atmosphere

MDPI

SupplementaryMaterials

Air Quality Measurements in Kitchener, Ontario, Canada Using Multisensor Mini Monitoring Stations

Wisam Mohammed [1], Nicole Shantz [1], Lucas Neil [2], Tom Townend [3], Adrian Adamescu [1] and Hind A. Al-Abadleh [1,*]

[1] Department of Chemistry and Biochemistry, Wilfrid Laurier University, Waterloo, ON N2L 3C5, Canada
[2] Hemmera Envirochem Inc., Burlington, ON L7L 6B8, Canada
[3] AQMesh, Environmental Instruments Ltd., Unit 5, The Mansley Centre, Timothy's Bridge Road, Stratford-upon-Avon CV37 9NQ, UK
* Correspondence: halabadleh@wlu.ca; Tel.: +1-519-884-0710 (ext. 2873)

Table S1. Provincial-led public health orders to limit the spread of COVID-19 in 2020-2021 in the province of Ontario (ON).

Date	Province	Description
Aug-12	ON	All regions in Ontario in tier 3 **(Orange). Duration: 30 days**
Oct-10	ON	Some restrictions re-implemented in Ottawa, Peel, and Toronto regions **Duration: 28 Days**
Oct-19	ON	Some restrictions re-implemented in York region. **Duration: 14 Days**
Nov-14	ON	"Restrict" measurements were implemented in Ottawa and York regions. **Duration: 28 Days**
Nov-07	ON	Peel region moved to "control" tier. **Duration: 14 Days**
Nov-10	ON	Toronto moved to "control" tier. **Duration: 28 Days**
Nov-23	ON	Peel Region and Toronto move to lockdown. **Duration: 28 Days**
Dec-11	ON	York and Windsor-Essex regions move to lockdown. **Duration: 14 Days**
Dec-26	ON	Province-wide lockdown in effect. **Duration: 28 Days**
Jan-23	ON	Province-wide "restrict" order initiated (exceptions: York region, Toronto, Peel which are still in lockdown). **Duration: 14 Days**
Feb-08	ON	Province-wide "restrict" order extended. **Duration: 28 Days**
Mar-15	ON	"Control" Restrictions in place province-wide. **Duration: 28 Days**
Apr-03	ON	Second Province-wide lockdown initiated. **Duration: 28 Days**
Apr-16	ON	Lockdown orders extended. **Duration: 45 Days**
Jun-11	ON	**Phase 1** of the province-wide reopening plan initiated
Jun-30	ON	**Phase 2** of the province-wide reopening plan initiated
Jul-16	ON	**Phase 3** of the province-wide reopening plan initiated.
Aug-17	ON	Reopening plan paused indefinitely as a result of a fourth wave of COVID-19.

Organized Public Events, Social Gatherings, and Religious Services, Rites and Ceremonies

PREVENT (Standard Measures)	PROTECT (Strengthened Measures)	RESTRICT (Intermediate Measures)	CONTROL (Stringent Measures)	LOCKDOWN (Maximum Measures)
Limits for certain organized public events and social gatherings where physical distancing can be maintained: • 10 people indoors • 25 people outdoors This includes functions, parties, dinners, gatherings BBQs or wedding receptions held in private residences, backyards, or parks.	Same as previous level	Same as previous level	**Limit for all organized public events and social gatherings,** where physical distancing can be maintained: • **NEW** 5 people indoors • 25 people outdoors	**No indoor organized public events and social gatherings,** except with members of the same household. **Limit for outdoor organized public events and social gatherings,** physical distancing can be maintained: • 10 people outdoors Virtual and drive-in gatherings and events permitted.
Limits for organized public events and social gatherings where physical distancing can be maintained: • 50 people indoors • 100 people outdoors This includes events and gatherings in staffed businesses and facilities.	Same as previous level	Same as previous level		
Limits for weddings, funerals and other religious services, rites or ceremonies, where physical distancing can be maintained: • 30% capacity of the room indoors • 100 people outdoors	Same as previous level	Same as previous level	Same as previous level	**Weddings, funerals and other religious services, rites or ceremonies** where physical distancing can be maintained: • 10 people indoors • 10 people outdoors Virtual and drive-in services, rites or ceremonies permitted

