Filling the Gaps:
Improving Measurement of Ambient Air Quality in Low and Middle Income Countries

Draft preliminary guidance for low and middle income countries on the application of available air measurement technologies and data management methods to air quality policy design and implementation.

Acknowledgements

The authors would like to acknowledge the World Bank, the United States Environmental Protection Agency, the United States Department of State and the many individuals who participated in the Filling the Gaps Workshop and contributed to the development of this document. The financial support of the World Bank-administered Pollution Management and Environmental Health multi-donor trust fund is also acknowledged.

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Filling the Gaps: Executive Summary

Governments, multi-lateral organizations and the private sector are increasingly motivated to take action as a result of a growing understanding of the negative health and environmental effects associated with high levels of air pollution. Unfortunately, there is a critical lack of air quality data in most low and middle income countries (LMICs). Countries can take action without making substantial investments in air measurements systems. However, any robust air quality management system should include a measurement component to address country-specific policy objectives and document trends over time. This document provides preliminary guidance and recommendations, oriented by measurement objectives and country contexts, to decision makers at various stages in the air quality management process.

Key Messages

1. **Measurement strategies must be selected to fit a purpose.** Air quality monitoring strategies should be informed by countries' air quality management goals and monitoring needs.
2. **Measurement systems are necessary but not sufficient to reduce air pollution.** Air quality measurement strategies must be placed in the context of a broader air quality management program, with a focus on achieving emission reductions and improvements to public health, rather than being an end itself.
3. **A successful, sustainable monitoring strategy requires more than equipment.** There are critical human and institutional systems needed to sustain equipment and ensure that data quality remains high, and that any data collected can be analyzed and communicated to decision makers in support of desired objectives.
4. **The purchase price of monitoring equipment is not the full cost.** Other considerations include ongoing operation and maintenance, spare parts, filters (if applicable), data management and staff training. When considering a purchase, full consideration of all these costs is critical.
5. **Satellite-based remote sensing is promising, but does not replace ground based monitors.** There is a role for this information and certain purposes that make it worth exploring but can only be fully effective when combined with some amount of ground level data.
6. **Quality assurance plans are one of the most critical components of an air measurement strategy.** Decision makers must have confidence that the monitoring data underpinning their decisions is of an adequate quality to withstand scrutiny, especially when there are significant financial and programmatic investments being made based, at least in part, on that data.
7. **Air quality data can be a powerful tool to inform the public about the dangers of air pollution**. Publicly available data can support communication efforts so people can take action to protect themselves. An informed public can help advocate for the investments needed to reduce pollution and also be a part of people powered emission reduction strategies, e.g., vehicle emission testing or cookstove change-out programs.
8. **Securing and sustaining high quality air quality data globally is a challenge.** This challenge can be met if governments, academics, the private sector and civil society work together to find creative

solutions. There is a clear business case to be made for improving public health by reducing air pollution.

Filling the Gaps: Chapter 1
Problem Statement and Overview

1.0 Introduction

Ambient air pollution is a leading cause of disease and death. It is estimated that over 4.2 million deaths globally were caused by ambient air pollution from fine particulate matter ($PM_{2.5}$) in 2015[1], more premature deaths than malaria and HIV. An additional 254,000 deaths were attributable to exposure to ozone. Ambient air pollution contributes to a range of other negative health outcomes, including cardiovascular disease, stroke, chronic obstructive pulmonary disease, lung cancer, increased asthma attacks and respiratory diseases. In addition, air pollution decreases crop yields, impacts temperature and rainfall patterns, and imposes a host of other costly burdens.[2] Over the last 40-50 years, high-income countries have established robust systems of air quality management, including widespread ambient monitoring, emission source characterization, and emission reduction programs. The result of these efforts has been a general downward trend in emissions and ambient air pollutant concentrations concurrent with robust economic development and growth in vehicle use and industrial development.[3] For these reasons, reducing air pollution is a key public health policy goal and is also part of the Sustainable Development Goals (SDGs).

