love my air

Replication Guide

DENVER
THE MILE HIGH CITY

Love My Air Replication Guide

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Abstract

The purpose of this document is to provide guidance to municipalities or organizations who would like to replicate all or aspects of the Love My Air Program developed by Denver Department of Public Health and Environment (DDPHE). DDPHE has gained a wealth of knowledge during the development of the Love My Air program, from how to develop a robust air quality sensor network, how to communicate data to the public, conduct outreach on air quality, and the challenges associated with running an air quality program.

Bloomberg Philanthropies

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1. Love My Air Program Overview

The Love My Air (LMA) program was developed by the Denver Department of Public Health and Environment (DDPHE) in 2018 by partnering with Denver Public Schools (DPS) to bring real-time, local, and actionable air quality information to help students with asthma. Since 2018, Love My Air has grown to include PM2.5 sensors at over 38 schools and locations across Denver. The near-real time data from all the sensors is compiled into the Love My Air app and website so that it can be visible and used by school community members and beyond. LMA uses the AQI color scheme and plain language to communicate the near real-time air quality on the dashboards within schools, the website, and the phone app.

Figure 1. Dashboard displayed at school.

Figure 2. "No Idling" sign made by a student.

The platform was built with expandability in mind and can incorporate data from almost any low-cost sensor, pollutant agnostic. This guide focuses on setting up a PM2.5 sensor network, because PM2.5 is the most widely used measured air pollutant in the LMA network thus far. DDPHE is continuously testing sensor technologies to expand types of pollutants measured in the sensor network.

Beyond the technological components of LMA, DDPHE has developed various toolkits and educational resources including toolkits for: anti-idling campaigns, nurse education, communicating air quality to the public, and classroom science education (grades 6-12) that meet Colorado's educational standards. The air quality sensor network is incorporated into nurse trainings delivered by the Love My Air team as well as science labs. These resources are available by request. The team learned that education and outreach is increasingly important after the foundational technology was developed.

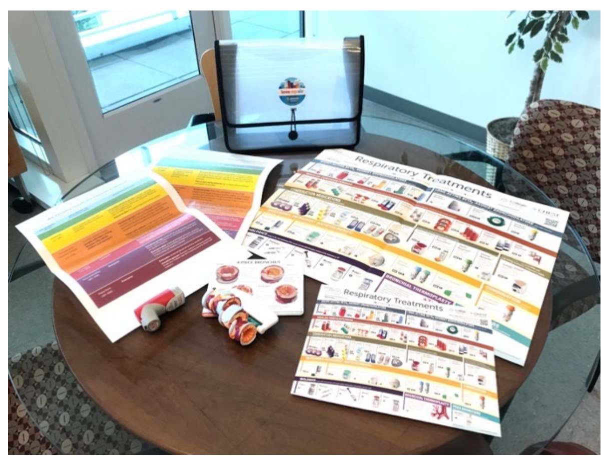

Figure 3. Example of a nurse toolkit developed by LMA.

The Denver team is always open to sharing knowledge and resources with others wanting to implement similar programs. This document aims to answer some of the most common questions that the Love My Air team gets, especially about establishing an air quality sensor network.

2. Components of the Love My Air Sensor Network

Denver's sensor network includes multiple components: air quality sensors, state reference monitors, a backend data system with an interface to view sensor data, dashboards in schools, and the Love My Air app, available on both iOS and Android. Each of these components is important to the success of the LMA program and will be discussed in this guide.

As of August 2023, DDPHE had 45 sensors placed at schools, state run monitoring sites, parks, and a few sensors at other locations across Denver. Most of the sensors are placed in Disproportionately Impacted (DI) communities, which are defined by low-income, or predominately English-as-a-second-language neighborhoods. The map in Figure 4 shows that most of Denver's sensors are placed in low-equity areas.

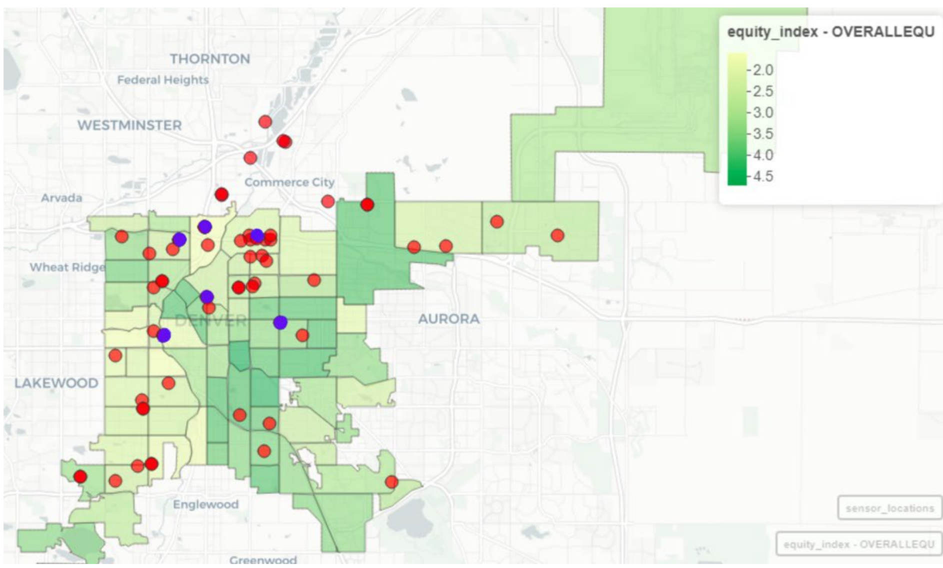

Figure 4. Location of Love My Air sensors and state reference monitors overlayed on a map of equity across Denver.

2.1 How DDPHE Chooses Air Sensors

An air quality sensor package consists of a weather-proof box containing the air pollution (PM2.5, etc.) and meteorological sensors (temperature and humidity), a power source, a sign that shows what the box is doing and how to access the data, and a way to transmit data. Additionally, you may want to add instruments to measure wind direction and wind speed so that you can begin to understand potential sources of pollutants, if desired or applicable. Since Denver has many state-run regional air monitors that measure wind speed and direction, the LMA team has opted to not have these additional meteorological measurements as part of the network.

As of early 2023, Denver is beginning to incorporate additional pollution measurements into their network beyond PM2.5. . This is for a few reasons: some pollutants are hard to accurately measure with low-cost sensors at this time (NOx, PM10, odors), some pollutants are difficult to translate to an AQI (TVOC, H2S, PM1), and most have not been tested at wide scale, so it is difficult to make comparisons as to what is “high” for the sensor readings. Denver has sensor boxes that can be expanded upon as new sensor technologies come out, making the sensor network more versatile as technologies improve.

2.2 How Denver Places a New Sensor

Sensor location is just as important as getting the right sensor. This section describes how DDPHE decides where to place a new sensor to the network.

DDPHE uses a solar panel that connects to each sensor to power the components. Power is often difficult to find (or the team may not have permission to access) in the locations that each of the sensors will be placed, particularly when trying to place the sensor away from a building. The sign placed with each sensor gives a brief description of what the sensor is and what it is monitoring. The sign also has a QR code that can easily be modified by the team whenever the team wants (making it more flexible than a website displayed on the sign), with the LMA signs linking back to the data homepage.. The LMA network transmits all data over cellular because WIFI in various locations, even at schools, can be spotty or require regularly updated permissions to grant access. By using cellular rather than WIFI, the data stream is much more reliable with less maintenance from the team.

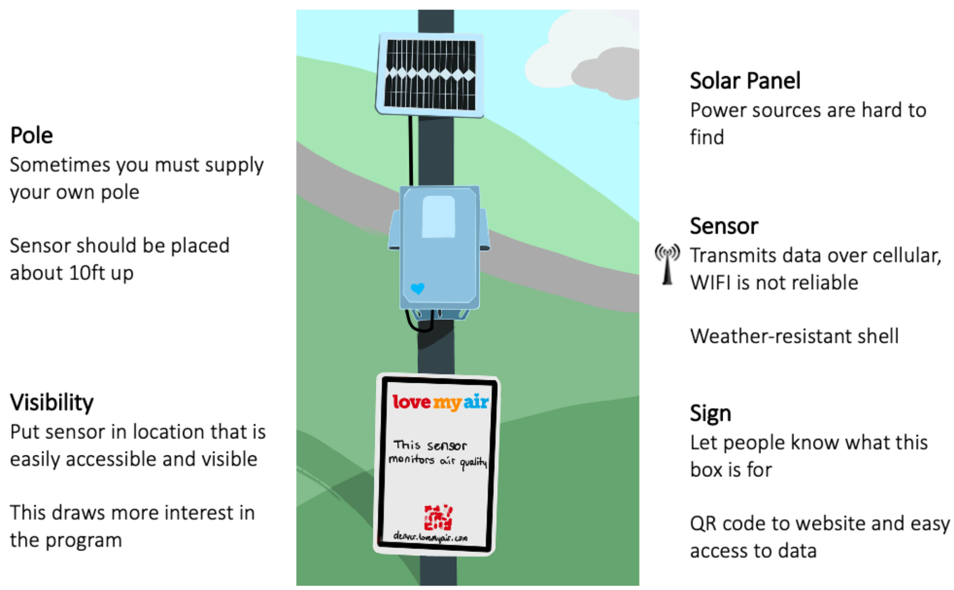

Figure 5. Important considerations for placing a low-cost sensor.

