followed by the 8pm-12am peak can be explained by the combination of evening traffic rush and the ground being cooler, which leads to boundary layer contraction and thus decreased $PM_{2.5}$ dispersal. Daily $PM_{2.5}$ concentrations are lowest around midday, 12pm, due to increased air mixing/convection/expansion of the boundary layer and dispersion of $PM_{2.5}$.

The variation in $PM_{2.5}$ concentration throughout the week is displayed in Figure 5b, which generally shows increasing $PM_{2.5}$ concentrations during weekdays (Monday-Friday) and decreasing concentrations on the weekends (Friday-Sunday). Maximum $PM_{2.5}$ concentrations tend to occur on Fridays, while minimum concentrations are more likely to occur on Mondays. With vehicle exhaust emissions and road dust being sources of $PM_{2.5}$,[33] the increasing $PM_{2.5}$ values during the week could be the result of higher traffic on business days and lower traffic on weekends,[34] especially the operation of heavy-duty trucks on business days compared to weekend days.[35]

When looking at the seasonal patterns of $PM_{2.5}$ (Figure 5c), we see that the highest concentrations are observed in the summer months (June-July). As seen in other studies, this is the result of emissions plus high temperatures and calm winds, but not necessarily low wind speeds.[36] It is also notable that these months contained the Canadian wildfire period in 2023 (April - October), which increased $PM_{2.5}$ concentrations over the Northeastern United States.[37] The lowest concentrations are seen at the beginning of the year in the winter and spring months (January-May).

Spatial patterns in annual $PM_{2.5}$ concentrations (Figure 5d) show that the highest average $PM_{2.5}$ concentrations by sensor tend to be observed in the peripheral neighborhoods of Providence (Silver Lake, Blackstone, Elmhurst), whereas the lowest concentrations are found in neighborhoods towards the center of the city (West End, Federal Hill, Olneyville). This suggests that $PM_{2.5}$ concentrations in Providence are dominated by regional influence. Rogers et al., 2020 provide support for this claim in their paper, as they found evidence for the long-distance transportation of particles from events such as wildfires and other biomass burning in the Northeastern United States.[38]

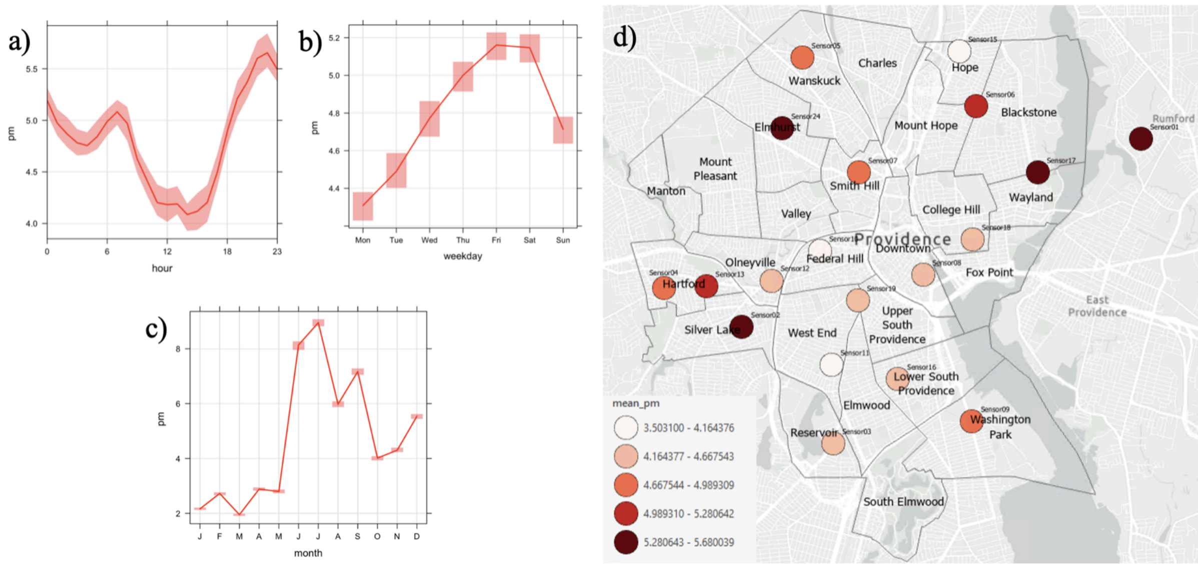

Figure 5: Temporal and spatial trends of $PM_{2.5}$ in Providence for 2023. Figures a-c show mean $PM_{2.5}$ values (red line) and the 95% confidence interval in the mean (pale red shading). a) Daily trend with hourly averages connected with straight lines. b) Weekly trend with daily averages connected by straight lines. c) Annual trend with monthly averages connected by straight lines. d) Map of Providence, showing sensor averages for sensors used in the All Period as colored circles — darker colors correspond with greater sensor averages.

3.2 WaterFire & Local Impacts

It was important to understand the general trends across the city as context for investigating the potential impact of a local event. With the annual trends in mind, the effects on local $PM_{2.5}$ concentrations from the regularly occurring WaterFire events in Providence were analyzed. During the Test period, $PM_{2.5}$ concentrations had a maximum of 30.8 $\mu g/m^3$, a minimum of 0.0 $\mu g/m^3$, and an average of 7.8 ± 1.4 $\mu g/m^3$. Diurnal patterns for this period show decreasing concentrations from 5pm-12am local time — the entire duration of WaterFire events — and show greater values than for the All period (Supp. Figure 4a). This could be explained by increased $PM_{2.5}$ dispersal, despite the boundary layer contraction at night. With only 4 days of the week — Wednesday, Friday, Saturday, Sunday — included in the Test period, day-of-week data for WaterFire are limited; however, they show the same trends as that of the All period, with increasing concentrations on business days (Wednesday-Friday), a peak on Friday, and decreasing concentrations into the weekend (Friday-Sunday) (Supp. Figure 4c). Therefore, this trend is likely also influenced by traffic patterns. Given that there were only 2 Fridays in the dataset, versus 12 Saturdays, the distinction of day of the week $PM_{2.5}$ concentrations in

Providence is strengthened. Looking at the seasonal patterns for the Test period, $PM_{2.5}$ concentrations increase towards the end of the year, from the beginning of the period in April to its end in December (Supp. Figure 4b), which could be due to increased background concentrations from the increase in fossil fuel combustion for heating during the winter season.

3.2.1 Test vs. Control

A comparison of $PM_{2.5}$ for the Test and Control study periods is displayed in Figure 6, which shows average concentrations at each sensor. The Test period clearly shows greater values than the Control at every sensor, with an overall sensor average of 7.7 µg/m^3 for the Test period, and 6.5 µg/m^3 for the control period (ANOVA: p-value = 1.30×10^{-5}). Here, with the nights before WaterFire being contrasted with the nights of the events, it is likely that WaterFire is the cause of these increases. Additionally, there is some correlation of spatial patterns between the Test and Control periods. For example, for both periods, the order of sensors in terms of increasing average $PM_{2.5}$ concentration is Sensor16 (South Providence Library) < Sensor07 (Smith Hill Library) < Sensor17 (Blackstone Residence) < Sensor02 (Silver Lake Residence). Similarly, Sensor11 at the West End Community Center shows the lowest average concentrations for both periods. In general, sensors that have relatively high average fine particulate matter concentrations for the Control period tend to have relatively high concentrations in the Test period as well (Supp. Figure 3).

