



Air Quality Monitoring Sampling Design Internship

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National Park Service Mission: The National Park Service preserves unimpaired the natural and cultural resources and values of the National Park System for the enjoyment, education, and inspiration of this and future generations. The Park Service cooperates with partners to extend the benefits of natural and cultural resource conservation and outdoor recreation throughout this country and the world.

Information about NPS

- Since 1916, NPS has been entrusted with the care of national parks
- Bureau of the U.S Department of the Interior
- Led by a director nominated by the president and confirmed by the U.S Senate
- Our region of focus is the Northeast Region of the National Park Service- Maine to Virginia
- Role and function of the regional office: to provide employees with specialized expertise and tools that will foster growth, development, and safety of regional park service employees, volunteers and partners.
- List of Parks in the National Capital Region: <https://www.nps.gov/orgs/1465/visit-the-parks.htm>

Objective:

To design a monitoring system and protocols to evaluate air pollution exposure to visitors within urban parks

Goals:

- Understand the purpose of the different parks within this region.
- Understand park visitor experiences within various parks and how they differ between parks
- Examine trends in Natural Resource Condition Assessments
- Talk with professional air quality scientists on UMDs campus and collect information about what gasses and particulate matter they emphasize in studies and why.
- Design a study that caters to the unique needs of each park while remaining cost-effective and informative.
- Accompany physical monitoring equipment with an educational or interactive tool that bridges the behavioral and action gap of pro-environmentalism.



Acknowledgements

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National Capital Region Parks Overview

Antietam National Battlefield Sharpsburg, MD

History

- 23,000 soldiers killed, wounded or missing after 12 hours of savage combat on September 17th, 1862.
- Battle of Antietam ended the Confederate Army of Northern Virginia's first invasion into the North and led Abraham Lincoln to issue the preliminary Emancipation Proclamation

Places to go

- Visitor Center
- Dunker Church
- National Cemetery
- Pry House Field Hospital

Things to Do

- Explore museum exhibits in visitor center
- 26-minute introductory film
- Join Park ranger for battlefield talk
- Museum store
- Self-guided 8.5 mile auto tour: has 11 stops
- Join Park-ranger for guided walk tour
- Self-guided hike on Bloody Lane, Cornfield, Final Attack, Union Advance, Antietam Remembered, Sherrick Farm or Snively Ford Traits
- Battlefield scavenger hunt

Catoctin Mountain Park

Location: Thurmont, MD

History

- Native Americans: used mountain resources for food, clothing
 - During Archaic Period (8,000-1,200 BC) mountain was source of rhyolite to make tools, with most active period being 1,200 BC to A.D 1600.
 - No year-round residents, but base camps were used as sources of potable water while at quarry sites, and also used to finish products



- At around A.D 900 quarrying of Catoctin ended, and year-round residents began to appear
- Area has since then been historically used in charcoal and iron industry, including farms, sawmills, and old moonshine still
- Historically used as the nation's first Job Corps Center- impactful youth programs to strengthen nation's economic and social prosperity
- Resources from Catoctin Mountain Park reflect much of the early ingredients of our history

African Americans

Source: <https://www.nps.gov/cato/learn/historyculture/africanamericans.htm>

- Free and runaway slaves in the area worked as laborers in Iron Making, woodcutting, hauling and stacking wood for the collier, transported charcoal to the furnace, and worked in molding sheds with molten iron
- Prominent families in the area had slaves and servants assist with household chores and tasks
- Slaves could earn extra commodities through the iron-work system like food clothing, credit at stores
- 1820 John Brien and brother-in-law John McPherson bought the Catoctin Iron Works. By 1830, they had 20 male slaves. This reduced dramatically in 1835, and 1841. Remainders were 12

Charcoal and Iron Industry

Source: <https://www.nps.gov/cato/learn/historyculture/charcoal.htm>

- The production of charcoal was a major source of industry during the industrial revolution during peak years (1859-1885)
- Charcoal fueled the Catoctin Iron Furnace which separated out the iron from the raw iron ore
- Woodcutters entered a forested area and cut every live standing tree, and only left 1 or 2 trees to reseed the forest
- Forest was cut down every 3 years during the 97 years that charcoal was used at the Catoctin Iron Furnace
- The collier supervised the stacking of the wood. The stack was covered with leaves and dirt, and collier tended the mound for about 2 weeks until the charring was complete



- After the collier burns the mound, he would take it into small piles to cool
- Collier was paid by the bushel

Sawmill industry

- Water-powered sawmills were built by entrepreneurs who owned forested land and had little money to invest in a family run business
- Old mills with their slow production of 48 planks for a 12-hour day at best
- Sawmill near Owens Creek Campground has an unknown date of origin, but appeared in maps at 1857 and operated until probably 1890's.

Whiskey Still Industry

- Corn and grain produced on the mountain were expensive to transport but became more equitable when it was converted into Whiskey. A horse may only be able to haul 4 bushels of corn but the same horse could haul 24 bushels of grain if it was made into whiskey.
- Liquor conversion began around 1734, but the Excise Tax of 1791 demanded those who operated stills to pay a tax
- This tax took the profitability out of making liquor from corn and grain, so many people operated by the light of the moon- AKA Moonshine

Recreational Demonstration Area Program

- By 1934 Land Planning Committee had been set up within Federal Emergency Relief Act to consider issue of land utilization
- Income from poor lands was less than the profit made to maintain them
- 5 million dollars were used to convert land ravaged by agriculture and industry into recreational areas by 1936. Blighted chestnut trees were used for building materials and Catoclin Furnace, which was closed in 1903 provided historical interest

Works Progress Administration

- Works Progress Administration construction started in 1936 and ended in 1941.
- Facilities were built using characteristic rustic arch style using natural colors and few straight.
- Dead standing trees were used initially, and a lot of chestnut was used. Eventually Maryland foresters provided guidance for live trees



Civilian Conservation Corps

- Build useful citizens by instructing young men to use tools, take orders, respect supervisors, and give an honest day's work.
- Objectives: promote conservation and instill leadership abilities, and train young men in at least one skill enabling them to get a job in the future
- Director Mike Williams had developed plans to reforest mountain and plant 100,000 native trees where minimum of 25% were oak. The state was unable to do this and he settled on 2,000 maple, and 2,000 pine.
- Strips of lespedeza and grains were planted on contours for birds and rabbits, and forest encroachment was battled using grains to control the edge of the woods
- Stream improvement projects were used to deepen lakes and increase fishing sport

World War II at Catoctin Mountain Park

- 10,000 recreational area became a place for soldiers, spies and allied leaders used it to win the war.
- Roosevelt used a cabin as a "Bear's Den"
- Events of WWII were the defining moment that kept Catoctin Mountain Park as a unit of the National Park Service

Job Corps

- Patterned after the creation of the Civilian Conservation Corps to recruit economically deprived young men between ages of 16 and 21, most with 9th grade education level and teach them work habits and attitude along vocational skills
- Catoctin was a sit for the Job Corps
 - Men completed the camp, built sidewalks, landscaping, and went to school half the day in the winter
- Today a form of the Job Corps exists, with men and women involved in National Parks.

Places to go

- Catoctin Iron Furnace
- 1776- production of iron ore began, changed over to coal in 1873.
- Located at the base of the Catoctin Mountains in Cunningham Falls State Park, Frederick MD
- Uses: car wheels, Franklin Stoves, cannonballs and cannons during the revolutionary war for George Washington's army when Johnsons owned
- Raw material for production of charcoal was obtained from forests
- Blown out for the last time in 1903
- Presidential Retreat
- The muggy climate of D.C was considered harmful to President Franklin D. Roosevelt's health, so Camp Hi-Catoctin Recreational Demonstration Area was selected on 1942.



- Renamed the camp to Shangri-La
- Eisenhower renamed retreat “Camp David” after his grandson in 1953
- NOT OPEN TO THE PUBLIC
- Historic Camp Misty Mount and Camp Round Meadow
- Cabins, dining hall, rec hall, pool, field for sports, fire circles
- Trails
- Horseback riding
- Wolf Rock for climbing (permit required)
- Collections (viewing available by appointment only)
- Small lepidoptera collection
- Small mammal survey
- Herbarium used in local park research projects

Chesapeake and Ohio Canal National Historical Park

Location: DC, MD, WV

History

- “184.5 miles of Adventure”
- C&O canal began as a dream of passage to Western wealth
- Canal operated for about 10 years
- Was important in coal, lumber, and agricultural product transportation
- Pathway for historical, natural, and recreational activities
- Places:
 - Great Falls: busiest trail in D.C area, total 8 miles
 - Section A,B or C
- Curriculum-based education programs are available at multiple park locations
 - Cumberland (Allegany County)
 - Williamsport (Washington County)
 - Great Falls (Frederick, Montgomery, PG)

George Washington Memorial Parkway

Location: D.C., Arlington County, Fairfax County, and the City of Alexandria

History

- Designed for recreational driving and environmental conservation
- GWMP was developed as a scenic parkway to preserve the Potomac River Gorge and shoreline while serving as a memorial to GW
- Potomac River Gorge is home to many rare species and communities
- Home to unique habitats
 - Major river systems with numerous tributaries, upland forests, seeps/springs harboring rare groundwater fauna, wetlands



- 7,300 acres of land, connecting historic, natural, and cultural sites from Mount Vernon to Great Falls Park
- Runs 28 mi long over western shore of the Potomac River through DC and northern Virginia
- The parkway is a key transportation artery in northern Virginia, providing access to Washington, D.C., Arlington County, Fairfax County, and the City of Alexandria.
- GWMP provides opportunities for species preservation, biological diversity, natural systems and processes, and the value of natural open space in an urban environment
- Commemorates important part of American History and to preserve habitat for local wildlife

Places to go

- U.S Marine Corps War Memorial
 - Visited by about 1.5 million visitors
- Arlington House
- Arlington Memorial Bridge
- Dyke Marsh Wildlife Preserve
 - 3/4th of a mile The Haul Road Trail- old mining
 - Belle Haven Marina
- Great Falls

Harpers Ferry National Battlefield Park

Location: Virginia, Maryland

Things to do

- Encompasses about 4,000 acres
- Midpoint of 2,178-mile Appalachian National Scenic Trail
- Considered one of the best walking parks in America
- Quaint, historic community, at the confluence of the Potomac and Shenandoah rivers
- Stroll streets, visit exhibits and museums
- Hike trails and battlefields
 - Hike: 20 miles of hiking trails
 - <https://www.nps.gov/hafe/planyourvisit/hikes.htm>
- Harpers Ferry Park Association
 - Park rangers, contractors, workshops that focus on 19th century trades
- Natural Resource Walk
- Cultural Resources Programs
 - Guided hikes, presentations, talks

Manassas National Battlefield Park



Location: Manassas, VA

History

- Site of confederate and union battles in 1861 and 1862
 - Confederates won

Things to do

- Guided ranger tours
- Henry Hill Visitor Center
- Brawner Farm Interpretive Center
- Stone House

Monocacy National Battlefield

Location: Frederick MD

History

- “The Battle that saved Washington, DC”

Things to do

- Has 6 walking trails ranging from easy/wheel-chair accessible-difficult

National Mall and Memorial Parks

Location: DC

Things to do

- Sites around DC

Potomac Heritage National Scenic Trail

Location: Virginia

History

- Links tidal Potomac and upper Youghiogheny river basins

Things to do

- Foot, bicycle, horse, boat, paddle

President’s Park

Location: DC

Things to do

- Ellipse
- Lafayette Park
- White House Grounds

Prince William Forest

Location: Triangle, VA

History

- Prince William Forest Park was created as a Recreation Demonstration Area, a program established by President Franklin D. Roosevelt to provide an outdoor experience for inner city youth and to teach job skills to the unemployed. Work began in 1935 to build cabins and establish what was then known as Chopawamsic Recreation Demonstration Area. In



1948, the name was changed to Prince William Forest Park. Prince William Forest Park covers over 15,000 acres of land, and includes cabins, campgrounds, an RV park, a 12-mile scenic loop, 37 miles of hiking trails, and on and off-road bike routes. Over the last few years between 215,000 and 250,000 people have visited the park annually.

Things to do

- Hiking
- On/off road biking
- Tent/RV camping
- Cabin Camping
- Fishing
- 18 miles of streams/man-made lakes
- Biking
- 12 miles of paved roads and 9 miles of gravel roads
- Picnics in the Park
- 60 point orienteering course
- Map and compass free of charge at visitor center
- Chopawamsic Backcountry Area- 1,500 acres of backcountry area with 8 campsites and a two-mile loop trail
- Wildlife watching

Rock Creek Park

Location: DC

- 1,754 acre city park
- Planetarium
- 32 miles of hiking trails
- Old Stone House
- Peirce Mill
- Meridian Hill Park

Wolf Trap National Park for the Performing Arts

Location: Vienna, Virginia

- Filene Center
- Theatre-in-the-Woods

Park Categorization

General Trend: To assess the goals and uses of the parks so that appropriate air quality monitoring studies can be designed, parks can be divided into 5 main categories:



Urban Historical 	• Located within dense cities and highways • Historical importance
Battlefields 	• Open view over expansive land • Some hiking, but limited wooded region around main site • Historical importance
Forested 	• Used for recreational purposes • Vegetation • Waterways
Entertainment 	• Performances • Trails
Urban Forested 	• Green spaces • Waterways • Vegetation encompassed by city

Summarization of National Resource Condition Assessments (NRCA)

Goal of NRCA's:

- 1) Determine indicators of current status within each habitat
- 2) Establish a reference condition for each indicator
- 3) Then assess the percentage attainment of reference condition

Chesapeake and Ohio Canal (2014)

- Five metrics were used to assess air quality (Chp 4.1 Air Quality, Pg. 45)



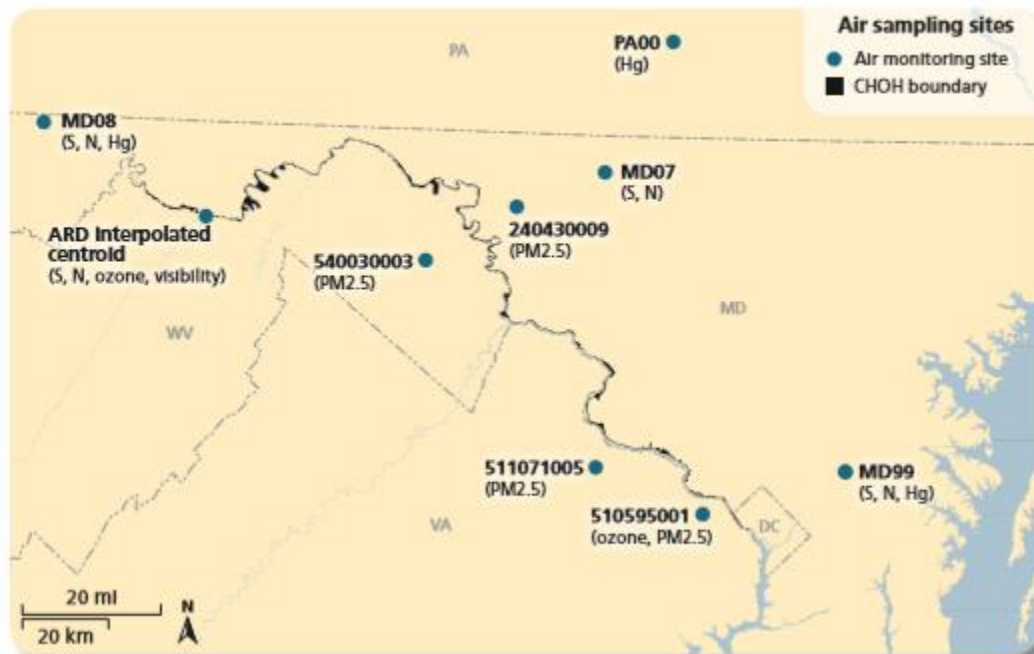
- **Obtained from:** NPS Air Resources Division Air Quality Estimates
- **Calculated by:** ARD on national scale between 2005 and 2009 using interpolation model based on monitoring data. Values for individual parks taken at the park center. 2 metrics (particulate matter and mercury deposition) were taken from monitoring network sites
- Wet sulfur deposition (S)
- Wet Nitrogen deposition (N)
- Ozone (ppb)
- Visibility
- Particulate matter
 - Not included: ozone (W126) and mercury deposition

Table 4.3. Categorical ranking of the reference condition attainment categories for Air Quality metrics.

Metric reference conditions					Attainment of reference condition	Natural resource condition
S & N deposition (kg/ha/yr)	Ozone (ppb)	Ozone (W126)	Visibility (dv)	Particulate matter (µg/m³)		
< 1	≤ 60	< 7	< 2	≤ 12	100%	Good
1–3	60.1–75	7–13	2–8	12.1–15	0–100% (scaled)	Moderate
> 3	> 75	> 13	> 8	> 15	0%	Significant concern

Table 4.4. Summary of resource condition assessment of Air Quality in CHOH. The ozone W126 metric and mercury deposition were not included in the overall assessment of air quality condition.

Metric	Result	Reference conditions	% attainment	Condition	Air quality condition
Wet sulfur deposition (kg/ha/yr)	5.26	< 1; 1–3; > 3	0	Significant concern	12% Very degraded
Wet nitrogen deposition (kg/ha/yr)	4.51	< 1; 1–3; > 3	0	Significant concern	
Ozone (ppb)	72.5	≤ 60; 60.1–75; > 75	17	Moderate	
Ozone (W126; ppm-hrs)	10.7	< 7; 7–13; > 13	38	Moderate	
Visibility (dv)	12.0	< 2; 2–8; > 8	0	Significant concern	
Particulate matter (PM2.5; µg/m³)	13.7	≤ 12; 12.1–15; > 15	44	Moderate	
Mercury deposition (ng/L)	8.6	N/A	N/A	N/A	



Wet Sulfur Deposition

- SO₂ has increased from 9 million metric tons (1990) to 28.8 million metric tons (1973)
 - 60% came from utilities
 - 41% came from 7 Midwest states in Ohio Valley
- Due to Clean Air Act SO₂ has reduced to 17.8 million metric tons by 1996
- SO₂ is highly mobile and can be deposited up to 500 km (311 miles).

Data and Methods

- Natural background total sulfur is 0.5 kg/ha/yr which equates to wet deposition of 0.25 kg/ha/yr

Condition and Trend

- CHOH is at very high risk from sulfur and nitrogen acidification effects since streams and soils are susceptible to sulfur

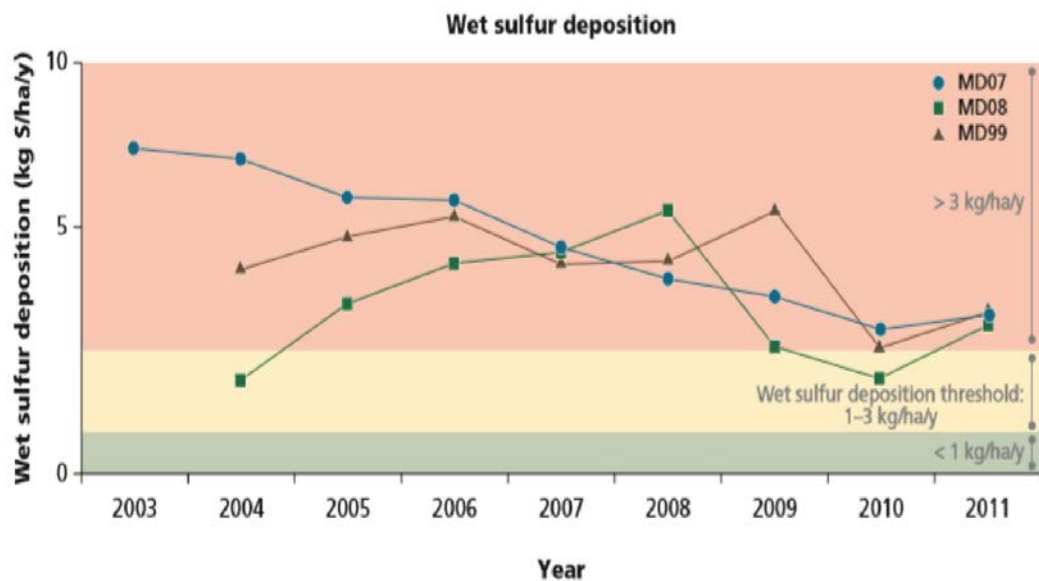
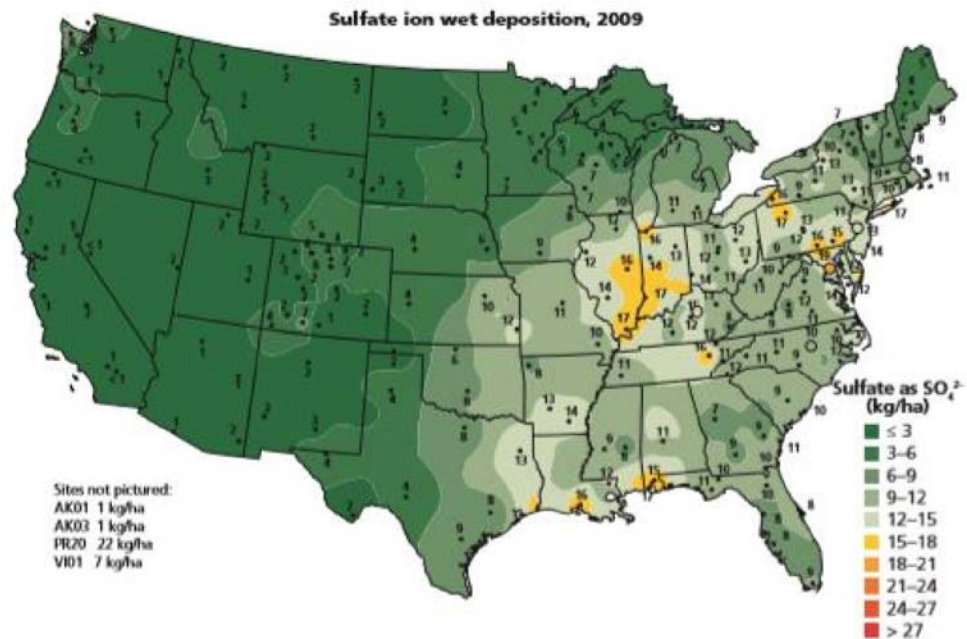


Figure 4.4. Annual wet deposition of sulfate ($\text{kg SO}_4/\text{ha}/\text{yr}$) at the three sites closest to CHOH. Data were reported as SO_4 deposition; these data were converted to total S deposition using atomic weights (multiplying by 0.333). Reference conditions are shown in gray.

Figure 4.2. Total wet deposition of sulfate (SO_4^{2-}) for the continental United States in 2009 (NADP/NTN 2010).



Wet Nitrogen Deposition

Description

- During the 1940's and 1950's, the US and Great Britain contributed greatly to degraded air quality in major cities due to the coal burning industry and power plants/ steel mills
- 1973 National Ambient Air Quality Standards (NAAQS)
- Effects include acidification and nutrient fertilization of waters and soils



- Affect nutrient cycling, vegetation, loss of stream biodiversity, eutrophication

Data and Methods

- Natural background total sulfur is 0.5 kg/ha/yr which equates to wet deposition of 0.25 kg/ha/yr
- There has been no significant improvement within the decade

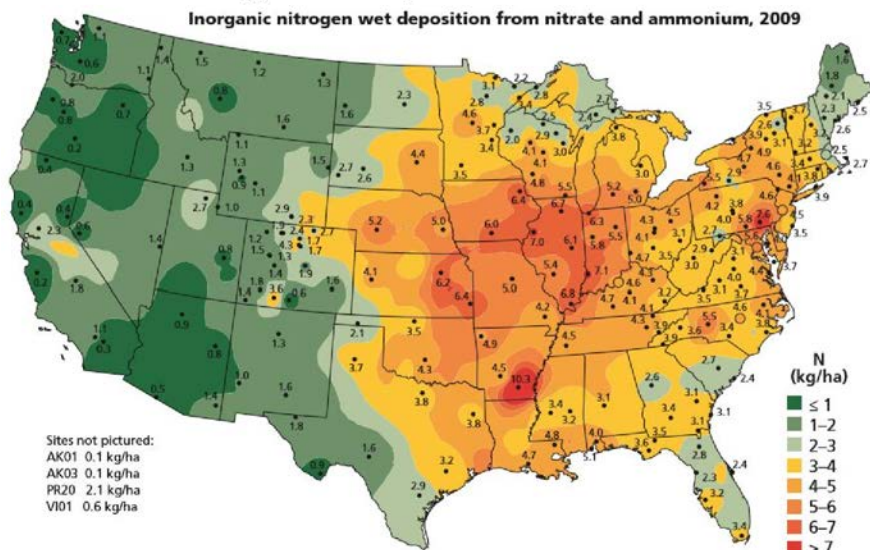
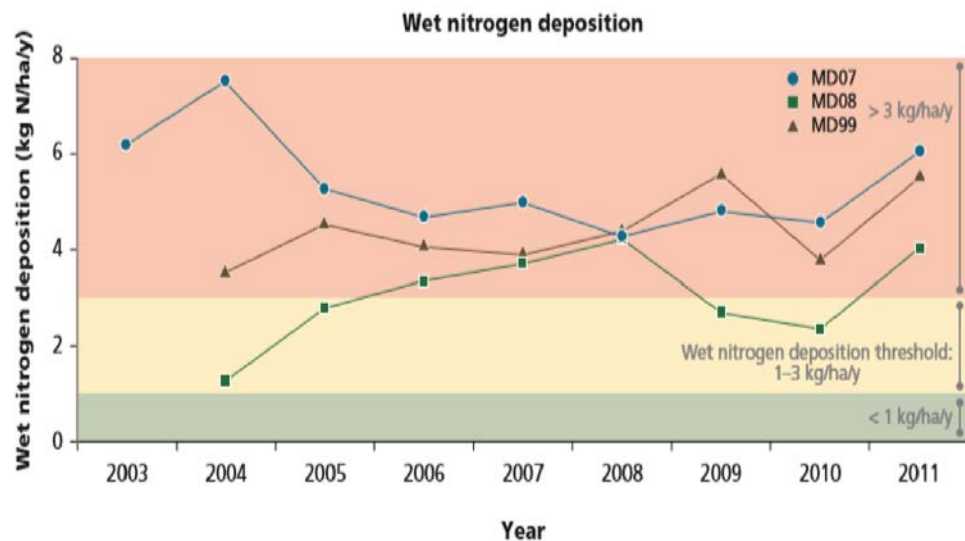


Figure 4.5. Total wet deposition of nitrate (NO_3^-) and ammonium (NH_4^+) (kg/ha) for the continental United States in 2009 (NADP/NTN 2010).

Figure 4.7. Annual wet deposition of total nitrogen (kg N/ha/yr) at the three sites closest to CHOH. Reference conditions are shown in gray.



Ozone

Description

- Secondary pollutant: formed by sunlight-driven chemical reactions on nitrogen oxides and volatile organic compounds emitted from burning fossil fuels
- Effects on humans: lung inflammation, reduced lung function → hospitalization



- Adverse health effects can occur in sensitive groups below ppb
- 60-70 ppb is protective of the population
- Secondary metric that affects plants (W126), because some plants can develop foliar injury from elevated ozone levels especially when soil moisture is high.
 - Plants have their stomata open allowing gas exchange for photosynthesis, but also letting in ozone

Data and Methods

- Ground-level ozone is regulated under the Clean Air Act
- EPA is required to set standard concentrations
- Current National Ambient Air Quality Standards is 75 ppb
- Overall significant concern

Condition and Trend

- CHOH is at high risk from ozone effects since vegetation is greatly affected
- Country-wise assessment of ozone from 159 parks show that ozone trends are improving over the past decade due to the NOX State Implementation Plan (SIP) Call rule (EPA 2010, NPS ARD 2010) (Figure 4.10).

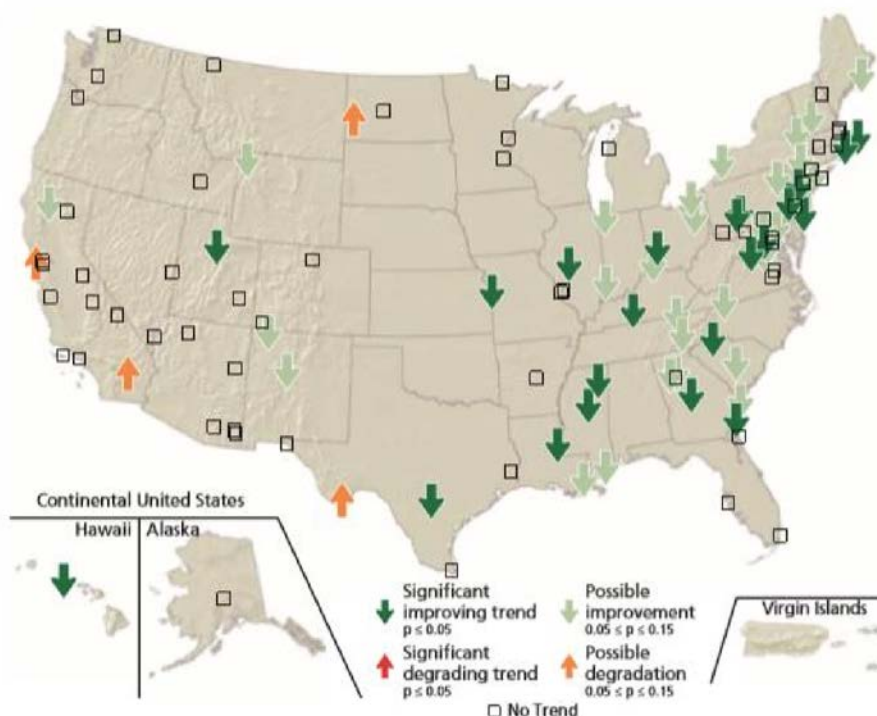


Figure 4.10. Trends in annual fourth-highest eight-hour ozone concentration (ppb), 1999–2008 (NPS ARD 2010b).

Conclusions: Since streams and soils are especially susceptible to acidification from sulfur and nitrogen and nitrogen has a large effect on vegetation, nutrient cycling etc., I would suggest



measuring these components within wooded areas. Areas where there are a lot of older or younger people or who have asthma would be affected by ozone.

Visibility

Description

- Presence of sulfates, organic matter, soot, nitrates, soil, dust
- In Eastern US reduced visibility is sulfate particles formed from SO₂ emitted from coal combustion

Data and Methods

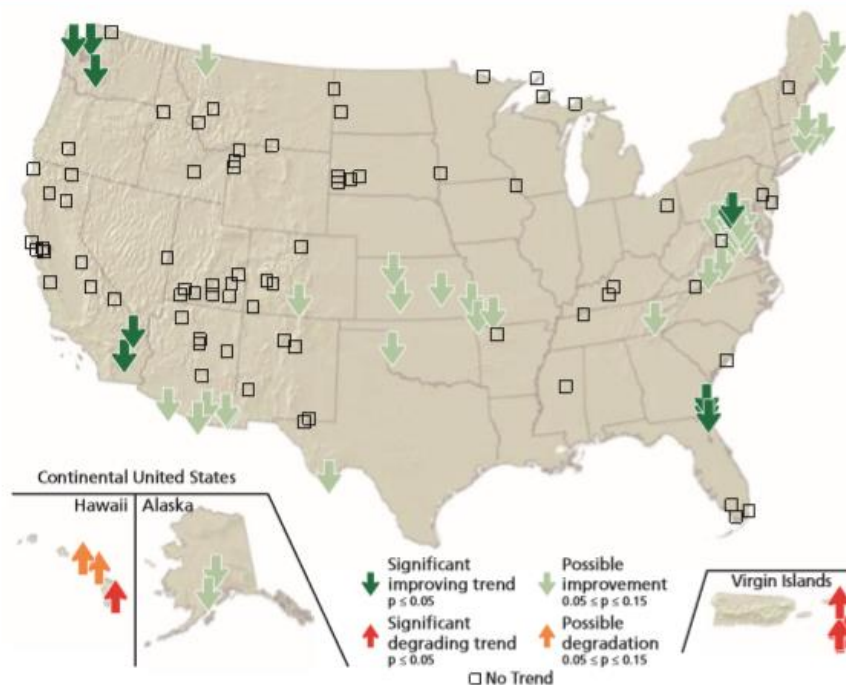
- Measured using the Haze Index in deciviews (dv)
- Visibility Condition = average current visibility – estimated average natural visibility
- Reference condition for visibility is based on national goal of restoring natural visibility
- Regional Haze Rule requires remedying existing and preventing future visibility impairment in nation's largest parks and wilderness areas known as Class I
- NPS adopted goal for Class II parks like CHOH

Condition and Trend

- Condition of significant concern
- Country-wide assessment shows no significant trend
- General region trend shows improvement

Chesapeake and Ohio Canal National Historical Park Natural Resource Condition Assessment

Figure 4.12. Visibility trends measured by the haze index (deciview) on haziest days, 1999–2008 (NPS ARD 2010b).





Particulate Matter

Description

- Fine particles less than $2.5\mu\text{m}$ diameter are emitted as smoke from power plants, gasoline and diesel engines, wood combustion, steel mills, forest fires
- Sulfur dioxide and nitrogen dioxide transform in the atmosphere to sulfate and nitrate particles
- Health impacts: aggravate lung disease, non-fatal heart and asthma attacks, acute bronchitis, respiratory infections, coughing, wheezing, shortness of breath, changes in lung function
- Regulated under the Clean Air Act, EPA is required to set standards

Data and methods

- Data was obtained from the Interagency Monitoring of Protected Visual Environments (IMPROVE) database through the U.S. EPA's AirData interface (Table 4.1) for the four sampling locations closest to CHOH: sites 240430009 near St. James in Washington County, MD, 510595001 near McLean in Fairfax County, VA, 511071005 in Loudoun County, VA, and 540030003 near Martinsburg in Berkeley County, WV (Figure 4.1, Table A-1)

Condition and Trend

- 4 sites closest to CHOH had a moderate condition, and all 4 sites showed an improving trend of particulate matter over the past decade.

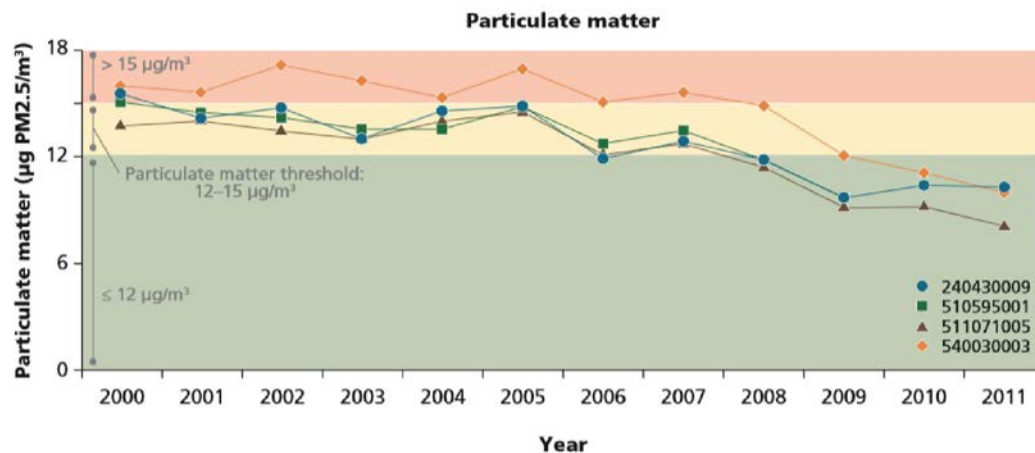


Figure 4.14. Particulate matter ($\mu\text{g PM}_{2.5}/\text{m}^3$) at the four sites closest to CHOH. Reference conditions are shown in gray. Data show the annual mean concentrations.

Mercury Deposition

Description

- Atmospheric Mercury comes from natural sources: volcanoes, geothermal activity, weathering, burning fossil fuels, processing mineral ores, incineration of waste products
- Annual anthropogenic emissions equal all natural and marine emissions in North America



- Exposure to mercury and other mammals to mercury in utero can result in cerebral palsy, deafness, blindness, speech disorder, and exposure as adults can lead to motor dysfunction and other neurological disorders / mental impacts
- Avians can experience reduced reproductive rates
- Also recorded to have toxic effects in flora, but no ecological threshold is currently established

Data and methods

- Data was obtained from the National Atmospheric Deposition Program, Mercury Deposition Network (Table 4.1) for three sites: Piney Reservoir (MD08) in Garrett County, MD, Beltsville (MD99) in Prince Georges County, MD, and Arendtsville (PA00) in Adams County, PA (Figure 4.1). Samples are collected weekly and within 24 hours of a precipitation event and analyzed for mercury concentration, measured in nanograms (ng) of Hg/L. Annual mean mercury concentrations were calculated for each sampling site.

Condition and trend

- Low risk for aquatic life
- No significant trend

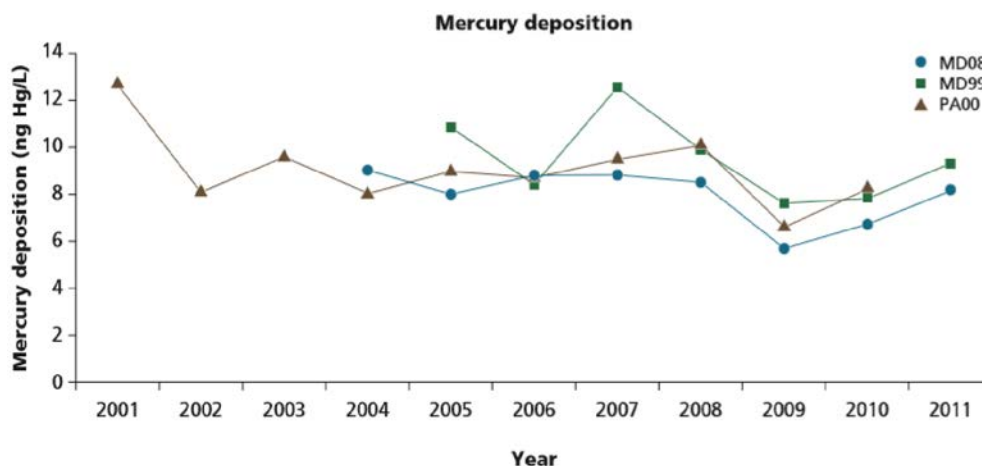


Figure 4.15. Median annual mercury concentrations (ng Hg/L) in precipitation from three sites in the region of CHOH.

2015 Air Quality Summary <https://www.nps.gov/subjects/air/park-conditions-trends.htm>

Air Quality Indicator	Specific Measure	Condition Status/Trend*	Rationale
Ozone	Human Health: Annual 4th-highest 8hr concentration		Condition: Human health risk from ground-level ozone warrants moderate concern at Chesapeake & Ohio Canal NHP. This status is based on NPS Air Resources Division benchmarks and the 2011–2015 estimated ozone of 70.6 parts per billion (ppb). Part of the park is in one or more areas designated by the Environmental Protection Agency (EPA) as nonattainment in 2015 for the 2008 8-hour ozone standard (75 ppb). Trend: For 2006–2015, the trend in ozone concentration at Chesapeake & Ohio Canal NHP improved (AQS Monitor ID: 110010043, DC). Confidence: The degree of confidence at Chesapeake & Ohio Canal NHP is high because there is an on-site or nearby ozone monitor.



Vegetation Health:
3-month maximum
12hr W126



Condition: Vegetation health risk from ground-level ozone warrants moderate concern at Chesapeake & Ohio Canal NHP. This status is based on [NPS Air Resources Division benchmarks](#) and the 2011–2015 estimated W126 metric of 10.2 parts per million-hours (ppm-hrs). The W126 metric relates plant response to ozone exposure. A risk assessment concluded that plants in at Chesapeake & Ohio Canal NHP were at high risk for ozone damage ([Kohut 2007](#); [Kohut 2004](#)). See [list of ozone-sensitive plant species](#).

Trend: For 2006–2015, the trend in the W126 metric at Chesapeake & Ohio Canal NHP improved (AQS Monitor ID: 110010043, DC).

Confidence: The degree of confidence at Chesapeake & Ohio Canal NHP is high because there is an on-site or nearby ozone monitor.