Where to place a sensor:

- **Easily accessible to your team.** DDPHE, for example, has site access agreements with DPS at each school where sensor is located. Some access agreements are easier than others, so you may want to think through all the potential partners in your area.

- **Visible to community members.** For program visibility, the sign associated with the sensor should be close to eye-level with the sensor still visible. The QR code with information directing back to the data should easily scannable.
- **Approximately 10ft up and away from buildings.** Air near a building flows differently than the bulk air around it. Being too close to a building will not give you a good reading for the ambient outdoor air pollution.
- **Sunny area for the solar panel.** Be sure that the solar panel is not shaded too often so that the solar panel can charge fully.

Setting up a new sensor requires a few key steps no matter what manufacturer you buy your sensor from. While the specifics may change, the overall process is similar for every type of sensor Denver has put up.

1. Find an interested party to allow the sensor to be placed. When finding a location for a sensor, you may need an agreement to access the location and set up your equipment. This will most likely be an agreement by-site.
2. Identify a location on the property that you and the other party agree upon. Note the "Where to place a sensor" above.
3. Choose a sensor to install and record the serial number or other identifying information with the site name of the installation. Name the sensor based on criteria your team chooses to keep naming conventions the same across sensors. Record the type of sensor unit you are installing.
4. Install the sensor (and MET station if applicable) and solar panel to a pole.
5. Activate the sensor.
6. Connect the sensor to WIFI or cell service following the manufacturer's instructions.
7. Take a photo of the sensor for your records.
8. Record the latitude and longitude where you placed the sensor.
9. Work with manufacturer's instructions and data management platform to ensure sensor API is being pulled into the database.
10. Check that sensor data is being pulled into the database. The sensor may take a couple of weeks to have appropriate readings.
11. Set up correction algorithms for the installed sensor.

2.3 Collocations and Correction Algorithms for Low-Cost Sensors

After a sensor is installed, it is important to make sure the sensor is producing high-quality data that can be used to inform the public. This is where collocations and correction algorithms come in!

A collocation is when a sensor is placed at the same location as a reference monitor that also measures the same pollutant. The sensor also measures other variables, including temperature and relative humidity, with is later used to inform a correction algorithm that is applied to the sensor. There are multiple ways to conduct a sensor collocation and calibration study depending on the time and resources available (lab tests, field collocations, intermittent, continuous, etc.). Denver uses a multi-linear regression of one sensor continuously collocated with a reference monitor and applies this algorithm to the rest of the network. There are some advantages and disadvantages to this method.

Advantages to this method:

- This method is relatively quick to compute and does not take much computational bandwidth because it uses only 1 month of data.
- Less time commitment – once the sensor is co-located, you do not have to do much work with maintenance or running experiments for shorter periods of time.
- Takes into account changing air pollution and weather. LCS operate differently in different weather conditions and to different types of particulate matter.

Disadvantages to this method:

- If the sensor or monitor is down, then the correction has problems and may go down as well.
- If there are large changes in weather or air pollution conditions (such as very polluted from wildfires to very low air pollution), the algorithm may over-correct, making the readings show negative for a few hours.

Other methods for correcting sensors and calibration tests can be found in EPA's air sensor guidebook[1].

Figure 6 is a diagram that shows how Denver's calibration method works.

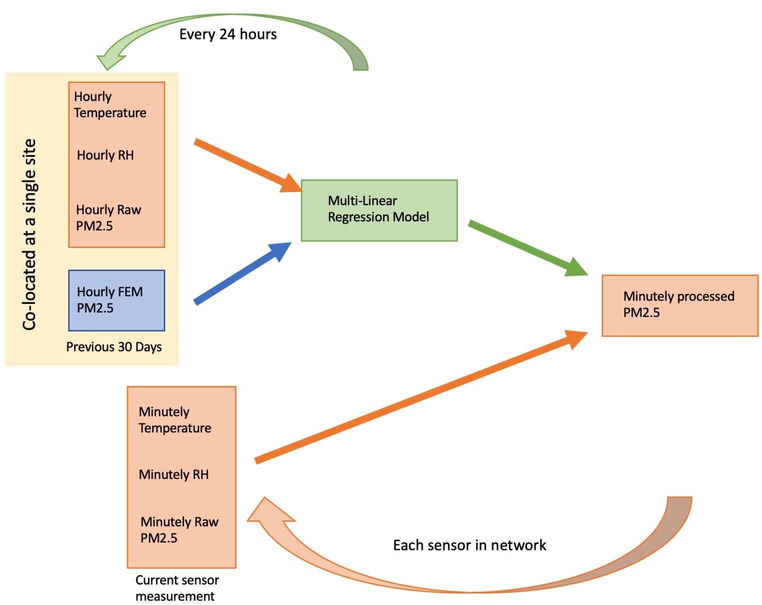

Figure 6. Diagram of Love My Air's process for correcting air quality sensors.

A multi-linear regression equation creates a predicted fit between a collocated sensor with the respective monitor. Denver's sensor network uses the past 30 days of hourly data of a

[1] Clements, et al. *The Enhanced Air Sensor Guidebook*. Environmental Protection Agency. 2022. https://cfpub.epa.gov/si/si_public_record_report.cfm?Lab=CEMM&dirEntryId=356426

collocated sensor at La Casa air monitoring station to create the correction algorithm. This is a rolling algorithm that changes every 24 hours. Low-cost PM2.5 sensors are impacted by many variables, including PM2.5 composition, Temperature, and Humidity. There are also likely decreases in sensor quality over time as well as sensor drift -- this is to be expected by any left outside for multiple years. The current sensor correction is the multilinear regression below in equation 1:

$$PM2.5_{Monitor} = A*(PM2.5_{raw}) + B*(T_{sensor}) + C*(RH_{sensor}) + D \qquad (1)$$

$PM2.5_{Monitor}$ = The PM2.5 concentration (ug/m^3) from FEM reference monitor
$PM2.5_{raw}$ = Raw data from the PM2.5 sensor
T_{sensor} = Temperature from the sensor
RH_{sensor} = Relative humidity from the sensor
A, B, C are multipliers for the multilinear regression variables
D = intercept for multilinear regression

This correction between the PM2.5 monitor data and raw sensor data is used to create a sensor PM2.5 fit, which is an estimate from the multilinear regression equation. The new data for the day goes into the equation to get estimated, corrected values. Packages in Python (Pandas package), R (Caret package), and the Data Analysis tab in Excel can be utilized to create multi-linear regressions. DDPHE's low-cost sensor data management system includes the feature to include regression models – the internal data management dashboard displays both the raw data and corrected data across the sensor network.

The LMA team receives daily reports that shows a heatmap of the sensors in the network and the correction equation for the previous day. The correction equation can be checked to make sure that there are no issues with the sensor using to correct the rest of the network. Normally when the collocation is functioning properly, the variables of Equation 1 are as follows:

A: ~1, between 0.5 and 1.5
B: between -0.1 to 0.1
C: between -0.1 to 0.1
D: between -5 and 5

Outside of this range, we will often see the impacts of the algorithm on the network; the other collocated sensors may appear to be running too high or too low when the correction is applied.

To learn more about sensor correction algorithms, you can reference the papers that used LMA network data. The algorithm described in this manuscript is described in further detail in Considine et al, 2021.

