Environmental Protection for the 21st Century:
Putting Equity at the Top of the Agenda

Enhanced Air Monitoring Working Paper

Water and air quality have traditionally been monitored by regulators and polluters to gauge adherence to standards established under the Clean Air Act and the Clean Water Act. The citizen suit provisions of both laws created an opening for non-governmental parties to use the legal system to apply enforcement pressure. These legal levers, combined with the proliferation of low-cost air and water monitors, growing applications of and acceptance for citizen science,[1] and the growing availability of data analytics have created opportunities for strengthening protection from pollution in vulnerable communities.

While federal regulations mandate monitoring of both water and air quality, this paper will focus on air quality monitoring, with a focus on expanded air quality monitoring -- the monitoring conducted by non-regulators and outside of the Federal Reference Method (FRM) framework. It will discuss evolving monitoring technologies and associated policy issues, as well as considerations for addressing equity concerns.

The air quality monitoring landscape is evolving rapidly. New technologies are being developed and deployed and users are expanding beyond the traditional research and regulatory communities. Access to inexpensive monitoring and data analyses equipment is creating tremendous opportunities for democratization of air quality monitoring. However, the traditional regulatory frameworks are not designed for non-FRM data collected by non-governmental actors. Tremendous opportunities for improved environmental protection and community engagement lie in these new tools and users if quality and reliability can be assured.

Defining the Problem

Despite the accomplishments of the Clean Air Act since its enactment 51 years ago, air pollution remains an urgent threat to human health. In fact, air pollution poses the greatest environmental risk for early death, responsible for more than 6 million premature deaths each year from heart attacks, strokes, diabetes and respiratory diseases. Air pollution is the 4th leading risk factor for death globally, exceeding the impacts of other risk factors for chronic disease like obesity, high cholesterol, and malnutrition.[2] Of particular concern are pollutants such as Particulate Matter (PM), very small diameter particles that are inhaled into the respiratory system and can contribute to respiratory and cardiovascular diseases, reproductive and central nervous system dysfunctions, and cancer; and ground level ozone which also impacts the respiratory and cardiovascular system. There are many other pollutants of concern including nitrogen oxide,

[1] Wyeth, G., Paddock, L., Parker, A., Glicksman, R., and Williams, J. 2019. "The Impact of Citizen Environmental Science in the United States." Environmental Law Reporter, 10237.

[2] Health Effects Institute. 2020. State of Global Air 2020. Special Report. Boston, MA: Health Effects Institute.

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sulfur dioxide, volatile organic compounds (VOCs), dioxins, and polycyclic aromatic hydrocarbons (PAHs), among others. The impacts of pollutants include both acute and chronic illnesses such as respiratory problems (i.e., chronic obstructive pulmonary disease, asthma), as well as lung cancer, cardiovascular events, central nervous system dysfunctions, and adverse neurodevelopmental effects.[3,4]

Research shows that communities face different levels of air pollution which are determined by a combination of factors including geographic location, race, social economic status and housing conditions. Specifically, nonwhite populations, especially Black people, face greater risks from particle pollution than other populations.[5] Structural racism, historic segregation, outdated zoning laws, discrimination and other factors have created situations in which pollution poses a disproportionate burden on vulnerable communities. For example, Black people are more likely than white people to experience hazardous air pollution near their residences in general.[6,7,8] In addition, Black people are over-represented in non-attainment areas in which the air quality is below the Clean Air Act's National Ambient Air Quality Standards.[9] In addition, while industrial toxics exposure has been steadily decreasing nationally,[10] the gap in exposure between Black and white people remains unchanged, with lower-class white Americans having lower exposures than middle class African Americans.[11]

Racial Disparities in COVID-19 Impacts

According to the American Lung Association, an estimated 141 million Americans live in counties with unhealthy levels of air pollution. Lower income communities of color are more likely to have historical exposures to higher levels of air pollution. This chronic exposure is thought to worsen underlying diseases, including many that represent risk factors for severe COVID-19. Further, researchers have found that with an increase of only 1 $\mu g/m^3$ in chronic $PM_{2.5}$ exposure, the COVID-19 mortality rate increased by 15%.[9]

Sources: Eric B. Brandt, Andrew F. Beck, Tesfaye B. Mersha, Air pollution, racial disparities, and COVID-19 mortality, Journal of Allergy and Clinical Immunology, Volume 146, Issue 1, 2020, Pages 61-63,ISSN 0091-6749.

https://www.lung.org/blog/covid-19-mortality-and-air-pollution

https://www.american.edu/spa/cep/air-quality/index.cfm

Types of Air Pollution

Air quality monitoring is used to measure two major categories of pollution, as defined below.

