SensWA Quality Assurance Project Plan

By

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For the

Air Quality Program

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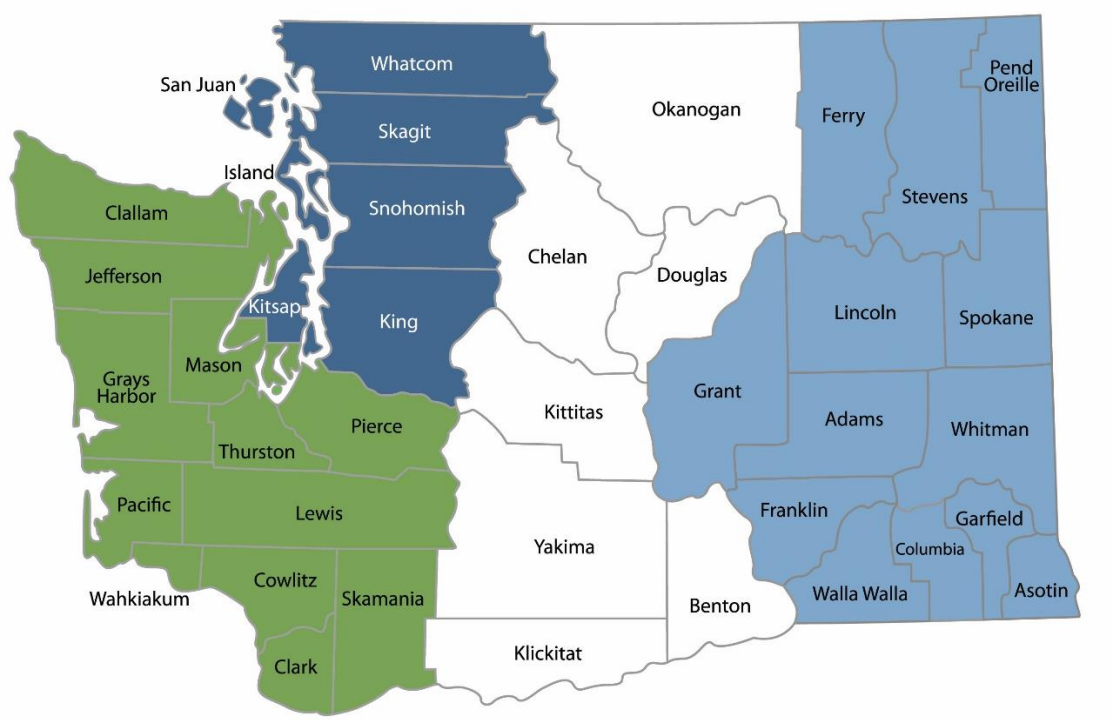
Department of Ecology's Regional Offices

Map of Counties Served



Southwest Region 360-407-6300	Northwest Region 206-594-0000	Central Region 509-575-2490	Eastern Region 509-329-3400

Region	Counties served	Mailing Address	Phone
Southwest	Clallam, Clark, Cowlitz, Grays Harbor, Jefferson, Mason, Lewis, Pacific, Pierce, Skamania, Thurston, Wahkiakum	PO Box 47775 Olympia, WA 98504	360-407-6300
Northwest	Island, King, Kitsap, San Juan, Skagit, Snohomish, Whatcom	PO Box 330316 Shoreline, WA 98133	206-594-0000
Central	Benton, Chelan, Douglas, Kittitas, Klickitat, Okanogan, Yakima	1250 W Alder St Union Gap, WA 98903	509-575-2490
Eastern	Adams, Asotin, Columbia, Ferry, Franklin, Garfield, Grant, Lincoln, Pend Oreille, Spokane, Stevens, Walla Walla, Whitman	4601 N Monroe Spokane, WA 99205	509-329-3400
Headquarters	Across Washington	PO Box 46700 Olympia, WA 98504	360-407-6000

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Revision History

Revision Date	Revision Number	Summary of Changes	Revised Sections	Revised By
07/30/2024	1.0	Initial Publication.		Christopher Atherly

Table of Contents

List of Figures and Tables

Figures

Tables

Acronyms and Abbreviations

AAMG	Ambient Air Monitoring Group
AMTIC	Ambient Monitoring Technology Information Center
APTI	Air Pollution Training Institute
AQI	Air Quality Index
AQP	Air Quality Program
AQPLT	Air Quality Program Leadership Team
AQS	Air Quality System
CCA	Climate Commitment Act
CRO	Central Region Office
CV	Coefficient of Variation
DQO	Data quality objective
Ecology	Washington State Department of Ecology
EPA	U.S. Environmental Protection Agency
ERO	Eastern Region Office
FEM	Federal Equivalent Method
FRM	Federal Reference Method
MAC	Ecology AQP Monitoring Advisory Committee
MAE	Mean absolute error
MQO	Measurement Quality Objectives
NAAQS	National Ambient Air Quality Standards
NRMSE	Normalized root mean square error
NWRO	Northwest Region Office
PM	Particulate Mater
$PM_{2.5}$	PM less than or equal to 2.5 micrometers in diameter
PM_{10}	PM less than or equal to 10 micrometers in diameter
PQAO	Principal Quality Assurance Organization
QA	Quality assurance
QAP	Quality Assurance Plan
QAPP	Quality Assurance Project Plan
QC	Quality control
r^2	Coefficient of determination
RMSE	Root mean square error
sMAPE	Symmetric mean absolute percentage error
SOP	Standard Operating Procedure
SWRO	Southwest Region Office

Distribution

This plan has been distributed to the individuals currently occupying the organizational roles listed below.

Washington State Department of Ecology

- Air Quality Program Manager, Headquarters, Lacey
- Air Quality Program Deputy Manager, Headquarters, Lacey
- Air Quality Program Central Region Office Section Manager, Union Gap
- Air Quality Program Eastern Region Office Section Manager, Spokane
- Air Quality Program Technical Services Section Manager, Headquarters, Lacey
- Environmental Assessment Program Ecology Quality Assurance Officer, Headquarters, Lacey

EPA Region 10

- Air Monitoring Specialist
- Senior Air Monitoring Specialist

Executive Summary

This Quality Assurance Project Plan (QAPP) outlines Ecology's quality system for ensuring accurate and reliable collection of $PM_{2.5}$ measurements using its custom-designed, low-cost air sensor, the SensWA.

While Ecology operates many Federal Equivalent Method (FEM) $PM_{2.5}$ monitors across the state, their high cost restricts their widespread deployment. With wildfire smoke becoming a greater air quality concern in Washington, and additional monitoring in overburdened communities being required by Washington's Climate Commitment Act, there is a need for many more PM2.5 measurements within the state.

PM2.5 sensors are a low cost, portable, and easy to operate alternative to regulatory air quality monitors and nephelometers. However, the data produced by commercially available sensors is highly variable and depends on the make and model of sensor. Most sensors also lack any indication of sensor deterioration over time. Furthermore, EPA guidance on evaluating sensor performance continues to evolve, meaning that there is no singular method for evaluating sensor data quality.

Ecology developed the SensWA to address these challenges and developed this QAPP to establish methods for evaluating their performance, conducting ongoing maintenance, and ensuring data quality through rigorous assessment procedures. It also provides information on the organizational structure, functional responsibilities of management and staff, lines of authority, and required interfaces for those planning, implementing, and assessing activities involving environmental data collected by SensWA.