About 90 percent of global premature deaths from air pollution occur in low and middle income countries (LMICs). The health effects of ambient PM2.5 were estimated to cost the global economy about nearly US$ 3.3 trillion in 2015, or US$ 5.5 trillion in purchasing power parity (PPP) adjusted dollars.[4] This was equivalent to 4.5% of global GDP in 2015. The economic cost of health damage associated with ambient air pollution can amount to 0.1-3.2% of gross domestic product in some individual developing countries.[5] Ambient air pollution is driven by various factors, notably rapid urbanization, increased motorization and energy use, and burning of wastes and solid fuels, including for domestic cooking and heating[6]. Some regions are experiencing an upward trend in emissions. Notwithstanding the significant health and economic burden of air pollution in developing countries, many developing countries lack reliable data on air quality to provide the basis for informing decision making and action to reduce air pollution and its health impacts. In sum, there is a significant air quality measurement and data gap at the LMIC country-level and a need to build institutional systems to address these gaps and ultimately create local strategies to reduce emissions in these countries.

The measurement gap is highly problematic, because while reliable and sustainable air quality measurement is only one element of comprehensive air quality management (AQM), it serves as the foundation for many of the

[1] Health Effects Institute. 2017. State of Global Air 2017. Special Report. Boston, MA: Health Effects Institute.

[2] Maas, R., P. Grennfelt (eds), 2016. Towards Cleaner Air. Scientific Assessment Report 2016. EMEP Steering Body and Working Group on Effects of the Convention on Long-Range Transboundary Air Pollution, Oslo.

[3] For example, in the U.S. https://gispub.epa.gov/air/trendsreport/2017/#highlights

[4] Larsen, B. (2017) Cost of Ambient $PM_{2.5}$ Air Pollution: Global, regional and national estimates for 2015. Consultant report for the World Bank. Washington. DC.

[5] Awe, Y., Nygard, J., Larssen, S., Lee, H., Dulal, H., and Kanakia, R. 2015. *Clean Air and Healthy Lungs: Enhancing the World Bank's Approach to Air Quality Management*. World Bank: Washington DC.

[6] World Health Organization. *Ambient (Outdoor) Air Quality and Health Fact Sheet*. http://www.who.int/mediacentre/factsheets/fs313/en/

subsequent steps in the AQM process. Measurement data provides the underpinnings for: assessing the extent of air pollution; identifying sources of air pollution; understanding how air pollutants are transported and dispersed in the environment; identifying alternative interventions and selecting economically efficient interventions to reduce human exposure at the local level; evaluating and tracking the implementation of interventions; enforcing compliance with air quality standards; taking corrective measures where needed; and activating contingency plans. Further, each country will have its own set of sources, pollution mix and governance systems, thus requires its own capacity to generate local data and knowledge needed to manage air quality.

Significant advances have been made with respect to air quality monitoring in developed countries, based on a range of technologies, from extensive ground level monitoring networks to satellite and other remote sensing technologies. Unfortunately, these advances are not routinely applied or accessible in most of the developing world. In addition, new lower cost measurement devices are becoming more widespread. Experimentation with lower cost sensors is increasing in both developed and developing countries, but it requires scientific scrutiny and guidance.

Overall, little is known about the levels of air pollution and the associated health burden in LMICs, though estimates suggest both are significant.[7] Additionally, the lack of air quality monitoring in most developing countries undermines knowledge about actual ambient air pollution levels in those countries and estimation of the associated health burdens. This measurement and knowledge gap has led to a critical lack of capacity in these countries to address significant health and development challenges. The gap also means that the residents of these countries may not be well informed about the dangers of air pollution, and nor do they have the information they need to advocate for mitigation policies. Publicly available air pollution data can be a powerful tool for motivating change for both the public and policy makers. Closing the measurement gap can enable LMICs to meet both local development and public health objectives and our global goals under the SDGs.

1.1 Filling the Gaps Workshop

In July 2017, the World Bank and the United States Environmental Protection Agency convened experts from government, academia, and development and multi-lateral organizations. These experts discussed what can be done to fill the air quality data gaps in developing countries. Through presentations and small group discussions, participants explored a spectrum of technical strategies, ranging from satellite remote sensing and ground-level monitoring to emerging, lower cost air sensors, and how to increase available air quality (AQ) data and support country policy needs. A number of key themes emerged from the presentations and discussions:

- Air quality monitoring strategies should be informed by countries' air quality management goals and monitoring needs. Guidance and recommendations are needed based on individual monitoring goals (e.g., baseline assessments, health impact assessment, compliance monitoring, source identification, mitigation planning)

[7] WHO 2016. Global Urban Ambient Air Pollution Database. Available at http://www.who.int/phe/health_topics/outdoorair/databases/cities/en/

