SensWA Correlations for $PM_{2.5}$ Reporting

Technical Document

DEPARTMENT OF ECOLOGY
State of Washington

Introduction

The Washington Department of Ecology (Ecology) operates a network of SensWA sensors for monitoring fine particulate matter ($PM_{2.5}$) across Washington. The SensWA are non-regulatory monitoring instruments used to provide real-time Air Quality Index (AQI) data to the public and to estimate $PM_{2.5}$ concentrations. Their applications include monitoring smoke impacts from wildland fires, responding to isolated or emergent events, monitoring to aid in smoke management decisions, surveys or saturation studies of unmonitored areas, and high-density monitoring of overburdened communities.

More information about the SensWA can be found in the following Ecology publications: Focus on SensWA, Particulate Matter Sensors Standard Operating Procedures, and SensWA Quality Assurance Project Plan (QAPP). This technical document describes Ecology's procedure for correlating raw sensor data with Federal Equivalent Method (FEM) $PM_{2.5}$ data in order to report estimated $PM_{2.5}$ mass concentrations meeting the Data Quality Objectives (DQOs) defined in the QAPP.

Ecology develops separate correlation equations for different regions across Washington and applies different correlation equations during the summer and non-summer seasons. Based on a tendency to underpredict at low concentrations and overpredict at high concentrations, Ecology applies a three-phase equation to more accurately capture concentrations across the range of observed values.

Correlation Approach

Ecology has extensive experience using non-regulatory optical instruments to report estimated $PM_{2.5}$ concentrations and has operated a network of nephelometers for $PM_{2.5}$ and AQI reporting since the 1990s. This vast data record indicates significant seasonal and regional variation in the relationship between optical instrument response and $PM_{2.5}$ mass concentrations across Washington's different aerosol environments. This variation corresponds to both temporal and spatial variability in the sources and composition of $PM_{2.5}$, with wildfire smoke the dominant source in the summer months and a broader range of sources dominant in the winter months. Dominant wintertime sources of $PM_{2.5}$ include smoke from residential wood combustion and outdoor burning, road and construction dust, agricultural activities, and mobile and industrial sources, with significant variation by region and site (Ecology, *2020 Washington Comprehensive Emissions Inventory)*.

Ecology's approach to SensWA correlation development is informed by this experience, which indicates the need for seasonally- and regionally-specific correlation factors for optical instruments to accurately estimate $PM_{2.5}$ mass concentrations. This approach is supported by a large body of published research indicating that the response from optical PM sensors varies widely when measuring PM from different sources (Dejchanchaiwong et al., 2023; Hagan and Kroll, 2020; Jaffe et al., 2022; Kang et al., 2024; Kumar et al., 2023; Kushwaha et al., 2022; Malings et al., 2019; Malyan et al., 2023; Tryner et al., 2020).

Data inputs

The sensing element in the SensWA is a pair of Sensirion SPS30 particulate matter sensors, which report concentrations in multiple size ranges: ≤1 µm, ≤2.5 µm, ≤4 µm, and ≤10 µm. Laboratory and field studies indicate that the PM_1 (particles ≤1 µm in diameter) data from these and similar sensors approximate a raw light-scattering signal and are highly correlated with nephelometer backscatter. Concentrations in the larger size ranges reported by sensors are thought to be calculated from the light-scattering signal based on assumptions about particle size distribution and density, and are not reflective of true measurements in accurately size-binned data (Caseiro et al., 2024; Hagan and Kroll, 2020; He et al., 2019; Molina Rueda et al., 2023; Oimette et al., 2022 Oimette et al., 2023). In practice, Ecology has found that the sensor PM_1 output is consistently better-correlated with reference $PM_{2.5}$ across Ecology's network than is sensor $PM_{2.5}$. Due to both the weight of evidence in the published literature and the empirical results from sensor collocations, Ecology uses the sensor PM_1 output to develop the correlation equations and report estimated $PM_{2.5}$ from the SensWA.

Ecology uses Met One BAM 1020s and Met One BAM 1022s as reference instruments for SensWA collocation and correlation development. Both are FEM monitors for $PM_{2.5}$. Ecology calculates NowCast averages (U.S. EPA, 2024) in order to relate BAM $PM_{2.5}$ concentrations to the raw sensor PM_1 data.