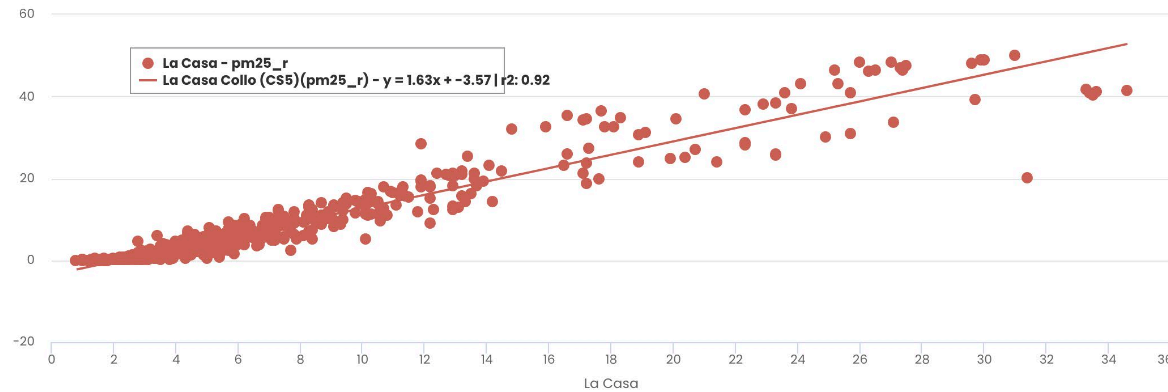

Figure 7. Linear regression of raw data from a collocated PM2.5 sensor compared to the monitor data with trendline.

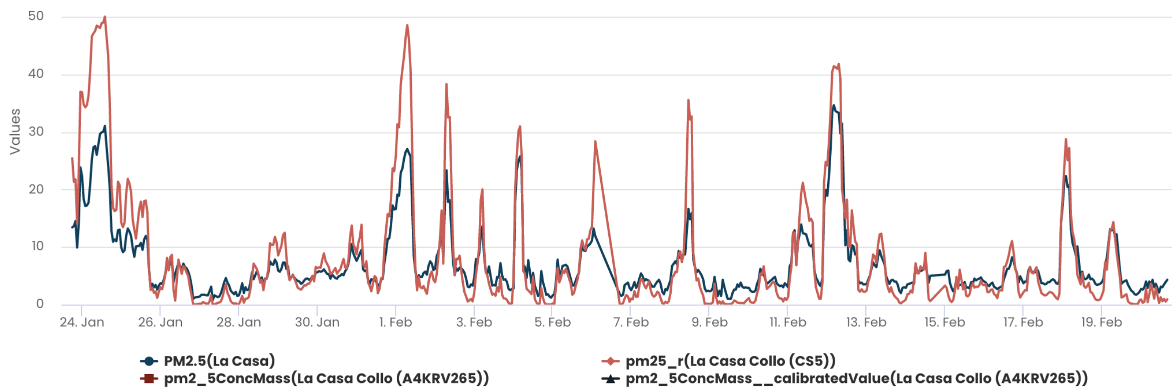

Figure 8. Time series showing the difference between raw data, calibrated data, and the data from the monitor.

Additional Information about Correction Algorithms

The field of low-cost air quality sensors is expanding quickly. And thus, there is a lot of new research about how to best correct these sensors released all the time. From analysis of Denver's LMA sensor Network, we have found that these sensors respond differently to wildfire smoke compared to the normal urban background and are looking into how to correct data differently for each of these cases. Like other studies, Denver's air quality sensors respond differently in high humidity and various temperatures. We have also found that low-cost air quality sensors tend to drift and become less accurate over time. In higher dust environments, the low-cost sensors perform differently than in low-dust environments. However, in general, we have found good agreement in the sensors collocated at Federal Reference Monitor sites.

Nowcast

Many people may wonder why the PM2.5 concentration displayed by Denver's low-cost PM2.5 sensors do not directly correlate to an AQI. This is because raw data measurements are not used to share information to the public. Only hourly averages of PM2.5 concentrations are shown to the public, but the AQI calculation is also calculated differently to better reflect health outcomes associated with the AQI.

For near real-time AQI of PM2.5 from the sensor network displayed on the Love My Air App, Denver uses the EPA's Nowcast method. The Nowcast method calculates the AQI averaged over time rather than for a single data point. This is because longer exposure to pollution has a higher implication than a shorter exposure. If the air pollutant is relatively stagnant in concentration, then a longer time average is used (12 hours), but if the air pollutant concentration is changing quickly, a shorter time average is used. Nowcast uses the change in concentration as a factor for calculating the AQI. For more about the Nowcast method, visit Airnow.[2]

Swimming in Data

The LMA team gets monthly downloads of minutely data for all the sensors and monitors in the network. A challenge of low-cost sensor data is that there is a lot of it, so it can be difficult to process and understand long term trends. However, there are many helpful tools that can be used to process air quality sensor data. These tools require some programming knowledge, but there are many free tutorials and a lot of documentation and example that can be found online. Some valuable (free) tools include:

- **OpenAir R Package[3]** – OpenAir is a free package downloadable in R that has many useful features, including creating a variety of air-pollution related plots, averaging data, and discovering data trends.
- **AirSensor R Package[4]** – This R package was designed to process data from air sensor networks.

There are many best practices when it comes to working with a large amount of data. This processing is important not just for creating corrections algorithms, but also for creating graphs and analyzing the data. Creating a standard data format and naming convention is extremely important, for everything you use the data for will depend on this structure. Keeping the meteorological and pollutant names the same across sensors/sensor types will save you a lot of time when you start doing analysis.

It is also important to keep standardize the date format, this includes the way it is written (ie, mm/dd/yyyy hh:MM:ss) and also the time zone (some sensors report in UTC time, while others report in the local time zone). If you use different types of sensors, the sensors may not have the same reporting times for data, so getting the date formats standardized across all sensors will make comparing data across sensors easier.

There is some common metadata (data that is associated with the sensor and is not included in the streaming data) that will be important to keep track of for each sensor. This includes: date deployed, location (latitude, longitude), sensor type (manufacturer or sensor identifier), sensor name (how you are referencing the sensor to the public), sensor ID (how you reference the sensor within your data analysis). Note that many sensors send their location each time they send data, however, we have found that these are not always accurate and may

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[2] *How is the NowCast algorithm used to report current air quality?* AirNow. https://usepa.servicenowservices.com/airnow?id=kb_article_view&sys_id=bb8b65ef1b06bc10028420eae54bcb98&spa=1.

[3] David Carslaw. *The Openair Manual*. 2019. https://davidcarslaw.com/files/openairmanual.pdf

[4] *Air Sensor R Package and Data Viewer*. South Coast AQMD. https://www.aqmd.gov/aq-spec/special-projects/airsensor

drift or error out. It is better to rely on the original latitude and longitude that you record when setting up a new sensor.

2.4 Denver's Data Management System

To see and understand data from the sensor network, the team needs a Data Management System. The responsibilities of DDPHE's air sensor management system include: ingesting real-time data from the low-cost sensors, showing the status of each sensor, applying correction algorithms to the sensor network, displaying and sharing network health, interfacing with the individual sensor dashboards, and sending corrected data to the Love My Air app.

Denver has chosen to use a "sensor-agnostic" data management system. This means that sensors from almost any manufacturer can be added to the system. The LMA team has decided to keep a diverse sensor network because technologies and companies that produce air quality sensors are constantly changing. By having a data management system that can incorporate different types of sensors (various manufacturers, pollutants, meteorological data, etc.), we are able to add new pollutants or remove sensors that are no longer fitting our needs.

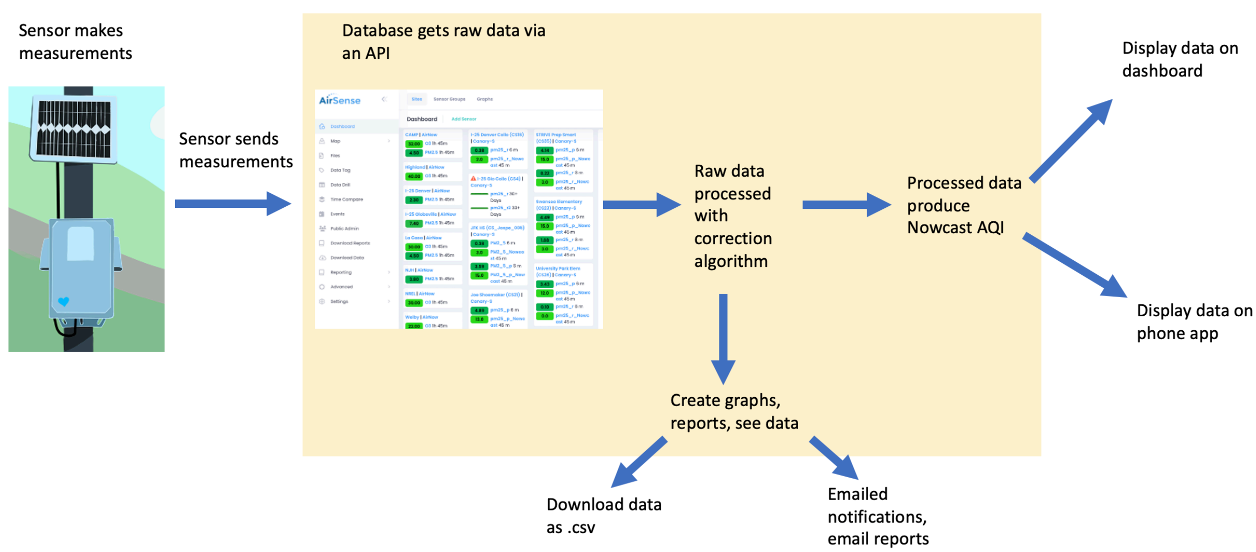


Figure 9. Diagram of Love My Air's data management system.