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[3] Manisalidis, I., Stavropoulou, E., Stavropoulos, A., & Bezirtzoglou, E. (2020). Environmental and Health Impacts of Air Pollution: A Review. *Frontiers in public health*, *8*, 14. https://doi.org/10.3389/fpubh.2020.00014

[4] Devon C. Payne-Sturges et al. "Healthy Air, Healthy Brains: Advancing Air Pollution Policy to Protect Children's Health." *American Journal of Public Health* 109, no. 4 (April 1, 2019): pp. 550-554.

[5] U.S. EPA, 2019, Section 12.5.4.

[6] Victor Brajer and Hall, J. 1992. "Recent Evidence On The Distribution Of Air Pollution Effects," Contemporary Economic Policy, Western Economic Association International, vol. 10(2), pages 63-71, April.;

[7] Liu 1996;

[8] Morello-Frosch R, Pastor M, Sadd J. Environmental Justice and Southern California's "Riskscape": The Distribution of Air Toxics Exposures and Health Risks among Diverse Communities. Urban Affairs Review. 2001;36(4):551-578. doi:10.1177/10780870122184993

[9] Wernette, D. R. and L. A. Nieves. 1992. ''Breathing Polluted Air: Minorities are Disproportionately Exposed.'' EPA Journal 18(1):16–7.

[10] Monitoring and Assessment Branch Air Quality Division Department of Energy and Environment. (2020). Ambient air quality trends report, 1996-2019.

[11] Kerry Ard (2015) Trends in exposure to industrial air toxins for different racial and socioeconomic groups: A spatial and temporal examination of environmental inequality in the U.S. from 1995 to 2004. *Social Science Research* 53, 375-390. https://doi.org/10.1016/j.ssresearch.2015.06.019

Ambient Air Pollution – "That portion of the atmosphere, external to buildings, to which the general public has access." (EPA)

Point-Source Air Pollution -- "Any single identifiable source of pollution from which pollutants are discharged, such as a pipe, ditch, ship or factory smokestack." (EPA)

The Governmental Air Quality Monitoring Network

Under the Clean Air Act, EPA and state regulators assess the public's exposure to the criteria air pollutants (the six pollutants identified as posing public health threats under the Clean Air Act) and evaluate the effectiveness of pollutant control strategies using Federal Reference Methods (FRM). Air quality monitoring as it is currently employed is valuable and has contributed to great improvements in ambient air quality over time, however, it is limited in its ability to address discrepancies in exposures, as described below.

- In most cities, there are 2-3 stationary air monitoring sites per 1 million people. The gaps between air monitoring sites are too vast for the network to provide a reliable spatial picture of local pollution clusters. Further, the fixed locations of sensors prevent a complete spatial picture of air quality. For example, one end of a city street may be adjacent to a congested traffic corridor while the other end of the block may abut a school. The air quality on opposite sides of such a block would vary drastically.
- Intermittent air monitors collect data over pre-determined time intervals (i.e., 10 minutes, 30 minutes) and run the risk of missing short-lived, high-intensity spikes in pollution. Continuous, or more frequent monitoring would provide a more complete temporal picture.
- Lack of real-time, easily accessible air quality data limit the ability of stakeholders to collect, collaborate, analyze, and use FRM air quality data.[12]

Expanded air monitoring is the practice of collecting monitoring data that are more granular, frequent, hyperlocal, less costly and accessible to the public, than those data gathered using the nationwide air quality monitoring network that relies on the FRM for Clean Air Act standards.