Though Ecology's work to develop and collocate the SensWA began in 2018, only data collected since May 2022 is used in correlation development. In May 2022, Ecology deployed the current iteration of the SensWA design and expanded SensWA collocation to most regions of the state. Ecology does not use data collected prior to this date for correlation development since the availability of collocated data varies by region, and in case sample flow and sensor performance were impacted by changes in enclosure design.

Regions

Ecology develops correlations specific to regions of the state. Regions are either individual counties or groups of nearby counties expected to have similar aerosol characteristics due to common meteorological conditions and source impacts. The division of counties into regions is informed by several factors, including the jurisdictional boundaries of Washington's seven local clean air agencies, terrain boundaries such as Puget Sound and the Cascade mountain range, and the locations of $PM_{2.5}$ BAMs. Each region includes at least one $PM_{2.5}$ BAM used to develop the correlation equation for that region. When regions contain multiple $PM_{2.5}$ BAM sites, Ecology generally pools the collocated data from all sites together after evaluating site-specific correlations to ensure consistency across the region. In some cases, $PM_{2.5}$ BAM monitors that are not considered broadly representative of the region due to unique site-specific issues (e.g. microscale monitors) are excluded. The map in Figure 1 shows the correlation regions, collocated $PM_{2.5}$ BAM sites in large black circles, and publicly-reporting SensWA in small gray circles.