Visibility	Haze Index ⁵		Condition: Visibility warrants significant concern at Chesapeake & Ohio Canal NHP. This status is based on NPS Air Resources Division benchmarks and the 2011–2015 estimated visibility on mid-range days of 10.0 deciviews (dv) above estimated natural conditions.[†] Trend: No trend information is available because there are not sufficient on-site or nearby visibility monitoring data. Confidence: The degree of confidence at Chesapeake & Ohio Canal NHP is medium because estimates are based on interpolated data from more distant visibility monitors.
Nitrogen	Wet Deposition		Condition: Wet nitrogen deposition warrants significant concern at Chesapeake & Ohio Canal NHP. This status is based on NPS Air Resources Division benchmarks and the 2011–2015 estimated wet nitrogen deposition of 4.3 kilograms per hectare per year (kg/ha/yr). Although Chesapeake & Ohio Canal NHP receives high levels of nitrogen deposition, ecosystems in the park are not typical of nitrogen-sensitive systems and were rated as having very low sensitivity to nutrient-enrichment effects relative to all Inventory & Monitoring parks (Sullivan et al. 2011c; Sullivan et al. 2011d). Trend: No trend information is available because there are not sufficient on-site or nearby deposition monitoring data. Confidence: The degree of confidence at Chesapeake & Ohio Canal NHP is medium because estimates are based on interpolated data from more distant deposition monitors.
Sulfur	Wet Deposition		Condition: Wet sulfur deposition warrants significant concern at Chesapeake & Ohio Canal NHP. This status is based on NPS Air Resources Division benchmarks and the 2011–2015 estimated wet sulfur deposition of 2.8 kilograms per hectare per year (kg/ha/yr), a level that normally warrants moderate concern. However, the status has been elevated to significant concern because ecosystems at Chesapeake & Ohio Canal NHP may be very highly sensitive to acidification effects relative to all Inventory & Monitoring parks (Sullivan et al. 2011a; Sullivan et al. 2011b). Acidification effects can include changes in water and soil chemistry that impact ecosystem health. Plants sensitive to the effects of acidification in the park include <i>Acer saccharum</i> (sugar maple) trees. Trend: No trend information is available because there are not sufficient on-site or nearby deposition monitoring data. Confidence: The degree of confidence at Chesapeake & Ohio Canal NHP is medium because estimates are based on interpolated data from more distant deposition monitors.

National Mall and Memorial Parks

*No NCRA data available



2015 Air Quality Summary <https://www.nps.gov/subjects/air/park-conditions-trends.htm>

Air Quality Indicator	Specific Measure	Condition Status/Trend*	Rationale
Ozone	Human Health: Annual 4th-highest 8hr concentration		Condition: Human health risk from ground-level ozone warrants significant concern at National Mall & Memorial Parks. This status is based on NPS Air Resources Division benchmarks and the 2011–2015 estimated ozone of 75.7 parts per billion (ppb). The park is in one or more areas designated by the Environmental Protection Agency (EPA) as nonattainment in 2015 for the 2008 8-hour ozone standard (75 ppb). Trend: For 2006–2015, the trend in ozone concentration at National Mall & Memorial Parks improved (AQS Monitor ID: 110010043, DC). Confidence: The degree of confidence at National Mall & Memorial Parks is high because there is an on-site or nearby ozone monitor.
	Vegetation Health: 3-month maximum 12hr W126		Condition: Vegetation health risk from ground-level ozone warrants significant concern at National Mall & Memorial Parks. This status is based on NPS Air Resources Division benchmarks and the 2011–2015 estimated W126 metric of 13.3 parts per million-hours (ppm-hrs). The W126 metric relates plant response to ozone exposure. Trend: For 2006–2015, the trend in the W126 metric at National Mall & Memorial Parks improved (AQS Monitor ID: 110010043, DC). Confidence: The degree of confidence at National Mall & Memorial Parks is high because there is an on-site or nearby ozone monitor.



Visibility	Haze Index ⁶		Condition: Visibility warrants significant concern at National Mall & Memorial Parks. This status is based on NPS Air Resources Division benchmarks and the 2011–2015 estimated visibility on mid-range days of 10.3 deciviews (dv) above estimated natural conditions.⁷ Trend: No trend information is available because there are not sufficient on-site or nearby visibility monitoring data. Confidence: The degree of confidence at National Mall & Memorial Parks is medium because estimates are based on interpolated data from more distant visibility monitors.
Nitrogen	Wet Deposition		Condition: Wet nitrogen deposition warrants significant concern at National Mall & Memorial Parks. This status is based on NPS Air Resources Division benchmarks and the 2011–2015 estimated wet nitrogen deposition of 3.7 kilograms per hectare per year (kg/ha/yr). Nitrogen deposition may disrupt soil nutrient cycling and affect biodiversity of some plant communities. Trend: No trend information is available because there are not sufficient on-site or nearby deposition monitoring data. Confidence: The degree of confidence at National Mall & Memorial Parks is medium because estimates are based on interpolated data from more distant deposition monitors.
Sulfur	Wet Deposition		Condition: Wet sulfur deposition warrants moderate concern at National Mall & Memorial Parks. This status is based on NPS Air Resources Division benchmarks and the 2011–2015 estimated wet sulfur deposition of 2.3 kilograms per hectare per year (kg/ha/yr). Acidification effects can include changes in water and soil chemistry that impact ecosystem health. Trend: No trend information is available because there are not sufficient on-site or nearby deposition monitoring data. Confidence: The degree of confidence at National Mall & Memorial Parks is medium because estimates are based on interpolated data from more distant deposition monitors.

Rock Creek Park

*No NCRA or Air Quality Monitoring Data

Data and Methods

Metric (by vital sign category)	Agency	Reference/source
Air Quality		
Ozone	NPS ARD (U.S. EPA)	NPS CUE
Total NO ₃ ⁻ deposition (forest habitat)	NADP	http://nadp.sws.uiuc.edu/
Total NO ₃ ⁻ deposition (cultivated)	NADP	http://nadp.sws.uiuc.edu/
Wet SO ₄ deposition	NADP	http://nadp.sws.uiuc.edu/
Particulate matter (soot; PM2.5) concentration	IMPROVE	http://vista.cira.colostate.edu/improve/
Hg deposition	MDN-NADP	http://nadp.sws.uiuc.edu/mdn/



Categories and Metrics	Mean (refer to Chapter 4)	Condition	
		% attainment	Assessment
Air Quality			
Ozone	0.09 ppm	0	Very degraded
Total NO ₂ deposition (forest habitat)	10.8 kg ha ⁻¹ yr ⁻¹	90	Very good
Total NO ₂ deposition (cultivated)	10.8 kg ha ⁻¹ yr ⁻¹		
Wet SO ₄ deposition	18.2 kg ha ⁻¹ yr ⁻¹	0	Very degraded
Particulate matter (soot; PM2.5) concentration	14.4 mg m ⁻³	27	Degraded
Hg deposition	13.5 ng L ⁻¹	0	Very degraded

Condition and Trend

- Air Quality within Rock Creek Park was overall in a degraded condition reflecting regional and local trends.

ARTIFICIAL-TERRESTRIAL

This habitat is poorly characterized

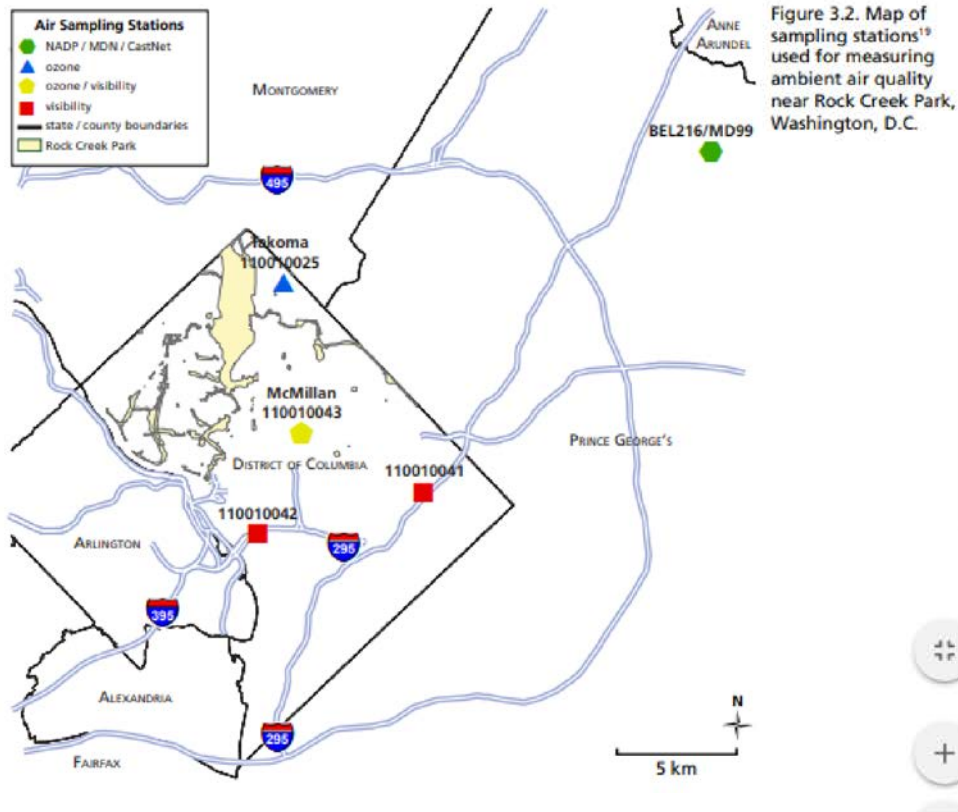
•These habitats are highly visible and heavily used by visitors

•Identify priority monitoring needs (soil compaction, invasive exotic species)
•Inventories (e.g. pollinator species)

Air quality severely compromised—least buffered in this habitat

•Human and ecosystem health impacted

•Regional partnerships and education to improve air quality



Prince William Forest Park Natural Resource Condition Assessment (2015)

Background

- The greatest threat to PRWI is industrialization, auto emissions, local interstate traffic
 - Cars, trucks, burning oil, coal, fossil fuels, manufacturing chemicals
 - Common pollutants: ozone, particulate matter, carbon monoxide, nitrogen oxides, sulfur dioxides, lead
 - Effects of elevated ozone: premature defoliation in plants, high levels of nitrogen deposition acidify/fertilize soils and water affecting nutrient cycling, vegetation composition, biodiversity and causing eutrophication
 - Since it can travel long distances, air pollution can be hard to tackle on a local level
 - They picked ozone, wet deposition species (NO₃, SO₄, NH₄, etc.), dry deposition species (NO₃, SO₄, HNO₃, NH₄, SO₂), and visibility (extinction for 20% cleanest days and 20% worst days for visibility) because those affect vegetation, wildlife water quality and soils
 - Criteria pollutants designate by EPA: ozone, particle pollution, lead, nitrogen dioxide, carbon monoxide, sulfur dioxide



- 5 indicators used at PRWI: wet sulfur deposition, wet nitrogen deposition, ozone (ppb and W126), visibility and particulate matter. Mercury deposition was also measured but only for informational purposes
- Data obtained from: NPS Air Resources Division, collected between 2006-2010



Figure 4-61 Regional air quality monitoring sites for wet deposition of sulfur and nitrogen, ozone, visibility, particulate matter, and mercury deposition. Wet deposition, ozone, and visibility data for 2006-2010 were interpolated by NPS ARD to estimate mean concentrations for PRWI.



Table 4-28 Air Quality reference conditions for PRWI.

Indicator	Reference conditions	Sites	Samples	Period
Wet sulfur deposition (kg/ha/yr)	< 1; 1-3; >3	Whole park	N/A*	2006-2010
Wet nitrogen deposition (kg/ha/yr)	< 1; 1-3; >3	Whole park	N/A*	2006-2010
Ozone (ppb)	≤ 60; 60.1-75; >75	Whole park	N/A*	2006-2010
Ozone (W126; ppm-hrs)	< 7; 7-13; >13	Whole park	N/A*	2006-2010
Visibility (dv)	<2; 2-8; >8	Whole park	N/A*	2006-2010
Particulate matter (PM2.5; µg/m3)	≤12; 12.1-15; >15	2	1974	2002-2012
Mercury deposition (ng/L)	N/A	2		2002-2012

* One interpolated value represents a five-year average of weekly measurements at multiple sites.

Table 4-29 Categorical ranking of the reference condition attainment categories for Air Quality indicators.

Indicator reference condition					Percent attainment	Natural resource condition
S & N deposition (kg/ha/yr)	Ozone (ppb)	Ozone (W126)	Visibility (dv)	Particulate matter (µg/m3)		
< 1	≤ 60	< 7	< 2	≤ 12	100%	Good
1-3	60.1-75	7-13	2-8	12.1-15	0-100% (scaled)	Moderate
> 3	> 75	> 13	> 8	> 15	0%	Significant concern

To assess trends, data from the NPS ARD were used where possible (NPS ARD 2011). Otherwise, monitoring sites closest to PRWI from the National Atmospheric Deposition Program (NADP) and Interagency Monitoring of Protected Visual Environments (IMPROVE) program (Table 4-22).



Table 4-30 Summary of resource condition assessment of Air Quality in PRWI.

Indicator	Result	Reference conditions	Percent attainment	Condition	Air quality condition
Wet sulfur deposition (kg/ha/yr)	4.7	< 1; 1-3; >3	0	Significant concern	13.4% Very degraded
Wet nitrogen deposition (kg/ha/yr)	4.2	< 1; 1-3; >3	0	Significant concern	
Ozone (ppb)	77.5	≤ 60; 60.1-75; >75	0	Significant concern	
Ozone (W126; ppm-hrs)	13.7	< 7; 7-13; >13	0	Significant concern	
Visibility (dv)	12.6	<2; 2-8; >8	0	Significant concern	
Particulate matter (PM2.5; µg/m3)	12.6	≤12; 12.1-15; >15	82.76	Very good	
Mercury deposition (ng/L)		N/A	N/A	N/A	

Data and Methods

- Because there are no air quality monitoring sites within PRWI to assess trends, National Atmospheric Deposition Program (NADP) data from the three monitoring sites closest to PRWI were used. These included sites VA00 (Charlottesville) and VA28 (Shenandoah National Park-Big Meadows) in Virginia, and site MD99 (Beltsville, Prince Georges County) in Maryland.

Condition and Trend

- Interpolated wet sulfur deposition between 2006 and 2010 for PRWI was 4.7 kg/ha/yr, which resulted in 0% attainment of reference condition, or a condition that is of significant concern
- PRWI did not rank as a NPS unit with very high ecosystem sensitivity ranking for acidification impacts (Sullivan et al. 2011a; NPS 2013)

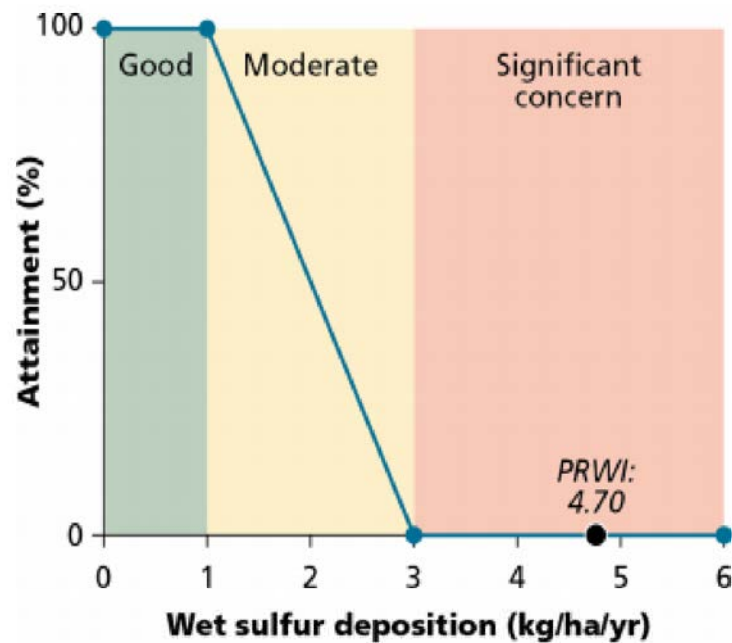


Figure 4-63 Application of the percent attainment categories to the wet sulfur deposition at PRWI was 4.70 kg/ha/yr which equated to 0% attainment of the reference condition.

Nitrogen Deposition

Data and Methods

- Interpolated wet nitrogen deposition between 2006 and 2010 for PRWI was 4.2 kg/ha/yr which resulted in 0% attainment of reference condition, or a condition of significant concern

Condition and Trend

- PRWI did not rank as a NPS unit with very high ecosystem sensitivity for acidification impacts

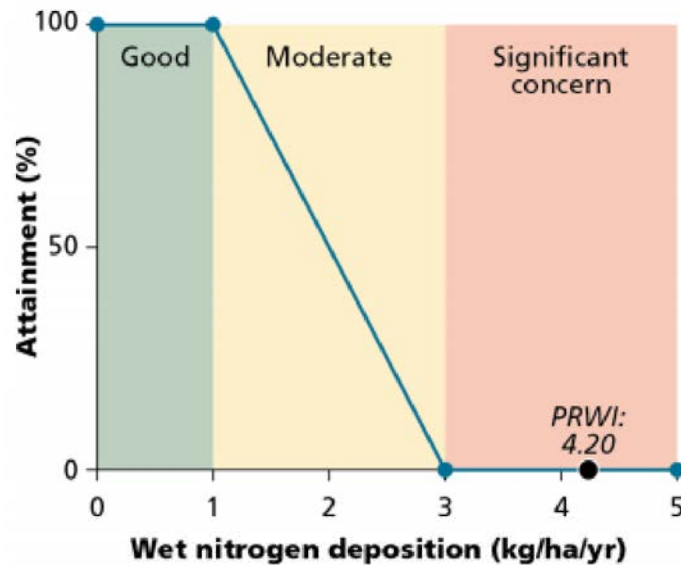


Figure 4-66 Application of the percent attainment categories to the wet nitrogen deposition value categories. Wet nitrogen deposition at PRWI was 4.20 kg/ha/yr which equated to 0% attainment of the reference condition.

Wet nitrogen deposition (kg/ha/yr)

Figure 4-66 Application of the percent attainment categories to the wet nitrogen deposition value categories. Wet nitrogen deposition at PRWI was 4.20 kg/ha/yr which equated to 0% attainment of the reference condition.

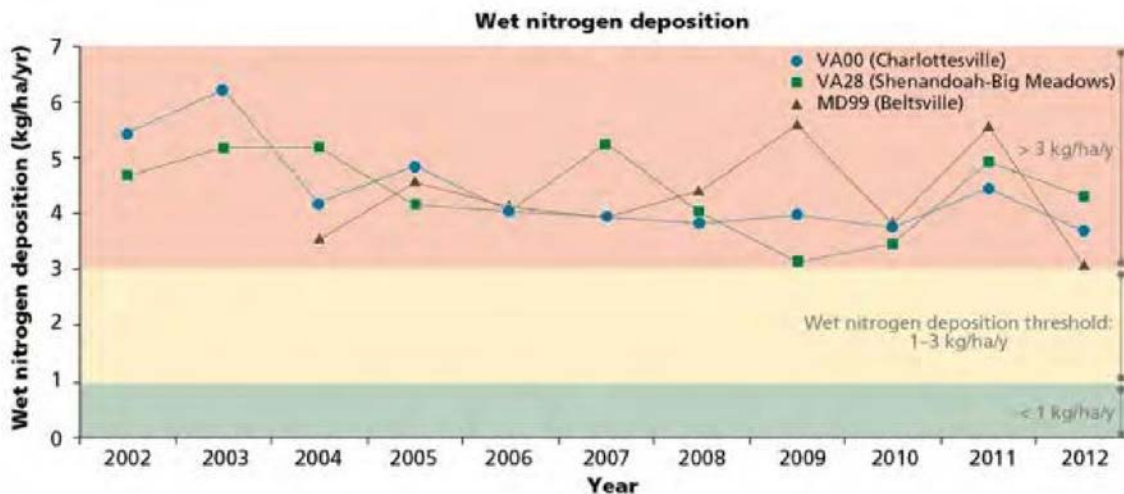


Figure 4-67 Annual wet deposition of total nitrogen (kg/ha/yr) at the three sites closest to PRWI. Reference conditions are shown in green.



Ozone

- Interpolated fourth-highest daily maximum eight-hour ozone concentration between 2006 and 2010 for PRWI was 77.5 ppb, which resulted in 0% attainment of reference condition, or a condition of significant concern
- PRWI is located in an EPA designated 8-hour ozone nonattainment county (Figure 4-50), and therefore, the overall air quality condition is automatically placed in the Warrants Significant Concern category
- Interpolated W126 value between 2006 and 2010 for PRWI was 13.7 ppm-hrs, which resulted in 0% attainment of reference condition, or conditions of significant concern (Figure 4-48, Table 4-25). PRWI was evaluated at high risk for ozone injury to vegetation

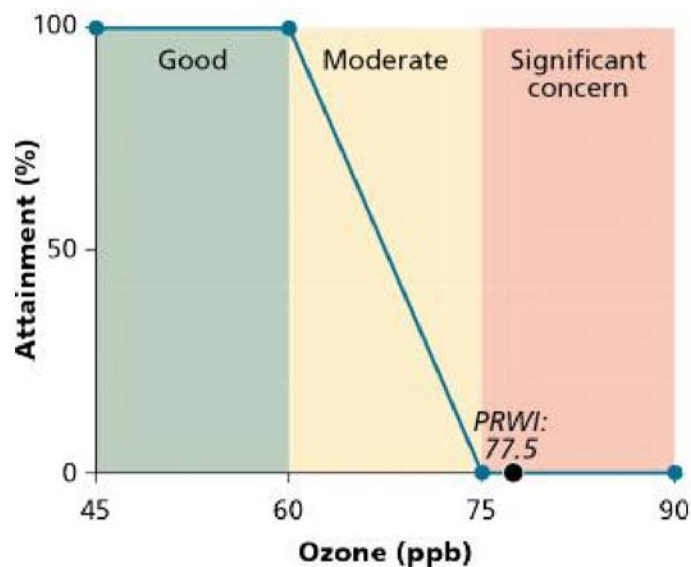


Figure 4-68 Application of the percent attainment categories to the ozone (ppb) value categories. Ozone at PRWI was 77.5 ppb, which equated to 0% attainment of the reference condition.

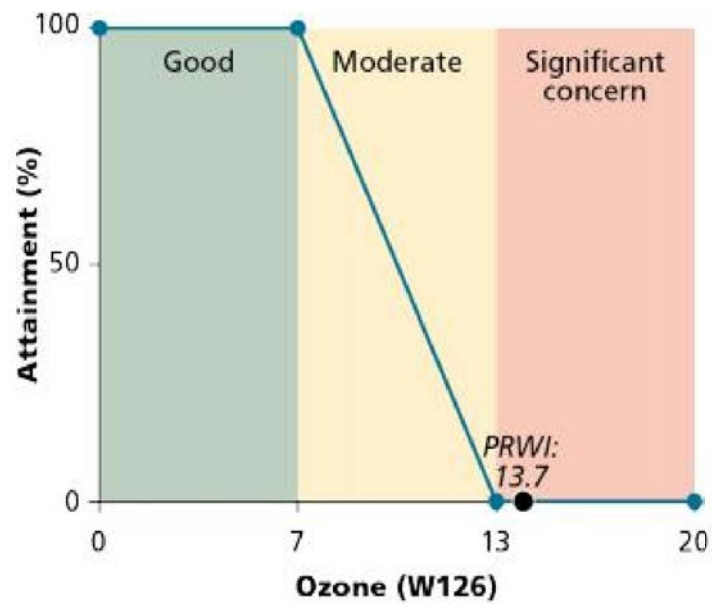


Figure 4-69 Application of the percent attainment categories to the ozone (W126 in ppm-hrs) value categories. W126 at PRWI was 13.7 ppm, which equated to 0% attainment of the reference condition.

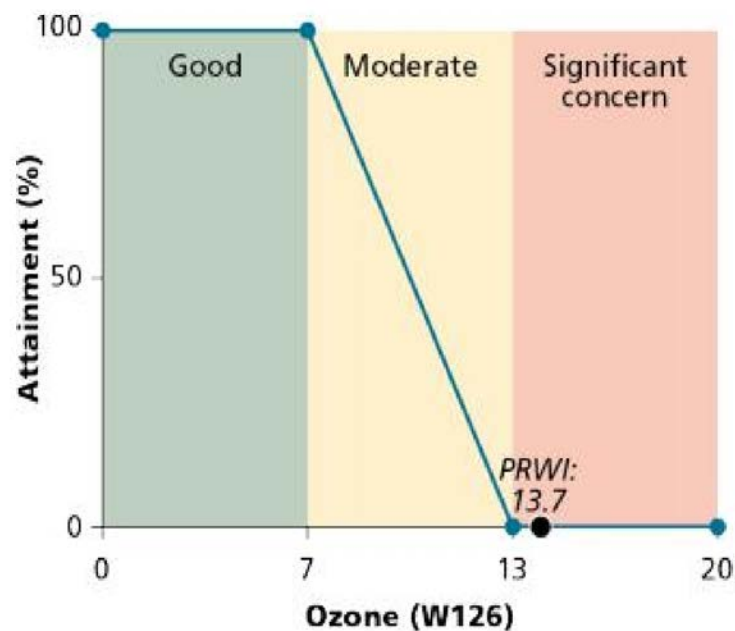


Figure 4-69 Application of the percent attainment categories to the ozone (W126 in ppm-hrs) value categories. W126 at PRWI was 13.7 ppm, which equated to 0% attainment of the reference condition.

Visibility

Condition and Trend

- Interpolated haze index between 2006 and 2010 for PRWI was 12.6 dv, which resulted in 0% attainment of reference condition, or a condition of significant concern

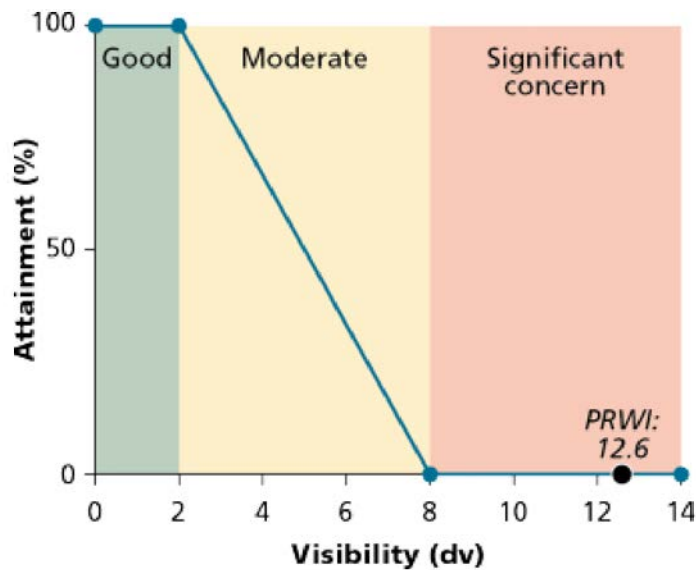


Figure 4-71 Application of the percent attainment categories to the visibility value categories. Visibility at PRWI was 12.6 dv, which equated to 0% attainment of the reference condition.

Particulate Matter

Data and Methods

- Data was obtained from the Interagency Monitoring of Protected Visual Environments (IMPROVE) database (Table 4-22) through the U.S. EPA AirData interface for the two sampling locations closest to PRWI. These included sites 510590030 (Lee District Park) and 511071005 (Broad Run High School, VA).

Condition and Trend

- The two sites closest to PRWI had a median of 12.5 $\mu\text{g}/\text{m}^3$ between 2002 and 2012, with 82.76% attainment of the reference condition, or very good condition
- Over the data range available, there appears to be a decreasing trend in PM 2.5 at both sites. Both sites showed a significant improving trend of particulate matter over the past decade (p value < 0.01)

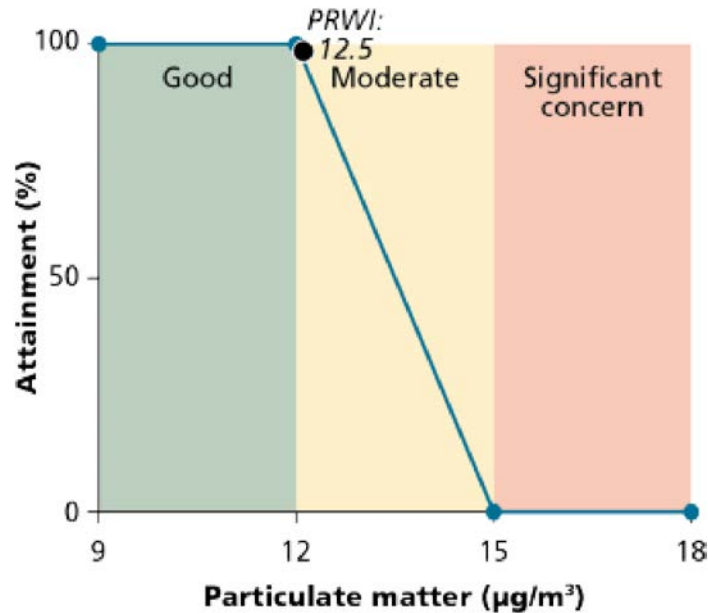


Figure 4-73 Application of the percent attainment categories to the particulate matter value categories. The median for particulate matter at PRWI was $12.5 \mu\text{g}/\text{m}^3$ which equated to 100% attainment of the reference condition.

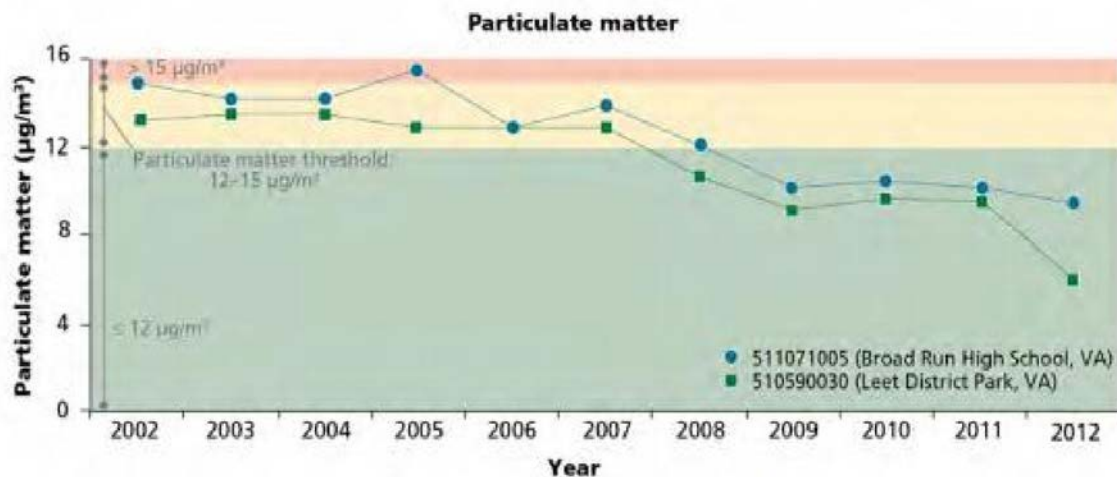


Figure 4-74 Particulate matter ($\mu\text{g}/\text{m}^3$) at the two sites closest to PRWI. Reference conditions are shown in green. Data shown are the annual mean concentrations.

Data and Methods

- Data was obtained from the National Atmospheric Deposition Program, Mercury Deposition Network (Table 4-22) for two sites: MD99 (Beltsville, MD) and VA28 (Shenandoah-Big Meadows, VA). Samples are collected weekly within 24 hours of a



precipitation event and analyzed for mercury concentration, measured in nanograms (ng) of Hg per liter. Annual mean mercury concentrations were calculated for each sampling site.

- Annual median mercury concentrations in precipitation from two sites in the region of PRWI over the past decade range from ~4.97 to 12.56 ng/L (Figure 4-56), and the Mid-Atlantic region in general has relatively low levels of mercury deposition.
- Over the data range available, no significant trend was present (p-value >0.01)

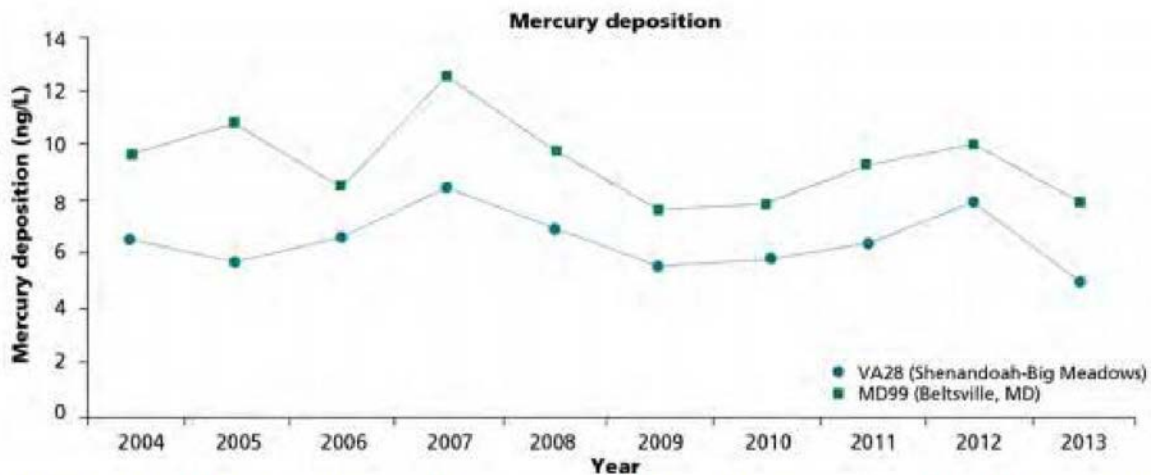


Figure 4-76 Median annual mercury concentrations (ng/L) in precipitation from two sites in the region of PRWI.

Overall Conditions

- Very degraded: 13% attainment of reference conditions (lower % the worse)
- “Causes of which are largely out of the park’s control”

Recommendations:



Table 5-9 Key findings, management implications, and recommended next steps for air quality in PRWI.

Key findings	Management implications	Recommended next steps
Air quality is very degraded and is a regional problem	- Impacts of poor air quality on park largely unknown. - Nearby parks (e.g. Shenandoah NP) have clear ecological impacts of poor air quality (i.e. acid rain impacts).	- Investigate effects of poor air quality on sensitive habitats and species within the park. (e.g. ozone damage to vegetation). - Continue participation in Climate Friendly Parks program (www.nps.gov/climatefriendlyparks). - Investigate effects of poor air quality on sensitive habitats and species within the park. - Continue previous bioindicator monitoring efforts (e.g. tolerant vs. non tolerant lichen species presence). - Stay engaged with the wider community in terms of air quality education and activities.
Lack of park-specific air quality data	- Air quality is only measured and interpolated on regional and national scales. - Unknown impact of traffic (specifically standing traffic) from I-95 near the western corner of the park.	- Use transport and deposition models to predict specific pollution effects by location. - Implementation of park-scale air quality monitoring would give better insights into park-level air quality condition and possible effects on park habitats and species.
Ecological references for mercury wet deposition are not available	Mercury deposition is reported for PRWI but no reference exists for protection of species.	Adopt standards once NPS Air Resources Division establishes mercury wet deposition reference.
Minimal soundscape information	Traffic noise from I-95 corridor and weapon fire from Marine Corps Base-Quantico potentially affect	Noise/soundscape study.

Key findings	Management implications	Recommended next steps
	bird distribution and recreational experience. Effect greater in fall and winter when foliage not present to dampen noise.	Approach Virginia Department of Transport regarding feasibility of a noise containment wall.



Air Quality Indicator	Specific Measure	Condition Status/Trend*	Rationale
Ozone	Human Health: Annual 4th-highest 8hr concentration		Condition: Human health risk from ground-level ozone warrants moderate concern at Prince William Forest Park. This status is based on NPS Air Resources Division benchmarks and the 2011–2015 estimated ozone of 69.7 parts per billion (ppb). The park is in one or more areas designated by the Environmental Protection Agency (EPA) as nonattainment in 2015 for the 2008 8-hour ozone standard (75 ppb). Trend: For 2006–2015, the trend in ozone concentration at Prince William Forest Park improved (AQS Monitor ID: 511790001, VA). Confidence: The degree of confidence at Prince William Forest Park is high because there is an on-site or nearby ozone monitor.
	Vegetation Health: 3-month maximum 12hr W126		Condition: Vegetation health risk from ground-level ozone warrants moderate concern at Prince William Forest Park. This status is based on NPS Air Resources Division benchmarks and the 2011–2015 estimated W126 metric of 9.1 parts per million-hours (ppm-hrs). The W126 metric relates plant response to ozone exposure. A risk assessment concluded that plants in at Prince William Forest Park were at high risk for ozone damage (Kohut 2007; Kohut 2004). See list of ozone-sensitive plant species. Trend: For 2006–2015, the trend in the W126 metric at Prince William Forest Park improved (AQS Monitor ID: 511790001, VA). Confidence: The degree of confidence at Prince William Forest Park is high because there is an on-site or nearby ozone monitor.
Visibility	Haze Index [§]		Condition: Visibility warrants significant concern at Prince William Forest Park. This status is based on NPS Air Resources Division benchmarks and the 2011–2015 estimated visibility on mid-range days of 9.7 deciviews (dv) above estimated natural conditions.¹ Trend: No trend information is available because there are not sufficient on-site or nearby visibility monitoring data. Confidence: The degree of confidence at Prince William Forest Park is medium because estimates are based on interpolated data from more distant visibility monitors.
Nitrogen	Wet Deposition		Condition: Wet nitrogen deposition warrants significant concern at Prince William Forest Park. This status is based on NPS Air Resources Division benchmarks and the 2011–2015 estimated wet nitrogen deposition of 3.6 kilograms per hectare per year (kg/ha/yr). Although Prince William Forest Park receives high levels of nitrogen deposition, ecosystems in the park are not typical of nitrogen-sensitive systems and were rated as having very low sensitivity to nutrient-enrichment effects relative to all Inventory & Monitoring parks (Sullivan et al. 2011c; Sullivan et al. 2011d). Trend: No trend information is available because there are not sufficient on-site or nearby deposition monitoring data. Confidence: The degree of confidence at Prince William Forest Park is medium because estimates are based on interpolated data from more distant deposition monitors.



Sulfur	Wet Deposition		Condition: Wet sulfur deposition warrants moderate concern at Prince William Forest Park. This status is based on NPS Air Resources Division benchmarks and the 2011–2015 estimated wet sulfur deposition of 2.2 kilograms per hectare per year (kg/ha/yr). Ecosystems in the park were rated as having moderate sensitivity to acidification effects relative to all Inventory & Monitoring parks (Sullivan et al. 2011a; Sullivan et al. 2011b). Acidification effects can include changes in water and soil chemistry that impact ecosystem health. Plants sensitive to the effects of acidification in the park include <i>Acer saccharum</i> (sugar maple) trees. Trend: No trend information is available because there are not sufficient on-site or nearby deposition monitoring data. Confidence: The degree of confidence at Prince William Forest Park is medium because estimates are based on interpolated data from more distant deposition monitors.
* Condition assessments for contiguous U.S. parks use the Inverse Distance Weighted (IDW) interpolation method is used to estimate 5-year average (2011–2015) values. Trend analyses use 10 years (2006–2015) of data from on-site or nearby monitors. † Reporting units for wet deposition conditions and trends are different. Wet deposition trends are evaluated using pollutant concentrations in precipitation (micro equivalents/liter) so that yearly variations in precipitation amounts do not influence trends analyses. Wet deposition conditions are based on nitrogen and sulfur loading (kilograms per hectare per year) to ecosystems. § Visibility trends and conditions are both expressed in terms of a Haze Index in deciviews (dv); however, the benchmark metrics are different. Condition assessments are based on estimated five-year average visibility on mid-range days (40th to 60th percentile) minus the estimated natural visibility condition on mid-range days. Visibility trends are computed from the haze index values on the 20% haziest days and the 20% clearest days.			

Programs at PRWI that Cater Towards Educating Citizens

Check out: <https://www.nps.gov/subjects/climatechange/cfpprogram.htm>

- The Climate Friendly Parks (CFP) Program is one of many initiatives supporting the National Park Service (NPS) **Green Parks Plan**.



park is leading by example. In so doing, the park commits to reducing GHG emissions from park operations by 20% below 2008 levels by 2016 through the following actions:

1. Reduce energy consumption of park buildings.
2. Explore the use of renewable energy technology and alternative energy.
3. Encourage energy saving behavior among staff and visitors.
4. Reduce transportation emissions from park operations.
5. Reduce transportation emissions from visitor vehicles in the park.
6. Divert solid waste from the landfill by increasing recycling capacity and educating staff and visitors.
7. Decrease the amount of solid waste sent to the landfill by revamping the "Trash Free" program.
8. Educate park employees and visitors about climate change and how to reduce GHG emissions.

