Department of Planning, Industry and Environment

Indicative Air Quality Instrument Evaluation

Assessing indicative air quality sensors across metropolitan and regional NSW, and their potential to support air quality compliance monitoring

environment.nsw.gov.au

© 2021 State of NSW and Department of Planning, Industry and Environment

With the exception of photographs, the State of NSW and Department of Planning, Industry and Environment are pleased to allow this material to be reproduced in whole or in part for educational and non-commercial use, provided the meaning is unchanged and its source, publisher and authorship are acknowledged. Specific permission is required for the reproduction of photographs.

The Department of Planning, Industry and Environment (DPIE) has compiled this report in good faith, exercising all due care and attention. No representation is made about the accuracy, completeness or suitability of the information in this publication for any particular purpose. DPIE shall not be liable for any damage which may occur to any person or organisation taking action or not on the basis of this publication. Readers should seek appropriate advice when applying the information to their specific needs.

All content in this publication is owned by DPIE and is protected by Crown Copyright, unless credited otherwise. It is licensed under the Creative Commons Attribution 4.0 International (CC BY 4.0), subject to the exemptions contained in the licence. The legal code for the licence is available at Creative Commons.

DPIE asserts the right to be attributed as author of the original material in the following manner: © State of New South Wales and Department of Planning, Industry and Environment 2021.

Cover photo: Jordan Capnerhurst/DPIE

Published by:

Environment, Energy and Science
Department of Planning, Industry and Environment
Locked Bag 5022, Parramatta NSW 2124
Phone: +61 2 9995 5000 (switchboard)
Phone: 1300 361 967 (Environment, Energy and Science enquiries)
TTY users: phone 133 677, then ask for 1300 361 967
Speak and listen users: phone 1300 555 727, then ask for 1300 361 967
Email: info@environment.nsw.gov.au
Website: www.environment.nsw.gov.au

Report pollution and environmental incidents
Environment Line: 131 555 (NSW only) or info@environment.nsw.gov.au
See also www.environment.nsw.gov.au

ISBN 978-1-922738-31-8
EES 2021/0537
November 2021

Find out more about your environment at:

www.environment.nsw.gov.au

Contents

List of tables

List of figures

Acronyms and abbreviations

API T300	Teledyne API T300
AQMN	air quality monitoring network
AQMU	Air Quality Monitoring Unit
API	application programming interface
ARC	Australian Research Council
BAM	beta attenuation monitor
CAS	Climate and Atmospheric Science Branch
CO	carbon monoxide
DIY	do it yourself
EM	equivalence method
FEM	federal equivalence method
KOALA	knowing our ambient local air quality
LD	Luftdaten
NAAQS	National Ambient Air Quality Standards (United States)
PA2	PurpleAir 2
PM	particulate matter
PM1	particles with a mass median aerodynamic diameter of 1 μm
PM2.5	particles with a mass median aerodynamic diameter of 2.5 μm
PM10	particles with a mass median aerodynamic diameter of 10 μm
PPM	parts per million
QUT	Queensland University of Technology
SD	secure digital
TEOM	tapered element oscillating microbalance
US EPA	United States Environmental Protection Agency
USB	universal serial bus

1. Background

In summary:

- An indicative air quality monitor does not meet strict Australian Standards.
- In 2019, indicative sensors were co-located within sites in the NSW air quality monitoring network (AQMN).
- Indicative sensors are marketed as being good value for money.
- This report provides summary statistics of indicative sensor performance to determine whether these sensors are good value for money.

There are four main groupings of air monitoring instruments according to Australian Standards:

- **$PM_{2.5}$ low-volume sampler gravimetric methods (AS 3580.9.10:2017):** a method to determine the suspended particle matter with aerodynamic diameter less than 2.5µm using a weighed filter paper in a low-volume sampler run over a known period of time (generally 24 hours).
- **Equivalence monitors (AS/NZS 3580.9.17:2018):** particle monitors based on different sampling or analysing technologies than gravimetric methods but required to provide the same decision-making quality when making United States National Ambient Air Quality Standards (NAAQS) attainment determinations. Monitors must conform with the requirements of European Standard EN 15267 or have obtained United States Environmental Protection Agency (US EPA) equivalence status.
- **Direct-reading instrumental methods (AS 3580.7.1-2011):** a continuous direct-reading instrument in which the response of the detector is recorded as a concentration.
- **Indicative monitors**: a monitor that does not meet strict Australian Standards.

Throughout 2019, the Department of Planning, Industry and Environment Climate and Atmospheric Science (CAS) Branch trialled indicative particle and gaseous instruments to determine their potential to complement the NSW AQMN.

The purpose of this report is to provide summary statistics of indicative sensor performance to determine whether these sensors provide good value for money. From this we can determine if further analysis is worthwhile or if these sensors are not appropriate for further deployment as a complement to the NSW AQMN.

The indicative sensors assessed in this report have also been used as an educational tool and for raising community awareness in projects such as the Blue Mountains and Lithgow Air Watch monitoring project.

Indicative sensors are marketed with benefits including, but not limited to, being:

- good value for money
- easy to deploy and maintain
- able to provide accurate real-time measurements on an accessible cloud-based system.

This contrasts with reference and equivalence methods with low upfront costs, such as high- and low-volume samplers (Figure 1). These do not deliver real-time data and are labour-intensive due to daily filter-paper handling.

Because they are small, indicative sensors can be deployed in a much wider range of environments compared with reference and equivalence methods. They do not require mains power, as they do not require external cooling or environmental shielding (such as the tapered element oscillating balance [TEOM] in Figure 1).

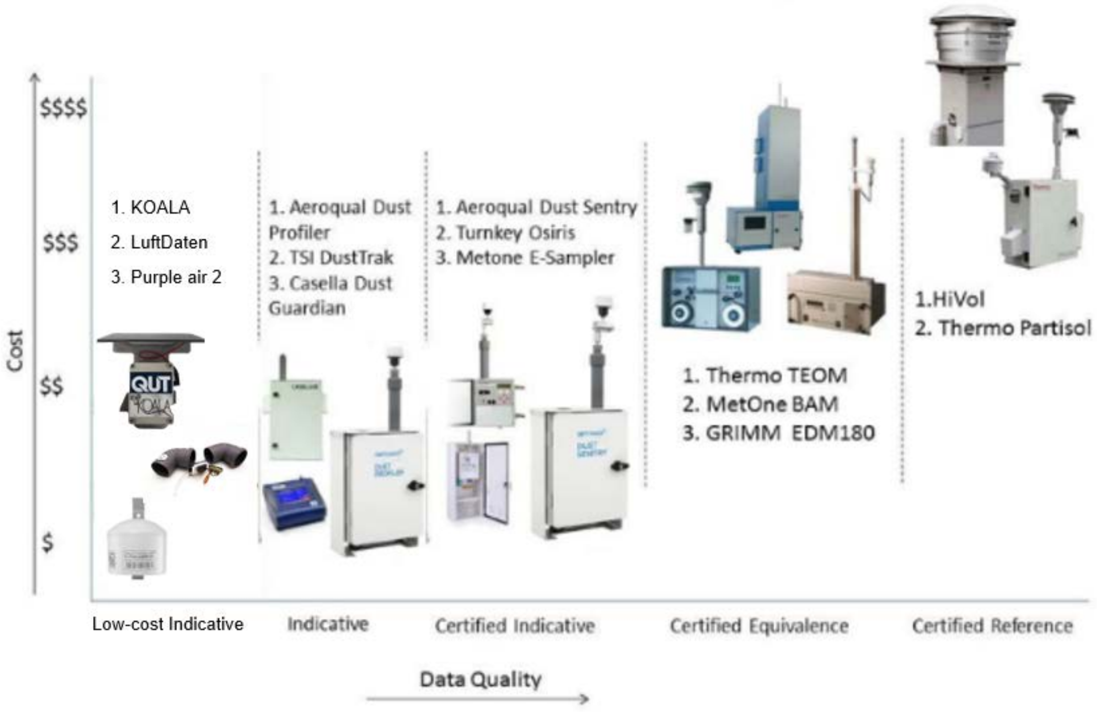


Figure 1 **Comparison of cost for low-cost indicative, indicative, certified indicative, certified equivalence and certified reference instruments**

Source: www.aeroqual.com

Due to these features, indicative sensors allow for increases in both temporal and spatial coverage of networks (Morawska et al. 2018).

Indicative sensor technology has been tested both in Australia and internationally, showing that it can be used in several different situations including indoor, outdoor and personal monitoring (Morawska et al. 2018). The data quality generated by these platforms has been found to be variable depending on temporal and spatial factors, such as season and particle composition (Castell et al. 2016). Sensor measurements have also been found to change over time as the instruments age and become contaminated (Clements et al. 2017). However, further investigation is required to understand how to integrate indicative instruments into compliance networks to use them to their fullest potential.

Several sensors assessed in this study were co-located in the NSW AQMN across a range of different environments (Table 1). These differing environments exposed the sensors to a range of pollution types and meteorology, allowing the sensor performance to be determined under varying conditions while co-located with instruments from our compliance network.

2. Project scope

The scope of this project is to determine the suitability of indicative air quality instruments as an alternative monitoring solution in instances where compliance monitors and associated station hardware are not possible (e.g. crowded city centres) or are impractical (e.g. emergency monitoring and remote locations).

Monitored parameters

The following parameters were monitored:

- particles with a mass median aerodynamic diameter of 2.5 μm (PM2.5)
- particles with a mass median aerodynamic diameter of 10 μm (PM10)
- carbon monoxide (CO)
- visibility
- temperature
- humidity.

However, not all parameters were measured at each location (Table 1). Data comparisons were based on hourly average data. Data obtained from the department's monitoring network is treated according to in-house quality assurance procedures to ensure that air quality and meteorological parameters measured by the network are reliable and fit for purpose. Data validation is carried out both automatically by rules implemented within the logging software and manually by an operator. Data undergoes quality assurance both in-the-field and post-data-collection with data being invalidated for reasons such as instrument issues, calibration issues, negativity or missing data. (Quality assurance for the air quality monitoring network).

3. Measurement principles employed by sensors

The particle sensors trialled during this project were all light-scattering particle counters. These sensors count particles based on the scattering of a visible red beam of light which is detected on a photodetector (Morawska et al. 2018). The particle count is then converted to an estimate of mass based on several assumptions, including particle shape, density, colour and size (Wang et al. 2020). Particle mass is reported in numerous particle size bins (e.g. PM2.5, PM10) as a digital signal. The conversion between particle count and concentration is based on proprietary algorithms built into the individual particle sensors.

The CO sensor trialled was an electrochemical cell (Morawska et al. 2018). Electrochemical gas sensors operate by measuring changes in the properties of a sensing material (e.g. mass, electrical conductivity) when exposed to a specific gas species, producing a measurable output signal.

4. Instruments tested

In summary:

Three low-cost indicative sensors were tested:

- PurpleAir 2, measuring PM2.5 and PM10
- KOALA, measuring PM2.5, PM10, and CO
- Luftdaten, measuring PM2.5 and PM10.

PurpleAir 2

The PurpleAir 2 (PA2) is an indicative instrument created by a grass-roots organisation in the United States of America, primarily to fill gaps across compliance monitoring networks (Tryner et al. 2020).

PA2 instruments employ two modern, light-scattering Plantower PMS5003 particle counters, which report inferred PM1, PM2.5 and PM10 concentrations (Tryner et al. 2020).The two-sensor configuration triggers an alarm if one of the sensors deviates from the other. PA2 instruments also record temperature, humidity and pressure, using a BME280 sensor. Measurements are recorded to an SD card and uploaded continuously to the cloud over wi-fi. PA2 instruments are powered via a micro-USB port, requiring a small external power source.

KOALA

KOALAs (knowing our ambient local air quality) are the product of an Australian Research Council (ARC) linkage project partnership (LP160100051) between many Australian universities and government agencies. To date, around 100 KOALAs have been produced by a small team at the Queensland University of Technology (QUT) with plans for the units to be mass-produced beginning in 2022.

The KOALA units are stand-alone, powered by a solar panel and built-in battery unit. Each unit has a SIM card and all data are transmitted from the instrument to a central database using the 3G/4G network. KOALAs employ an older Plantower PMS1003 sensor running for five seconds every five minutes, also reporting inferred PM1, PM2.5 and PM10 concentrations (Morawska et al. 2018). KOALAs also measure CO (using an electrochemical Alphasense CO-B4 sensor), and temperature and humidity inside the unit.

Luftdaten

Luftdaten (LD) instruments were developed by a German citizen science group to promote open air quality data and foster transparency.

They can be fitted with a variety of particle sensors, including Plantower PMS 1003–7003 sensors and the NOVA SDS011. They can also be fitted with a variety of ambient weather sensors, including temperature, barometric pressure and humidity. The sample length and measurement frequency of these sensors can be adjusted. Sensors deployed as part of this study were fitted with either a NOVA SDS011, PMS1003, PMS3003 or PMS5003.

The LD sensors transfer data to a website in real time via an external wi-fi modem, and it can also be sent to a database using an application programming interface (API). The units are powered using a micro-USB cord.

Instrument measurement frequencies

Each indicative sensor has its own sampling interval and sampling time. The sampling interval describes how frequently each measurement is recorded. The sampling time describes the length of time over which the measurement is averaged.

Instrument	Sampling interval (seconds)	Sampling time (seconds)
PurpleAir 2	80	80
KOALA	300 (user adjustable)	5
Luftdaten	60 (user adjustable)	60 (user adjustable)

5. Monitoring locations

We deployed low-cost indicative sensors at six of the department's Air Quality Monitoring Unit (AQMU) sites throughout New South Wales (Table 1). At each site the sensors were co-located with at least one particle equivalence method (EM) and a direct reading method for CO measurements. Department air quality stations are sited to satisfy the Australian Standard AS/NZS 3580.1.1:2016 for sampling of ambient air quality i.e. 120° clear sky angle, etc. The sites included in this study are a mix of metropolitan and regional centres. Armidale Regional Council had already installed two PA2 units at the Armidale site. We deployed an additional PA2 unit for this study.

Table 1 **Sensor deployment details**

Compliance stations	Site type	Long-term monitoring instruments	Indicative sensors	Expected primary pollutant sources	Sensor deployment period
Armidale	Regional	1405DF TEOM, Aurora 1000 nephelometer	3 x PurpleAir 2	Wood smoke	30/05/19 – 1/1/20
Chullora	Metropolitan	5014i BAM, 1405A TEOM, Aurora 1000 nephelometer	PurpleAir 2	Bushfires, light industry, motor vehicles	11/07/19 – 1/12/19
Sydney CBD	Metropolitan	Aurora 1000 nephelometer	LD_N (NOVA SDS011)	Bushfires, motor vehicles	12/9/19 – 31/12/19
Katoomba	Regional	1405DF TEOM, Aurora 1000 nephelometer, Teledyne API T300	PurpleAir 2 2 x KOALAs CO LD_5 (PMS5003)	Bushfires, wood smoke	18/06/19 – 1/1/20
Orange	Regional	1405DF TEOM, Aurora 1000 nephelometer	PurpleAir 2	Dust, wood smoke	1/06/19 – 1/1/20
Port Macquarie	Regional / Coastal	1405DF TEOM, Aurora 1000 nephelometer, Teledyne API T300	2 x KOALAs CO LD_N (NOVA SDS011) LD_1 (PMS1003) LD_3 (PMS3003) LD_5 (PMS5003)	Bushfires	1/08/19 – 1/1/20* *LDs deployed 19/11/19 – 1/1/20
Wagga Wagga	Regional	5014i BAM, 1405A TEOM, DustTrak 8533 DRX	PurpleAir 2	Dust, wood smoke	10/06/19 – 1/1/20

BAM: beta attenuation monitor
TEOM: tapered element oscillating microbalance

6. Events during the study period

During the sensor deployment there were many exceedances of PM2.5 and PM10 throughout the NSW AQMN, due to large regional-scale events including continuing intense drought conditions and unprecedented bushfire activity. This bushfire activity resulted in widespread smoke impacts on many regions through spring and early summer (Figure 2).