Ecology uses SensWA for various air quality monitoring applications, including:

- Supplementing existing fixed-site air monitoring networks.
    - Increasing density of monitoring in communities where FRM/FEM-reported $PM_{2.5}$ concentrations are above 50% of the NAAQS.
    - Report AQI in communities lacking FRM/FEM monitoring and where $PM_{2.5}$ concentrations are below 50% of the NAAQS.
- Temporary monitoring of smoke from wildfires.
- Responding to isolated or emerging air quality events.
- Long-term high-density monitoring in identified overburdened communities.

This QAPP is to be used in conjunction with the Washington State Ambient Air Monitoring Network Quality Assurance Plan (QAP) (ECY-99-201) which describes Ecology's overall quality system for ambient air monitoring, and Ecology's Particulate Matter Sensors SOP (ECY -23-02-088) which contains extensive details and operational requirements for the use of SensWA and other potential low-cost PM sensor devices within the Washington Network.

1. Project Management

Federal, state, and local air agencies all have roles in developing air monitoring programs. The EPA sets the NAAQS and establishes minimum requirements for ambient air monitoring. State and local organizations implement quality systems to meet these requirements. Ecology's quality system for the SensWA is designed to produce non-regulatory monitoring information that is FEM-like in quality.

1.1. Ecology

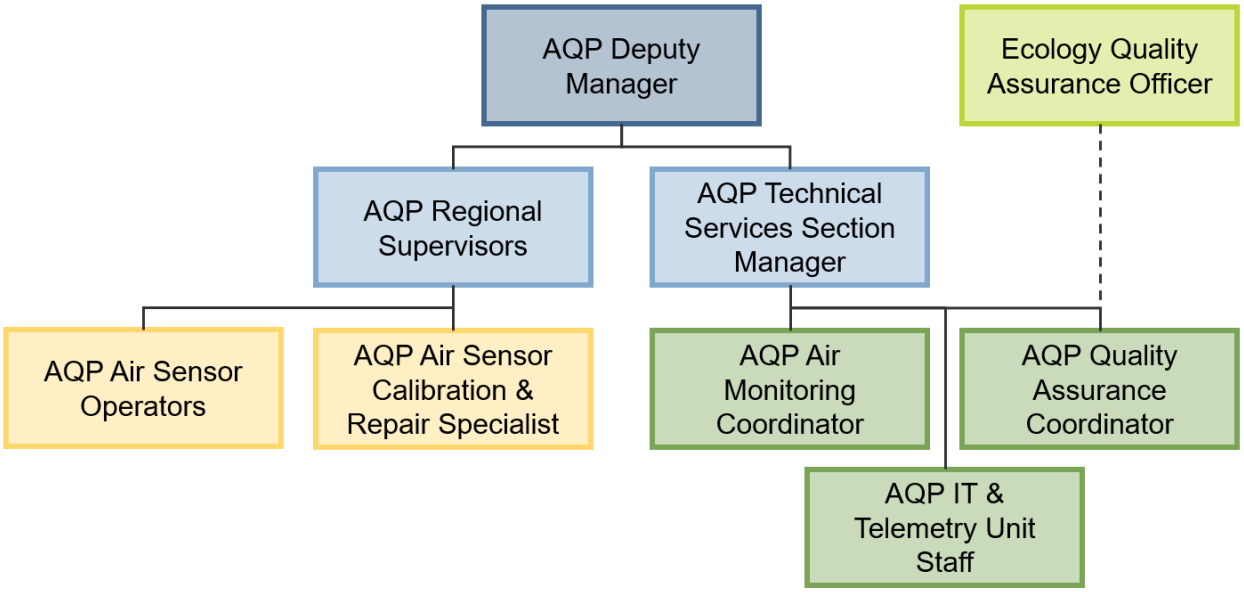

Figure 1-1: Organization hierarchy of Ecology's SensWA program

Air Quality Program Deputy Manager:

- Supervises Technical Services Section Manager

Air Quality Program Technical Services Section Manager:

- Supervises the Air Monitoring Coordinator, AQP QA Team, and IT and Telemetry Unit Staff

Air Quality Program Air Monitoring Coordinator:

- Develops and coordinates overall air sensor policy and SensWA deployment strategy.
- Selects monitoring sites in consultation with operators.
- In coordination with the Air Sensor Calibration and Repair Specialist and Quality Assurance Coordinator, develops SensWA regional correction factors.

Air Quality Program Air Sensor Calibration and Repair Specialist:

- Collaborates with Air Monitoring Coordinator and regional air monitoring operators to manage SensWA acquisition, distribution, and deployment.

- Designs, acquires component parts, constructs, tests, and performs annual maintenance on SensWA.
- In coordination with the Air Monitoring and Quality Assurance coordinators, develops regional SensWA correction factors.
- Writes and maintains the Particulate Matter Sensors SOP.

Ecology Quality Assurance Officer:

- Reviews and approves Ecology environmental program QAPPs.
- Reviews and approves SOPs written by environmental program staff, or delegates approval to program Quality Assurance Coordinators.

Air Quality Program Quality Assurance Coordinator:

- Leads QA team.
- Provides independent assessment of SensWA operations and validation of final dataset. Organizationally independent from air monitoring operations.
- In coordination with the Air Sensor Calibration and Repair Specialist and Air Monitoring Coordinator, develops SensWA regional correction factors and ensures adherence to this QAPP.
- Writes and maintains this QAPP.

Air Quality Program Air Sensor Operators:

- In consultation with the Air Monitoring Coordinator and Air Sensor Calibration and Repair Specialist, identify monitoring sites and deploy SensWA.
- Return SensWA annually to the Calibration and Repair Specialist.
- Review SensWA data and alert QA Team of any data issues.
- Perform in-field QC every 90 days.

Air Quality Program IT and Telemetry Unit Staff:

- Manage SensWA data telemetry, storage, and submittal to EPA's AirNow system.
- Write scripts to apply initial data screening steps and SensWA correction factors developed by Air Monitoring Coordinator, QA Coordinator, and Air Sensors Calibration and Repair Specialist.
- Track SensWA locations.

1.2. EPA Region 10

EPA regional offices oversee environmental programs for states within their jurisdiction. For Washington's SensWA program, EPA Region 10 provides technical assistance and oversight through activities such as:

- Serving as a liaison between Ecology and EPA's Office of Air Quality Planning and Standards and Office of Research and Development for technical and quality assurance matters.
- Evaluating Ecology's quality system performance through Technical Systems Audits.

2. Project Description

2.1. Background

The proliferation of low-cost PM sensors offers great promise for characterizing and communicating air quality at a high spatial resolution. These portable and readily deployable sensors offer a cost-effective approach to greatly expand the Washington State Ambient Air Monitoring Network (Washington Network), understand pollution at a finer spatial scale, and provide valuable air quality information to the public. However, because data quality from commercially available low-cost PM sensors varies widely by make and model, it is crucial to understand their performance in different aerosol environments in comparison to PM FEMs and apply correction factors to correct for bias.

Evaluations by Ecology and external governmental organizations have shown that many sensors exhibit moderate to strong correlation with regulatory-grade monitors (FRM/FEM). However, these relationships are not uniform across different aerosol environments, and correction factors are necessary to align sensor data more closely with FRM/FEM measurements.

It's important to note that sensor correction factors are not a one-size-fits-all solution. They can vary significantly depending on location, time of year, and environmental conditions. Factors like relative humidity, aerosol properties, and sensor age can all impact sensor performance and must be accounted for in both sensor design and correction factors.