Wolf Trap Natural Resource Condition Assessment (2015)

Background

- The park is therefore subjected to high ozone and atmospheric deposition, potentially impacting flora, fauna, and park visitors.
- WOTR is one of the largest green spaces near Tysons Corner, Virginia, and will likely see increased visitation with increased nearby development.
- Watershed-wide urbanization and development result in challenges to water quality and pest management.
- With WMATA (Metro) silver line, visitor use within the park could increase dramatically, causing increased pressure on the natural resources within WOTR
 - Provides an opportunity for increased education and experiences within the park.
- Purpose of WOTR: venue for live performances, visitor use, from hiking to picnicking, has the potential to place increasing demands on the protected areas within the park.
- 1.5 miles Wolf Trap TRACK Trail, and the 2.5 miles Wolf Trap Trail. ‘

Data and Methods

- Source: NPS Air and Resources Division

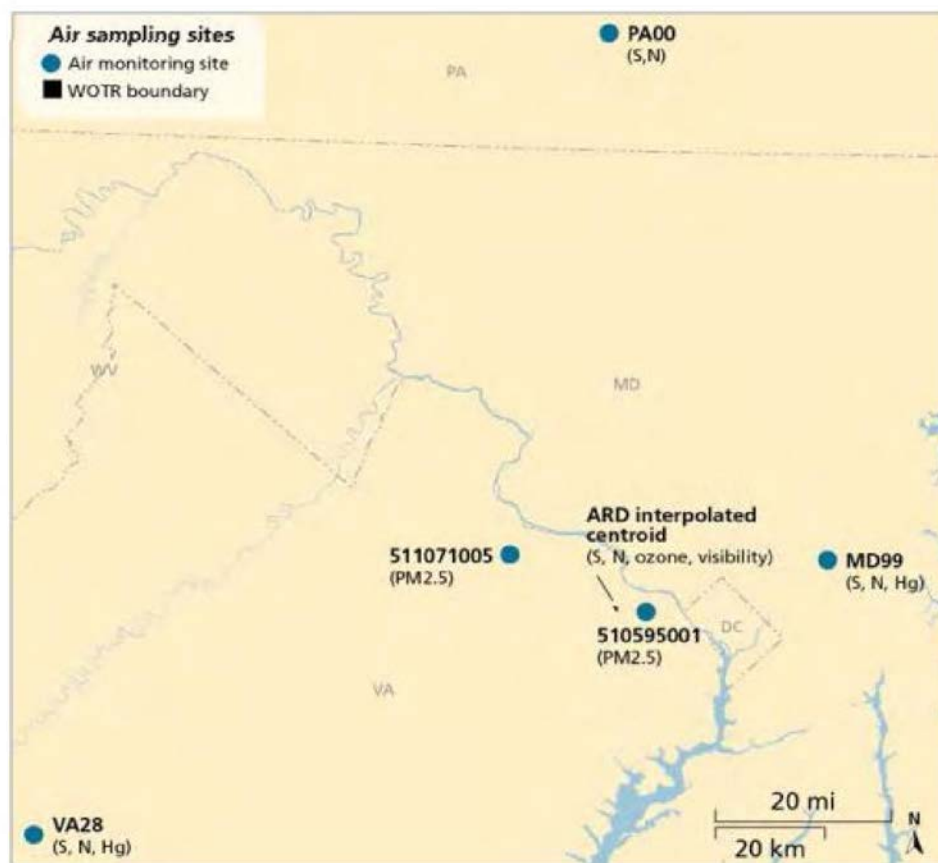


Figure 4-26 Regional air quality monitoring sites for wet deposition of sulfur and nitrogen, ozone, visibility, particulate matter, and mercury deposition. Wet deposition, ozone, and visibility data for 2006-2010 were interpolated by NPS ARD to estimate a mean concentration for WOTR.



Table 4-22 Air resource indicators, data availability, reference conditions, and condition assessment categories.

Air resource indicator	Number of sites	Number of samples	Period of observation	Reference condition	% attainment applied
Wet sulfur deposition (kg/ha/yr)	1*	N/A*	2006-2010	< 1 1-3 >3	100% 0-100% (scaled) 0%
Wet nitrogen deposition (kg/ha/yr)	1*	N/A*	2006-2010	< 1 1-3	100% 0-100% (scaled)

Air resource indicator	Number of sites	Number of samples	Period of observation	Reference condition	% attainment applied
Ozone (ppb)	1*	N/A*	2006-2010	>3 ≤ 60 60.1-75.0 >75	0% 100% 0-100% (scaled) 0%
Ozone (W126; ppm-hrs)	1*	N/A*	2006-2010	< 7 7-13 >13	100% 0-100% (scaled) 0%
Visibility (dv)	1*	N/A*	2006-2010	<2 2-8 >8	100% 0-100% (scaled) 0%
Particulate matter (PM _{2.5} ; µg/m ³)	2	1974	2002-2012	≤12 12.1-15.0 >15	100% 0-100% (scaled) 0%
Mercury deposition (ng/L)	2	701	2005-2011	N/A	N/A

Condition and Trend

- Overall air quality condition attainment of 8.0%, or very degraded condition
- Inspection of available air quality data over time, presented in Figure 4-28 and Figure 4-29, does show improving trends on the eastern USA for wet sulfur deposition, particulate matter, mercury deposition, ozone, and the haze index.
- Wet nitrogen deposition does not follow this trend and is stable or increasing based on the data obtained from sites used for this assessment
- Good/moderate condition of water resources and biological integrity were offset by degraded air resources
- Migration rest stop for wildlife and serves as a biology classroom to communities



- increases in impervious surfaces, traffic, and population of the developed area puts Wolf Trap at risk of decreased water and air quality, increased light pollution, and habitat squeeze.
- On a regional scale, degraded air quality associated with vehicular traffic affects aquatic habitats and sensitive species.

Table 5-1 Natural resource condition assessment of WOTR.

Vital sign	Reference attainment	Condition
Water resources	60%	Good
Biological integrity	44%	Moderate
Landscape dynamics	2%	Very degraded
Air resources	10%	Very degraded
WOTR Overall	29%	Degraded

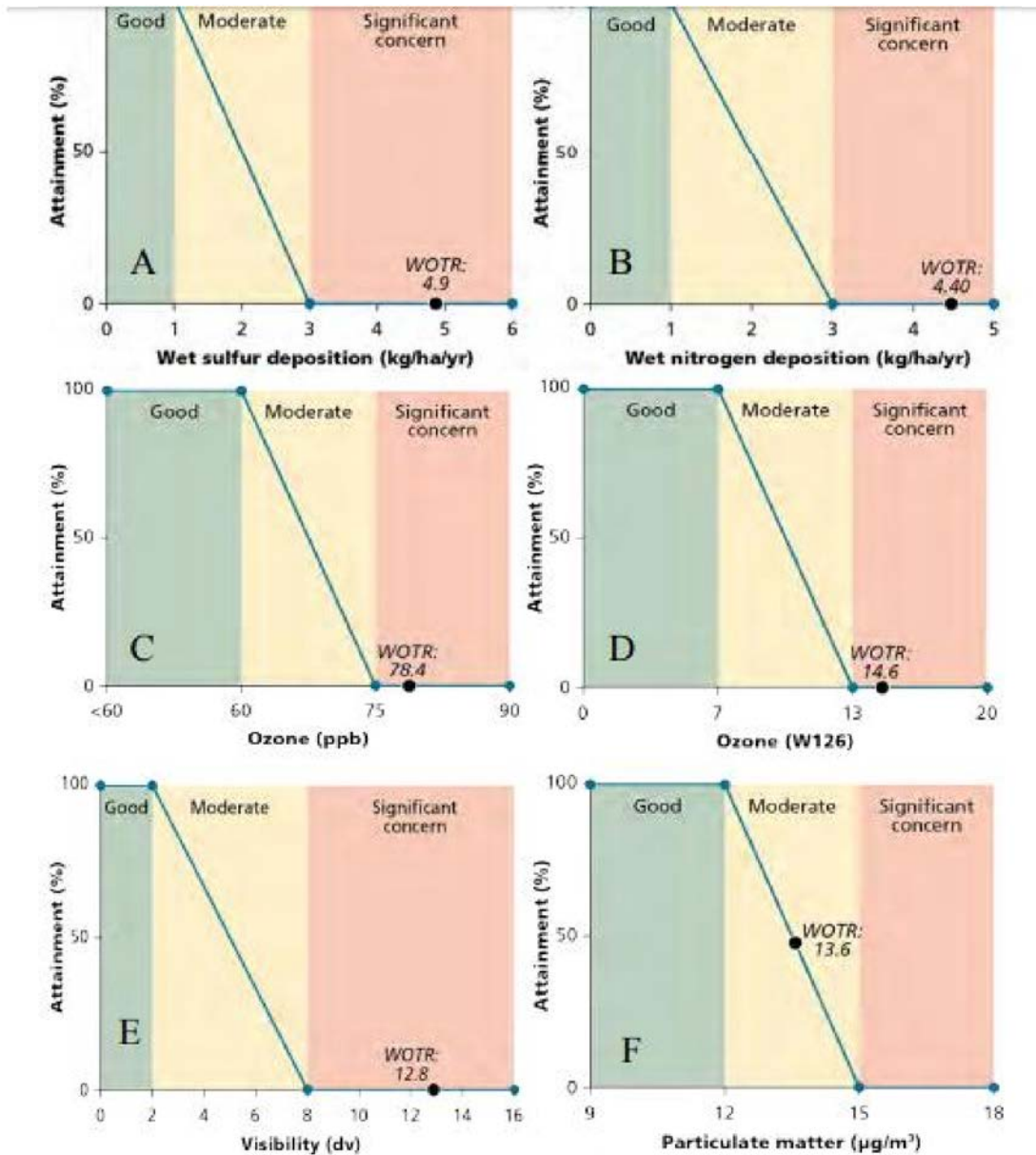
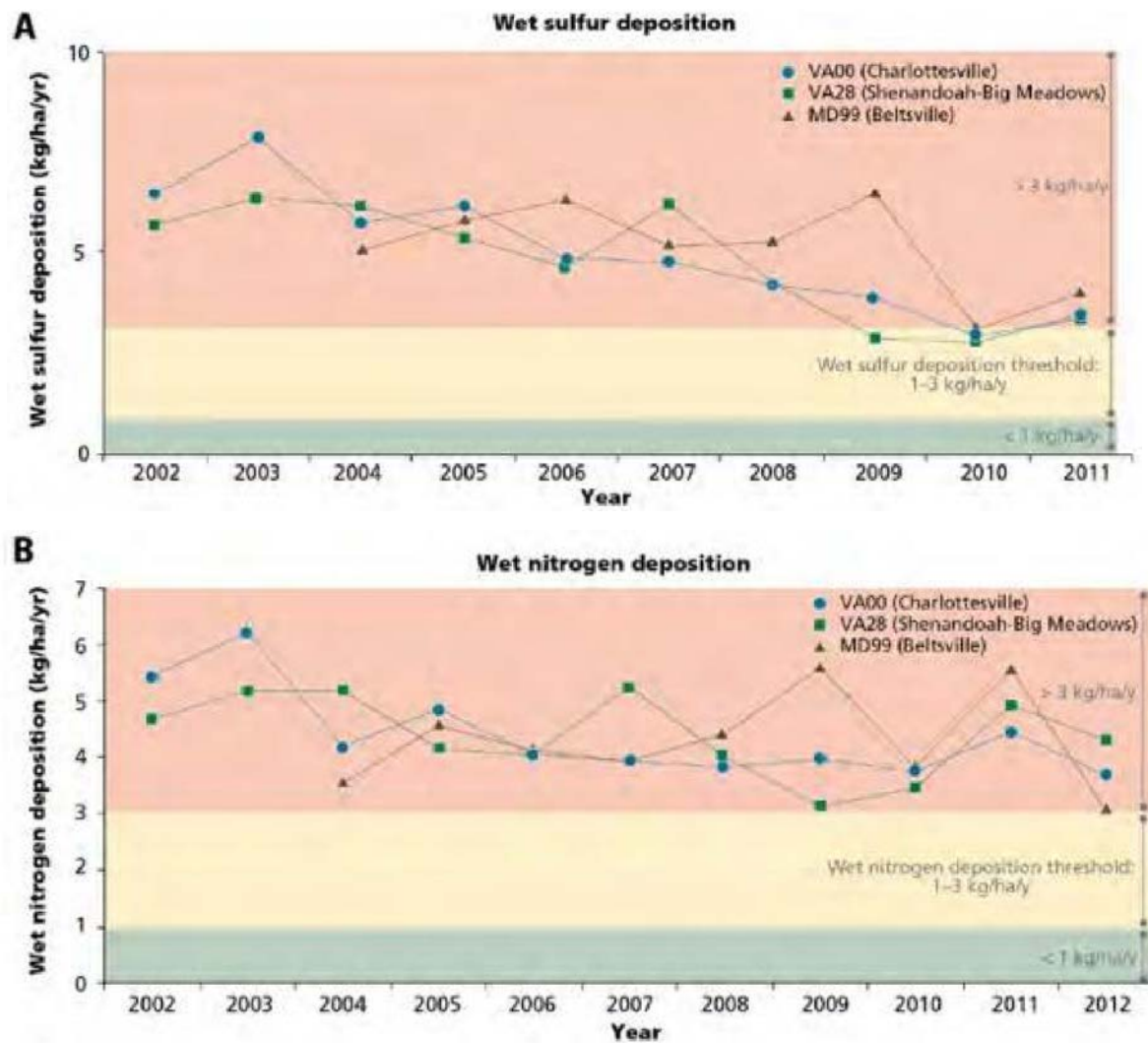


Figure 4-27 Application of the percent attainment categories to results for: A) wet sulfur deposition (kg/ha/yr); B) wet nitrogen deposition (kg/ha/yr); C) Ozone (ppb); D) Ozone (W126); E) Visibility (dv); F) Particulate matter ($\mu\text{g}/\text{m}^3$).



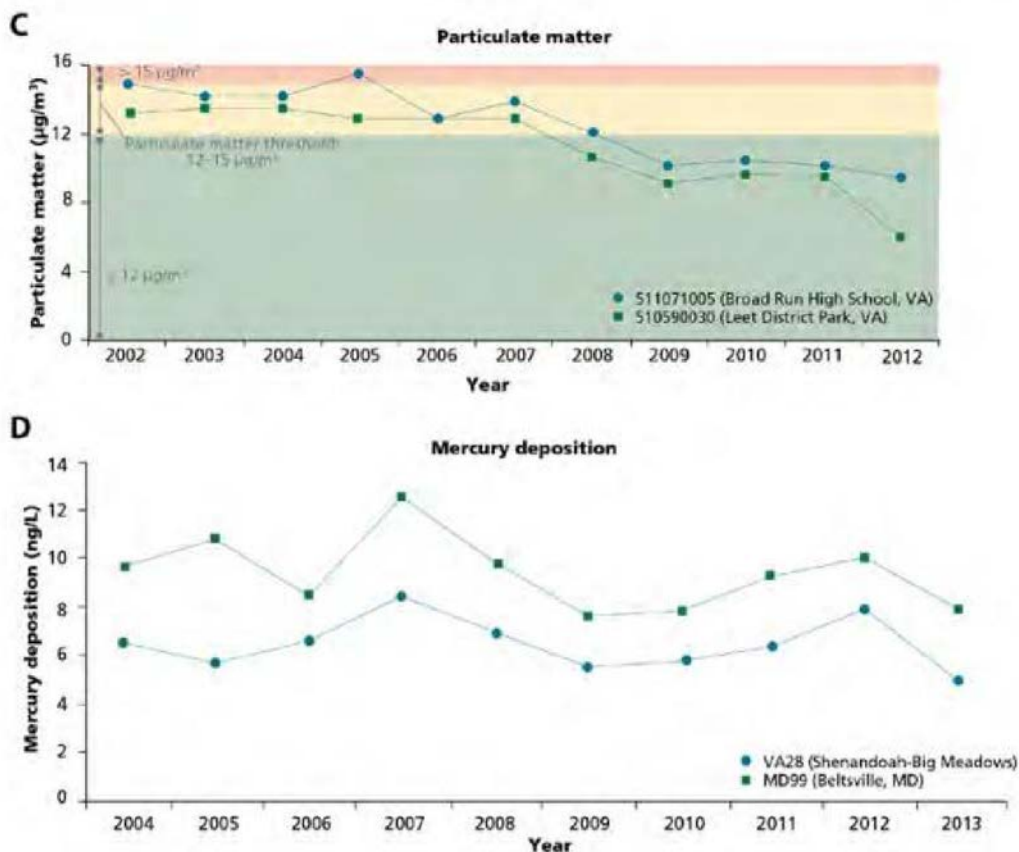


Figure 4-28 Trends observed over time in: A) wet sulfur deposition ($\text{kg}/\text{ha}/\text{yr}$); B) wet nitrogen deposition ($\text{kg}/\text{ha}/\text{yr}$); C) Particulate matter ($\mu\text{g}/\text{m}^3$); D) Mercury deposition (ng/L). No reference condition/reference condition is available for mercury deposition.

Table 4-23 Summary of air quality condition assessment at WOTR.

Air quality indicator	WOTR Result	% attainment of reference condition	Condition assessment	Overall air quality condition
Wet sulfur deposition ($\text{kg}/\text{ha}/\text{yr}$)	4.9	0	Significant concern	8.0% Very degraded
Wet nitrogen deposition ($\text{kg}/\text{ha}/\text{yr}$)	4.4	0	Significant concern	
Ozone (ppb)	78.4	0	Significant concern	
Ozone (W126; ppm-hrs)	14.6	0	Significant concern	
Visibility (dv)	15.7	0	Significant concern	
Particulate matter ($\text{PM}_{2.5}$; $\mu\text{g}/\text{m}^3$)	13.6	48	Moderate	
Mercury deposition (ng/L)	7.6	N/A	N/A	



Recommendations

Table 5-12 Key findings, management implications, and recommended next steps for air quality in WOTR.

Key findings	Management implications	Recommended next steps
Air quality is very degraded	Habitats and species in the park may be affected	Monitor for local effects (e.g. ozone damage to vegetation).
Air quality is a regional problem	Habitats and species in the park may be affected	- Continue participation in Climate Friendly Parks program www.nps.gov/climatefriendlypark - Stay engaged with the wider community in terms of air quality education and activities.

Table 5-13 Data gaps, justification, and research needs for air quality in WOTR.

Data gaps	Justification	Research needs
Park-specific air quality data	- Air quality is measured and interpolated on regional and national scales - Need to implement park-specific management actions	- Use transport and deposition models. - Implementation of park-scale air quality monitoring would give better insights into park-level air quality condition and possible effects on park habitats and species. - Planting and monitoring a garden of ozone-sensitive plants.
Effects of poor air quality on park habitats and species	Need to implement park-specific management actions	Investigate effects of poor air quality on sensitive habitats and species within the park.
Ecological references for mercury wet deposition	Mercury deposition is reported for WOTR but no reference exists for protection of species	Adopt standards once NPS Air Resources Division establishes mercury wet deposition reference.
Lightscape information	Night sky visibility is affected by primary park activities and neighboring influences	Light study.
Soundscape information	Potential increase in traffic noise over time, from either an increase in vehicles or the opening of the Washington Metropolitan Area Transit Authority's new Silver Line	Noise/soundscape study.

****Planting and monitoring a garden of ozone-sensitive plants!****



2015 Air Quality Summary

Air Quality Indicator	Specific Measure	Condition Status/Trend*	Rationale
Ozone	Human Health: Annual 4th-highest 8hr concentration		Condition: Human health risk from ground-level ozone warrants significant concern at Wolf Trap National Park for the Performing Arts. This status is based on NPS Air Resources Division benchmarks and the 2011–2015 estimated ozone of 73.4 parts per billion (ppb). The park is in one or more areas designated by the Environmental Protection Agency (EPA) as nonattainment in 2015 for the 2008 8-hour ozone standard (75 ppb). Trend: No trend information is available because there are not sufficient on-site or nearby ozone monitoring data. Confidence: The degree of confidence at Wolf Trap National Park for the Performing Arts is medium because estimates are based on interpolated data from more distant ozone monitors.
	Vegetation Health; 3-month maximum 12hr W126		Condition: Vegetation health risk from ground-level ozone warrants moderate concern at Wolf Trap National Park for the Performing Arts. This status is based on NPS Air Resources Division benchmarks and the 2011–2015 estimated W126 metric of 11.9 parts per million-hours (ppm-hrs). The W126 metric relates plant response to ozone exposure. A risk assessment concluded that plants in at Wolf Trap NP for the Performing Arts were at high risk for ozone damage (Kohut 2007; Kohut 2004). See list of ozone-sensitive plant species. Trend: No trend information is available because there are not sufficient on-site or nearby ozone monitoring data. Confidence: The degree of confidence at Wolf Trap National Park for the Performing Arts is medium because estimates are based on interpolated data from more distant ozone monitors.



Visibility	Haze Index ⁵		Condition: Visibility warrants significant concern at Wolf Trap National Park for the Performing Arts. This status is based on NPS Air Resources Division benchmarks and the 2011–2015 estimated visibility on mid-range days of 10.1 deciviews (dv) above estimated natural conditions.⁴ Trend: No trend information is available because there are not sufficient on-site or nearby visibility monitoring data. Confidence: The degree of confidence at Wolf Trap National Park for the Performing Arts is medium because estimates are based on interpolated data from more distant visibility monitors.
Nitrogen	Wet Deposition		Condition: Wet nitrogen deposition warrants significant concern at Wolf Trap National Park for the Performing Arts. This status is based on NPS Air Resources Division benchmarks and the 2011–2015 estimated wet nitrogen deposition of 3.9 kilograms per hectare per year (kg/ha/yr). Although Wolf Trap National Park for the Performing Arts receives high levels of nitrogen deposition, ecosystems in the park are not typical of nitrogen-sensitive systems and were rated as having low sensitivity to nutrient-enrichment effects relative to all Inventory & Monitoring parks (Sullivan et al. 2011c; Sullivan et al. 2011d). Trend: No trend information is available because there are not sufficient on-site or nearby deposition monitoring data. Confidence: The degree of confidence at Wolf Trap National Park for the Performing Arts is medium because estimates are based on interpolated data from more distant deposition monitors.



Sulfur	Wet Deposition		Condition: Wet sulfur deposition warrants moderate concern at Wolf Trap National Park for the Performing Arts. This status is based on NPS Air Resources Division benchmarks and the 2011–2015 estimated wet sulfur deposition of 2.4 kilograms per hectare per year (kg/ha/yr). Ecosystems in the park were rated as having moderate sensitivity to acidification effects relative to all Inventory & Monitoring parks (Sullivan et al. 2011a; Sullivan et al. 2011b). Acidification effects can include changes in water and soil chemistry that impact ecosystem health. Trend: No trend information is available because there are not sufficient on-site or nearby deposition monitoring data. Confidence: The degree of confidence at Wolf Trap National Park for the Performing Arts is medium because estimates are based on interpolated data from more distant deposition monitors.
* Condition assessments for contiguous U.S. parks use the Inverse Distance Weighted (IDW) interpolation method is used to estimate 5-year average (2011–2015) values. Trend analyses use 10 years (2006–2015) of data from on-site or nearby monitors. † Reporting units for wet deposition conditions and trends are different. Wet deposition trends are evaluated using pollutant concentrations in precipitation (micro equivalents/liter) so that yearly variations in precipitation amounts do not influence trends analyses. Wet deposition conditions are based on nitrogen and sulfur loading (kilograms per hectare per year) to ecosystems. § Visibility trends and conditions are both expressed in terms of a Haze Index in deciviews (dv); however, the benchmark metrics are different. Condition assessments are based on estimated five-year average visibility on mid-range days (40th to 60th percentile) minus the estimated natural visibility condition on mid-range days. Visibility trends are computed from the haze index values on the 20% haziest days and the 20% clearest days. ± Natural visibility conditions are those estimated to exist in a given area in the absence of human-caused visibility impairment. Estimated annual average natural condition on mid-range days equals 7.8 deciviews (dv) at Wolf Trap NP for the Performing Arts.			

George Washington Memorial Parkway Natural Resource Condition Assessment

Data and Methods

- Both the algae and fungus in lichens absorb water, minerals, and pollutants from the air. Sensitive lichen species can develop structural changes in response to air pollution. Over time, sensitive species may be replaced by pollution-tolerant species. Therefore, the species of lichens present in a location and the concentration of pollutants measured within lichens can be indicative of air quality (Nortrup 2011). Five permanent lichen biomonitoring sites have been established in GWMP. At each location, abundance of tree-inhabiting macrolichens is recorded and a specimen of the common lichen *Flavoparmelia caperata* is collected for elemental analysis (George Mason 2014).

Conditions and Trends

- 0% attainment for all air quality indicators except particulate matter. Overall, GWMP scored a 9.2%, or very degraded condition
-



Table 4-26 Ecological monitoring framework data for Air Quality provided by agencies and specific sources included in the assessment of GWMP.

Indicator	Agency	Reference/source
Wet sulfur deposition	NPS ARD	NPS ARD 2012b; http://nadp.sws.uiuc.edu/data/animaps.aspx
Wet nitrogen deposition	NPS ARD	NPS ARD 2012b; http://nadp.sws.uiuc.edu/data/animaps.aspx
Ozone (ppb and W126)	NPS ARD	NPS ARD 2012a;
Visibility	NPS ARD	NPS ARD 2012c;
Particulate matter (PM 2.5)	IMPROVE	http://www.epa.gov/airdata
Mercury deposition	NADP-MDN	http://nadp.sws.uiuc.edu/data/mdndata.aspx

Table 4-27 Air quality indicators, data availability, reference conditions, and condition assessment categories used in the natural resource condition assessment of George Washington Memorial Parkway.

Air quality indicator	Number of sites	Number of samples	Period of observation	Reference conditions	Percent attainment applied
Wet sulfur deposition (kg/ha/yr)	Whole park	N/A*	2006-2010	< 1; 1-3; >3	0-100% scaled linearly
Wet nitrogen deposition (kg/ha/yr)	Whole park	N/A*	2006-2010	< 1; 1-3; >3	0-100% scaled linearly
Ozone (ppb)	Whole park	N/A*	2006-2010	≤ 60; 60.1-75; >75	0-100% scaled linearly
Ozone (W126; ppm-hrs)	Whole park	N/A*	2006-2010	< 7; 7-13; >13	0-100% scaled linearly
Visibility (dv)	Whole park	N/A*	2006-2010	<2; 2-8; >8	0-100% scaled linearly
Particulate matter (PM2.5; µg/m3)	2	1974	2002-2012	≤12; 12.1-15; >15	0-100% scaled linearly
Mercury deposition (ng/L)	2	701	2005-2011	N/A	N/A

*one interpolated value represents a five-year average of weekly measurements at multiple sites.



Table 4-28 Summary of air quality resource condition assessment at GWMP.

Air quality indicator	GWMP result	Percent attainment of reference condition	Condition assessment	Overall air quality condition
Wet sulfur deposition (kg/ha/yr)	4.8	0%	Significant concern	9% Very degraded
Wet nitrogen deposition (kg/ha/yr)	4.3	0%	Significant concern	
Ozone (ppb)	79.4	0%	Significant concern	
Ozone (W126; ppm-h)	15.4	0%	Significant concern	
Visibility (dv)	13.0	0%	Significant concern	
Particulate matter (PM _{2.5} ; µg/m ³)	13.4	55%	Moderate	
Mercury deposition (ng/L)	7.6	N/A	N/A	



Figure 4-39 Regional air quality monitoring sites for ozone, visibility, particulate matter, mercury deposition, and wet deposition of sulfur and nitrogen. Wet deposition, ozone, and visibility data for 2006-2010 were interpolated by NPS ARD to estimate mean concentrations for GWMP.



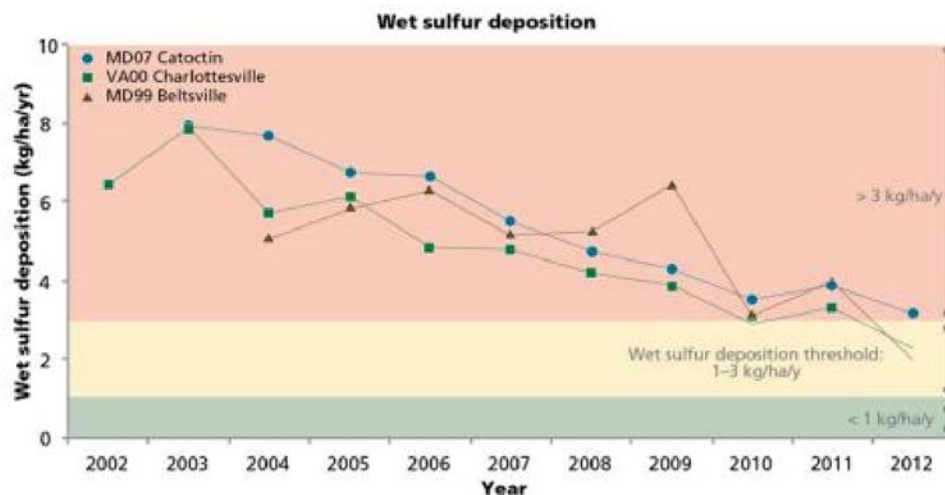
Wet Sulfur

Data and Methods

- data were analyzed from the three locations closest to the park (MD07, MD99 and VA00), MD07 and VA00, showed a significant improvement over the past decade (p-value < 0.01)

Condition and Trend

- GWMP was ranked at moderate risk of ecosystem sensitivity→ streams and soils in park are vulnerable to acidification
- At this time, park streams are not showing signs of acidification



Wet

Figure 4-42 Annual wet deposition of sulfate (kg/ha/yr) at three sites closest to GWMP reported as SO₄ deposition.

Nitrogen Deposition

Data and Methods

- National Atmospheric Deposition Program (NADP) data from the three monitoring sites closest to GWMP were used.
 - VA00 (Charlottesville) in Virginia, and sites MD99 (Beltsville), and MD07 (Catocin) in Maryland (Figure 4-39).

Condition and Terms

- None of the sites showed a significant improvement of wet deposition over the past decade (p-value > 0.01)

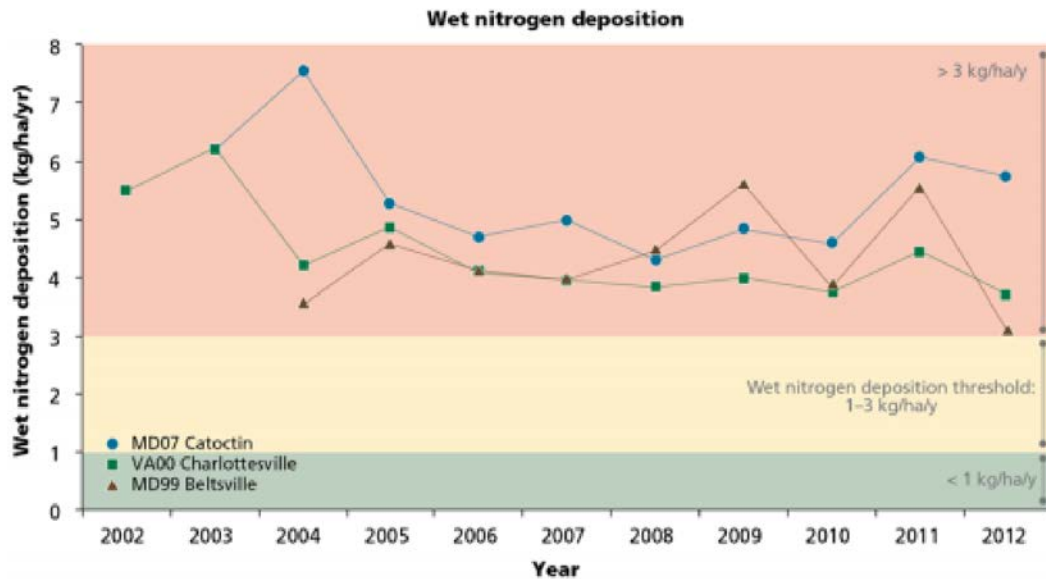
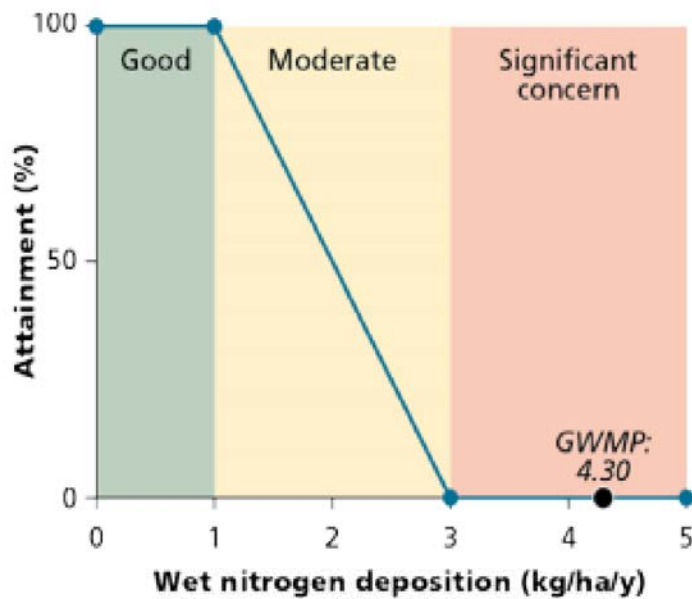


Figure 4-45 Annual wet deposition of total nitrogen (kg/ha/yr) at the three sites closest to GWMP.



Ozone

Condition and Trends

- 0% attainment of reference condition → condition of significant concern
- GWMP is located in an EPA designated 8 hour ozone non-attainment county, so overall quality condition is placed in Warrants Significant Concern category

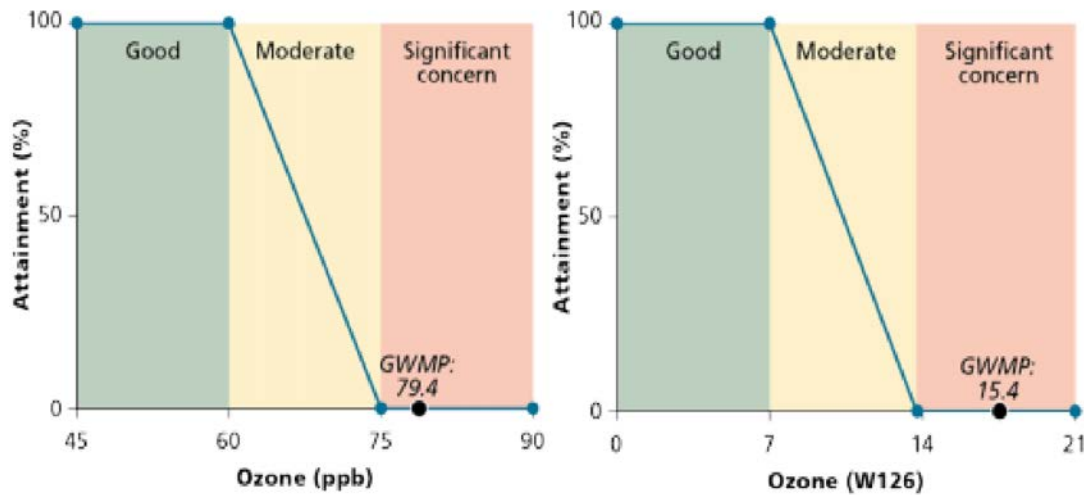


Figure 4-46 At GWMP, ozone was 79.4 ppb and ozone W126 was 14.6, which equated to 0% attainment for both reference conditions.

Visibility

Condition and trend

- 0% attainment, or condition of significant concern
- Based on country-wide assessment of visibility trends there was a statistically significant improving trend in improving visibility

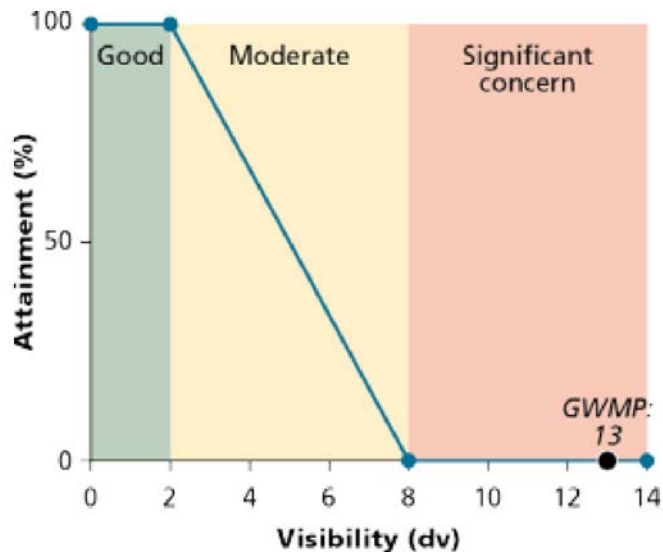


Figure 4-48 Application of the percent attainment categories to the visibility value categories. Visibility at GWMP was 13.0 dv, which resulted in 0% attainment of the reference condition.

Particulate Matter

Data and Methods



- EPA AirData interface for the three sampling locations closest to GWMP. These included sites 510595001 (McLean, VA) 511071005 (Broad Run High School, VA) and 510590030 (Lee District Park, VA) (Table 4-26, Figure 4-39).

Condition and trend

- 55.17% attainment, or moderate condition
- Improving trend of particulate matter over the past decade

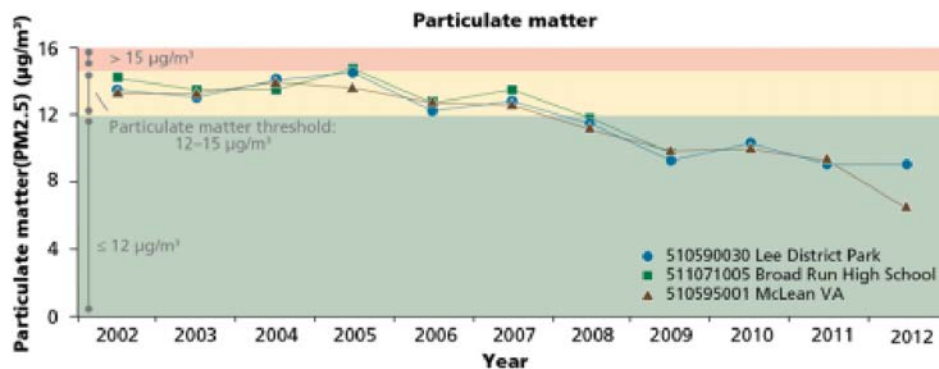


Figure 4-50 Particulate matter ($\mu\text{g}/\text{m}^3$) at the two sites closest to GWMP. Reference conditions are shown in gray. Data show the annual mean concentrations.

Mercury Deposition

Data and Methods

- Data obtained from 2 sites: MD99 (Beltsville, MD) and VA28 (Shenandoah-Big Meadows) (Table 4-26, Figure 4-39).

Condition and Trend

- No significant trend

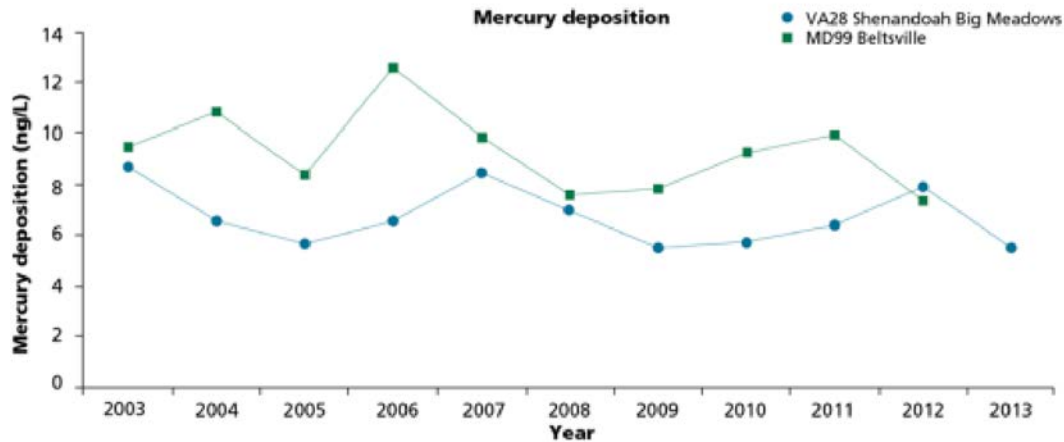


Figure 4-52 Median annual mercury concentrations (ng/L) in precipitation from two sites in the region of GWMP.