Democratizing Environmental Protection

The EPA's role in monitoring air quality has not evolved significantly in 50 years. In 2018, the EPA Office of Inspector General called for the agency to develop a vision and strategy to use citizen science results.[13] Since that time, the agency has been working to develop standards for quality and reliability in citizen generated data, as well as to promote public engagement using citizen science such as through the **Environmental Benefits Mapping and Analysis Program - Community Edition**. The rise in inexpensive monitoring and data processing tools and the movement towards democratization of environmental data has led other actors to fill the voids in traditional FRM air monitoring. Non-governmental actors such as NGOs, the private sector, community groups, educators/students and the general public have increased their involvement in local air monitoring significantly. For example, the University of California at Berkeley's

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[12] Snyder, E. G., Watkins, T. H., Solomon, P. A., Thoma, E. D., Williams, R. W., Hagler, G. S. W., Shelow, D., Hindin, D. A., Kilaru, V. J., & Preuss, P. W. (2013). The Changing Paradigm of Air Pollution Monitoring. *Environmental Science & Technology*, *47*(20), 11369–11377.

[13] U.S. EPA, Office of Inspector General, EPA Needs a Comprehensive Vision and Strategy for Citizen Science That Aligns with Its Strategic Objectives on Public Participation (2018).

BEACON program runs a high-density network of sensors in urban areas for real-time, high-resolution CO_2 (and other pollutant) monitoring. BEACON also incorporates a K-12 curriculum that uses the data for student research.

The private sector is getting involved in strengthening the accuracy and quality of air quality data collection as well. For example, in 2019, Aclima partnered with Google to perform hyperlocal air monitoring collection using Google cars in Oakland, California. Fifty cars were fixed with air monitors to collect 350,000 air-quality data points daily. So far, these sensors have collected more than 3 million data points and logged more than 15,000 miles gathering data on black carbon particles (BC), nitric oxide (NO) and NO2 (nitrogen dioxide) (APTE, 2020).

Advanced data analytics are used to standardize disparate data sets to aggregate, compare and ultimately use data from a variety of sources. These tools put data into context to identify trends and inform decision making.

Use and Ownership of Data serve as a both a determinant and an indicator of community engagement and access to technical capabilities. Historically, point source pollution data had been privately held to protect industry trade secrets and communities were notified after the fact about exceedances. Through monitoring of local conditions, community members can stay informed, communicate conditions to local authorities, take personal measures to mitigate exposure, and advocate for needed changes.

Monitoring Technology Platforms. There are several categories of sensor technologies; these are listed below with examples of providers and applications.

- **Regulatory sensors** – Also known as FRM monitors, sensors in this category are designed to detect specific pollutants using a range of technologies in a fixed location at a fixed frequency. These air monitors have "strict measurement performance criteria" and a one-year performance period of "inspection and validation of data prior to final data reporting and usage" (EPA Tools and Resources Webinar, 2018). Specific monitors are needed to track the Clean Air Act criteria pollutants and hazardous air pollutants with a price range of $15,000 to $40,000 per monitor (EPA, 2018).
- **Non-regulatory sensors**–This broad category includes any sensor that collects data on one or more air quality measures, but which does not meet the performance criteria of regulatory sensors. These sensors, because of their lower price points, can be used as part of a network of sensors to gather detailed air quality data on a hyperlocal scale. One such example is the Purple Air monitor, which gathers data

Understanding Personal Exposure to Air Pollutants

One argument against relying on non-regulatory sensors is that collected data cannot be used to impact policy and therefore goes unused because individuals do not understand the data. This limitation was tested in Denver, CO, when 20 participants wore RTI MicroPEM sensors for 3 seasons (Summer, Fall and Winter) for 72-hour time periods. At the start of the study, participants were only 25% confident they knew when to be concerned about PM, how to interpret air quality reports, and how to develop an action plan (Cicutto et al, 2020). By the end, participants were 85% confident and PM knowledge test scores nearly tripled over the study period. This study shows that while there is a learning curve for understanding air quality measurements, standard education and exposure to air quality concepts makes Non-FRM data collection valuable in mitigating personal exposure to pollutants.

on fine particulate matter (PM2.5) as well as accompanying weather conditions. It is relatively low-cost, wi-fi enabled and incorporates a publicly available digital mapping tool ($250-$300). However, while low-cost monitors are useful to provide relative data (e.g., detecting a spike or comparison of point A to point B), they devices may not be suitable for absolute measurements. Please see Appendix A for an exemplary list of non-regulatory sensors in use today. Please see the Community Air Monitoring Network Case Study for example applications of nonregulatory sensors.