Dust storms (Figure 2 and DustWatch Reports) resulting from long-term drought conditions affected most of the state (Seasonal Conditions and Drought).

Local impacts, such as wood smoke pollution, also affected regional centres throughout the state, with concentrations particularly high in Armidale (Robinson, Monro & Campbell 2007).

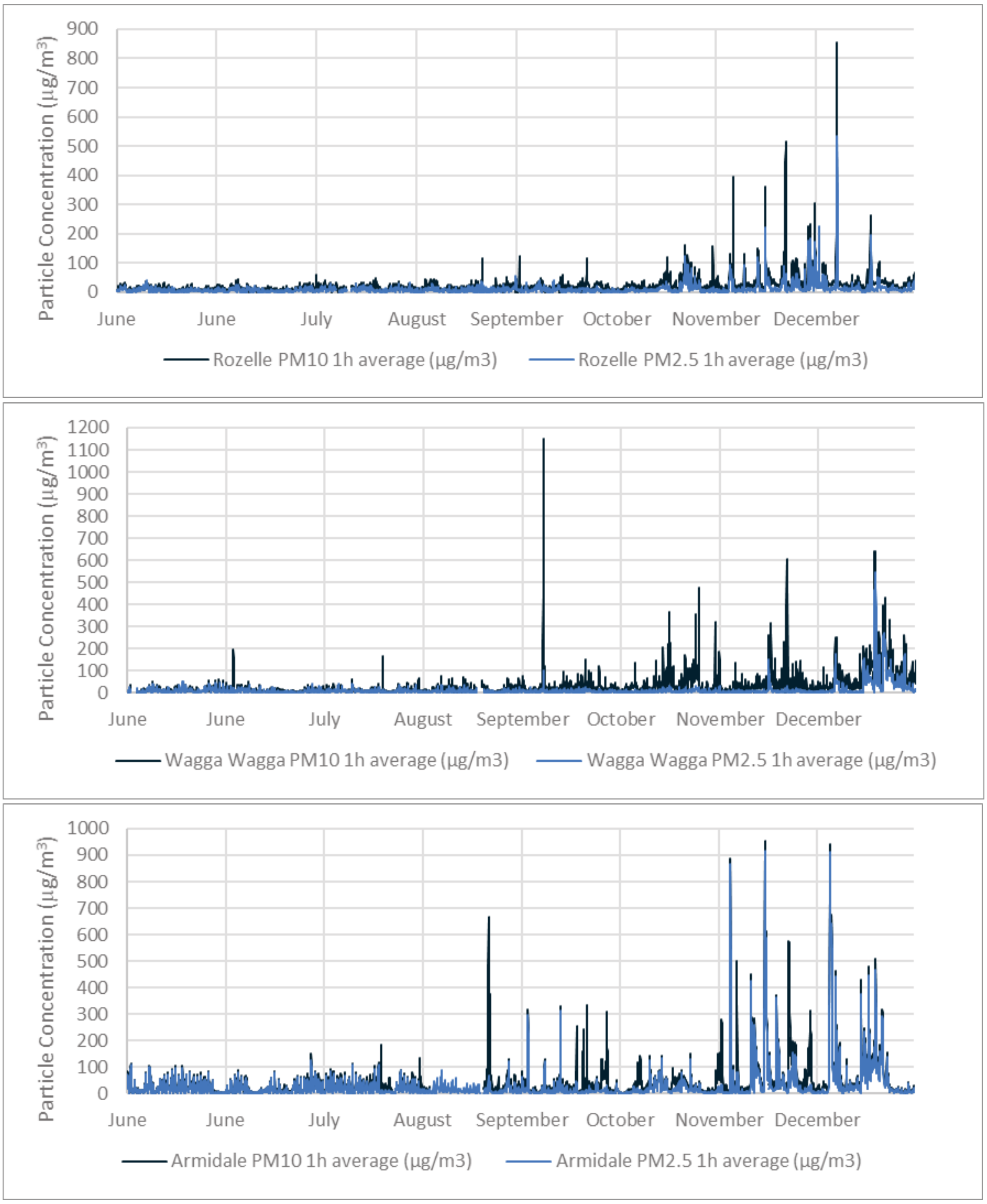


Figure 2 **Time series of PM2.5 and PM10 concentrations at Rozelle, Wagga Wagga and Armidale measured using federal equivalence method (FEM) instruments during 2019**

7. Installation

Before modification and installation, rudimentary acceptance testing of the instruments included:

- performing a zero check on the sensors by placing them in a container which was purged with filtered, clean (zero) air
- a response check by spraying the sensors with ‘PSA Lifesaver Smoke Detector Tester’ spray
- co-locating the sensors for two weeks indoors to ensure they trend together and do not output erratic data.

After acceptance testing, numerous modifications were applied to the sensors including:

- fixing course flyscreen mesh to the inlet and exhaust of all the sensors to prevent small insects interfering with measurements
- fixing aluminium covers to the PA2 units as per manufacturer’s instructions to prevent weather damage (Figure 3b).

Most sensors were installed in the NSW AQMN on arms one to two metres long (Figure 3a) to attempt to satisfy the siting criteria outlined in AS/NZ 3580.1.1:2016.

These criteria are:

- unrestricted airflow of 270° around the sample inlet
- 1 metre minimum distance to supporting structure
- 2–5 metre height of sampling inlet above ground
- 2–4 metres between co-located high-volume sensors.

Note: the sensors co-located at Port Macquarie did not satisfy these criteria as they were mounted to the side of a smaller rapid response pod.

Basic maintenance was undertaken on the sensors at scheduled site visits including removing cobwebs from the sensor and cleaning solar panels.

At the conclusion of the study in December 2019 the majority of the sensors were removed and co-located indoors again to ensure they still trended and did not return erratic data.

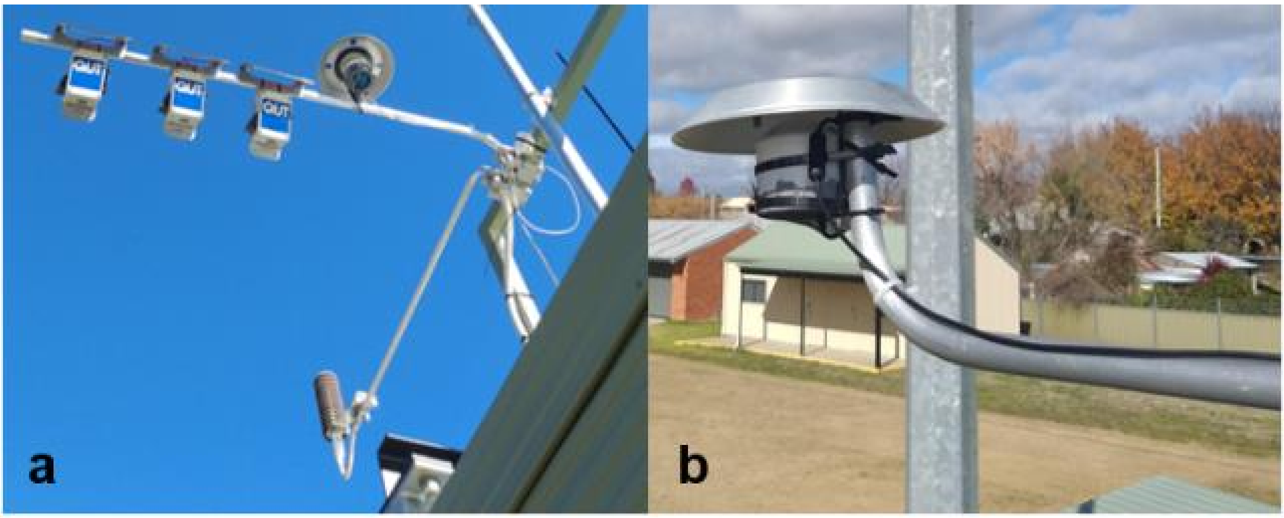


Figure 3 **Installed indicative sensors**

8. PurpleAir 2

In summary:

- PA2 sensors were easy and quick to deploy.
- They require mains or external solar power.
- They also require a wi-fi modem or wi-fi hotspot.
- The only data loss was due to power outages of the air quality monitoring station.
- The cloud-based online platform is easy to use but can crash.
- Data is easy to analyse once extracted from the web portal.
- PM2.5 trends very well with AQMU instruments.
- PM10 is occasionally inconstant with AQMU instruments.

Ease of deployment

The PA2 sensors were very easy to deploy and took less than half an hour to be fully operational and logging data once at the site. The only difficulty encountered was running the USB power cable from an outdoor AC power plug in a tidy manner. An indoor USB port was also required for the wi-fi modem. With additional hardware, these could also be configured with solar power and wi-fi modem for remote installations.

Reliability, maintenance and repairs

Generally, over the study period the PA2 sensors were very reliable and the only data loss that occurred was due to site power outages – a disadvantage of relying on mains power. The PA2 sensor co-located at Chullora required a new Plantower particle sensor replacement as the particle readings were erratic and not comparable with the second particle channel, a huge advantage of a two-sensor configuration (Figure 4). This could be because this unit had been used extensively for testing and demonstration purposes. Besides the unit at Chullora, none of the other units required maintenance of any kind during the study period. The PA2 sensor units contain internal electronics that are held together by tape, protected by an external case. This tape needed to be cut in order to repair or replace components of the sensor, making repairs difficult.

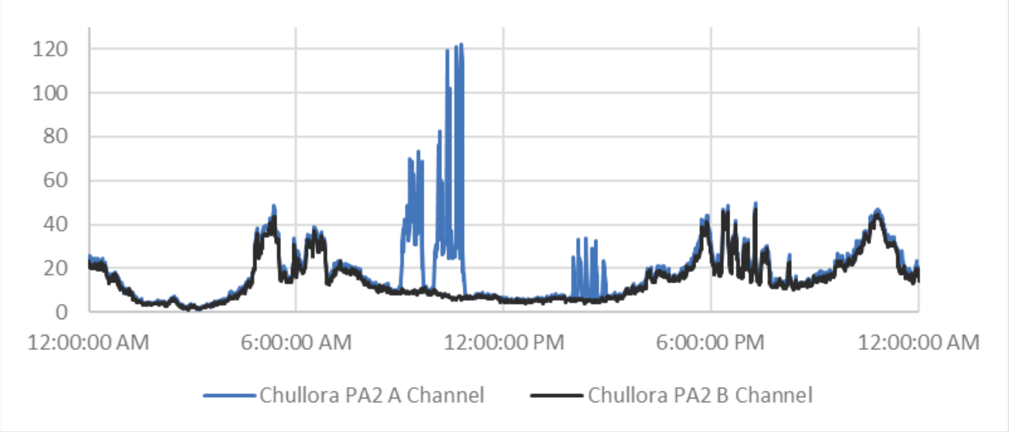


Figure 4 Minute PM2.5 data from the two channels within a PA2 unit showing erratic readings

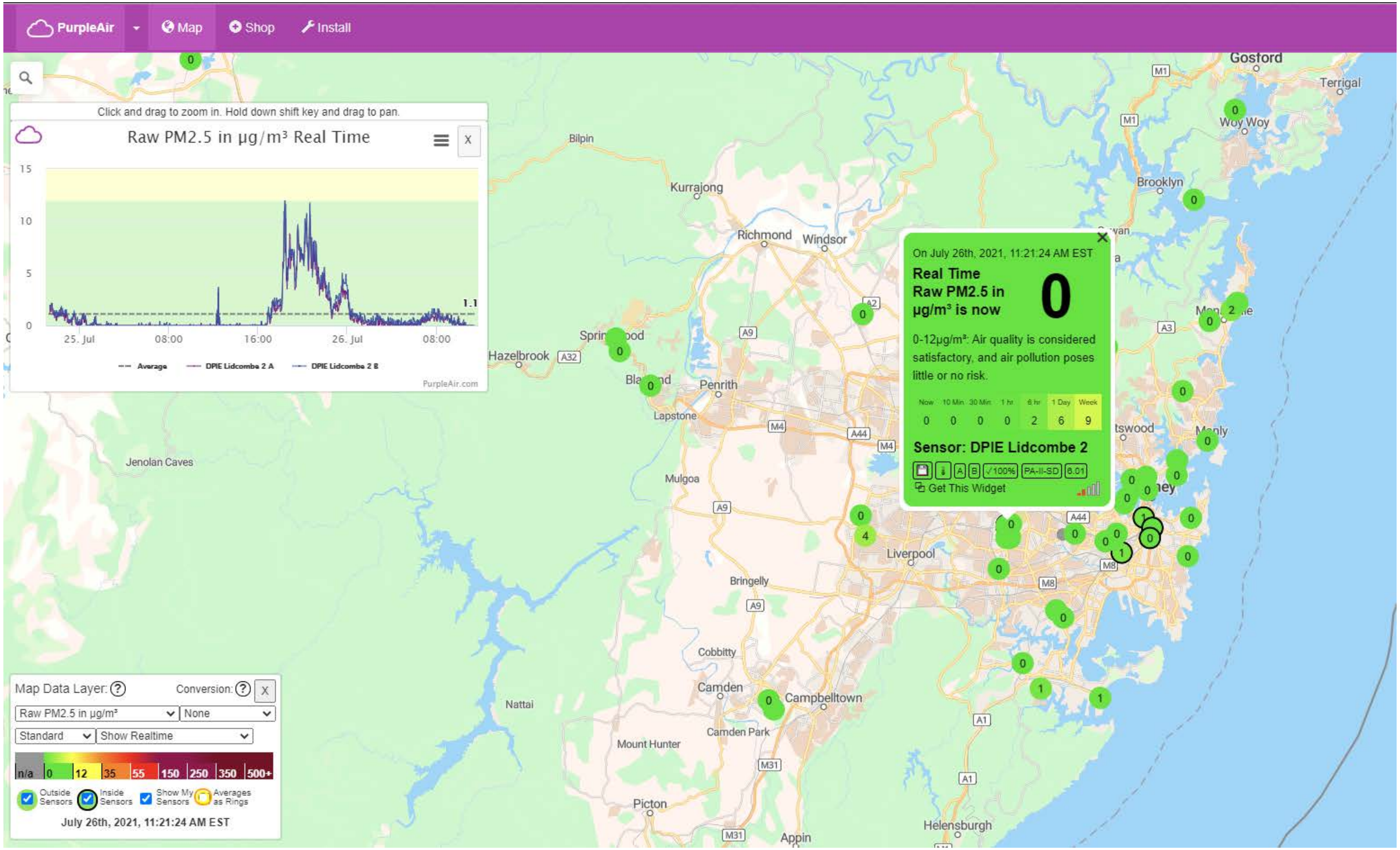
Data retrieval and online interface

The free cloud-based data portal for the PA2 sensors was simple, and easy to understand and use (Figure 5). However, there were a few instances where the interface crashed consistently, and the browser cache needed to be cleared. This was a constant issue in Internet Explorer 11, Google Chrome and Mozilla Firefox. These crashes did not cause any problems with data collection but made the interface frustrating to use. According to online documentation, data from the sensors can be loaded into an enterprise database using an API but this was not tested as part of this study.

It was relatively simple to confirm that all sensors were online and reporting measurements at any point in time. This could be checked by using a query in ‘the R software suite’ to report the time period since the sensor last sent data, which was tested in R V3.5.0.

The data download interface for the PA2 sensors was intuitive and easy to use. The sensors are set up to report 80-second averages, recorded every 80 seconds, in an easy-to-use and easy-to-process format. These recording periods are not user adjustable. From this interface it was possible to download the data for the entire study period. This eliminated the need for stitching different datasets together into one central dataset. When power outages caused gaps in the recorded measurements, the sensors did not record blank measurements at those timesteps, but simply did not record those timesteps in the sensor cloud storage. This caused some difficulty when comparing the PA2 sensor data with other co-located instruments, as it was necessary to manipulate the data from the PA2 sensors to line up the timesteps from each instrument.