DDPHE has a subscription to a service for managing all the air sensors on the network. Figure 10 shows the sensor dashboard. This dashboard is customizable and the LMA team decided to show a map of near-real time sensor readings as well as the current sensor readings that can be clicked to be brought into the individual sensor dashboard. A map view of a sensor network enables the network operator to see if there are any unusually high readings from a sensor compared to other sensors. This can then be diagnosed as a "real" reading or because of a sensor malfunction.

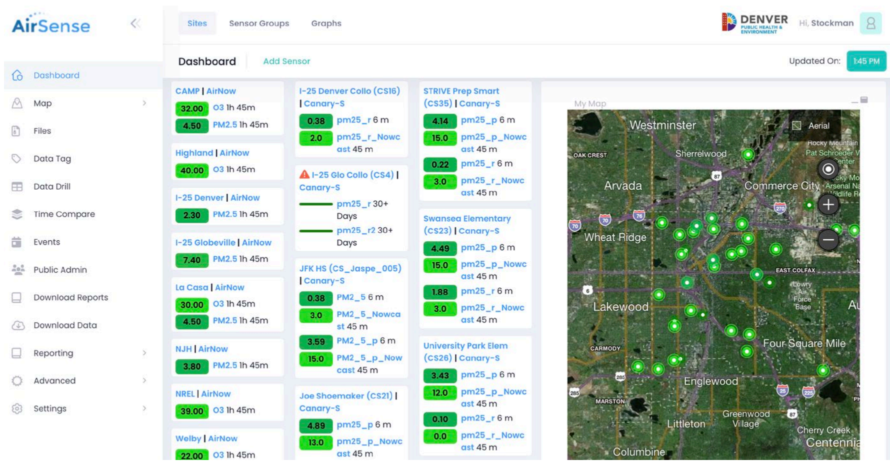


Figure 10. Love My Air team's internal sensor dashboard.

The dashboard has many features that a replicator may want based on their needs. "Must" haves for a sensor management system software are required to get the data from the sensors within the network and ensure that the network is operational. This includes:

- **Access to sensor application program interface (API)** – the sensors must be connected to the internet in some way (WiFi or cellular) and the data management system must have the capability of pulling in data frequently (once every 1-10 minutes).
- **Accessing sensor data from retired sensors** – sensors are rated to last 2-5 years, so it is likely they will be replaced. When a sensor is taken offline, you will want to make sure you can still access the historical data from the sensor.
- **Version control** – if a sensor is replaced by another sensor, being able to see which sensor is currently active and access datasets from both sensors is important for both temporary maintenance and long-term retirement of a sensor.
- **Showing sensor readings in near-real time** – it is important for the sensor network operator to diagnose issues. One benefit of sensor networks is high-time resolution.
- **Showing sensor status in near-real time** – when a sensor goes down, it is important to be able to diagnose the issue and get the sensor back online in a timely manner. If you do not know if a sensor is functioning, this becomes difficult.
- **Basic plotting of sensor data**– many reports using networks include time series plots. Time series are useful for seeing what may be wrong with a sensor and for simple reports to share with the public.
- **Ability to apply a correction algorithm to the sensors within the network** – no matter what correction you apply to sensors in the network, correcting sensor data is very important. A platform should be able to apply a new correction and show you both the raw data and processed data.
- **Ability to download historical data** – the main benefit of a sensor data is the amount of data you can collect. Downloading data from the data management system is important for doing more advanced analysis and sharing data with the public and research community.

- **Ability to share your data** – there can be many forms of sharing data, both in real time and for historical data.

Some "nice" to have features in a sensor management network include:

- **Other plots** – wind roses, pollution roses, box and whisker plots, advanced mapping (including spatial integration), scatter plots – these plots are great to have in a sensor management system but can be created elsewhere if needed using the downloaded data. There are many tools to create these plots, including the OpenAir package in R (free and open source), Excel, Tableau, and other data visualization tools.
- **Notifications of sensor functioning** – email notifications for sensors being down for many hours is very useful for continued maintenance of the sensor network.
- **Automatic daily reports** – another useful feature is an emailed nightly report that shows the status or hourly concentrations across the entire network. These reports can be quickly scanned each day to determine if any air pollution events occurred or if there are any sensors malfunctioning in the network.
- **Shareable API of your management system** – for online systems, an accessible API of your system is a must. This will allow you to share your data to other platforms, including individual sensor dashboards (such as at a school or health clinic), phone apps (such as the LMA app), opensource data platforms (such as OpenAQ), and other local or state agencies.
- **Multi-account access to the system** – although not imperative, having multiple accounts to access the data management system is useful for managing who has access to the raw data.
- **Ability to add different types of sensors to the network** – there are many sensor management systems that only allow for ingestion of their own sensors. This can be good for consistency of the network; however, it is also limiting in many ways. Because the low-cost sensor market is progressing rapidly in technology and contains a plethora of startups (many of which are being bought by large companies and then have a change of business model), the LMA team in Denver has a sensor-agnostic platform. This enables the team to try out sensors from different companies and expand to other pollutants as new technologies are available on the market.

Part of the sensor management system outside of the software are the processes in place to ensure data is of high quality and sensor maintenance is prompt and efficient. Data quality is ensured by the application of proper correction algorithms through software and proper maintenance of the sensors themselves. The previous section described correction algorithms and different methods for creating corrections. Here, we will discuss sensor network maintenance planning in more detail.

The LMA team relies on daily emailed reports of sensor hourly averages of PM2.5 concentrations (ug/m^3) of the past day. This heat-map shows the team both what the air quality was generally like the previous day as well as any outlier sensors that may exist. Then the team can go in to determine if the outlier data points were real or if the sensor is malfunctioning and should be repaired. The daily report also includes a summary of the multi-linear regression, since this is updated daily. If there are large changes in the coefficients in front of the variables or if the R^2 value drops too low, then we know there is a problem with the correction and it needs to be adjusted (such as the collocated sensor is not functioning properly and needs to be repaired or replaced).

Denver: 24 Hour (5/15/2023 12:00:00 AM - 5/16/2023 12:00:00 AM Mountain Standard Time)