Recommendations

Table 5-12 Key findings, management implications, and recommended next steps for air quality in GWMP.

Key findings	Management implications	Recommended next steps
Air quality is very degraded and is a regional problem	Specific impacts of poor air quality on park largely unknown. Nearby parks (e.g. Shenandoah NP) have clear ecological impacts of poor air quality (i.e. acid rain impacts).	Investigate effects of poor air quality on sensitive habitats and species within the park. (e.g. ozone damage to vegetation). Continue to support regional air quality initiatives such as Climate Friendly Parks (www.nps.gov/climatefriendlyparks). Develop park-specific management actions. Stay engaged with the wider community in terms of air quality education and activities.
Lack of park-specific air quality data	Air quality is only measured and interpolated on regional and national scales.	Use transport and deposition models to estimate air quality indicator conditions. Implement park-scale air quality monitoring for better insight into park-level air quality condition and possible effects on park habitats and species.
Minimal soundscape information	Traffic noise from roadway potentially affects wildlife behavior and distribution, and visitor recreational experience. Effect greater in fall and winter when foliage absent.	Noise/soundscape study.



Air Quality Indicator	Specific Measure	Condition Status/Trend*	Rationale
Ozone	Human Health: Annual 4th-highest 8hr concentration		Condition: Human health risk from ground-level ozone warrants significant concern at George Washington Memorial PKWY. This status is based on NPS Air Resources Division benchmarks and the 2011–2015 estimated ozone of 75.9 parts per billion (ppb). The park is in one or more areas designated by the Environmental Protection Agency (EPA) as nonattainment in 2015 for the 2008 8-hour ozone standard (75 ppb). Trend: For 2006–2015, the trend in ozone concentration at George Washington Memorial PKWY remained relatively unchanged (no statistically significant trend) (AQ5 Monitor ID: 510130020, VA). Confidence: The degree of confidence at George Washington Memorial PKWY is high because there is an on-site or nearby ozone monitor.
	Vegetation Health: 3-month maximum 12hr W126		Condition: Vegetation health risk from ground-level ozone warrants significant concern at George Washington Memorial PKWY. This status is based on NPS Air Resources Division benchmarks and the 2011–2015 estimated W126 metric of 13.3 parts per million-hours (ppm-hrs). The W126 metric relates plant response to ozone exposure. A risk assessment concluded that plants in at George Washington Memorial PKWY were at high risk for ozone damage (Kohut 2007; Kohut 2004). See list of ozone-sensitive plant species. Trend: For 2006–2015, the trend in the W126 metric at George Washington Memorial PKWY improved (AQ5 Monitor ID: 510130020, VA). Confidence: The degree of confidence at George Washington Memorial PKWY is high because there is an on-site or nearby ozone monitor.
Visibility	Haze Index ⁵		Condition: Visibility warrants significant concern at George Washington Memorial PKWY. This status is based on NPS Air Resources Division benchmarks and the 2011–2015 estimated visibility on mid-range days of 10.4 deciviews (dv) above estimated natural conditions.¹ Trend: No trend information is available because there are not sufficient on-site or nearby visibility monitoring data. Confidence: The degree of confidence at George Washington Memorial PKWY is medium because estimates are based on interpolated data from more distant visibility monitors.
Nitrogen	Wet Deposition		Condition: Wet nitrogen deposition warrants significant concern at George Washington Memorial PKWY. This status is based on NPS Air Resources Division benchmarks and the 2011–2015 estimated wet nitrogen deposition of 3.9 kilograms per hectare per year (kg/ha/yr). Although George Washington Memorial PKWY receives high levels of nitrogen deposition, ecosystems in the park are not typical of nitrogen-sensitive systems and were rated as having low sensitivity to nutrient-enrichment effects relative to all Inventory & Monitoring parks (Sullivan et al. 2011c; Sullivan et al. 2011d). Trend: No trend information is available because there are not sufficient on-site or nearby deposition monitoring data. Confidence: The degree of confidence at George Washington Memorial PKWY is medium because estimates are based on interpolated data from more distant deposition monitors.



Sulfur	Wet Deposition		Condition: Wet sulfur deposition warrants moderate concern at George Washington Memorial PKWY. This status is based on NPS Air Resources Division benchmarks and the 2011–2015 estimated wet sulfur deposition of 2.4 kilograms per hectare per year (kg/ha/yr). Ecosystems in the park were rated as having moderate sensitivity to acidification effects relative to all Inventory & Monitoring parks (Sullivan et al. 2011a; Sullivan et al. 2011b). Acidification effects can include changes in water and soil chemistry that impact ecosystem health. Plants sensitive to the effects of acidification in the park include <i>Acer saccharum</i> (sugar maple) trees. Trend: No trend information is available because there are not sufficient on-site or nearby deposition monitoring data. Confidence: The degree of confidence at George Washington Memorial PKWY is medium because estimates are based on interpolated data from more distant deposition monitors.
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* Condition assessments for contiguous U.S. parks use the Inverse Distance Weighted (IDW) interpolation method is used to estimate 5-year average (2011–2015) values. Trend analyses use 10 years (2006–2015) of data from on-site or nearby monitors.

† Reporting units for wet deposition conditions and trends are different. Wet deposition trends are evaluated using pollutant concentrations in precipitation (micro equivalents/liter) so that yearly variations in precipitation amounts do not influence trends analyses. Wet deposition conditions are based on nitrogen and sulfur loading (kilograms per hectare per year) to ecosystems.

§ Visibility trends and conditions are both expressed in terms of a Haze Index in deciviews (dv); however, the benchmark metrics are different. Condition assessments are based on estimated five-year average visibility on mid-range days (40th to 60th percentile) minus the estimated natural visibility condition on mid-range days. Visibility trends are computed from the haze index values on the 20% haziest days and the 20% clearest days.

± Natural visibility conditions are those estimated to exist in a given area in the absence of human-caused visibility impairment. Estimated annual average natural condition on mid-range days equals 7.8 deciviews (dv) at George Washington Memorial PKWY.

Catoctin Mountain Natural Resource Condition Assessment (2013)

Data and Methods

- Data was collected from NPS Air Resources Division between 2005–2009

Table 4.2. Air Quality reference conditions for CATO.

Metric	Reference conditions	Sites	Samples	Period
Wet sulfur deposition (kg/ha/yr)	< 1; 1–3; > 3	Whole park	N/A*	2005–2009
Wet nitrogen deposition (kg/ha/yr)	< 1; 1–3; > 3	Whole park	N/A*	2005–2009
Ozone (ppb)	≤ 60; 60.1–75; > 75	Whole park	N/A*	2005–2009
Ozone (W126; ppm-hrs)	< 7; 7–13; > 13	Whole park	N/A*	2005–2009
Visibility (dv)	< 2; 2–8; > 8	Whole park	N/A*	2005–2009
Particulate matter (PM _{2.5} ; µg/m ³)	≤ 12; 12.1–15; > 15	2	5,476	2001–2010
Mercury deposition (ng/L)	N/A	2	701	2001–2011

* One interpolated value represents a five-year average of weekly measurements at multiple sites.



Table 4.3. Categorical ranking of the reference condition attainment categories for Air Quality metrics.

Metric reference conditions					Attainment of reference condition	Natural resource condition
S & N deposition (kg/ha/yr)	Ozone (ppb)	Ozone (W126)	Visibility (dv)	Particulate matter ($\mu\text{g}/\text{m}^3$)		
< 1	≤ 60	< 7	< 2	≤ 12	100%	Good
1–3	60.1–75	7–13	2–8	12.1–15	0–100% (scaled)	Moderate
> 3	> 75	> 13	> 8	> 15	0%	Significant concern

39

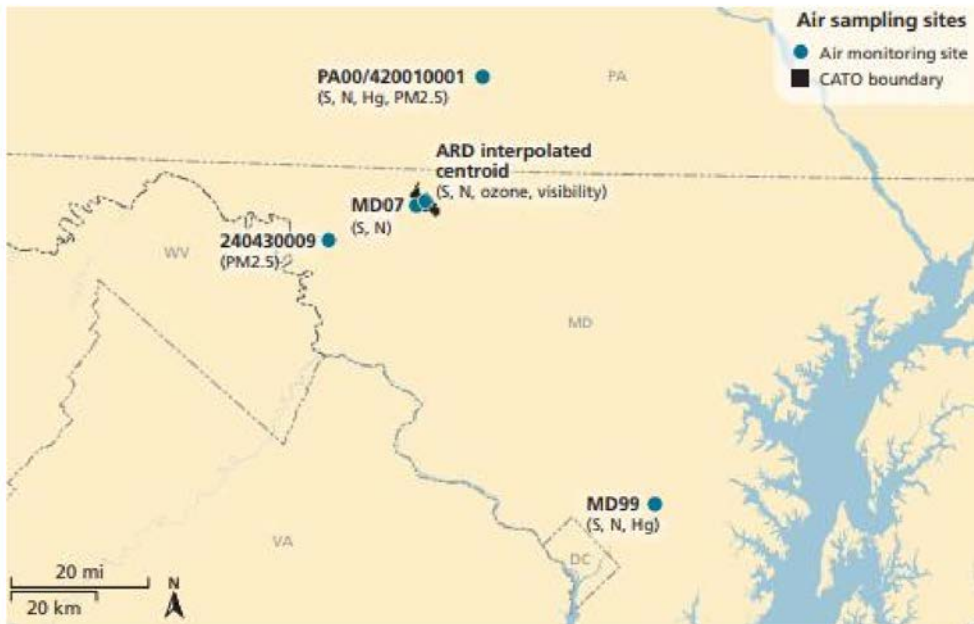
Table 4.2. Air Quality reference conditions for CATO.

Metric	Reference conditions	Sites	Samples	Period
Wet sulfur deposition (kg/ha/yr)	< 1; 1–3; > 3	Whole park	N/A*	2005–2009
Wet nitrogen deposition (kg/ha/yr)	< 1; 1–3; > 3	Whole park	N/A*	2005–2009
Ozone (ppb)	≤ 60; 60.1–75; > 75	Whole park	N/A*	2005–2009
Ozone (W126; ppm-hrs)	< 7; 7–13; > 13	Whole park	N/A*	2005–2009
Visibility (dv)	< 2; 2–8; > 8	Whole park	N/A*	2005–2009
Particulate matter (PM _{2.5} ; $\mu\text{g}/\text{m}^3$)	≤ 12; 12.1–15; > 15	2	5,476	2001–2010
Mercury deposition (ng/L)	N/A	2	701	2001–2011

* One interpolated value represents a five-year average of weekly measurements at multiple sites.

Table 4.4. Summary of resource condition assessment of Air Quality in CATO.

Metric	Result	Reference conditions	% attainment	Condition	Air Quality condition
Wet sulfur deposition (kg/ha/yr)	5.40	< 1; 1–3; > 3	0	Significant concern	13% Very degraded
Wet nitrogen deposition (kg/ha/yr)	4.65	< 1; 1–3; > 3	0	Significant concern	
Ozone (ppb)	75.9	≤ 60; 60.1–75; > 75	0	Significant concern	
Ozone (W126; ppm-hrs)	12.6	< 7; 7–13; > 13	6.7	Moderate	
Visibility (dv)	13.0	< 2; 2–8; > 8	0	Significant concern	
Particulate matter (PM _{2.5} ; $\mu\text{g}/\text{m}^3$)	13.1	≤ 12; 12.1–15; > 15	65	Moderate	
Mercury deposition (ng/L)	9.1	N/A	N/A	N/A	



Wet Sulfur deposition

Data and Methods

- MD07, PA00 and MD99

Condition and Trend

- Streams and soils are not showing signs of acidification
- MD07 showed a significant reduction in sulfur deposition
- PA00 and MD99 did not show a trend

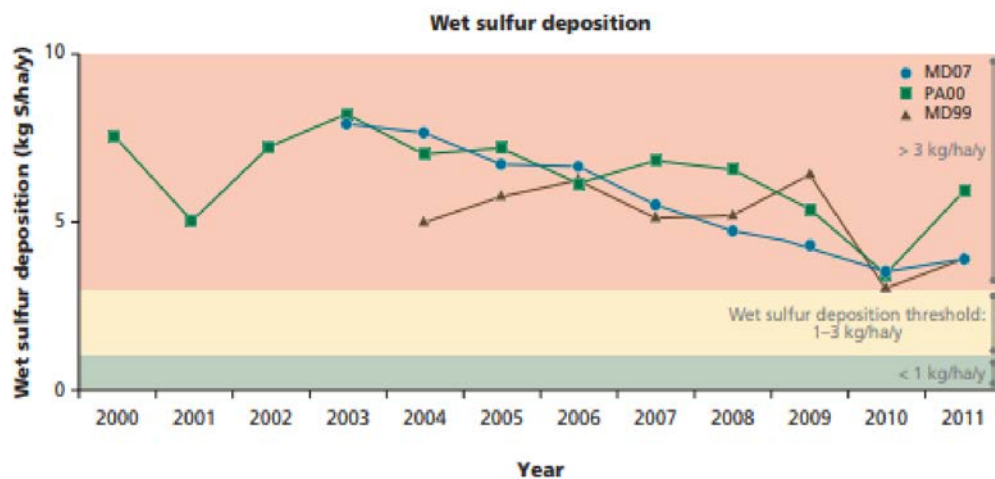


Figure 4.4. Annual wet deposition of sulfate (kg SO₄/ha/yr) at the three sites closest to CATO. Data were reported as SO₄ deposition; these data were converted to total S deposition using atomic weights (multiplying by 0.333). Reference conditions shown in gray.

Wet Nitrogen Deposition

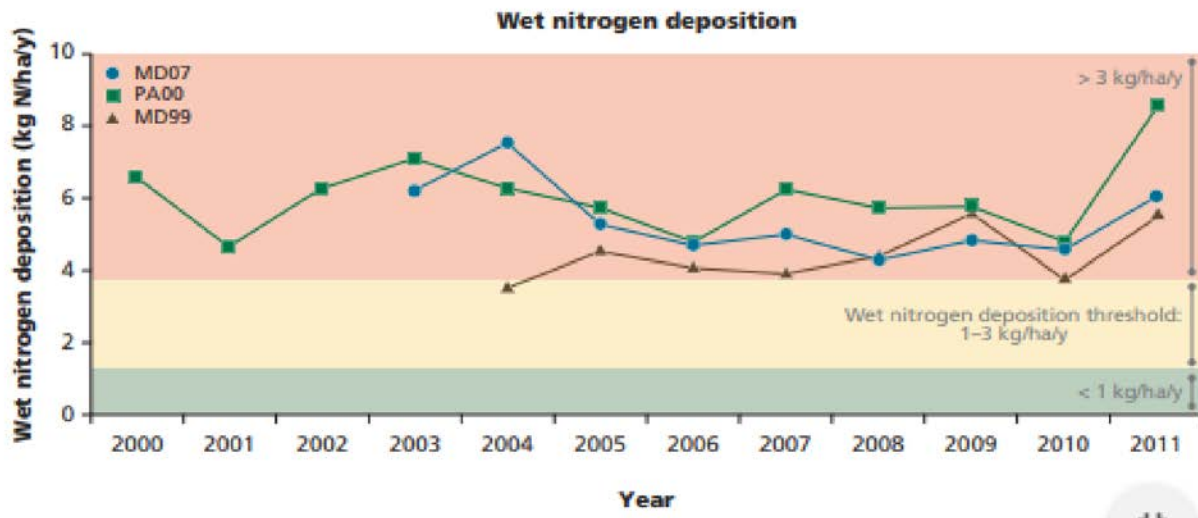
Data and Methods

- MD07, PA00 and MD99

Condition and Trend



- None of the sites showed a significant improvement of wet deposition over the past decade ($p\text{-value} > 0.01$)



2015 Air Quality Summary

Air Quality Indicator	Specific Measure	Condition Status/Trend*	Rationale
Ozone	Human Health: Annual 4th-highest 8hr concentration		Condition: Human health risk from ground-level ozone warrants moderate concern at Catoctin Mountain Park. This status is based on NPS Air Resources Division benchmarks and the 2011–2015 estimated ozone of 69.2 parts per billion (ppb). The park is in one or more areas designated by the Environmental Protection Agency (EPA) as nonattainment in 2015 for the 2008 8-hour ozone standard (75 ppb). Trend: No trend information is available because there are not sufficient on-site or nearby ozone monitoring data. Confidence: The degree of confidence at Catoctin Mountain Park is medium because estimates are based on interpolated data from more distant ozone monitors.
	Vegetation Health: 3-month maximum 12hr W126		Condition: Vegetation health risk from ground-level ozone warrants moderate concern at Catoctin Mountain Park. This status is based on NPS Air Resources Division benchmarks and the 2011–2015 estimated W126 metric of 9.8 parts per million-hours (ppm-hrs). The W126 metric relates plant response to ozone exposure. A risk assessment concluded that plants in at Catoctin Mountain Park were at high risk for ozone damage (Kohut 2007; Kohut 2004). See list of ozone-sensitive plant species. Trend: No trend information is available because there are not sufficient on-site or nearby ozone monitoring data. Confidence: The degree of confidence at Catoctin Mountain Park is medium because estimates are based on interpolated data from more distant ozone monitors.



Visibility	Haze Index [§]		Condition: Visibility warrants significant concern at Catoctin Mountain Park. This status is based on NPS Air Resources Division benchmarks and the 2011–2015 estimated visibility on mid-range days of 9.0 deciviews (dv) above estimated natural conditions.[†] Trend: No trend information is available because there are not sufficient on-site or nearby visibility monitoring data. Confidence: The degree of confidence at Catoctin Mountain Park is medium because estimates are based on interpolated data from more distant visibility monitors.
Nitrogen	Wet Deposition		Condition: Wet nitrogen deposition warrants significant concern at Catoctin Mountain Park. This status is based on NPS Air Resources Division benchmarks and the 2011–2015 estimated wet nitrogen deposition of 5.6 kilograms per hectare per year (kg/ha/yr). Although Catoctin Mountain Park receives high levels of nitrogen deposition, ecosystems in the park are not typical of nitrogen-sensitive systems and were rated as having very low sensitivity to nutrient-enrichment effects relative to all Inventory & Monitoring parks (Sullivan et al. 2011c; Sullivan et al. 2011d). Trend: No trend information is available because there are not sufficient on-site or nearby deposition monitoring data. Confidence: The degree of confidence at Catoctin Mountain Park is medium because estimates are based on interpolated data from more distant deposition monitors.
Sulfur	Wet Deposition		Condition: Wet sulfur deposition warrants significant concern at Catoctin Mountain Park. This status is based on NPS Air Resources Division benchmarks and the 2011–2015 estimated wet sulfur deposition of 3.2 kilograms per hectare per year (kg/ha/yr). Ecosystems in the park were rated as having very high sensitivity to acidification effects relative to all Inventory & Monitoring parks (Sullivan et al. 2011a; Sullivan et al. 2011b). Acidification effects can include changes in water and soil chemistry that impact ecosystem health. Plants sensitive to the effects of acidification in the park include <i>Acer saccharum</i> (sugar maple) trees. Trend: No trend information is available because there are not sufficient on-site or nearby deposition monitoring data. Confidence: The degree of confidence at Catoctin Mountain Park is medium because estimates are based on interpolated data from more distant deposition monitors.
* Condition assessments for contiguous U.S. parks use the Inverse Distance Weighted (IDW) interpolation method is used to estimate 5-year average (2011–2015) values. Trend analyses use 10 years (2006–2015) of data from on-site or nearby monitors. § Visibility trends and conditions are both expressed in terms of a Haze Index in deciviews (dv); however, the benchmark metrics are different. Condition assessments are based on estimated five-year average visibility on mid-range days (40th to 60th percentile) minus the estimated natural visibility condition on mid-range days. Visibility trends are computed from the haze index values on the 20% haziest days and the 20% clearest days. † Natural visibility conditions are those estimated to exist in a given area in the absence of human-caused visibility impairment. Estimated annual average natural condition on mid-range days equals 7.4 deciviews (dv) at Catoctin Mountain Park.			

National Capital Parks-East Natural Resource Condition Assessment (2016)



Table 4-2 Air Quality reference conditions for NACE.

Metric	Reference conditions	Sites	Samples	Period
Wet sulfur deposition (kg/ha/yr)	< 1; 1-3; >3	6	N/A*	2008-2012
Wet nitrogen deposition (kg/ha/yr)	< 1; 1-3; >3	6	N/A*	2008-2012
Ozone (ppb)	≤ 60; 60.1-75; >75	6	N/A*	2008-2012
Ozone (W126; ppm-hrs)	< 7; 7-13; >13	6	N/A*	2008-2012
Visibility (dv)	<2; 2-8; >8	6	N/A*	2008-2012
Particulate matter (PM2.5; µg/m ³)	≤12; 12.1-15; >15	2	1974	2008-2012
Mercury deposition (ng/L)	N/A	2	701	2008-2012

* one interpolated value represents a five-year average of weekly measurements at multiple sites.

Table 4-4 Summary of resource condition assessment of Air Quality in NACE.

Metric	Result	Reference conditions	% Attainment	Condition	Air quality condition
Wet sulfur deposition (kg/ha/yr)	3.55	< 1; 1-3; >3	0	Significant concern	16.7% Very degraded
Wet nitrogen deposition (kg/ha/yr)	4.15	< 1; 1-3; >3	0	Significant concern	
Ozone (ppb)	77.45	≤ 60; 60.1-75; >75	0	Significant concern	
Ozone (W126; ppm-hrs)	14.20	< 7; 7-13; >13	0	Significant concern	
Visibility (dv)	11.30	<2; 2-8; >8	0	Significant concern	
Particulate matter (PM2.5; µg/m ³)	10.80	≤12; 12.1-15; >15	100	Good	
Mercury deposition (ng/L)	7.86	N/A	N/A	N/A	

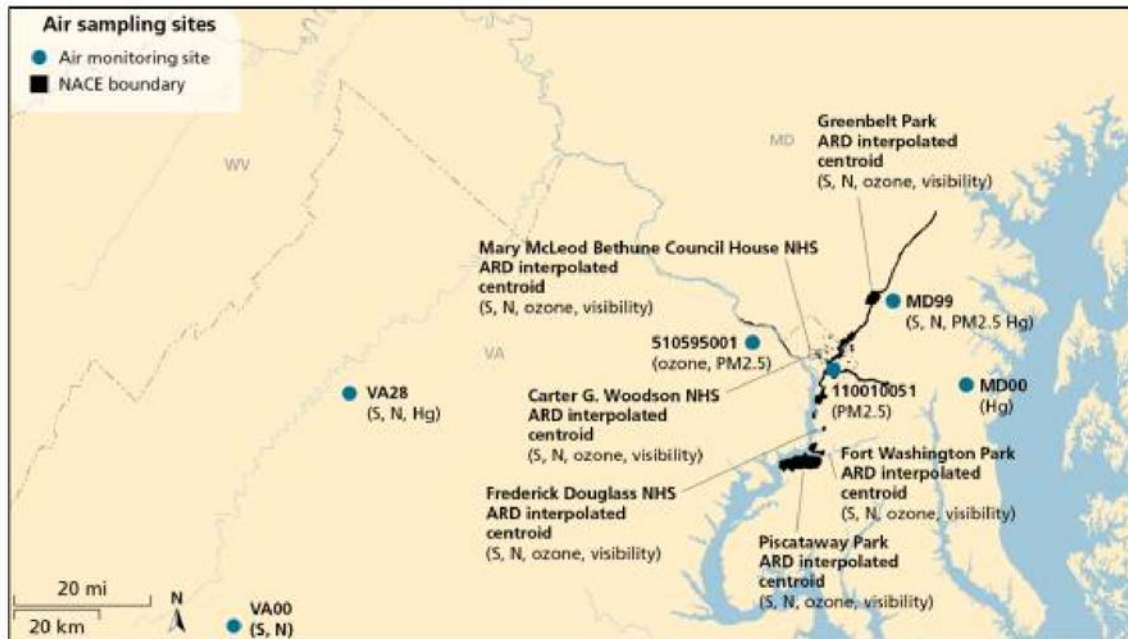


Figure 4-1 Regional air quality monitoring sites for wet deposition of sulfur and nitrogen, ozone, visibility, particulate matter, and mercury deposition. Wet deposition, ozone, and visibility data for 2008-2012 were interpolated by NPS ARD to estimate mean concentrations for NACE.

Wet Sulfur Deposition

Data and Methods

- Carter G. Woodson Home NHS (DC), Fort Washington Park (MD), Frederick Douglass NHS (DC), Greenbelt Park (MD), Mary McLeod Bethune Council House NHS (DC), and Piscataway Park (MD) (Table 4-6)
- Sites: VA00 (Charlottesville) and VA28 (Shenandoah-Big Meadows) in Virginia, and site MD99 (Beltsville, Prince Georges County in Maryland)
 - Median value used

Condition and Trend

- 0% attainment of reference conditions→ significant concern
- All three sites showed a significant improvement in wet sulfur deposition over the past decade

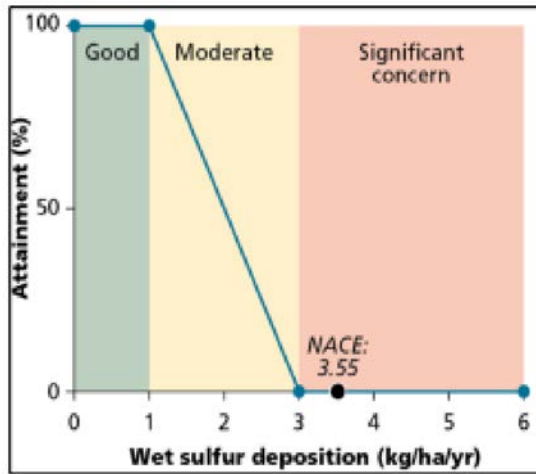


Figure 4-3 Application of the percent attainment categories to the wet sulfur deposition value categories. Wet sulfur deposition at NACE was 3.55 kg/ha/yr, which equated to 0% attainment of the reference condition.

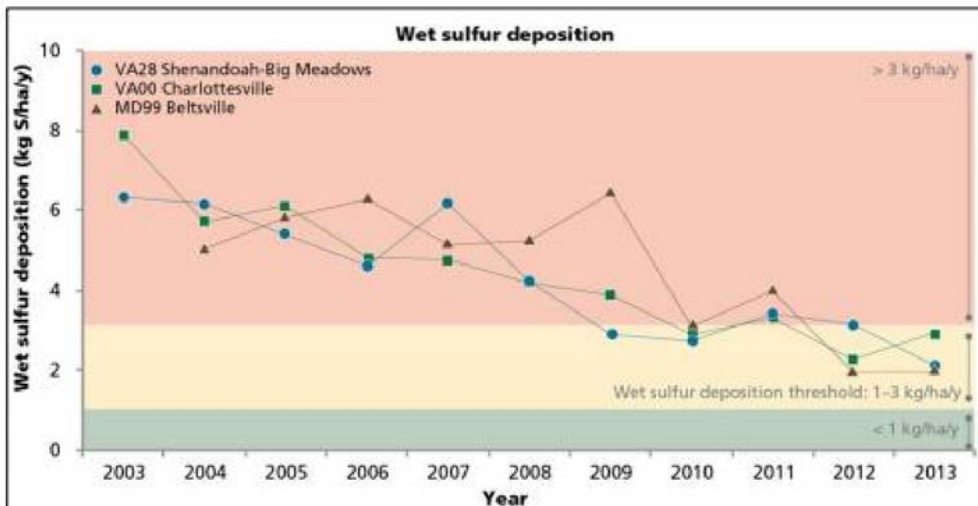


Figure 4-4 Annual wet deposition of sulfate (kg/ha/yr) at the three sites closest to NACE reported as SO_4 deposition.



Table 4-10 Ozone values from sites within NACE. The values for individual parks were taken from the interpolation at the park centroid. The median of these values was used to compare against the reference condition for ozone.

Park Name	ppb	W126 ppm-hrs
Carter G. Woodson Home NHS	77.5	14.3
Fort Washington Park	77.4	13.9
Frederick Douglas NHS	77.4	14.1
Greenbelt Park	78.1	14.7
Mary McLeod Bethune Council House NHS	77.5	14.3
Piscataway Park	77.4	13.9

Wet Nitrogen Deposition

Data and Methods

- Sites: To assess trends, National Atmospheric Deposition Program (NADP) data from the three monitoring sites closest to NACE were used. These included sites VA00 (Charlottesville) in Virginia, and sites MD99 (Beltsville), and MD07 (Catocin) in Maryland (Figure 4-1)
 - Parks in sites: Carter G. Woodson Home NHS (DC), Fort Washington Park (MD), Frederick Douglass NHS (DC), Greenbelt Park (MD), Mary McLeod Bethune Council House NHS (DC) and Piscataway Park (MD)

Condition and Trend

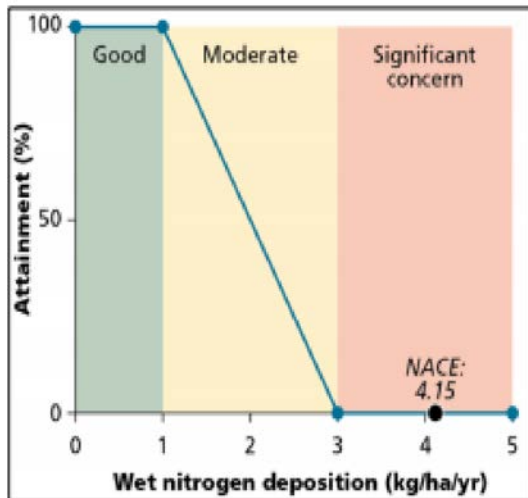


Figure 4-6 Application of the percent attainment categories to the wet nitrogen deposition value categories. Wet nitrogen deposition at NACE was 4.15 kg/ha/yr, which equated to 0% attainment of the reference condition.

When deposition data were analyzed from the three locations closest to the park, there was no significant trend in nitrogen deposition at any of the sites (p -value < 0.01) (Figure 4-7).

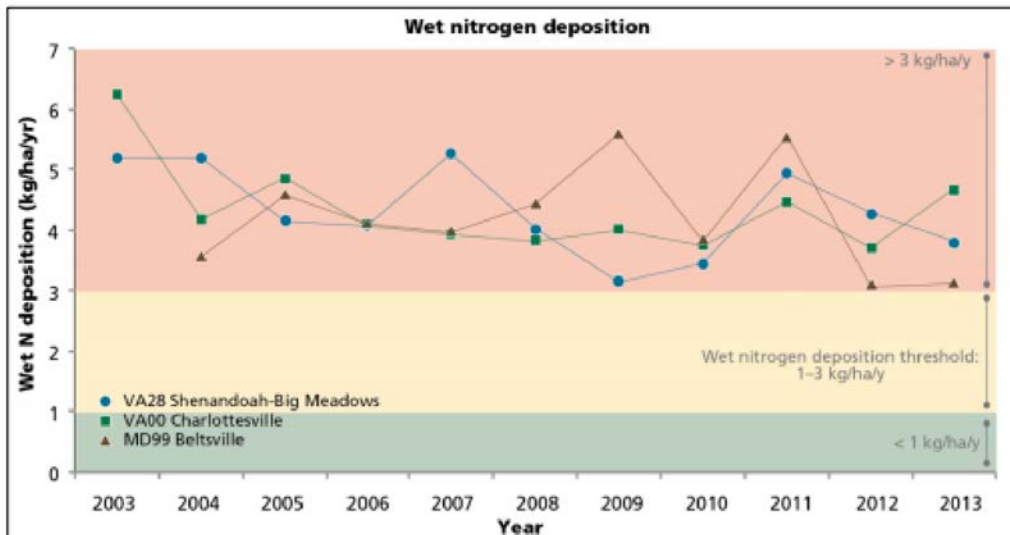


Figure 4-7 Annual wet deposition of total nitrogen (kg/ha/yr) at the three sites closest to NACE.

- 0% attainment of reference condition, or condition of significant concern
- No significant trend in nitrogen deposition at any of the sites

Ozone



Data and Methods

- Sites: Carter G. Woodson Home NHS (DC), Fort Washington Park (MD), Frederick Douglass NHS (DC), Greenbelt Park (MD), Mary McLeod Bethune Council House NHS (DC), and Piscataway Park (MD).
- 0% attainment of reference condition, or a condition of significant concern

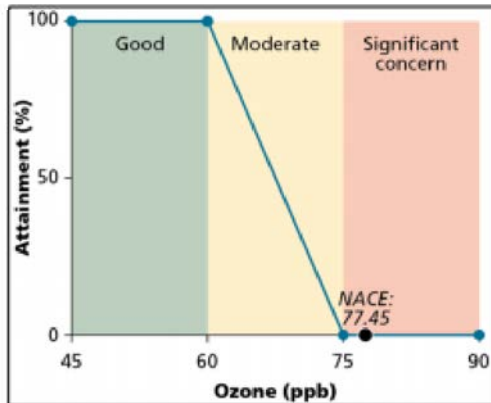


Figure 4-8 Application of the percent attainment categories to the ozone (ppb) value categories. Ozone at NACE was 77.45 ppb, which equated to 0% attainment of the reference condition.

Table 4-10 Ozone values from sites within NACE. The values for individual parks were taken from the interpolation at the park centroid. The median of these values was used to compare against the reference condition for ozone.

Park Name	ppb	W126 ppm-hrs
Carter G. Woodson Home NHS	77.5	14.3
Fort Washington Park	77.4	13.9
Frederick Douglas NHS	77.4	14.1
Greenbelt Park	78.1	14.7
Mary McLeod Bethune Council House NHS	77.5	14.3
Piscataway Park	77.4	13.9

Visibility

Data and Methods

- Sites: Carter G. Woodson Home NHS (DC), Fort Washington Park (MD), Frederick Douglass NHS (DC), Greenbelt Park (MD), Mary McLeod Bethune Council House NHS (DC), and Piscataway Park (MD).

Condition and Trend

- 0% attainment of reference conditions→ significant concern



Particulate matter

Data and Methods

- Sites: Data was obtained from the Interagency Monitoring of Protected Visual Environments (IMPROVE) database through the U.S. EPA AirData interface for the three sampling locations closest to NACE. These included sites 240330030 (Beltsville, MD), 110010041 (River Terrace, DC) and 510590030 (Lee District Park, VA)

Condition and Trend

- Sites has a 100% attainment of the reference conditions within the last 10 years, but there were years in which the particulate matter amount was higher than attainment
 - Parks within sites: Sites: Carter G. Woodson Home NHS (DC), Fort Washington Park (MD), Frederick Douglass NHS (DC), Greenbelt Park (MD), Mary McLeod Bethune Council House NHS (DC), and Piscataway Park (MD).

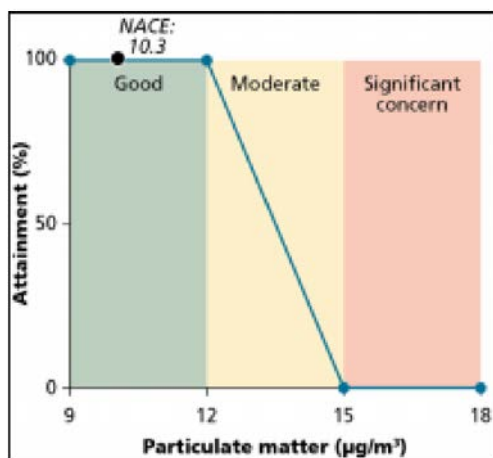


Figure 4-13 Application of the percent attainment categories to the particulate matter value categories. Particulate matter at NACE was $10.3 \mu\text{g}/\text{m}^3$ which resulted in 100% attainment of the reference condition.

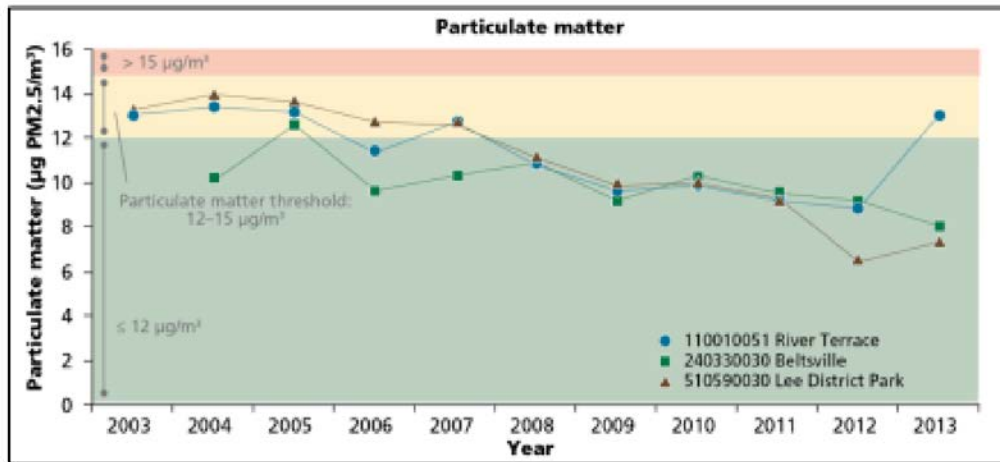


Figure 4-14 Particulate matter ($\mu\text{g}/\text{m}^3$) at the two sites closest to NACE. Reference conditions are shown in gray. Data show the annual mean concentrations.

Mercury

Data and Methods

- Sites: National Atmospheric Deposition Program, Mercury Deposition Network (NADP-MDN) for three sites, MD99 (Beltsville, MD), MD00 (Smithsonian Environmental Research Center) and VA28 (Shenandoah-Big Meadows) (Figure 4-1).

Condition and Trend

- No significant trend

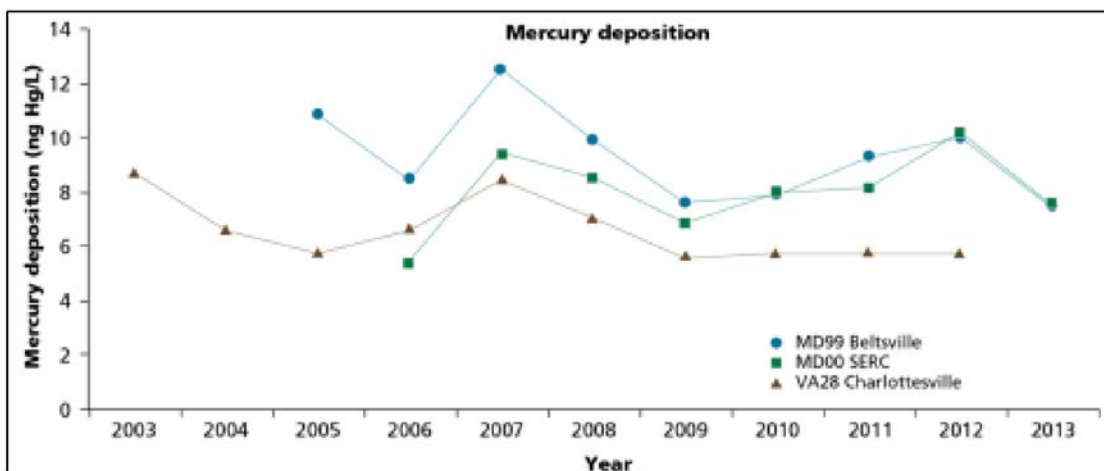


Figure 4-15 Median annual mercury concentrations (ng/L) in precipitation from three sites in the region of NACE.