Low-cost sensors lack built-in drying mechanisms which can lead to the inclusion of water vapor in PM mass concentrations. Additionally, the size, density, and composition of airborne particles can affect sensor response by influencing light scattering and absorption. Finally, long-term sensor deployment and exposure to varying pollution levels can also influence sensor performance and underscores the need for periodic recertification of accuracy and/or replacement.

Ecology conducted 3 years of comparative analysis of several different commercially available low-cost $PM_{2.5}$ air sensors in a wide range of aerosol environments across Washington State. Of the sensors tested, the Sensirion SPS30 sensor demonstrated the best statistical agreement with collocated $PM_{2.5}$ FEMs as well as a unique resistance to interference from humidity. In 2020, Ecology used the information from this comparative analysis to build a protype of its $PM_{2.5}$ SensWA low-cost sensor device. It includes two Sensirion SPS30 sensors to measure $PM_{2.5}$ concentrations. The SensWA is shown in Figure 2-1 below.

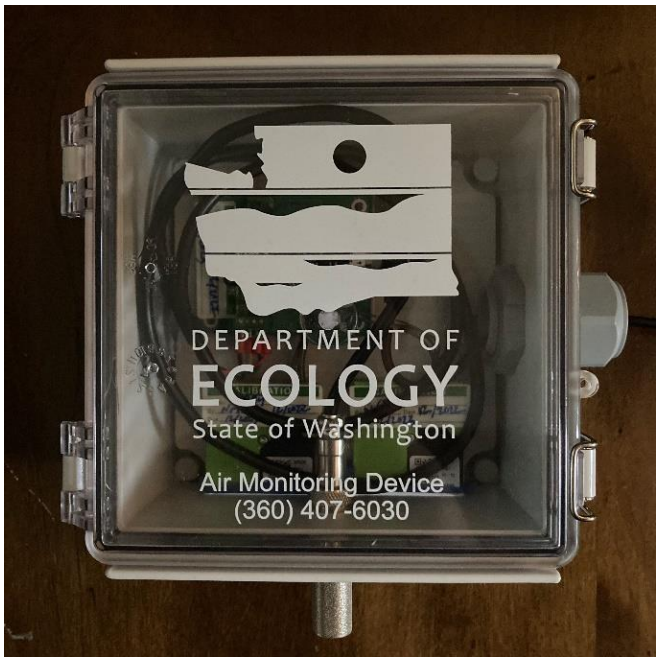

Figure 2-1: SensWA

Over the last 4 years, Ecology has made improvements to the design and performance of the SensWA and has scaled it up for wide-scale use within the Washington Network.

Ecology uses the SensWA for a variety of monitoring needs:

- Supplementing its existing fixed-site air monitoring network to improve spatial understanding of $PM_{2.5}$ gradients in communities across Washington State
- Temporary monitoring of smoke from wildfires
- Responding to isolated or emergent air quality events
- Aiding in smoke surveys or saturation studies of unmonitored areas
- High-density monitoring of identified overburdened communities,as required by the environmental justice provisions of the Washington State Climate Commitment Act (CCA)

2.1.1. Ecology air sensor policy and tiered approach

Ecology's Air Sensor Policy approved by its Monitoring Advisory Committee defines tiers of PM sensors based on the intended use and level of quality control/assurance required. The SensWA which is used for both Tier 2 and Tier 3 applications and the corresponding Data Quality Objectives for use within the Washington Network.

Tier 2 SensWA use is aimed at emergent, short-term, monitoring needs, such as wildland smoke and emergency response monitoring or saturation studies in currently unmonitored areas.

Tier 3 SensWA are deployed for long-term, fixed-site monitoring. They are used to supplement existing air quality monitoring stations and to provide finer spatial scale information in locations where it would otherwise be infeasible due to logistical or operational constraints.

Differences between Tier 2 and Tier 3 SensWA are listed in Table 2-1.

Table 2-1: SensWA Tiers

Tier	Use Case	30-day Collocation	Maximum Continuous Deployment	Siting Requirements	Data Review
2	Short-term monitoring	Recommended, but not required	6 months	Meet 40 C.F.R. Part 58 Appendix E if possible	Automated checks, daily dashboard review, cursory review by QA Coordinator
3	Long-term, fixed-site monitoring	Required	1 year	Must meet 40 C.F.R. Part 58 Appendix E	Tier 2 review + full review by QA (see Section 7)

Sensor tiering policy is developed by the Air Monitoring Coordinator in collaboration with the Air Sensor Calibration and Repair Specialist. Changes to the air sensor tiering policy require Monitoring Advisory Committee approval.

2.1.2. Sensor deployment

SensWA are sited, operated, and maintained solely by fully trained air quality professionals. This oversight results in much more trustworthy data than that gathered by most sensors. The level of oversight varies by sensor tier.

Tier 2:

- SensWA will be distributed to Ecology region operators by June 1 each year.
- Region operators will deploy Tier 2 SensWA at regional collocation hub when not in use at specific sites.
- Region operators must follow the quality control and annual maintenance procedures outlined in the SOP and this QAPP for Tier 2 SensWA.
- Region operators return Tier 2 SensWA to the Air Sensors Calibration and Repair Specialist by February 1 each year for annual maintenance and recertification.

Tier 3:

- Region operators will maintain a cluster of SensWA deployed at regional hubs, with each sensor collocated for 30+ days. Data obtained during collocation must meet acceptance criteria before deployment.
- Region operators interested in a SensWA for a Tier 3 deployment must submit a Tier 3 project proposal to the Air Monitoring Coordinator. The Air Monitoring Coordinator will collaborate with the Air Sensor Calibration and Repair Specialist and QA Coordinator to vet and approve Tier 3 proposals.
- Once a Tier 3 project is approved, region operators will work with the Air Sensors Calibration and Repair Specialist to ensure necessary supplies and equipment for site installation.
- Region operators will follow the quality control and annual maintenance procedures outlined in the SOP and this QAPP for 3 sensors.

2.2. Regulatory Background

The SensWA is not an approved FRM/FEM and the data generated by it cannot be used for determination of compliance with National Ambient Air Quality Standards.

Ecology's use of Tier 3 PM SensWA is intended to augment regulatory quality (FRM/FEM) PM measurements within overburdened communities highly impacted by air pollution. While air sensor data cannot be used for regulatory purposes, it is essential for communicating local air quality to the public, identifying potential pollution problems that are missed at a coarser resolution of monitors, and informing Ecology's efforts to track and reduce pollution levels within these communities.

2.3. Project Tasks

Ecology's activities for managing the SensWA include:

- Parts/supplies acquisition, construction, and SensWA distribution.
- SensWA deployment and data collection.
- QC, maintenance, and replacement schedules.
- Data review and validation procedures.
- Data management and reporting.
- Development of SOP for SensWA setup, operation, and data acquisition.
- Collocation verification by deploying sensors alongside FEM monitors for a minimum of 30 days before deployment.
- Assessment of SensWA performance to collocated PM2.5 FEM at collocation hubs.
- Development of regional/seasonal correction factors.

2.4. Study Locations and Collocation Hubs

Washington is divided into two distinct geographic regions by the north-south Cascade Mountain Range. West of the Cascade Range, summers are relatively cool and dry, and winters are marked by mild cool temperatures and frequent precipitation. Annual precipitation in Western Washington ranges from approximately 20 inches along the Strait of Juan de Fuca to 150 inches on the southwest slopes of the Olympic Range. Western Washington is more densely populated, containing approximately 60% of the state's population and most of its major cities. Dominant sources of criteria pollutants include on-road and non-road vehicles, residential wood combustion, and industrial point sources.