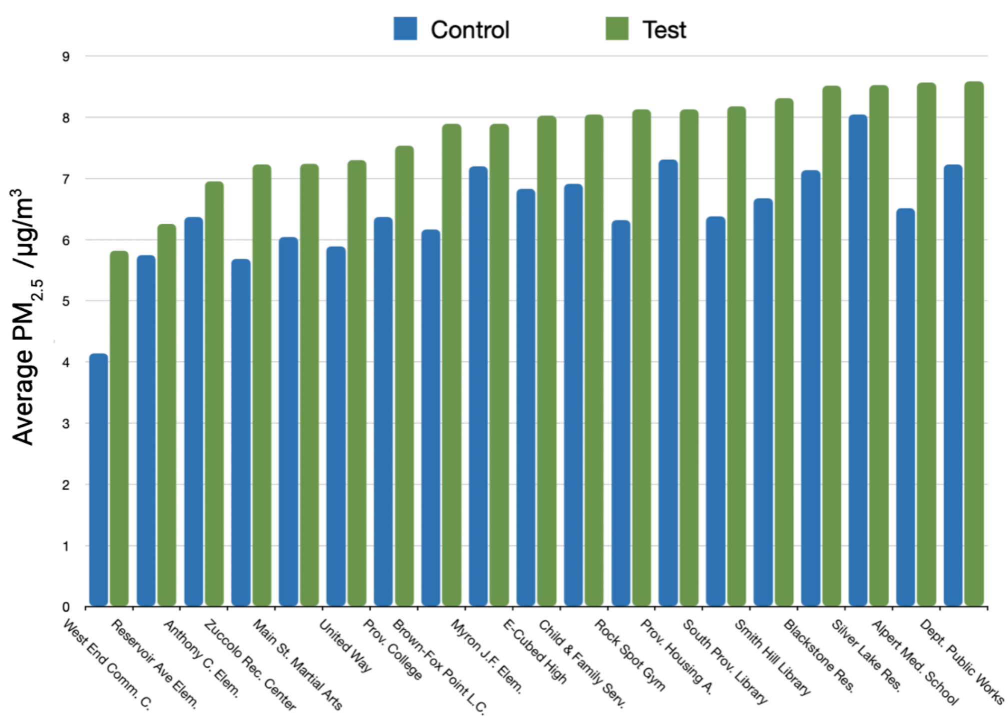

Figure 6: Average $PM_{2.5}$ concentrations across each of the 19 sensors included in the Test (green bars) and Control (blue bars) periods.

Comparing average concentration by day, the Test period shows increasing $PM_{2.5}$ concentrations towards the end of the year, from April - January (Figure 7), which is also observed in Supp. Figure 4b. Out of the 16 WaterFire event dates, 10 dates show higher average $PM_{2.5}$ concentrations than the night before, with a daily average of 7.3 μg/m^3 for Test and 6.5 μg/m^3 for Control. The figure shows increased positive enhancement from the Control value towards the end of the year, during the winter months. However, in a few instances at the beginning of the period, the Control value more than quadruples the Test value, indicating other significant sources of $PM_{2.5}$ on some nights. This suggests that the greater Test sensor averages observed in Figure 6 are enormously driven by wintertime $PM_{2.5}$ enhancements.

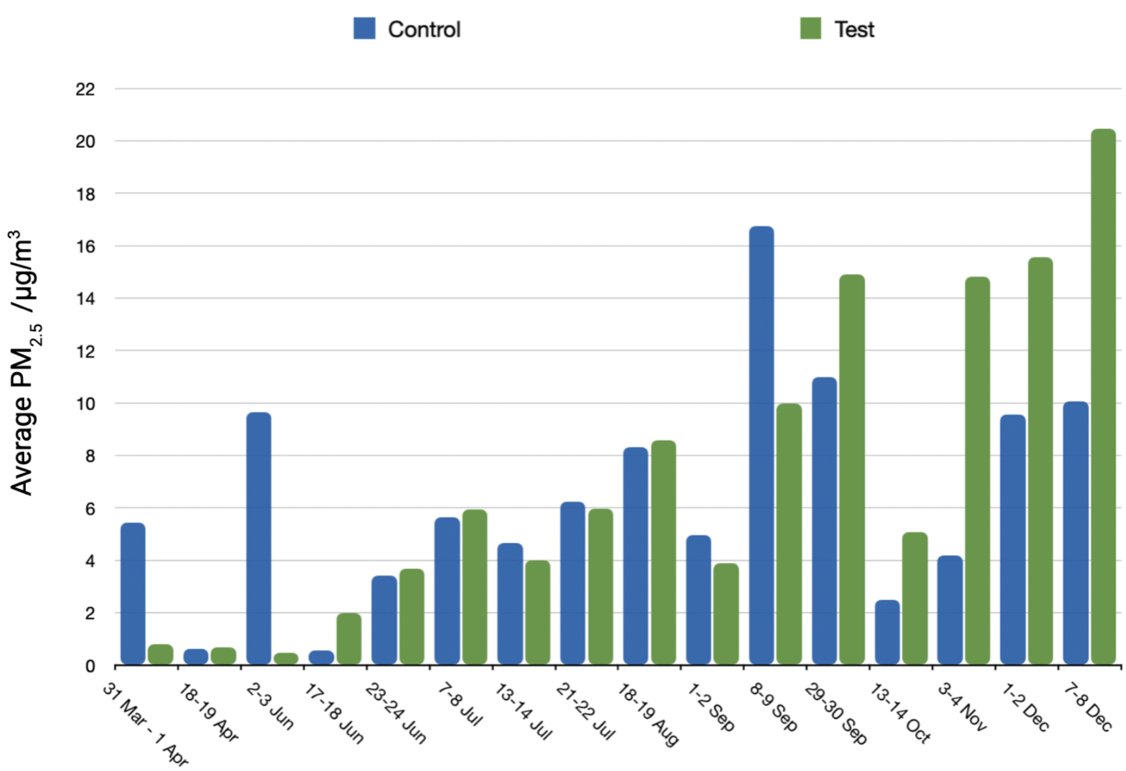

Figure 7: Daily average $PM_{2.5}$ concentrations for each day in the Control (blue bars) and the Test (green bars) study periods.

3.2.2 Partial vs. Full Lighting

In looking at the sensor averages of the Partial and Full periods, it is notable that the Full period shows the greatest overall sensor average (8.0 μg/m^3) of the 2 periods, with Partial having an average of (7.2 μg/m^3) (Supp. Figure 5). Yet, there is significant variation within these periods, as the Partial period shows the greatest and least sensor averages of the two, making for insignificant statistical differences between the periods (ANOVA: p-value = 0.113).

3.2.3 Comparisons to Case Studies

To provide context on the impact of WaterFire on Providence's air quality, the sensor averages for the Cold period were first compared to that of the Test (Supp. Figure 6). From this, it is observed that the Test period shows a greater average (7.5 $\mu g/m^3$) than Cold (5.4 $\mu g/m^3$), indicating that WaterFire has a greater air quality impact on Providence than home-heating combustion on the 16 coldest days of the year. However, ANOVA results for this comparison display an insignificant difference in sensor averages, with a p-value of 0.525. Since these 16 coldest days are a mere subset of cold days requiring heating for the winter season, fossil fuel combustion remains a significant source of $PM_{2.5}$ concentrations, to which attention is required.

The average $PM_{2.5}$ concentrations by sensor for the Test period is compared with that of the Fireworks period in Supp. Figure 7. Despite the short period of the Fourth of July fireworks, their impact on Providence air quality appears to be greater than the regularly occurring WaterFire events. When the 2 nights of Independence Day fireworks were compared to 16 WaterFire events in 2023, fireworks proved to be the more air polluting event of the two, with an overall average sensor value of 22.5 $\mu g/m^3$ towering over the 7.5 $\mu g/m^3$ sensor average of WaterFire (ANOVA: p-value = 7.48×10^{-5}). This supports the point raised earlier that there are other significant, local, anthropogenic sources of $PM_{2.5}$ in Providence, which also need to be addressed.

Lastly, the Test period was contrasted with the Wildfire period, finding significantly greater sensor averages for wildfires (21.1 $\mu g/m^3$) than for WaterFire (ANOVA: p-value = 2.99×10^{-4})(Supp. Figure 8). This finding supports the claim that regional sources of $PM_{2.5}$, transported over long distances are an important influence on pollution in Providence. Sources of this nature cannot as easily be addressed by local interventions.

Table 3: Summary Statistics for Case Studies

Study Period	Max / $\mu g/m^3$	Min / $\mu g/m^3$	Mean / $\mu g/m^3$	SD / $\mu g/m^3$	SE / $\mu g/m^3$
Cold	57.4	0.0	5.4	5.4	1.3
Fireworks	40.3	0.0	22.5	10.0	2.2
Wildfire	64.4	0.0	21.0	8.8	1.9
Test	30.8	0.0	7.8	6.1	1.4

Table 3: Summary statistics — maximum value, minimum value, mean, standard deviation (SD), and standard error (SE) — of the hourly $PM_{2.5}$ values used in the 3 case studies and the WaterFire events (Test).