PA2 sensors can have their data posted publicly on the PurpleAir website, or be set as private during initial set-up, which prevents other users from viewing sensor data unless they log in as the user who set up the sensor.



On July 26th, 2021, 11:21:24 AM EST

Real Time Raw PM2.5 in µg/m³ is now 0

0-12µg/m³: Air quality is considered satisfactory, and air pollution poses little or no risk.

Now	10 Min	30 Min	1 hr	6 hr	1 Day	Week
0	0	0	0	2	6	9

Sensor: DPIE Lidcombe 2

A B ✓100% PA-II-SD 6.01

Get This Widget

Map Data Layer: Raw PM2.5 in µg/m³
Conversion: None
Standard
Show Realtime

n/a 0 12 35 55 150 250 350 500+

☑ Outside Sensors ☑ Inside Sensors ☑ Show My Sensors ☐ Averages as Rings

July 26th, 2021, 11:21:24 AM EST

Figure 5 **PurpleAir web interface showing raw 1-minute average PM2.5 concentrations at the Lidcombe AQM site**

Particle comparison

PA2 sensors at all locations performed very well compared to Aurora 1000 nephelometers, with Pearson product moment correlation coefficients of 0.83–0.94. This high correlation is likely because both PA2 sensors and nephelometers use light scattering as their principle of measurement.

When measuring PM2.5, the sensors showed a high level of correlation with 1405DF TEOMs when measuring PM2.5, showing correlation coefficients of 0.80–0.90. The sensors showed a lower level of correlation with 5014i BAMs measuring PM2.5, with correlation coefficients of 0.64–0.94. The PA2 co-located with an 8533 DRX DustTrak showed an extremely high level of correlation, with a correlation coefficient of 0.99; this is likely due to the fact the instruments use light scattering as their principle of measurement. The sensors were able to successfully record events of high PM2.5 measurements as can be seen in Figure 6.

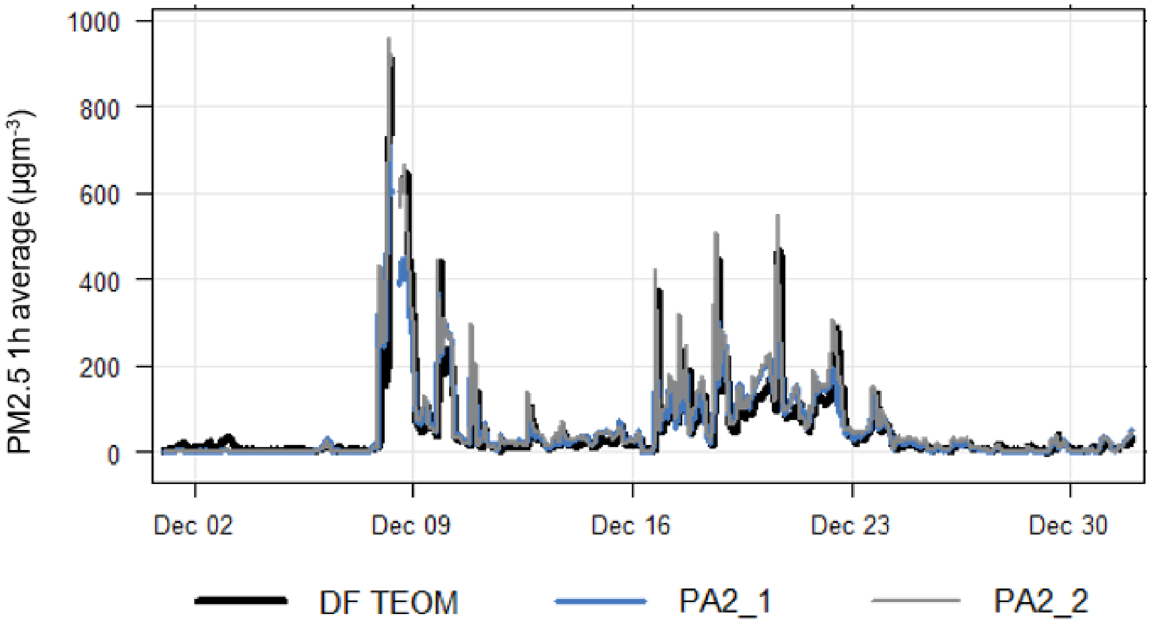


Figure 6 **PA2 sensor measurements of PM2.5 from three units at Armidale compared to a TEOM for December 2019**

When measuring PM10, the PA2 units were inconsistent in their correlation with 1405 and 1405DF TEOMs and the 8533 DRX DustTrak, with correlation coefficients of 0.53–0.62, 0.67–0.83 and 0.91 respectively. On numerous occasions the PA2 units failed to record extreme concentrations that were captured by the TEOM (Figure 7). This could be because the inlet fan in the PA2 units is not powerful enough to draw larger particles into the measurement cell. Another possible cause for this discrepancy is the wavelength of the PA2 sensor light source does not allow it to consistently detect these larger particle sizes. Further research is planned to determine the cause of this issue; however, it is outside the scope of this study.

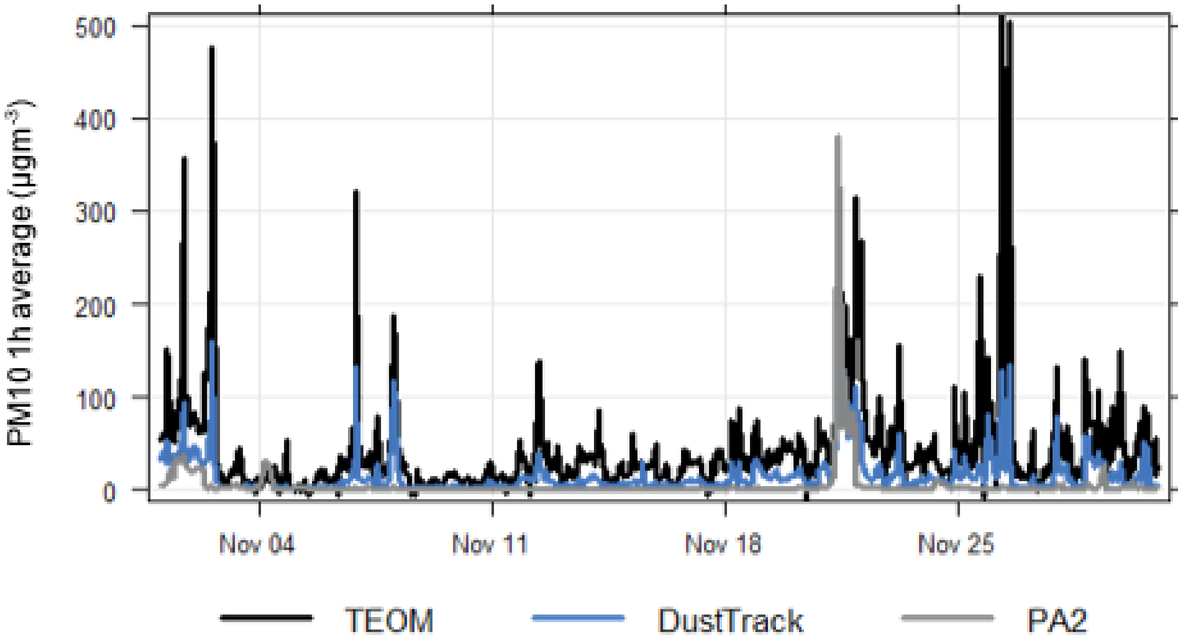


Figure 7 **PA2 sensor measurements of PM10 at Wagga Wagga compared to a TEOM and a DustTrak for November 2019**

9. KOALA

In summary:

- KOALA sensors were easy and quick to deploy.
- They can be deployed anywhere because of their battery and onboard telemetry.
- There was minor data loss with some units.
- They have an easy-to-use cloud-based online platform.
- Data is easy to analyse once extracted from the web portal.
- PM2.5 trends very well with AQMU instruments.
- PM10 is occasionally inconstant with AQMU instruments.
- CO trends very well with AQMU instruments.

Ease of deployment

Deployment of the KOALA sensors was easy and completed in fewer than 30 minutes. These compact, solar-powered units will take readings of airborne particles and CO concentrations and send this data via the mobile phone network to a cloud-based data management centre for collection and analysis. Once the units are in position, the telemetry can be checked by forcing them to send data using a specific command through a USB serial interface.

Reliability, maintenance and repairs

The KOALA sensors were generally reliable during the study period with very few hours of data being missed. However, there were occasions where the sensors missed data collection for unknown reasons. One sensor required restarting as it was not communicating, but it recorded data locally on the onboard SD card, and once the sensor was restarted it sent the data to the central database. No data loss occurred. None of the onboard particle or CO sensors required replacing.

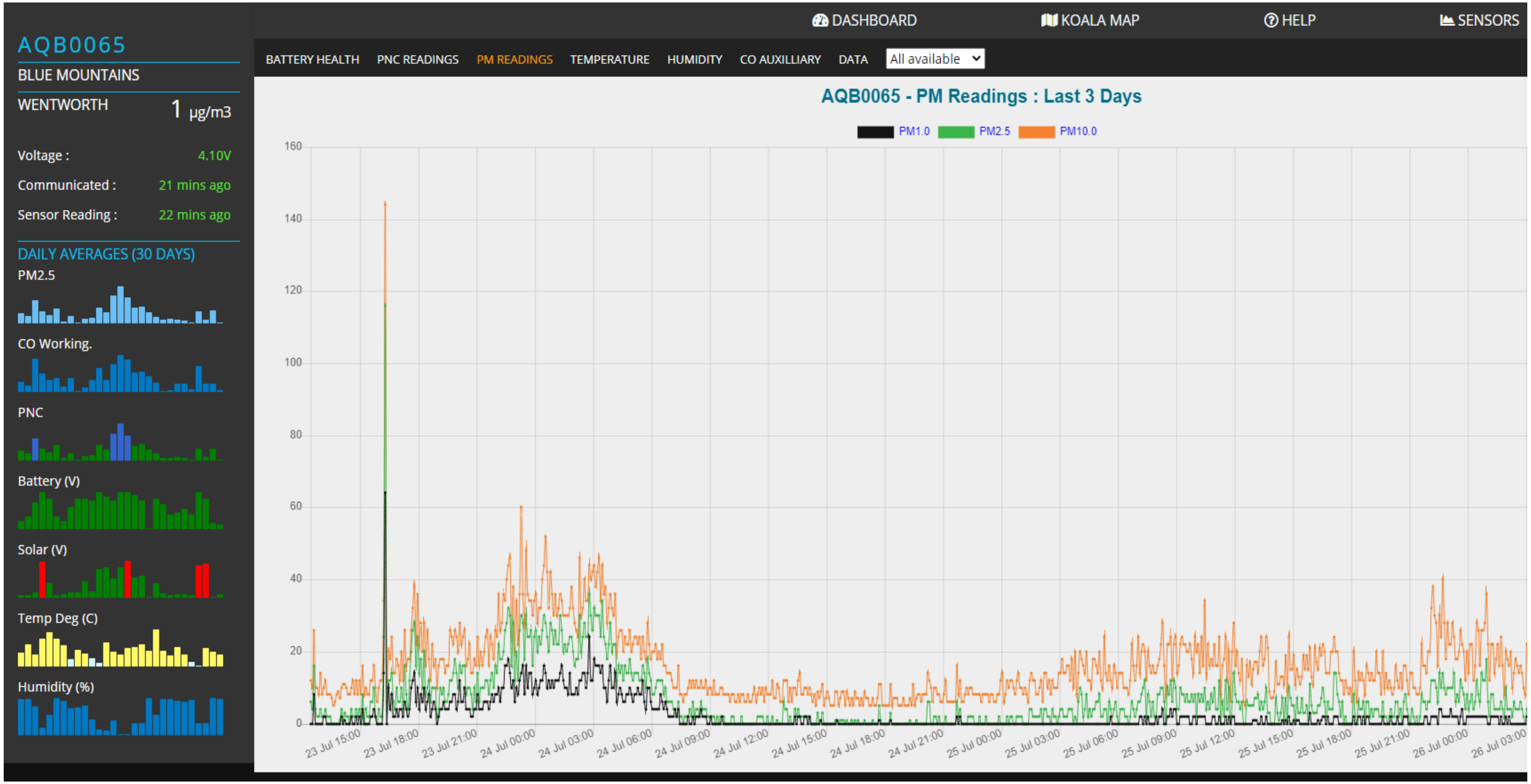
No KOALA units required repairs during the study period but before they were deployed one unit was taken apart and reassembled to check the ease of repairs. The unit has a modular design and was easy to disassemble and reassemble consistently. The only issue with repairing the unit is that the particle sensor, which is the most likely to fail due to insect ingress, is located under all the other components so could not be swapped quickly.

Data retrieval and online interface

The Amazon cloud-based data portal for the KOALA units was simple and easy to understand and use. The main difficulty encountered while using the online interface is the data recorded from the CO sensor is not automatically converted to a concentration, but is left as two raw analogue output voltages. This shortfall means that quick checks on CO sensor performance are not possible, as the data needs to be downloaded and processed to calculate a CO concentration. Also, the interface needs to be run in Google Chrome otherwise the data might not display properly. The KOALA units can also be set up with a public-facing website.

KOALAs record five-second averages every five minutes, and the status of the sensor can be checked using automated scripting for all the logged parameters, such as battery voltage. The data from the sensors is currently available through the online cloud interface and cannot be linked via an API.

The data from the KOALAs can only be downloaded in one-month intervals per sensor and needs to be stitched together manually. As described above, concentrations of CO also need to be calculated manually from two analogue voltages recorded from the KOALA. Once the data is stitched together, the data is easy to align with the data recorded at the reference station. This is simple, as the KOALA units do not omit data when they fail to report to the database for whatever reason and instead a blank cell is inserted.



AQB0065
BLUE MOUNTAINS
WENTWORTH 1 µg/m3

Voltage : 4.10V
Communicated : 21 mins ago
Sensor Reading : 22 mins ago

Figure 8 **Private KOALA user interface showing PM2.5 concentrations for the previous three days in a time series**

KOALA - Gold Coast

Knowing Our Ambient Local Air-Quality

KOALA-07 - Very Good $4\mu g/m^3$

Battery: 4.03 Volts
11 mins ago
Zoom to Sensor

KOALA-09 - Very Good $4\mu g/m^3$
KOALA-10 - Very Good $3\mu g/m^3$
KOALA-11 - Very Good $7\mu g/m^3$
KOALA-12 - Very Good $4\mu g/m^3$
KOALA-13 - Very Good $8\mu g/m^3$
KOALA-15 - Very Good $6\mu g/m^3$
KOALA-26 - Very Good $8\mu g/m^3$
KOALA-28 - Very Good $7\mu g/m^3$

KOALA Air quality monitoring sensors measure the concentration of pollutants at each monitoring station. The Air Quality Index (AQI) is derived from Australian air quality standards as detailed by NEPM Standards.

View Australia's Air Quality map.

Project Partners
Queensland University of Technology
Griffith University
Southport State High School
GC2018
QLD Dept. of Environment and Science

Figure 9 **Public KOALA user interface showing instantaneous PM2.5 readings in a spatial interface**

Carbon monoxide comparison

The CO sensor installed in the KOALA units is an electrochemical cell. Other studies have found the performance of these instruments is strongly dependant on ambient conditions such as temperature and humidity (Morawska et al. 2018). Despite this dependence, it was found the CO sensors performed quite well compared with reference instruments in Katoomba (R^2 ~ 0.93). The unit at Port Macquarie also performed well despite the KOALAs being located approximately 500 metres away from the air quality monitoring station. Units at both sites trended well with the reference instruments: peaks and troughs coincided despite there being an obvious offset. The sensors were able to successfully record events of high CO measurements as can be seen in Figure 10. KOALAs 2,3 and 5 were some of the first units produced by QUT in 2018 and are now approximately two years old. Despite the sensor's age, KOALA 5 trended very well with the newer KOALA 98, demonstrating the cell has not degraded significantly. There was also no discernible change in performance after the sites experienced heavy bushfire smoke in late 2019.