- Key challenges exist, including: fragmentation of efforts and data; data management and public access; political changes and sharing of responsibilities across levels of government; lack of adequate and sustained resources and capacity.
- BUT, there is a growing appetite for air quality management work, and many LMICs are looking for a way forward.
- There is need to document success stories, as well as to share lessons learned from successful or unsuccessful efforts to improve air quality monitoring. When working on new programs, it is important to build on what already exists, e.g., regional networks. There is a need to inventory what exists before initiating new programs.
- It is critical to build partnerships and engage both government and academia to better promote successful, long-term air monitoring, described by some participants as “sustainable air monitoring.”
- Awareness raising and education are also needed to inform the public about health impacts. This includes development of consumer friendly messages about what actions the public can take.
- “Making the case” for air monitoring is needed within all sectors of government, given other competing and important priorities in LMICs. Analyses connecting improved air quality with economic and health impacts and benefits is a strong motivating factor noted by multiple country representatives.

The workshop culminated with the charge to develop this document, which aims to help provide high level guidance to governments and other key actors on how to fill critical gaps in air quality measurement and knowledge for policy-making and action. Teams collaboratively wrote the report, which is designed to be widely reviewed experts and stakeholders, culminating with condensed guidance on using diverse air quality data to drive a clean air agenda.

1.2 Document Structure

This document is organized into five chapters and an Executive Summary:

Executive Summary

Chapter 1: Introduction

This chapter offers background on the air quality measurement challenges facing LMICs, as well as the *Filling the Gaps* workshop that initiated the development of this document.

Chapter 2: Factors Influencing Air Monitoring in LMICs

This chapter is designed to describe the context in which countries conduct air quality measurement. It describes first the objectives for which countries may be measuring air quality, and second the physical, technical and policy constraints in which the measurement occurs. This should help users identify for themselves their own objectives and where their country fits on the spectrum of air quality management capacity, such that they can find the recommendations in Chapter 5 that fit their purpose and capacity.

Chapter 3: Technical Steps to Address LMIC Goals and Future Research Needs

This chapter describes the current state of technologies to provide observational air quality data and how the different technical options align with common monitoring priorities. The options summarized include ground-level monitoring with regulatory-grade and non-regulatory-grade technologies and satellite remote sensing data, and the chapter also covers quality assurance, data management, and data integration.

Chapter 4: Sustainable and Successful Monitoring: The Human and Institutional Dimension
This chapter explores a range of human and institutional arrangements areas that must be considered as LMIC develop air quality measurement strategies. Technical solutions alone (i.e. monitoring equipment and protocols, QA and data management solutions, etc.) are necessary, but not sufficient to sustain widespread air quality measurement and characterization programs over the long term and translate those into broader emission reduction programs.

Chapter 5: Recommendations
This section provides low- and middle-income countries, depending on their unique context and goals, with an ordered list of steps toward incrementally building air quality monitoring capacity that will enable them to meet various monitoring objectives, which are likely to evolve over time as country capacity evolves over time.

Filling the Gaps: Chapter 2
Factors Influencing Air Quality Monitoring in Low and Middle Income Countries

2.0 Introduction

There are two lenses through which to view and determine the appropriate air measurement approach for any given country. First, it is important to have a clear understanding of the objectives that a country seeks to achieve. Second, it is important to be realistic about the physical and capacity constraints in which the country is operating, referred to as the "country type" in this document. Users of this guide will find the recommendations in Chapter 5 tailored to these monitoring objectives and country types.

In terms of monitoring objectives, the following section first outlines various air quality monitoring objectives that are particularly relevant where routine monitoring does not exist or is limited, and where air pollution accounts for a significant share of the burden of disease and mortality, as is the case in many developing countries. This is followed by a discussion of additional important monitoring objectives related to air quality- and exposure-related research, which are more likely to be featured where routine monitoring networks are established. The Chapter continues with descriptions of a spectrum of country types, oriented around certain physical and human parameters that impact the feasibility and sustainability of various measurement approaches.

2.1 Framing Air Quality Measurement by Objective

2.1.1 Air Quality Measurement Objectives in Contexts with Absent or Limited Monitoring

Given the centrality of monitoring to air quality management, defining air quality measurement objectives is a crucial first step in selecting an air quality monitoring approach. Different air quality measurement objectives require different tools including measurement methods, technologies, and quality assurance and quality control procedures. Objectives have evolved over time in countries with significant history of routine air quality measurement.