Eastern Washington is part of an inland basin spanning several states between the Cascade and Rocky Mountains. Eastern Washington experiences warmer summers, cooler winters and less precipitation than does western Washington. In eastern Washington, annual precipitation ranges from approximately 7-9 inches near the Tri-Cities to approximately 75-90 inches near the Cascade Range, though most of the region experiences fewer than 25 inches of precipitation per year (Western Regional Climate Center). Eastern Washington contains the state's major agricultural areas. Dominant sources of criteria pollutants in eastern Washington

include wildfires, on-road and non-road mobile sources, agricultural and silvicultural burning, and dust from tilling, harvesting and roads.

Low-cost sensor performance can be affected by meteorological conditions, localized aerosol properties, and source emissions. The variability of Washington State's climate, topography, population density, and dominant sources creates regions with very different aerosol composition.

For this reason, Ecology has established regional $PM_{2.5}$ SensWA collocation hubs to develop region-specific correction factors for PM sensors used within the Washington Network. These correction factors ensure a high degree of accuracy of $PM_{2.5}$ measurements across regions of relatively homogenous aerosol composition. The regional collocation hubs listed by Ecology region are listed in Table 2-2.

Table 2-2: SensWA Collocation Hub locations

Region	Site Name	Latitude	Longitude
Northwest	Seattle Beacon Hill	47.5682	-122.309
Southwest	Lacey College St	47.0294	-122.822
Southwest	Tacoma L St	47.1864	-122.4517
Southwest	Vancouver NE 84th Ave	45.64336	-122.587
North Central	Ellensburg Ruby St	46.99364	-120.545
South Central	Yakima 4th Ave S	46.59495	-120.512
Eastern	Spokane Valley E Broadway Ave	47.66396	-117.258

Figure 2-2 below shows the location of each collocation hub, as well as the location of each currently deployed sensor (as of June 2024).

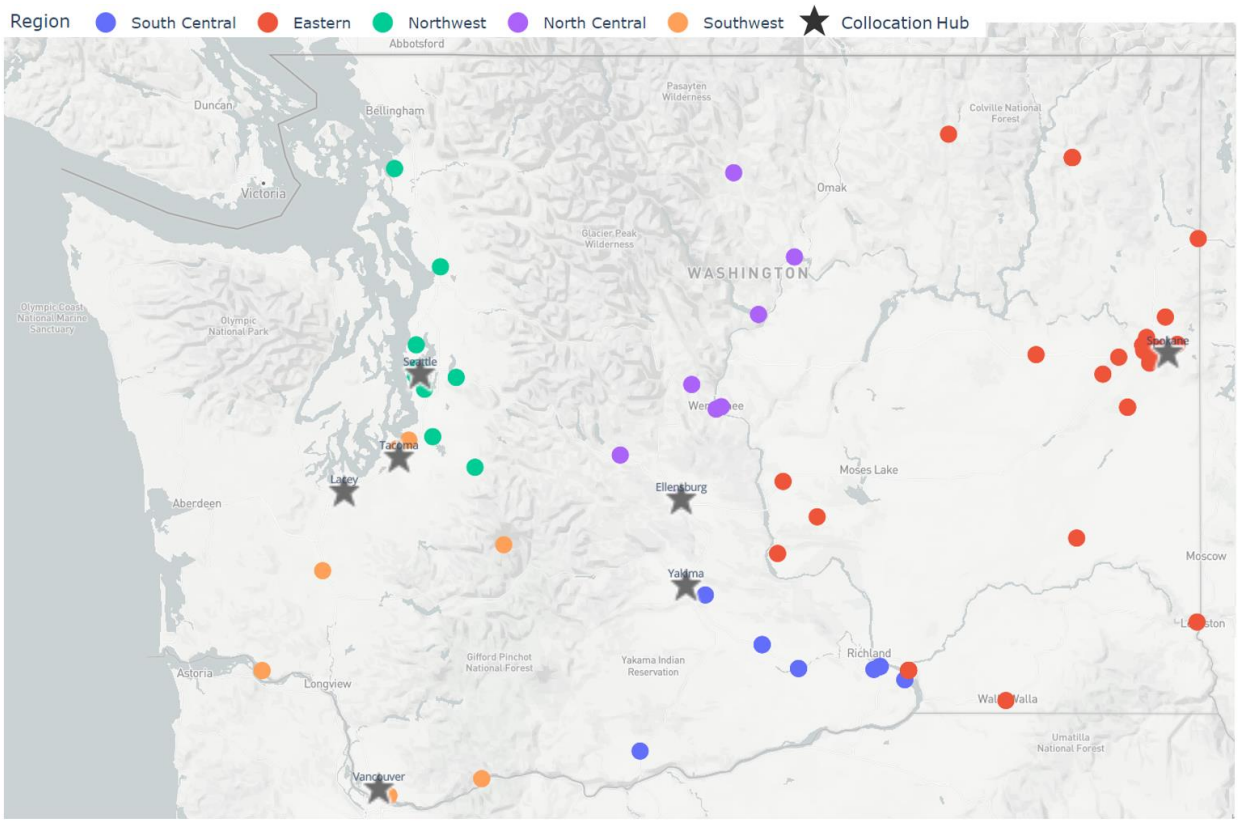

Figure 2-2: Location of $PM_{2.5}$ FEM-SensWA collocation hubs and regionally deployed sensors

2.5. Project Timeline

Sensor deployments are ongoing. The project has no defined end date.

3. Data Quality Objectives and Criteria

Ecology's approach to defining Data Quality Objectives (DQOs) and Measurement Quality Objectives (MQOs) for Tier 2 and 3 SensWA within the Washington Network is consistent with the EPA Quality Assurance Handbook (EPA-454/B-18-006) and Ecology's Air Monitoring Quality Assurance Plan (ECY-99-201) to ensure that data collected is of appropriate type and known quality for intended uses. To achieve this goal, MQOs have been defined. All MQOs in Table 3-1 apply to Tier 3 sensors and Tier 2 sensors when a collocation was performed. If a collocation was not performed for a Tier 2 sensor, only the deployment MQOs apply.

MQOs were developed using EPA's 2021 publication *Performance Testing Protocols, Metrics, and Target Values for Fine Particulate Air Sensors*, particularly Section 3, *Performance Metrics and Supporting Calculations for Evaluating $PM_{2.5}$ Air Sensors*. Ecology has elected to use stricter MQOs in some cases, to ensure that only the best-performing sensors are deployed.

3.1. Measurement Quality Objectives

Project specific MQOs and Ecology's approach to achieve them are discussed in the following sections. A summary of all MQOs is provided in Table 3-1.

Table 3-1: Collocation performance criteria

MQO	Data Quality Indicator	Applies During	Acceptance Criteria
Precision	Channel Agreement	Deployment, Collocation	See section 3.2
Precision	CV	Collocation	≤ 10%
Linearity	r^2	Collocation	≥ 0.7
Bias	Slope	Collocation	1 ± 0.3
Bias	Intercept	Collocation	± 0.3 µg/m^3
Bias	Zero Test	Annual Testing	≤ 0.5 µg/m^3
Completeness	Percent valid data	Deployment, Collocation	≥ 90%
Accuracy	RMSE	Collocation	≤ 6 µg/m^3
Accuracy	sMAPE	Collocation	≤ 30%
Accuracy	MAE	Collocation	≤ 6 µg/m^3

Statistical metrics are calculated separately for:

- **24-hour averages:** Consistent with the reference FEM PM monitor and EPA recommendations for $PM_{2.5}$ sensor evaluation.
- **1-hour averages:** While 1-hour metrics may not always meet MQOs due to inherent variability in short-term measurements (from both sensors and FEMs), they allow for analysis of sensor response time to changing concentrations.
- **Wildfire vs. non-wildfire periods:** Separating data by wildfire influence helps isolate the impact of these events on sensor performance.