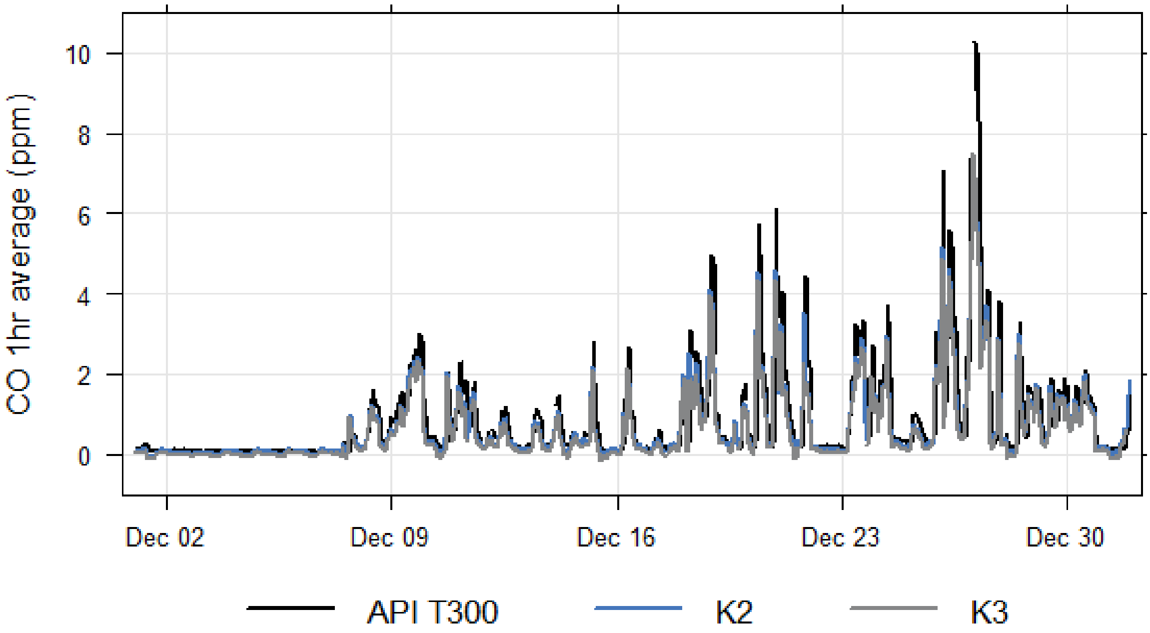


Figure 10 **KOALA sensor measurements of CO at Katoomba compared to an API T300 for December 2019**

Particle comparison

The KOALAs co-located at both regional centres and metro areas performed well compared with TEOM 1405DF for PM2.5 measurements (R^2 0.66–0.88). The sensors also performed very well compared with Aurora 1000 nephelometer readings (R^2 0.77–0.95). The KOALA units also demonstrated good consistency between units (R^2 0.94–0.98). Sensors were typically able to pick up peaks in PM2.5 concentration but didn't always record the magnitude of the peak as measured by the TEOM (Figure 11). The likely reason the KOALA units did not perform quite as well as the other sensors is the shorter measurement period with a greater interval between measurements is not as comparable with the minute data from AQMU sites. The KOALAs also employ an older model Plantower PMS1003 sensor, compared with the PA2 Plantower PMS5003 sensor.

The performance of KOALAs compared with TEOM 1405 and 1405DF for PM10 was found to be inconsistent, for the same reasons as the PA2 sensors. On numerous occasions the KOALA units failed to record extreme concentrations that were captured by the TEOM (see Figure 12).

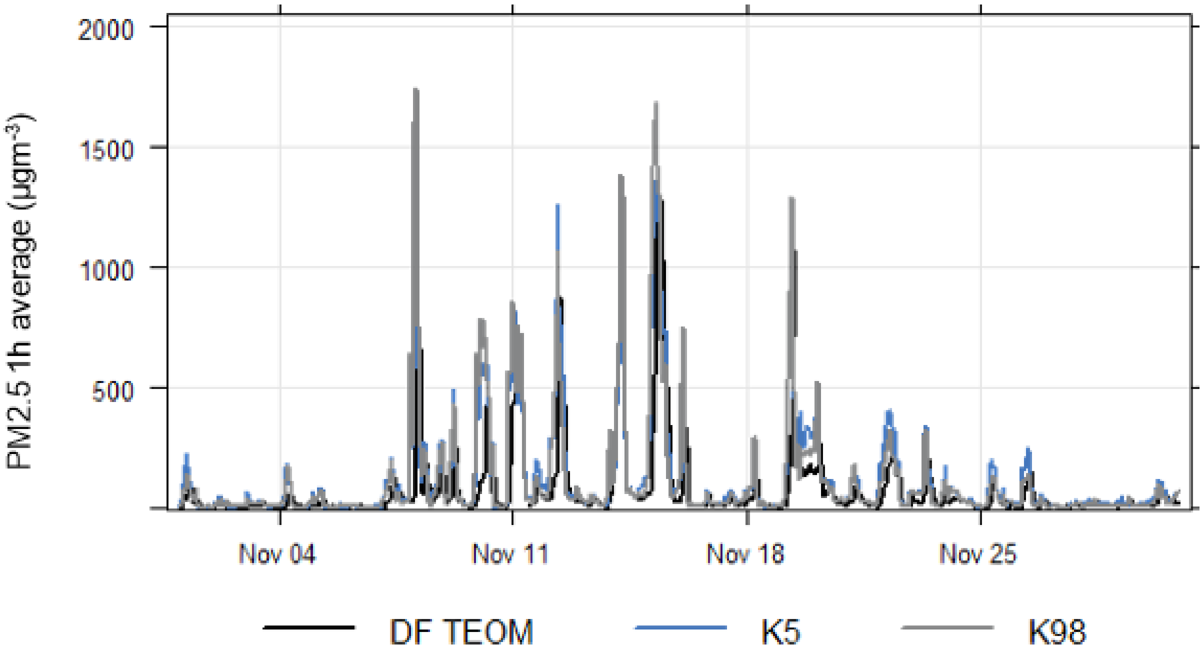


Figure 11 **KOALA sensor measurements of PM2.5 at Port Macquarie compared to a TEOM for November 2019**

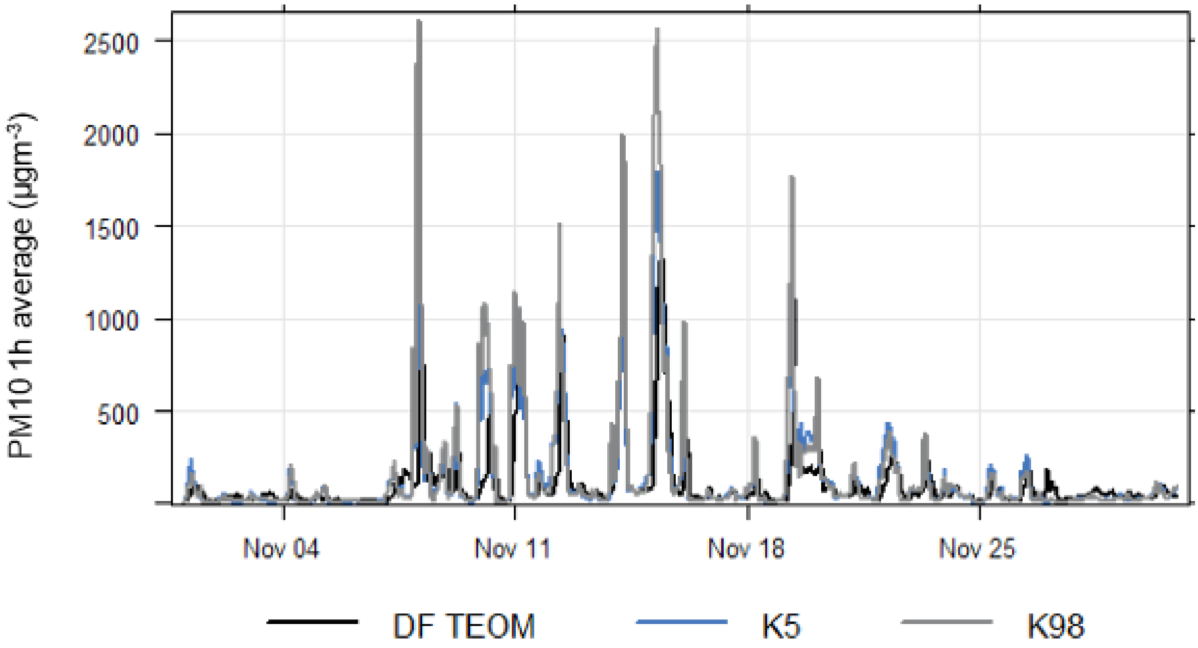


Figure 12 **KOALA sensor measurements of PM10 at Port Macquarie compared to a TEOM for November 2019**

10. Luftdaten

In summary:

- Luftdaten (LD) require mains or external solar power.
- LD sensors require a wi-fi modem or wi-fi hotspot.
- They have do-it-yourself (DIY) assembly and housing.
- Particle sensor and settings can be changed by the user.
- The web interface is clunky.
- PM2.5 trends very well with AQMU instruments.
- PM10 is occasionally inconstant with AQMU instruments.
- The data download is labour-intensive and complicated.

Ease of deployment

The LD sensors were easy to deploy and took less than half an hour to be fully operational and logging data once at the site. The only difficulty encountered was running the USB power cable from an outdoor AC power plug in a tidy manner. An indoor USB port was required for the wi-fi modem. With additional hardware, these could also be configured with solar power and wi-fi modem for remote installations.

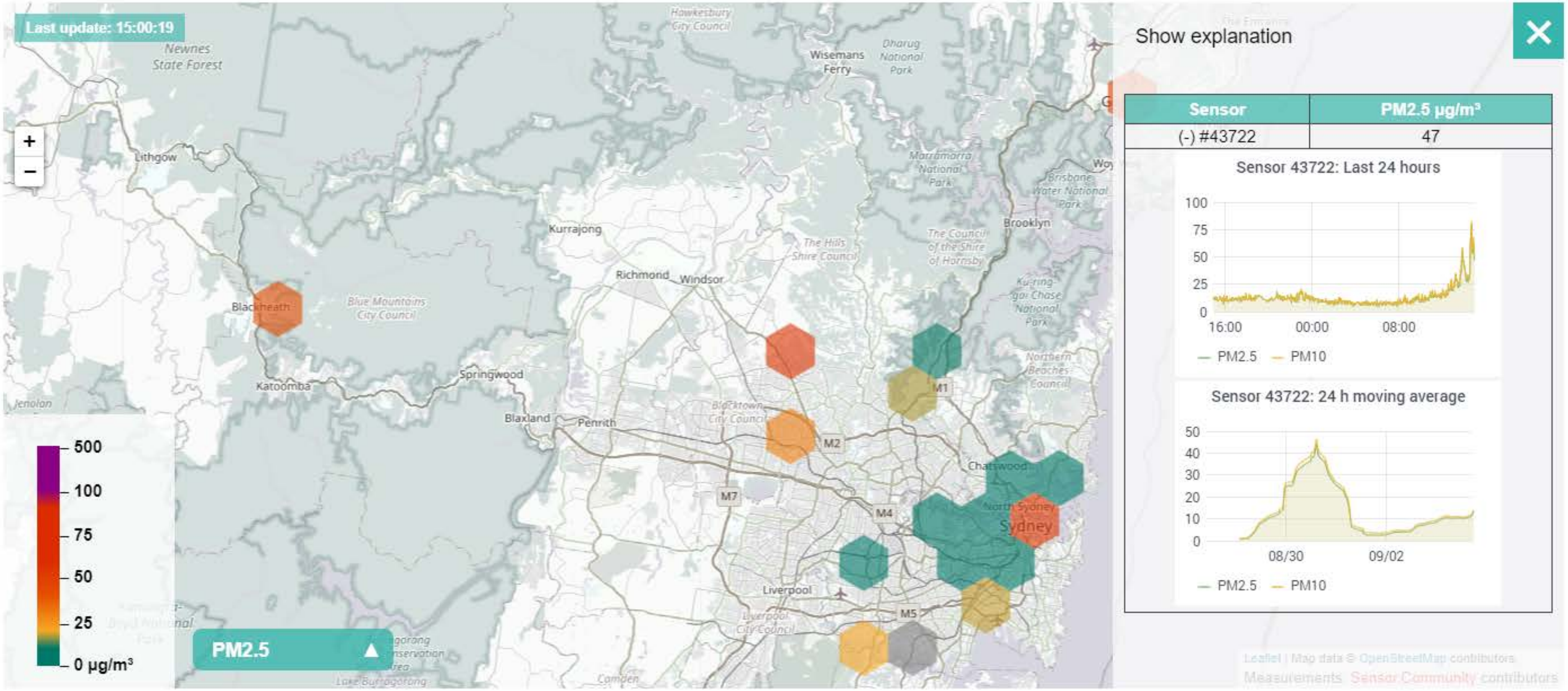
Reliability maintenance and repairs

During the study period the LD sensors were very reliable and the only data loss that occurred was due to site power outages. None of the units required maintenance of any kind during the study period. The DIY housing allows users to make the design as modular as they need, and is therefore easy to repair.

Data retrieval and online interface

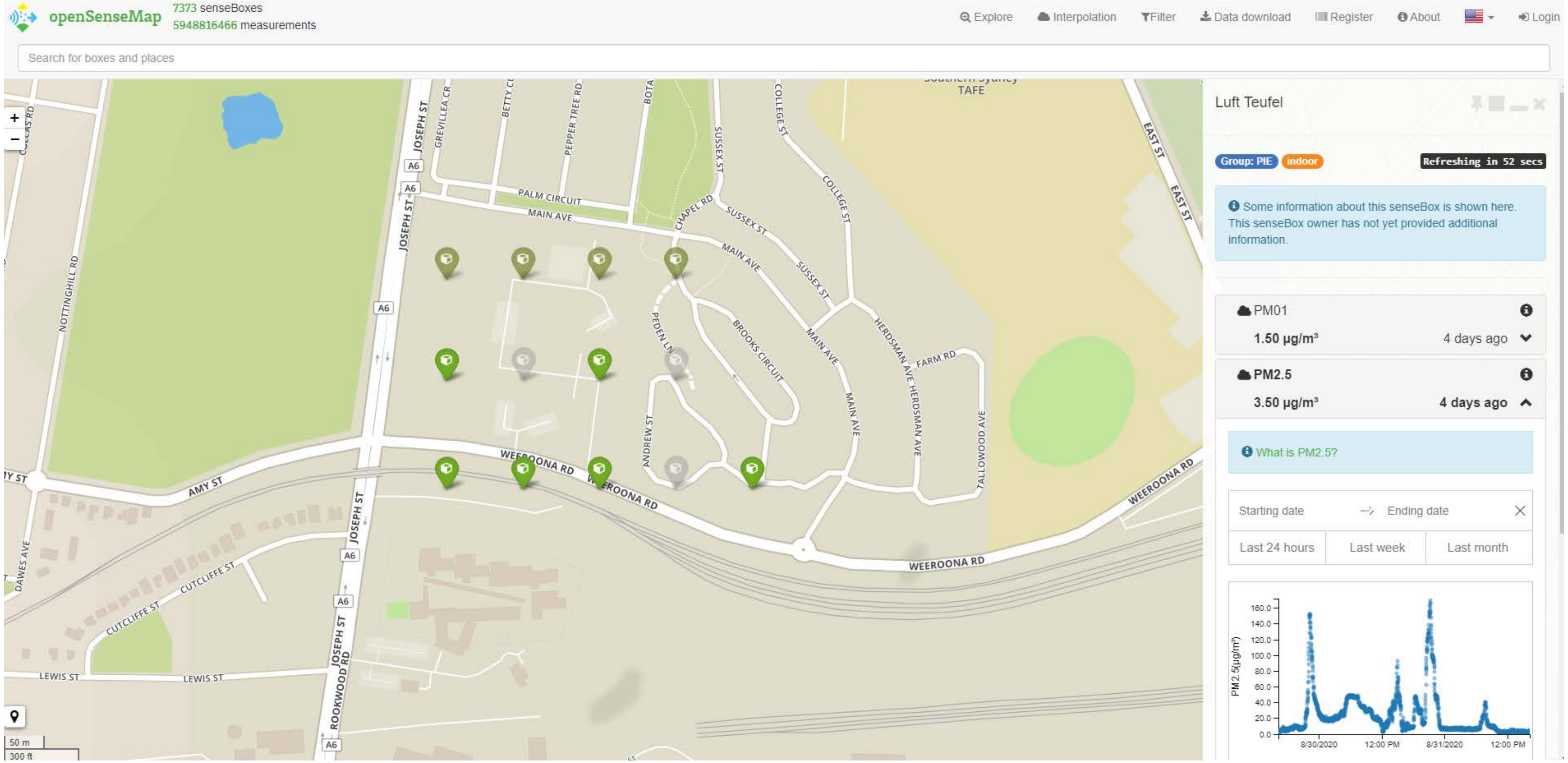
The LD sensors allow the user to change parameters, such as sampling interval, warm-up time and averaging period. During this study, the sensor at Katoomba was set to measure for five seconds every five minutes, so the data is comparable to KOALAs. The other sensors were set to record minute averages for comparison with FEMs. However, to change the data averaging period of the sensor required complicated changes to the sensor's code.