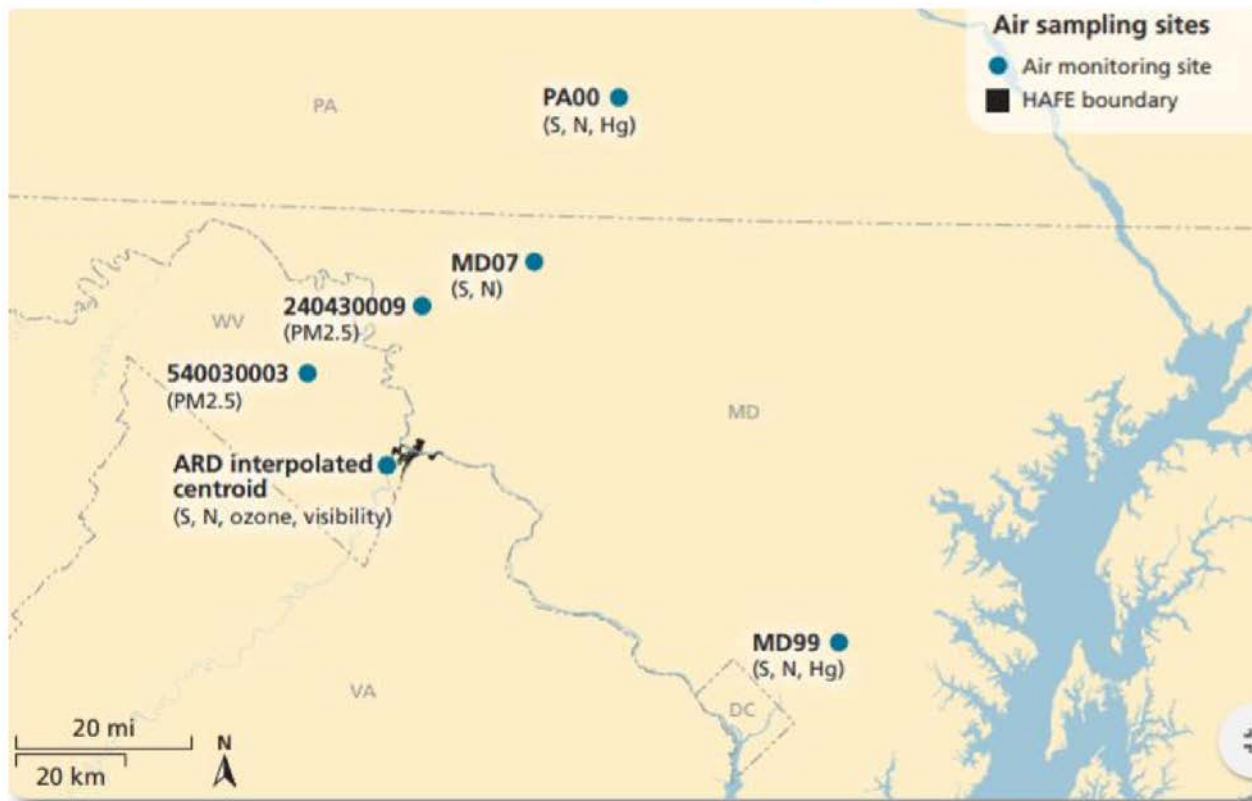


Data and Methods

Table 4.2. Air Quality reference conditions for HAFE.

Metric	Reference conditions	Sites	Samples	Period
Wet sulfur deposition (kg/ha/yr)	< 1; 1–3; > 3	Whole park	N/A*	2005–2009
Wet nitrogen deposition (kg/ha/yr)	< 1; 1–3; > 3	Whole park	N/A*	2005–2009
Ozone (ppb)	≤ 60; 60.1–75; > 75	Whole park	N/A*	2005–2009
Ozone (W126; ppm-hrs)	< 7; 7–13; > 13	Whole park	N/A*	2005–2009
Visibility (dv)	< 2; 2–8; > 8	Whole park	N/A*	2005–2009
Particulate matter (PM _{2.5} ; μg/m ³)	≤ 12; 12.1–15; > 15	2	3,170	2001–2010
Mercury deposition (ng/L)	N/A	2	701	2001–2011

* One interpolated value represents a five-year average of weekly measurements at multiple sites.



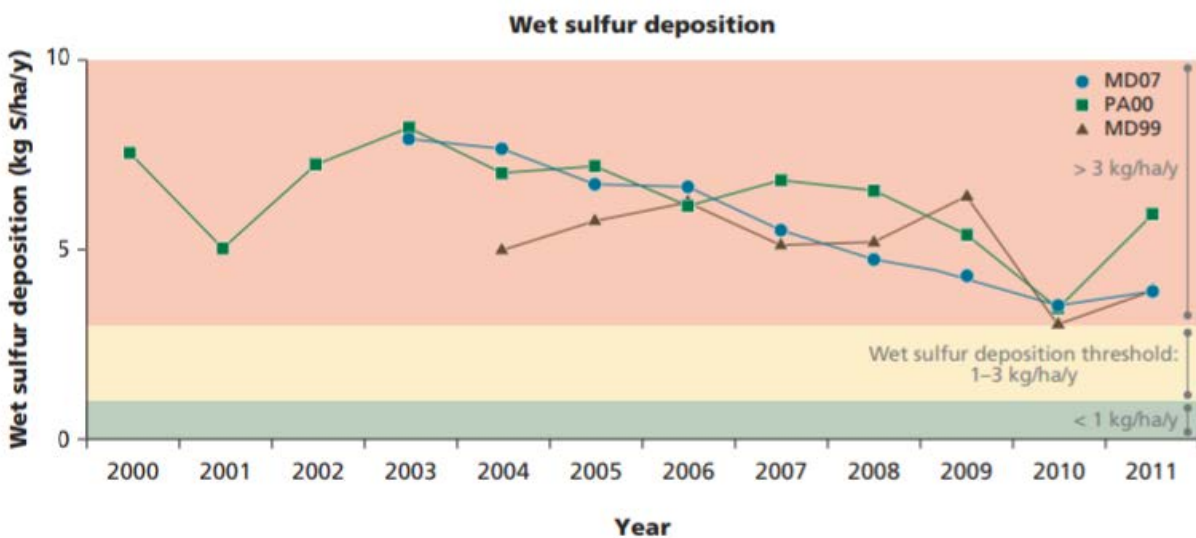
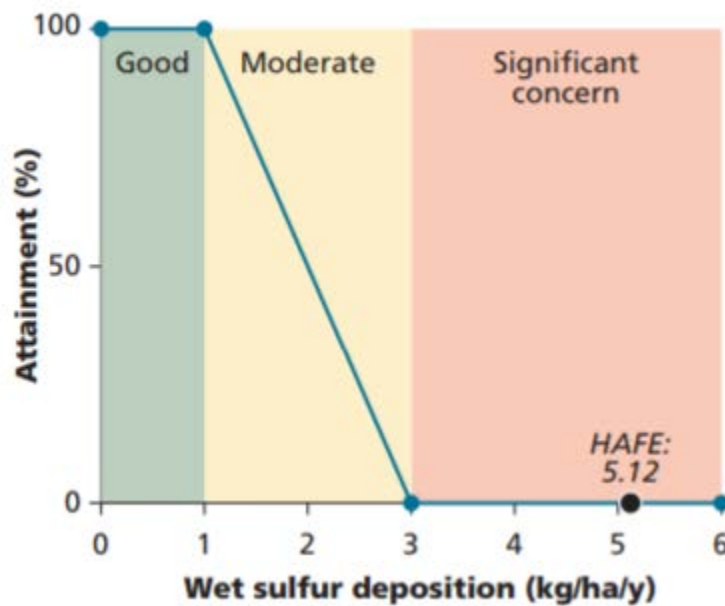
Wet Sulfur Deposition

Data and Methods

- HAFE were used—sites MD07, PA00, and MD99 (Table 4.1, Figure 4.1)

Condition and Trend

- 0% attainment of reference condition, or a condition of significant concern
- Streams are not showing signs of acidification
- MD07 showed a significant improvement of wet deposition over the past decade
- PA00 and MD99 did not show much of a trend



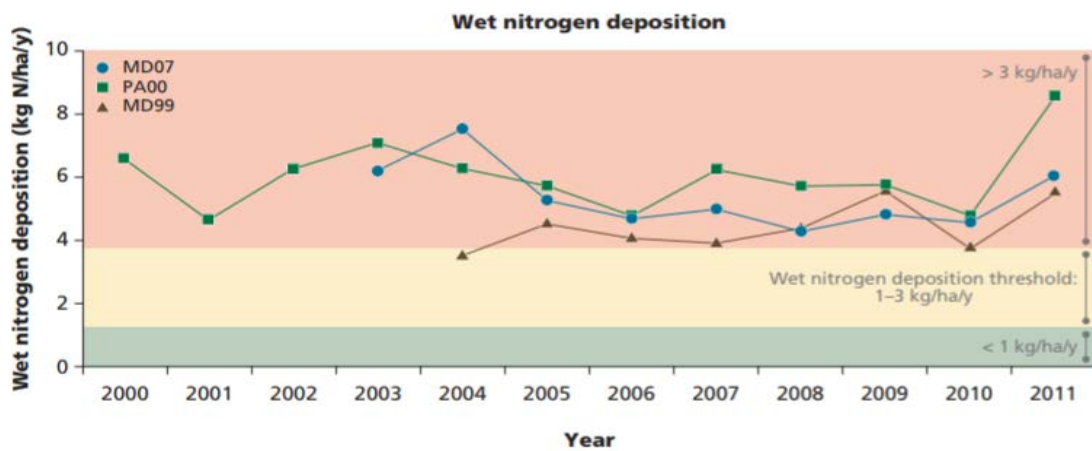
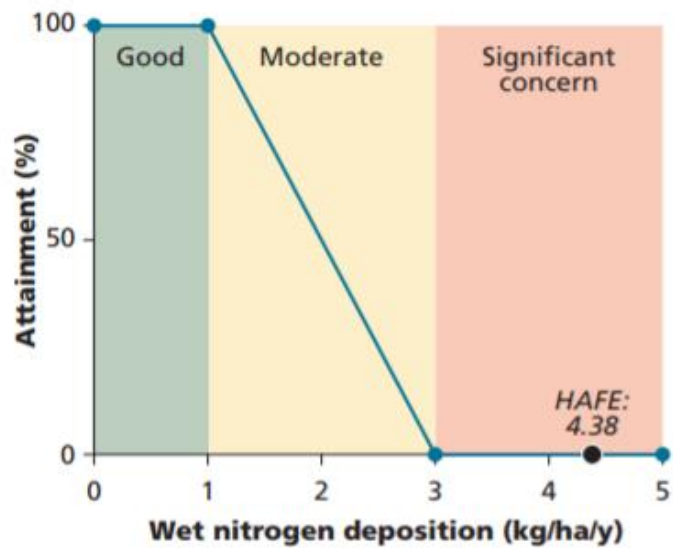
Wet Nitrogen Deposition

Data and Method

- MD07, PA00, and MD99

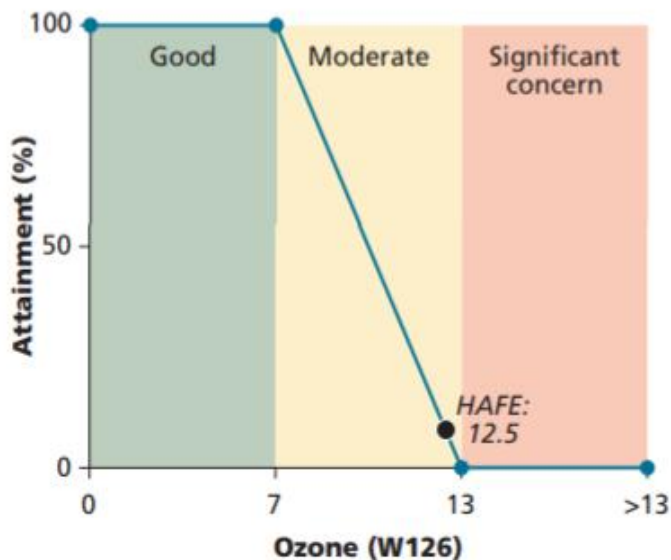
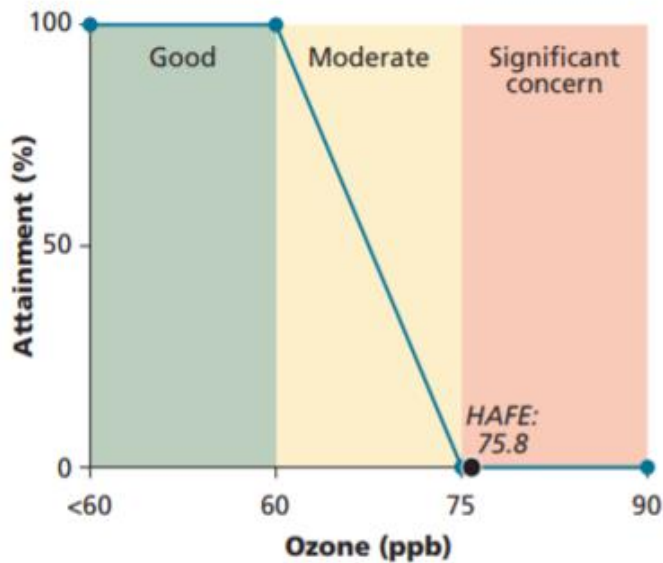
Condition and Trend

- 0% attainment of reference condition or a condition of significant concern
- No sites showed a significant improvement



Ozone

Data and Method



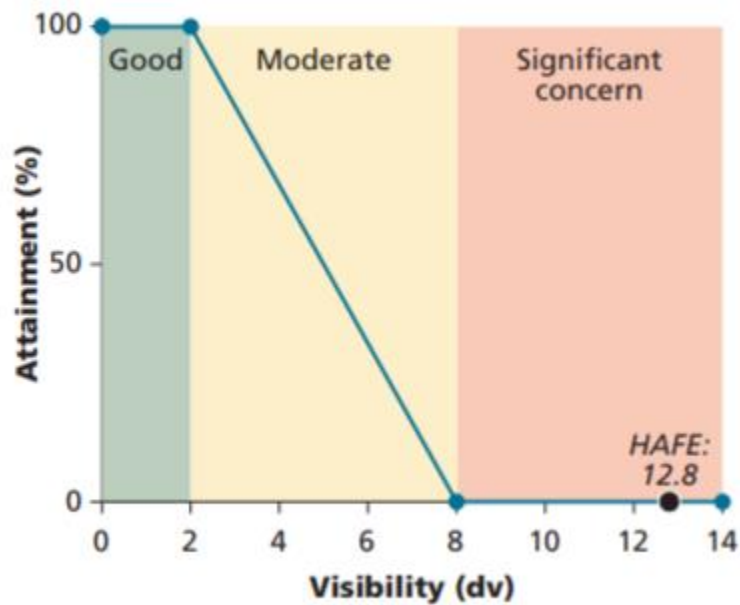
Condition and Trend

- HAFE was at a high risk of injury from ozone
- Of significant concern, and exceeds the human health standard

Visibility

Condition and Trend

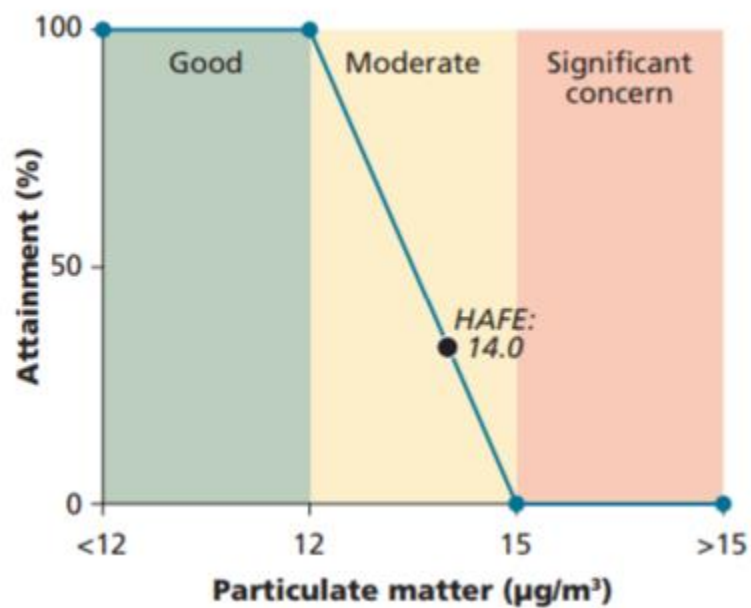
- 0% attainment of reference condition, of significant concern
- No significant trend country-wise, but generally improving trends in the region

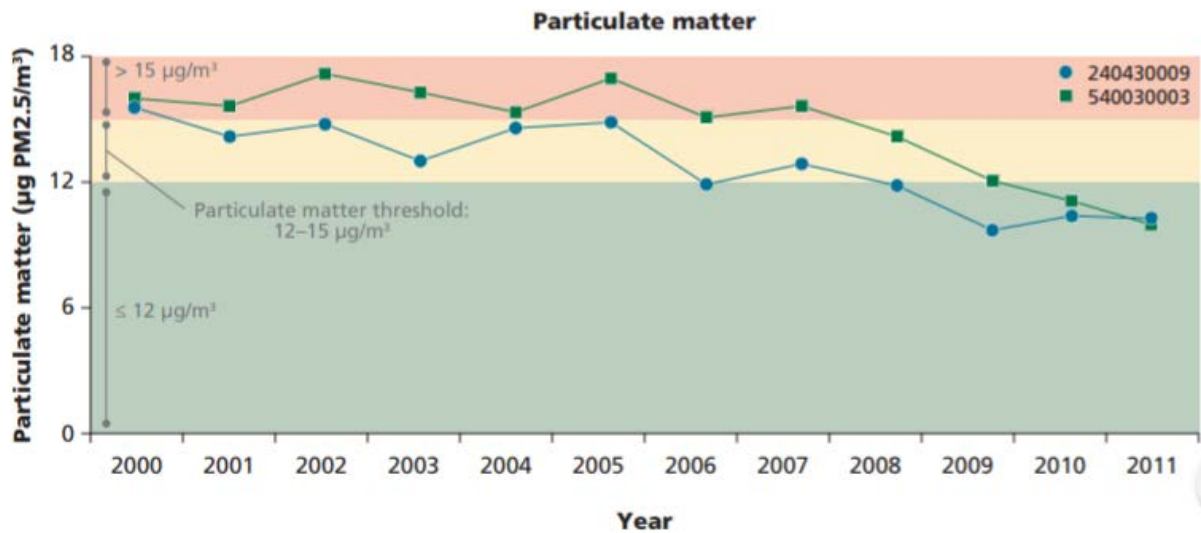


Particulate matter

Condition and Trend

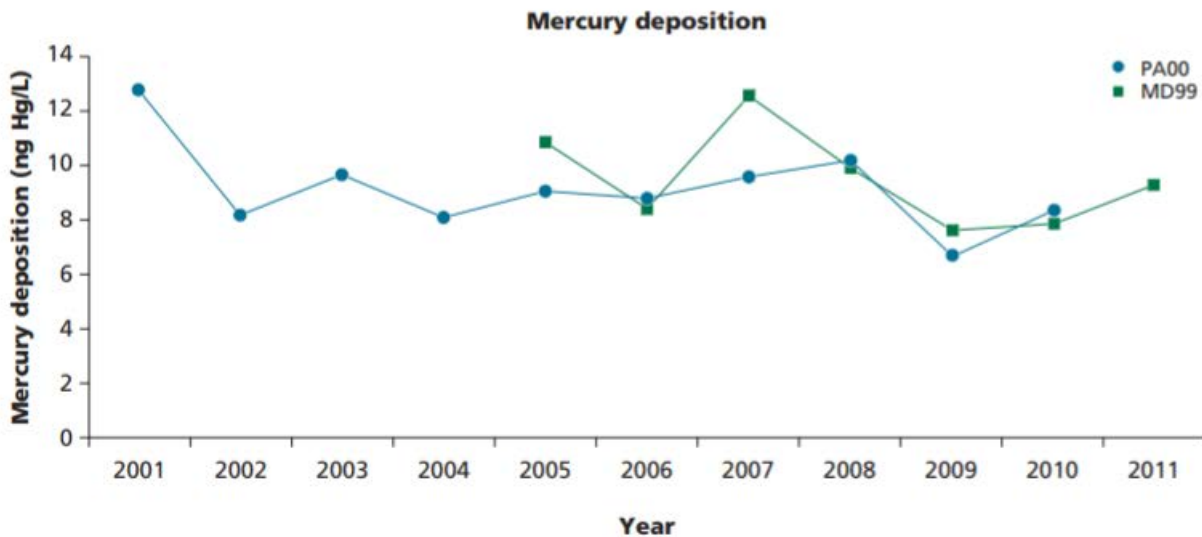
- sites 240430009 near St. James in Washington County, MD and 540030003 near Martinsburg in Berkeley County, WV





- Significant improving trend of particulate matter over the past decade

Mercury Deposition Condition and Trend



- No significant trend



2015 Air Quality Summary

Air Quality Indicator	Specific Measure	Condition Status/Trend*	Rationale
Ozone	Human Health: Annual 4th-highest 8hr concentration		Condition: Human health risk from ground-level ozone warrants moderate concern at Harpers Ferry NHP. This status is based on NPS Air Resources Division benchmarks and the 2011–2015 estimated ozone of 68.0 parts per billion (ppb). A small portion of the park is in one or more areas designated by the Environmental Protection Agency (EPA) as nonattainment in 2015 for the 2008 8-hour ozone standard (75 ppb). Trend: No trend information is available because there are not sufficient on-site or nearby ozone monitoring data. Confidence: The degree of confidence at Harpers Ferry NHP is medium because estimates are based on interpolated data from more distant ozone monitors.
	Vegetation Health: 3-month maximum 12hr W126		Condition: Vegetation health risk from ground-level ozone warrants moderate concern at Harpers Ferry NHP. This status is based on NPS Air Resources Division benchmarks and the 2011–2015 estimated W126 metric of 9.0 parts per million-hours (ppm-hrs). The W126 metric relates plant response to ozone exposure. A risk assessment concluded that plants in at Harpers Ferry NHP were at high risk for ozone damage (Kohut 2007; Kohut 2004). See list of ozone-sensitive plant species. Trend: No trend information is available because there are not sufficient on-site or nearby ozone monitoring data. Confidence: The degree of confidence at Harpers Ferry NHP is medium because estimates are based on interpolated data from more distant ozone monitors.
Visibility	Haze Index ⁸		Condition: Visibility warrants significant concern at Harpers Ferry NHP. This status is based on NPS Air Resources Division benchmarks and the 2011–2015 estimated visibility on mid-range days of 8.9 deciviews (dv) above estimated natural conditions.⁹ Trend: No trend information is available because there are not sufficient on-site or nearby visibility monitoring data. Confidence: The degree of confidence at Harpers Ferry NHP is medium because estimates are based on interpolated data from more distant visibility monitors.
Nitrogen	Wet Deposition		Condition: Wet nitrogen deposition warrants significant concern at Harpers Ferry NHP. This status is based on NPS Air Resources Division benchmarks and the 2011–2015 estimated wet nitrogen deposition of 4.2 kilograms per hectare per year (kg/ha/yr). Although Harpers Ferry NHP receives high levels of nitrogen deposition, ecosystems in the park are not typical of nitrogen-sensitive systems and were rated as having very low sensitivity to nutrient-enrichment effects relative to all Inventory & Monitoring parks (Sullivan et al. 2011c; Sullivan et al. 2011d). Trend: No trend information is available because there are not sufficient on-site or nearby deposition monitoring data. Confidence: The degree of confidence at Harpers Ferry NHP is medium because estimates are based on interpolated data from more distant deposition monitors.



Sulfur	Wet Deposition		Condition: Wet sulfur deposition warrants significant concern at Harpers Ferry NHP. This status is based on NPS Air Resources Division benchmarks and the 2011–2015 estimated wet sulfur deposition of 2.6 kilograms per hectare per year (kg/ha/yr), a level that normally warrants moderate concern. However, the status has been elevated to significant concern because ecosystems at Harpers Ferry NHP may be very highly sensitive to acidification effects relative to all Inventory & Monitoring parks (Sullivan et al. 2011a; Sullivan et al. 2011b). Acidification effects can include changes in water and soil chemistry that impact ecosystem health. Plants sensitive to the effects of acidification in the park include <i>Acer saccharum</i> (sugar maple) trees. Trend: No trend information is available because there are not sufficient on-site or nearby deposition monitoring data. Confidence: The degree of confidence at Harpers Ferry NHP is medium because estimates are based on interpolated data from more distant deposition monitors.
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Antietam National Battlefield Natural Resource Condition Assessment (2011)

Data and Methods

- Data used in the assessment was obtained from multiple sources, with the Air & Climate data coming from national air monitoring programs and the NPS Air Resources Division, Water Resources and Biological Integrity data from the NCRN I&M monitoring program and Antietam National Battlefield monitoring, and Landscape Dynamics data from a collaborative project between NCRN I&M and the University of Maryland Center for Environmental Science (Table 3.6). Air & Climate results for ozone, wet nitrate and sulfur deposition, and visibility (2003–2007) were taken from interpolated results from an NPS (2009) report, while mercury deposition data (2004–2008) came from two nearby monitoring sites (Figure 3.6).
- Air quality is poor within parks
- Metrics measured: Air & Climate Ozone (ppm) Wet nitrogen deposition (kg N ha⁻¹ yr⁻¹) Wet sulfate deposition (kg S ha⁻¹ yr⁻¹) Visibility condition (dv) Mercury deposition (ng Hg L⁻¹)



Figure 3.6. Map of sampling stations PA00/ARE128 and MD99/BEL116²⁹ used for measuring mercury concentrations near Antietam National Battlefield.

Table 5.6. Data gaps, justification, and research needs for Air & Climate in Antietam National Battlefield.

Data gaps	Justification	Research needs
Air & Climate		
Ecological thresholds (for atmospheric effects on water and grasslands—deposition of nitrogen, sulfur, and mercury)	Ecosystem impacts from deposition and human influence (acid rain and fertilization) unknown	- Investigating habitat-specific effects - Deposition impacts to wetlands and grasslands - Prevailing wind patterns within the park
Park-scale air quality data	Need to implement park-specific management actions	- Using transport and deposition models - Calibrating with roadside data within the park

Condition and trends

- Using the interpolated results from NPS Air Resources Division and mercury monitoring data, Air & Climate in Antietam National Battlefield were measured to be in a very degraded condition (0% attainment of threshold condition; Table 4.4). Ozone concentration and wet nitrogen and sulfur deposition were within an order of magnitude of the threshold; however, visibility and mercury deposition were all an order of magnitude higher than threshold concentrations (Figure 4.3, Table 3.7).



Table 4.4. Summary resource condition assessment for Antietam National Battlefield by metric categories.

Categories and metrics	Mean	Attainment of threshold condition		
		Metric %	Category %	Park %
Air & Climate				
Ozone	0.078 ppm	0		
Wet nitrogen deposition	4.6 kg N ha ⁻¹ yr ⁻¹	0		
Wet sulfur deposition	5.8 kg S ha ⁻¹ yr ⁻¹	0	0	
Visibility	13.75 dv	0		
Hg deposition	13.1 ng Hg L ⁻¹	0		

2015 Air Quality Summary

Air Quality Indicator	Specific Measure	Condition Status/Trend*	Rationale
Ozone	Human Health: Annual 4th-highest 8hr concentration		Condition: Human health risk from ground-level ozone warrants moderate concern at Antietam NB. This status is based on NPS Air Resources Division benchmarks and the 2011–2015 estimated ozone of 68.1 parts per billion (ppb). A small portion of the park is in one or more areas designated by the Environmental Protection Agency (EPA) as nonattainment in 2015 for the 2008 8-hour ozone standard (75 ppb). Trend: For 2006–2015, the trend in ozone concentration at Antietam NB improved (AQS Monitor ID: 240430009, MD). Confidence: The degree of confidence at Antietam NB is high because there is an on-site or nearby ozone monitor.
	Vegetation Health: 3-month maximum 12hr W126		Condition: Vegetation health risk from ground-level ozone warrants moderate concern at Antietam NB. This status is based on NPS Air Resources Division benchmarks and the 2011–2015 estimated W126 metric of 9.0 parts per million-hours (ppm-hrs). The W126 metric relates plant response to ozone exposure. A risk assessment concluded that plants in at Antietam NB were at high risk for ozone damage (Kohut 2007; Kohut 2004). See list of ozone-sensitive plant species. Trend: For 2006–2015, the trend in the W126 metric at Antietam NB improved (AQS Monitor ID: 240430009, MD). Confidence: The degree of confidence at Antietam NB is high because there is an on-site or nearby ozone monitor.



Visibility	Haze Index ⁵		Condition: Visibility warrants significant concern at Antietam NB. This status is based on NPS Air Resources Division benchmarks and the 2011–2015 estimated visibility on mid-range days of 8.9 deciviews (dv) above estimated natural conditions.⁴ Trend: No trend information is available because there are not sufficient on-site or nearby visibility monitoring data. Confidence: The degree of confidence at Antietam NB is medium because estimates are based on interpolated data from more distant visibility monitors.
Nitrogen	Wet Deposition		Condition: Wet nitrogen deposition warrants significant concern at Antietam NB. This status is based on NPS Air Resources Division benchmarks and the 2011–2015 estimated wet nitrogen deposition of 4.3 kilograms per hectare per year (kg/ha/yr). Although Antietam NB receives high levels of nitrogen deposition, ecosystems in the park are not typical of nitrogen-sensitive systems and were rated as having very low sensitivity to nutrient-enrichment effects relative to all Inventory & Monitoring parks (Sullivan et al. 2011c; Sullivan et al. 2011d). Trend: No trend information is available because there are not sufficient on-site or nearby deposition monitoring data. Confidence: The degree of confidence at Antietam NB is medium because estimates are based on interpolated data from more distant deposition monitors.
Sulfur	Wet Deposition		Condition: Wet sulfur deposition warrants significant concern at Antietam NB. This status is based on NPS Air Resources Division benchmarks and the 2011–2015 estimated wet sulfur deposition of 2.7 kilograms per hectare per year (kg/ha/yr), a level that normally warrants moderate concern. However, the status has been elevated to significant concern because ecosystems at Antietam NB may be very highly sensitive to acidification effects relative to all Inventory & Monitoring parks (Sullivan et al. 2011a; Sullivan et al. 2011b). Acidification effects can include changes in water and soil chemistry that impact ecosystem health. Plants sensitive to the effects of acidification in the park include <i>Acer saccharum</i> (sugar maple) trees. Trend: No trend information is available because there are not sufficient on-site or nearby deposition monitoring data. Confidence: The degree of confidence at Antietam NB is medium because estimates are based on interpolated data from more distant deposition monitors.

Condition Status		Trend		Confidence In Assessment	
	Indicator is in Good Condition		Improving		High
	Warrants Moderate Concern		Unchanging		Medium
	Warrants Significant Concern		Deteriorating		Low

Manassas National Battlefield Park Natural Resource Condition Assessment



Data and Methods

- Currently available air quality data is regional, it would be beneficial to translate this data down to a park scale with modeling efforts as well as some strategic calibration, especially on major roadways within the park
- Air & Climate results for ozone, wet nitrate and sulfur deposition, and visibility (2003–2007) were taken from interpolated results from an NPS (2009) report, while mercury deposition data (2004–2008) came from two nearby monitoring sites

Table 5.4. Data gaps, justification, and research needs for Air & Climate in Manassas National Battlefield Park.

Data gaps	Justification	Research needs
Air & Climate		
• Ecological thresholds (for atmospheric effects on water and grasslands—deposition of nitrogen, sulfur, and mercury)	• Ecosystem impacts from deposition and human influence (acid rain and fertilization) unknown	• Investigating habitat-specific effects • Deposition impacts to wetlands and grasslands • Prevailing wind patterns within the park
• Park-scale air quality data	• Need to implement park-specific management actions	• Using transport and deposition models • Calibrating with roadside data within the park





Condition and trends

- Using the interpolated results from NPS Air Resources Division and mercury monitoring data, Air & Climate in Manassas National Battlefield Park were measured to be in a very degraded condition (0% attainment of threshold condition; Table 4.3). Ozone concentration and wet nitrogen and sulfur deposition were within an order of magnitude of the threshold; however, visibility and mercury deposition were all an order of magnitude higher than threshold concentrations

Table 4.3. Summary resource condition assessment for Manassas National Battlefield Park by metric categories.

Categories and metrics	Mean	Attainment of threshold condition		
		Metric %	Category %	Park %
Air & Climate				
Ozone	0.081 ppm	0		
Wet nitrogen (N) deposition	4.2 kg N ha ⁻¹ yr ⁻¹	0		
Wet sulfur (S) deposition	5.1 kg S ha ⁻¹ yr ⁻¹	0	0	
Visibility	13.93 dv	0		
Mercury (Hg) deposition	11.5 ng Hg L ⁻¹	0		
Water Resources				



FIGURE 1

Data gaps	Justification	Research needs
Air & Climate		
Ecological thresholds (for atmospheric effects on water and grasslands—deposition of nitrogen, sulfur, and mercury)	Ecosystem impacts from deposition and human influence (acid rain and fertilization) unknown	- Investigating habitat-specific effects - Deposition impacts to wetlands and grasslands - Prevailing wind patterns within the park
Park-scale air quality data	Need to implement park-specific management actions	- Using transport and deposition models - Calibrating with roadside data within the park

Air Quality Indicator	Specific Measure	Condition Status/Trend*	Rationale
Ozone	Human Health: Annual 4th-highest 8hr concentration		Condition: Human health risk from ground-level ozone warrants moderate concern at Manassas NBP. This status is based on NPS Air Resources Division benchmarks and the 2011–2015 estimated ozone of 69.5 parts per billion (ppb). The park is in one or more areas designated by the Environmental Protection Agency (EPA) as nonattainment in 2015 for the 2008 8-hour ozone standard (75 ppb). Trend: For 2006–2015, the trend in ozone concentration at Manassas NBP improved (AQS Monitor ID: 511530009, VA). Confidence: The degree of confidence at Manassas NBP is high because there is an on-site or nearby ozone monitor.
	Vegetation Health: 3-month maximum 12hr W126		Condition: Vegetation health risk from ground-level ozone warrants moderate concern at Manassas NBP. This status is based on NPS Air Resources Division benchmarks and the 2011–2015 estimated W126 metric of 9.4 parts per million-hours (ppm-hrs). The W126 metric relates plant response to ozone exposure. A risk assessment concluded that plants in at Manassas NBP were at high risk for ozone damage (Kohut 2007; Kohut 2004). See list of ozone-sensitive plant species. Trend: For 2006–2015, the trend in the W126 metric at Manassas NBP remained relatively unchanged (no statistically significant trend) (AQS Monitor ID: 511530009, VA). Confidence: The degree of confidence at Manassas NBP is high because there is an on-site or nearby ozone monitor.



Visibility	Haze Index ⁶		Condition: Visibility warrants significant concern at Manassas NBP. This status is based on NPS Air Resources Division benchmarks and the 2011–2015 estimated visibility on mid-range days of 9.7 deciviews (dv) above estimated natural conditions.⁺ Trend: No trend information is available because there are not sufficient on-site or nearby visibility monitoring data. Confidence: The degree of confidence at Manassas NBP is medium because estimates are based on interpolated data from more distant visibility monitors.
Nitrogen	Wet Deposition		Condition: Wet nitrogen deposition warrants significant concern at Manassas NBP. This status is based on NPS Air Resources Division benchmarks and the 2011–2015 estimated wet nitrogen deposition of 3.7 kilograms per hectare per year (kg/ha/yr). Although Manassas NBP receives high levels of nitrogen deposition, ecosystems in the park are not typical of nitrogen-sensitive systems and were rated as having low sensitivity to nutrient-enrichment effects relative to all Inventory & Monitoring parks (Sullivan et al. 2011a; Sullivan et al. 2011d). Trend: No trend information is available because there are not sufficient on-site or nearby deposition monitoring data. Confidence: The degree of confidence at Manassas NBP is medium because estimates are based on interpolated data from more distant deposition monitors.
Sulfur	Wet Deposition		Condition: Wet sulfur deposition warrants moderate concern at Manassas NBP. This status is based on NPS Air Resources Division benchmarks and the 2011–2015 estimated wet sulfur deposition of 2.3 kilograms per hectare per year (kg/ha/yr). Ecosystems in the park were rated as having moderate sensitivity to acidification effects relative to all Inventory & Monitoring parks (Sullivan et al. 2011a; Sullivan et al. 2011b). Acidification effects can include changes in water and soil chemistry that impact ecosystem health. Trend: No trend information is available because there are not sufficient on-site or nearby deposition monitoring data. Confidence: The degree of confidence at Manassas NBP is medium because estimates are based on interpolated data from more distant deposition monitors.

Monocacy National Battlefield Park National Resource Condition Assessment (2011) Condition and Trend

Table 4.4. Summary resource condition assessment for Monocacy National Battlefield by metric categories.

Categories and metrics	Mean	Attainment of threshold condition		
		Metric %	Category %	Park %
Air & Climate				
Ozone	0.080 ppm	0		
Wet nitrogen (N) deposition	5.1 kg N ha ⁻¹ yr ⁻¹	0		
Wet sulfur (S) deposition	6.2 kg S ha ⁻¹ yr ⁻¹	0	0	
Visibility	14.14 dv	0		
Mercury (Hg) deposition	13.1 ng Hg L ⁻¹	0		



2015 Air Quality Summary

Air Quality Indicator	Specific Measure	Condition Status/Trend*	Rationale
Ozone	Human Health: Annual 4th-highest 8hr concentration		Condition: Human health risk from ground-level ozone warrants significant concern at Monocacy NB. This status is based on NPS Air Resources Division benchmarks and the 2011–2015 estimated ozone of 71.1 parts per billion (ppb). The park is in one or more areas designated by the Environmental Protection Agency (EPA) as nonattainment in 2015 for the 2008 8-hour ozone standard (75 ppb). Trend: For 2006–2015, the trend in ozone concentration at Monocacy NB improved (AQS Monitor ID: 240210037, MD). Confidence: The degree of confidence at Monocacy NB is high because there is an on-site or nearby ozone monitor.
	Vegetation Health: 3-month maximum 12hr W126		Condition: Vegetation health risk from ground-level ozone warrants moderate concern at Monocacy NB. This status is based on NPS Air Resources Division benchmarks and the 2011–2015 estimated W126 metric of 10.9 parts per million-hours (ppm-hrs). The W126 metric relates plant response to ozone exposure. A risk assessment concluded that plants in at Monocacy NB were at high risk for ozone damage (Kohut 2007; Kohut 2004). See list of ozone-sensitive plant species. Trend: For 2006–2015, the trend in the W126 metric at Monocacy NB improved (AQS Monitor ID: 240210037, MD). Confidence: The degree of confidence at Monocacy NB is high because there is an on-site or nearby ozone monitor.
Visibility	Haze Index [§]		Condition: Visibility warrants significant concern at Monocacy NB. This status is based on NPS Air Resources Division benchmarks and the 2011–2015 estimated visibility on mid-range days of 9.4 deciviews (dv) above estimated natural conditions.[§] Trend: No trend information is available because there are not sufficient on-site or nearby visibility monitoring data. Confidence: The degree of confidence at Monocacy NB is medium because estimates are based on interpolated data from more distant visibility monitors.
Nitrogen	Wet Deposition		Condition: Wet nitrogen deposition warrants significant concern at Monocacy NB. This status is based on NPS Air Resources Division benchmarks and the 2011–2015 estimated wet nitrogen deposition of 4.4 kilograms per hectare per year (kg/ha/yr). Although Monocacy NB receives high levels of nitrogen deposition, ecosystems in the park are not typical of nitrogen-sensitive systems and were rated as having low sensitivity to nutrient-enrichment effects relative to all Inventory & Monitoring parks (Sullivan et al. 2011c; Sullivan et al. 2011d). Trend: No trend information is available because there are not sufficient on-site or nearby deposition monitoring data. Confidence: The degree of confidence at Monocacy NB is medium because estimates are based on interpolated data from more distant deposition monitors.