Site	Instrument	Sensor	Last Updated	% Complete	01 AM	02 AM	03 AM	04 AM	05 AM	06 AM	07 AM	08 AM	09 AM	10 AM	11 AM	12 PM	01 PM	02 PM	03 PM	04 PM	05 PM	06 PM	07 PM	08 PM	09 PM	10 PM	11 PM	12 AM	Max Reading	Min	Ave
	Bruce Randolph (CS19)	pm25_r	05/16/23 07:04	100	2.5	2.1	2.9	5.2	6.5	6.1	9.8	10.1	7.2	5.6	4.9	6.4	7.4	9.1	9.5	10.6	9.3	9.3	11.0	12.1	14.5	25.1	25.0	18.3	38.7	0.1	9.6
	CAMP Collo (CS13)	pm25_r	05/16/23 07:04	100	1.3	1.5	1.8	2.7	10.8	5.6	6.0	8.3	4.9	5.9	4.7	4.8	5.2	6.7	7.5	8.4	8.9	10.9	12.0	14.7	16.7	21.4	24.8	16.8	159.8	0.1	8.8
	CEC Early College (CS31)	pm25_r	05/16/23 07:04	100	2.2	2.4	1.3	1.2	2.3	3.5	5.0	2.8	1.0	2.5	3.7	5.5	8.6	10.2	10.6	13.1	15.7	12.5	13.3	15.7	16.5	21.7	27.5	22.0	31.0	0.0	9.2
	Centennial (CS12)	pm25_r	05/16/23 07:04	99.93	1.5	0.7	0.6	1.1	1.4	2.8	5.0	1.3	1.8	1.3	2.4	5.0	6.2	8.7	11.8	11.7	11.5	10.5	12.2	12.5	12.3	20.0	26.0	16.1	33.5	0.0	7.7
	Columbian Elem	pm25_r	05/16/23 07:04	100.07	2.3	1.7	0.7	1.2	2.0	2.7	5.1	1.7	1.2	1.8	2.9	5.4	7.2	10.8	10.8	13.8	14.8	12.3	11.8	11.5	11.6	18.4	26.5	21.6	33.7	0.0	8.3
	Columbine Elem (CS22)	pm25_r	05/16/23 07:04	99.93	0.7	0.4	0.5	1.8	2.7	2.4	4.5	4.4	7.1	4.1	3.3	3.1	3.1	4.7	5.2	5.4	5.6	5.0	6.2	8.8	8.1	12.9	18.2	13.1	22.2	0.0	5.5
	Denver Montessori High (CS27)	pm25_r	05/16/23 07:04	99.44	2.1	1.6	1.0	1.6	2.2	3.3	5.0	2.8	1.3	2.1	2.4	5.0	7.0	8.8	9.4	11.5	12.5	10.2	10.0	12.0	11.7	18.4	24.5	23.0	29.2	0.0	7.9
	Emily Griffith HS (CS28)	pm25_r	05/16/23 07:04	99.86	0.1	0.1	0.4	1.2	0.9	2.1	2.6	3.7	2.1	3.3	4.0	3.3	4.9	6.3	7.0	7.3	8.5	7.3	9.7	12.3	12.3	12.4	16.1	10.1	21.2	0.0	5.7
	Farrell B Howell (CS25)	pm25_r	05/16/23 07:04	99.58	2.8	1.0	3.5	3.8	4.9	3.9	5.3	6.7	3.7	3.5	3.3	2.9	4.8	5.6	5.2	4.6	4.1	4.2	5.3	7.9	13.2	14.5	15.8	13.7	26.9	0.4	6.0
	Garden Place (CS8)	pm25_r	05/16/23 07:04	99.93	1.7	2.6	1.9	2.4	3.1	4.7	6.3	8.1	3.5	3.1	3.5	5.0	5.9	7.0	7.9	9.7	9.4	9.4	9.4	13.7	11.4	19.7	24.9	20.2	28.4	0.1	8.1
	Gust (CS15)	pm25_r	05/16/23 07:04	99.65	1.0	1.1	0.4	3.5	4.7	3.2	3.7	3.2	3.0	1.2	1.4	3.6	6.4	7.8	8.2	9.2	9.2	9.0	12.0	12.6	13.1	19.8	18.4	12.8	24.2	0.0	7.1
	Hallett Academy (CS29)	pm25_r	05/16/23 07:04	99.93	1.1	0.6	0.7	2.3	3.2	3.8	4.8	5.6	4.8	5.3	3.0	2.8	3.7	5.2	4.7	5.2	5.0	4.5	5.5	6.0	6.6	7.7	12.1	10.9	19.9	0.0	4.8
	I-25 Denver Collo (CS16)	pm25_r	05/16/23 07:04	100.35	0.1	0.2	1.1	2.0	2.3	2.2	3.0	3.9	0.6	1.7	3.5	3.5	5.8	5.2	6.5	8.0	7.1	9.5	10.3	11.1	11.3	18.1	20.0	14.6	43.3	0.0	6.3

Adjustment	Intercept	x1Coef	x2Coef	x3Coef	r2	Last Updated
CS5_Sub (pm25_r l old)	3.27112396	0.51091556	0.01599100	-0.01540077	0.71281000	Subsciber
CS5_Sub (pm25_r l Garden Place (CS8))	3.27112396	0.51091556	0.01599100	-0.01540077	0.71281000	Subsciber
CS5_Sub (pm25_r l Gust (CS15))	3.27112396	0.51091556	0.01599100	-0.01540077	0.71281000	Subsciber
CS5_Sub (pm25_r l Northeast Early (CS10))	3.27112396	0.51091556	0.01599100	-0.01540077	0.71281000	Subsciber
CS5_Sub (pm25_r l Prep Academy (CS17) Replacement)	3.27112396	0.51091556	0.01599100	-0.01540077	0.71281000	Subsciber
CS5_Sub (pm25_r l Sabin (CS11))	3.27112396	0.51091556	0.01599100	-0.01540077	0.71281000	Subsciber
CS5_Sub (pm25_r l South High (CS18))	3.27112396	0.51091556	0.01599100	-0.01540077	0.71281000	Subsciber
CS5_Sub (pm25_r l Swansea Elementary (CS23))	3.27112396	0.51091556	0.01599100	-0.01540077	0.71281000	Subsciber
CS5_Sub (pm25_r l University Prep-Steele (CS20))	3.27112396	0.51091556	0.01599100	-0.01540077	0.71281000	Subsciber
CS5_New (pm25_r l La Casa Collo (CS5))	1.92813007	0.81747055	0.01870772	-0.00644140	0.83912000	Never
CS5_Sub (pm25_r l Manual HS (CS9))	3.27112396	0.51091556	0.01599100	-0.01540077	0.71281000	Subsciber
CS5_Sub (pm25_r l Joe Shoemaker (CS21))	3.27112396	0.51091556	0.01599100	-0.01540077	0.71281000	Subsciber
CS5_Sub (pm25_r l Columbine Elem (CS22))	3.27112396	0.51091556	0.01599100	-0.01540077	0.71281000	Subsciber
CS5_Sub (pm25_r l Columbian Elem)	3.27112396	0.51091556	0.01599100	-0.01540077	0.71281000	Subsciber
CS5_Sub (PM2_5 l STOLEN (CS24))	3.27112396	0.51091556	0.01599100	-0.01540077	0.71281000	Subsciber
CS5_Sub (pm25_r l Farrell B Howell (CS25))	3.27112396	0.51091556	0.01599100	-0.01540077	0.71281000	Subsciber
CS5_Sub (pm25_r l University Park Elem (CS26))	3.27112396	0.51091556	0.01599100	-0.01540077	0.71281000	Subsciber
CS5_Sub (pm25_r l Denver Montessori High (CS27))	3.27112396	0.51091556	0.01599100	-0.01540077	0.71281000	Subsciber
CS5_Sub (pm25_r l Hallett Academy (CS29))	3.27112396	0.51091556	0.01599100	-0.01540077	0.71281000	Subsciber
CS5_AirNow (pm25_r l La Casa Collo (CS5))	3.27112396	0.51091556	0.01599100	-0.01540077	0.71281000	5/16/2023
CS5_Sub (pm25_r l Centennial (CS12))	3.27112396	0.51091556	0.01599100	-0.01540077	0.71281000	Subsciber

Figure 11. Daily emailed report on a good air quality day.

Note the high value maximum reading of CAMP Collo (CS13) in Figure 11. Given that there is one very high reading that does not impact the hourly averages, this is likely a sensor malfunction that resolved itself, such as an electrical glitch. This is not of concern because no hourly averages are impacted, and it does not appear to cause any long-term issues. Another explanation would be a short-lived source local source, which also would not be a cause of concern for replacing this sensor.

Denver: 24 Hour (5/19/2023 12:00:00 AM - 5/20/2023 12:00:00 AM Mountain Standard Time)