The data collected by the LD sensors can be sent to numerous online interfaces that have varying amounts of functionality. The default interface the data is sent to is the 'mein.luftdaten' interface **(**Figure 13**)** which was created specifically for the sensors. The 'mein.luftdaten' interface provides both a graphical display and a data-download facility. An alternative interface is the 'openSenseMap' interface (Figure 14) which was found to have greater functionality and a better data download facility.



Sensor	PM2.5 µg/m³
(-) #43722	47

Figure 13 **Luftdaten interface, showing the location of sensors monitoring air quality around Sydney**



7373 senseBoxes
5948816466 measurements

Luft Teufel

Some information about this senseBox is shown here. This senseBox owner has not yet provided additional information.

PM01
1.50 µg/m³ 4 days ago

PM2.5
3.50 µg/m³ 4 days ago

What is PM2.5?

Figure 14 **The openSenseMap interface displaying Luftdaten measurements**

Particle comparison

The LD units co-located at both regional centres and metro areas performed well compared with both 5014i BAMs and TEOM 1405DF for PM2.5 measurements (R^2 0.8–0.97).

Data from four LD sensors co-located with the 1405DF TEOM and Aurora 1000 nephelometer at Port Macquarie were assessed along with an LD sensor at the Katoomba and Sydney CBD compliance stations.

The LD sensors at Port Macquarie performed very well against the TEOM 1405DF PM2.5 measurements (R^2: 0.84–0.86) as can be seen in Figure 15.

The LD sensors also compared well with the co-located Aurora 1000 nephelometers at all sites (R^2: 0.91–0.96).

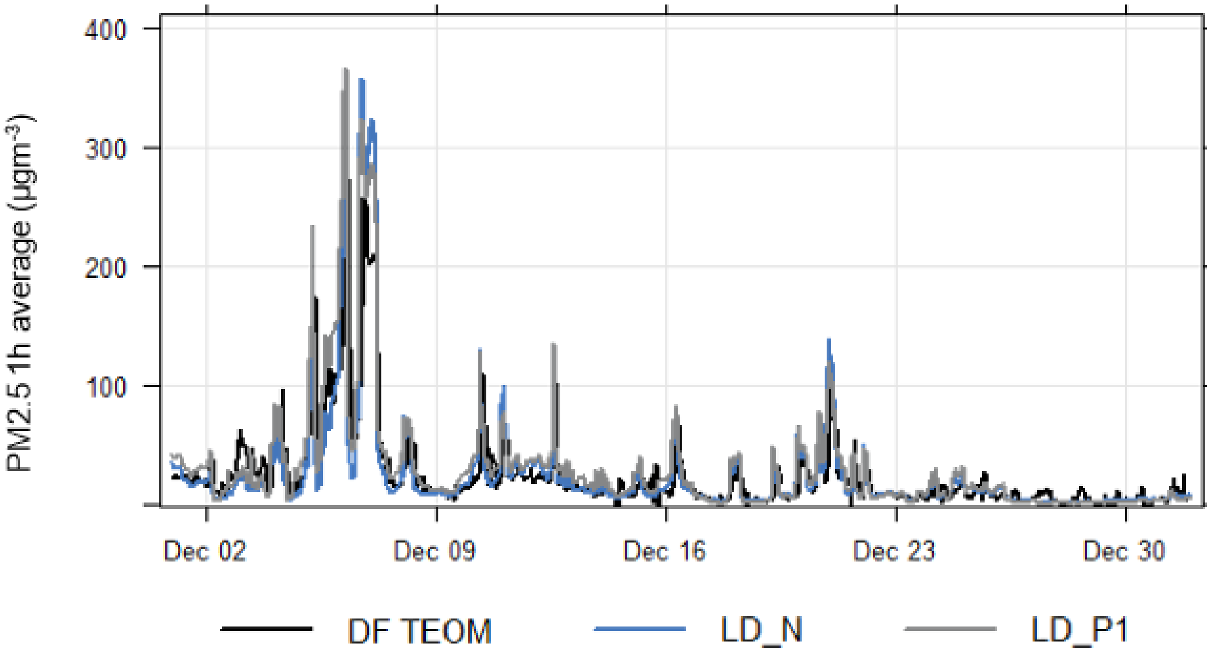


Figure 15 **LD sensor measurements of PM2.5 at Port Macquarie compared to a TEOM for December 2019**

As noted with the other indicative sensors, the LD does not compare with TEOM 1405A and 1405DF for PM10 measurements at any site, for similar reasons (see Figure 16).

At Port Macquarie, the correlation coefficients between the Luft sensors and the TEOM 1405DF for PM10 ranged from 0.74–0.80. It is however notable that the Luft sensor fitted with a NOVA SDS011 particle sensor performed slightly better for PM2.5 and PM10 measurements than the other units co-located in Port Macquarie, which were fitted with Plantower sensors. This could be due to the larger fan size on the NOVA SDS011 particle sensor (Figure 17).

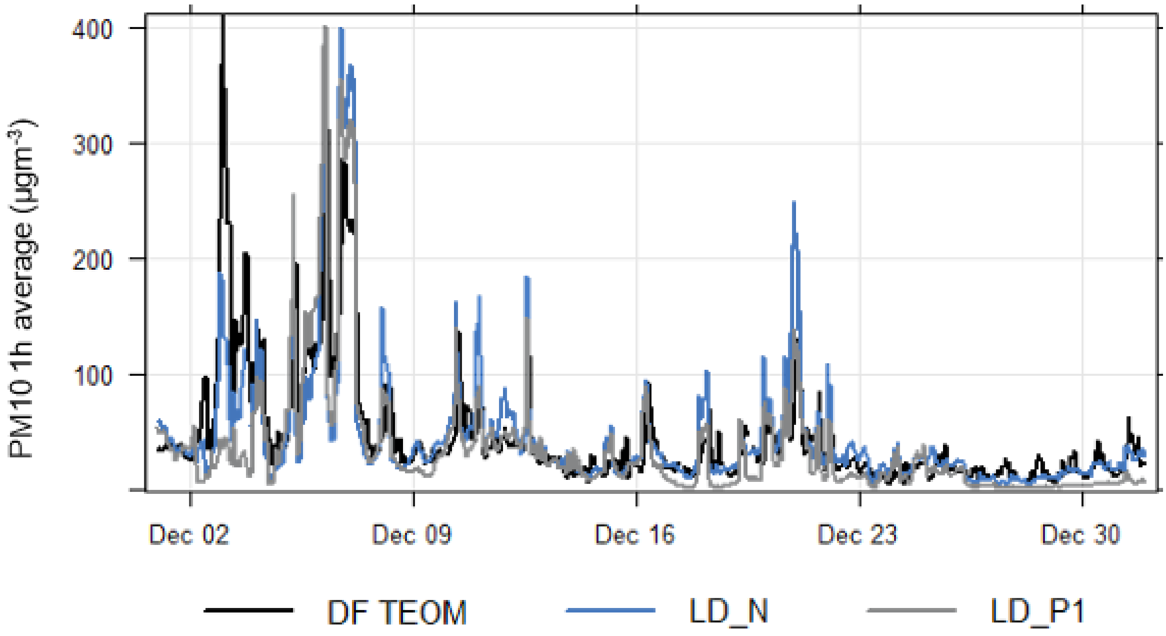


Figure 16 LD sensor measurements of PM10 at Port Macquarie compared to a TEOM for December 2019

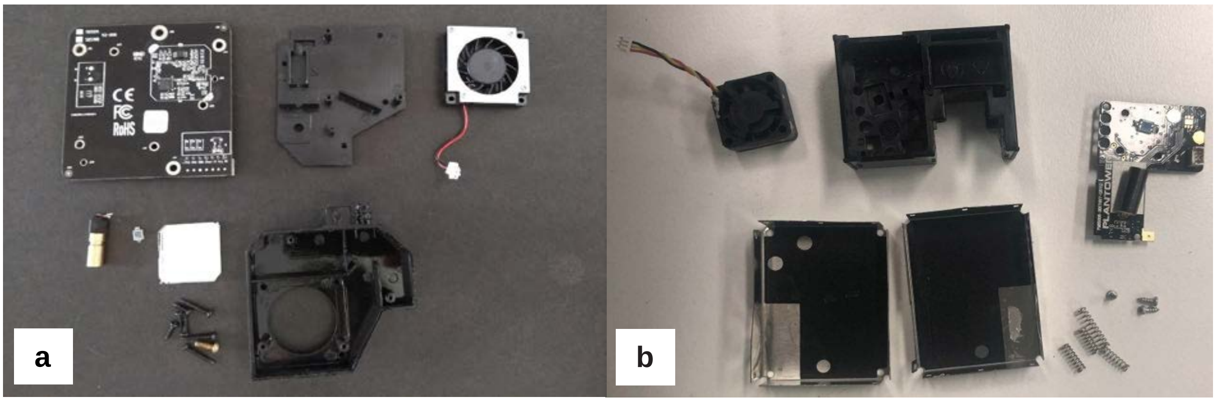


Figure 17 a. NOVA SDS011 disassembled; b. Plantower PMS5003 disassembled

11. Discussion

In summary:

- All indicative sensors tested were quick and easy to deploy.
- Replacement particle sensors are very cheap – approximately $30.
- Sensors were very cost-effective, and require very little to no maintenance.
- All sensors tested compared well with AQMU instruments for PM2.5 measurements.
- PM10 is occasionally inconstant with AQMU instruments.
- Numerous issues with data-logging and retrieval were encountered.
- Further work is needed to determine the effect of different averaging periods on measurements.

All indicative sensors tested were quick and easy to deploy. The sensors were extremely low cost, and the cost for maintenance or replacements would also be low, as a new particle sensor costs approximately $30. All three indicative sensors were effective at measuring PM2.5 concentrations when compared with FEM instruments and nephelometers. The sensors showed less correlation with the FEM instruments when measuring PM10 concentrations and were not able to pick up PM10 events.

The consistency in correlation of PM2.5 measurements with FEM instruments across subtropical climates at varying altitudes demonstrates potential future uses as bushfire emergency monitoring or hazard reduction burns monitoring, or for monitoring domestic wood-heating in urban settings. However, before these instruments can be deployed in the field, further work needs to be done to determine why the correlation with FEM measurements appears to break down beyond ~400 ug/m^3. We also need to complete further work to assess the impact of fog on these sensors.

There are some small difficulties that would need to be overcome to use indicative sensors to effectively monitor air quality:

- We would need to find an efficient way to create empty records for date/time stamps where data was not recorded, to avoid inconsistent data truncation between sensors and FEM instruments.
- Another difficulty was that all three sensors employed a third-party data portal for downloading the measurement data. This made it difficult to compare the sensors and analyse the data.
- Indicative sensors also have no automated way to flag bad data: the user is required to manually check the data to identify bad data. To make using these sensors effective, we would need to work out how to automate this check.

The indicative sensors and FEM instruments had different averaging periods, which made comparisons between them difficult. It would be necessary to identify the ideal sampling time or interval for those sensors, and to develop a method for comparing the measurements with different averaging periods.

While the deployment period for this study was only six months, a separate study involved deploying 12 KOALA units to the Blue Mountains for a one-year period between May 2019 and June 2020. In this time the units required minimal maintenance, and much of the required maintenance was completed by volunteers.

12. Summary points

- The indicative sensors tested in this study were quick and easy to deploy and did not require much maintenance.
- All sensors performed reasonably well for measuring PM2.5 when compared to FEM instruments and nephelometers.
- The sensors did not perform as well for measuring PM10.
- These results suggest indicative sensors could be extremely useful for monitoring air quality.
- They should **not** be used as a replacement for FEM instruments, but could be used in addition to the FEM network by providing a greater density of measurements.
- Measurements from these sensors would be useful for indicative purposes, such as rapid response monitoring and community engagement.
- Indicative sensor technologies are a growing field. New sensors are being developed regularly, and keeping up with the available technologies would be an ongoing task.

13. Recommendations for future work

We recommend additional work to test the effectiveness of the sensors over a long-term period, and to determine the optimal deployment conditions for indicative sensors. Our recommendations for future work include:

- doing a multi-year co-location exercise to assess the long-term quality of the measurements and the impacts of seasonality, humidity and wind speed on the sensors
- investigating the effectiveness of flyscreen mesh to stop insect interference and impact on flows
- evaluating the temperature, pressure and humidity sensors in the indicative sensor units
- increasing flow through the sensors to determine if PM10 measurements are improved
- comparing the data between the SD card and the cloud storage, and assessing how well the sensors pick good versus poor data
- co-locating indicative sensors with a rural node to determine the measurement quality in an area of high PM10 concentrations (such as from dust storms)
- testing the capability of indicative sensors for measuring PM10 by performing an experiment with a stronger inlet pump or fan
- completing a more widespread investigation into the efficiency of the LD sensor fitted with a NOVA SDS011 sensor to measure PM10.

The last three actions may allow for the development of a correction factor to be applied to measurements of PM10 by these indicative sensors.

14. References and further reading

Castell N, Dauge FR, Schneider P, Vogt M, Lerner U, Fishbain B, Broday D & Bartonova A 2016, Can commercial low-cost sensor platforms contribute to air quality monitoring and exposure estimates? *Environment International* 99*,* pp. 293–302*.*

Clements AL, Griswold WG, Rs A, Johnston JE, Herting MM, Thorson J, Collier-Oxandale A & Hannigan M 2017, Low-cost air quality monitoring tools: from research to practice (a workshop summary), *Sensors* 17(11), p. 2478.

Gupta P, Doraiswamy P, Levy R, Pikelnaya O, Maibach J, Feenstra B, Polidori A, Kiros F & Mills KC 2018, Impact of California fires on local and regional air quality: the role of a low-cost sensor network and satellite observations, *GeoHealth* 2(6), pp. 172–181.

Jayaratne R, Liu X, Thai P, Dunbabin M & Morawska L 2018, The influence of humidity on the performance of a low-cost air particle mass sensor and the effect of atmospheric fog, *Atmospheric Measurement Techniques* 11(8), pp. 4883–4890*.*

Li J, Mattewal SK, Patel S & Biswas P 2020, Evaluation of nine low-cost-sensor-based particulate matter monitors, *Aerosol and Air Quality Research* 20, pp. 254–270.