3.2.4 Impact on Neighborhoods

Given the use of low-cost sensors to obtain hourly $PM_{2.5}$ concentrations, percent enhancement was used in the following analysis, as opposed to absolute enhancement. This is because offsets from sensor biases or those introduced during calibrations may affect measurements. This with the context of known regional influence of $PM_{2.5}$ concentrations in Providence[38] makes percent enhancement a more accurate tool for analyzing intra-neighbourhood $PM_{2.5}$ trends.

The increase in $PM_{2.5}$ concentrations from WaterFire events shows a clear spatial pattern across Providence neighborhoods, as visualized in Figure 8. From Figure 8b, we observe that Sensor11 at the West End Community Center displays the greatest percent enhancement from the WaterFire events in 2023, with an enhancement of 40.46%, despite having the lowest sensor average for the Test period (5.82 µg/m^3). Conversely, even though Sensor02 at a Silver Lake Residence has the second highest sensor average for the Test period (8.52 µg/m^3), it displays the lowest percent enhancement of 5.90%. In general, there is an average percent enhancement of 20.37% across the city. Sensors surrounding WaterFire locations (Memorial Park and Waterplace Park) in the center of Providence — West End, Downtown Providence, South Providence — show the greatest percent enhancement from WaterFire, which is visualized in the map in Figure 8a. Furthermore, there is a clear correlation between percent enhancement and mean distance to WaterFire, where mean distance is the average distance from each sensor to both WaterFire locations, as percent enhancement increases with decreases in mean distance (Figure 8c). This illustrates the disproportionate impact on $PM_{2.5}$ from WaterFire in Providence.

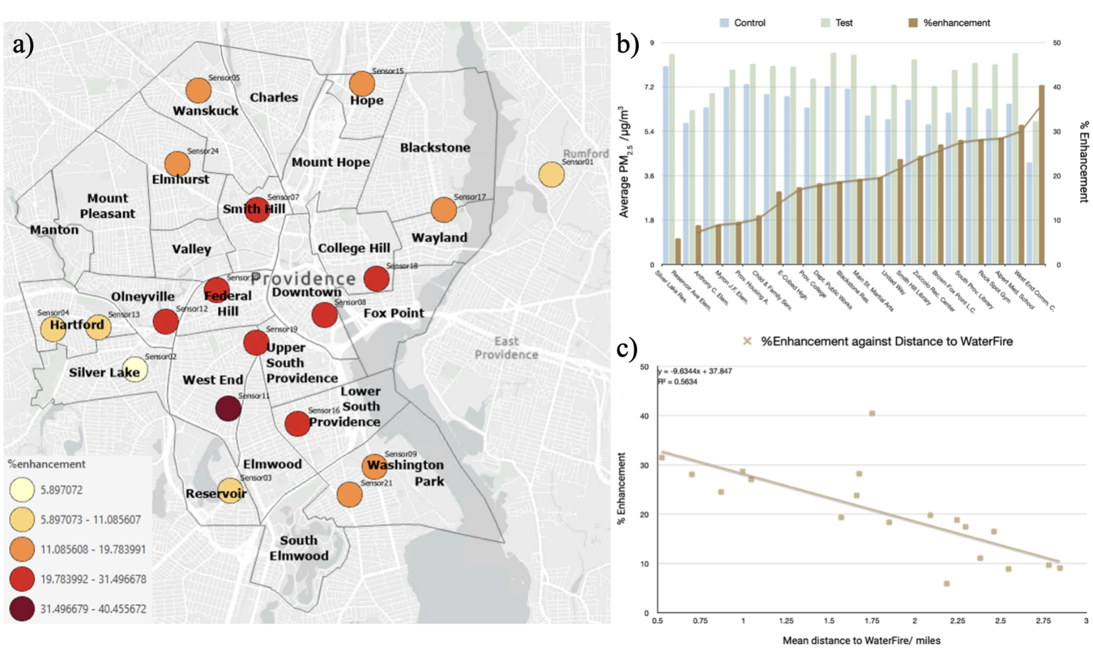

Figure 8: a) Map of Providence with Breathe Providence sensors represented as colored circles — the darker colors correspond to greater % enhancement. b) % Enhancement of each sensor (brown bars) plotted against a background of their average $PM_{2.5}$ values for the Test (pale green bars) and Control (pale blue bars) periods. c) % Enhancement of each sensor plotted against their mean distance to WaterFire locations.

3.2.5 Impact on Health

RIDOH's hospital discharge data was analyzed to determine the impact of the events on human health. First, cumulative ED visits from the 7 day period – 2 days before to 4 days after WaterFire (Figure 4) – were plotted for the 6 health condition categories – asthma, COPD, heart disease, brain bleed/ tissue death, hypertension, and pulmonary embolism – in the dataset (Figure 9).

From the figure, asthma has the highest and pulmonary embolism has the lowest number of ED visits for all 7 days. Cumulative ED visits for heart disease, brain bleed/ tissue death, and pulmonary embolism showed no clear association, as visits either stayed constant, decreased, or increased by 1 visit. Asthma, COPD, and hypertension show increased ED visits in the days following WaterFire. Asthma displays a peak of 67 ED visits 2 days after WaterFire (IIAWF) with an enhancement of 9 visits (15.5%) from the day of the events. For COPD, ED visits peak at 21 the day after WaterFire (AWF) with a 12 visit (133.3%) enhancement. Hypertension shows increasing visits from the day before WaterFire (BWF) to 4 days after WaterFire (IVAWF), with a peak of 45 visits at the end of the 7 day period and a positive enhancement of 17 ED visits (60.7%) from WaterFire (WF) to IVAWF.

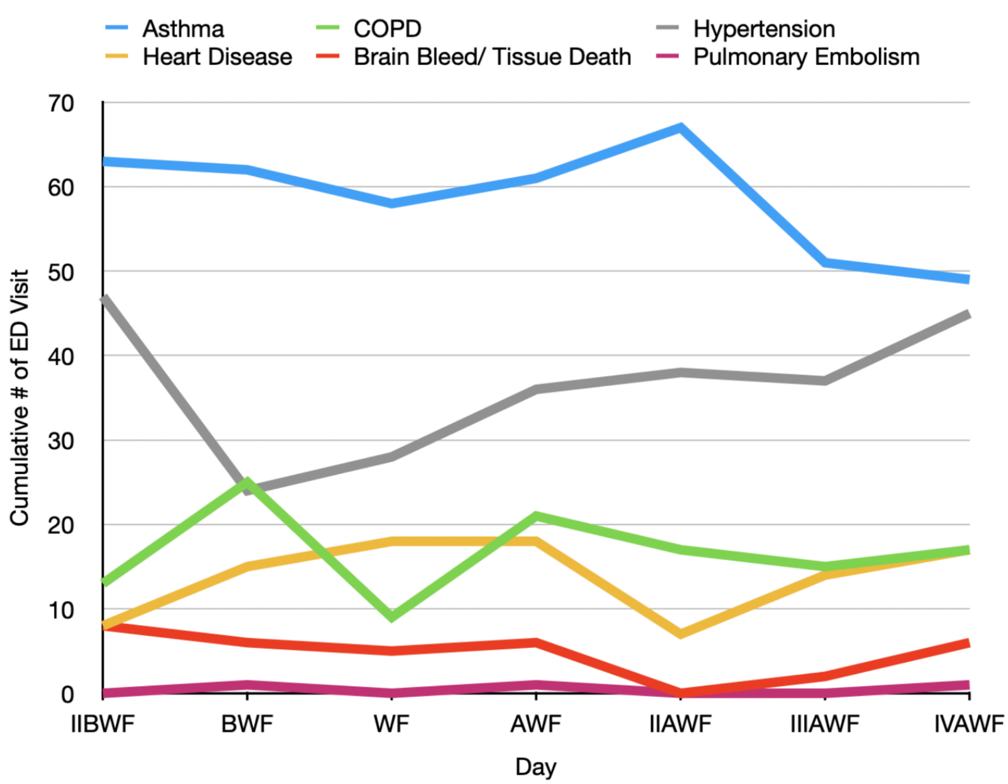

Figure 9: Cumulative ED visits for each day in the 7 day study period for the 16 WaterFire dates, where IIBWF = 2 days before WaterFire, BWF = day before WaterFire, WF = day of WaterFire, AWF = day after WaterFire, IIAWF = 2 days after WaterFire, IIIAWF = 3 days after WaterFire, and IVAWF = 4 days after WaterFire.