Last Updated	% Complete	01 AM	02 AM	03 AM	04 AM	05 AM	06 AM	07 AM	08 AM	09 AM	10 AM	11 AM	12 PM	01 PM	02 PM	03 PM	04 PM	05 PM	06 PM	07 PM	08 PM	09 PM	10 PM	11 PM	12 AM	Max Reading	Min	Ave
05/20/23 07:09	99.79	13.3	13.6	21.1	40.6	50.8	55.9	59.3	68.7	103.7	102.7	100.5	108.7	135.8	135.7	123.8	117.5	111.3	101.5	93.4	96.1	101.2	103.3	100.8	104.9	147.2	12.1	86.0
05/20/23 07:09	1500	12.3	13.0	21.1	37.5	52.3	47.5	47.3	59.5	90.5	87.8	87.3	85.4	91.1	105.5	99.5	100.6	100.6	95.9	89.0	82.7	87.5	92.4	89.2	91.6	112.9	11.1	73.6
05/20/23 07:09	1509.38	12.8	15.1	22.8	38.6	49.7	47.4	46.7	57.2	85.6	81.7	80.4	79.0	86.1	97.3	96.4	94.1	93.8	92.0	88.2	83.4	90.5	93.3	87.1	82.0	104.8	10.0	70.8
05/20/23 07:09	1500	12.6	14.8	22.8	37.8	52.4	51.1	50.6	60.0	94.0	90.9	103.5	90.9	95.8	113.0	105.0	103.1	103.4	99.4	91.6	81.0	88.4	94.3	90.7	96.5	133.8	9.8	76.8
05/20/23 07:09	1497.92	9.8	10.2	15.3	27.9	34.9	41.2	38.8	47.1	73.1	71.5	69.8	71.3	84.5	95.8	89.8	83.8	74.7	67.3	62.0	67.4	70.9	69.3	59.4	62.9	102.7	8.1	58.3
05/20/23 07:09	1461.46	11.6	11.3	20.1	30.4	42.1	44.6	41.2	52.6	81.6	80.5	78.8	78.6	85.4	97.8	93.7	91.2	88.8	85.8	76.2	71.6	79.3	82.9	78.5	82.5	106.0	9.3	67.5
05/20/23 07:09	99.93	8.4	8.4	15.8	27.8	36.0	39.4	40.8	46.6	65.7	63.7	63.0	63.0	66.9	83.8	79.6	78.9	72.2	67.8	62.7	61.4	63.4	64.8	67.8	66.7	89.5	6.9	54.8
05/20/23 07:09	1498.96	15.1	15.0	16.7	29.2	40.2	46.3	49.3	63.0	93.2	96.0	113.7	130.2	132.5	125.4	113.3	104.0	99.9	93.3	89.1	86.3	92.2	96.8	100.9	98.8	138.3	12.4	80.8
05/20/23 07:09	1498.96	12.4	12.6	21.0	32.1	44.5	49.9	47.0	58.0	84.1	83.5	80.7	83.2	97.5	105.4	99.3	94.7	92.3	88.2	77.5	73.2	82.2	85.6	80.9	76.2	117.0	10.4	69.2
05/20/23 07:09	1503.12	7.5	7.3	9.8	23.3	38.0	41.5	51.2	54.8	77.0	83.2	79.5	81.1	79.0	78.5	82.6	81.7	87.1	92.1	84.6	75.7	80.8	87.1	85.7	78.7	98.0	6.3	64.4
05/20/23 07:09	1498.96	10.3	10.0	15.0	28.2	33.9	35.4	36.8	46.8	67.7	67.6	67.0	74.4	92.7	92.0	83.1	76.3	73.0	67.2	63.2	64.0	65.0	63.4	61.6	62.7	97.2	8.1	56.5
05/20/23 07:09	100	7.8	9.6	12.4	22.5	36.2	48.2	57.6	64.2	92.5	93.1	95.5	94.9	91.7	92.2	97.9	95.2	98.1	106.0	97.3	90.4	89.0	94.1	95.2	99.2	110.5	5.9	74.2
05/20/23 07:09	1498.96	10.7	12.0	11.2	22.5	38.4	43.3	49.3	62.3	90.8	93.9	99.8	115.6	128.1	122.4	119.4	110.2	105.6	99.2	93.9	88.2	95.7	93.6	97.0	93.1	132.5	8.8	79.0
05/20/23 07:09	94.65	10.3	10.6	17.2	30.1	38.1	45.8	45.8	51.0	78.3	77.7	77.1	78.2	89.5	102.8	95.2	90.7	84.9	80.6	72.2	71.4	76.3	79.4	78.7	79.0	107.8	8.6	65.8
05/20/23 07:09	99.93	11.7	10.5	10.6	28.8	37.7	43.5	47.6	59.4	90.4	91.0	91.5	90.6	113.4	120.0	109.5	106.0	103.8	99.9	89.2	86.4	89.3	94.9	93.5	98.0	130.1	8.2	75.7
05/20/23 07:09	1498.96	15.3	16.6	15.4	30.3	34.6	43.7	52.1	70.4	100.9	110.4	131.3	142.3	138.1	127.0	116.1	107.2	99.9	94.1	89.2	87.8	90.7	92.9	97.7	95.8	146.9	10.9	83.3
05/20/23 07:09	99.79	9.5	8.8	16.8	32.8	50.2	48.8	51.2	64.4	85.9	89.9	90.1	89.2	89.8	94.5	102.5	95.2	101.7	98.3	87.8	82.7	87.6	93.8	92.0	93.3	112.6	7.1	73.2
05/20/23 07:09	99.93	10.2	10.0	18.1	34.8	49.4	48.3	55.3	64.5	94.2	92.4	89.5	89.0	90.5	100.3	100.0	97.2	106.8	104.6	98.3	87.6	94.4	102.4	100.2	98.4	114.8	8.3	76.5

Figure 12. Example of daily report on a wildfire day.

The heatmap of daily averages can also show interesting trends, like smoke settling into the city and when the smoke was the worst during the day as shown in Figure 12. When there are days like this with very high air pollution, it is important to check the sensors once the air pollution passes to make sure that they are still functional. Sometimes large events can cause the sensors to get dirty and they must be cleaned to function properly going forward. These daily reports, thus, inform whether or not maintenance needs to be performed on the sensors in the network.

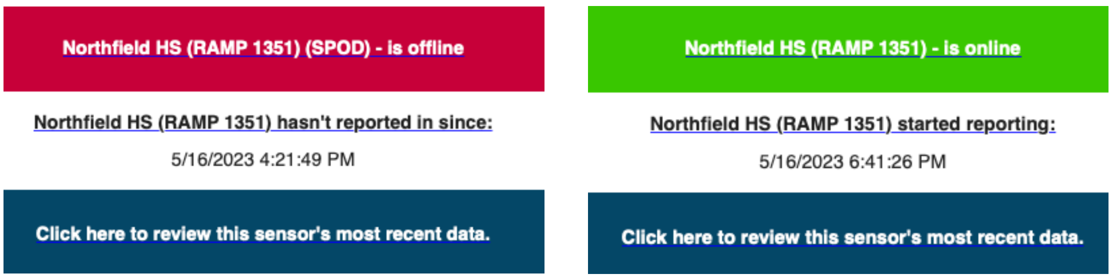


Figure 13. Example email notification of a sensor going offline (left) and back online (right).

When the LMA team receives a notification that a sensor is offline, there are a few steps that are taken. First, we can determine if there was an event that occurred that caused it to lose power. In the winter the day after a big snowstorm, some of the solar panels may still be covered. Once the battery runs out, the sensor goes offline. In these cases, we normally wait a few days until the snow melts before going out into the field to see if there is another problem.

If there was not something obvious like a snowstorm, the hourly averages daily reports can be used to determine when the sensor went offline and if it was reporting strange values before it went offline (such as the values spiking and suddenly going offline). The LMA team has contractors that check on down sensors, but the team may also go out as well depending on the situation. Sometimes there is an issue with the unit and it needs to be replaced, while other times, the issue is that the cell service was disconnected, and the unit just needs to be restarted.

2.5 Love My Air School Dashboards and Phone App

Once a sensor is placed and data is being collected, it is important to display that data with the public, real-time, historically, or both. LMA has multiple methods for sharing the data publicly, including dashboards for individual sensors, a phone app, and accepting requests for specific data from the public. The main LMA dashboard displays all the sensors in a map view with the AQI of each of the sensors represented by a color (green, yellow, orange, red, purple, maroon) based on the EPA AQI scale.

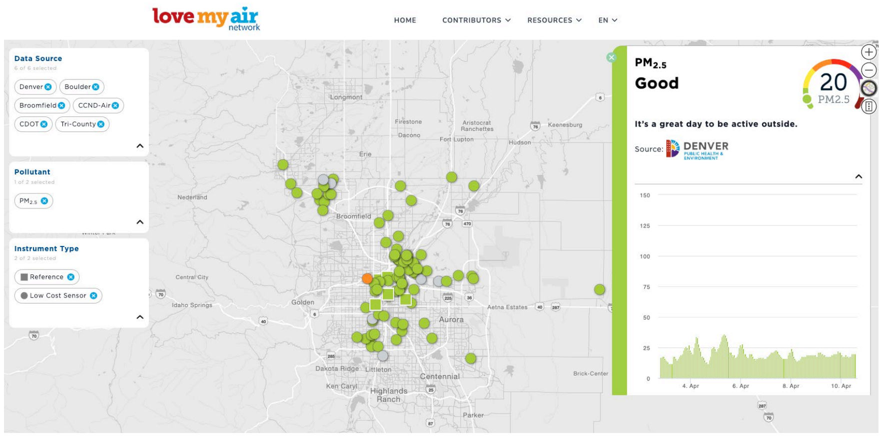


Figure 14. Snapshot of map from denver.lovemyair.com displaying the LMA sensor network. The website has both a map view and time series for each sensor for the previous few days.

The dashboards of individual sensors are displayed both on TVs within schools and on a website. The website has multiple views, including a map view and individual sensor views. The dashboards are designed to be easy to understand using the AQI color coding and simple language to explain what the color and data means. There is also a graphical historical view that shows the previous few days of hourly averages and color-coding for each of those data points. The time series is also colored by AQI.