Liu X, Jayaratne R, Thai P, Kuhn T, Zing I, Christensen B, Lamont R, Dunbabin M, Zhu S, Gao J & Wainwright D 2020, Low-cost sensors as an alternative for long-term air quality monitoring, *Environmental Research* p. 109438.

Morawska L, Thai PK, Liu X, Asumadu-Sakyi A, Ayoko G, Bartonova A, Bedini A, Chai F, Christensen B, Dunbabin M & Gao J 2018, Applications of low-cost sensing technologies for air quality monitoring and exposure assessment: How far have they gone? *Environment International* 116, pp. 286–299.

Robinson DL, Monro JM & Campbell EA 2007, Spatial variability and population exposure to PM2.5 pollution from woodsmoke in a New South Wales country town, *Atmospheric Environment* 41(26), pp. 5464–5478.

Tryner J, L'Orange C, Mehaffy J, Miller-Lionberg D, Hofstetter JC, Wilson A & Volckens J 2020, Laboratory evaluation of low-cost PurpleAir PM monitors and in-field correction using co-located portable filter samplers, *Atmospheric Environment* 220, p. 117067.

Wang Z, Delp WW & Singer BC 2020, Performance of low-cost indoor air quality monitors for PM2.5 and PM10 from residential sources, *Building and Environment* 171*,* p. 106654.

US EPA, *How to Evaluate Low-Cost Sensors by Collocation with Federal Reference Method Monitors*, United States Environmental Protection Agency, viewed 29 April 2020, www.epa.gov/air-research/instruction-guide-and-macro-analysis-tool-evaluating-low-cost-air-sensors-collocation.

PurpleAir, *FAQ*, viewed 4 May 4 2020, www2.purpleair.com/community/faq.

Appendix A – Data summary statistics

Armidale

PM2.5

Instrument (units)	Minimum*	Maximum	Data availability rate** (%)	5thPercentile	25th percentil	50th percentile	75th percentile	95th percentile
TEOM (µg/m^3)	-5	918	99	0.8	5	10	27	92
NEPH (bsp)	0	60	99	0.04	0.1	0.4	1.2	4
PA2 #1 (µg/m^3)	0	756	65	0.1	2	9	35	142
PA2 #2 (µg/m^3)	0	958	100	0.1	2	11	41	121
PA2 (µg/m^3)	0	898	100	0.2	2	12	40	110

* 0 is the lowest value the indicative sensors are able to record
** Including power outages and other non-instrument faults

PM10

Instrument (units)	Minimum*	Maximum	Data availability rate** (%)	5thPercentile	25th percentil	50th percentile	75th percentile	95th percentile
TEOM (µg/m^3)	-4	954	92	3	11	21	44	152
NEPH (bsp)	0	60	99	0.04	0.1	0.4	1.2	4
PA2 #1 (µg/m^3)	0	1136	65	0.1	2	9	37	214
PA2 #2 (µg/m^3)	0	1438	100	0.1	2	11	48	182
PA2 (µg/m^3)	0	1348	100	0.2	2	12	47	166

* 0 is the lowest value the sensors are able to record
** Including power outages and other non-instrument faults

Chullora

PM2.5

Instrument (units)	Minimum*	Maximum	Data availability rate** (%)	5thPercentile	25th percentil	50th percentile	75th percentile	95th percentile
BAM (µg/m^3)	-2	299	63	1	4	8	13	31
NEPH (bsp)	0	24	99	0.05	0.1	0.2	0.4	1
PA2 (µg/m^3)	0	495	99	0.2	2	5	15	44

* 0 is the lowest value the indicative sensors are able to record
** Including power outages and other non-instrument faults

PM10

Instrument (units)	Minimum*	Maximum	Data availability rate** (%)	5thPercentile	25th percentil	50th percentile	75th percentile	95th percentile
TEOM (µg/m^3)	-5	789	100	6	13	19	28	63
NEPH (bsp)	0.01	24	99	0.05	0.1	0.2	0.4	1
PA2 (µg/m^3)	0	744	99	0.2	2	5	15	57

* 0 is the lowest value the indicative sensors are able to record
** Including power outages and other non-instrument faults

Katoomba

PM2.5

Instrument (units)	Minimum*	Maximum	Data availability rate** (%)	5thPercentile	25th percentil	50th percentile	75th percentile	95th percentile
TEOM (µg/m³)	-5	1415	97	-0.7	2	4	8	95
NEPH (bsp)	0	76	98	0.02	0.04	0.09	0.4	6
PA2 (µg/m³)	0	1016	100	0.01	0.2	1	9	156
K2 (µg/m³)	0	1649	100	1	2	4	17	214
K3 (µg/m³)	0	1225	100	1	2	3	12	180
LD_P5 (µg/m³)	0	919	99	1	2	4	13	127

* 0 is the lowest value the indicative sensors are able to record
** Including power outages and other non-instrument faults

PM10

Instrument (units)	Minimum*	Maximum	Data availability rate** (%)	5th percentile	25th percentil	50th percentile	75th percentile	95th percentile
TEOM (µg/m³)	-4	1416	98	0.4	3	7	14	119
NEPH (bsp)	0	77	98	0.02	0.04	0.09	0.4	6
PA2 (µg/m³)	0	1526	100	0.01	0.2	1	10	234
K2 (µg/m³)	0	2313	100	1	2	4	21	252
K3 (µg/m³)	0	1744	100	1	2	3	15	208
LD_P5 (µg/m³)	0	1289	98	1	2	4	16	150

* 0 is the lowest value the indicative sensors are able to record
** Including power outages and other non-instrument faults

CO

Instrument (units)	Minimum	Maximum	Data availability rate** (%)	5th percentile	25th percentil	50th percentile	75th percentile	95th percentile
API T300 (ppm)	-0.2	10	95	0.005	0.04	0.07	0.1	1
K2 (ppm)	-0.07	7	99	0.02	0.04	0.06	0.1	0.9
K3 (ppm)	-0.1	8	99	-0.04	-0.02	-0.005	0.04	0.8

** Including power outages and other non-instrument faults

Orange

PM2.5

Instrument (units)	Minimum*	Maximum	Data availability rate** (%)	5th percentile	25th percentil	50th percentile	75th percentile	95th percentile
TEOM (µg/m^3)	-5	616	96	-1	3	8	17	72
NEPH (bsp)	0	38	100	0.04	0.09	0.2	0.6	3
PA2 (µg/m^3)	0	684	99	0.09	0.9	5	22	89

* 0 is the lowest value the indicative sensors are able to record
** Including power outages and other non-instrument faults

PM10

Instrument (units)	Minimum*	Maximum	Data availability rate** (%)	5th percentile	25th percentil	50th percentile	75th percentile	95th percentile
TEOM (µg/m^3)	-5	887	96	2	8	16	31	125
NEPH (bsp)	0	38	100	0.04	0.09	0.2	0.6	3
PA2 (µg/m^3)	0	1027	99	0.09	0.9	5	23	134

* 0 is the lowest value the indicative sensors are able to record
** Including power outages and other non-instrument faults

Port Macquarie

PM2.5

Instrument (units)	Minimum*	Maximum	Data availability rate** (%)	5th percentile	25th percentil	50th percentile	75th percentile	95th percentile
TEOM (µg/m³)	-2	1280	95	2	5	11	26	113
NEPH (bsp)	0.03	80	99	0.09	0.2	0.4	1	6
K5 (µg/m³)	0	1513	100	3	7	17	46	242
K98 (µg/m³)	0	1742	100	4	8	15	40	230
LD_N (µg/m³)	1	370	99	2	7	13	30	128
LD_P1 (µg/m³)	0.3	366	100	1	8	20	39	154
LD_P3 (µg/m³)	0.1	402	100	1	9	23	42	165
LD_P5 (µg/m³)	0.1	392	100	1	8	22	42	174

* 0 is the lowest value the indicative sensors are able to record
** Including power outages and other non-instrument faults

PM10

Instrument (units)	Minimum*	Maximum	Data availability rate** (%)	5th percentile	25th percentil	50th percentile	75th percentile	95th percentile
TEOM (µg/m³)	-2	1319	95	7	15	25	47	156
NEPH (bsp)	0.03	80	99	0.09	0.2	0.4	1	6
K5 (µg/m³)	0	2030	100	4	8	18	49	272
K98 (µg/m³)	0	2614	100	6	11	20	50	289
LD_N (µg/m³)	4	442	99	9	21	34	58	176
LD_P1 (µg/m³)	0.9	402	100	2	10	23	49	167
LD_P3 (µg/m³)	0.6	426	100	2	12	26	53	172
LD_P5 (µg/m³)	0.3	416	100	2	10	24	51	183

* 0 is the lowest value the indicative sensors are able to record
** Including power outages and other non-instrument faults

CO

Instrument (units)	Minimum*	Maximum	Data availability rate** (%)	5th percentile	25th percentil	50th percentile	75th percentile	95th percentile
API T300 (µg/m^3)	-0.1	13	97	-0.03	0.03	0.1	0.3	1
K5 (µg/m^3)	0	8	100	0.07	0.1	0.2	0.3	1
K98 (µg/m^3)	0	8	100	0.08	0.1	0.2	0.3	1

* 0 is the lowest value the indicative sensors are able to record
** Including power outages and other non-instrument faults

Wagga Wagga

PM2.5

Instrument (units)	Minimum*	Maximum	Data availability rate** (%)	5th percentile	25th percentil	50th percentile	75th percentile	95th percentile
BAM (µg/m^3)	-2	545	95	0.02	3	7	12	40
DustTrak (µg/m^3)	0	949	75	0	1	2	5	53
PA2 (µg/m^3)	0	774	100	0.06	0.7	3	15	52

* 0 is the lowest value the indicative sensors are able to record
** Including power outages and other non-instrument faults

PM10

Instrument (units)	Minimum*	Maximum	Data availability rate** (%)	5th percentile	25th percentil	50th percentile	75th percentile	95th percentile
TEOM (µg/m^3)	-9	1151	99	4	9	17	33	113
DustTrak (µg/m^3)	0	981	75	2	5	9	20	96.5
PA2 (µg/m^3)	0	1162	100	0.06	0.7	3	15	75

* 0 is the lowest value the indicative sensors are able to record
** Including power outages and other non-instrument faults

Appendix B – Scatter plots and instrument correlations

Armidale

PM2.5

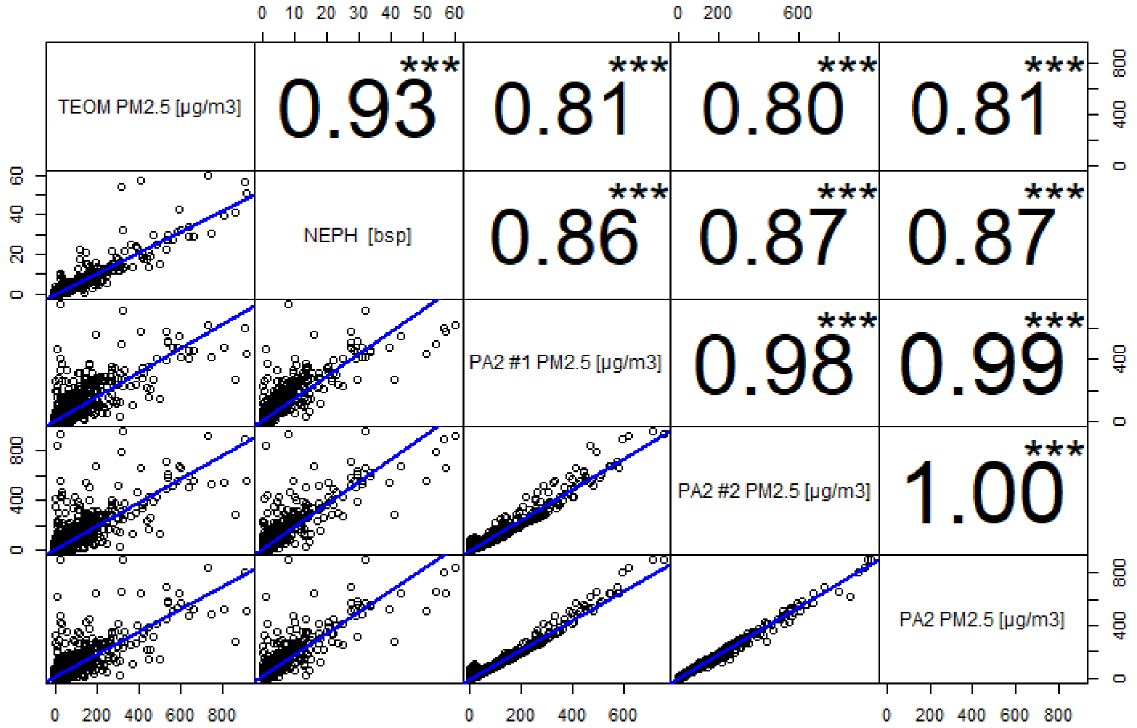


Figure 18 **Correlation between instruments at Armidale measuring PM2.5 (hourly averages)**

On the bottom of the diagonal are the bivariate scatter plots with a fitted line and on the top of the diagonal is the value of the Pearson product moment correlation coefficient plus the significance level as stars (where *** equates to p-values <0.001).

PM10

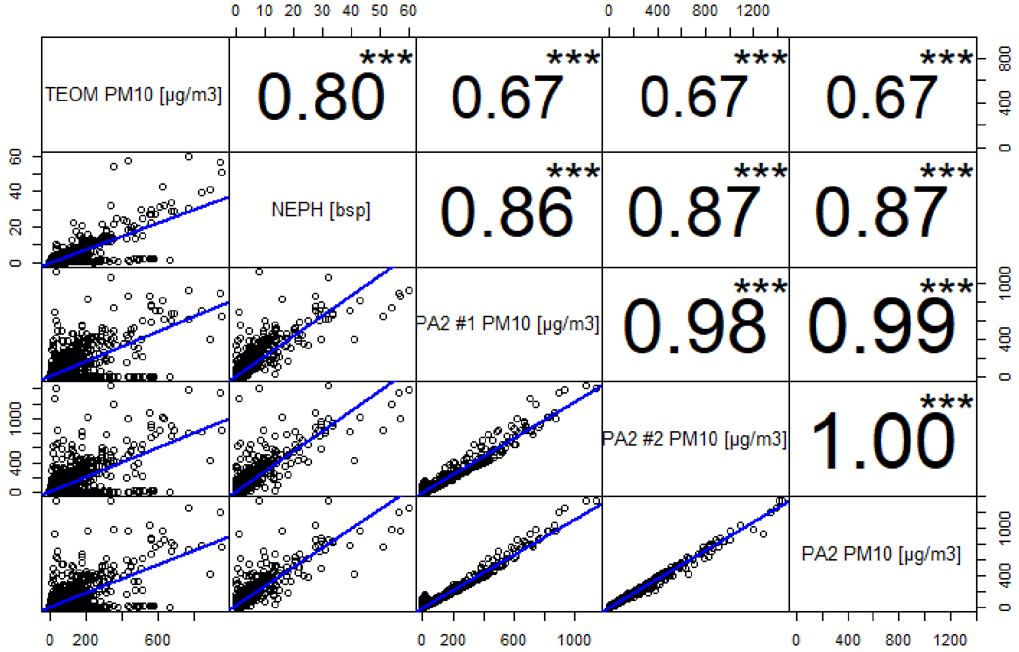


Figure 19 **Correlation between instruments at Armidale measuring PM10 (hourly averages)**

On the bottom of the diagonal are the bivariate scatter plots with a fitted line and on the top of the diagonal is the value of the Pearson product moment correlation coefficient plus the significance level as stars (where *** equates to p-values <0.001).