3.1.1. Precision

Precision is a measure of how reproducible sensor measurements are. High precision means that repeated measurements under identical conditions will produce very similar results.

Precision is defined to mean different things during collocation and deployment. During collocation, it is a measure of the reported standard deviation. During deployment, precision is a measure of comparison between channels.

3.1.1.1. During deployment

The SensWA is equipped with two sensing elements that report on separate channels. To identify when one sensor starts to drift or fail, values between these channels are compared periodically (by the QA Unit) and continuously (by automated data screening).

The specific procedures for screening sensor data are described in Section 3.2.

3.1.1.2. During collocation

Over the collocation period, precision is measured by calculating the coefficient of variation (CV) using Formula 1:

$$CV = \frac{SD}{x} * 100 \quad (1)$$

Where:

CV = coefficient of variation (%)
SD = standard deviation of sensor concentration (µg/m^3)
x = average sensor concentration (µg/m^3)

3.1.2. Bias and Linearity

Bias is the difference between a sensor's average measurement and the "true" (in this case, FEM) concentration. A positive bias means the sensor consistently overestimates.

Linearity describes a sensor's ability to produce a response that is proportional to an actual concentration.

Ecology evaluates SensWA bias through collocation with $PM_{2.5}$ FEM at one of six regional collocation hubs. Over a 30+ day collocation period, a linear regression model is used to compare SensWA and FEM data. The slope and offset from this model are used to assess bias and linearity. An offset of 0 means that the SensWA is not biased. A slope of 1 means that the sensing element (SPS30) responds linearly across a range of concentrations on average.

Additionally, a low coefficient of determination (r^2) indicates that the SensWA does not vary widely from true concentrations.

If a SensWA's slope, offset, or r^2 differ significantly from other sensors, that can be an indication that the SensWA is lacking precision. Therefore, bias and linearity are determined before applying any correction factor.

3.1.3. Representativeness

Representativeness is a measure of how well a given monitor captures actual PM concentrations in the target area it is monitoring. Factors like siting, local topography, and meteorological variations can influence representativeness.

SensWA are being used with the goal of obtaining more representative data. For many locations in Washington, the nearest regulatory monitor is 100+ miles away. In the complex terrain of the Cascades and the Rocky Mountains, conditions can vary significantly over a short distance.

To ensure a SensWA is reporting representative data, site selection is critical. The selected location must consider local sources of air pollution, topography, and meteorology. Furthermore, sensors must be installed with unrestricted airflow to allow for proper circulation. The full range of siting requirements for SensWA is described in section 3.1 of Ecology's PM Sensor SOP (ECY-23-02-088).

3.1.4. Completeness

Completeness is the percentage of valid data obtained out of the total amount planned. Incomplete datasets can lead to the wrong conclusion, or indicate an underlying issue, such as sensor malfunction.

Causes of invalid data include communication issues and SensWA malfunction. If completeness from a SensWA falls below 90% over a 24-hour period, it will continue to collect data, but will stop streaming to external data displays.

3.1.5. Comparability

Comparability describes how well SensWA data can be compared to measurements obtained from other SensWA or monitors (e.g., FEM $PM_{2.5}$ monitors). This ensures consistency across different data sources and allows for comparison between locations and instruments.

SensWA $PM_{2.5}$ concentrations are reported to Ecology's Air Quality Map and EPA's AirNow map as 1-hour averages. Data from these sites can be viewed and downloaded as a 1-hour or 24-hour average. This allows for comparison between PM instruments for multiple time periods, as well as comparison to the 24-hour NAAQS.

3.1.6. Sensitivity

Sensitivity is the ability to detect changes in air pollutant concentrations. A high sensitivity sensor can pick up small fluctuations in PM levels.

SensWA reports concentrations to one tenth of a microgram per cubic meter and have demonstrated more than sufficient sensitivity for the purposes of this project.

3.1.7. Accuracy

Accuracy describes how close a sensor's measurements are to true (FEM) concentrations.

Accuracy is assessed by calculating error, using root mean square error (RMSE), mean absolute error (MAE), or symmetric mean absolute percentage error (sMAPE). RMSE and MAE provide

an absolute value in concentration units. As such, their magnitudes depend on measured concentration. sMAPE is relative and provides values as a percent. It can be more informative at high concentrations and allows for comparison across concentration ranges. It is less affected by low-concentration data than other percentage-based measures of accuracy. It also allows for a percentage-based calculation of accuracy even when FEM concentrations are 0. However, all measures of accuracy are dependent on the range of measured concentrations to some extent. Results should be interpreted within the context of the range of measured concentrations.

Equations for calculating RMSE, MAE, and sMAPE are provided in Equations 2, 3, and 4 below:

$$RMSE = \sqrt{\frac{1}{(N * M)} \sum_{j=1}^{M} \left[\sum_{d=1}^{N} \left(x_{dj} - R_d \right)^2 \right]} \quad (2)$$

Where:

RMSE = root mean square error (µg/m^3)

N = number of periods

M = number of sensors

x_{dj} = sensor concentration for day d and instrument j (µg/m^3)

R_d = average FEM concentration for day d (µg/m^3)

$$MAE = \frac{\sum_{i=1}^{n} | |y_i - x_i|}{n} \quad (3)$$

Where:

MAE = mean absolute error (µg/m^3)

n = number of 24-hour paired data points

y = sensor concentration

x = FEM concentration

$$sMAPE = \frac{100}{n} \sum_{1=1}^{n} \frac{|y_i - x_i|}{|y_i| + |x_i|} \quad (4)$$

Where:

sMAPE = Symmetric Mean Absolute Percentage Error

n = number of 24-hour paired data points

y = sensor concentration

x = FEM concentration

3.2. Data Screening Rules

This section outlines the data screening procedures applied to SensWA data. The objective is to ensure data quality and identify potentially invalid measurements.

Data is streamed from the SensWA's dual Sensirion SPS30 in 10-minute chunks, comprised of 1-minute measurements.

3.2.1. Initial data ingest

The data are first scrubbed to format the data for import, and identify instrument power-up events:

- Replace "nan" or "-nan" values with "-9.9" and set the status to "no data" for all parameters except temperature, which is replaced with "-99".
- If a value in the timestamp column is "UNIX__TIME", discard the entire 10-minute data set. This indicates a device power-up event, resulting in potentially unreliable data.

3.2.2. Data screening and validation

The SensWA reports its dual Sensirion SPS30 channels as EPM1 and EPM1_2. These values are multiplied by the appropriate regional/seasonal correction factor to create channels EPM25_corrected and EPM25_2_corrected.

EPM25_corrected is the default for public display through Ecology's air monitoring website and externally to EPA's AirNow, with EPM25_2_corrected serving as a backup.

To identify issues with sensors, values from each sensor channel are compared. If the values differ significantly, it indicates that one has failed or started to drift. The following checks are applied to compare the EPM25_corrected and EPM25_2_corrected channels:

- If the lesser value is > 35 ug/m^3, and the values differ by more than a factor of 1.5, invalidate both.
- If the lesser value is between 10 and 35 ug/m^3, and the values differ by more than a factor of 2, invalidate both.
- If the lesser value is < 10 ug/m^3, and the values differ by more than a factor of 3, invalidate both.