Taking into account the significant health burden associated with ambient air pollution in developing countries, measurement objectives that prioritize reduction of pollutants with the most detrimental effects to health are crucial. Particulate matter, notably $PM_{2.5}$, is ubiquitous and the most documented air pollutant associated with mortality and morbidity. Ambient air quality guidelines developed by the World Health Organization exist for particulate matter, in addition to sulfur dioxide (SO_2), nitrogen dioxide (NO_2) and ozone (O_3). Many countries also have national standards for these pollutants, and others, such as carbon monoxide and benzene. Strategies to measure those pollutants most dangerous for public health, and corresponding strategies to reduce those pollutants should be the first order of business for most LMICs.

Potential measurement objectives include:

<u>Assessment:</u> This could involve two types of assessments: (i) ***air quality assessment*** to understand the baseline local air quality by using scientific methods to measure the ambient concentration of pollutants. For fine particulate matter ($PM_{2.5}$) and PM_{10}, this is the mass concentration; for gaseous pollutants this can be expressed as either a fraction of total mass or volume. (ii) ***risk assessment***, which involves understanding the health and ecological risks associated with different levels of pollutants. For both assessments, it is important to have time series of air quality monitoring measurements under various conditions e.g. different locations, different weather conditions etc. For risk assessment, this can take the form of exposure monitoring, including indoor environments.

Source Attribution: Air pollution originates from various activities in various sectors e.g. energy, transportation, agriculture, biomass burning etc. Local air quality can also be affected by contributions from sources outside the monitoring area, even from a different country. Source attribution involves understanding which sources of specific air pollutants contribute and to what degree. By understanding the sources, appropriate control measures that target those sources can be designed. For particulate matter pollution, "source apportionment" analysis is the most common method to attribute source contributions to a region's $PM_{2.5}$ or PM_{10} pollution. Source apportionment typically requires filter-based methods to obtain samples for chemical analysis, which are then used to identify the different constituents using specific analytical methods.

Speciation: Beyond measuring the total quantity of a pollutant in the ambient air, there are reasons a country might want to measure the constituent parts or species of that pollutant. Understanding the chemically distinct components of particular pollutants is another aspect of monitoring. Understanding the specific molecules that make up air pollution provides decision makers and analysts with information regarding that pollutant's toxicity, bioavailability, fate and transport in the environment. For particulate matter, speciation is critical for source apportionment, i.e., understanding which sources are contributing to the measured concentrations (see above). For ozone, measurement techniques are used to determine which precursors are forming ozone, particularly to provide detailed information about volatile organic compounds (VOCs).

Compliance and Accountability: Compliance monitoring is used to determine whether air quality standards are being met, establishes baselines for issuing permits and supports enforcement actions. Measurement strategies support the implementation of air quality goals and standards, and enable an evaluation of the effectiveness of air pollution control strategies. Monitoring can help to identify where corrective measures are needed and where contingency plans may need to be activated. As such, accuracy in this realm of measurement is critical. In the USA, highly accurate monitors, known as federal reference monitors, are used to measure the six criteria pollutants for which ambient air quality standards exist ($PM_{2.5}$, PM_{10}, carbon monoxide, lead, sulfur dioxide, ozone, nitrogen dioxide).

Trend monitoring: Trend monitoring allows the determination of air quality trends and measurement of progress toward air quality goals. Trend monitoring requires reference type monitors and well calibrated measurements that are stable over time and comparable against certified standards. Trend monitoring could serve as part of an early warning mechanism to increase resilience of air quality monitoring efforts by informing future steps in air quality monitoring, where future monitoring objectives and efforts should be focused in order to ensure appropriate policy, technical and investment actions and interventions based on emerging pollution trends. Trend monitoring provides an opportunity for continuous improvement in air pollution control efforts.

Public Information: Monitoring data can inform the public of present air quality, air quality trends and exposure in the immediate locality e.g., in specific cities, and could extend to region-, state- and country-levels.

Monitoring for public information is useful for raising awareness about the severity of air pollution among the public; and for helping citizens to take precautionary measures to avoid or reduce their exposure to air pollution to protect their health, for example during periods of poor air quality. In addition, sharing air quality data provides a means for strengthening accountability for air pollution control through a well-informed public.

2.1.2 Additional Air Quality Measurement Objectives

Typically, air quality objectives fall in one or more of the basic types described in the previous section. As mentioned earlier, in countries with a history of air quality management, air quality measurement objectives have evolved over time. This section discusses monitoring objectives related to research and model validation, which often arise after basic measurement objectives are met.