- **Personal sensors**–Miniaturized monitoring devices for hyperlocal air quality data gathering are portable, and in some cases, wearable. One example is the AirBeam2 which can be used both indoor and outdoors, measures particulate matter and connects with an open-source visualization platform (PM 2.5) ($250). Another example is the RTI MicroPEM which measures both indoor and outdoor air for particulate matter (PM2.5 and PM10) (~$2,000).
- **Mobile sensors** – These portable sensors are designed for pedestrians or for vehicle mounting. They provide block-by-block mobile monitoring or a variety of measures, and incorporate geo-tagging, mapping and reporting technology. Aclima, for example, installs its sensors on vehicle fleets in select cities and gathers real time air quality data, and provides mapping and data analyses. Aeroqual makes sensors that can be affixed to vehicles or used in fixed location. Aeroqual also offers an operating system and data storage. (Aclima is only available on a subscription basis; Aeroqual hardware starts at $1,200 with additional costs for each sensor).
- **Nanosensors** – These highly sensitive paper-based sensors powered by biobatteries are low-cost, biodegradable and single use, making them inexpensive for a range of purposes, including citizen science and agriculture (under development). When air monitors are made from cellulose fiber, production costs are dramatically lowered.

Innovation abounds in the air quality monitoring space. Community groups in Louisiana are calibrating nonregulatory sensors against FRM sensors to be able to closely track regulatory monitoring data, to identify data gaps and ultimately, to advocate for policy change. California's Air Resources Board (CARB) implemented the California Community Air Protection Program in response to known environmental and health inequities from air pollution across communities (see text box). This program focuses on reducing pollution exposure for at-risk and overburdened communities near ports, rail yards, warehouses, freeways, and other large industrial facilities. In 2017-2018 the California Air Resources Board (CARB) allocated $250 million to clean up heavily polluting mobile sources, like diesel trucks and buses. In 2018-2019, CARB spent $245 million on purchasing cleaner vehicles and equipment and awarded $10 million in grants to 28 community projects to reduce exposure to harmful air emissions in disadvantaged or low-income communities. An example of how these grants have been used to reduce exposures is provided in the text box below.

California Community Air Program

A 2018 grantee for CARB's California Community Air Program, the City of Richmond-San Pablo, CA, has a population of 110,567, and is comprised of 37% White, 20% Black, 15% Asian, 43% Hispanic, and 1% American Indian, Alaskan Native, and Pacific Islander, and is home to third most productive port in California, with more than 200 permitted emissions sources including a 2,900-acre Chevron petroleum refinery. With funding from this the California Community Air Program, the City launched a Community Air Monitoring Plan (CAMP) consisting of three parts:

1) Hyperlocal block-to-block air monitoring from August 1 to October 31, 2019, conducted by Aclima, in which a fleet of vehicles driven by local community members measured $PM_{2.5}$, O_3, CO, CO_2, NO, and NO_2. Aclima also installed a network of 50 stationary devices across the community monitoring $PM_{2.5}$, O_3, and NO_2.
2) Throughout 2020, 52 stationary Clarity Node-S sensors measuring PM2.5 and NO_2 were deployed by Groundwork Richmond.
3) Real-time data in one-minute intervals measuring PM2.5, NO2, O3, temperature, relative humidity, and dew point using 50 stationary Aeroqual AQY air monitors were deployed in 2020 by PSE which also deployed three prototype air monitors measuring volatile organic compounds (VOC), CO and PM2.5.