As seen from the health conditions isolated from the RIDOH dataset for respiratory conditions the cardiovascular and nervous systems can be affected by air pollution as well. Despite this, in investigating the health impact of WaterFire, the intuitive conditions — asthma and COPD — stand out, so further analysis was conducted for these periods. Looking at the demography of the COPD dataset reveals that it is primarily comprised of individuals aged 18+, as out of the 416 patients visiting the ED for COPD conditions/symptoms, only 2 of them were under the age of 18. Thus, these 2 individuals were removed to create a COPD in adults dataset. In contrast, characterization of the asthma dataset showed that individuals below the age of 18 dominated the dataset, which provoked the creation of an asthma in children dataset.

Predictably, the trend in cumulative ED visits for COPD in adults is essentially identical to that of the full COPD dataset, with a peak at 21 visits on the day after WaterFire (Figure 10a). Spatial analysis of this data on the day of WaterFire (Figure 10b) and the day after WaterFire (Figure 10c) displays an increase in the number of census tracts that the ED patients live in. Particularly, increases in census tracts 1.01, 1.02, 6, and 12 in the South Elmwood, Washington Park, South Providence, and West End are notable. These visits increase from 0 to 2 – the maximum visits for a census tract in this dataset – in these neighborhoods. From Figure 8a, these neighborhoods, except South Elmwood due to the lack of a sensor in that region, also stood out as some of the most impacted neighborhoods by WaterFire, in terms of percent enhancement. Increases are also observed in census tracts 16.01, 18, 19, 24, and 27 in western and northern Providence, which also saw positive enhancement in $PM_{2.5}$, and decreases are seen in census tracts 9, 14, 21.02, and 28.02, which are in the same regions of Providence (Figure 10c). It is important to point out that the aggregation of ED visits from all 16 WaterFire events in 2023 was required to produce these relatively small numbers. But, there was also some missing census tract number/location data for a few patients in the dataset. Nevertheless, generally, on the day after WaterFire events, ED visits for COPD in adults increase noticeably in individuals from the southern Providence region.

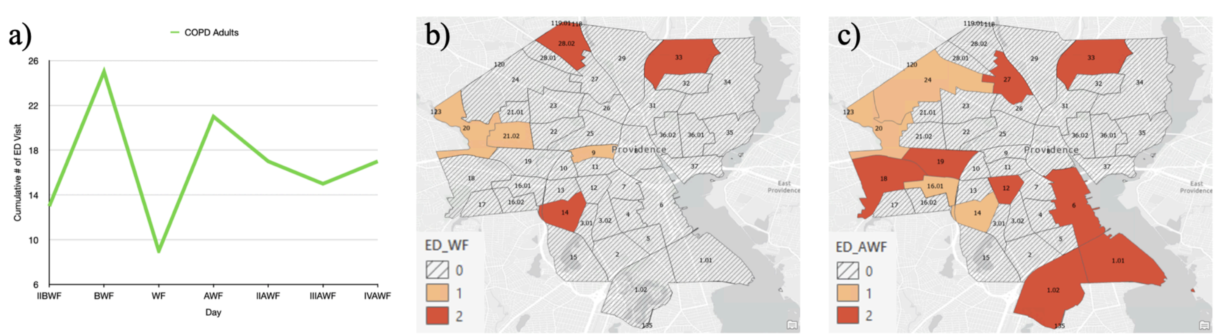

Figure 10: a-c display analysis for the COPD in adults. a) Cumulative number of ED visits for 2 days before WaterFire to 4 days after WaterFire. b) Map of Providence, sectioned by census tract number, with the cumulative number of ED visits in each census tract for the day of WaterFire (WF) represented by the colors. c) Map of Providence, sectioned by census tract number, with the cumulative number of ED visits in each census tract for the day after WaterFire (AWF) represented by the colors. For b&c, darker colors correspond with greater ED visits.

Similarly, the asthma in children dataset closely resembles its complete dataset, when analyzing the cumulative ED visits, as the visits climb after WaterFire and peak at a greater value of 12 ED visits (44.4%) after the event (Figure 11a). When spatially comparing ED visits on the day of WaterFire (Figure 11b) to this peak 2 days later (Figure 11c), we see a shift in ED patients' addresses from a concentration in western Providence to the addresses being more dispersed across Providence, but concentrated in southern Providence. Here, the southern Providence region stands out again, but at a greater degree than for the COPD in adults data, as a greater number of census tract numbers in this region – 1.01, 4, 5, and 6 – go from having 0 visits to having 1-6 visits. This may indicate that there is a greater degree of exacerbation in asthma than in COPD from increases in $PM_{2.5}$ concentrations. But, there was also a greater number of ED visits for asthma conditions than COPD conditions in the RIDOH dataset, as visualized in Figure 9. Additionally, census tract 8 in Downtown Providence – location of WaterFire – shows an increase from 0 visits to 4 visits and census tract 14 in West End increases from 2 to 6 visits. Both of these neighborhoods displayed high percent enhancement (Figure 8). An increase in ED visits was also observable in census tracts 23, 27, 29, and 35 in northern Providence, while decreases are seen in tracts 3.02, 10, 12, 16.01, 17, 19, and 25 in western Providence.

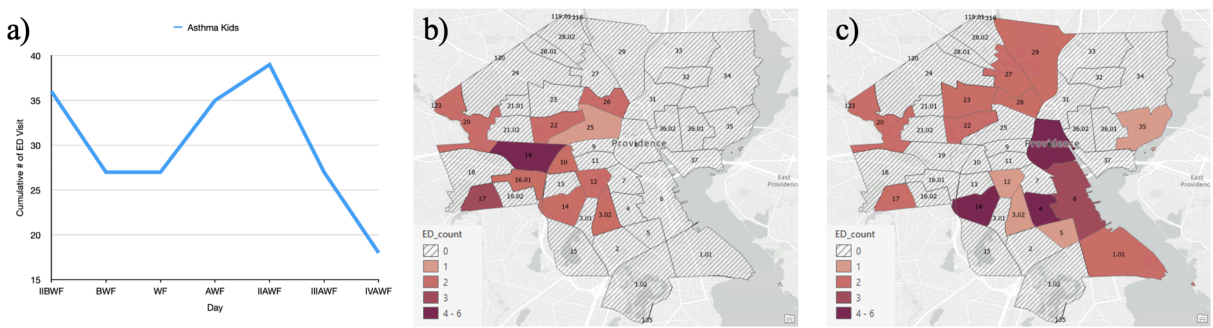

Figure 11: a-c display analysis for asthma in children. a) Cumulative number of ED visits for 2 days before WaterFire to 4 days after WaterFire. b) Map of Providence, sectioned by census tract number, with the cumulative number of ED visits in each census tract for the day of WaterFire (WF) represented by the colors. c) Map of Providence, sectioned by census tract number, with the cumulative number of ED visits in each census tract for 2 days after WaterFire (IIAWF) represented by the colors. For b&c, darker colors correspond with greater ED visits.

4. Conclusions & Recommendations

4.1 Summary

WaterFire events (Test) are associated with higher average $PM_{2.5}$ values across Providence when compared to the night before WaterFire (Control). The same sensor trends are observed between the Test and Control periods, as sensors with higher averages in the Test period also show higher averages in the Control period. This indicates regional influence of $PM_{2.5}$ concentrations, which made percent enhancement a useful metric in this analysis. WaterFire days show increasingly higher $PM_{2.5}$ concentrations heading into the winter months. Sensors surrounding WaterFire locations (Memorial and Waterplace Park) in Downtown Providence and in southern Providence show the greatest percent enhancement from WaterFire. In the 7-day period before and after WaterFire, ED visits reach a maximum on the day after WaterFire for COPD in adults and 2 days after the event for asthma in children, especially in southern Providence.