Research: Monitoring for ***atmospheric research*** helps to understand the composition of air, the fate and transport of polluting emissions in the environment, and chemical transformation. Monitoring for ***exposure research*** provides air quality data as an input to health impact assessment and epidemiological research to determine how pollutants are impacting human health. This provides useful information for understanding how ambient concentrations affect human health.

Model validation – This type of monitoring is closely associated with atmospheric and exposure research, and helps to compare measured changes in air quality against modeled changes to verify that model simulations can reproduce actual conditions, and to determine any needed adjustments to model parameters.

2.2 Framing Air Quality Measurement by Country Context

This section describes country “Types,” which are designed to be illustrative and to help users determine which recommendations are relevant for them. Each user will need to determine which type best describes their unique situation. The types represent hypothetical categories, but the reality on the ground is very likely to be fluid between these categories or individual countries may be best described by a combination of two.

The country types are described using seven parameters related to technological and capacity constraints and other considerations important for ambient air quality measurement: availability of electricity; peak pollution levels; capacity in-country to analyze monitor samples; capacity to manage and store data; staff size; staff capacity; available equipment and resources for air measurement, sample analysis and data management.

This document seeks to provide relevant information that recognizes the reality on the ground and inform countries, regardless of type, about options for measuring air quality. In many cases, preliminary air quality measurements, combined with local knowledge of emission sources of concern, can provide the necessary basis to begin air quality management planning. It is critical that air quality measurement be placed in the context of a broader air quality management program, with a focus on achieving emission reductions and improvements to public health, rather than being an end itself. A summary of these types and their characteristics are shown in Table 2.1.

Type I: Countries with no existing measurements and no history of routine measurements of atmospheric composition of any kind. Some anecdotal measurements or one-time sampling may have taken place.

Type II: Countries with some information on atmospheric composition available (perhaps PM10 or TSP) but of variable quality without rigorous QA procedures. Limited to a small number of monitors in one or two most populous urban areas.

Type III: Countries that possess reliable information but with poor spatial or temporal coverage. For example, monitoring may exist in only one city or routine monitoring may exist for a period of a year or two, but is no longer being collected due to equipment malfunction/lack of repairs.

Type IV: Countries with high quality, reliable monitoring underway with at least three years of reliable data from multiple pollutants. Major cities are monitored.

Type V: Countries conducting routine monitoring, country wide (urban and rural areas), with 10+ years of data available.

Table 2.1 Country Types

Country Type	Monitoring Constraints					
	Electricity	**Laboratory and Analytical Capacity**	**Data Management Capacity**	**Staff Size**	**Staff Capacity**	**Financial Resources**
I	No electricity available at site	None	Limited, e.g., individual computers	Fewer than 10 air focused staff	Basic technical training; some technical or analytical capacity may exist, non-existent or inadequate practical experience	None, donor dependent
II	Sporadic	Limited	Moderate, e.g., dedicated computers with backup	Fewer than 25 air focused staff	Basic technical training, some advanced technical or analytical capacity, limited practical experience	
III	Regular, some outages	Access to, or conducts own limited lab analysis	Dedicated data computers or servers, backup and data sharing agreements	At least 50 air focused staff	Some advanced technical training in addition to specialists in monitoring, emission inventory, some but inadequate technical experience	Some central funding, but significant donor funded projects
IV	Consistent, infrequent outages	Access to or conducts own advanced lab analysis	Dedicated data computers, QA procedures, secure data backup and data sharing agreements	At least 75 air focused staff	Some advanced technical training in addition to specialists in monitoring, emission inventory, air quality management	Centrally funded, some donor support
V	Consistent	In-house advanced lab analysis	Dedicated data computers and in-house data servers, secure backup and online data	Over 100 air focused staff	Advanced technical training in addition to specialists in monitoring, emission inventory, air quality management, communications, data management, economics etc.	Centrally funded, including in-house research

2.3 Policy and Legal Framework

In addition to the country contexts identified above, there is another important component to air quality measurement – the legal framework under which air quality measurement is conducted. These frameworks may define the government agency with the mandate to conduct air measurement, require private sector industries to conduct various forms of facility based monitoring, establish ownership of and access to measurement data; and could even provide for the ongoing financial support for an air measurement program. For example, the Ghana EPA is mandated by a 1994 Act of Parliament to conduct environmental quality monitoring and prescribe guidelines and standards for air, water, noise and soils.[8] The legal framework will vary from country to country, being nonexistent in some countries and being very detailed and explicit in others. The legal context will not necessarily constrain the type of measurement methodologies employed, but may have significant constraints on the ultimate uses of the data, and impact the sustainability of an air measurement program. This is discussed in more detail in Chapter 4.