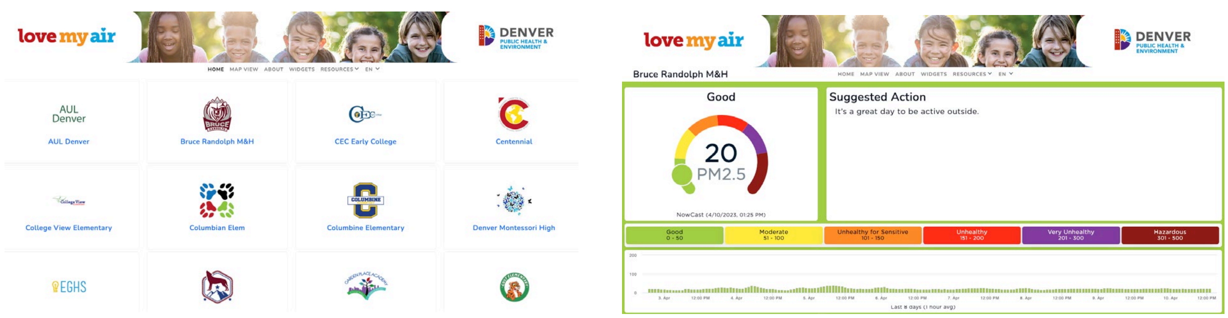


Figure 15. Love My Air school selection (left) and dashboard view (right).

The website has a page that shows all the sensor locations by showing the partners name and logo where the sensor is located. This is to make it easy for the community to know which sensor they should focus on.

In addition to dashboards, LMA also has an app that ingests data from the data management platform to display Nowcast AQI of the PM2.5 sensor network. The app shares similar information to the website and has many features including: a map view of all the sensors, an individual view for each sensor, resources (both created by LMA and government links), notifications, and alerts (a favorited sensor shows high). All aspects of the app are available in both English and Spanish. Notifications are opt-in for the networks that are requested (someone in Boulder does not have to receive notifications from Denver). As part of the on-boarding process, people can identify groups of which they belong, sensors they want to favorite, and agencies that they want to receive notifications from. This allows the LMA team (and other agencies who add information to the app) to see analytics of app usage and strategize improvements.

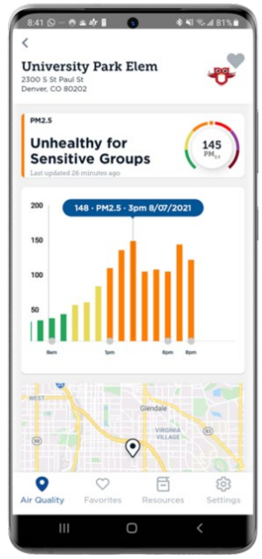


Figure 16. Love My Air app individual sensor view.

Some considerations for these data displays are:

- **Make displays simple** – keeping displays clean and simple, with not too many words makes it easier for users to understand the main message.
- **Use common color-coding** – it is important to use design language that people are already familiar with so that the main messages are easier to understand.
- **ADA Compliance is important to consider from the ground up** – understanding ADA compliance so that your data is accessible to everyone is important from the beginning. This includes color schemes, voice to text, etc. If you don't think about this at the beginning, you may have to redesign some parts of your data display system.
- **There is a lot that goes into designing data displays** – it may take longer and more money to design a data sharing platform than originally anticipated. Finding free or already-existing systems that fit your needs may be more feasible than building your own data display from scratch.

3. Communicating with the Public

The goal of collecting all this data is to figure out what is means, create change, and share the data with the public. A large challenge of running a Low-Cost Sensor Network is determining what should be done with the data and how to tell stories using this data in an accessible way. It is recommended that all data presented publicly should be at a 6th-8th grade reading level. Plain language and visuals should be prioritized over complicated language and a lot of text.

3.1 Data Analysis and Visualizations

Telling stories with the data is very important for the public to understand what information these sensor networks can give us. This section provides examples of figures that are useful in understanding air quality data from sensor networks and presenting this data in an understandable way to the public.

Time Series

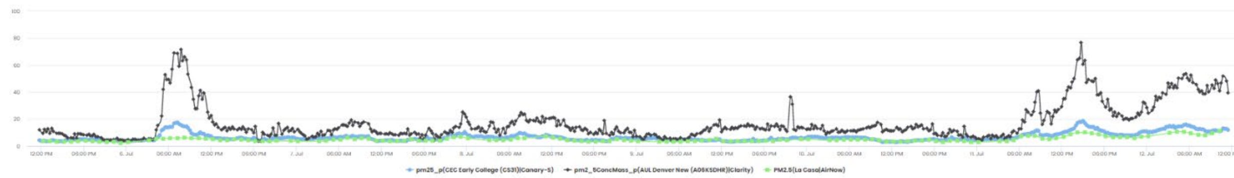


Figure 17. Example of time series plot.

There are some important considerations when creating time series. Some PM2.5 sensors report their data in UTC time, while others report data using Local Daylight Time (LDT) or Local Standard Time (LST) based on cell service or WIFI connection. It is important to know the time zone your sensor is sharing data in, otherwise, it can be confusing when later conducting analysis and trying to figure out the source of the air pollution. It is good to share all time series in your local time zone when presenting publicly.

Time series can be used at different averaging times to tell different stories with the data. While we do not recommend sharing many 1-min time series plots, 15-min or 1-hour averaged data can show how air pollution trends over the course of a day or week. If you want to understand how air pollution trends over the course of a month or longer, daily averages can be useful to plot via a time series.

It can be helpful to plot time series of multiple sensors or sensors and reference monitors on the same plot. This can give you an understanding of whether the pollution is regional or local.

Maps

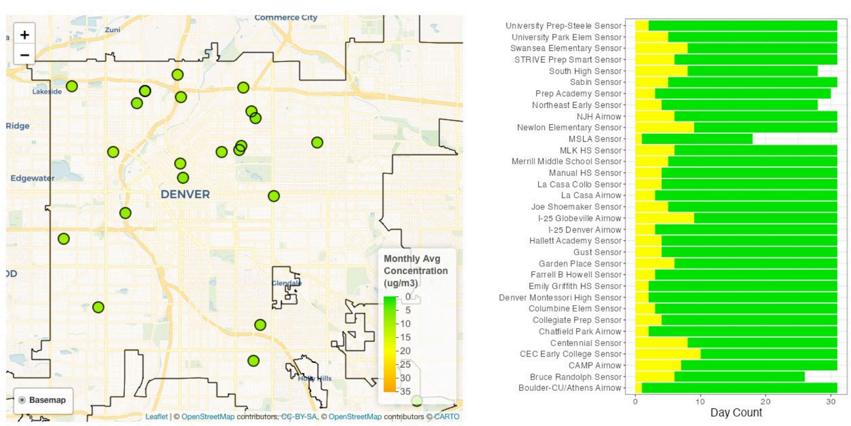


Figure 18. Example map of hourly averages across LMA sensors and bar chart of days of each AQI.

Maps are very important for air quality sensor networks and can be used for a variety of reasons, both when sharing data publicly, but also keeping track of the sensors internally. Maps can show different time spans as well, such as near-real time data or yearly averages. People like knowing where the closest air sensor to their house is located as well as the reading for that sensor.

More advanced maps can be made using interpolation methods (such as Kriging) to show what the spatial variation in a pollutant is like across a region. Creating these maps requires a high spatial resolution of sensors.

Pollution Roses

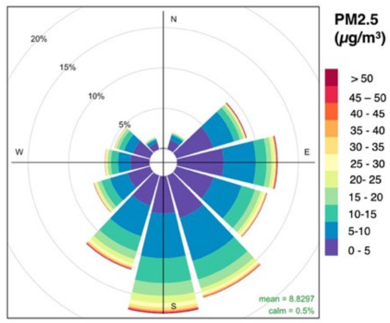


Figure 19. Example pollution rose, the coloring shows the concentration of PM2.5 (ug/m³). The pollution rose shows the percentage of data of each wind direction and within a concentration range of the pollutant.

Pollution roses combine data from an air quality sensor and either a collocated meteorology (MET) station or a nearby meteorology station. Because the City and County of Denver has six FEM monitors, the Love My Air team usually do not deploy a MET station along with a sensor. Instead, the team uses the closest MET station run by the state of Colorado to provide wind speed and direction data that is combined with the air pollutant data to create a pollution rose. A pollution rose is valuable to determine where an air pollutant is likely coming from.

Pollution roses are more difficult for non-scientists to understand. If you present these plots publicly, you will want to clearly explain what they show and how you arrived at your conclusions based on these plots.