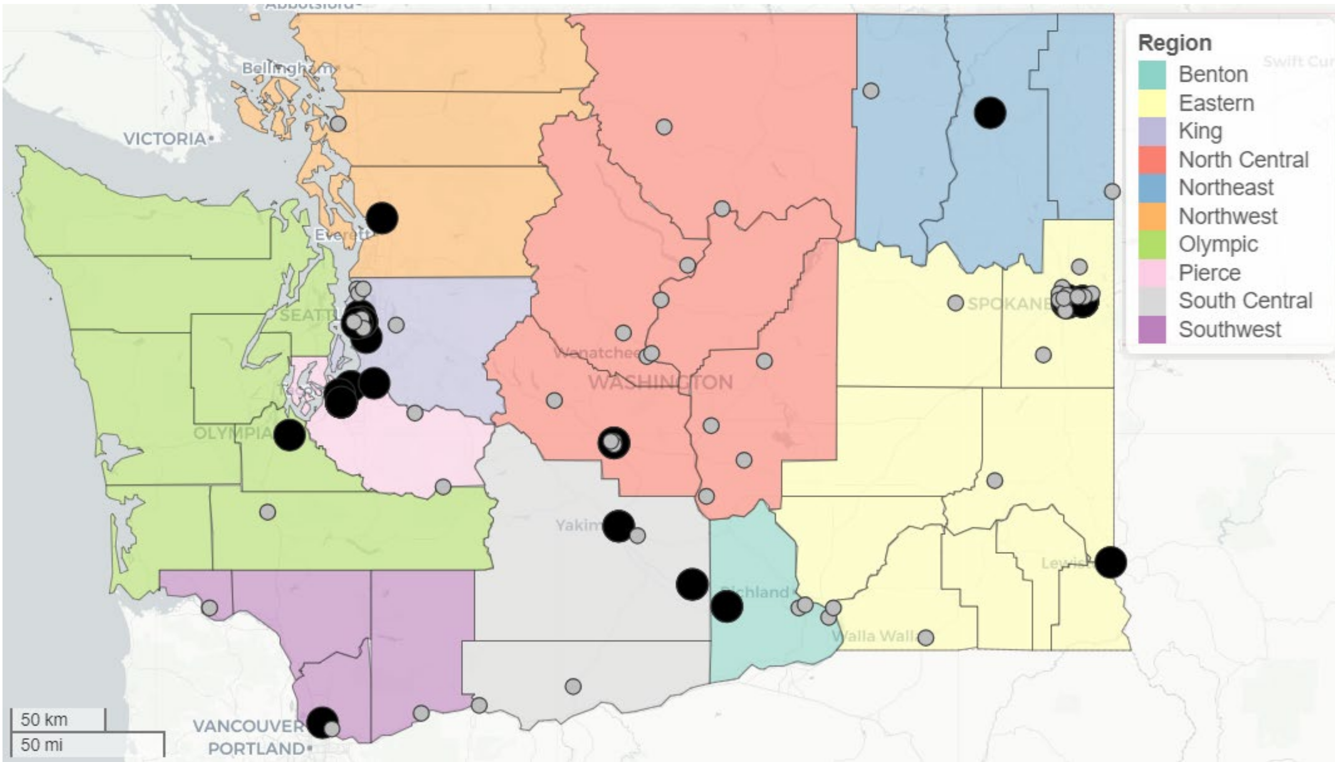

Figure 1. Map of correlation regions, collocated BAM sites (black), and SensWA (gray)

Seasons

Ecology evaluates correlations each year for the summer and non-summer seasons. Summer correlations are intended to be most accurate during wildfire smoke impacts across the wide range of concentrations typical of Washington wildfire smoke seasons, which can span up to 500 $\mu g/m^3$. Summer correlations are applied starting July 6 (after Independence Day-related firework impacts subside) through the end of September or the end of active wildfire smoke impacts, whichever is later. Non-summer correlations are developed to estimate impacts from a broader range of sources dominant in the colder months and are applied from October through July 5.

Equation structure

The linear correlation between raw SensWA PM_1 and BAM $PM_{2.5}$ generally exceeds an R^2 of 0.9, which is much higher than the minimum R^2 of 0.7 defined in Ecology's DQOs. However, despite the sufficient overall linearity, there are two ranges where application of a non-linear correlation equation can improve systematic under- and over-estimation. This trend can be seen in Figure 2, which compares NowCast SensWA PM_1 and BAM $PM_{2.5}$ data from the Northwest region from May 2022-Sept 2024. The SensWA PM_1 lags in the Good-low Moderate range, shows a strong linear fit in the Unhealthy for Sensitive Groups-Unhealthy range, and overestimates at high concentrations. Loess smoothing lines are shown for each season to highlight this shape.