Sulfur	Wet Deposition		Condition: Wet sulfur deposition warrants moderate concern at Monocacy NB. This status is based on NPS Air Resources Division benchmarks and the 2011–2015 estimated wet sulfur deposition of 2.6 kilograms per hectare per year (kg/ha/yr). Ecosystems in the park were rated as having moderate sensitivity to acidification effects relative to all Inventory & Monitoring parks (Sullivan et al. 2011a; Sullivan et al. 2011b). Acidification effects can include changes in water and soil chemistry that impact ecosystem health. Plants sensitive to the effects of acidification in the park include <i>Acer saccharum</i> (sugar maple) trees. Trend: No trend information is available because there are not sufficient on-site or nearby deposition monitoring data. Confidence: The degree of confidence at Monocacy NB is medium because estimates are based on interpolated data from more distant deposition monitors.
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Recommendations

Factors in recommendation:

- Which pollutant measurements have the lowest degree of certainty?
 - Use sensors to fill in data-gaps
- What are the most “important” pollutants for the specific park?
 - Different park, different goals
- Where are the most representative places sensors can be utilized?
 - Pollutant distribution can be highly variable



Type of Park	Parks	Important Aspects of Park	Target Pollutants
Forested	-Catoctin Mountain Park -Harpers Ferry National Historical Park/Battlefield -Prince William Forest -Rock Creek Park	-Recreation -Water quality and air for visitor, organism health -Maximum viewing ability for lookout points -Sometimes nestled in the city	-Wet sulfur/nitrogen deposition: sensitivity of soil and water to acidification, respiratory issues -NO₂: respiratory issues during recreation -Ozone for human (ppb) and vegetative (W126) health -Visibility/PM_{2.5} scenic views and for respiratory health of those conducting high intensity recreation
Battlefield	-Antietam National Battlefield -Manassas National Battlefield Park -Monocacy National Battlefield Park	-Educational material inside -View: walking around to different unwooded battlefields -Some trails, but minimal	-Ozone (ppb) young or old visitors are more susceptible to respiratory issues -Visibility/PM_{2.5} scenic views and respiratory health
Urban Forested	-George Washington Memorial Parkway -Chesapeake and Ohio Canal National Historic Park -Rock Creek Park	-Maximum viewing ability for sites -Air quality for visitors using for recreation -Green space	-Wet sulfur/nitrogen deposition: sensitivity of soil and water to acidification -NO₂: respiratory issues during recreation -Ozone (ppb): young or old visitors are more susceptible to respiratory issues -Visibility/PM_{2.5}: high vehicular use and industry emissions, respiratory issues during recreation
Entertainment	-Wolf Trap (WOTR)	-Maximum viewing ability for shows	-Ozone (ppb): young or old visitors are more susceptible to respiratory issues -Visibility/PM_{2.5} views of performance
Urban Historical	-National Mall and Memorial Parks -Presidents Park	-Maximum viewing ability for sites	-Visibility/PM_{2.5}: high vehicular use and industry emissions, respiratory issues -Wet sulfur/nitrogen deposition: sensitivity of infrastructure to corrosion by acid rain -NO₂: respiratory issues during recreation



Preliminary Study Ideas

- Using lichen plots in wooded areas to monitor Ozone threshold (ppb)
- Catoctin Mountain: using a timeline of catoctin mountain park's rich history to create a pamphlet about how the air quality has been affected at different milestones (ex: coal burning was beginning to take over matched with the air pollution levels indicate at that time to give perspective)
- Having "visibility stands" where citizens can conduct citizen science and take pictures from a lookout to send to NPS and add to a database that analyzes the photos and records visibility. We can also include pictures of different visibility levels as reference points and see how perceived air quality matches up.
- Include an "Up in the Air" information booth near measuring devices to educate passerby about what the device is measuring. Could have interactive parts to it that test the park-goers knowledge about air pollution, or even allow them to see the projected pollution levels in different hypothetical settings (e.g. "If ___% of American's use hybrid/electric vehicles how much ppm will the pollution be reduced?")
- Measuring carbon dioxide-an important greenhouse gas, and especially relevant around highways and cities.
- Recording temperature: urban cities are often great indicators and fortune tellers about how the environment will respond to rising greenhouse levels since they are "urban hotspots".. They can be instrumental if compared with other monitoring data even deeper into cities with less green space or from areas with more green space.
- Partner with the The Climate Friendly Parks (CFP) Program is one of many initiatives supporting the National Park Service (NPS) **Green Parks Plan** (ideas below).



park is leading by example. In so doing, the park commits to reducing GHG emissions from park operations by 20% below 2008 levels by 2016 through the following actions:

1. Reduce energy consumption of park buildings.
2. Explore the use of renewable energy technology and alternative energy.
3. Encourage energy saving behavior among staff and visitors.
4. Reduce transportation emissions from park operations.
5. Reduce transportation emissions from visitor vehicles in the park.
6. Divert solid waste from the landfill by increasing recycling capacity and educating staff and visitors.
7. Decrease the amount of solid waste sent to the landfill by revamping the "Trash Free" program.
8. Educate park employees and visitors about climate change and how to reduce GHG emissions.

Air Quality Monitoring and Pollutants

Background on Criteria Pollutants

Source: EPA (<https://www.epa.gov/criteria-air-pollutants>)

- Criteria Air Pollutants (6)
 - Ground-level Ozone
 - EPA Health information and public pamphlets <https://www.epa.gov/ground-level-ozone-pollution/health-effects-ozone-pollution>
 - Particulate Matter
 - Carbon Monoxide
 - Lead
 - Sulfur Dioxide (which is wet deposition of sulfate when it rains)
 - Nitrogen Dioxide (which is wet deposition of nitrate when it rains)
- Interactive map of current monitors: <https://www.epa.gov/outdoor-air-quality-data/interactive-map-air-quality-monitors>



Table 3. Different standards of the six common pollutants.

Pollutant	EPA [37]	WHO [38–40]	EC [41]	MEP [42]	EPD [43]
Carbon Monoxide (CO)	9 ppm (8 h) 35 ppm (1 h)	100 mg/m ³ (15 min) 15 mg/m ³ (1 h) 10 mg/m ³ (8 h) 7 mg/m ³ (24 h)	10 mg/m ³ (8 h)	10 mg/m ³ (1 h) 4 mg/m ³ (24 h)	30 mg/m ³ (1 h) 10 mg/m ³ (8 h)
Nitrogen Dioxide (NO ₂)	100 ppb (1 h) 53 ppb (1 year)	200 µg/m ³ (1 h) 40 µg/m ³ (1 year)	200 µg/m ³ (1 h) 40 µg/m ³ (1 year)	200 µg/m ³ (1 h) 80 µg/m ³ (24 h) 40 µg/m ³ (1 year)	200 µg/m ³ (1 h) 40 µg/m ³ (1 year)
Ozone (O ₃)	75 ppb (8 h)	100 µg/m ³ (8 h)	120 µg/m ³ (8 h)	200 µg/m ³ (1 h) 160 µg/m ³ (8 h)	160 µg/m ³ (8 h)
Sulfur Dioxide (SO ₂)	75 ppb (1 h) 0.5 ppm (3 h)	500 µg/m ³ (10 min) 20 µg/m ³ (24 h)	350 µg/m ³ (1 h) 125 µg/m ³ (24 h)	500 µg/m ³ (1 h) 150 µg/m ³ (24 h) 60 µg/m ³ (1 year)	500 µg/m ³ (10 min) 125 µg/m ³ (24 h)
Particulate Matter	PM _{2.5} 35 µg/m ³ (24 h) 12 µg/m ³ (1 year)	25 µg/m ³ (24 h) 10 µg/m ³ (1 year)	25 µg/m ³ (1 year)	75 µg/m ³ (24 h) 35 µg/m ³ (1 year)	75 µg/m ³ (24 h) 35 µg/m ³ (1 year)
	PM ₁₀ 150 µg/m ³ (24 h)	50 µg/m ³ (24 h) 20 µg/m ³ (1 year)	50 µg/m ³ (24 h) 40 µg/m ³ (1 year)	150 µg/m ³ (24 h) 70 µg/m ³ (1 year)	100 µg/m ³ (24 h) 50 µg/m ³ (1 year)
Lead (Pb)	0.15 µg/m ³ (3 month)	0.5 µg/m ³ (1 year)	0.5 µg/m ³ (1 year)	1 µg/m ³ (3 month) 0.5 µg/m ³ (1 year)	1 µg/m ³ (3 month) 0.5 µg/m ³ (1 year)

Source: Yi et. al 2015

Table 2. The six common pollutants and their health effects.

Pollutant	Health Effects
Carbon Monoxide (CO)	Reducing oxygen capacity of the blood cells leads to reducing oxygen delivery to the body's organs and tissues. Extremely high level can cause death.
Nitrogen Dioxide (NO ₂)	High risk factor of emphysema, asthma and bronchitis diseases. Aggravate existing heart disease and increase premature death.
Ozone (O ₃)	Trigger chest pain, coughing, throat irritation and congestion. Worsen bronchitis, emphysema and asthma.
Sulfur Dioxide (SO ₂)	High risk factor of bronchoconstriction and increase asthma symptoms.
Particulate Matter (PM _{2.5} & PM ₁₀)	Cause premature death in people with heart and lung diseases. Aggravate asthma, decrease lung function and increase respiratory symptoms like coughing and difficulty breathing.
Lead (Pb)	Accumulate in bones and affect nervous system, kidney function, immune system, reproductive systems, developmental systems and cardiovascular system. Affect oxygen capacity of blood cells.

Source: Yi et. al 2015



Examples of Air Quality Measuring Instruments

- Air-beam <https://nextcity.org/daily/entry/tools-measure-air-pollution-airbeam-aircaster-epa>
- OpenSense
(www.opensense.ethz.ch)(<http://people.ee.ethz.ch/~bmaag/files/maag18wair.pdf>)
- Citi-Sense-MOB (Castell et al., 2015) that use mobile platforms to monitor air pollution variation in cities
- Everyaware (www.everyaware.eu) that helps citizens collect and share noise and air pollution data
- Citi-Sense (www.citi-sense.eu) that empowers people to use low-cost air quality platforms in 8 cities across Europe.
- AirVisual, a crowdsourced community that has developed a home air quality monitor (<https://www.indiegogo.com/projects/airvisual-node-the-world-s-smartest-air-monitor#/>)
- AirCasting - an open-source solution for collecting, displaying and sharing air pollution data (<http://aircasting.org/>).

Company: Aeroqual

- How it works: Get a portable base model and then attach various sensor heads to measure a variety of pollutants:

<http://www.ayt.cl/files/2017/Aeroqual-AQS-Urban-Air-Quality-Monitor.pdf>

Benefits of each: <https://www.teeing.com/files/downloads/measurement-devices/aeroqual-portable-monitors-brochure.pdf>



Sensor Head options: <https://d2pwrxb99jwry6.cloudfront.net/wp-content/uploads/Aeroqual-Portable-Fixed-Sensor-Specifications.pdf>

Portable & Fixed Monitor Sensor Specifications

aeroqual[®]

Gas	Sensor Code	Sensor Type ¹	Range (ppm)	Minimum Detection Limit (ppm)	Accuracy of Factory Calibration ²	Resolution (ppm)	Response time (s) ³	Operating Conditions ⁴		Application Type ⁵			Compatibility					
								Temp	RH	ENV	IAQ	IND	S2/3/500 ⁶	S900	S930	S940	SM70	SM50
Ammonia (NH ₃)	NH	GSS	0-1000	2	<±5 ppm +15%	1	30	0 to 40°C	10 to 90%			✓	•	•				
Ammonia (NH ₃)	ENG	GSE	0-100	0.2	<±0.5 ppm +10%	0.1	120	0 to 40°C	15 to 90%			✓	•	•	•			
Carbon monoxide (CO)	ECM	GSE	0-25	0.05	<±0.5 ppm 0-5 ppm <±10% 5-25 ppm	0.01	60	0 to 40°C	15 to 90%	✓			•	•	•			
Carbon monoxide (CO)	ECN	GSE	0-100	0.2	<±1 ppm 0-10 ppm <±10% 10-100 ppm	0.1	30	0 to 40°C	15 to 90%	✓	✓	✓	•	•	•			
Carbon monoxide (CO)	CO	GSS	0-1000	1	<±2 ppm +15%	1	30	0 to 40°C	10 to 90%			✓	•	•				
Carbon dioxide (CO ₂)	CD	NDIR	0-2000	10	<±10 ppm +5%	1	120	0 to 40°C	0 to 95%	✓	✓	✓	•	•	•			
Carbon dioxide (CO ₂)	CE	NDIR	0-5000	20	<±20 ppm +5%	1	120	0 to 40°C	0 to 95%		✓	✓	•	•				
Chlorine (Cl ₂)	ECL	GSE	0-10	0.01	<±0.02 ppm +10%	0.01	30	0 to 40°C	15 to 90%	✓		✓	•	•	•			
Formaldehyde (CH ₂ O)	EF	GSE	0-10	0.01	<±0.05 ppm 0-0.5 ppm <±10% 0.5-10 ppm	0.01	120	0 to 40°C	15 to 90%			✓	•	•	•			
Hydrogen (H ₂)	HA	GSS	0-5000	5	<±10 ppm +10%	1	30	0 to 40°C	10 to 90%			✓	•	•				
Methane (CH ₄)	MT	GSS	0-10000	10	<±20 ppm +15%	1	60	0 to 40°C	10 to 90%			✓	•	•	•			
Hydrogen sulfide (H ₂ S)	EHS	GSE	0-10	0.04	<±0.05 ppm 0-0.5 ppm <±10% 0.5-10 ppm	0.01	30	0 to 40°C	15 to 90%	✓			•	•	•			
Hydrogen sulfide (H ₂ S)	EHT	GSE	0-100	0.4	<±0.5 ppm 0-5 ppm <±10% 5-100 ppm	0.1	30	0 to 40°C	15 to 90%			✓	•	•				
Nitrogen dioxide (NO ₂)	ENW	GSE	0-1	0.005	<±0.02 ppm 0-0.2 ppm <±10% 0.2-1 ppm	0.001	30	0 to 40°C	15 to 90%	✓			•	•	•			
NMHC	VN	GSS	0-25	0.1	<±0.1 ppm +10%	0.1	60	0 to 40°C	10 to 90%	✓			•	•	•			
Ozone (O ₃)	OZS	GSS	0-0.05	0.001	<±0.002 ppm	0.001	240	0 to 40°C	10 to 90%			✓	•	•	•			
Ozone (O ₃)	OZU	GSS	0-0.15	0.001	<±0.005 ppm	0.001	60	0 to 40°C	10 to 90%	✓	✓	✓	•	•	•	•	•	•
Ozone (O ₃)	OZL	GSS	0-0.5	0.001	<±0.008 ppm 0-0.1 ppm <±10% 0.1-0.5 ppm	0.001	60	0 to 40°C	10 to 90%	✓	✓	✓	•	•	•	•	•	•
Ozone (O ₃)	OZG	GSS	0-10	0.02	<±0.1 ppm +15%	0.01	60	0 to 40°C	10 to 90%			✓	•	•	•	•	•	•
Ozone (O ₃)	EOZ	GSE	0-10	0.01	<±0.01 ppm +7.5%	0.01	60	0 to 40°C	15 to 90%		✓	✓	•	•	•			
Particulate Matter (PM _{2.5} and PM ₁₀)	PM	LPC	0.001-1,000 mg/m ³	0.001 mg/m ³	± 0.005 mg/m ³ +15%	0.001 mg/m ³	5	0 to 40°C	0 to 90%	✓	✓	✓	•					
Perchloroethylene (C ₂ Cl ₄)	PE	GSS	0-200	1	<±5 ppm 0-50 ppm <±10% 50-200 ppm	1	30	0 to 40°C	10 to 90%		✓	✓	•	•				
Sulfur dioxide (SO ₂)	ESO	GSE	0-10	0.04	<±0.05 ppm 0-0.5 ppm <±10% 0.5-10 ppm	0.01	60	0 to 40°C	15 to 90%	✓	✓		•	•	•			
Sulfur dioxide (SO ₂)	ESP	GSE	0-100	0.4	<±0.5 ppm 0-5 ppm <±10% 5-100 ppm	0.1	30	0 to 40°C	15 to 90%			✓	•	•	•			
VOC	VM	GSS	0-25	0.1	<±0.1 ppm +10%	0.1	60	0 to 40°C	10 to 90%	✓	✓		•	•	•			
VOC	VP	GSS	0-500	1	<±5 ppm +10%	1	30	0 to 40°C	10 to 90%			✓	•	•	•			
VOC	PDL	PID	0-20	0.01	<±0.02 ppm +10%	0.01	30	0 to 40°C	0 to 95%	✓	✓		•	•	•			
VOC	PDH	PID	0-2000	0.1	<±0.2 ppm +10%	<1000 ppm: 0.1 >1000 ppm: 1	30	0 to 40°C	0 to 95%			✓	•	•	•			

Notes

- Sensor Types: Gas Sensitive Semiconductor (GSS), Gas Sensitive Electrochemical (GSE), Non-dispersive Infra-red (NDIR), Laser Particle Counter (LPC), Photo Ionization Detector (PID).
- The accuracy is valid for the conditions stated in the calibration certificates, not including calibration gas tolerance. Relative errors are % of reading.
- Response time is the time to reach 90% of final reading in response to a step change in gas concentration (T90). In practice response times vary due to air mass transport factors and concentration gradients.
- Sensor performance may degrade outside of stated conditions. Avoid condensation which may damage sensors. Sensors may exhibit temperature and humidity interferences which will affect accuracy. Additional enclosure protection may extend operating environmental conditions, please contact Aeroqual for further information. Note sensors are designed to operate in environments with oxygen levels similar to ambient air.
- Application type: ENV = outdoor environmental monitoring, IAQ = indoor air quality, IND = industrial health and safety
- Not all sensors can be used with the Series 200, 360 and 500 when inside the water and dustproof enclosure (NH ENC). Please contact Aeroqual for advice on your specific application.



Our Products



Product	AQM 65	AQS 1	AQY	AQY ⁿ	Portable Monitors
Application	- EIA - Environmental impact assessment - Industrial perimeter - Rapid response	- EIA - Seasonal pollutant mapping - Urban exposure studies	- EIA - Seasonal pollutant mapping - Urban exposure	- Grid monitoring - Smart cities - Pollution source detection	- EIA - Personal exposure - Urban exposure studies
Measurement parameters	PM10, PM2.5, PM1, TSP, NO2, CO, O3, SO2, NOx, VOC, H2S, CO2, NH3, meteorological, noise	PM10, PM2.5, PM1, TSP, NO2, O3, VOC, meteorological, noise	PM10, PM2.5, NO2, O3, Temp, RH	PM10, PM2.5, NO2, O3, Temp, RH	PM10, PM2.5, NO2, CO, O3, SO2, VOC, H2S, CO2, NH3, CH4, NMHC, Cl2, Temp, RH
Deployment size	1-20 units	1-50 units	1-10 units	10-1,000 units	1 unit
Deployment mode	Short / Long term, mobile	Short / Long term, mobile	Short term, mobile	Long term	Portable
Design lifetime	10 years	10 years	2+ years	1-2 years	2-5 years
Operating range	-35°C to +50°C	-10°C to +45°C	0°C to +40°C	-10°C to +45°C	0°C to +40°C
Power supply	Mains recommended	Mains, solar, battery	Mains, solar, battery	Mains, solar, battery	Mains, solar, battery
Calibration	Pre-shipment, Field (manual, auto)	Pre-shipment, Field (manual only)	Pre-shipment, Factory / Lab	Pre-shipment, Network calibration	Pre-shipment, Factory / Lab
Indicative price	\$\$\$\$\$	\$\$\$	\$	Varies by network size	\$

Many Instrumented

Sensors	Pollutant Measured	Cost
Dylos DC1100/DC1700	Particle # (relates to PM2.5 mass)	\$300
Landtec AQ Mesh	NO, NO2 and O3, CO, and SO2	10,000
Smart Citizen	N, NO2, CO, RH, T	\$175
Shinyei PMSensor	PM 2.5	\$1,000
AeroQual Ozone 500	O3	\$600
RTI MicroPEM	PM2.5 (real-time & integrated)	\$2,000
MetOne Community	PM	NA
Air Quality Egg	PM, CO, NO2	\$300
Cube	T, RH, CO2, VOC	\$125
Sharp PM2.5 Sensor	PM2.5	\$20
AirBeam PM monitor	PM2.5	\$200
Yoctpuce + Valarm app	VOC, CO2, RH, T	\$71-150
Grove Dust Sensor	PM (PM2.5?)	\$16
Sensorcon	CO	\$160



Typical Pollutants of Interest

Air Pollutant of Interest	Type	Source Example	Useful Detection Limits	Range to Expect	Level
Ozone (O_3)	Secondary	Formed via UV (sunlight) and pressure of other key pollutants	10 ppb	0-150 ppb	75 ppb (8 hr)
Carbon monoxide (CO)	Primary	Fuel combustion – mobile sources, industrial processes	0.1 ppm	0-0.3 ppm	9 ppm (8 hr) 35 ppm (1 hr)
Sulfur dioxide (SO_2)	Primary	Fuel combustion – electric utilities, industrial processes	10 ppb	0-100 ppb	75 ppb (1 hr) 0.5 ppm (3 hr)
Nitrogen dioxide (NO_2)	Primary and Secondary	Fuel combustion – mobile sources, electric utilities, off-road equipment	10 ppb	0-50 ppb	100 ppb (1 hr) 53 ppb (1 yr)
Carbon dioxide (CO_2)	Primary	Fuel combustion – electric utilities, mobile sources	100 ppm	350-600 ppm	None
Volatile organic compounds (VOCs)	Primary and Secondary	Fuel combustion (mobile sources, industries) gasoline evaporation; solvents	1 $\mu g/m^3$	5-100 $\mu g/m^3$ (total VOCs)	None
Benzene (an example of a VOC and air toxic)	Primary	Gasoline, evaporative losses from above ground storage tanks	0.01 – 10 $\mu g/m^3$	0-3 $\mu g/m^3$	None
Fine particulate matter ($PM_{2.5}$)	Primary and Secondary	Fuel combustion (mobile sources, electric utilities, industrial processes), dust, agriculture, fires	5 $\mu g/m^3$ (24-hr)	0-40 $\mu g/m^3$ (24-hr)	35 $\mu g/m^3$ (24 hr) 12 $\mu g/m^3$ (1 yr)
Particulate matter (PM_{10})	Primary and Secondary	Dust, fuel combustion (mobile sources, industrial processes), agriculture, fires	10 $\mu g/m^3$ (24-hr)	0-100 $\mu g/m^3$ (24-hr)	150 $\mu g/m^3$ (24 hr)
Black carbon (BC)	Primary	Biomass burning, diesel engines	0.05 $\mu g/m^3$	0-15 $\mu g/m^3$	None



Example - PM Sensors

DYLOS



SPECK



MET ONE



SHINYEI



AIRBEAM



TZOA



Example- Gas Sensors

SENSARIS



AIR CASTING



CAIRCLIP



AEROQUAL



AQ EGG



NODE





Example- MultiPollutant Stations



ELM



HAZ-SCANNER



AQ MESH

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Dylos DC110

- From 11/14/2014 to 01/09/2014 three **Dylos particle counters (model DC1100)** were deployed in Rubidoux and run alongside two different FEM PM monitors
- Dylos (3 units tested):
 - Optical particle counter (**non-FEM**)
 - Measures 3 different size fractions including PM(0.5-2.5) (used as an estimate of PM2.5)
 - Cost: ~\$300
 - Time resolution: 1-min
- MetOne BAM (reference method):
 - Beta-attenuation monitor (**FEM**)
 - Measures PM2.5
 - Cost: ~\$20,000
 - Time resolution: 1-hr
- GRIMM (reference method):
 - Optical particle counter (**FEM**)
 - Uses proprietary algorithms to calculate total PM, PM2.5, and PM1 from particle number measurements
 - Cost: ~\$25,000 and up
 - Time resolution: 1-min





Shinyei PM_{2.5} Sensor

- From 02/05/2015 to 03/03/2015, three **Shinyei Technology PM_{2.5} Sensor Evaluation Kits** were deployed in Rubidoux and ran alongside two different FEM PM monitors

- PM Sensor Eval Kit (3 units tested):
 - Particle sensors (**non-FEM**)
 - Each unit measures: PM2.5 (ug/m3)
Unit cost: ~\$1,000
 - Time resolution: 1-min
 - Units IDs: SHN #1, SHN #2, SHN #3



- MetOne BAM (reference method):
 - Beta-attenuation monitor (**FEM**)
 - Measures PM2.5
 - Cost: ~\$20,000
 - Time resolution: 1-hr
- GRIMM (reference method):
 - Optical particle counter (**FEM**)
 - Uses proprietary algorithms to calculate total PM, PM2.5, and PM1 from particle number measurements
 - Cost: ~\$25,000 and up
 - Time resolution: 1-min

RTI MicroPEM

- From 02/10/2015 to 03/09/2015, three **RTI MicroPEM** particle sensors were deployed in Rubidoux and run alongside with two different FEM PM monitors

- RTI MicroPEM (3 units tested):
 - Particulate Matter sensors (**non-FEM**)
 - Each unit measures: PM2.5 (µg/m3)
Unit cost: ~\$2,000
 - Time resolution: 10sec
 - Units IDs: 60N, 65N, 72N



- MetOne BAM (reference method):
 - Beta-attenuation monitor (**FEM**)
 - Measures PM2.5
 - Cost: ~\$20,000
 - Time resolution: 1-hr
- GRIMM (reference method):
 - Optical particle counter (**FEM**)
 - Uses proprietary algorithms to calculate total PM, PM2.5, and PM1 from particle number measurements
 - Cost: ~\$25,000 and up
 - Time resolution: 1-min



AeroQUAL S-500

- From 02/10/2015 to 03/05/2015, three **aeroQUAL Series 500** portable ozone sensors were deployed in Rubidoux and run alongside an FRM O3 monitor
- aeroQUAL S-500 (3 units tested):
 - Gaseous sensors (**non-FRM**)
 - Each unit measures: Ozone (pphm)
Unit cost: ~\$500
 - Time resolution: 1-min
 - Units IDs: AQ #1, AQ #2, AQ #3
- SCAQMD FRM instruments:
 - Ozone instrument; **cost: ~\$7,000**
 - Time resolution: 1-min
 - Meteorological station (wind speed, wind direction temperature, relative humidity, and pressure); **cost: ~\$5,000**
 - Time resolution: 1-min



AQ-SPEC Overview

- Main Goals & Objectives
 - Provide guidance & clarity for ever-evolving sensor technology & data interpretation
 - Catalyze the successful evolution / use of sensor technology
 - Minimize confusion
- Sensor Selection Criteria
 - Potential near-term use
 - Real- or near-real time
 - Criteria pollutants & air toxics
 - Turnkey products first
 - Price range:
 - < ~\$2,000 (purchase)
 - > ~\$2,000 (lease/borrow)

AQMesh



CairClip



Shinyei



Dylos
(prototype)



DC1100 Pro



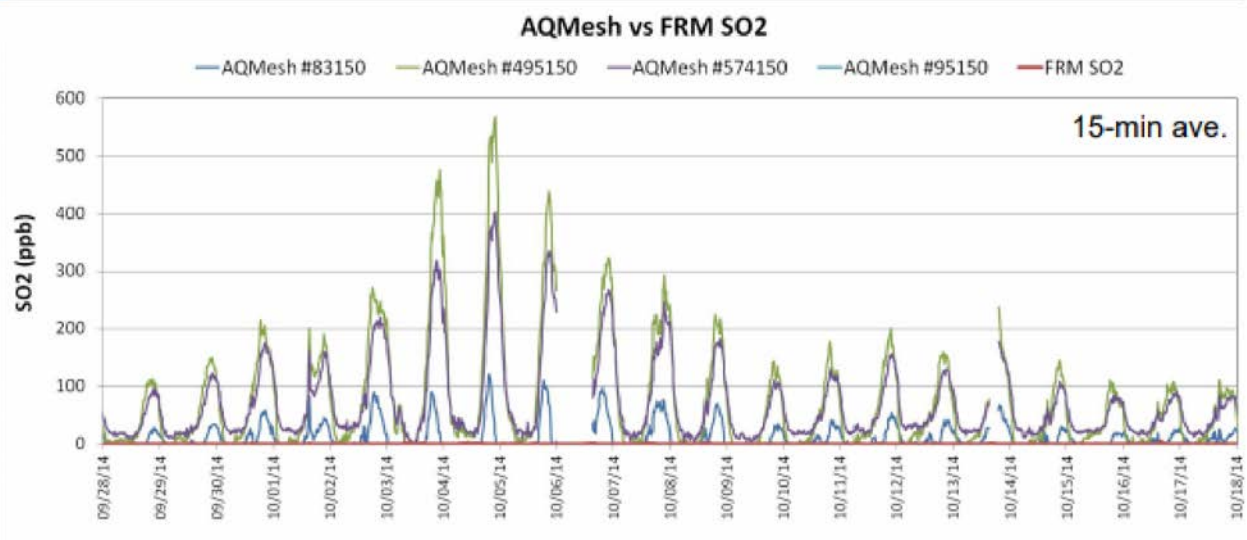
SmartCitizens





Landtec AQMesh (1st gen)

- From 09/27/2014 to 01/14/2015 four **Landtec AQMesh gaseous monitors** were deployed in Rubidoux and run alongside FRM instruments for measuring CO, NO, NO₂, SO₂, and O₃
- AQMesh (3 units tested):
 - Electrochemical sensors (**non-FEM**)
 - Each unit measures: CO, NO, NO₂, SO₂, and O₃
 - **Unit cost: ~\$10,000**
 - Time resolution: 1- or 15-min
 - Units IDs: #83150, #495150 (until 11/12/2014), #574150 (starting on 12/08/2014), #90150
- SCAQMD FRM instruments:
 - CO instrument; **cost: ~\$10,000**
 - Time resolution: 1-min
 - NO_x instrument; **cost: ~\$11,000**
 - Time resolution: 1-min
 - SO₂ instrument; **cost: ~\$13,000**
 - Time resolution: 1-min
 - O₃ instrument; **cost: ~\$7,000**
 - Time resolution: 1-min



- Complete lack of correlation between AQMesh and FRM SO₂ measurements



AQ-Spec Low Cost Sensor Evaluations

<http://www.aqmd.gov/aq-spec/evaluations/summary-pm>

Great comprehensive table of air sensors: <https://www.epa.gov/air-sensor-toolbox/evaluation-emerging-air-pollution-sensor-performance>

Village Green Project

<https://www.epa.gov/air-research/village-green-project>

USDA Air Quality Guidebook

file:///C:/Users/Daniel/Downloads/GUIDEBOOK%20-%20FINAL%20(1).PDF

Air Quality Monitoring Field/Lab test evaluation chart

PM: <http://www.aqmd.gov/aq-spec/evaluations/summary-pm>

Gaseous: <http://www.aqmd.gov/aq-spec/evaluations/summary-gas>

On Using Particulate Matter as a gauge for Visibility:

- Fine particles, generally characterized as PM_{2.5}, are believed to be primarily responsible for the scattering of visible light and a cause of the degradation of visibility ([Sloane et al., 1991](#)). Fine particulate matter is the principal pollutant in most urban areas in China ([Zhang et al., 2009](#); [Zhang et al., 2013](#)) and has acquired worldwide attention for its adverse impacts on visibility ([Ghim et al., 2005](#)) and public health ([Hong et al., 2002](#))

IR-DOAS Multi-gaseous measurement device (inquired with company):

<https://www.opsis.se/en/Products/Products-AQM/Open-path-UV-IR-DOAS-Systems#>

Measuring multiple Pollutants:

<https://www.qld.gov.au/environment/pollution/monitoring/air/air-monitoring/measuring/measuring-pollutants>

Measuring ammonium ions with a sensor

Source: <https://www.yysi.com/parameters/ammonia>

- Ammonium (NH₄⁺) — or its uncharged form ammonia (NH₃) — is a form of nitrogen which aquatic plants can absorb and incorporate into proteins, amino acids, and other molecules. High concentrations of ammonium can enhance the growth of algae and



aquatic plants. Bacteria can also convert high ammonium to nitrate (NO_3^-) in the process of nitrification, which lowers dissolved oxygen.

- Ammonia in water is either un-ionized ammonia or the ammonium ion. Typically, the value reported is the sum of both forms and is reported as total ammonia or simply - ammonia. The relative proportion of the two forms present in water is highly affected by pH.
- Un-ionized ammonia is the toxic form and predominates when pH is high. Ammonium ion is relatively non-toxic and predominates when pH is low. In general, less than 10% of ammonia is in the toxic form when pH is less than 8.0 pH units. This proportion increases dramatically as pH increases.
- The equilibrium between NH_3 and NH_4^+ is also affected by temperature. At any pH, more toxic ammonia is present in warmer water than in cooler water.
- The YSI ammonium sensor consists of a silver/silver chloride wire electrode in a custom filling solution. The internal solution is separated from the sample medium by a nonactin membrane, which selectively interacts with ammonium ions.

Measuring Nitrate (for Wet Nitrogen Deposition)

Example Sensor 1:

https://www.forestry-suppliers.com/product_pages/products.php?mi=49872&itemnum=76736&redir=Y

- Price: **\$546.25**
- YSI ProDSS Ammonium Smart Sensor with Module
- Ammonia with pH sensor for freshwater only; 20-meter maximum depth. Sensor Type: Ion Selective Electrode. Range: 0 to 200 mg/L $\text{NH}_4\text{-N}$. Accuracy: $\pm 10\%$ of reading or 2 mg/L, whichever is greater. Resolution: 0.01 mg/L. Units: $\text{NH}_4\text{-N}$ mg/L, $\text{NH}_4\text{-N}$ mV.
- Digital Smart Sensors are automatically recognized by the ProDSS instrument and store calibration data.

Example Sensor 2:

- YSI 1006 Nitrate (ISE) Sensor
- Add the YSI 1006 nitrate ISE sensor to your Pro Series multi-parameter instrument to complement your sampling regimen.



- Features
 - Freshwater use only
 - Best for sampling applications
 - Field-replaceable
-
- List Price: 356
 - <https://www.fondriest.com/ysi-1006-s.htm>
 - Example sensor 3:
-
- YSI 1004 Ammonium (ISE) Sensor
-
- Add the YSI 1004 ammonium ISE sensor to your Pro Series multi-parameter instrument to complement your sampling regimen.
-
- Features
 - Freshwater use only
 - Best for sampling applications
 - Field-replaceable
-
- List Price
 - \$375.00

Fenceline Ambient Air Monitoring

Source: <https://www.enveraconsulting.com/petroleum-refinery-fenceline-monitoring/>

- As part of the proposed rule, the EPA suggests six fenceline monitoring methods that refineries can use to comply with the proposed regulations. The following is a summary of each method, including the associated advantages, disadvantages, and operational costs.
-
- **Passive Diffusive Tube Monitoring Network**
-
- The underlying concept behind diffusive tube monitoring is the adsorption of the target pollutant onto a tube monitor, which has a special cap to allow air to enter at a fixed rate. If a target pollutant is present in the air, it will stick to the adsorbent inside the tube.



Following the exposure, these tubes can be removed from the field and analyzed in a lab, provided that the tubes were properly exposed to the ambient air (which takes about two weeks).

- **Pros:** Within the proposed rule, the EPA has confirmed through various studies the long-term effectiveness of passive diffusive tube monitoring, specifically for benzene. When the outcomes are combined with low setup and maintenance costs, passive diffusive monitoring is a top choice for meeting fenceline monitoring requirements.
 - **Cons:** The disadvantages of this method include data with low time resolution and possible contamination of samples during transits to the lab.
 - **Costs:** The EPA estimates that large refineries, which are assumed to have 24 sampling locations, will spend up to \$100,000 on equipment and installation. The agency also estimates that the approximate annual operational and maintenance costs for a 24-unit system to be \$40,000 a year.
- **Active Monitoring Station Networks**
 - Active monitoring stations are similar to passive diffusive tubes in that the same principal method of detection is used: materials get drawn into the sampler. One of the main differences is that active monitoring uses pumps to draw in ambient air.
 - **Pros:** The use of a pump allows for quicker data collection and, thus, greater time resolution. An active sampling system can be attached to the monitoring stations, which can further increase the rate of sample analysis.
 - **Cons:** Although this method is well-established and has been used in a variety of settings, the high cost is a major drawback.
 - **Cost:** The EPA estimates installation and equipment costs and maintenance costs to be two and ten times that of passive diffusive tube monitoring, respectively. Part of the reason for this significant difference is the need for highly trained personnel to operate and maintain the monitoring equipment.
 - **Ultraviolet Differential Optical Absorption Spectroscopy (UV-DOAS)**
 - UV-DOAS is categorized as “**open-path**” technology, meaning it uses a continuous beam of light to detect pollutants across an open path. In this case, UV light is emitted from a source that points towards a detector.
 - **Pros:** Benefits of this method include fewer monitoring stations when compared to the adsorption method, since the distance between the source and the detector can be more than 500 meters. Real-time data with a low detection threshold is attainable with this method.



- **Cons:** On the downside, this method is prone to interference from visible emissions like dust and smoke.
- **Costs:** The costs of this method are higher than both adsorption methods because the technology is more advanced. The EPA estimates \$500,000 for a complete fenceline monitoring set-up, which includes four beam-detector systems and four equipment shelters. The agency also estimates that maintaining these systems at two fenceline locations will cost nearly \$1,000,000 annually.
- **Open-Path Fourier Transform Infrared Spectroscopy (OP-FTIR)**
 - OP-FTIR is similar to UV-DOAS, but instead of UV light, an OP-FTIR uses infrared light that has spectral interferences with carbon monoxide (CO), carbon dioxide (CO₂), and water vapor, which makes organic vapors harder to detect.
 - **Pros:** According to a paper **published by the EPA**, “OP-FTIR is the most powerful and flexible technology for use in long-term monitoring programs at E&P sites as it can monitor almost all compounds of interest simultaneously.”
 - **Cons:** A significant disadvantage of the OP-FTIR method is that benzene has a high detection threshold, which means FTIR is less sensitive to benzene as compared to other materials. All else being equal to UV-DOAS, the EPA does *not* recommend FTIR for the purposes of benzene fenceline mentoring.
 - **Cost:** \$150,000-\$200,000 (according to a **2014 report on the AQMD website**).
- **Differential Absorption Lidar Monitoring (DIAL)**
 - DIAL monitoring is slightly different than the two open-path systems of OP-FTIR and UV-DOAS. In DIAL monitoring, two wavelengths of light — one strongly absorbed by the target pollutant, one weakly absorbed by the same pollutant — are emitted in pulses across a path. Light from these beams becomes backscattered as the beams encounter particles and aerosols. A detector adjacent to the light source picks up the backscattered light and measures the difference between the signal strength of the two pulsed beams. The timing of the received light allows for the distance between the plume of pollution and the DIAL apparatus to be calculated.
 - **Pros:** Typically, DIAL monitoring is used for specific short-term studies and has been used to measure emissions from a refinery and other petrochemical sources.
 - **Cons:** Coupled with its limited availability in the U.S. and its need for highly trained personnel, the EPA does not recommend the use of DIAL monitoring as a long-term fenceline monitoring solution.



- **Solar Occultation Flux (SOF) Monitoring**

- Solar occultation flux monitoring is another open-path technology that uses the sun as the light source and either a UV or FTIR detector. A van equipped with either detector is driven around the perimeter of the facility to record emissions data.
- **Pros:** This method provides excellent spatial resolution compared to the other open-path methods and is less costly than a DIAL system, though high costs are still an issue because this method requires a full-time staff to operate the vehicle.
- **Cons:** More importantly, this method is dependent on the presence of the sun. Consequently, the EPA does not advise the use of solar occultation flux monitoring.
- **Costs:** Unknown, but there are some examples in a **2014 paper from the AQMD**.

- **Feasibility of the Six Monitoring Methods**

- The EPA suggests the use of passive diffusive tube monitoring as the primary monitoring option, followed by active sampling, UV-DOAS, and FTIR, respectively.
- Passive monitoring's low costs and ease of setup and maintenance trump its lack of high-quality data relative to the other methods. DIAL monitoring and solar occultation flux monitoring have critical flaws that remove them from consideration.
- Regardless of which method is used, the implementation of fenceline monitoring will require additional effort by refineries because facilities must have the monitoring stations installed around their perimeter

Example of Fenceline Monitors

Source: Article from EPA titled "[SPod FENCELINE SENSORS UNDER DEVELOPMENT](#)"

Purpose: air pollutant sensors and inverse modeling approaches that can improve facility leak detection and repair and source emissions inventories. The commercialization of cost effective, implementable sensor systems that meet desired performance goals will help bring advanced approaches from the lab to the real-world.

- **How it works:** SPod (right) is a solar-powered sensor system that can be deployed at a facility fenceline.
 - SPod (right) is a solar-powered sensor system that can be deployed at a facility fenceline. It combines air pollutant and wind field data with inverse algorithms to detect and locate source emissions of volatile organic compounds. The use of SPods would cost less than most commercial fenceline monitoring



systems and are simple to deploy and operate (automated). The current SPod uses a passive photoionization detector but other air pollutant sensors can be added. Contained in a 3-D printed housing, the SPod sensor board also measures relative humidity, atmospheric pressure and temperature. The SPod is controlled by a microcomputer and communicates using a short range XBee® (IEEE 802.15.4) network. The units are coupled with commercial wind anemometers.