When compared to a larger scale, controllable event – winter home heating (Cold) – WaterFire shows higher average $PM_{2.5}$ values, although not statistically significant. However, the average concentrations from a short-term, controllable event, such as the Fourth of July fireworks (Fireworks), and a large-scale, uncontrollable event, such as the 2023 Canadian wildfires (Wildfire), are significantly higher than that of WaterFire.

4.2 WaterFire Sustainable/ Community Protection Practices

Despite the demonstrated increase in $PM_{2.5}$ concentrations from WaterFire events, and its disproportionate impact on central and southern Providence communities, it is important to note that WaterFire does not set out to harm the community that surrounds it. In fact, the organization goes out of its way to protect its community and its environment in a number of ways. Per their website,[44,45] WaterFire:

1. Encourages people to walk or use public transportation where possible.
2. Does not cut down trees for lightings. Instead, the majority of firewood is obtained from local tree trimming operations, and fires are started with recycled newspaper and abandoned fencing is used for kindling.
3. Turns off about 200 streetlights each night of an event, saving 120,000 kW of power per year.
4. Uses small amounts of gas for boats and trucks, as they do not travel long distances.
5. Organized an Earth month clean up event on 20th April, 2024, which saw 60 volunteers clean up the Valley neighborhood and remove litter/ debris – 20 bags of trash, a car bumper, a TV, and tree branches – from the Providence river by the end of the event.

Therefore, WaterFire aims to act in a community conscious manner. However, this research shows that more could be done to protect human and environmental health from the elevated $PM_{2.5}$ concentrations from WaterFire events.

4.3 Recommendations for Air Quality Improvement

To protect residents, low cost air filters could be used in residential buildings surrounding the sections of the Providence river in which WaterFire takes place to maintain good indoor air quality. Also, to achieve the same goal, building managers could place or replace air filters on building vents the day of or the day before WaterFire events, in accordance with WaterFire schedules that are posted in advance. As seen in Figure 12, fitting replaceable MERV 13 air filters on building air intake vents is highly effective in reducing the infiltration of wildfire smoke into buildings,[21] so they are likely to be effective in maintaining good indoor air quality following WaterFire events. These filters could be sold or given out for free at WaterFire events, advertised on WaterFire's website, or WaterFire could donate these filters to disproportionately affected neighborhoods, such as West End, Downtown Providence, and South Providence (Figure 8a).

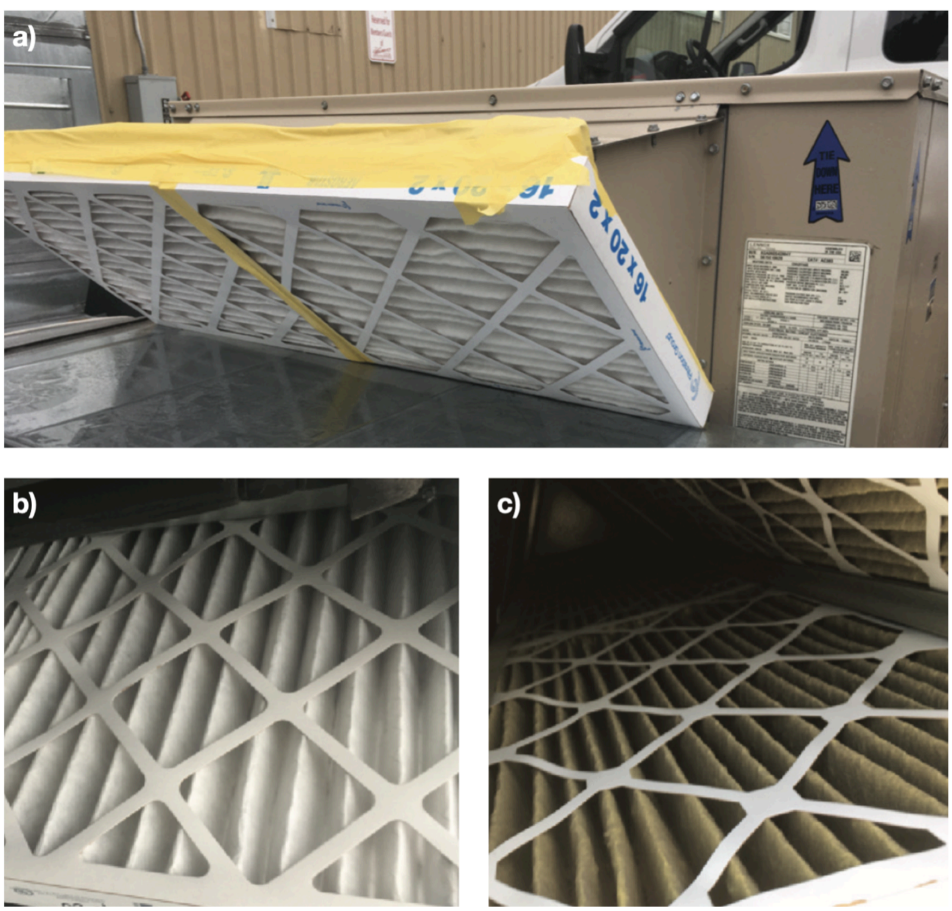

Figure 12: a) MERV 13 filter installed on an air intake vent. b) Clean filter. c) Filter heavily loaded with wildfire smoke.
(Javin et al., 2021)

Furthermore, the WaterFire events could be modified to reduce local $PM_{2.5}$ emissions in Providence. Firstly, it might be beneficial to alter the season and the day of the week on which these events occur. As previously stated, we observe the highest $PM_{2.5}$ concentrations for the Test period at the end of the year (November to December) and on Fridays (Figure 6). Thus, it is possible that increased $PM_{2.5}$ concentrations from the WaterFire events can be mitigated if the organization refrains from scheduling events at these times.

Secondly, WaterFire could reduce the quantity of fuel burnt by reducing the duration of the wood-burning portion of the event. With less wood being burnt, less $PM_{2.5}$ will be emitted from the events, resulting in mitigated impacts in terms of percent enhancement of $PM_{2.5}$ concentrations and emergency department visits. Alternatively, the event could be modified by creating LED displays. Since the organization saves around 120,000 kW annually from streetlight shutoffs, this power could be used to generate the LED displays. Although, this would require investment in new infrastructure.

4.4 Conclusions

To conclude, this analysis reveals that WaterFire events are associated with high percent enhancements in $PM_{2.5}$ concentrations (Figure 8a) and increases in ED visits for COPD in adults (Figure 10c) and asthma in children (Figure 11c) in southern Providence. Thus, it is reasonable to suggest that WaterFire is causing harm to the members of the South Providence HEZ, whose concerns motivated this research. Health impacts may be even greater than these results suggest, as individuals experiencing symptoms associated with the increases in $PM_{2.5}$ pollution might not go to the emergency department for evaluation due to lack of transportation, lack of health insurance, or lack of trust in the healthcare system, etc.[46]

Given WaterFire's status as a beloved community event, a nuanced evaluation of its potential hazards is required. It is important to ask whether the things we love doing may also be harming us, and if the answer is yes, can we modify them to achieve the same positive impacts while decreasing or eliminating the risk factor. Further research is required into seasonal variations in WaterFire $PM_{2.5}$ pollution, its impact on asthma and COPD rates, ways to mitigate the emission of fine particulate matter particles from WaterFire events, and effective methods of protecting human health from this pollutant. Future research would benefit from community engagement, to seek the perspective of individuals directly impacted, and conversations with the WaterFire organization, to raise awareness of the impacts of their events.