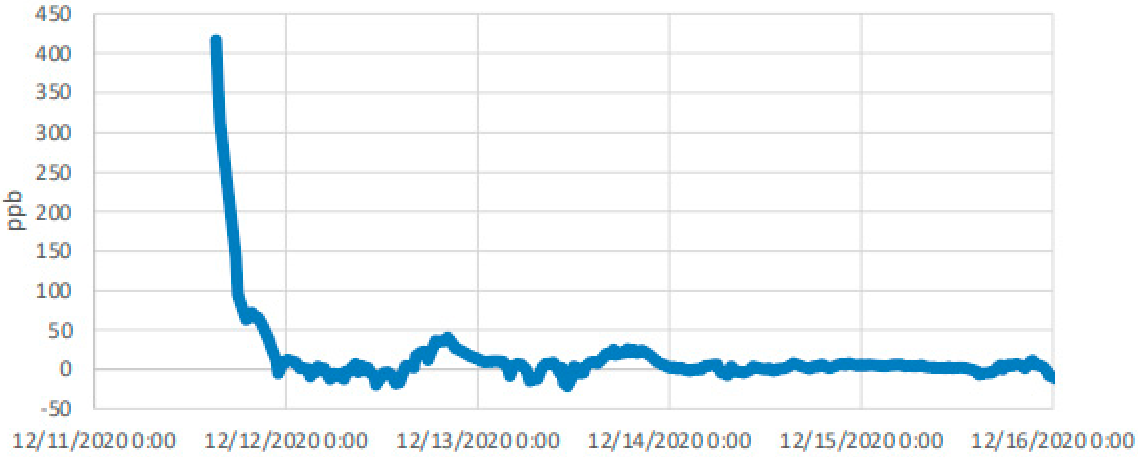
NO LOCKDOWN (PREVENT, PROTECT, RESTRICT) — LOCKDOWN (CONTROL, LOCKDOWN)

Measuring the quality of AQMesh multisensor system performance

Characterisation: While at factory, the response of each sensor is compared to reference instrumentation under ambient conditions to create a "map" of the sensor's response to target gas and its known interferants. This provides sensor specific variables that are used for the life of the sensor, as part of the AQMesh algorithm (see below). Each pod in the test batch is within 1m of the reference inlet, which is placed at the centre of the group of pods inside a specially designed enclosure to house up to 100 AQMesh pods. All other co-location criteria listed in the AQMesh standard operating procedure are also met. https://www.aqmesh.com/resources/user-manual/

Factory quality control: Every sensor (gas and PM) is quality checked at factory against reference instrumentation. Using the characteristics found, criteria need to be met for linearity (R2), bias (slope and offset) and error (RMSE). Should any sensor fail to meet these criteria, then it will fail to meet the standards required by AQMesh and not proceed for use by a customer. These criteria are similar to the guidance from US EPA on O3 and PM2.5 but vary for all sensor species depending on the pollution range experienced during the comparison period and what they are being compared against. This results in a yield of between 50% to 75% of sensors tested being used, depending on the season used for testing. In addition to this outdoor testing, indoor bench testing of the instrument is also completed. This is based on raw sensor outputs being within normal ranges, connections being made to the server, GPS being able to get a lock, etc. By this point the sensors have been compared to reference instruments 2-3 times prior to being shipped to the customer. This process is the same for sensors supplied in new AQMesh pods, as well as replacement sensors.