Live data for each project can be viewed at:
https://openmap.clarity.io/ (Aclima)
http://www.groundworkrichmond.org/air-rangers.html (Groundwork Richmond)

Applications of Enhanced Air Monitoring Data

Along with the significant progress that has been made in the development of air quality monitoring technologies, the EPA and several state agencies have sought to create standards for community air monitoring practices. Specifically, EPA has developed testing protocols for non-regulatory supplemental and informational monitoring of ozone and $PM_{2.5}$ (see text box).[14,15] Further, EPA sponsors research on air quality monitoring in partnership with states, local governments and non-governmental organizations to support public awareness of and engagement with air monitors and to develop new strategies for air quality and emission characterization. Specific projects include a study of the long-term capabilities of six different air sensors in seven locations with different meteorological and air quality conditions,[16] a partnership with the Maricopa County (AZ) Air quality Department to study PM2.5 sensors in Phoenix,[17] and a Wildland Fire Sensors challenge to promote the development of sensors for early smoke detection and therefore, early detection of wildfires.[18] Further, California's South Coast Air Quality Management Agency's Air Quality Sensor Performance Evaluation Center

[14] Duvall, R., A. Clements, G. Hagler, A. Kamal, Vasu Kilaru, L. Goodman, S. Frederick, K. Johnson Barkjohn, I. VonWald, D. Greene, AND T. Dye. Performance Testing Protocols, Metrics, and Target Values for Ozone Air Sensors: Use in Ambient, Outdoor, Fixed Site, Non-Regulatory and Informational Monitoring Applications. U.S. EPA Office of Research and Development, Washington, DC, EPA/600/R-20/279, 2021.
[15] Duvall, R., A. Clements, G. Hagler, A. Kamal, Vasu Kilaru, L. Goodman, S. Frederick, K. Johnson Barkjohn, I. VonWald, D. Greene, AND T. Dye. Performance Testing Protocols, Metrics, and Target Values for Fine Particulate Matter Air Sensors: Use in Ambient, Outdoor, Fixed Site, Non-Regulatory Supplemental and Informational Monitoring Applications. U.S. EPA Office of Research and Development, Washington, DC, EPA/600/R-20/280, 2021.
[16] Study Assesses Long-Term Capabilities of Air Sensors. *Science Matters.* Jan 2020 update. Accessed 8/27/2021. www.epa.gov/sciencematters/study-assesses-long-term-capabilities-air-sensors
[17] EPA Scientists Evaluate Low-Cost Air Sensors in Phoenix, Arizona. *Science Matters*, July 30, 2019. Accessed 8/26/2021.
[18] Winners of the Wildland Fire Sensors Challenge Develop Air Monitoring System Prototype. Accessed 8/26/2021. https://www.epa.gov/air-research/winners-wildland-fire-sensors-challenge-develop-air-monitoring-system-prototypes

(AQ-SPEC) conducts both laboratory and ambient air sensor testing on non-FRM air monitors to demonstrate the usability and limitations of commercially available air monitors.[19]

While EPA[20] and state grants for community monitoring are growing rapidly, the application of these data for regulatory purposes has not yet been realized. Virginia's Department of Environmental Quality (DEQ) has developed a model for incorporating community-based data into state regulatory decision making, albeit from a watershed protection, not an air quality, perspective. Virginia DEQ's Office of Watershed Protection has developed a *Virginia Citizen Water Quality Monitoring Methods Manual* that addresses quality assurance /quality control (QA/QC) and quality assurance project plans (QAPPs), water monitoring program design, and methods that meet the agency's standards for data collection. They have also developed a data ranking system that informs DEQ of the quality of the data received, and through that, DEQ assesses how the data can be used.[21] Under the ranking system, DEQ uses data submitted from groups that follow all DEQ protocols, quality assurance, and laboratory testing protocols and have a DEQ-approved QAPP and standard operating procedures with no deviations as if the samples were collected and analyzed by DEQ. Under these conditions, DEQ will use such data in the 305(b) water quality assessment and for 303(d) listing/delisting of impaired waters. At reduced levels of compliance with DEQ standards and practices, such data may be used for 305(b) assessment to identify possible waters with observed effects or waters that appear to be healthy but will need DEQ monitoring data to confirm status, to identify sites that may require DEQ to perform follow-up monitoring or for notifying DEQ of significant pollution events for rapid agency response.