This comparison check can be bypassed by setting the state of one channel to "off" in Envista Setup. Data should not be collected without this check for periods longer than one week.

If the EPM25_corrected or EPM25_2_corrected channels are reporting >10% invalid, data reporting to FASM and AirNow is turned off and the air monitoring operator and Air Sensors Calibration and Repair Specialist investigate the cause.

4. Personnel Qualifications and Training

Any instrument operated within the Washington Network, including SensWAs, are to be sited, installed, operated, and maintained by trained air quality professionals only. The requirements for air monitoring personnel qualifications and training are described in Section 6 of the Washington Ambient Air Monitoring QAP.

Requirements specific to SensWA operation include:

- Read and become familiar with Ecology's Air Sensors SOP and QAPP (this document).
- Read and become familiar with Ecology's Air Monitoring Documentation, Data Review and Validation, and Site Selection and Installation SOPs.
- Train with the Air Sensors Calibration and Repair Specialist on the following:
    - Deployment and siting of SensWA
    - Procedures for conducting quarterly field QC checks
    - Data review tools and procedures
    - Troubleshooting issues with power, connectivity, and component failure

5. Documentation and Records

Documentation and record keeping for SensWA follows the data management and record-keeping procedures outlined in the Washington Ambient Air Monitoring QAP (ECY-99-201).

An internal Microsoft Teams group has been established specifically for air monitoring personnel involved with the SensWA quality system. This platform facilitates collaboration on SensWA deployment plans, including deployment dates, locations, associated issues, and findings. Additionally, any R scripts developed for data review will be shared within this Teams group.

SensWA data are stored in Ecology's air monitoring SQL database and retained indefinitely. Data collected in the SQL database can be accessed by operators and QA staff through the EnvistaARM (ARM) desktop software. Data in ARM are backed up to an offsite server daily. Data suitable for public reporting are made available through Ecology's air monitoring website and EPA AirNow system.

All SensWA onsite maintenance and activities must be documented in the site-specific electronic logbook through the ARM.

As described in the Washington Ambient Air Monitoring QAP, documents are version controlled. Ecology posts all current air monitoring SOPs and QAP/QAPPs on its publicly accessible website. Links to the most current versions of the SensWA QAPP and Particulate Matter Sensors SOP are distributed via email to air monitoring personnel upon revision. These documents are retained electronically by the Quality Assurance Coordinator in a secure, backed-up network location and are available online for authorized access.

6. Data Generation and Acquisition

6.1. Sample Process Design

Tier 2 SensWA are distributed each spring to region operators by June 1st. Ecology Region offices can request Tier 3 SensWA by submitting a Tier 3 project proposal to be evaluated by a MAC-authorized subcommittee consisting of the Quality Assurance Coordinator, Air Monitoring Coordinator, Air Sensors Calibration and Repair Specialist, and IT staff.

SensWA data are reviewed daily by the Air Sensor Calibration and Repair Specialist to identify irregularities. The internal SensWA dual SPS30 channels are reviewed to ensure concentrations from each channel consistently track each other (precision). Where the dual channels diverge or other anomalies are seen, the automated checks described in Section 3.2 flag and invalidate incoming data. Upon noticing this issue, the site operator will inspect the SensWA in consultation with the Air Sensor Calibration and Repair Specialist.

When Tier 2 and Tier 3 SensWA are not actively deployed for monitoring, regional operators will place them at regional collocation hubs. Collocation hubs are used to develop and annually update regional correction factors.

Tier 3 SensWA must be installed according to the requirements and guidance in 40 CFR 58, Appendix E and described in Ecology's Air Monitoring Site Selection and Installation Procedure. To the extent possible, Tier 2 SensWA used for wildland fire smoke monitoring and other emergent, short-term, deployments should also follow Appendix E siting requirements. Additional siting requirements and guidance are discussed in Section 3 of Ecology's Particulate Matter Sensors SOP.

6.2. SensWA Collocation Method

Unlike FEM/FRM monitors that can be periodically calibrated, the Sensirion SPS30 sensors in SensWA cannot be adjusted. This is because these sensors don't accurately respond to the calibration gases used to calibrate other optical method monitors, such as nephelometers (CO_2 and Suva®) (J. R. Ouimette et al., 2022).

In lieu of calibration, Ecology collocates its SensWAs alongside $PM_{2.5}$ FEMs (Met One BAM 1020 or BAM 1022) monitors. Comparisons of the collocated SensWA data to the FEM are used to determine whether the SensWA is operating within the acceptance criteria described in Section 3.1. SensWAs that do not meet these criteria are not used, and returned to the Calibration and Repair Laboratory. Any SPS30 that did not meet collocation requirements will be discarded and replaced. Afterwards, the SensWA may undergo collocation once again.

SensWA that meet the requirements in Section 3.1 are used to develop correction factors at regional collocation hubs. SensWA concentrations at regional hubs are compared to $PM_{2.5}$ FEM regulatory concentrations through linear regression to determine a region-specific correction factor. Raw sensor concentrations from channels EPM1 and EPM1_2 are multiplied by this correction factor to improve accuracy.

The collocation-correction process improves the accuracy of SensWA to produce FEM-like concentrations.

6.2.1. Continuous subset collocation strategy

Tier 3 SensWAs must undergo a minimum of 30-day collocation prior to deployment. While 30-day collocation is not required before deploying a Tier 2 sensor, use of a sensor that has passed a 30-day collocation is preferable and recommended.

Ecology adapted the "Continuous Subset Strategy" from the EPA's Enhanced Air Sensor Guidebook. Under this approach, SensWA are collocated with a $PM_{2.5}$ FEM for a minimum of 30 days. Tier 3 SensWA that meet Section 3.1 requirements are deployed to monitoring sites within the region represented by the regional collocation hub. A subset of SensWA continuously remain at the collocation hub for ongoing correction development (see section 6.3) and performance monitoring over time.

Collocation hubs are selected based on the representativeness of the meteorological conditions and aerosol composition of regions within Washington State. Additionally, the amount of space required and frequency of access of collocation hubs place practical constraints on their location.

The minimum 30-day duration of collocation for Tier 3 SensWA balances the opposing needs for exposure to a range of ambient concentrations and reasonably quick deployment. If a sufficiently diverse range of concentrations is not observed in 30 days, a longer collocation may be required, as determined by the Air Sensor Calibration and Repair Specialist.

The Air Sensor Calibration and Repair Specialist and the QA Coordinator use 1-hour and 24-hour averaged data to evaluate sensor performance with the statistical metrics described in section 3.1, with a focus on agreement between a SensWA's raw data channels, agreement with other collocated SensWA, and comparability to the collocated FEM. Sensors not meeting performance standards must be returned to the Air Sensors Calibration and Repair Specialist to undergo repair or replacement. Each Tier 3 SensWA must pass a 30-day collocation before deployment.

Following a maximum of one year (365 days) of deployment (not including the collocation period), SensWA are returned to the Calibration and Repair Laboratory for annual maintenance and zero testing.

Figure 6-1 shows a SensWA collocated with a $PM_{2.5}$ FEM (BAM 1020).

Figure 6-1: SensWA collocated with a $PM_{2.5}$ BAM

6.2.2. Collocation assessment tools

Ecology has developed a spreadsheet tool that incorporates SensWA and FEM data to evaluate performance. The tables and charts it generates indicate whether the criteria for deployment are met, as determined by the Air Sensor Calibration and Repair Specialist. These criteria are described in Section 3.1, and listed in Table 3-1.