EPA SPod Science Inventory and contact info:

https://cfpub.epa.gov/si/si_public_record_report.cfm?Lab=NRMRL&dirEntryId=335108

PM Sensors: Air Quality Sensor Performance Evaluation Center

Device	Pollutant Measured	Data Communication	R ² Field	R ² Lab	Power Supply	Price
 Aeroqual	O3, No2, PM2.5	Wi-Fi, or cellular	0.85	0.99	12 VDC plug pack, US Plug: 24W	\$3,000
 Air Quality Egg (2018 model)	PM 2.5	Wi-Fi, serial output, SD	0.84	-	USB Power Adapter	\$249
 Alphasense (OPC-N2)	PM2.5	SPI/micro SD	0.65-0.80	0.99	5V DC	\$310
Alphasense (OPC N3)	PM2.5	SPI/micro SD	0.52-0.67		5V DC	\$338
 AS Lung Station	PM2.5	SSD,GSM,WiFi, Lora	0.59-0.81	-	10W Solar panel	\$2,000
 Dylos (DC1100 Pro)	PM2.5	USB to PC	0.65-0.85	0.89	120V 60Hz to 9VDC 500mA	\$300
Dylos (DC1700-PM)	PM2.5	USB to PC	0.58-0.68	-	Battery	\$475
 PurpleAir PA-I	PM2.5	Cloud	0.90-0.92	0.99	USB Power Adapter	\$150



Gaseous Sensors: Air Quality Sensor Performance Evaluation Center

Device	Pollutant Measured	Data Communication	R ² Field	R ² Lab	Power Supply	Price
 Aeroqual (AQY) Ver 5.0	O ₃ , NO ₂	Wi-Fi, or cellular, cloud	O ₃ : 0.95 NO ₂ : 0.77	O ₃ : 0.99 NO ₂ : 0.98	12 VDC plug pack, US Plug: 24W	\$3,000
 Aeroqual (S500)	O ₃	Software, USB to PC	0.85	0.99	Battery	\$500
 Unitec-SENS-IT	O ₃ , NO ₂	USB to PC	NO ₂ : 0.60-0.65, O ₃ : 0.40-0.58	-	12 V DC	\$2,200
 Vaisala (AQT410)	CO, NO ₂ , O ₃ , SO ₂	Wi-Fi	CO: 0.80-0.83 NO ₂ : 0.43-0.61 O ₃ : 0.66-0.82, SO ₂ : na	-	0.5W, max 2W	\$3,700
 AQ Mesh	O ₃ , NO ₂	Web-browser based, data storage on secure server	O ₃ : 0.7 NO ₂ : 0.89	-	Battery	\$10,000
 ENEA/AirBox	CO, NO ₂ , O ₃ , SO ₂ , PM ₁₀ , T, RH	SD card, Wirelessly communicated by GPRS to a network	SO ₂ : 0.20	-	Battery or main	R&D?

Historic Techniques for Measuring Air Quality Within National Parks

Source: Air Quality Monitoring Program in National Parks 1988

- Monitoring Program includes:
 - Teleradiometers for measuring visibility at over 30 parks
 - Cameras for measuring visibility at over 50 parks
 - Fine particulate monitors for identifying the causes and sources of visibility impairment at over 40 parks
 - The use of biomonitors (species of plants known to be sensitive to air pollution) to identify the presence of air pollution in several parks
 - Ozone monitors at over 30 parks
 - Sulfur dioxide monitors at over 25 parks for establishing baseline conditions, assisting the sulfur dioxide effects research, and evaluating new pollution sources

Visibility

- Fine particles (diameter less than 2.5 microns)
- Fine sulfate particles
- Fine aerosols: 0.2-1.0 micron are most efficient at scattering light and cause a larger fraction of visibility reduction than their fraction of total mass



- Coarse particles (2.5-15 microns) contribute to impairment, but not in proportion to their mass.
 - **3 forms of visibility structures:** uniform, layered, plumes
 - Uniform: air is well mixed and pollutants are evenly distributed
 - Plume: surface wind to carry visible pollutants horizontally from emission source into a stable atmosphere
 - Layered haze: stable air masses with little mixing
 - Human Perception of Visual Air Quality: was accurate for the main part.

Pollution Effects on Biological Resources

- Foliar injury from ozone and sulfur dioxide (and fluorides, nitrogen dioxide, ethylene, chlorine, ammonia)
- Bioindicators: lichens and milkweeds- many species are sensitive to sulfur dioxide and are unable to survive when exposed to certain ozone levels.
 - Downside: cannot tell you exactly what the levels are, and most of our national parks are at “nonattainment status”

Literature on Current Air Quality Methods

Article: Can commercial low-cost sensor platforms contribute to air quality monitoring and exposure estimates? (Castell et. al, 2017)

- We have conducted an exhaustive evaluation of 24 identical units of a commercial low-cost sensor platform against CEN (European Standardization Organization) reference analyzers, evaluating their measurement capability over time and a range of environmental conditions
- High costs of installation and maintenance of reference monitoring stations in sparse areas provides accurate data but only in a few locations not counting localized gradients
- Can have fixed monitoring systems or mobile monitoring stations in conjunction with one another
- **Mobile systems** can be mounted on cars
 - Limitation: are often costly
- **Passive samplers** can also be used
 - Does not require active air movement from a pump
 - Limitation: not as accurate as reference instrumentation, suffer from chemical interference, and affected by atmospheric conditions
- **Air Quality models** can be used
 - To analyze and forecast



- Limitations: run in hypothetical, suffer from systematic errors, depending on the input data and on the modeller parametrization choices
- Study used: Several research projects are exploring the possibility of collecting air quality data using low-cost sensor platforms. Examples include:
 - OpenSense (www.opensense.ethz.ch)(<http://people.ee.ethz.ch/~bmaag/files/maag18wair.pdf>)
 - Citi-Sense-MOB (Castell et al., 2015) that use mobile platforms to monitor air pollution variation in cities
 - Everyaware (www.everyaware.eu) that helps citizens collect and share noise and air pollution data
 - Citi-Sense (www.citi-sense.eu) that empowers people to use low-cost air quality platforms in 8 cities across Europe.
 - AirVisual, a crowdsourced community that has developed a home air quality monitor (<https://www.indiegogo.com/projects/airvisual-node-the-world-s-smartest-air-monitor#/>)
 - AirCasting - an open-source solution for collecting, displaying and sharing air pollution data (<http://aircasting.org/>).

2 different types of air pollution sensors:

- Ones that measure particulate matter and ones that measure gas phases
- Commercially available gas sensors operate by measuring either the electrochemical interaction between the sensing material and pollutant and the absorption of light in the visible range
- Particulate matter is measured by light scattering or absorption, using algorithms to relate the attenuated signal to the particle size/composition

Components of a sensor

- Individual sensors need to be integrated into a sensor platform or node. Sensor contains a sensor board, sensors, and a control board that integrates all required electronics (signal, GPS, communication ports, data storage)
- Commercial sensors range from \$570-\$5,0000
- PM10 and PM2.5
- In order to employ low cost platforms for air quality management and health studies, it is necessary to ensure their measurement reproducibility and assess any associated uncertainty

Conclusion:



- commercial low-cost sensors are suitable for raising awareness or engaging the community by monitoring local air quality, and other things that do not require the same accuracy as scientific or regulative monitoring

Article: A Survey of Wireless Sensor Network Based Air Pollution Monitoring Systems (Yi et. al, 2015)

Traditional Air Quality Monitoring Systems

- Traditionally, monitoring stations are monitored by highly conventional air pollution monitoring systems with stationary monitors
 - **Advantage:** reliable, accurate, and able to measure a wide range of pollutants through use of gas-chromatograph-mass-spectrometers
 - **Limitations:** large size, heavy weight, extraordinary expensiveness
- Road traffic is a large source of pollution, an acute/short-term change of pollutants may trigger or worsen some health events or diseases
- Solution? Could be Wireless Sensor Network (WSN)

Conventional methods use temperature controller (heater/cooler), relative humidity controller, air filter (for PM), built in calibrator

- **Limitation:** high cost, higher power consumption, large volume, heavy weight

Ambient sensors have a low cost, small size and fast response time

- **Limitation:** no low-cost sensor can achieve the same data accuracy and quality as conventional instruments
- **Advantage:** current interpolations are not very accurate, so ambient low-cost portable sensors could provide an opportunity in increasing the spatio-temporal resolution of the air pollution info and are able to verify, fine tune, or improve the existing method of measuring air quality
- TNGAPMS: combining the low-cost portable ambient sensors and the Wireless Sensor Network (WSN) into one system which is known as The Next Generation Air Pollution Monitoring System (TNGAPMS)



Table 5. Instruments used in air quality monitoring systems (Part A).

Pollutant	Example Product	Measurement Method	Resolution	Accuracy	Range	Price (USD)
PM _{2.5}	Met One Instrument BAM-1020 Beta Attenuation Monitor [56]	Beta Attenuation	1 µg/m ³	±1 µg/m ³	0–1000 µg/m ³	About \$25,000
	Met One Instrument Aerocet 831 Aerosol Mass Monitor [57]	Light Scatting	0.1 µg/m ³	±10% of reading	0–1000 µg/m ³	About \$2000
	Alphasense OPC-N2 Particle Monitor [58]	Light Scatting	Not Provided	Not Provided	Not Provided	About \$500
	Sharp Microelectronics DN7C3CA006 PM2.5 Module [59]	Light Obscuration (Nephelometer)	Not Provided	Not Provided	25–500 µg/m ³	About \$20
	Teledyne Model 602 BetaPLUS Particle Measurement System [60]	Beta Attenuation	0.1 µg/m ³	±1 µg/m ³	0–1500 µg/m ³	About \$30,000
PM ₁₀	Met One Instrument Aerocet 831 Aerosol Mass Monitor [57]	Light Scatting	0.1 µg/m ³	±10% of reading	0–1000 µg/m ³	About \$2000
	Alphasense OPC-N2 Particle Monitor [58]	Light Scatting	Not Provided	Not Provided	Not Provided	About \$500
	Sharp GP2Y1010AU Air Quality Sensor [61]	Light Obscuration (Nephelometer)	Not Provided	Not Provided	0–500 µg/m ³	About \$20
Lead (Pb)	Operation in Lab	-	-	-	-	-

Table 6. Instruments used in air quality monitoring systems (Part B).

Pollutant	Example Product	Measurement Method	Resolution	Accuracy	Range	Price (USD)
Carbon Monoxide (CO)	Teledyne Model T300U Gas Filter Correlation Carbon Monoxide Analyzer [62]	IR Absorption with Gas Filter Correlation Wheel	0.1 ppb	±0.5% of reading	0–100 ppb or 0–100 ppm	About \$30,000
	Aeroqual Series 500 with CO Sensor Head [63]	Electrochemical Sensor	10 ppb	±0.5 ppm at 0–5 ppm or ±10% at 5–25 ppm	0–25 ppm	About \$2000
	Alphasense B4 Series CO Sensor [64]	Electrochemical Sensor	4 ppb	Not Provided	0–1000 ppm	About \$200
	Hanwei MQ-7 CO Sensor [65]	Solid-State Sensor	Not Provided	Not Provided	20–2000 ppm	About \$10
Nitrogen Dioxide (NO ₂)	Teledyne Model T500U Nitrogen Dioxide Analyzer [66]	Cavity Attenuated Phase Shift Spectroscopy	0.1 ppb	±0.5% of reading	0–5 ppb or 0–1 ppm	About \$30,000
	Aeroqual Series 500 with NO ₂ Sensor Head [67]	Electrochemical Sensor	1 ppb	±0.02 ppm at 0–0.2 ppm or ±10% at 0.2–1 ppm	0–1 ppm	About \$2000
	Alphasense B4 Series NO ₂ Sensor [68]	Electrochemical Sensor	12 ppb	Not Provided	0–20 ppm	About \$200
	SGXSensorTech MiCS-2714 NO ₂ Sensor [69]	Solid-State Sensor	Not Provided	Not Provided	0.05–10 ppm	About \$10
Ozone (O ₃)	Teledyne Model 265E Chemiluminescence Ozone Analyzer [70]	Chemiluminescence Detection	0.1 ppb	±0.5% of reading	0–100 ppb or 0–2 ppm	About \$25,000
	Aeroqual Series 500 with O ₃ Sensor Head [71]	Solid-State Sensor	1 ppb	±5 ppb	0–150 ppb	About \$2000
	Alphasense B4 Series O ₃ Sensor [72]	Electrochemical Sensor	4 ppb	Not Provided	0–5 ppm	About \$200
	Hanwei MQ-131 O ₃ Sensor [73]	Solid-State Sensor	Not Provided	Not Provided	10–1000 ppm	About \$10
Sulfur Dioxide (SO ₂)	Teledyne Model 6400T/6400E Sulfur Dioxide Analyzer [74]	UV Fluorescence	0.1 ppb	±0.5% of reading	0–50 ppb or 0–20 ppm	About \$30,000
	Aeroqual Series 500 with SO ₂ Sensor Head [75]	Electrochemical Sensor	10 ppb	±0.05 ppm at 0–0.5 ppm or ±10% at 0.5–10 ppm	0–10 ppm	About \$2000
	Alphasense B4 Series SO ₂ Sensor [76]	Electrochemical Sensor	5 ppb	Not Provided	0–100 ppm	About \$200
	Hanwei MQ-136 SO ₂ Sensor [77]	Solid-State Sensor	Not Provided	Not Provided	0–200 ppm	About \$50



Table 7. Comparison of the five types of gas sensors.

Sensor Type	Detectable Gases	Linearity	Cross Sensitivity	Power Consumption	Maintenance	Response Time (T90)	Life Expectancy
Electro-chemical [78]	Gases which are electrochemically active, about 20 gases	Linear at room temperature	Can be eliminated by using chemical filter	Lowest, very little power consumption	Low	<50 s	1–2 years
Catalytic [79]	Combustible gases	Linear at 400 °C to 600 °C	No meaning when measuring mixed gases	Large, need to heat up to 400 °C to 600 °C	Lose sensitivity with time due to poisoning and burning out	<15 s	Up to 3 years
Solid-state [80]	About 150 different gases	Linear at operational temperature	Can be minimized by using appropriate filter	Large, need heating element to regulate temperature	Low	20 s to 90 s	10+ years
Non-dispersive Infrared [81]	Hydrocarbon gases and carbon dioxide	Nonlinear, need linearize procedure	All hydrocarbons share a similar absorption band, make them all cross sensitive	Small, mainly consume by the infrared source	The least	<20 s	3–5 years
Photo-ionization [82]	Volatile organic compounds (VOCs)	Relatively linear	Any VOCs with ionization potentials less than the ionizing potential of the lamp used will be measured	Medium, mainly consume by the ultraviolet source	The lamp requires frequent cleaning	<3 s	Depend on the Ultraviolet lamp, normally 6000 h

- CO: Can be well detected by solid-state and electrochemical sensors.
- NO₂: Can be well detected by solid-state and electrochemical sensors. Need to consider the interference gas O₃. Proper methods can be applied to reduce the interference.
- O₃: Can be well detected by solid-state and electrochemical sensors. Need to consider the interference gas NO₂. Proper methods can be applied to reduce the interference.
- SO₂: Can only be well detected by solid-state and electrochemical sensors. It poisons the catalytic sensors. The sensitivity of NDIR sensors is not high enough.
- In a word, the solid-state and electrochemical sensors are the most suitable types of sensors to monitor these four types of hazard gases in building the TNGAPMS scenario.
- How sensors work

Table 8. Comparison of four types of particulate matter (PM) measurement methods.

Measurement Method	Advantages	Disadvantages	Accuracy
Tapered Element Oscillating Microbalance (TEOM) analyzers	Provide real time (<1 h) data with high precision.	A heater must be used which leads to lose of semi-volatile material. Usually with large size, heavy weight and high cost.	$\pm 0.5 \mu\text{g}/\text{m}^3$
β -attenuation analyzers (BAM)	Provide real time (<1 h) data with high precision.	A radioactive source is used. If heater is used some semi-volatile material may be lost. Need to replace the paper filter periodically. Usually with large size, heavy weight and high cost.	$\pm 1.0 \mu\text{g}/\text{m}^3$
Black smoke method	Simple, robust and inexpensive. Easy to maintain. Short sample time (in minutes).	Measure the darkness rather than the mass concentration of the particulate matters. Darkness-mass factor may change from time to time and location to location.	$\pm 2.0 \mu\text{g}/\text{m}^3$, or higher
Optical analyzers	Small, light weight and usually battery operated. Short sample time (in seconds or minutes). Can measure different sizes of particles simultaneously.	Depends on some assumptions of particle characteristics (e.g. each particle is perfect bean-like shape). These assumptions may be different from time to time and location to location.	Depends on the analyzer type and usually not specifically declared by the manufacture.



- Could use Vehicle Sensor Network, Static Sensor Network (SSN. Sensor nodes are usually mounted on the streetlight or traffic light poles, or carefully selected locations.), Community Sensor Network (CSN. Sensor nodes are carried by the public communities, usually by volunteers or people who are keen on air quality.), and Vehicle Sensor Network (VSN. Sensor nodes are carried by the public transportations or specially equipped cars.)

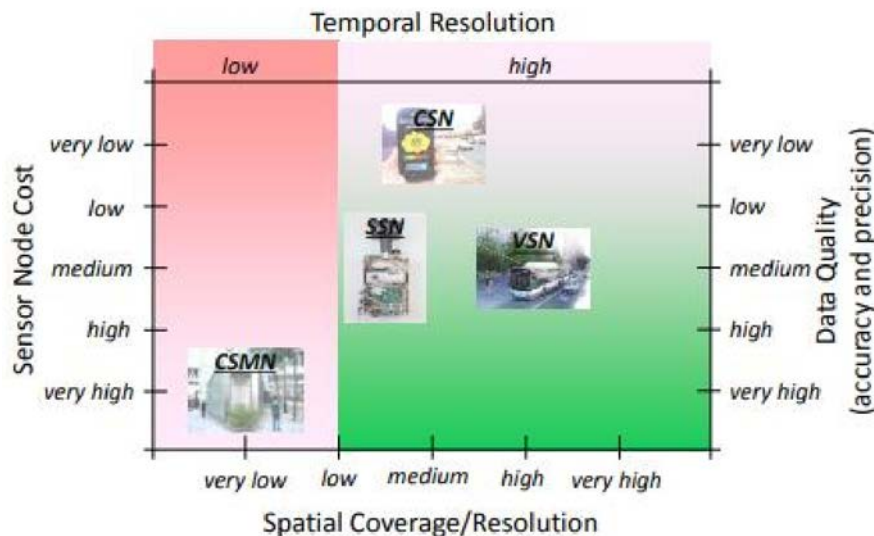


Figure 7. Trade-off between tolerable sensor node cost, obtainable measurement coverage/resolution, expected data quality and achievable measurement temporal resolution for Conventional Stationary Monitoring Network (CSMN), Static Sensor Network (SSN), Community Sensor Network (CSN) and Vehicle Sensor Network (VSN) [100].

Static Sensor Network (SSN)

- Sensor nodes are typically mounted on the streetlight or traffic light poles, or walls

Advantages:

- Loose constraint on energy consumption (The sensor nodes are typically powered by batteries with large capacity or energy harvest devices or power line.)
- No locating device (The location of a sensor node is known once it was deployed since the sensor node is stationary.)
- Loose limitations on weight and size (The carrier of the sensor node is able to carry sufficient enough weight.) 31409 Sensors 2015, 15, 3139231427
- Multiple sensors per node (One sensor node can equip with several types of sensors because of the loose limitations on weight and size.)
- Accurate and reliable data (Sensor node can integrate with assisting tools because of the loose limitations on weight and size.)



- Guaranteed network connectivity (Once the stationary sensor node joined the network, the topology is fixed and the connectivity is guaranteed.)
- Well calibrated and maintained sensors (The sensor nodes can be well calibrated and maintained by the professionals periodically.)

Disadvantages or Challenges:

- Careful placement of sensor nodes requirement (This is because of the location dependence of air pollutants.)
- Large number of sensor nodes requirement (Data with sufficient geographic coverage and spatial resolution are only achievable by increasing the number of the stationary sensor nodes.)
- Resource wasting in certain level (The stationary sensor nodes are in sleep mode most of the time because continuously updating data at one location is pointless[13].)
- Inconveniences of calibration and maintenance (The professionals need to visit all stationary sensor nodes, which is a time and manpower consuming task, to perform operations.)
- 2-Dimensional data acquisition (Only the air quality of urban surface is monitored.)
- Customized network requirement (A customized wireless or wired network is required when the cellular network is not utilized.)

Community Sensor Network (CSN)

Advantages:

- Cost efficiency (The sensor node utilizes the cellphone's GPS module and the cellular network, or even the cellphone's computational power.)
- Coupled data generators and consumers (Local or personal air pollution information is available.) 31411 Sensors 2015, 15, 3139231427
- Public-driven property (The cost of the sensor nodes and the data transmission can be apportioned by the users. It is costly and infeasible for a single agency to acquire all the sensor nodes.)
- Automatic gathering property (The sensor nodes are densely distributed at locations with gathering (?) people automatically. Data with higher spatial resolution and accuracy are achievable in such case.)
- Mobility of sensor nodes (The mobility of the cellphones or users enlarges the sensor node's geographic coverage.)
- Public behaviors acquisition ability (Information such as the public movement patterns, and interaction between air quality and public behaviors, is achievable.)

Disadvantages or Challenges:



- Low data accuracy and reliability (The sensor nodes are typically put in pockets or handbags. Also, the users spend significant amount of time indoor or inside cars [114]).
- Privacy issues (The users may not want to make their location information public for privacy issues).
- Badly calibrated and maintained sensors (Professional calibrations of sensors performed by the public users are very unlikely. Frequent collections and calibrations of sensors by the professionals are infeasible).
- Serious constraint on energy consumption (The sensor nodes is typically powered by cellphone's battery or battery with small capacity).
- Uncontrolled or semi-controlled mobility (The routes of the sensor nodes or users are pre-determined. The sensor nodes may squeeze into a small place with crowded people and cause redundant sampling. Some locations may never be visited).
- 2-Dimensional data acquisition (Only the air quality of urban surface is monitored).
- Serious limitations on weight and size (The sensor node should be portable, which affects the accuracy, reliability and number of sensors equipped, because it is carried by user).

Vehicle Sensor Network (VSN)

Advantages:

- Loose constraint on energy consumption (The sensor nodes are powered by the vehicles' batteries.)
- Loose limitations on weight and size (The carrier of the sensor node is able to carry sufficient enough weight.)
- Multiple sensors per node (One sensor node can equip with several types of sensors because of the loose limitations on weight and size.)
- Accurate and reliable data (Sensor node can integrate with assisting tools because of the loose limitations on weight and size.)
- High mobility of sensor nodes (The highly mobile vehicles significantly enlarge the sensor node's geographic coverage.)
- Feasibility in maintenance (The vehicles mounted with sensor nodes can be driven to a specific location. Professionals can perform maintenance on large amount of sensor nodes simultaneously.)
- Well calibrated and maintained sensors (This is because of the feasibility in maintenance of the VSN systems.)



- Automatic gathering property (The sensor nodes are densely distributed at locations with gathering public transportations automatically. Data with higher spatial resolution and accuracy are achievable in such case.)

Disadvantages or Challenges:

- Uncontrolled or semi-controlled mobility (The routes of the sensor nodes or public transportations are pre-determined. The sensor nodes may squeeze into a small place with crowded transportations and cause redundant sampling. Some locations may never be visited.)
- Redundant sampling issues (The vehicles may be trapped in traffic jams or parked in parking lots that cause redundant sampling. This issue compromises the spatial and temporal resolutions.)
- Cost inefficiency on carriers (The specially equipped cars may cost a huge amount of money.)
- Locating and communication devices requirement (The system requires GPS modules, and wireless modules or cellular modules.)
- Customized network requirement (A customized wireless network is required when the cellular network is not utilized. The network connectivity may not be guaranteed due to the mobility of vehicles.)
- 2-Dimensional data acquisition (Only the air quality of urban surface is monitored.)
- Spatial-to-Temporal resolution trade-off (Higher spatial coverage at the expense of lower temporal resolution [99].)

Ranking VSNs, CSNs, and SSNs

Mobility/Geographic-Coverage

Ranking: VSN > CSN > SSN

Reasons: The mobility of the carrier enables a sensor node to cover sufficiently large geographic areas within a short period of time. Higher spatial resolution of the sensed data can be achieved and fewer number of sensor nodes are required compared with systems using stationary carriers

. Temporal Resolution Ranking: SSN > VSN > CSN Reasons: One of the objectives of TNGAPMS is to increase the temporal resolution of the acquired air pollution information. And the air pollution information from all TNGAPMSs has much higher temporal resolution than that from the conventional monitoring systems. However, the temporal resolution of the acquired pollution information in SSN, CSN and VSN are slightly different due to several reasons.



Cost Efficiency

Ranking: CSN > VSN > SSN

Reasons: The air pollution situation in rapid industrializing countries is much more critical than that in industrialized countries [38]. Several pollution sources (over-polluting industry, poorly tuned diesel engines and burning of trash) in developing countries contribute to the air pollution much more significantly than that in developed countries [111]. Moreover, the governments in developing countries spend less fraction of their GDPs on environmental protection than developed countries [119]. In a word, the environmental protection agencies in developing countries are dealing with serious air pollution situation with little amount of money. Hence, the cost efficiency of the air pollution monitoring system becomes a non-negligible property for comparison.

Endurance

Ranking: SSN > VSN > CSN

Reasons: The endurance of the sensor nodes is a major property for comparison because it will further influence the Maintenance property and the Data Quality property. A sensor node with energy constraint (e.g., powered by a small capacity battery) requires replacing battery frequently, which increases the burden of maintenance. Moreover, the energy constraint of sensor nodes limits the use of conditioning appliances (e.g., temperature controllers, humidity controllers, gas pumps, etc.) that help improve the data quality.

Maintenance

Ranking: VSN > SSN > CSN

Reasons: In order to guarantee the data quality, maintenance on the sensor nodes like changing dead batteries, replacing malfunction components or calibrating sensors are indispensable. As a matter of fact, all TNGAPMSs require massive deployment of the sensor nodes and the sensors used in these systems need frequent calibration to be efficient [83]. We expect that, in real-life large-scale deployment, the maintenance on the sensor nodes will occupy the vast majority of efforts of the maintenance on the whole system. The feasibility of maintenance on the sensor nodes is critical in this case.

Data Quality

Ranking: SSN > VSN > CSN

Reasons: Good data quality is essential for developing TNGAPMSs. The data quality of the low-cost portable ambient sensors used in TNGAPMSs is poorer than that of the high-end instruments used in the conventional air pollution monitoring systems.



However, the low-cost portable ambient sensors still provide a fair enough accuracy and detection range [46], and flexibility in massive deployment.

Article: Performance Evaluation and Community Application of Low-Cost Sensors for Ozone and Nitrogen Dioxide (Duvall et.al, 2016)

CairClip Technologies

- CairClip O3/NO2 and the CairClip NO2 sensors (Figure 1), manufactured by Cairpol (Alès, France). The CairClip O3/NO2 sensor provides a sum of O3 and NO2 (herein referred to as O3 + NO2) whereas the CairClip NO2 sensor measures NO2 only. The CairClip sensors were selected based on good performance relative to FRM/FEM analyzers ($R^2 > 0.99$ and precision < 10 ppb)
- Low-cost instrument can help augment a scientific study by adding data, expanding spatial coverage of data, and involving communities in real science.

Article: Miniaturized Monitors for Assessment of Exposure to Air Pollutants: A Review (2017)

Disadvantage to fixed monitoring site: needs secure enclosures, power supplies, need for maintenance and continued power supply

- Then, miniaturized sensors devices are usually low cost (i.e., ~\$100–\$5000), easy to use and easily portable, and they can provide data with high spatial and temporal resolution [29,30] and real-time continuous measurement of air pollutants
- The results arising from mobile tests (the system was mounted on a **bicycle**) showed that measurements did not suffer significant variation compared to the measurements made with instruments used as fixed monitors.
 - Could be mounted on park vehicles or ATV/UTVs
- In conclusion, the authors asserted that measurements carried out with the use of a mobile sensor network are less accurate than reference instruments used at fixed locations by the Regional Environmental Agency. However, this kind of sensor has the potential to provide insight about air pollution and to complement data acquired from official and reference monitoring stations.
 - Could give hikers/pedestrians sensors to give back, citizen science
 - Would require and honor system to give back, or cost more money to have staff more accessible to hold visitors accountable/distribute
 - NPS could sign them out - not a huge concern
- In particular, the VOC sensor performance was validated using gas chromatography and selected ion flow tube mass spectrometry as reference



methods, showing accuracy higher than 81%. Moreover, a comparison conducted outdoors showed results with accuracy values higher than 84%, demonstrating the capability of the tested sensor to provide reliable measurements in outdoor environments

- WSNs can eliminate barriers related to installation, remove connectors and increase scalability.

Website: [Basic Information About Air Emissions Monitoring](#)

Ambient air quality monitoring:

- collects/ measures samples of ambient air pollutants to evaluate the status of the atmosphere as compared to clean air standards and historical information

Stationary source emissions monitoring

- collects and uses measurement data at individual stationary sources of emissions

Ambient Air Monitoring Program

- Collects national air quality data on criteria pollutants: Carbon Monoxide (CO), Oxides of Nitrogen (NO₂ and NO₃), Ozone (O₃), Lead (Pb), Particulate Matter (PM) - both particulates with aerodynamic diameters below 10 micrometers (PM-10) and particulates with aerodynamic diameters below 2.5 micrometers (PM-2.5), Sulfur Dioxide (SO₂), and Volatile Organic Compounds (VOC)

Purpose of stationary source emission monitoring:

- To provide data and information from a regulated stationary source to show compliance with regulations
- Performance information to the facility operator so that corrective action can be taken

3 types of continuous monitoring systems:

- CEMS continuously measure actual emissions levels from a stationary source
 - Ex: CO is an indicator of Volatile Organic Compounds (VOC) because low CO concentrations indicate complete combustion of VOC compounds)
- COMS continuously measure opacity (light attenuated by particulate matter in effluent emissions). Percentage of visible light attenuated by particulate matter in effluent emissions. Used in particulate matter emissions
- CPMS parametric monitoring that measures a parameter that is a key indicator of system performance

Presentation by EPA: [Air Quality Monitoring and Sensor Technologies](#)

- Value of continuous measures:



- Provides greater understanding of time and location changes of environmental conditions
 - Has the potential of defining episodic events that would not be discovered otherwise
- A typical regulatory monitor:
 - Produces data of known value and highly reliable
 - Stationary- cannot be easily relocated
 - Instruments are often large and require a building to support their operation
 - Expensive to purchase and operate (typically > \$20K each)
 - Requires frequent visits by highly trained staff to check on their operation
 - Often operate for 10+ years before needing to be replaced
- A typical low-cost monitor
 - Inexpensive (\$100 to \$5000) to purchase
 - Highly portable and easy to operate (often mobile)
 - Requires little or no training to start collecting data
 - Inexpensive to operate (replace or recharge batteries)
 - Lifetime of service not expected to exceed 1-2 years
- Metal Oxide (MOS)
 - The most widely available of all sensor types
 - Inexpensive (\$15-\$300)
 - Available in a wide array of pollutants
 - Often not specific to any one pollutant
 - Co-factors often influence their output
 - Response relational to some given parameter
- Light scattering sensors dominate market
 - Cost varies (\$50-6000)
 - Sensitive to RH and stray light
 - Size definition varies widely
 - Unit output definition varies widely
 - Aerosol composition influences response •Not true mass measurement

Quality Assurance Parameters



- **Bias** - is it routinely high or low with respect to the true value
- **Precision** - how repeatable is the measurement
- **Calibration** - does it respond in a systematic fashion as conc. changes
- **Detection limit** - how low and high will it measure successfully
- **Response time** - how fast does the response vary with conc. change
- **Linearity of sensor response** - what is the linear or multilinear range
- **Measurement duration** - how much data do you need to collect
- **Measurement frequency** - how many collection periods are needed
- **Data aggregation** - value in aggregating data (1 sec, 1 min, 1 hr, etc)
- **Selectivity/specificity** - does it respond to anything else
- **Interferences** - how does heat, cold, effect response
- **Sensor poisoning and expiration** - how long will the sensor be useful
- **Concentration range** - will the device cover expected highs and lows
- **Drift** - how stable is the response
- **Accuracy of timestamp** - what response output relates to the event
- **Climate susceptibility** - does RH, temp, direct sun, etc impact data
- **Data completeness** - what is the uptime of the sensor
- **Response to loss of power** - what happens when it shuts down

Factors to Consider

- Weather. Many devices are temperature and/or relative humidity (RH) sensitive
- Most sensors are not weather protected
- Battery life. Wide range in operational ranges exist
- Orientation. Some devices require a very specific orientation
- Data storage/transmission. WiFi, data card, cellular, tablet, PC. Lots of variants and often problematic
- Lack of sensitivity. Failure to measure at ambient levels
- Interferences. Gas sensors often respond to “other” pollutants



- Define the pollutant or exposure variable(s) of interest
 - What is the hypothesis that needs to be tested?
 - Are continuous measurements truly needed? Are simple time integrated options (e.g., y/n) as valuable?
 - What parameters need to be co-measured to facilitate the testing?
 - Do they all lend themselves to continuous monitoring or only some of them? Does it matter?
 - What analytical methods are available to collect the raw data?
- Are these methods readily available?
 - Are they within your financial budget and timeline relative to acquisition (number of sensors)? Would you need to make the devices “field worthy”?
 - Based on relevant statistical tests, what population size of data need be collected? What assumptions are you having to make to develop those statistical tests?
 - Can you successfully execute a study design once you have defined the data size population (with respect to study resources)?
- What do you need to do to “validate” or prepare the continuous monitor before its use? Is this feasible with your resources and expertise. Are there others who could do this for you if you lack the expertise?
 - Do you have software that will reduce the labor of recovering big data for the purpose at hand? If not, can you handle the labor to more laboriously recover/organize/validate data?
 - Data validation is paramount to your success. Will you be able to use collocation or other QA schemes to ensure data is and peer acceptable?



- What is the shortest duration of measurement that is feasible, reasonable, and logical with respect to the study design and hypothesis. Do you collect “it all” and then decide if aggregation is profitable as part of your post-processing effort?
- How do you plan to handle monitor refurbishment, calibration, repair and upkeep as part of the day to day operation of the equipment? Are there any “off days” where such work can occur with no impact on the data collection schedule?

Source: [Ministry For the Environment](#)

Things to consider while looking at air quality monitoring systems

- **Purpose of monitoring:** ie, screening, compliance monitoring or research. Different sensitivities may apply to different types of monitors. For example, compliance monitoring may require a higher level of sensitivity and resolution than a monitor used for screening purposes.
- **Duration of deployment:** if the instrument is to be used for short-term screening surveys then portability, size, weight and robustness may be factors to consider.
- **Detection limit, precision and measurement range:** will the instrument be able to measure within the required range, based on the monitoring objective?
- **Consumables:** how frequently do parts need to be changed or replaced?
- **Ability to conform to relevant monitoring standards:** does the instrument conform to monitoring standards such as those required in the NES for air quality?
- **Frequency of calibration:** the time taken to complete automatic zero and span checks, and operational and multipoint calibrations. Instruments that spend significant time on an automatic zero and span checks will reduce your percentage data recovery. An instrument that requires frequent calibration in order to comply with a particular standard will impose costs on an organization (time and resources).
- **Ease of use:** some instruments can be extremely difficult to operate, which imposes costs in terms of training and person-hours spent resolving problems.
- **Communication:** ideally instruments should have ethernet/IP ports, analogue and RS232 connectivity to allow connection to dataloggers and telemetry.
- **Ability to interface remotely:** most modern instruments will allow an operator to remotely operate an instrument.



- **Environmental requirements:** does the instrument require air conditioning, temperature or humidity control?
- **Cost:** consider both the cost of the instrument and the cost of consumables.
- **Reliability:** find out who else has operated similar instruments and discuss the pros and cons with other organizations before committing to a purchase.
- **Memory or on-board storage capacity:** determine if memory capacity is sufficient for your current and future needs (eg, memory expansion features).
- **Instrument parameters that may be recorded in addition to output concentration:** can the instrument record any other parameters (eg, temperature)?

Review Article: Atmospheric Pollution Research (APR) Urban air quality management (Gulia et al. 2015)

A study on the effectiveness of selected sensors

- Low-cost sensor devices, defined here as below USD 2000 per pollutant (i.e., under USD 4000 for a two-pollutant device), typically utilize electrochemical or metal oxide sensors for gas-phase pollutants such as carbon monoxide (CO), nitrogen dioxide (NO₂), nitrogen oxide (NO), ozone (O₃), and, to some extent, total volatile organic compounds (VOCs). Commercially available particle sensor devices currently use laser-based or light-emitting diode (LED)-based optical detection of particles.
- The SAFT sensor set included five types of PM sensors (Shinyei, Dylos, Airbeam, MetOne, and Air Quality Egg), three types of ozone sensors, three types of NO₂ sensors, two types of CO sensors, and one SO₂ sensor (Table 1)



Sensor/manufacturer	Measured pollutants/internal sensor (units)	Mechanism	N
PMS-SYS-1/Shinyei (Japan)	PM _{2.5} (μg m ⁻³)	Light scattering	2
Dylos Particle Counter (DC1100-PRO-PC)/Dylos Corporation (Riverside, CA, USA)	Particle ≥ 0.5 μm (pt 0.01 cf ⁻¹) ^a	Light scattering	2
Dylos Particle Counter, DC1100-PC/Dylos Corporation (Riverside, CA, USA)	Particle ≥ 1 μm (pt 0.01 cf ⁻¹) ^a	Light Scattering	1
Airbeam/HabitatMap (Brooklyn, NY, USA)	PM _{2.5} /Shinyei PPD60PV (hpcf)	Light scattering	3
Aercet 831/MetOne (Grants Pass, OR, USA)	PM _{2.5} (μg m ⁻³) ^a	Light scattering	3
SM50/Aeroqual (New Zealand)	O ₃ (ppm)	Gas-sensitive semiconductor (GSS)	2
Cairclip/Cairpol (France)	NO ₂ and O ₃ combined (ppb)	Electrochemical	2
Air Quality Egg/Wicked Device (Ithaca, NY, USA)	NO ₂ /e2v MiCS-2710, CO/e2v MiCS-5525, VOC/e2v MiCS-5521, PM/Shinyei PPD42 (pt 283 mL ⁻¹)	Metal oxide sensors for gases, light scattering for PM	3
AQMesh (Gen. 3)/AQMesh Corp. (UK)	NO, NO ₂ , CO, SO ₂ , O ₃ (all in ppb)	Electrochemical	2

^a Note that the Dylos and the MetOne also include additional size channels in their data output. The Dylos DC1100-PRO-PC and DC1100-PC include particle size channel representing particles ≥ 2.5 μm and ≥ 5 μm, respectively. The MetOne sensor includes size channels for PM₁, PM₄, PM₁₀, and TSP.

- Like the remote nodes, the base station had an Arduino microcontroller and Xbee radio to receive signals from the nodes and an SD card for on-board data logging. The base node included a Sierra Airlink® GX440 cellular gateway and associated antenna to connect the base node to the internet. Data were uploaded and stored on a remote server in a Microsoft SQL database and displayed on private web page that updated every minute. The web page displayed the data in a tabular format and supported direct data downloading. The communication base station and the sensor node 4 collocated at the NCore site used 120 V (nominal) AC electricity, while the remaining satellite stations (nodes 1–3) operated on solar power with battery backup
- ***Preliminary review after WSN deployment revealed brief spurious PM readings (e.g., 10 to 50 times higher than FEM) that occurred during midday, which appeared to be caused by side-scattered sunlight intrusion to the Shinyei sensor. As an experimental measure, aluminum foil was placed surrounding the radiation shielding that encompassed the sensor to reduce light penetration, while still allowing the sensor to have access to ambient air. After



foil was applied, very high values were greatly reduced (Fig. S4 in the Supplement); therefore, the foil covers were left in place for the remainder of the WSN data collection.