2.4 Integrating Objectives with Context

The next chapter, which discusses the technology aspects of air quality measurement, reorients the aforementioned broad measurement objectives into four overarching objectives that are likely to be the top priorities of LMICs, based on input from the Filling the Gaps Workshop participants: (i) establishing a baseline; (ii) increasing public communication and awareness; (iii) identifying sources; and (iv) exposure assessment. This sets the stage for summarizing the final set of recommendations in Chapter 5.

[8] http://www.ilo.org/dyn/natlex/docs/ELECTRONIC/39863/101264/F1742544814/GHA39863.pdf

Filling the Gaps: Chapter 3
Technical Steps and Future Research Needs to Meet LMIC goals

3.0 Introduction

A recurring theme of the Filling the Gaps workshop was the need to fit technology for the desired purpose. To do this, it is critical to understand the range of available options and the strengths and weaknesses, and associated requirements and costs for each. This chapter discusses these issues and explores the related needs for data management, quality assurance and how decision makers can begin to make sense of their options. In addition, the chapter offers a few suggestions for research to advance the state of air measurement knowledge.

3.1 Ground-level Monitoring – State of the Art

The level of cost, complexity, and effort involved with regulatory-grade approaches of air monitoring have thus far stymied the widespread installation and operation of air monitoring networks in many LMICs. Summarized in Table 3.1, regulatory-grade approaches for $PM_{2.5}$ are nontrivial to install and operate, requiring laboratory support capabilities for integrated filter methods and usually reliable electricity. Sub-regulatory-grade continuous monitoring methods also exist, and here are classified into two general groups: 1) well-established non-regulatory-grade technology (WNT) that have been on the market for over a decade and extensively used in research studies, and are generally more portable and lower cost than regulatory-grade monitors (e.g., thousands of USD), but have inferior accuracy and precision compared to regulatory-grade monitors, and, 2) emerging non-regulatory-grade technology (ENT), often referred to as "sensors", which have desirable attributes of being miniaturized and at a low purchase price point (e.g., hundreds to thousands of USD), but their accuracy, reliability, longevity, and full cost of use are not well-established.

Gas-phase pollutants – such as ozone, sulfur dioxide, nitrogen dioxide, and carbon monoxide – can be monitored by regulatory-level technology which measures continuously (e.g., minute by minute data). For a number of gases, passive measurement approaches also exist, which involve a sample media that is placed in an environment for a period of time and then laboratory analyses conducted afterwards. Passive samples for gas-phase species (e.g., NO_2) are commonly conducted at time-scales of weeks.

Routine testing by two groups in the United States, the USEPA[9] and the South Coast Air Quality Management District[10], has revealed some promising performance for select $PM_{2.5}$, ozone, and NO_2 ENTs. However, these results were obtained in lower concentration environments than commonly occur in many LMICs and no long-term testing (>1 year) has been accomplished. Over long-term use, gas-phase ENTs are anticipated to expire within a timeframe of 1-2 years and particulate matter ENTs may degrade due to dirtying of the sensor over time. This means that long-term use would require longer-term funding support and commitment to replace

[9] https://www.epa.gov/air-sensor-toolbox/evaluation-emerging-air-pollution-sensor-performance
[10] http://www.aqmd.gov/aq-spec/evaluations/

sensors. Despite the uncertainty in ENT performance, many research groups, nonprofits, government institutions, and the private sector are moving quickly to establish pilot ENT networks in locations around the world. In addition, ENTs are being sold as consumer products for in-home or outdoor air quality monitoring and use as a wearable technology.

The total cost of monitoring, in particularly ENT monitoring, is of heavily debated. Although ENTs are being often referred to as "low-cost", the low upfront cost of the hardware may be offset to some degree by the cost of data analysis and management. Analysis of ENT data is more difficult because data quality is uncertain and data are produced in very high volume. Full consideration of ancillary costs, as well as consideration of the length of monitoring and lifetime of technology, should be included in any accounting.