6.3. Correction Factor Development

Ecology has three primary goals that drive the SensWA correction approach:

- Aim for highest accuracy around 35 µg/m^3. This is the level of the 24-hour $PM_{2.5}$ standard, and the point at which the $PM_{2.5}$ AQI changes from Moderate to Unhealthy for Sensitive Groups (EPA-454/B-02-002).
- Minimize misclassification by AQI category.
- Err on the side of overestimation to be more protective of human health, especially in higher AQI categories.

Ecology uses a linear regression model to derive a linear correction factor (slope) to correct SensWA readings. A constant intercept of 1.5 µg/m^3 is added to all values to avoid underprediction of concentrations.

While the SensWA reports concentrations for PM_1, $PM_{2.5}$, and PM_{10} on the EPM1, EPM25, and EPM10 channels respectively, Ecology has seen the best linear regression results with the EPM1 channel to estimate $PM_{2.5}$ concentrations. For this reason, the correction factor is derived from and applied to this channel.

Ecology currently develops regional corrections by combining correlation data from multiple collocation sites that are in the same region of the state and expected to have similar airshed conditions. At this time, Ecology generally defines two seasons for SensWA correction based on predominant $PM_{2.5}$ source: wildfire smoke (late-spring to early-fall) and home-heating smoke (late-fall to early-spring). Ecology will continue to refine its regional and seasonal SensWA correction factor approach in the future.

In addition to PM, SensWA measures ambient temperature and relative humidity. While EPA studies (Barkjohn et al., 2021) have shown that high temperatures (>80° F) coinciding with high RH (>70%) can cause interference with sensors, these conditions are extremely unlikely to occur at the same time in Washington. The scatter plot provided in Figure 6-2 shows that these conditions have not co-occurred at the Seattle Beacon Hill site. Therefore, Ecology is not currently adjusting sensor readings based on temperature or RH. We will continue to evaluate this relationship as more information is collected to determine if a temperature or RH correction factor is warranted in the future.

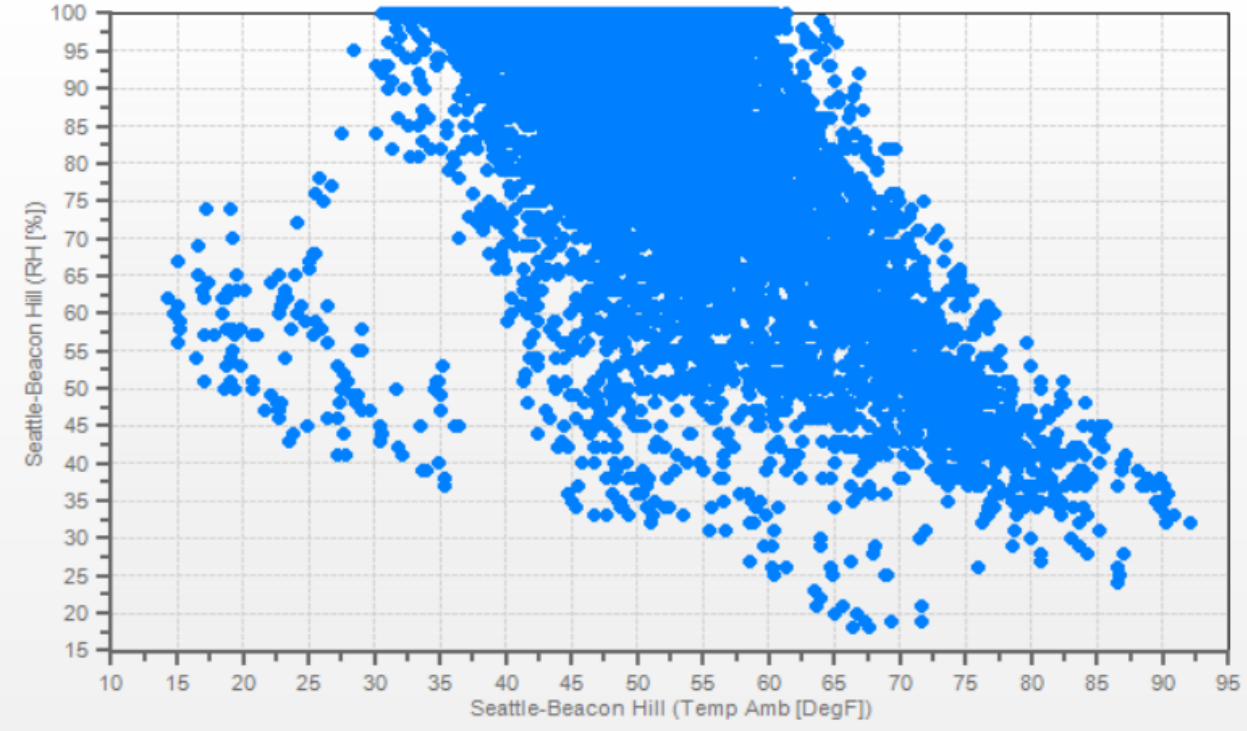

Figure 6-2: Temperature vs RH at Seattle Beacon Hill site

6.4. Sampling Methods

Documents supporting SensWA monitoring, including relevant SOPs and Ecology's QAP, are provided in Table 6-1.

Table 6-1: Supporting documents

Document Title	Ecology Publication Number	Date Revised
Washington Ambient Air Monitoring Network Quality Assurance Plan	99-201	January 2021
Air Monitoring Documentation, Data Review and Validation Procedure	17-02-013	May 2024
Air Monitoring Site Selection and Installation Procedure	16-02-021	February 2024
Ecotech Nephelometer Operating Procedure	09-02-005	November 2022
M903 Nephelometer Operating Procedure	01-02-001	June 2023
Met One BAM 1020 Operating Procedure	17-02-005	July 2024
Met One BAM 1022 Operating Procedure	24-02-002	March 2024
PM Sensors Operating Procedure	23-02-088	June 2024

6.5. Quality Control Activities

The frequency and type of QC checks conducted on SensWA and the data they produce are summarized in Table 6-2.

Table 6-2: Frequency and types of quality control activities for Tier 2 and Tier 3 SensWA

Location	Quality Control Activities	Frequency
Site Inspection	Inspect the inlets for signs of spider webs and water damage Ensure that the SensWA is securely attached to its support Clean the solar panel (when applicable) Reposition the solar panel to the appropriate seasonal angle	Quarterly
Calibration and Repair Laboratory	Zero-point box test Cleaning Functional checks Replacement of parts as needed	Annually
Data Review	Dual-channel Sensirion SPS30 comparison Automated data checks	Weekly

6.6. Field Quality Control Activities

Routine visual inspections and basic maintenance are essential for ensuring SensWA data quality. Site operators are responsible for conducting the following QC activities at a minimum of every 90 days:

- Check for water damage or spiderwebs around inlets.
- Ensure the SensWA is securely attached to its support structure.
- Clean the solar panel (if applicable).
- Reposition the solar panel to the appropriate seasonal angle (as instructed in the SOP).

While the SensWA is designed to be relatively maintenance-free, operators must contact the Air Sensor Calibration and Repair Specialist if any issues impacting measurements or data quality arise during QC checks.

If a SensWA becomes inaccessible, such as during heavy winter snowstorms or hazardous air quality wildfire smoke events, but is still reporting data, data review will solely be relied on to determine data validity. As soon as the SensWA again becomes accessible, the site operator must perform the quality control inspection as soon as feasible.