Results

- **PM** For three selected sensors that showed the highest correlation with FEM among identical sensors – the Shinyei SAFT-2, Dylos SAFT-2, and Airbeam SAFT-2 – incorporation of artifacts such as temperature, RH, and number of measurement days made some minor improvements in agreement with the FEM as indicated by R^2 adj values from the multiple linear regression analysis (Table 5).
- **Gas Phase** Gas-phase sensor measurements of O₃, NO₂, NO, CO, and SO₂ were compared with hourly average NCore reference monitors (Table 4)
- **Ozone** weak correlation was evident for two AQMesh units ($r = 0.39$ – 0.45), high for two Cairclip sensors ($r = 0.82$ – 0.94), and consistently very high for three Aeroqual SM50 sensors ($r = 0.91$ – 0.97) when compared to FRM/FEM measurements (Fig. S2). For the Aeroqual SM50 sensor, no apparent improvement in agreement was observed when temperature, RH, or sampling day length factors were incorporated (Table 5). However, incorporating RH appeared to provide some improvement ($+0.07$ in R^2 adj) to the Cairclip sensor agreement with a reference monitor.
- **Nitrogen dioxide** Only one Cairclip NO₂ sensor that had sufficient correlation was further explored for artifact correction. Significant improvement was evident when temperature and RH were incorporated as adjustment factors, with very slight additional improvement by incorporating days of use (Table 5). **Nitrogen oxide** One sensor device – the AQMesh – was tested that reported NO measurements. The two identical AQMesh units had high correlation with the reference monitor ($r = 0.88$ – 0.93). No apparent improvement in agreement was determined when incorporating environmental or days of use as adjustment factors (Table 5). In absolute terms, the NO original sensor output also agreed closely with mean FEM values (Table 4).
- **Carbon monoxide** Good correlation ($r = 0.79$ – 0.82) was observed between the AQMesh and a reference monitor
- **Sulfur dioxide** Only one sensor device was available that measured SO₂ – the AQMesh. The reported SO₂ values by the AQMesh were generally far higher than the reference monitor, on average a factor of 172 and 163 higher. While the two AQMesh units had high correlation



with one another for SO₂ ($r = 0.94$), they had weak correlation ($r = 0.13$ – 0.17) with the reference monitor.

Conclusion:

- Widely variable sensor performance under real-world conditions. Some sensors were observed to have very strong agreement with FEMs over an extended period of time (e.g., SM50 O₃ sensor). Application of select sensors in a local wireless sensor network revealed useable ~ 8-month data sets for both ozone and particulate matter. ZigBee-based network communications were feasible over short ranges (e.g.,

Source: [Air Quality Sensor Performance Evaluation Center \(AQ-SPEC\), 2015 PEMS Conference](#)

Traditional Air Monitoring

- Permanent, large, fixed
- Address NAAQS
- Comply with CFR specs
- Sophisticated and highly accurate
- Limited spatial resolution

Community-based Air Monitoring

- Started based on local concerns and issues
- Often source-specific
- Non-regulatory
- Technologies deployed
- Enlist help of residents
- Risk communication

Monitoring by Community Groups/others

- Current efforts in South Coast
- Tech used: portable monitors, “low-cost” air quality sensors
 - Uncertain data quality
 - Not up to Federal Reference Method (FRM) and Federal Equivalent Method (FEM) instruments to assess compliance of air pollution monitoring advances
- Low cost sensor technology
 - Air monitoring sensor information already available on the web
- Air Quality Sensor Performance Evaluation Center: <http://www.aqmd.gov/aq-spec>
 - Field testing + Lab testing → results to categorize sensors based on performance

Source: [US Code of Federal Regulations, Title 40, Part 50](#): (40CFR § 50.1)



Reference Method means a method of sampling and analyzing the ambient air for an air pollutant that is specified as a reference method in an appendix to this part, or a method that has been designated as a reference method in accordance with part 53 of this chapter; it does not include a method for which a reference method designation has been cancelled in accordance with §53.11 or §53.16 of this chapter.

- Equivalent Method means a method of sampling and analyzing the ambient air for an air pollutant that has been designated as an equivalent method in accordance with part 53 of this chapter; it does not include a method for which an equivalent method designation has been cancelled in accordance with §53.11 or §53.16 of this chapter.
- The EPA has defined reference methods “FRM” for the measurement of various criteria pollutants, such as carbon monoxide, ozone, nitrogen dioxide, PM₁₀ and PM_{2.5}. These methods are described in great detail in the various appendices in 40CFR §50. For PM₁₀ and PM_{2.5}, the reference methods are both based upon manual sampling techniques where a pre-weighed filter is installed into a sampling device, ambient air is sampled for 24 hours, the filter is retrieved, equilibrated and then reweighed in order to produce the result. Only the measurement techniques defined in the various appendices in 40CFR §50 can be reference methods.

Low Cost Sensor Technology

Potential concerns

- Rapid proliferation
- Data quality not on par with that of FRM and FEM instruments
- Potential “overload” in the amount of non-agency air monitoring data
- Technical Issues
 - Calibration, accuracy, interferences, time averaging, longevity, expertise of user
- Data interpretation
 - Which pollutant?
 - What levels?
 - False positives: unwarranted alarm
 - False negatives: false sense of security
- Confusion

Opportunities

- Low cost
- Relatively small size
- Ease of operation
- Broader community participation and awareness
- Wider spatial and temporal distribution
 - More refined control strategy
 - Early warning/community alert system
- Data available on web, smart-phones, etc.



Recommendations from Dr. Dickerson

- Recommendations from Dickerson: start with a few sensors at the sites where reliable sensors are already located to evaluate and throw out ones that do not work. Then deploy in clusters of 3-5 identical sensors. Use a linux computer such as the BeagleBone to upload data.

Article Source: Evaluating the performance of low cost chemical sensors for air pollution research (Lewis et. al, 2016)

General Point:

- Low cost sensors offer increased information on the distribution of air pollution and wide-reaching availability of measurements to amateur users.
- Tested over a period of three weeks, 20 identical commercial sensor packages alongside standard measurements, and report on the degree of agreement.

Introduction

- Long-term atmospheric monitoring of NO_x, O₃, SO₂, CO, VOCs and Particulate matter (PM) have typically been investigated to support air quality compliance and national frameworks for pollution control
- The most common observational strategy for urban atmospheric chemistry is the use of high accuracy air pollution measurements at a small number of representative locations , using modeling to interpolate the values at unmonitored locations
- The adoption of low-cost air quality sensors is gaining traction and could allow the democratization of air quality measurements to the general public making measurements more common than meteorological stations
- This paper refers to low-cost devices that make autonomous observations of multiple pollutant parameters at a cost range of 100-1000 USD per location
- Classical air pollutant measuring instruments are first tested by a few early adopters, and then next users receive the advantage of using that technology first because they read about it in scientific papers, and the widespread use depends on if that method meets requirements for legal compliance or regulatory emission requirements
- Conversely, sensors were originally made for different purposes; combustions/occupational health measurement, and used for ambient measuring afterwards

Paper has three goals:



- 1: report a detailed laboratory analytical study of common sensor sensitivities and comprehensive analysis of cross interferences to other atmospheric constituents including other air pollutants and variable species like CO₂, H₂, and H₂O.
- 2: report on initial performance of commercial low-cost air pollution sensing systems when compared alongside more traditional measurement technologies
- 3: describe how VOC sensors can perform well and the interferences stopping them from succeeding.

Results and Discussion

- There is potential for sensor measurement techniques to suffer from interference
 - Water vapor, temperature, and co-pollutants can affect sensor performance
- 5 commercially available sensors from Alphasense to measure CO, O₃, NO, NO₂, and SO₄
 - Aim to establish selectivity of sensors to target compounds
 - Evaluate the impact of co-pollutants on measurements
- **Chemical Interference of Co-pollutants**

Sensor	Compound							
	CO	SO ₂	NO	O ₃	NO ₂	CO ₂	H ₂	%RH
CO-B4	0.378	-0.013	0.000	0.0200	0.032	0.000	-0.032	0.201
OX-B421	0.000	-0.016	-0.110	0.439	0.44	9.5×10^{-5}		0.560
SO ₂ -B4	0.013	0.210	0.023	-0.014	-0.32	9.8×10^{-6}		0.000
NO-B4	0	0.007	0.558	-0.011	-0.590	1.8×10^{-5}		-0.303
NO ₂ -B4	0	0.004	-0.008	0	0.148	2.3×10^{-5}		0.000

- **Interference from ambient air**
 - Roadside measurements of CO₂ was overwhelmed by NO₂ gas, this effect reduced as one went further from the road
- **Multisensor Package**
 - 20 identical sensor units with O₃, NO, NO₂, VOC and PM measuring capability
 - ANONYMISED commercial supplier of the devices
 - Sensors were deployed for 3 weeks without being calibrated again
 - **O₃**: 70% of observations fall within 5 ppb and 95% of observations fall within 10 ppb of the reference values
 - **NO**: in general “good” temporal agreement against reference measurement with R² value: 0.72 ± 0.21
 - **NO₂**: Poor, with R² of 0.25 ± 0.13, indicating sensor was measuring more than just NO₂. However, 25th-75th percentile range were small between sensors, indicating that they are consistent.



- **PM:** Generally good statistical agreement between individual sensor measurements but with significant spread. Had an uncertainty of $\sim 20 \mu\text{g m}^{-3}$, which is considerable for current regulatory limits. Statistical agreement between reference and PM was modest ($R^2 = 0.35$)
- **Volatile Organic Compounds (VOCs):** metal oxide sensing approach. Poor agreement between reference and sensor- sensors overestimated pollutants
- **New strategies for VOC sensors**
 - Photo Ionisation Detectors (PIDS)
 - Using combination of statistical models and comprehensive data sets using both laboratory and real world experimental data meaningful information can be retrieved from complex sensor signals

Conclusion

- Ozone, good agreement was found between reference measurements once calibration were linked to the in situ reference observation
- NO and PM, general trends in atmospheric pollution were recreated by the sensors
- NO₂ did not track reference NO₂ (could be responding to different air pollution metrics)
- Work in progress

Article Source: Evaluation and enhancement of a low-cost NDIR CO₂ sensor (Martin et. al 2017)

Evaluation and enhancement of a low-cost NDIR CO₂ sensor

- Non-Dispersive Infrared (NDIR) are low-cost way to observe carbon dioxide concentrations in the air
- SenseAir K30 showed promising estimates compared to reference CO₂
 - \$100-200 per sensor
 - Chosen because it has the highest manufacturer's specified accuracy
 - To correct for external factors, Successive regression measures and Multivariate linear regression method
 - If sensors are individually calibrated, selected for stability, and corrected for sensitivity to temperature, pressure and humidity they can achieve about 1% of the observed value

Source: Low-cost sensors for the measurement of atmospheric composition: Overview of topic and future applications [Scholarly project]. In World Meteorological Organization. (Lewis et. al, n.d)



Sensor: the basic sub-component technology that actually makes the analytical measurement of a greenhouse gas or an air pollutant. The presence of a relevant gas or particle is typically converted into an electrical signal where the relative magnitude of that signal is related to the atmospheric concentration. Examples include low-cost sensors for temperature and pressure, capacitive sensors, electrochemical sensors, metal oxide sensors, or self-contained optical sensors including ultra-violet (UV) or nondispersive infrared sensor (NDIR) absorption cells or optical light scattering sensors. A range of sensor examples are illustrated by Figure 1.



understanding of the types or limitations of many of these sensor types.

Sensor type	Pollutant	Known issue (effect) with sensors
Electrochemical	Ozone (O ₃)	Relative humidity Temperature Cross-sensitivity of oxidizing gases (e.g. NO ₂ , H ₂ S, Cl ₂) Long term stability (ageing or drift)
	Nitrogen Dioxide (NO ₂)	Relative humidity Temperature Cross-sensitivity of oxidizing gases (e.g. O ₃ , H ₂ S, Cl ₂) Long term stability (ageing or drift)
	Sulfur Dioxide (SO ₂)	Relative humidity Temperature Cross-sensitivity of reducing gases (e.g. NO ₂ , H ₂ S) Long term stability (ageing or drift)
	Carbon monoxide (CO)	Relative humidity Temperature Cross-sensitivity of reducing gases (e.g. H ₂ S, SO ₂ , CH ₄ , Alcohols, NH ₃ [MG1] , etc.) Long term stability (ageing or drift)
Metal oxide	Ozone (O ₃)	Response time > 5 min Sensor response is not linear Relative humidity Temperature Long term stability (drift) Varying baseline after re-start
	Nitrogen Dioxide (NO ₂)	Response time > 5 min Sensor response is generally not linear Relative humidity Temperature Short and long-term stability(drift) Varying baseline after re-start
	Sulfur Dioxide (SO ₂)	Relative humidity Temperature Cross-sensitivity of reducing gases (e.g. H ₂ S)

Source: Evaluation of Low-Cost Air Quality Sensors [Scholarly project] (Polidori et. al, 2017)

- Federal Reference Method (FRM): A FRM is an "EPA approved" method, sampler or analyzer that utilizes the measurement principles and calibration procedures specified in the Code of Federal Regulations (40 CFR Part 50). Federal Equivalent Method (FEM): A



FEM is an ambient air monitoring method that has been designated by EPA as an equivalent method under 40 CFR Part 53. To be considered as a viable FRM/FEM candidate, a potential measurement technique must:

- Provide accurate and reliable measurements
- Be relatively free of significant interference from gases or other agents that may occur in ambient air
- Provide continuous or nearly continuous measurements in near real-time
- Be commercially available at modest or reasonable cost
- Be reasonably easy and convenient to operate by typical air monitoring personnel to produce measurements of good accuracy and precision
- Be reasonably and routinely field-deployable for use as a quality assurance reference in monitoring networks

Article: The Changing Paradigm of Air Pollution Monitoring (Snyder et. al, 2013)

General Idea: However, challenges remain regarding the use of sensors and sensor data, chiefly sensor data quality and derivation of meaningful information from data sets.

- (1) the sensor element that responds to the species of interest and varies with the pollutant mass in a given volume of sampled air
- (2) the transducer that converts the responses to electrical signals
- (3) data storage capability or a link to a communication device (e.g., microradio transmitter or cell phone)
- (4) a source of power (e.g., battery or energy harvesting).

Article: Integrating Sensor Monitoring Technology into the Current Air Pollution Regulatory Support Paradigm: Practical Considerations (Hall et. al, 2014)

Table 1. Summary: Sensor Types and Characteristics

Sensor Type	Pollutants Measured (criteria)	Range	Interferences [IF]	Setup
Electro-chemical	CO, SO ₂ , NH ₃ , H ₂ S	1 ppb to 10-1200 ppm	SO ₂ [IF]: Cl, CO, H ₂ O _(g) , C ₃ H ₈ , C ₄ H ₈ , C ₇ H ₈	fixed/hand-held/portable
Metal oxide	Non-CH ₄ hydro-carbons (NHMC), C ₆ H ₆ , CH ₄ , total VOCs, NH ₃ , CO, NO ₂ , SO ₂ , NO _x	0.1 to 25-100 ppm (1 ppb?: NO ₂ , CH ₄ , C ₆ H ₆)	CO [IF]: H ₂ O _(g) , CO ₂ , H ₂	fixed/hand-held/portable
Spectroscopic	NO (chemi-luminescence [CL]), CH ₄ , VOCs (non-dispersive infrared: NDIR)	9 ppb (CL) or 1-100% (NDIR)	NO [IF]: H ₂ S, CO ₂ , O ₃ , H ₂ O, NO ₂ , SO ₂ , NH ₃	fixed/hand-held
Particle	PM to 0.5 micron particle size: light scattering (> 0.16 µg/m ³ : Light absorption measurement [density])	0.1 to 0.5 microns (scattering) > 0.16 µg/m ³ (absorption)	N/A	Hand-held



- Sensors developed for measurement of PM_{2.5} would be tested, analyzed, and characterized by their developers under Class III test procedures.
- Sensors measuring PM_{2.5} being tested under Class III test procedures would need to implement the following testing protocol:
 - a) 2 test campaigns during two different seasons (summer and winter) at a single test location (site 1 – Los Angeles Basin or Central Valley in California)
 - b) An additional winter test campaign at two different sites (site 2 – western US city [e.g., Las Vegas or Phoenix], and site 3 – midwestern city)
 - c) An additional summer test campaign at a single site (site 4 – large city east of the Mississippi River). The selection of these sites includes consideration of: i) PM_{2.5} nitrates, semi-volatile organic pollutants (site 1); ii) windblown dust (site 2); iii) high temperature variation, high nitrates, winter conditions (site 3), and; iv) high sulfate concentrations, and high humidity levels (site 4).

Factors encouraging use of this next generation of air pollution monitoring technology include:

- smaller size
- portability
- ability to communicate with different networks (e.g., wireless, Bluetooth, TCP/IP, Ethernet, etc.) – need standard communication protocol
- significantly lower cost than regulatory monitors/analyzers/samplers
- greater spatial coverage since expensive infrastructure is not required
- generating real-time data that can be linked with human activity and location information for exposure assessment
- potential use in tracking vehicle (fleet) emissions.

Article: Can commercial low-cost sensor platforms contribute to air quality monitoring and exposure estimates (Castell et. al, 2017)

- Commercially available gas sensors operate by measuring either the electrochemical interaction between the sensing material and the pollutant (i.e., electrochemical or metal oxide technologies) or the absorption of light at the visible range (Alexandre and Gerboles, 2012). Particulate matter is measured by light scattering or absorption, using algorithms to relate the attenuated signal to the particle size and/or composition.
- These individual sensors need to be integrated into a sensor platform or node. The sensor node contains a sensor board, the sensors, and a control board that integrates all the required electronics (e.g., signal conditioning, GPS, communication ports, data storage). The number and type of commercially available sensor platforms is increasing at a rapid



pace. Whereas the price of individual gas sensors ranges from €20 to €100, the cost of a commercial sensor node that includes several sensors can reach €500–€5000.

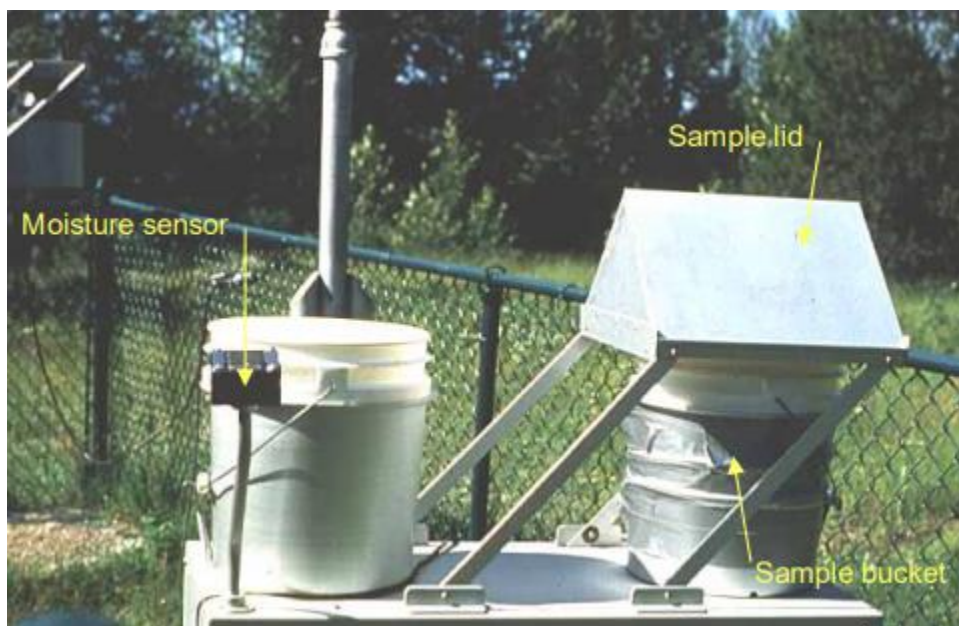
How can we assess the input of acid rain with a sensor?

Source: Natural Condition Report: Wet Deposition Monitoring Protocol Monitoring Atmospheric Pollutants in Wet Deposition , 2005

NADP uses a standard precipitation collector at all its sites. Either line power or solar power is needed to operate the collector. An electronic moisture sensor causes the lid to retract from the sample bucket, allowing a precipitation sample to be collected. Every week on Tuesday mornings, operators all over the country retrieve the samples, weigh them, transfer the sample to a shipping bottle and send it to the NADP Central Analytical Laboratory in Champaign, Illinois. Each site is also equipped with a raingage to record precipitation amounts. Moisture sensor Sample bucket Sample lid Figure 2-1. NADP/NTN Sampler Wet Deposition Monitoring 12 Protocol for the National Park Service, August 2005 7 Wet Deposition Monitoring Protocol for the National Park Service, August 2005 8 Information on NADP/NTN is at <http://nadp.sws.uiuc.edu>. This web site contains a monitoring site selection and installation manual, a site operation manual, and quality management and quality assurance plans. Site data are also available on the web site, including annual, seasonal, monthly, and weekly data, and trend plots. NADP/NTN ensures the collection of high quality data at its monitoring sites. The network: 1) designates specific precipitation collection equipment to be used throughout the network which allows precipitation to be recorded, collected, and verified; 2) requires this equipment to be maintained in good working order at the original approved location; 3) specifies a strict weekly sampling protocol and a clear definition of sample types; 4) requires every sample to be analyzed at a single laboratory, the Central Analytical Laboratory operated by the Illinois State Water Survey, Champaign, Illinois; and 5) expects each site to operate continuously for a 5-10 year period. The NTN (NADP) Site Selection and Installation Manual (<http://nadp.sws.uiuc.edu/lib/manuals/siteinst.pdf>) contains information on sampling strategy, and site selection, installation, and testing. Siting criteria include regional, local, and on-site requirements for the raingage and precipitation collector. It lists requirements for the sponsoring agency (e.g., NPS) and the site operator (e.g., NPS employee or contractor), who is responsible for the monitoring equipment, site maintenance, and sample collection. The manual also discusses power requirements and facilities and equipment for measurements of field pH and conductivity. Measurements of field pH and conductivity are no longer required, as of January 2005. Lastly, the manual discusses site installation and testing. 2.2 FIELD METHODS



In general, every Tuesday morning at 0900 local time the site operator changes the sample collection bucket, checks the raingage and replaces the rainfall recording chart, completes a field observer report form, weighs and packages the sample, and mails the sample to the NADP Central Analytical Laboratory. These procedures take approximately 30-60 minutes, which does not include travel time to the site. The NTN (NADP) Site Operation Manual (<http://nadp.sws.uiuc.edu/lib/manuals/opman.pdf>) discusses the site operating procedure, site maintenance, quality assurance procedures, and equipment troubleshooting. It also describes in detail the responsibilities of the site operator and the site supervisor.



Possibility for measuring wet nitrogen and sulfur deposition

Source: (<https://www.nps.gov/articles/lichens-as-bioindicators.htm>)



Questions a Park Leader may ask?

- **How many monitors?**
 - Depends on the study
 - Depends on number of pollutants
 - Ex: monitoring
- **What type of monitor?**
 - Depends on goal
 - EPA's Near Road Monitoring Guidance says, "The air pollutants measured should be chosen based on emission characteristics of motor vehicles as well as potential public health concerns."
 - "In addition to these local wind flow and turbulence measurements, data on other parameters, such as temperature and relative humidity, will still be important since these parameters affect the generation, transformation, and transport of pollutants emitted by motor vehicles"
 - In addition to health concerns from CO exposures, CO may be a useful indicator of the transport and dispersion of inert, primary combustion emissions from traffic sources since CO does not react in the near-road environment.
 - Motor vehicles also significantly contribute to ambient NO_x emissions in most countries. Although all motor vehicles emit NO_x, the majority of on-road emissions occur from diesel vehicles. For primary emissions, the majority of NO_x exhaust is in the form of nitrogen oxide (NO). Nitrogen dioxide (NO₂), which is the compound of concern for adverse health effects, quickly forms by photochemical reaction in the ambient air in the presence of NO and Ozone.
 - **SO₂:** Although motor vehicles emit SO₂ and other sulfur containing compounds, traffic sources typically have small contributions to ambient concentrations. In addition, the introduction of low-sulfur fuels in the United States and other countries to allow for the use of after-treatment devices in diesel vehicles should



further reduce SO₂ emissions. Therefore, this pollutant is not commonly monitored in near-road applications.

- However, SO₂ monitoring may be useful to measure near other types of transportation facilities such as airports, railyards, and seaports where sources may still burn high sulfur fuels
- **O₃** measurements are not typically collected for near-road applications since it is not directly-emitted from motor vehicles. However, the presence of elevated NO concentrations in the near-road microenvironment may lead to lower concentrations due to “ozone scavenging” as part of the formation of NO₂ from NO and O₃. Thus O₃ measurements may be useful in select circumstances to support health studies investigating the role of ozone and other co-pollutants on adverse health effects given the potentially lower concentrations of this pollutant relative to other pollutants in this microenvironment.
- **PM**: In general, PM emitted by combustion will be in the PM_{2.5} size fraction, although PM emitted through mechanical processes (brake wear, tire wear, resuspended road dust) will tend to be in the PM₁₀ size fraction and can lead to elevated mass concentrations.
- **How involved would setup/upkeep be?**
 - Costs of setting up fixed monitoring systems using traditional technologies are about \$6,000-80,000 with significant resources for maintenance and calibration
 - Operations of fixed monitoring sites are dependent on need for significant infrastructure like secure enclosures, mains power
 - Impractical and prohibitively expensive
 - Strict routines of maintenance and calibration of instruments
- **Power Supply?**
 - Some have longer battery usage times, like AQ Mesh
 - Others have short battery usage times like Dylos, where it has up to 6 hours of continuous use, with an alternate power supply
 - Depends on length of experiment
 - Longer length: battery or solar panel
 - Shorter length: handheld or battery with short deployment/recollection period
 - Deployed close to power supply (eg: park visitor center or urban/urban wooded park)
- **Data Accessibility and Manipulation**
 - Post-data collection temperature-correction methodology described in (https://www.repository.cam.ac.uk/bitstream/handle/1810/261726/Popoola_et_al-2016-Atmospheric_Environment-VoR.pdf?sequence=1&isAllowed=y),



electrochemical sensors may be used to provide quantitative measurements at the parts per billion volume mixing ratio level typical of ambient conditions in the urban environment

- Depends on scale: larger more expensive and involved study may deploy a more expensive sensor system, like AQ Mesh which has an integrated GPRS modem that allows data transfer to the AQMesh database server, which can be downloaded from a dedicated website. OR, a smaller sensor like the Alphasense sensor may be used, where the data is stored on an SD card and must be retrieved after a certain period of time
 - Deployed in more accessible places if data cannot be accessed remotely with capability for large amounts of internal storage
 - Consider devices Wi-fi capabilities?
 - If using different sensors, data handlers may have to be trained on how to use multiple data platforms in order to synthesize study data
- **How often should these pollutants be monitored?**
 - Depends on pollutant
 - Ex: PM: Diurnal variations in traffic and meteorology can have a tremendous impact on near-road air quality that may not be identifiable in 24-hour average measurements. Thus, continuous PM measurements provide useful information for near-road applications;
 - Does it interact with other pollutants? (eg. ozone and NO, so it may be more useful to measure immediately, closer to direct source)
 - Meteorological effects: temperature, humidity, and seasonal effects on pollutants, so repeated measures may be useful
 - Multiple times a day for a couple weeks
 - **Participants**
 - **Multidimensional investigation:** multiple fixed monitoring systems that require constant long-term upkeep and training
 - **Short-term simple single/multi pollutant monitoring system:** shorter time investment in consolidated bursts. Less training required
 - Someone designated to analyze data and calibrate
 - **Other things to consider in roadway measurements**
 - The effects of different roadway designs on pollutants
 - Road grades, ramps, intersections, and traffic merge locations can all impact the type and amount of vehicle emissions. Road grades create an



increased load on vehicles ascending the grade, leading to increased exhaust emissions and potential tire wear, while vehicles descending the grade likely experience increased brake emissions. The presence of ramps, intersections, and lane merge locations can also lead to increased brake wear emissions and idling vehicle conditions due to increased congestion. The type of pavement on the road may also affect the amount of wear emissions and re-suspended road dust, while asphalt pavements also emit small levels of VOCs.

- Type of road affects pollutants
 - Concrete vs. asphalt etc.
- Structure by roads affects pollutants
 - Noise barriers, vegetation, buildings

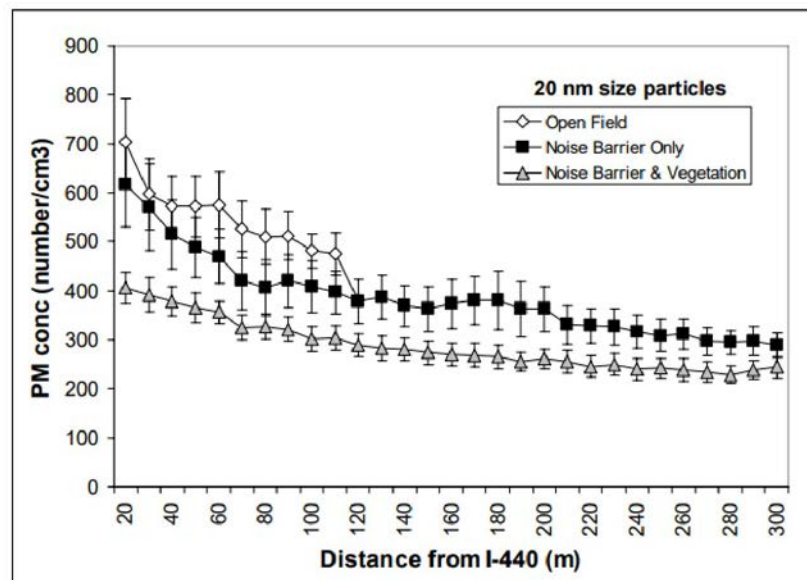


Figure 2. Mobile monitoring measurements of the number of 20 nm size particles present at varying distances from a 125,000 AADT highway for an at-grade road with no obstructions (open field), behind only a noise barrier (noise barrier only), and behind a noise barrier with mature vegetation stands (noise barrier & vegetation). Bars represent 95 percent confidence intervals for each distance (Baldauf et al., 2008b).

- Distance from road
 - Concentration gradients are quite steep near the road, with studies showing traffic generated pollutants decrease exponentially with distance
 - Should use multiple monitoring stations at varying distances from roads, with highest density within the first 100m from road. If resource prevent establishment of multiple monitoring stations, a minimum distance of 10-20m should be considered to minimize influence of vehicle-induced turbulence



- Upwind/background monitoring
 - Paired monitoring stations can be used to limit influence of changing wind directions
 - Vehicle induced turbulence may allow traffic generated pollutants to “meander” upwind, resulting in elevated pollutant concentrations at distances as far as 50-100 meters upwind of the road (Venkatram et al., 2007)
- Horizontal spacing
 - multiple samplers at equal distances from the road, but under varying topographic or roadside structure conditions, can be used to confirm the effect of these varying conditions. In addition to fixed-site sampling at multiple locations, temporary or mobile monitoring using instrumented vehicles may be considered for short-term monitoring comparisons.
- Vertical spacing
 - Concentration measurements at multiple elevations can assess the variability in plume height with changing traffic, meteorology, and roadway designs. In addition, vertical measurements may be useful to identify pollutant concentrations at air inlet heights for nearby buildings such as schools or residences.

Infrastructure/ Enclosures

- **Multidimensional study with fixed monitoring study:** Usually waterproof enclosures built into design
 - Stable foundation
 - Large object to stabilize against
- **Low cost sensor:** sensor itself not waterproof, usually have to buy enclosure separate or store in weatherproof enclosure.
 - Enclosure must not interfere with sampling technique
 - Small pole/other object can be used
 - Possibly attached to trees?
 - Deployed on informational plaques or trail marker signs

Notes from conversation with John Vinmont-Chief of Air and Research Division

- particulate is how visibility is monitored
- relative concentrations
- interpolations are abused/misused in generating a status
- portable ozone monitors being tested and considered by WASO Air Quality Division
- can't just take things off the shelf - need calibration rather than just off the shelf - some are ok compared to just interpolation
- saturation studies could be very good - across the landscapes
- Q: deploy, retrieve, gather data for lower cost sensors - what makes a sensor more or less desirable to use?



- power is the first question - could be solar
- portable have a tripod
- Wi-Fi can be flaky for PurpleAir
- Full on stations are visited once per week
- ozone is continuous and can be accessed online
- phone lines can also be used
- remote monitoring of remote instruments can be done from Colorado
- filter based measurement is once every 3rd day - on a carousel - operator has to change out the filter
- wet deposition, too - all on Tuesdays
- Storage on the card allows monitors left in place until almost filled
- cheap monitors - allow for redundancy
- window of time to visit the monitor allows for more flexibility for park staff involvement
- mobile sensors PWR bought some as a CitSci test - we have thought about it but have not done anything, yet.
- before one puts out a CitSci project need to have a good question
- Good question: are these interpolations any good?
- Could cooperate with people in backyards to develop a gradient between neighbors and park
- Q: slide 16 target pollutants
- NO₂ and SO₂ oxidation means NO₂ and SO₂ are not long lived so N deposition are remnants of the NO₂ oxidation - not too excited about these unless very near the source (coal burning, volcanoes). Breathing NO₂ and SO₂ is a problem so at Volcano National Park has monitors for harmful levels.
- Maybe roadside (NO₂): cycling paths near to roadways - we do not cover this much at all
- Q: NR Condition Assessment reports not occurring as often in favor of the more rapid assessment, 2015 air quality summary trends is there another place she is missing or is this a transition period?
- designed detailed data digestible by a park manager - very over simplified into gross statistics, all the data is available - will provide links to some of the data sets
- Trying to move to a more online approach to distributing the findings
- Q: Village Green project - is this a monitoring success - community, sensors - was is costly and/or useful?
- Is an EPA program - is being installed at the GRCA. Paid for by Arizona, money transfer was a pain - project was \$100K includes installation, and a year of operation
- Q: any thoughts about her work?
- Nothing jumped out except 126 on slide 16 for plants not people



- Need to have a calibration protocol (verification protocol)
- ex. full on monitor that was calibrated to test the tracking between monitors near volcanoes (was biased just a little high) - can't just take out of the box
- Corrects for bias - complicates things
- plug in monitors - were ok to install because of safety concerns

Citizen Science

EPA ScienceMatters Magazine: July 2018 issue

Source: https://www.epa.gov/sites/production/files/2018-08/documents/science_matters_special_edition_-_innovations_in_air_quality_monitoring.pdf

- AirMappers: Citizen scientists in the communities are taking part in the study by using AirMappers. These lunchbox-size monitors developed by EPA enable residents and students to collect local air quality data by carrying or attaching the devices to a bicycle while walking or biking around the study area. AirMappers include rechargeable battery power, a global positioning system, and particle and carbon dioxide sensors
 - Study Page: www.epa.gov/air-research/kansas-citytransportation-and-local-scale-air-quality-study
 - **Disclaimer: research only and is not a health-based assessment and/or is not intended for regulatory purposes.
- Visit the Air Sensor Toolbox: www.epa.gov/air-sensor-toolbox



Take a Look Inside the Toolbox

These and other resources are available on the online Air Sensor Toolbox.

Air Sensor Guidebook Provides Monitoring How-To

The Air Sensor Guidebook is a comprehensive resource for anyone interested in monitoring local air quality. Topics covered include information on air pollutants and uses for air sensors, what to look for in a sensor, how to collect useful data using sensors, sensor performance guidance, and maintaining your sensing device.

Air Sensor Guidebook: www.epa.gov/air-sensor-toolbox/how-use-air-sensors-air-sensor-guidebook

Guide and Analysis Tool for Community-led Monitoring

EPA has developed a guide and analysis tool for citizen scientists interested in air quality monitoring to evaluate the performance of lower-cost air sensors and interpret the data collected. While EPA developed the resources to be suitable for citizen scientists and communities, they are also useful to the broader air sensor user community, both experts and non-experts.

Guide and Analysis Tool: www.epa.gov/air-research/instruction-guide-and-macro-analysis-tool-community-led-air-monitoring

Mapping Air Data Using RETIGO

Real Time Geospatial Data Viewer (RETIGO) is a free, web-based tool developed by EPA that can be used to explore environmental data that you have collected either stationary or in motion (e.g., air quality sensors added to a bike). It is designed to reduce technical barriers to visualize collected air quality data or other data, enabling users to explore geospatial data over time and space.

RETIGO: www.epa.gov/hesc/real-time-geospatial-data-viewer-retigo



Air Sensor Performance Evaluations

Emerging air quality sensors have a wide appeal to professional researchers, community groups, students, and citizen scientists alike because they are lower in cost, compact, portable, and provide real-time air quality data. Since this technology is still under development, little information exists on the quality of data that these sensors produce. To help those interested in using sensors as part of air monitoring projects, EPA researchers evaluate sensors for how well they measure air pollutants and how easy they are to use.

Air Sensor Evaluations: www.epa.gov/air-sensor-toolbox/evaluation-emerging-air-pollution-sensor-performance

How to Build and Operate a Village Green Air Monitoring Station

The Village Green Project has successfully demonstrated the capabilities of new real-time monitoring technology for residents and citizen scientists to learn about local air quality. The project involved the development of a solar-powered, park-bench style air monitoring station that includes miniaturized air sensors and other instruments that provide information on local air quality and meteorological conditions.

Through partnerships with cities and other organizations, EPA installed stations in eight cities across the United States for use by the public. The stations are lower in cost and require less maintenance, but they are not off-the-shelf products that can be purchased. The system requires technical skills to build and some experience in air quality monitoring.

Researchers developed a manual and training video on how to construct, operate and maintain a Village Green station.

Village Green Project: www.epa.gov/air-research/village-green-project



Sensor Data Compilation Techniques

1.) RETIGO: Real Time Geospatial Data Viewer

Source: <https://www.epa.gov/hesc/real-time-geospatial-data-viewer-retigo>

- REal TIme Geospatial Data Viewer (RETIGO) is a free, web-based tool that can be used to explore environmental data that you have collected either stationary or in motion (e.g., air quality sensors added to a bike).
- RETIGO allows you to add data from nearby air quality and meteorological stations.
- RETIGO can be used by anyone to explore data that they collected, but it does not move the data from the user's computer, unless you decide to post your data to the RETIGO data repository.
- To collect the data, monitoring equipment is needed and ranges in price from ten dollar sensors, on up to professional grade equipment costing tens of thousands of dollars.
- Online tutorial: <https://www.epa.gov/hesc/real-time-geospatial-retigo-tutorials#online>
- Some sensors are not made to spit out accurate daily data, and quarterly may be easier to work with regarding RETIGO



2.) Macro Analysis Tool

- EPA's Excel-based Macro Analysis Tool helps users compare data from low-cost sensors to data from regulatory monitors and interpret their results. The tool allows input of data from low-cost and regulatory monitors for comparison, even if measurements weren't recorded at precisely the same time, or were collected at different time intervals, such as 1-minute versus 5-minute intervals. This tool addresses one of the major hurdles in citizen-led community air monitoring projects, which is working with and understanding the data.
 - **What are the benefits of using the Guide and Analysis Tool?**
 - Low-cost sensors make it possible for citizens to collect air quality data in their own communities, but they still require instruction for optimal results. While low-cost sensors can measure many of the same air pollutants that costlier regulatory monitors measure, they aren't required to meet the same rigorous standards of accuracy and reliability. Understanding how to collocate low-cost sensors with regulatory monitors and compare their results ensures that data from the low-cost monitors is on par with federal standards.
 - **Who should use these tools?**
 - While EPA developed each of these tools to be suitable for citizen scientists and communities, they are also useful to the broader air sensor user community, both experts and non-experts. Furthermore, the Macro Analysis Tool can be used to compare datasets beyond the specific collocation application it was designed for, such as comparing data from one low-cost sensor to another.
 - **How were these tools developed?**
 - The tools were developed as part of a community-led air sensor evaluation project that began during fall 2016 in support of EPA's emerging technologies research program. During the year-long project, EPA partnered with one community group (Clean Air Carolina) and one tribal nation (Eastern Band of Cherokee Indians) to conduct a sensor performance evaluation using their choice of low-cost sensors. Both project partner groups used the



tools and gave feedback on how to better tailor them for citizen users.

- **Download the Instruction Guide & Macro Analysis Tool**
 - Macro Analysis Tool and Instruction Guide: Evaluating Low-Cost Air Sensors by Collocation with Federal Reference Monitors

Fact Sheet About Citizen Science

- Community-led Air Sensor Evaluation: New Tools for Citizen Scientists Fact Sheet



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