Stabilisation: The electrochemical sensors used in AQMesh are sensitive and can be affected by being moved. Therefore, after it has shipped, or otherwise moved, transported or changed, the sensor needs to physically "settle" into its new environment and find a point of equilibrium. This process of stabilisation takes up to 48 hours to complete during which data from the sensor is withheld. An example of data during the physical stabilisation of a sensor is shown below, indicating how important it is to allow the sensor to find its equilibrium before processing and presenting data. Without understanding this process of sensor stabilisation, wildly erroneous data could be included in data presented to stakeholders.



Rebasing: The rebasing process is a two-day period of data collection that needs to be completed before normal processing using the algorithm can begin. This standardises the sensor output in relation to its point of stabilisation in its current environment. To do this, rebasing defines a set of fixed values for the individual sensor that describe how it responds to environmental conditions, which are then used in it's processing as part of the algorithm moving forward or until rebasing is reinitialised. Without this stage, providing accurate "out of box" data from the gas sensors is not possible.

Algorithm: All AQMesh processing is linear, traceable and repeatable, with no use of machine learning or artificial intelligence (AI). Each algorithm used by AQMesh has a unique identifier, such as v5.1 or v5.3. Processing, via the algorithm, is how the standardised output from the sensor is turned into meaningful readings. All data presented in this paper have been processed using the most recent version of the algorithm (v5.3).

Pre-ratification flags: Specific, labelled data flags are a part of any set of data from a trustworthy source. They allow the data user to know when instrument faults or conditions have occurred which may require specific data points to be used, redacted or investigated further. AQMesh offers the same by highlighting data that was gathered during stabilisation or rebasing periods, when extreme environments or specific interferences might cause an impact on data quality (e.g., deliquesence of particles), as well as when the instrument suffers any sensor failures. This provides confidence in the data gathered by the instrument.

Validation through Calibration/Scaling: The term "calibration" is not appropriate for most small sensor systems, as "calibration" refers directly to comparison to a standard gas bottle or similar, allowing single or multi-point span and zero checks. Small sensor systems typically do not measure gases via active (pumped) sampling. AQMesh uses ambient diffusive sampling for gases via electrochemical sensors, while PM does require a pumped sample, which is done separately from gas samples. Consequently, calibrating via gas bottles is not possible. To counter this, comparison needs to be done differently; consequently the term "scaling" is used instead of "calibration". This is achieved through co-location with the inlet of a serviced and calibrated reference instrument, such that comparison can be made using as many data points across the available ambient range as possible. For example, as reference instruments may be calibrated using a single span value and a zero gas, in contrast the small sensor could be scaled over the course of a week or more at 15 to 60-minute intervals (typically >670 data points at ambient levels). Scaling provides similar corrections in the form of a slope (span) and offset (zero) and simply affects the accuracy of the instrument data as compared to the local reference, without changing the algorithm processing or the linearity of the data set.

While co-location within 1m is still the ideal means of validating and testing the accuracy and linearity of a small sensor instrument this is not always an option, due to a variety of factors such as space at the reference site, access to the reference site if not owned by the small sensor user, size of the small sensor network making the task too onerous, or simply the logistics being too great to make comparisons of larger networks of small sensors worthwhile. Therefore, an alternative method of comparison has been developed and used for the purpose of scaling small sensor network and providing traceability to a known standard or reference. A proven methodology is the gold pod method, where scaled small sensors are moved and used as transfer standards for co-location with individual or groups of other co-located small sensor systems. Alternatively, network scaling methods have been shown to provide a similar level of improvement in accuracy as direct co-location, without the need for costly and time-consuming logistics of moving pods or gold pods from location to location. One example of this is the Breathe London pilot study (https://www.globalcleanair.org/files/2021/05/BL-Pilot-Final-Technical-Report.pdf).