Table 3.1 Summary of detection approaches for $PM_{2.5}$

Approach	Detection approach	Strengths	Weaknesses
Integrated filter regulatory-grade monitor	Particles are size-selected (impactor or cyclone), collected to a pre-weighed filter, then weighed after collection	Highest-fidelity measurement of particle mass concentration; laboratory analyses can include chemical composition. Expected technology working life exceeds 10 years.	24 hour samples; requires analytical laboratory capability, generally requires land power for long-term use.
Continuous, regulatory-grade monitor	Particles are size-selected (e.g., cyclone) then measured through one of several types of methods - beta attenuation, tapered element oscillating microbalance, or optical detection.	Continuous measurement, with data available typically on an hourly basis (some on a minute basis). Well-established approach for regulatory use. Expected technology working life exceeds 10 years.	High cost of sampler; maintenance of monitor; power consumption generally requires land power for long-term use. Correlation factors needed for integrated filter regulatory-grade monitor.
Continuous, well-established non-regulatory technology (WNT)	Particles are size-selected (e.g., cyclone), detected either optically or via beta attenuation. Sometimes includes on-board measurement of relative humidity to provide artifact-correction.	Continuous measurement, with data available typically on the order of seconds to minutes. Lower cost, lower power consumption, and greater portability. Expected technology working life exceeds 5 years.	Less accurate than regulatory-grade monitors.
Continuous, emerging non-regulatory technology (ENT)	Particles are detected via either: 1) an optical particle counter, which sizes and counts the particles optically, or 2) without any sizing and measuring how the ensemble of particles	Low purchase price point; miniaturized and low power consumption support small integrated ENT systems for dense sensor networks or portable monitoring.	Does not size-select for strictly <2.5 um particles; performance under varying pollution mixtures and concentration levels is poorly known. Technology expected to degrade or fail

	scatter light.		in 1-2 years.

3.2 Satellite Remote Sensing

Satellite-based remote sensing of air quality is promising, because it offers the prospect of daily observational information for most locations in the world. Satellite sensors measure interference in the light energy reflected or emitted from the Earth, which scientists use to calculate concentrations of air pollutants such as particulate matter, nitrogen dioxide, carbon monoxide, and ozone. In the case of particles, the satellite sensors measure the Aerosol Optical Depth (AOD) -- the degree to which light has been absorbed or scattered by particles in the atmosphere. Using geophysical models and statistical calibration, scientists continue to refine how they relate the satellite-based AOD observations to the surface concentration of $PM_{2.5}$.

There are several challenges to converting the AOD to an estimate of particle concentration. Some challenges include:

- No universally agreed upon methodology to determine relationship between AOD and surface concentrations: Columnar aerosol optical depth is influenced by aerosol throughout the entire atmospheric column. Scientists have used the vertical distribution of aerosols from chemical transport models (such as GEOS-Chem) to then infer the surface aerosol contribution to the columnar AOD to infer surface level PM.
- Effect of humidity: AOD is measured at ambient relative humidity, while ground-level $PM_{2.5}$ in reference monitors is usually measured at a controlled relative humidity.
- Coarse spatial resolution: the sensor observes an average value over a spatial resolution of a few kilometers. (Note that the research algorithm for these instruments can sample the data at a finer spatial resolution; however, such a computation is more expensive).
- Effect of clouds, deserts, snow, dust and complex topographies: It is difficult to differentiate the particles on cloudy days or over particularly bright deserts and snow covered surfaces, and accuracy is unreliable in complex topographies such as mountainous areas, and in areas affected by natural dust and sea salt.
- Measurements cannot be taken at night. The satellites only pass over a specific place once a day, usually between mid-morning and early afternoon.

It is important to understand that currently, there are significant technical challenges in using satellite data. As a result, NASA has developed the ARSET training series (https://arset.gsfc.nasa.gov/) to help users access and use satellite data. Pre-made maps of pollutant derived from satellite data, such as the global surface $PM_{2.5}$ map in Figure 3.2, can also be used. These and other useful data sets are available online[11,12].

Because of the challenges listed above, satellite remote sensing cannot replace ground based monitors. The satellite data are most accurate when calibrated using ground-based measurements. The uncertainty increases without ground-based calibration, especially over bright surfaces like deserts and snow. However, this technique has been used to study the global distribution of $PM_{2.5}$ and implications for human health on a global level, track

[11]Annual average PM2.5: http://fizz.phys.dal.ca/~atmos/martin/

[12]WMO Sand and Dust Warning System: https://www.wmo.int/pages/prog/arep/wwrp/new/Sand_and_Dust_Storm.html

year-to-year trends, and provide an early warning system for dust storms and smoke plumes. In addition, such data can help guide the deployment locations of ground based monitors. One example of using satellite data in a global context is the global satellite-based estimates of annual mean $PM_{2.5}$ concentrations used for Global Burden of Disease assessments.[13] The availability of these $PM_{2.5}$ estimates for every LMIC worldwide offers valuable public information about $PM_{2.5}$ concentrations. For example, in China and India this publicly available information source has been used to draw attention to severe air quality issues to motivate additional ground-based monitoring and air pollution mitigation activities. Integration of the satellite data with ground-based measurements enables more accurate, precise, and complete information as discussed in the next section.