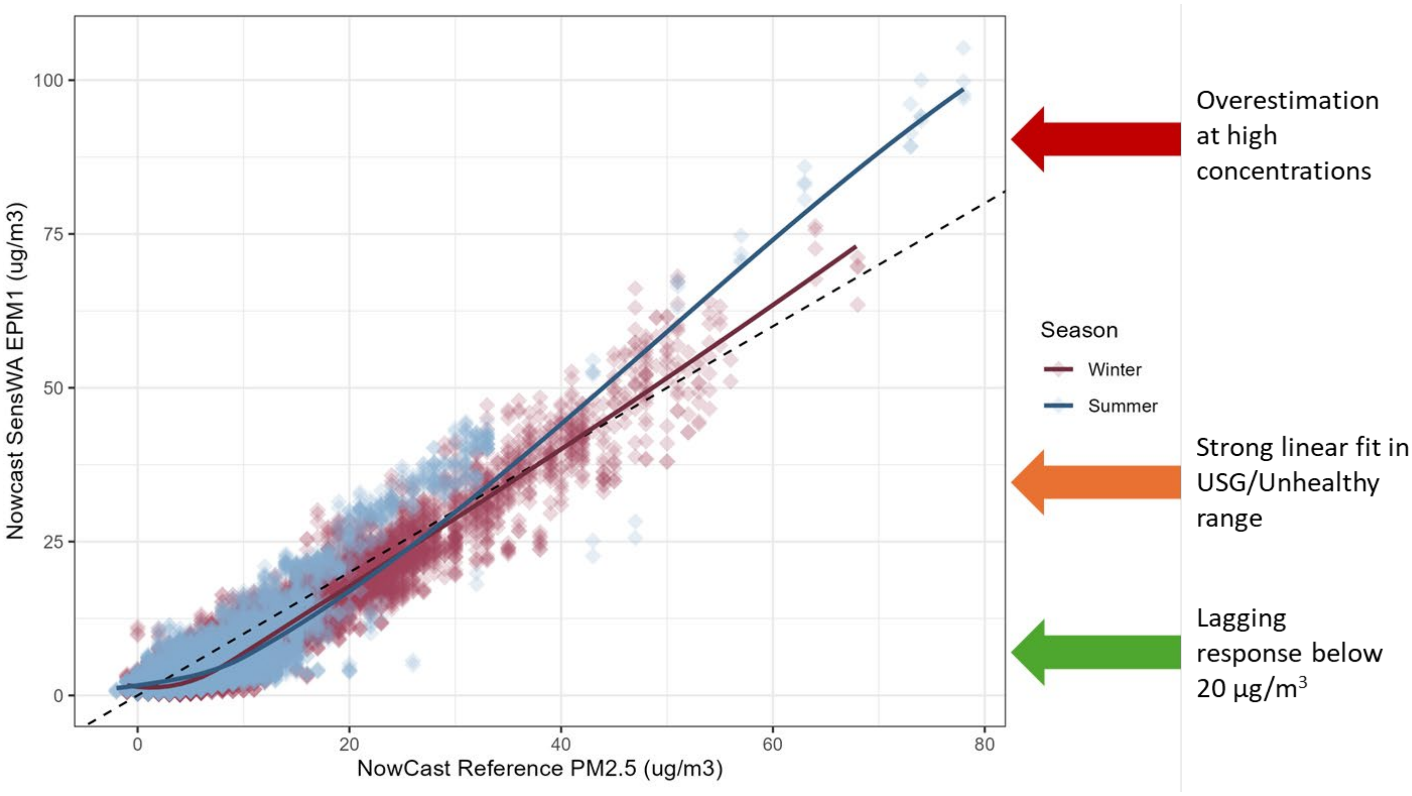

Figure 2. Typical three-phase shape of Nowcast SensWA PM_1 relative to BAM $PM_{2.5}$, Northwest region, May 2022 to September 2024.

Based on the consistency of this pattern across Washington, Ecology applies a three-phase equation to SensWA PM_1 to improve the linearity of the results and reduce systematic error:

- From 20 to 100 µg/m^3, Ecology applies a linear equation with the slope and intercept determined by median regression using collocated SensWA PM_1 and BAM $PM_{2.5}$ data in this range. Median regression is preferred over ordinary least squares regression because it is more robust to outliers, which can occur due to causes such as dust events, fireworks, and other unusual events that could skew estimates in non-robust regression.
- Above 100 µg/m^3, Ecology applies a linear equation with the slope and intercept determined by median regression using collocated SensWA PM_1 and BAM $PM_{2.5}$ data in this range. Since the calculated slopes above 100 µg/m^3 are generally lower than the slopes in the 20 to 100 µg/m^3 range, Ecology adjusts the intercept in this range by adding the difference between the two slopes at SensWA PM_1=100 µg/m^3 in order to create a smooth transition between the two ranges. The slopes calculated from the summer data in this range are also applied to non-summer data in this range, as non-summer values above 100 µg/m^3 are rare and assumed to be smoke-related when they occur.

- Below 20 µg/m^3, Ecology corrects for the non-linear and lagging SensWA response with a quadratic equation. The terms of this equation are determined by the slope and intercept in the 20 to 100 µg/m^3 range.
    - From 0 to 20 µg/m^3, the intercept is scaled linearly from a minimum of 0 to a maximum of the intercept identified for the 20 to 100 µg/m^3 range at PM_1=20.
    - The intercept (*b)* for each PM_1 value between 0 and 20 µg/m^3 can be calculated with the following equation, where *x* is PM_1:

$$b_i = \frac{b_{max}}{20} * x_i$$

    - From 0 to 20 µg/m^3, the slope is scaled linearly from a maximum of 1.4 at PM_1=0 to a minimum of the slope identified for the 20 to 100 µg/m^3 range at PM_1=20.
    - The slope (*m*) for each PM_1 value between 0 and 20 µg/m^3 can be calculated with the following equation, where *x* is PM_1:

$$m_i = 1.4 - \left(\frac{(1.4 - m_{min})}{20} * x_i\right)$$

    - Combining these two equations in the form *y* = *mx* + *b*, where *y* is the resulting estimated sensor $PM_{2.5}$ and *x* is the input sensor PM_1, can be simplified to:

$$y = \frac{(m_{min} - 1.4)}{20} * x^2 + \left(1.4 + \frac{b_{max}}{20}\right) * x$$

Figure 3 shows how effective this three-phase equation is at improving the linearity of SensWA estimated $PM_{2.5}$ using the same example of the Northwest region shown above. On the left shows the uncorrected SensWA PM_1, with its clear underestimation below 20 µg/m^3 and overestimation at high concentrations in the summer. On the right shows SensWA estimated $PM_{2.5}$ with the correlation equation applied and improved linearity. Loess smoothing lines are shown for each season.