Standard Setting for Community Air Monitoring

Beginning in 2018, EPA initiated a process to develop testing protocols to uniformly evaluate air sensors and guide future technology improvement for both ozone and $PM_{2.5}$ air sensors. In February 2021, EPA released two resulting reports to providing a consistent set of testing protocols, metrics, and target values to evaluate the performance of air sensors specifically for non-regulatory supplemental and informational monitoring applications for use outdoors and at fixed locations. Testing results do not constitute certification or endorsement by EPA.

The ASTM Proposed Standard WK64899 *New Practice for the Performance Evaluation of Ambient Air Quality Sensors and Other Sensor-Based Instruments* seeks to address unknowns about the repeatability, sensitivity, temperature and other impacts as well as other measurement uncertainties with community air monitors. As of this writing, the standard is under development.

Sources: EPA Air Sensor Toolbox (www.epa.gov/air-sensor-toolbox/)
ASTR International (www.astm.org/DATABASE.CART/WORKITEMS /WK64899.htm)

Conclusions

- Current FRM air monitoring practices are inadequate for protecting vulnerable communities from localized air pollution risks, both from point sources and ambient air pollution.

[19] http://www.aqmd.gov/aq-spec/evaluations. Accessed 8/26/2021.

[20] https://www.epa.gov/newsreleases/epa-announces-additional-50-million-under-american-rescue-plan-enhance-air-pollution. Accessed 8/12/2021.

[21] Email exchange with William Isenberg, VA DEQ, 8/13/2021.

- The rise in citizen science air monitoring and data availability facilitates community-level action to take steps to reduce risks directly (such as through pressuring local and state regulators as well as behavioral changes that reduce personal risks).
- Progress is underway in developing quality and reliability standards for enhanced air monitoring data. However, further development and acceptance of community air monitoring is needed.
- Regulatory acceptance of community air monitoring remains a barrier.

Opportunities for Further Research

- Examine how community monitoring can be used to measure the cumulative impacts of multiple pollution sources combined with specific events such as wildfires.
- Survey the landscape of standards organizations (i.e., ASTM), federal and state efforts to standardize and accept enhanced monitoring data.
- Evaluate local efforts to expand enhanced monitoring within a community (see Community Air Monitoring Network Case Study).

Preliminary Recommendations

- Incorporate community air monitoring into Administration's equitable infrastructure and resilience planning efforts
- Consider community air monitoring in annual OSTP and NSF priorities
- Develop frameworks for assessing the quality and reliability of community air data and explore how to use them in state and federal agency decision making
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Appendix A

Table 1: Examples of Non-Regulatory Air Monitors

Air Monitor	**Price (USD)**	**Link**
DC1100 Air Quality Monitor	$199	http://www.dylosproducts.com/ornodcproair.html
PurpleAir PA-II	$249	https://www2.purpleair.com/collections/air-quality-sensors/products/purpleair-pa-ii
OMC-1108	$1,200	https://www.scribd.com/document/81591408/OMC-1108-Manual
Aeroqual Series 500	$1,500	https://www.aeroqual.com/product/series-500-portable-air-pollution-monitor
831 Aerosol Mass Monitor	$2,000	https://metone.com/products/aerocet-831-handheld-particle-counter/
Model 205 Dual Beam Ozone Monitor	$5,000	https://twobtech.com/model-205-ozone-monitor.html
microAeth® Model AE51	$6,000	https://aethlabs.com/microaeth/ae51/overview
BAM 10-22	$20,000	https://metone.com/products/bam-1022/
AQY 1 – Micro	-*	https://www.aeroqual.com/product/aqy-micro-air-quality-station
Clarity Node-S	-**	https://www.clarity.io/air-quality-monitoring-solution#ClarityNodeS

- * - Quote Requested
- ** - Quote Unavailable
- EPA Air Sensor Guidebook, 2014