Many different efforts have been made to determine standards for small sensor data. The US EPA has recently proposed comparison targets for ozone and PM2.5 (https://www.epa.gov/air-sensor-toolbox/air-sensor-performance-targets-and-testing-protocols), and there is currently an EU working group determining standards for small sensor system certification, to provide comparable standards to reference and equivalence standards used for traditional methods. These are all based on co-location to reference instruments, using comparison statistics to measure data capture rate, linearity, bias, error and, in the case of the EU, measurement uncertainty too. These are all-important factors to consider when evaluating small sensors, but they are only a snapshot of performance from the instrument, at most for a period of 30 to 40 days, but often much less. Therefore, traceability of the sensor system's processes, as highlighted above, and longer-term performance – both also vital to validation of data from a project - are not covered by these targets. To have complete confidence over a project, a well-planned and feasible QA/QC process needs to be determined and used throughout the project. Depending on the size and aspirations of the project team, this could be co-location at the start and end of the project, potentially months apart, or comparisons completed on even a daily basis. The approach taken will depends on the rigour required for the project stakeholders and the user's confidence in the small sensor system's process for providing the quality of data required.

atmosphere MDPI

Table S2. Sensors used to collect pollutant data for the low-cost sensor pods (AQMesh). Data averaged in 15 minute intervals.

AQMesh Sensors					
Sensor	**Sensor Type**	**Units**	**Limit of Confidence (LOC)**	**Accuracy**	**Range**
NO_2	Electrochemical	ppb	< 10 ppb >	< 10 ppb >	0-4000 ppb
O_3	Electrochemical	ppb	< 10 ppb >	< 10 ppb >	0-1800 ppb
Particulate Matter ($PM_{2.5}$)	Optical Particle Counter	μg/m^3	< 20 μg/m^3>	< 20 μg/m^3>	0-500 μg/m^3
Reference Station (MECP) Research-Grade Sensors					
NO_2	Chemiluminescent Gas Analyzer	ppb	< 1 ppb >	< 0.2 ppb >	<0,5 -100 ppb
O_3	UV Photometric Ozone Analyzer	ppb	< 0.4 ppb >	< 0.25 ppb >	<0.5 - 200000 ppb
Particulate Matter ($PM_{2.5}$)	Light Scattering Photometry	μg/m^3	< 2 μg/m^3>	< 2 μg/m^3>	<0.5 -10 000 μg/m^3