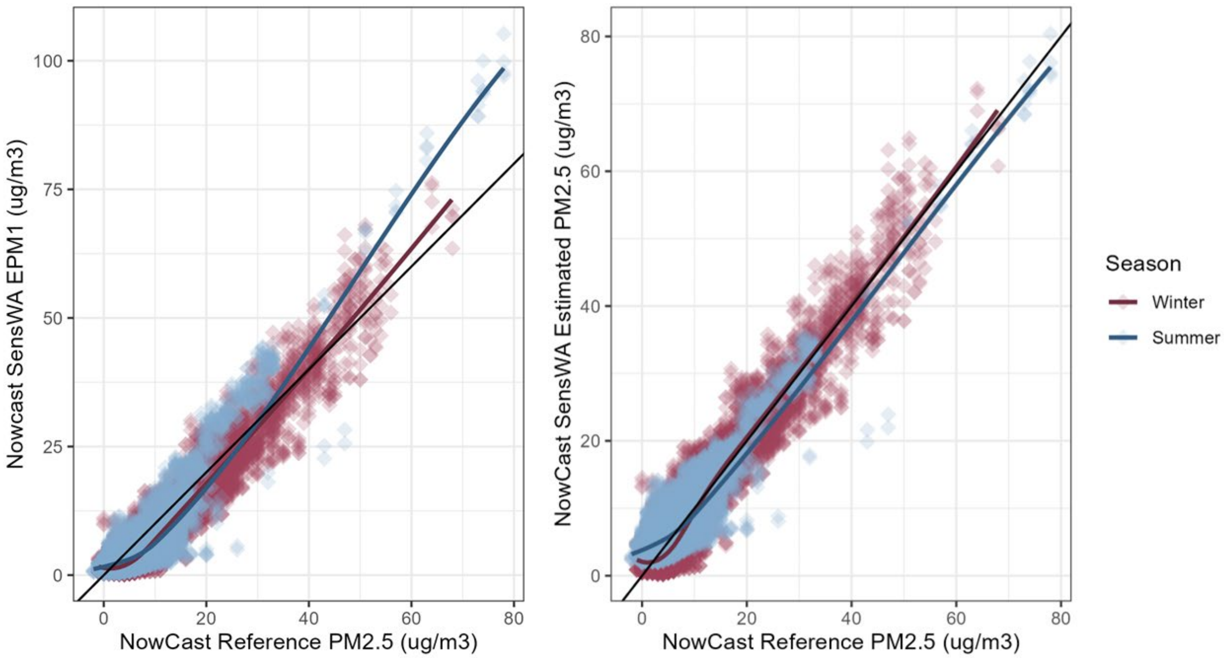

Figure 3. Northwest region SensWA PM_1 (left) and estimated SensWA $PM_{2.5}$ (right) by BAM $PM_{2.5}$, May 2022 to September 2024.

Correlation equations

The correlation equations by region and season in use as of winter 2024-2025 are provided in Table 1 below.

Table 1. SensWA correlation equations by region and season, winter 2024-2025.