6.7. Initial and Ongoing Testing, Inspection, and Maintenance

All SensWA undergo initial testing by the Air Sensor Calibration and Repair Specialist in the Lacey building laboratory before deployment. This testing checks that the instrument is recording concentrations, transmitting data, and that all components are functioning properly. SensWAs that pass initial testing are distributed to air monitoring operators for installation at a regional collocation hub to begin their 30-day collocation. Data collected during collocation is used to assess performance and ensure proper function before deployment at permanent monitoring locations. Specific metrics are discussed in Section 3.

Following deployment, operators inspect SensWA for damage and general cleanliness at a minimum of once every 90 days. If issues are identified, or after a maximum deployment of one year (365 days), SensWA are returned to the Calibration and Repair Laboratory for inspection, maintenance, and zero testing. Following cleaning and any necessary replacement of parts, a zero test is performed by the Air Sensors Calibration and Repair Specialist by placing the SensWA into a chamber filled with particulate free air for 4 hours. If the average concentration reported over this period is less than 0.5 $\mu g/m^3$, the zero test passes. PM concentrations measured during this test are then analyzed to identify a bias in sensor readings.

6.8. Calibration Frequency

SensWA have no calibration requirements for normal operation. Instead, collocation analysis and data review are used to assess performance over time. If an issue with one of the internal Sensirion SPS30 elements is identified, that SensWA is returned to the Calibration and Repair Laboratory, and the faulty element is replaced with a factory-calibrated spare.

6.9. Non-Direct Measurements

SensWA records RH and temperature measurements in addition to PM concentrations. While these parameters are not used for correction factor development, they are recorded in Ecology's central database to allow for their use in the future.

6.10. Data Management

SensWA data are collected with 1-minute resolution and transmitted every 10 minutes via cellular connection to Ecology's central database. Screened and corrected data from publicly-reporting SensWA are made available through Ecology's air monitoring website and submitted to EPA's AirNow. Data from SensWA collocated with FEMs are available upon request.

For a full discussion of data management practices, please see section 17 of the Washington Air Monitoring QAP (ECY-99-201).

7. Data Validation and Usability

7.1. Preliminary Review

Preliminary data review is conducted by site operators for both SensWA tiers. The data should be checked at least weekly, preferably on a Monday to allow time in the week to schedule a site visit to address any identified issues. Operators must report any suspected data quality issues to the QA Coordinator and the Air Sensor Calibration and Repair Specialist.

Preliminary review includes the following:

- Begin by comparing the data from each SPS30 channel. If a clear outlier is identified:
    - Try to identify which channel has the fault by comparing to other nearby PM monitors or looking at the rate of change over time.
    - If the faulty channel can be identified, ensure that this channel is not being used for data reporting (Channel 1 is default).
    - If it cannot be identified, invalidate both channels.
    - Schedule a time to replace the SensWA as soon as possible. Only report from a SensWA with one valid channel for a maximum of one week.
- Investigate hourly data points greater than 2 standard deviations above the daily mean.
- If a FEM monitor exists within 50 miles, compare the hourly and daily means of the sites. Investigate significant discrepancies (difference > 50 $\mu g/m^3$).
- Within the ARM, "Group Reports" should be used for routine comparisons. Time series plots can compare nearby $PM_{2.5}$ measurements using multiple methods.
- Review data completeness. If daily completeness falls below 90%, investigate further. Data incompleteness can be the result of:
    - Intermittent power failure
    - Poor cell signal
    - Malfunctioning components
- Investigate occurrences of 8+ hours with identical values. A "stuck value" could indicate sensor malfunction.

7.2. Secondary Review

After preliminary review, QA staff conduct a more in-depth validation of Tier 3 data using the methods described in Section 4 of Ecology's Data Review, Documentation, and Validation SOP (ECY 17-02-013). This includes the following:

- When a sensor channel reports data concentrations > 1000 $\mu g/m^3$, review the data more closely. Consider the following:
    - Is the area impacted by wildfire smoke?
    - Are other PM instruments in the area reporting high concentrations?
    - Do both sensor channels agree?

  If the high concentrations appear to indicate an issue with the SensWA, invalidate its data and schedule a replacement as soon as possible.

- Compare hourly and daily averages between sensor channels if data from both channels is > 75% complete. Ensure that the data screening rules described in section 3.2 have been implemented.

7.3. Invalidation Criteria

SensWA data must be invalidated when outside acceptable limits of error as described in earlier sections of this QAPP. If data are within acceptable limits of error but an issue is identified in field operation, QA personnel will use a weight-of-evidence approach to determine data validity. Data quality criteria include:

- **Completeness:** 54+ minutes per hour, and 22+ hours per day.
- **Sensor channel agreement:** See Section 3.2.

Other issues that may warrant invalidation include:

- **Sensor drift:** Concentrations become progressively lower or higher over time.
- **Outliers:** Odd patterns in data, sporadic periods of high concentration, values inconsistent with nearby ambient concentrations recorded by other monitors.
- **Noisy data:** Highly variable concentrations from minute to minute or hour to hour.
- **Power/communication issues:** All concentrations are zero or error codes.

References

Ambient Air Quality Surveillance, 40 C.F.R. Part 58, 2024.

Barkjohn, K. K., Gantt, B., & Clements, A. L. (2021). Development and application of a United States-wide correction for PM2.5 data collected with the PurpleAir sensor. *Atmospheric Measurement Techniques*, *14*(6), 4617–4637. https://doi.org/10.5194/amt-14-4617-2021

Clements, A., Duvall, R., Greene, D. and Dye, T., 2022. The enhanced air sensor guidebook. *Washington, DC: US Environmental Protection Agency*.

Cooperative Climatological Data Summaries, Western Regional Climate Center, 2024. Web. 12 May 2024. https://wrcc.dri.edu/summary/Climsmwa.html

Duvall, R., Clements, A., Hagler, G., Kamal, A., Kilaru, V., Goodman, L., Frederick, S., Barkjohn, K., VonWald, I., Greene, D. and Dye, T., 2021. Performance Testing Protocols, Metrics, and Target Values for Fine Particulate Matter Air Sensors: Use in Ambient, Outdoor, Fixed Sites, Non-Regulatory Supplemental and Informational Monitoring Applications. *US EPA Office of Research and Development*. (EPA/600/R-20/280).

Ouimette, J. R., Malm, W. C., Schichtel, B. A., Sheridan, P. J., Andrews, E., Ogren, J. A., and Arnott, W. P. (2022). Evaluating the PurpleAir monitor as an aerosol light scattering instrument. *Atmospheric Measurement Techniques*, *15*(3), 655–676. https://doi.org/10.5194/amt-15-655-2022

U.S. Environmental Protection Agency. Office of Air Quality Planning and Standards. *Data Quality Objectives (DQOs) For Relating Federal Reference Method (FRM) and Continuous $PM_{2.5}$ Measurements to Report an Air Quality Index (AQI).* (EPA-454/B-02-002).

U.S. Environmental Protection Agency. Office of Air Quality Planning and Standards, Air Quality Assessment Division. *Guide to Writing Quality Assurance Project Plans for Ambient Air Monitoring Networks.* (EPA-454/B-18-006).

U.S. Environmental Protection Agency. Office of Research and Development. *Performance Testing Protocols, Metrics, and Target Values for Fine Particulate Matter Air Sensors*. Research Triangle Park, 2021 (EPA-600/R-20-280).

Washington Climate Commitment Act. (RCW 70A.65.900).