atmosphere

MDPI

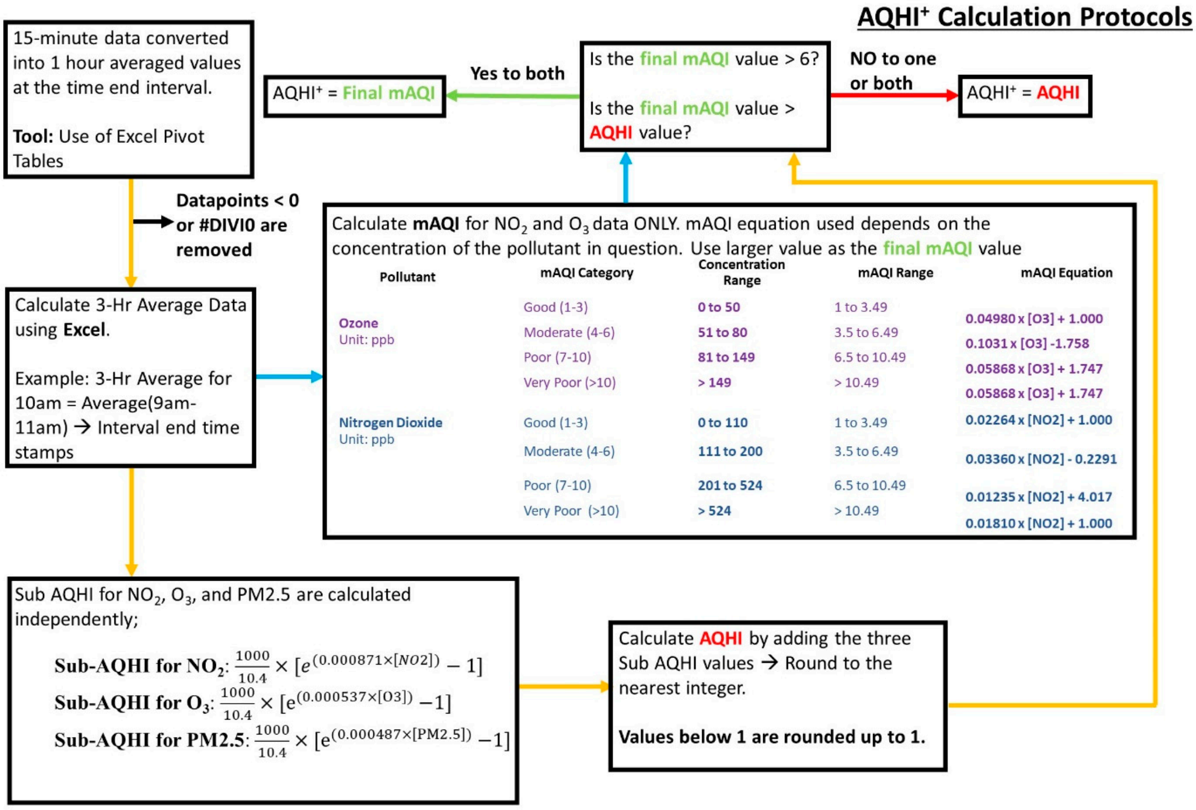


Figure S1. Flowchart detailing the QA/QC and AQHI+ calculation protocols followed after applying the long-distance scaling calibration to each dataset. In essence, if the NO_2 or O_3 levels are abnormally high, the mAQI for each is calculated using the equations provided in the figure. The larger of the two values is then compared to the AQHI. Two criteria must be satisfied before replacing the AQHI value with the mAQI value; the mAQI must be both larger than 6 and larger than the AQHI value.

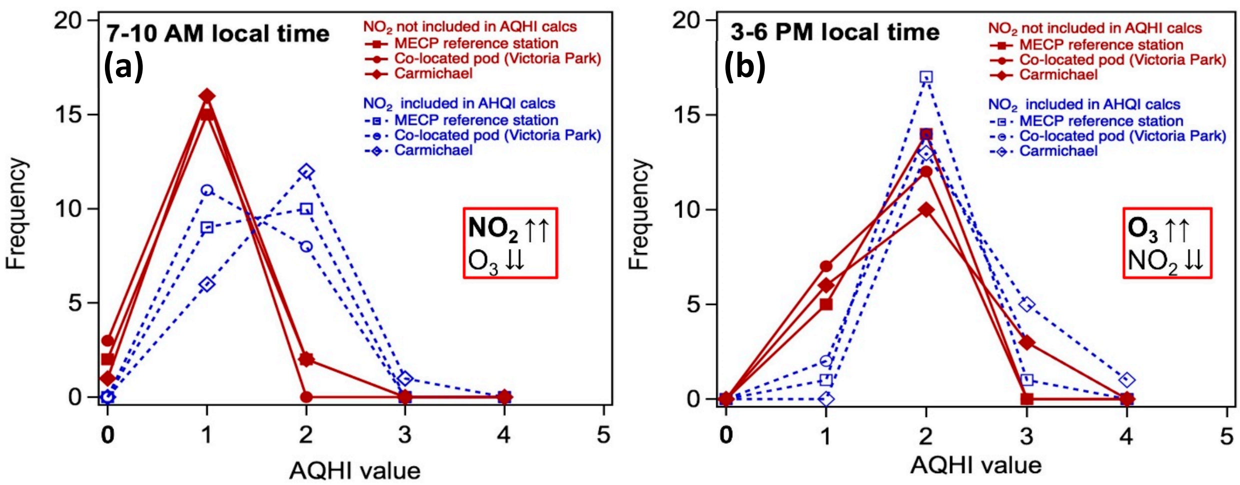


Figure S2. Histograms generated for October 2020 (wet days excluded) for weekdays only. Data in red represents the exclusion of NO_2 from the AQHI calculation, while data in blue represents the calculated AQHI using all three pollutants. **(a)** dropoff times show a shift in the peak AQHI frequency from a 2 to a 1, indicating that NO_2 is dominant for this time interval. **(b)** pickup times show no shift in AQHI with the removal of NO_2, indicating that ozone is the dominant species for this time interval.