Region	Season	Under 20 µg/m³	20-100 µg/m³	Over 100 µg/m³
Benton	Summer	$-0.0320 *PM_1$^2 + 1.520 * PM_1	0.76 *PM_1 + 2.4	0.55 *PM_1 + 23.4
Eastern	Summer	$-0.0350 *PM_1$^2 + 1.515 * PM_1	0.70 *PM_1 + 2.3	0.58 *PM_1 + 14.3
King	Summer	$-0.0315 *PM_1$^2 + 1.555 * PM_1	0.77 *PM_1 + 3.1	0.68 *PM_1 + 12.1
North Central	Summer	$-0.0335 *PM_1$^2 + 1.500 * PM_1	0.73 *PM_1 + 2.0	0.57 *PM_1 + 18.0
Northeast	Summer	$-0.0330 *PM_1$^2 + 1.515 * PM_1	0.74 *PM_1 + 2.3	0.54 *PM_1 + 22.3
Northwest	Summer	$-0.0335 *PM_1$^2 + 1.535 * PM_1	0.73 *PM_1 + 2.7	0.73 *PM_1 + 2.7
Olympic	Summer	$-0.0375 *PM_1$^2 + 1.475 * PM_1	0.65 *PM_1 + 1.5	0.55 *PM_1 + 11.5
Pierce	Summer	$-0.0290 *PM_1$^2 + 1.465 * PM_1	0.82 *PM_1 + 1.3	0.69 *PM_1 + 14.3
South Central	Summer	$-0.0270 *PM_1$^2 + 1.515 * PM_1	0.86 *PM_1 + 2.3	0.63 *PM_1 + 25.3
Southwest	Summer	$-0.0320 *PM_1$^2 + 1.450 * PM_1	0.76 *PM_1 + 1.0	0.70 *PM_1 + 7.0
Benton	Non-summer	$-0.0390 *PM_1$^2 + 1.525 * PM_1	0.62 *PM_1 + 2.5	0.55 *PM_1 + 9.5
Eastern	Non-summer	$-0.0355 *PM_1$^2 + 1.470 * PM_1	0.69 *PM_1 + 1.4	0.58 *PM_1 + 12.4
King	Non-summer	$-0.0315 *PM_1$^2 + 1.500 * PM_1	0.77 *PM_1 + 2.0	0.68 *PM_1 + 11.0
North Central	Non-summer	$-0.0385 *PM_1$^2 + 1.515 * PM_1	0.63 *PM_1 + 2.3	0.57 *PM_1 + 8.3
Northeast	Non-summer	$-0.0365 *PM_1$^2 + 1.500 * PM_1	0.67 *PM_1 + 2.0	0.54 *PM_1 + 15.0
Northwest	Non-summer	$-0.0250 *PM_1$^2 + 1.580 * PM_1	0.90 *PM_1 + 3.6	0.73 *PM_1 + 20.6
Olympic	Non-summer	$-0.0370 *PM_1$^2 + 1.450 * PM_1	0.66 *PM_1 + 1.0	0.55 *PM_1 + 12.0
Pierce	Non-summer	$-0.0300 *PM_1$^2 + 1.480 * PM_1	0.80 *PM_1 + 1.6	0.69 *PM_1 + 12.6

South Central	Non-summer	$-0.0390 * PM_1^2 + 1.535 * PM_1$	$0.62 * PM_1 + 2.7$	$0.63 * PM_1 + 1.7$
Southwest	Non-summer	$-0.0295 * PM_1^2 + 1.475 * PM_1$	$0.81 * PM_1 + 1.5$	$0.70 * PM_1 + 12.5$

Figure 4 shows the resulting $PM_{2.5}$ values from these correlation equations based on theoretical SensWA PM_1 values.