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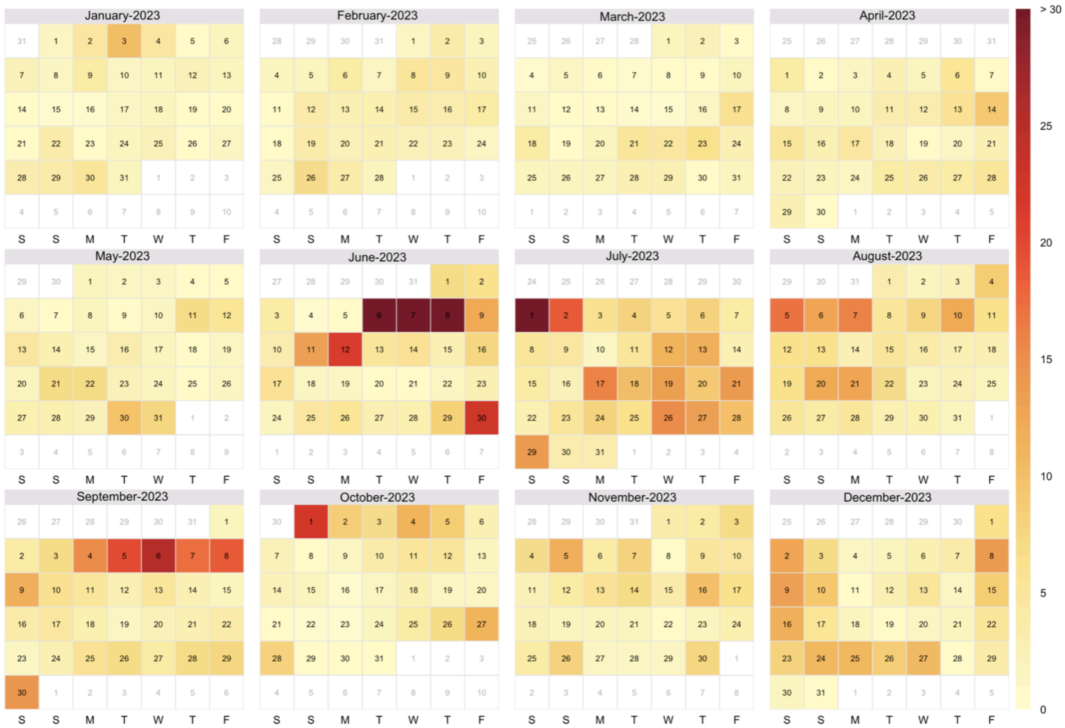
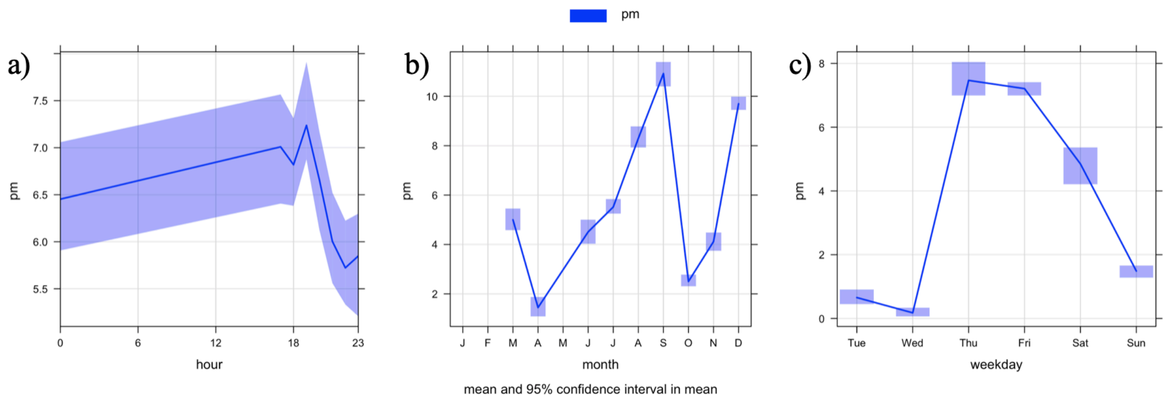
Supplemental Materials

Sensor #	Sensor Location	Code	Latitude	Longitude
Sensor01	Myron J. Francis Elementary	Myron J.F. Elem.	41.84094	-71.36097
Sensor02	Silver Lake Residence	Silver Lake Res.	41.810533	-71.447651
Sensor03	Reservoir Ave Elementary	Reservoir Ave Elem.	41.79157	-71.42788
Sensor04	Anthony Carnevale Elementary	Anthony C. Elem.	41.81678	-71.46458
Sensor05	E-Cubed Academy Senior High	E-Cubed High	41.85417	-71.43444
Sensor06	Rochambeau Library	Rochambeau Library	41.84621	-71.39663
Sensor07	Smith Hill Library	Smith Hill Library	41.83549	-71.42217
Sensor08	Alpert Medical School	Alpert Med. School	41.81899	-71.40828
Sensor09	Department of Public Works	Dept. Public Works	41.79521	-71.39783
Sensor10	Zuccolo Recreation Center	Zuccolo Rec. Center	41.82287	-71.43067
Sensor11	West End Community Center	West End Comm. C.	41.80439	-71.42825
Sensor12	United Way	United Way	41.81803	-71.44121
Sensor13	Providence Housing Authority	Prov. Housing A.	41.81715	-71.455331
Sensor14	CCRI - Liston Campus	CCRI	41.80745	-71.41341
Sensor15	Main St. Martial Arts	Main St. Martial Arts	41.85521	-71.40042
Sensor16	South Providence Library	South Prov. Library	41.80205	-71.41378
Sensor17	Blackstone Residence	Blackstone Res.	41.835491	-71.383413
Sensor18	Brown-Fox Point Early Childhood Learning Center	Brown-Fox Point L.C.	41.82469	-71.39755
Sensor19	Rock Spot Climbing Gym	Rock Spot Gym	41.81478	-71.42251
Sensor20	Rockefeller Library	Rockefeller Library	41.82551	-71.40528
Sensor21	Child & Family Services	Child & Family Serv.	41.7909	-71.4031
Sensor22	Mt. Pleasant Hardware	Mt. Pleasant Hardware	41.83168	-71.444401
Sensor23	Rhode Island College	RI College	41.84212	-71.46526
Sensor24	Providence College	Prov. College	41.84272	-71.43888

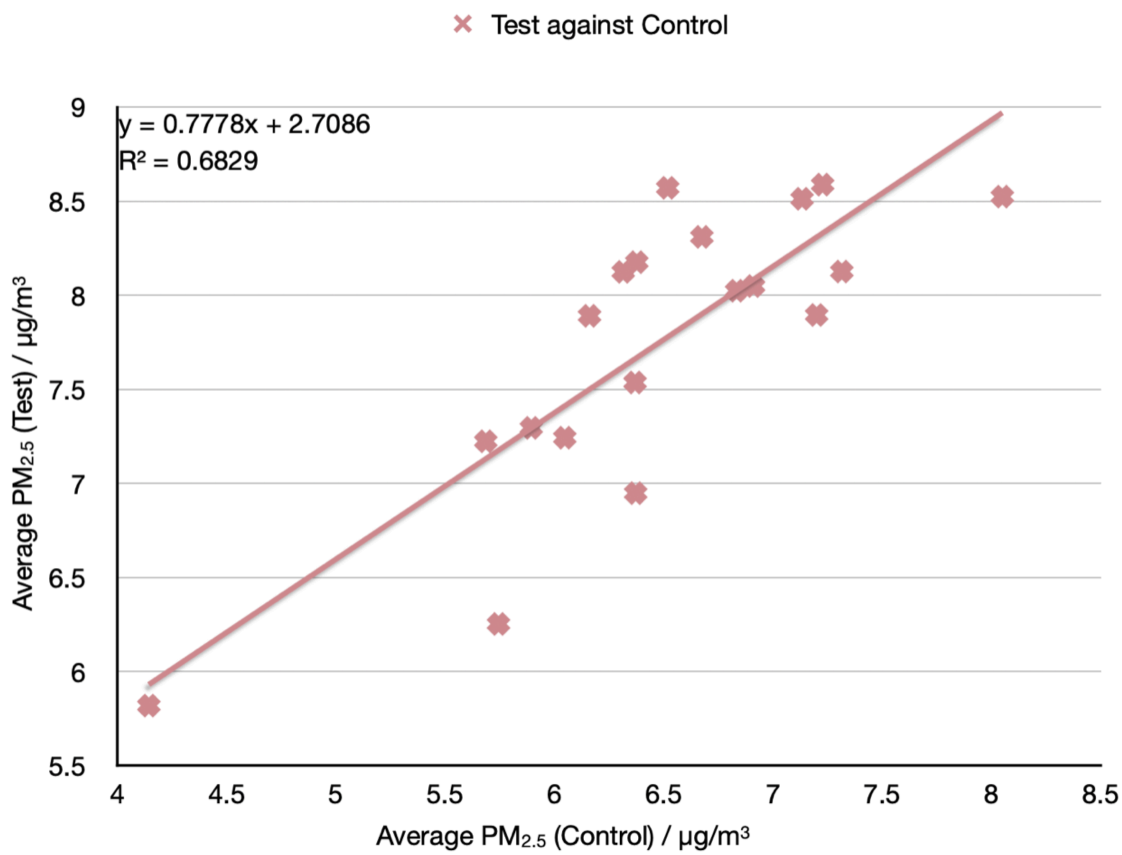
Supplemental Table 1: The 24 Breathe Providence sensors used in this study with their locations, latitude, longitude, and code names used in graphs.