Table S3. Results for p-value calculations for the two-tailed t-test conducted on the pod network difference whisker plots in Figure 5. Data comparisons were for the co-located pod (Pod 5) against other pods in the network.

Period	Pod 1	Pod 2	Pod 3	Pod 4
Nitrogen Dioxide (NO_2)				
Sept-Nov 2020	0	0	0.15	0
Jan-Mar 2021	0	0	0	0
Jun-Aug 2021	0	0	0	0
Ground-Level Ozone (O_3)				
Sept-Nov 2020	0	0	0	0
Jan-Mar 2021	0.01	0	0.04	0.35
Jun-Aug 2021	0	0	0	0
Fine particulate Matter (PM2.5)				
Sept-Nov 2020	0	0.02	0	0.96
Jan-Mar 2021	0	0.07	0	0.27
Jun-Aug 2021	0	0.24	0	0

* The null hypothesis for this analysis was that the mean of the co-located pod (Pod 5) was equal to the pod in question. p-values smaller than 0.05 indicate a statistically significant difference between these compared pods.

Table S4. Results for p-value calculations for the two-tailed t-test conducted on the pod network difference whisker plots in Figure 5. Data comparisons were for Pod 1 (near the highway) against other pods in the network.

Period	Pod 2	Pod 3	Pod 4
Nitrogen Dioxide (NO_2)			
Sept-Nov 2020	0	0	0
Jan-Mar 2021	0.06	0	0
Jun-Aug 2021	0	0	0
Ground-Level Ozone (O_3)			
Sept-Nov 2020	0	0	0.96
Jan-Mar 2021	0	0.54	0
Jun-Aug 2021	0	0	0.23
Fine particulate Matter (PM2.5)			
Sept-Nov 2020	0	0	0
Jan-Mar 2021	0	0	0
Jun-Aug 2021	0	0	0

* The null hypothesis for this analysis was that the mean of Pod 1 (near the highway) was equal to the pod in question. p-values smaller than 0.05 indicate a statistically significant difference between these compared pods.

atmosphere MDPI

Sample R Statistics coding used to calculate the background concentration of CO for each pod in the sensor pod network.

Sample Code:

```
> COdata <- read.csv(choose.files(), header=TRUE)
> i = 1
> backgroundCO = replicate(length(CO2data$Number), NA)
> firstPiece = COdata[c(1: 96),]
> quantile(firstPiece$Scaled.Pod.1, 0.10, na.rm = TRUE)
10%
406.5183
> for (i in 1: 48) {backgroundCO[i]=406.5183}
> lastPiece = COdata[c(7294: 7390),]
> quantile(lastPiece$Scaled.Pod.1, 0.10, na.rm = TRUE)
10%
422.3292
> for (i in 7342: 7390){backgroundCO [i]=422.3292}
> for (i in 49: 7341) {
        tempData = subset(COdata, Number >= COdata$Number[i]-48 & Number <= COdata$Number[i]+48)
        if(length(tempData$Number) != 0)
                {backgroundCO[i]=quantile(tempData$Scaled.King.Edward,0.10, na.rm=TRUE) }
        if (length(tempData$Number) == 0)
                { backgroundCO[i]=NA }
        remove(tempData)}
> write.table(backgroundCO2, file="BackgroundCO_Pod1_SeptNov2020.csv", sep =",")
```