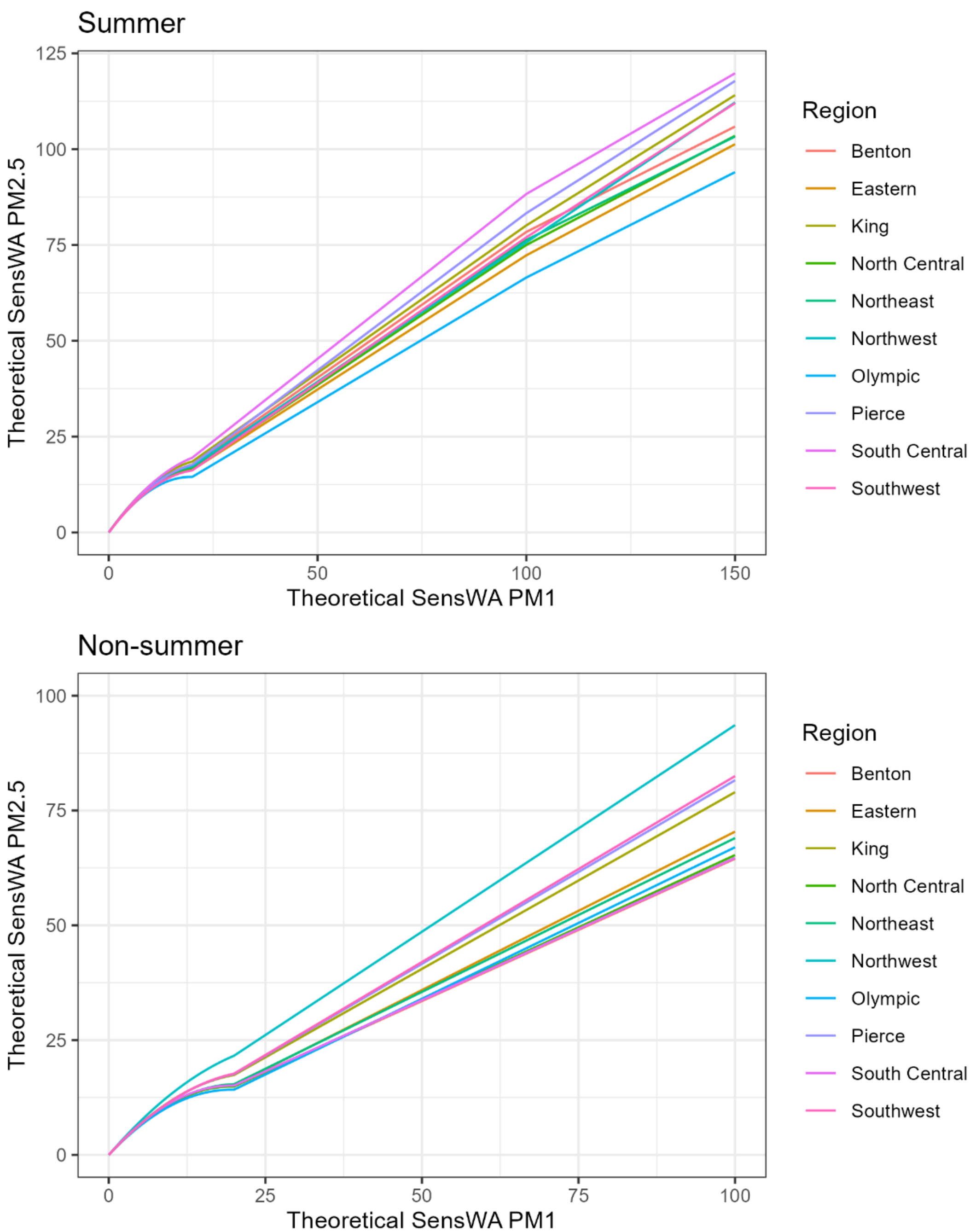

Figure 4. Calculated $PM_{2.5}$ values from theoretical SensWA PM_1 across correlation regions.

Performance

From May 2022 through October 2024, Ecology collected 944,547 paired NowCast SensWA and BAM $PM_{2.5}$ concentrations. Using the correlations in Table 1, the SensWA reported the correct AQI category in 89% of hours and reported within +/- one AQI category in >99% of hours. The SensWA reported one AQI category too high in 7% of hours and reported one AQI category too low in 4% of hours.

Of the 105,065 hours in which the AQI category was incorrect, over 96% were at the Good/Moderate breakpoint. EPA lowered the breakpoint between the Good and Moderate AQI categories from 12.0 μg/m^3 to 9.0 μg/m^3 in 2024, causing accurate AQI characterization at this breakpoint to be more difficult than in similar analyses conducted prior to this breakpoint change (e.g. Barkjohn et al., 2022). If the Good/Moderate breakpoint were still 12.0 μg/m^3, the SensWA and BAM would agree in 93% of Nowcast hours. Among hours when the AQI category was incorrect at the Good/Moderate breakpoint, both the root-mean square error (RMSE) and the mean absolute error (MAE) were still well within Ecology's acceptance criteria of 6 μg/m^3. Therefore, Ecology considers this to be an acceptable rate of misclassification by AQI category given that measures of error are still reasonably low.

Figure 3 shows the BAM AQI category in boxes and the sensor AQI in bars. AQI category agreement is expressed as a percent of BAM hours in each AQI category.