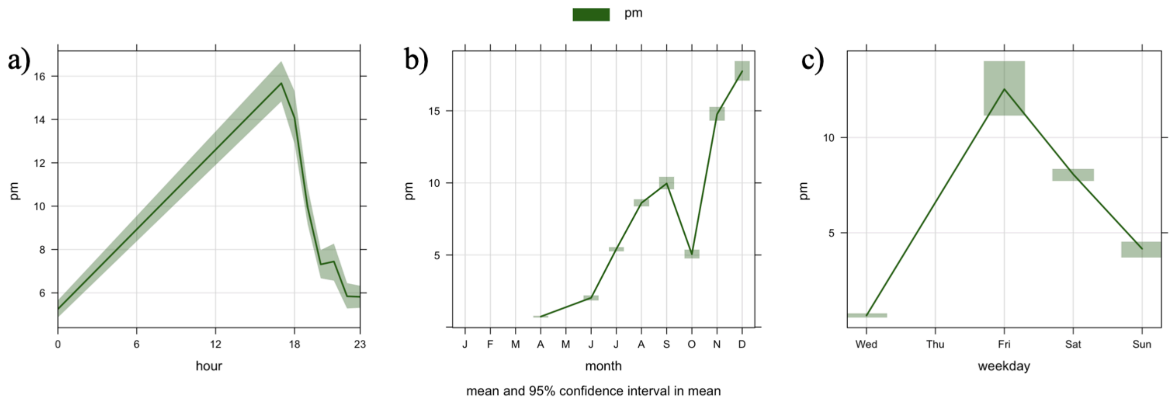
Supplemental Figure 1: Calendar plot showing the average daily $PM_{2.5}$ concentrations for the entirety of 2023 (All Period), where darker colors represent higher daily average $PM_{2.5}$ concentrations.



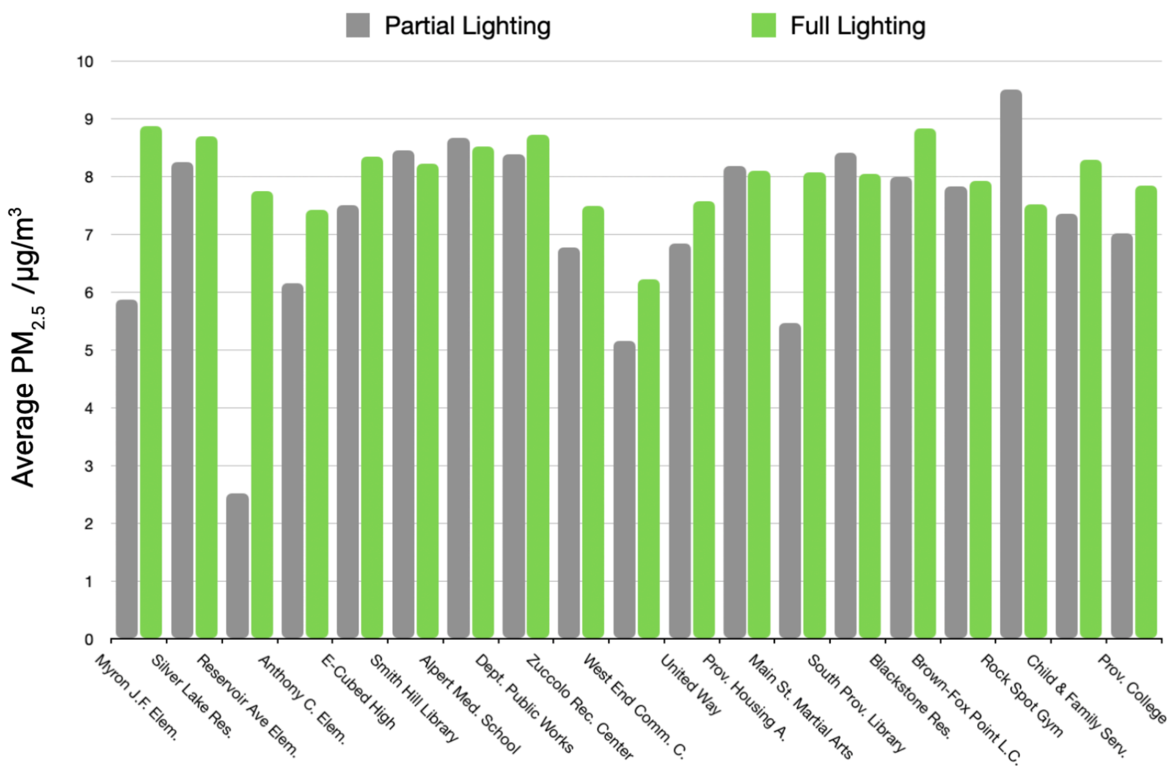
Supplemental Figure 2: Temporal trends of $PM_{2.5}$ from the night before WaterFire (Control). Figures a-c show mean $PM_{2.5}$ values (blue line) and the 95% confidence interval in the mean (pale blue shading). a) Daily trend with hourly averages connected by straight lines. b) Annual trend with monthly averages connected by straight lines. c) Weekly trend with daily averages connected by straight lines.



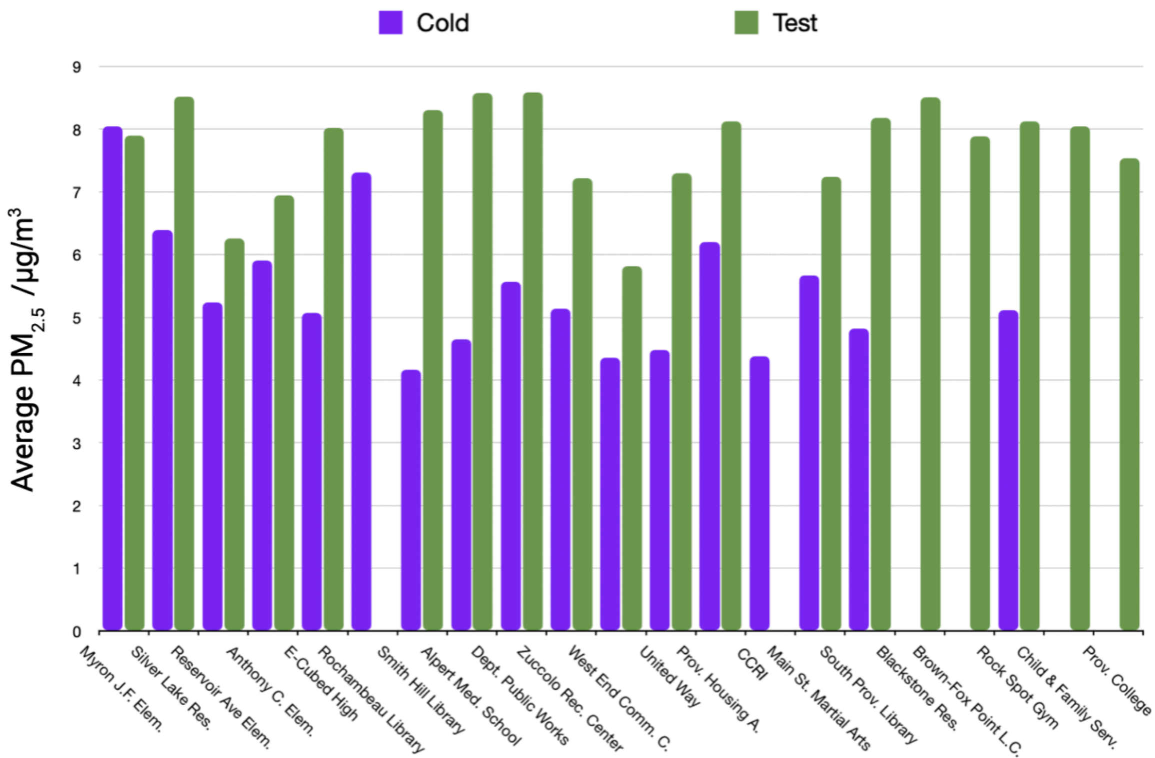
Supplemental Figure 3: Average $PM_{2.5}$ values for the night before WaterFire (Control) for each sensor plotted against the sensor averages for WaterFire (Test).