Combining Datasets

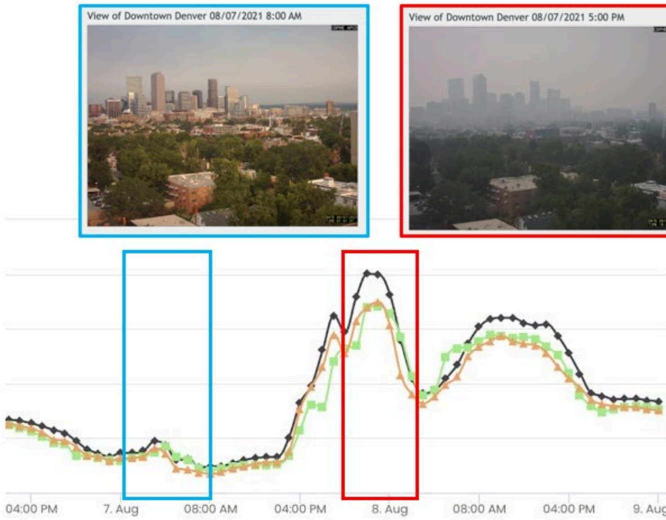


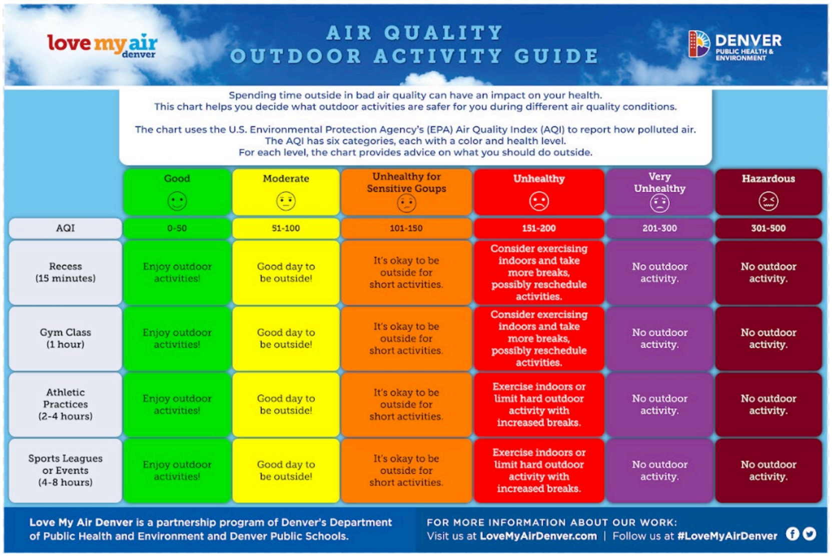
Figure 20. Example of how data from low-cost air quality sensors can be combined with other sources of data.

Data sources can be combined to tell interesting stories. The example in the figure above shows the PM2.5 concentration at 3 different sites before and during a wildfire event combined with two images of CDPHE's smoke view camera[5]. While there was some smoke in Denver in the morning (as you cannot easily see the mountains in the background), there is much higher smoke later during the day. The second image shows high smoke, with the visibility of the buildings diminished. This is reflected by the time series with a much higher concentration later in the day across all three of the sensors compared to earlier in the day. A similar increase in all the sensors shows that this event is regional, rather than within a specific area of the city.

3.2 AQI and Messaging

The team is creating notifications to be pushed out through the Love My Air app, website, and social media pages related to the Air Quality Index and what steps people can take to reduce their exposure to air pollution. The outdoor guide is an example of messaging that can be found in our toolkits. AQI-based messaging is a current work in progress. Subsequent versions of this document will contain additional information about notifications and messages, including how various stakeholder groups respond to messages.

[5]Colorado Air Quality. View of Downtown Denver. https://www.colorado.gov/airquality/live_image.aspx



love my air denver

AIR QUALITY OUTDOOR ACTIVITY GUIDE

DENVER PUBLIC HEALTH & ENVIRONMENT

Spending time outside in bad air quality can have an impact on your health.
This chart helps you decide what outdoor activities are safer for you during different air quality conditions.

The chart uses the U.S. Environmental Protection Agency's (EPA) Air Quality Index (AQI) to report how polluted air.
The AQI has six categories, each with a color and health level.
For each level, the chart provides advice on what you should do outside.

	Good	Moderate	Unhealthy for Sensitive Goups	Unhealthy	Very Unhealthy	Hazardous
AQI	0-50	51-100	101-150	151-200	201-300	301-500
Recess (15 minutes)	Enjoy outdoor activities!	Good day to be outside!	It's okay to be outside for short activities.	Consider exercising indoors and take more breaks, possibly reschedule activities.	No outdoor activity.	No outdoor activity.
Gym Class (1 hour)	Enjoy outdoor activities!	Good day to be outside!	It's okay to be outside for short activities.	Consider exercising indoors and take more breaks, possibly reschedule activities.	No outdoor activity.	No outdoor activity.
Athletic Practices (2-4 hours)	Enjoy outdoor activities!	Good day to be outside!	It's okay to be outside for short activities.	Exercise indoors or limit hard outdoor activity with increased breaks.	No outdoor activity.	No outdoor activity.
Sports Leagues or Events (4-8 hours)	Enjoy outdoor activities!	Good day to be outside!	It's okay to be outside for short activities.	Exercise indoors or limit hard outdoor activity with increased breaks.	No outdoor activity.	No outdoor activity.

Love My Air Denver is a partnership program of Denver's Department of Public Health and Environment and Denver Public Schools.

FOR MORE INFORMATION ABOUT OUR WORK:
Visit us at LoveMyAirDenver.com | Follow us at #LoveMyAirDenver

Figure 21. Outdoor activity guide based on the air quality index, also found in the Replication Toolkit.

3.3 General Communication Learnings

Communicating regularly with partners and the public is important for this program to be successful. We are particularly growing our communication strategies about reducing exposure to air pollution.

Communicating with underrepresented groups is both necessary and challenging. We especially want to educate community members that air pollution is often invisible but can still impact their health. There are many known health impacts of air pollution, including asthma and COPD, that our community members may not be aware about. This includes educating people on why they should care about air pollution and that there are steps they can take to reduce their own exposure. We share other government or community-based programs that have a similar mission to inform our community members on funded programs that will decrease their exposure (access to indoor air cleaners, radon programs, mold inspections, etc.).

We are also increasing our programs and communications to include more people of color (POC) so that there are more POCs who know there is space for them in public health and environmental quality. They can be part of the Love My Air program and other environmental work, and that it is important for them to get involved since their communities are the ones most impacted by air pollution and other environmental injustices.

4. Outreach

The Love My Air team has created many materials to be used in a variety of outreach settings, including to nurses in schools, school principals, teachers, and general community members. The Love My Air toolkits, in both English and Spanish, can be found here. The outreach materials include: toolkits to teach nurses about the connection between air pollution and asthma, classroom materials for K-12 teachers, anti-idling event ideas, guidance documents for AQI and outdoor versus indoor recess guidelines, and other communication materials created by the team.

Figure 22. Love My Air Toolkit overview.

Over the past few years, the team has learned a lot about air quality outreach, particularly within K-12 schools. The biggest advocates for our program are those who understand student health and are concerned about air pollution – particularly school nurses. While school nurses are stretched very thin, most understand that air pollution is a concern and can negatively impact student health. Many of the most vocal advocates for the Love My Air program and who check the air sensors the most often are school nurses.

When finding advocates for any program takes humility and the ability to sit back, listen, and hear the concerns of community members. It is important to be open to suggestions and be willing to adapt. This is not just a "government" program, this is a community program, so making the community feel included and heard is very important. Along with this, accepting feedback and changing to fit community member needs is important to running a successful program.

Because many community members and groups feel stretched thin, combining efforts with other governmental and community organizations can greatly reduce the burden on individuals. For some people, air pollution is a top concern, while for others, they do not realize how bad it can be or why it should be a concern. Meeting people where they are at and not over-asking community members to participate or do things for the program is important for long-term engagement.

In addition, the Love My Air team has been finding people ask more questions about indoor air quality. People are starting to become more aware that outdoor air pollution can come inside, so they are skeptical that staying indoors is helpful. The Love My Air team also has an indoor air primer to address community concerns about indoor air quality, particularly when outdoor air quality is poor.

In Denver, the Love My Air team has seen a lot of success through school nurses and is working on expanding that success and buy-in to the program to health clinics in the area. To expand the program outside of Denver Public Schools, the Love My Air team is working on building connections with community groups and breaking down siloes within the city's government.

5. Summary

This document provides an overview of the various components to the Love My Air program and sensor network to give other municipalities and groups a guide to replicating the Love My Air program in their own area. The guide includes information on how to set up a sensor network, how to ensure data is of good quality from air sensors, necessities for a database to store sensor data, and communicating this data to the public in an accessible way. This is a living document for the Love My Air team and will be expanded upon as program components are added to or modified within Denver.