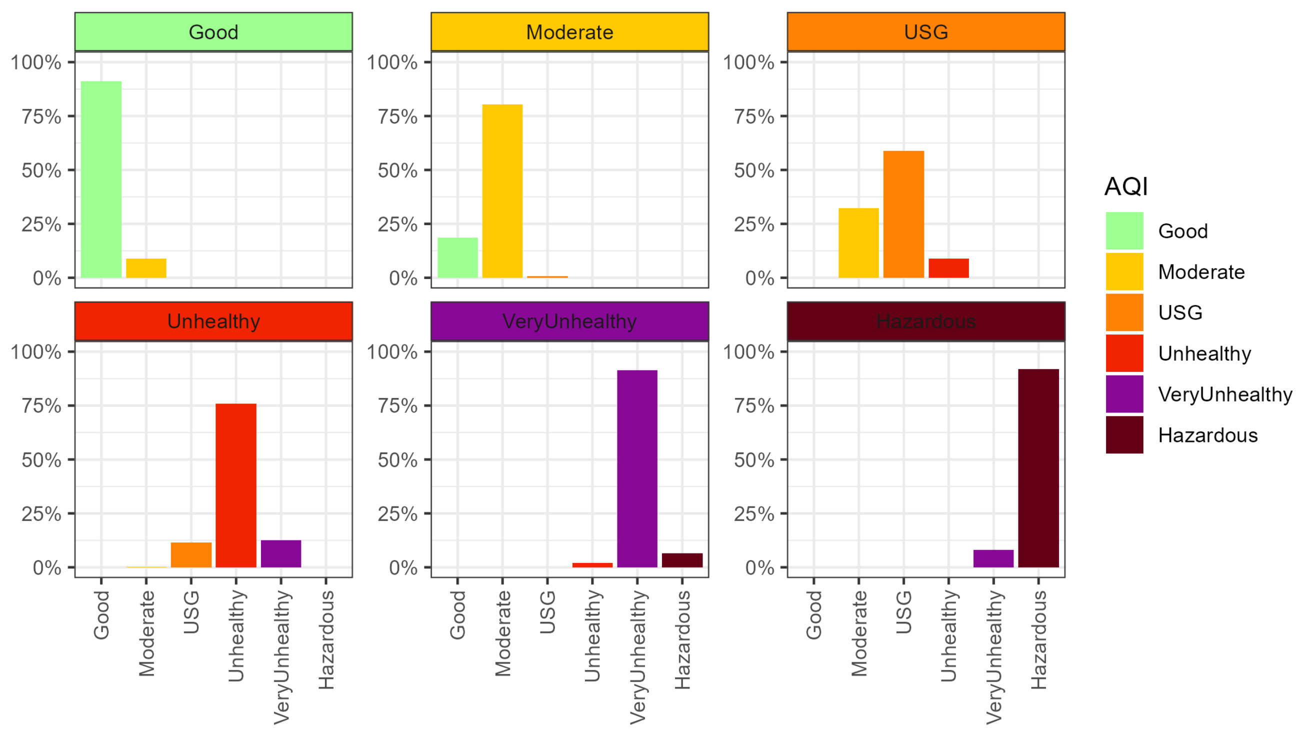

Figure 5. SensWA correlation performance by AQI category, May 2022 - October 2024. Calculated from 944,547 paired NowCast SensWA and BAM $PM_{2.5}$ concentrations. BAM AQI category is shown in boxes and sensor AQI category shown in bars.

Using the May 2022-October 2024 hourly NowCast dataset, SensWA performance was evaluated with the data quality indicators in the SensWA QAPP. The results were within Ecology's acceptance criteria for all indicators.

Table 2. Results of Data Quality Indicator evaluation with May 2022 – October 2024 NowCast BAM and SensWA data.

Measurement Quality Indicator	Data Quality Indicator	Acceptance Criteria	Results
Linearity	R^2	≥0.7	0.92
Bias	Slope	1 ± 0.3	1.02
Bias	Intercept	± 0.3 µg/m^3	0.05 µg/m^3
Accuracy	RMSE	≤6 µg/m^3	3.0 µg/m^3
Accuracy	MAE	≤6 µg/m^3	2.1 µg/m^3
Accuracy	sMAPE	≤30%	30% (when BAM $PM_{2.5}$ >5 µg/m^3)

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This report is available on the Department of Ecology's website at https://apps.ecology.wa.gov/ecy/publications/SummaryPages/2402052.html

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