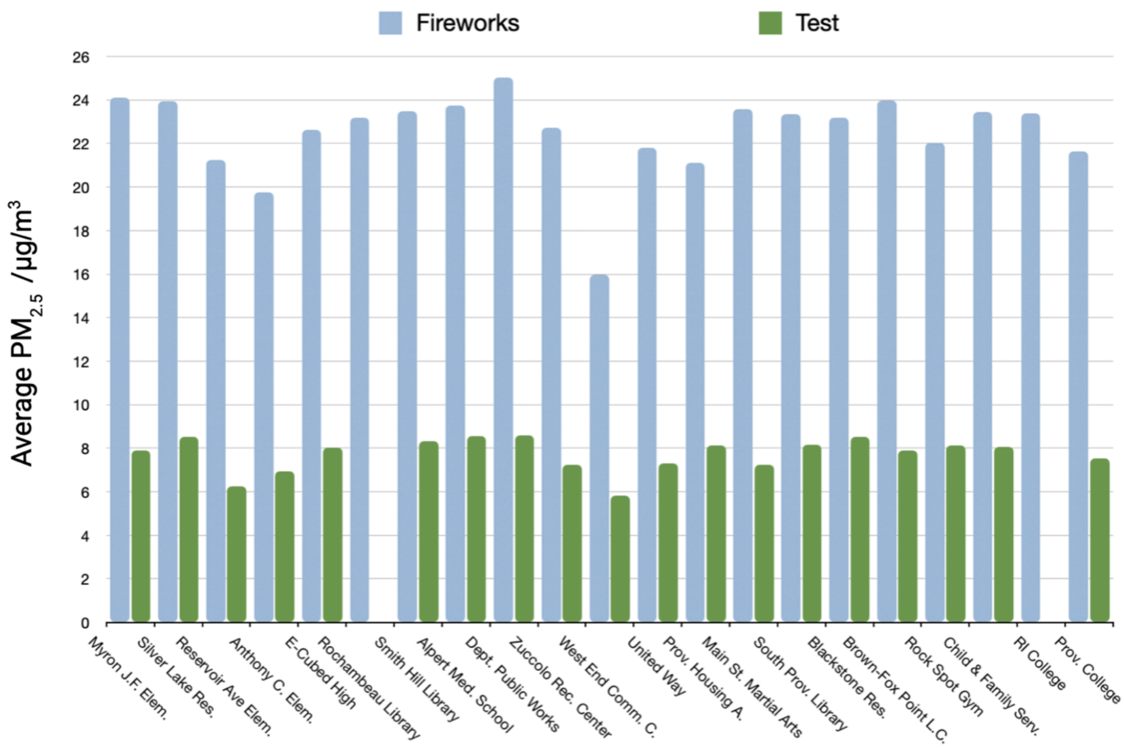
Supplemental Figure 4: Temporal trends of $PM_{2.5}$ from WaterFire. Figures a-c show mean $PM_{2.5}$ values (green line) and the 95% confidence interval in the mean (pale green shading). a) Daily trend with hourly averages connected by straight lines. b) Annual trend with monthly averages connected by straight lines. c) Weekly trend with daily averages connected by straight lines.



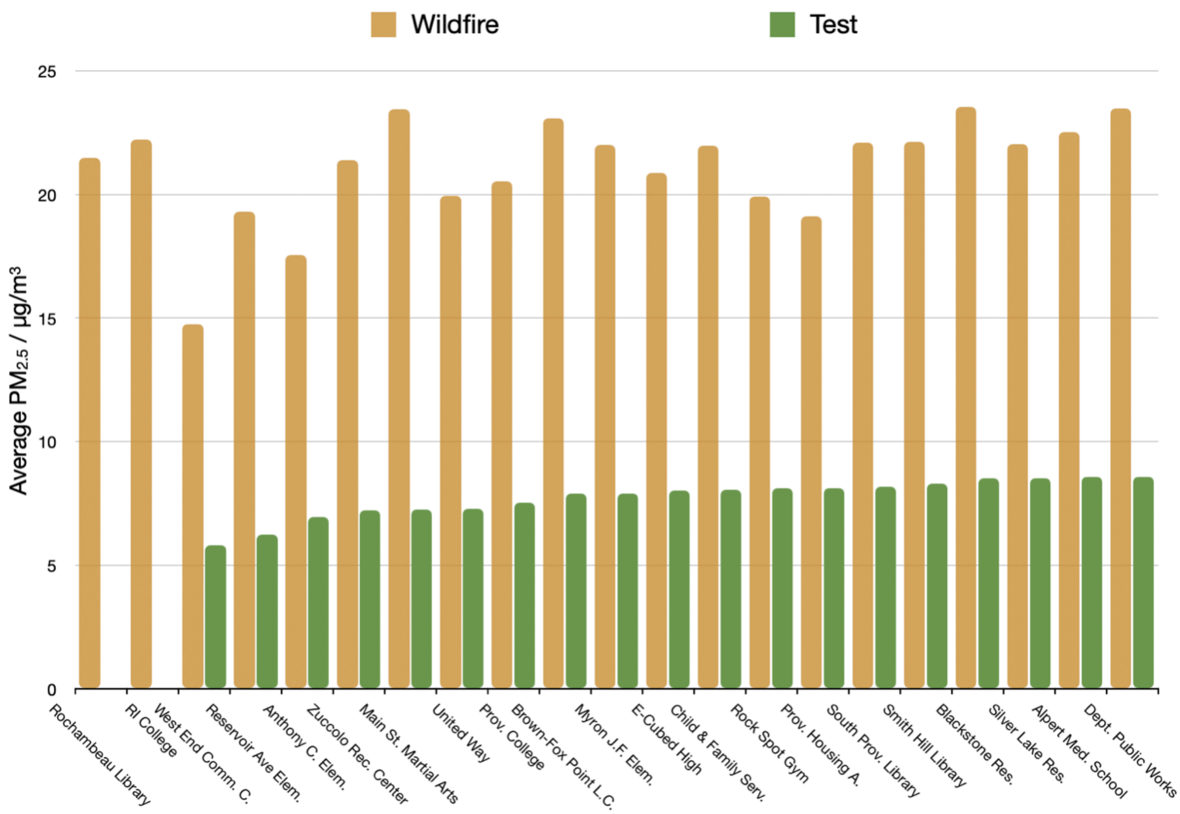
Supplemental Figure 5: Average $PM_{2.5}$ concentrations across each of the 19 sensors included in the Partial (grey bars) and Full (light green bars) periods.



Supplemental Figure 6: Average $PM_{2.5}$ concentrations across each of the 19 sensors included in the Test period (green bars) and the 17 sensors used for the Cold period (purple bars).



Supplemental Figure 7: Average $PM_{2.5}$ concentrations across each of the 19 sensors included in the Test period (green bars) and the 21 sensors used for the Fireworks period (light blue bars).



Supplemental Figure 8: Average $PM_{2.5}$ concentrations across each of the 19 sensors included in the Test period (green bars) and the 21 sensors used for the Wildfire period (orange bars).