Chullora

PM2.5

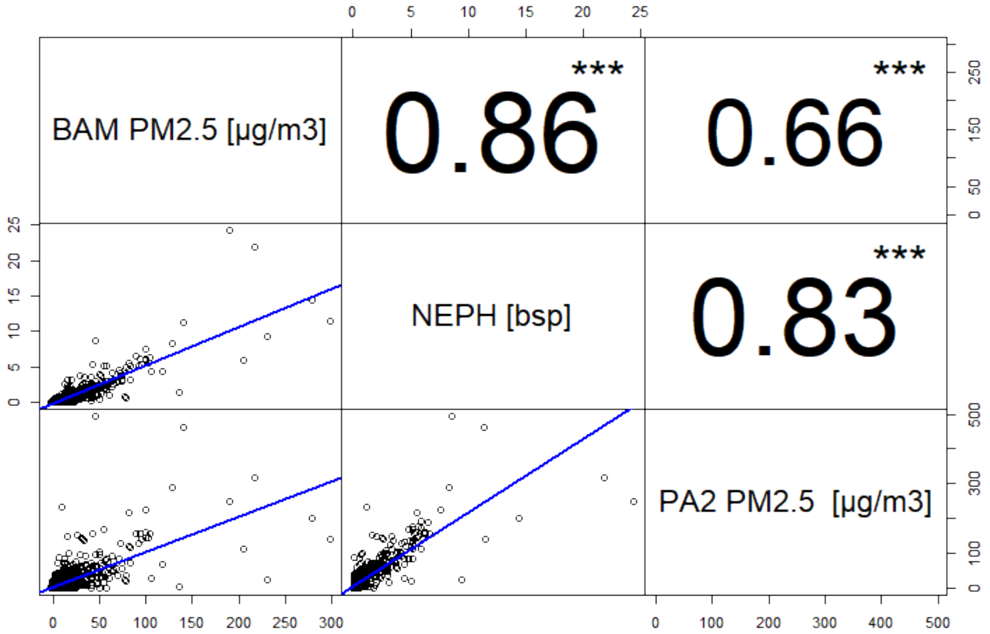


Figure 20 **Correlation between instruments at Chullora measuring PM2.5 (hourly averages)**

On the bottom of the diagonal are the bivariate scatter plots with a fitted line and on the top of the diagonal is the value of the Pearson product moment correlation coefficient plus the significance level as stars (where *** equates to p-values <0.001).

PM10

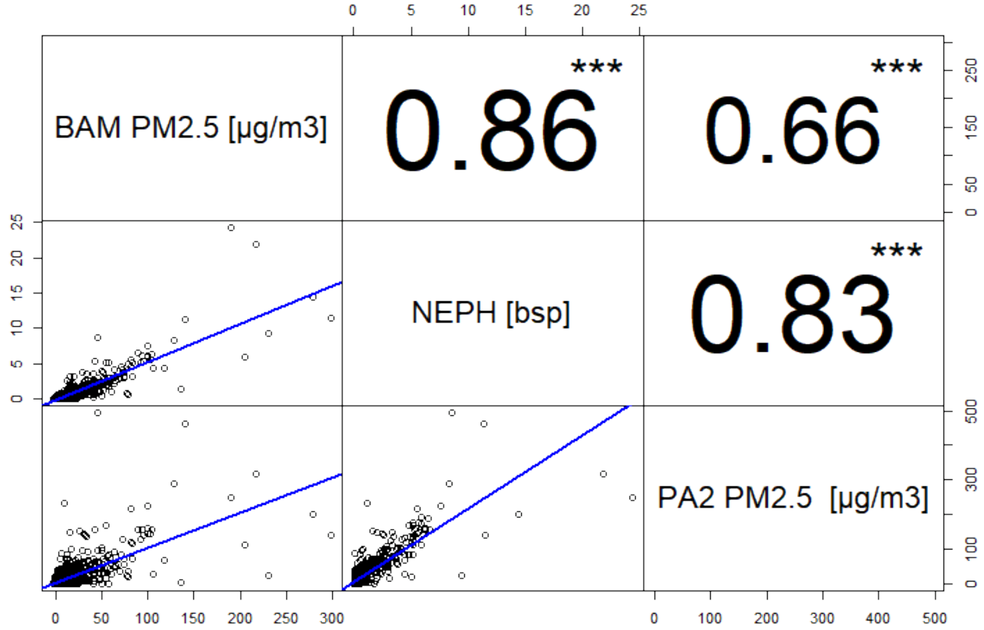


Figure 21 **Correlation between instruments at Chullora measuring PM10 (hourly averages)**
On the bottom of the diagonal are the bivariate scatter plots with a fitted line and on the top of the diagonal is the value of the Pearson product moment correlation coefficient plus the significance level as stars (where *** equates to p-values <0.001).

Katoomba

PM2.5

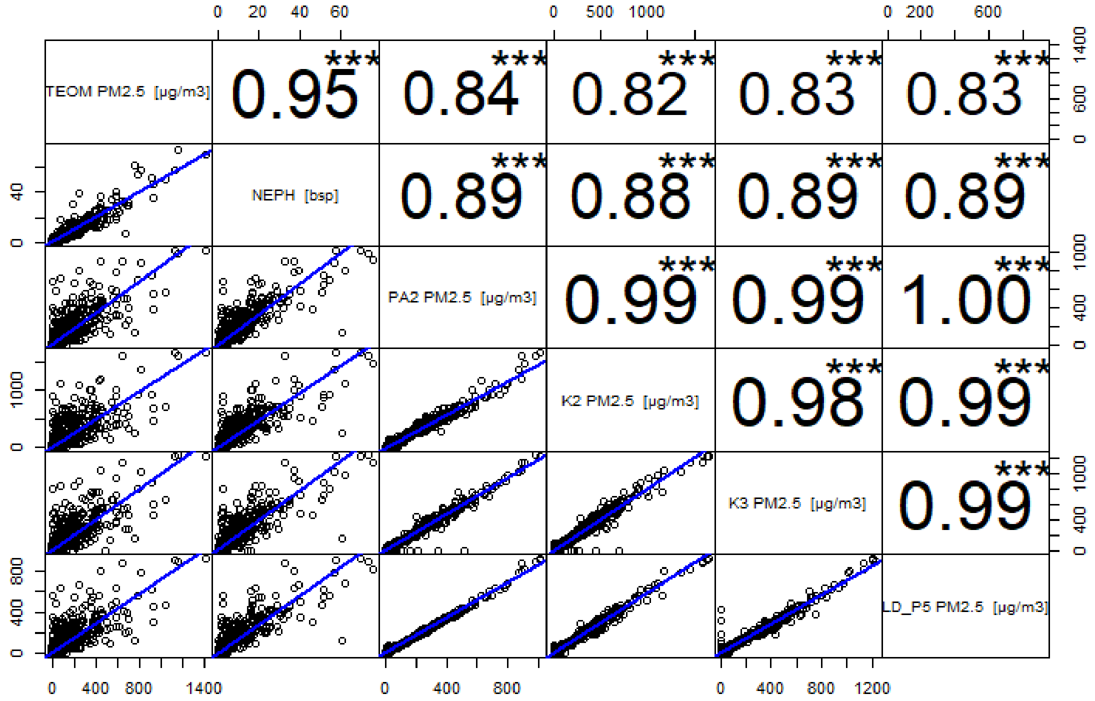


Figure 22 **Correlation between instruments at Katoomba measuring PM2.5 (hourly averages)**
On the bottom of the diagonal are the bivariate scatter plots with a fitted line and on the top of the diagonal is the value of the Pearson product moment correlation coefficient plus the significance level as stars (where *** equates to p-values <0.001).

PM10

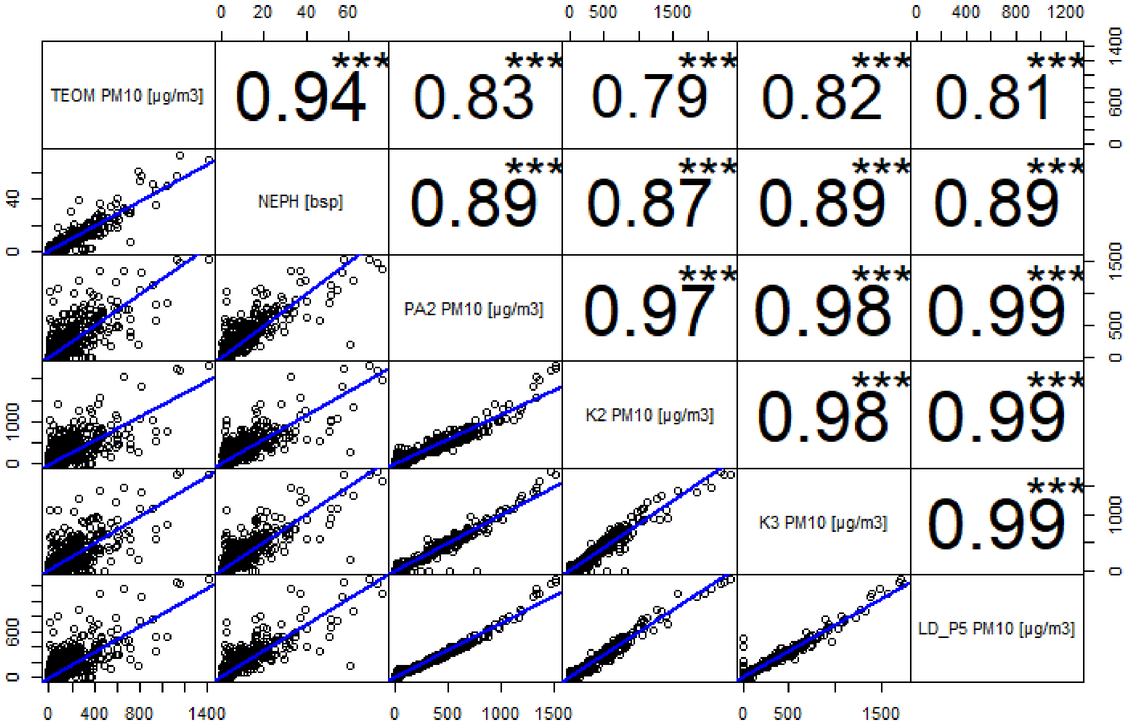


Figure 23 **Correlation between instruments at Katoomba measuring PM10 (hourly averages)**

On the bottom of the diagonal are the bivariate scatter plots with a fitted line and on the top of the diagonal is the value of the Pearson product moment correlation coefficient plus the significance level as stars (where *** equates to p-values <0.001).

CO

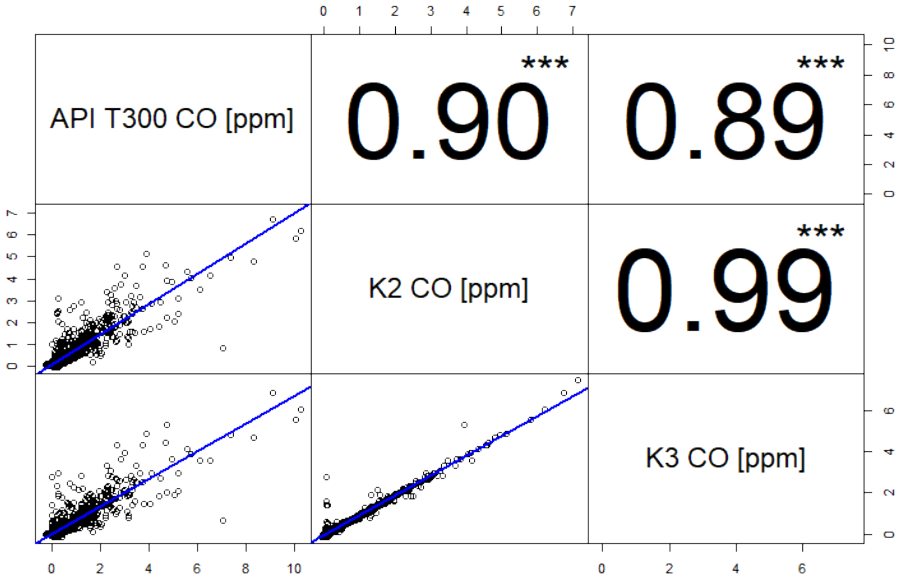


Figure 24 **Correlation between instruments at Katoomba measuring CO (hourly averages)**

On the bottom of the diagonal are the bivariate scatter plots with a fitted line and on the top of the diagonal is the value of the Pearson product moment correlation coefficient plus the significance level as stars (where *** equates to p-values <0.001).

Orange

PM2.5

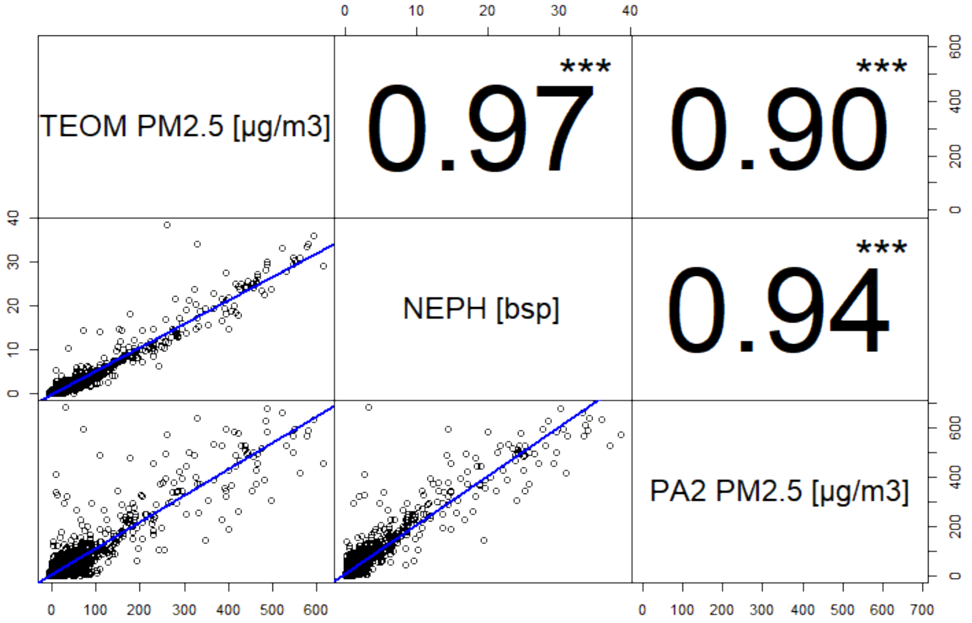


Figure 25 **Correlation between instruments at Orange measuring PM2.5 (hourly averages)**

On the bottom of the diagonal are the bivariate scatter plots with a fitted line and on the top of the diagonal is the value of the Pearson product moment correlation coefficient plus the significance level as stars (where *** equates to p-values <0.001).

PM10

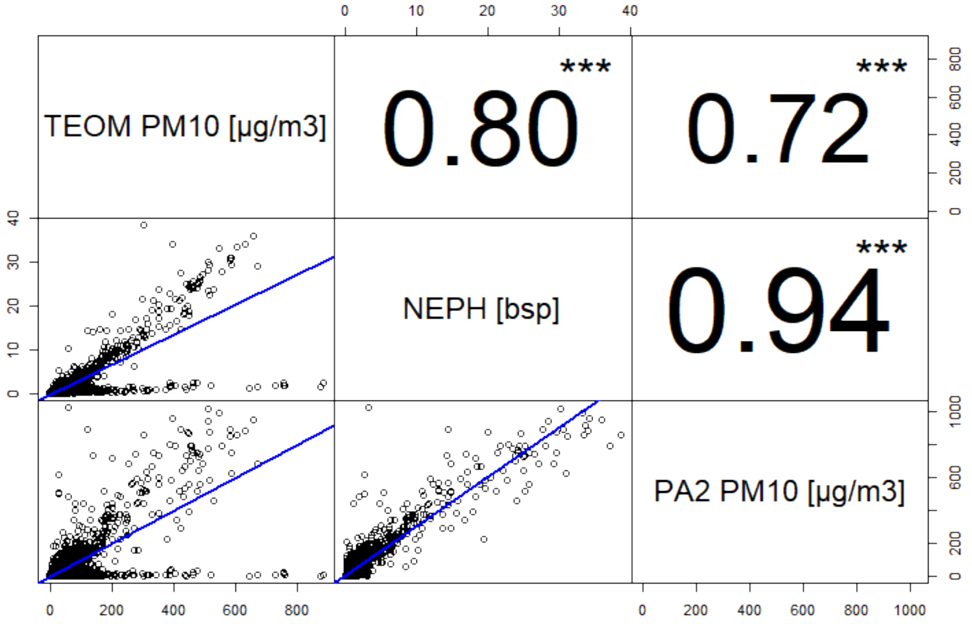


Figure 26 **Correlation between instruments at Orange measuring PM10 (hourly averages)**

On the bottom of the diagonal are the bivariate scatter plots with a fitted line and on the top of the diagonal is the value of the Pearson product moment correlation coefficient plus the significance level as stars (where *** equates to p-values <0.0

Port Macquarie

PM2.5

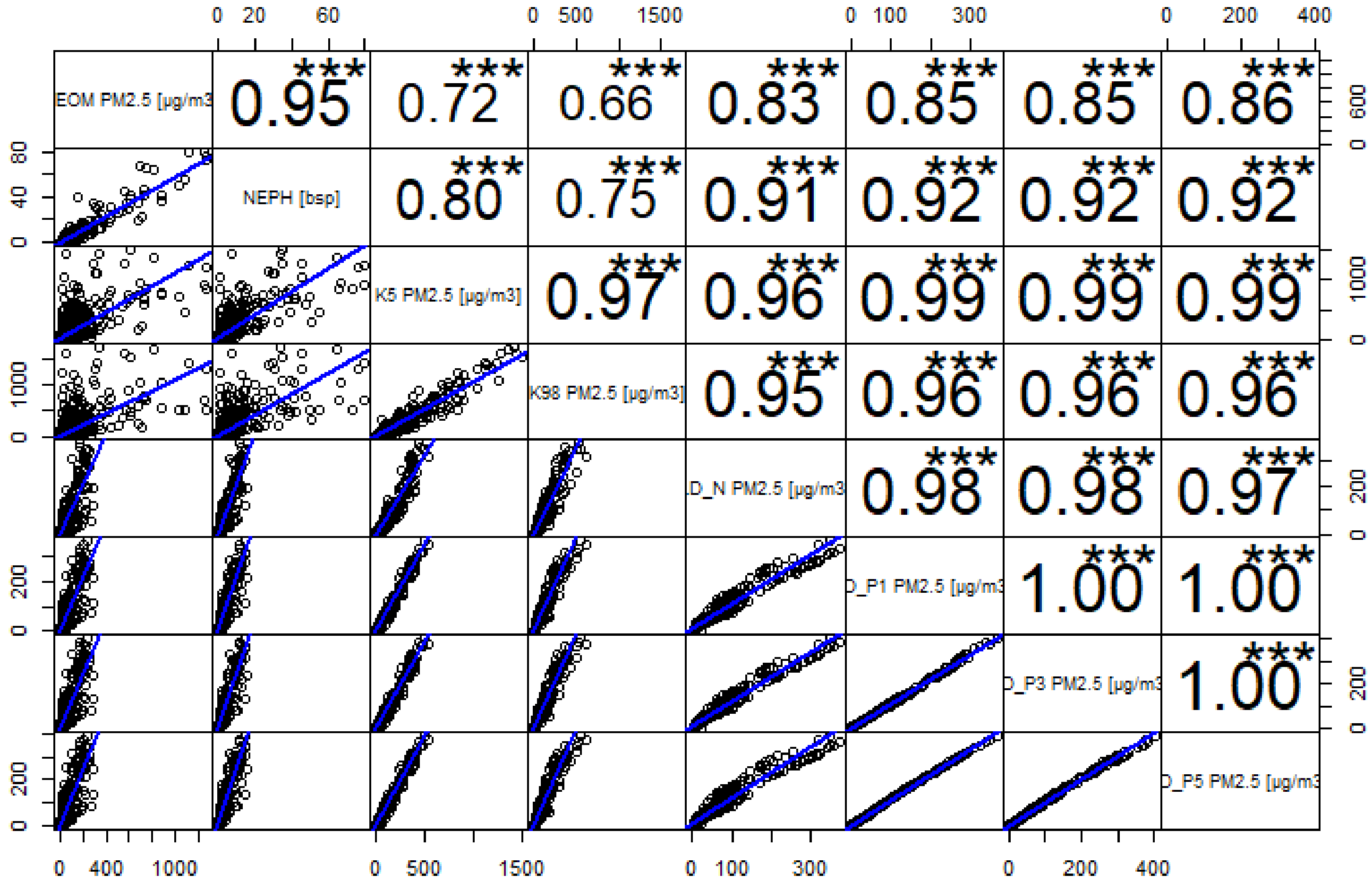


Figure 27 **Correlation between instruments at Port Macquarie measuring PM2.5 (hourly averages)**

On the bottom of the diagonal are the bivariate scatter plots with a fitted line and on the top of the diagonal is the value of the Pearson product moment correlation coefficient plus the significance level as stars (where *** equates to p-values <0.001).

PM10

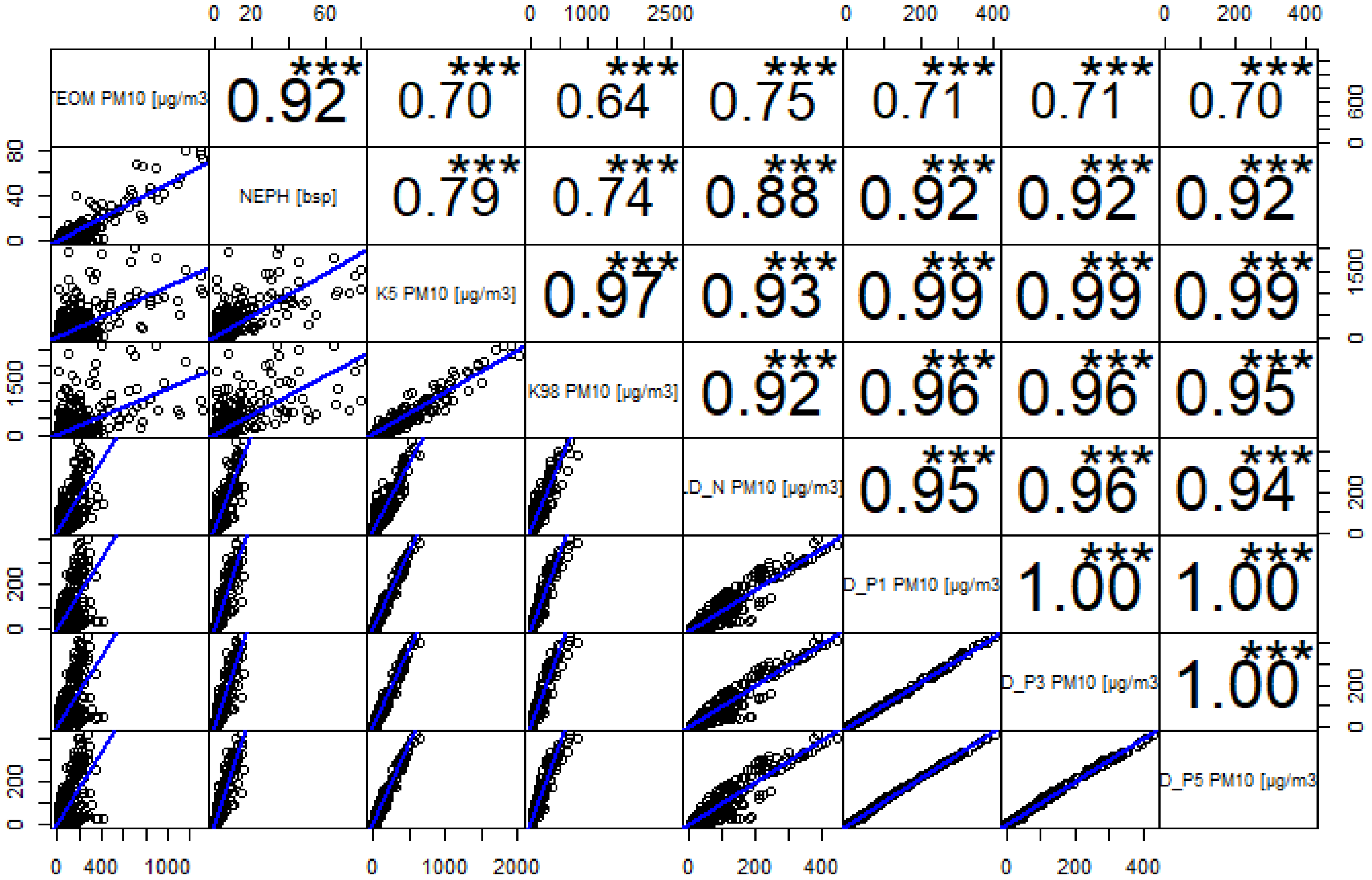


Figure 28 **Correlation between instruments at Port Macquarie measuring PM10 (hourly averages)**

On the bottom of the diagonal are the bivariate scatter plots with a fitted line and on the top of the diagonal is the value of the Pearson product moment correlation coefficient plus the significance level as stars (where *** equates to p-values <0.001).

CO

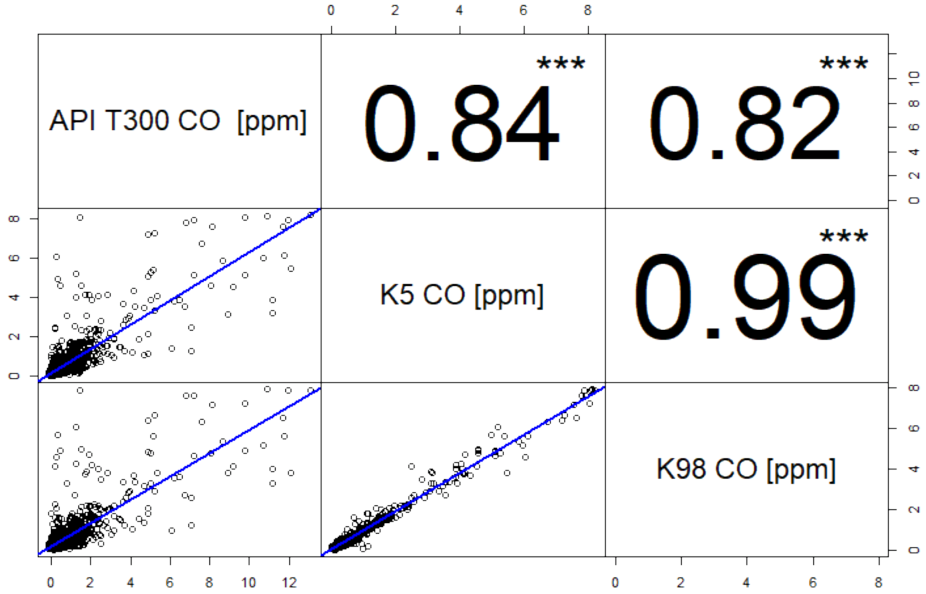


Figure 29 **Correlation between instruments at Port Macquarie measuring CO (hourly averages)**

On the bottom of the diagonal are the bivariate scatter plots with a fitted line and on the top of the diagonal is the value of the Pearson product moment correlation coefficient plus the significance level as stars (where *** equates to p-values <0.001).

Wagga Wagga

PM2.5

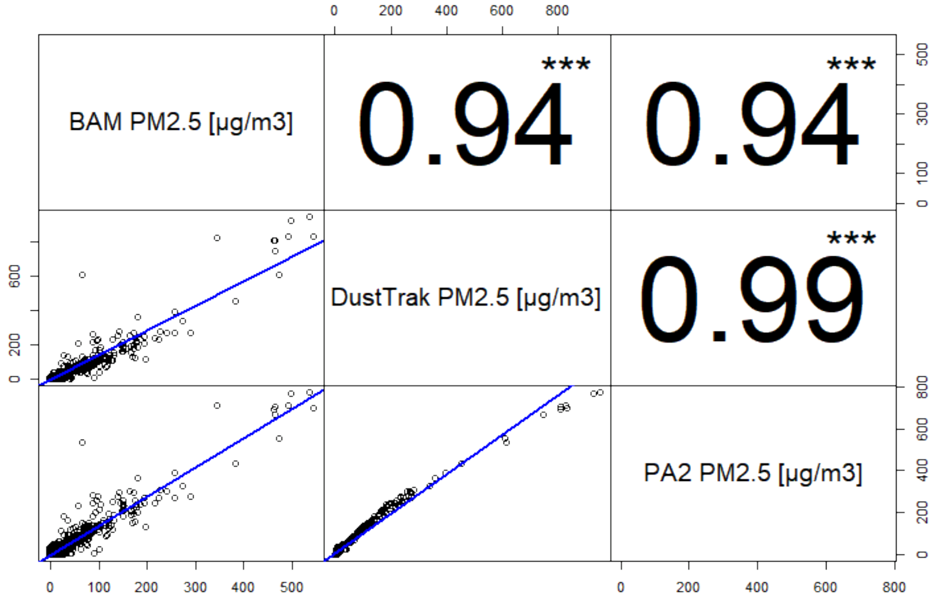


Figure 30 **Correlation between instruments at Wagga Wagga measuring PM2.5 (hourly averages)**

On the bottom of the diagonal are the bivariate scatter plots with a fitted line and on the top of the diagonal is the value of the Pearson product moment correlation coefficient plus the significance level as stars (where *** equates to p-values <0.001

PM10

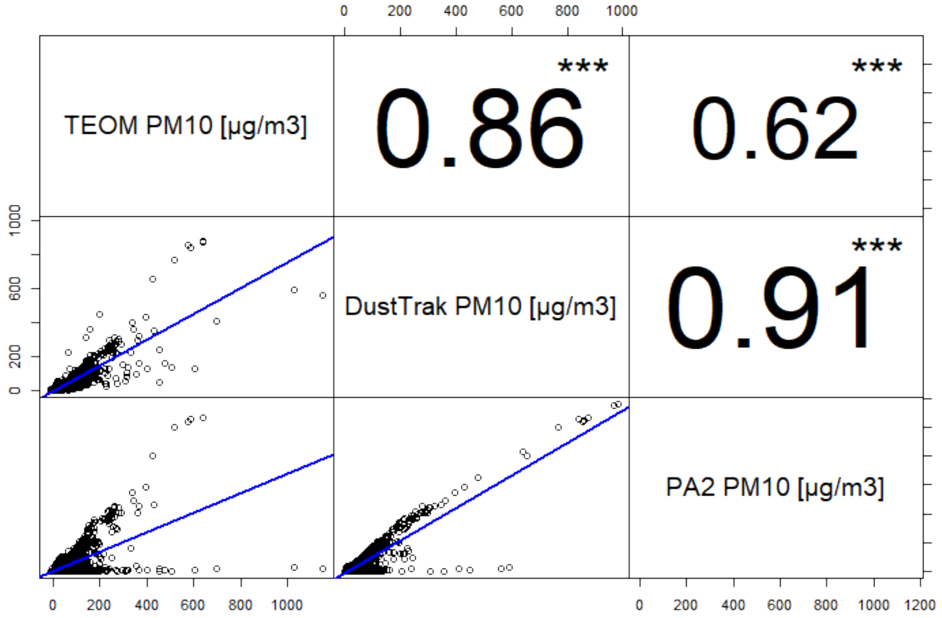


Figure 31 **Correlation between instruments at Wagga Wagga measuring PM10 (hourly averages)**

On the bottom of the diagonal are the bivariate scatter plots with a fitted line and on the top of the diagonal is the value of the Pearson product moment correlation coefficient plus the significance level as stars (where *** equates to p-values <0.001).