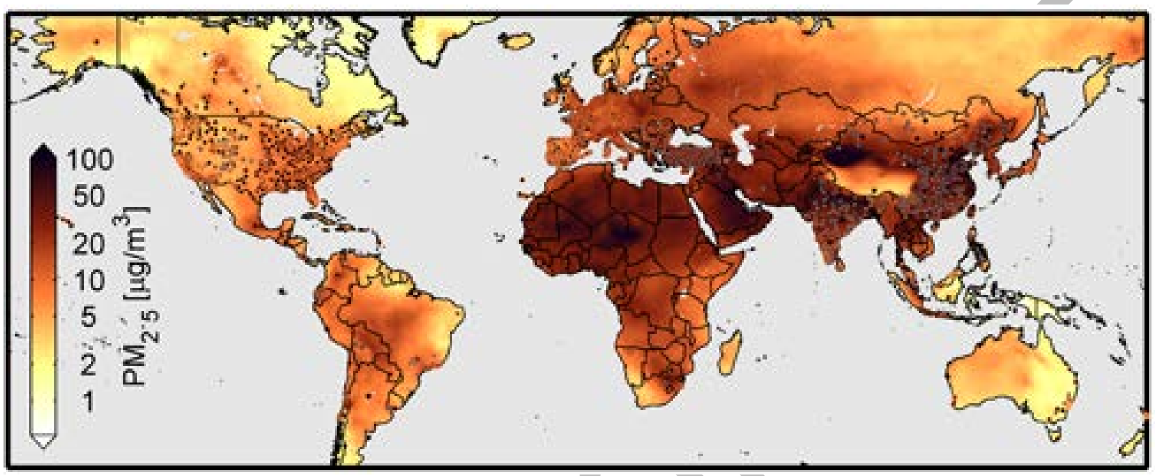

Figure 3-1: An example of $PM_{2.5}$ data from satellite remote sensing, with dots denoting the location of ground-based monitors.[14]

3.3 Integrating Air Quality Measurements

As air quality monitoring technology and methods develop, it becomes clear that the disparate data sources (e.g., regulatory-grade monitors, WNTs, ENTs, and satellite remote sensing) produce different, sometimes inconsistent, information. Regulatory-grade air monitoring stations often offer the most accurate measurement source, but at a single point with limited spatial representativeness. WNTs or ENTs, in a network or on a mobile platform, offer measurements across a broader area, but with lower accuracy. Satellite remote sensing offers observational information across an entire country and beyond, but has lower spatial resolution as well as fixed time windows, and is more complicated to interpret. Integration of these different measurement platforms offers the opportunity to capitalize on their attributes to have an enhanced understanding of air quality.

[13] Cohen AJ, Brauer M, Burnett R, Anderson HR, Frostad J, Estep K, Balakrishnan K, Brunekreef B, Dandona L, Dandona R, Feigin V, Freedman G, Hubbell B, Jobling A, Kan H, Knibbs L, Liu Y, Martin R, Morawska L, Pope CA 3rd, Shin H, Straif K, Shaddick G, Thomas M, van Dingenen R, van Donkelaar A, Vos T, Murray CJL, Forouzanfar MH. Estimates and 25-year trends of the global burden of disease attributable to ambient air pollution: an analysis of data from the Global Burden of Diseases Study 2015. Lancet. 2017;389:1907–1918. doi: 10.1016/S0140-6736(17)30505-6.

[14] van Donkelaar A, R.V Martin, M.Brauer, N. C. Hsu, R. A. Kahn, R. C Levy, A. Lyapustin, A. M. Sayer, and D. M Winker, Global Estimates of Fine Particulate Matter using a Combined Geophysical-Statistical Method with Information from Satellites, Models, and Monitors, Environ. Sci. Technol, doi: 10.1021/acs.est.5b05833, 2016

Integration of these disparate data sources could be facilitated with a supersite that includes fixed monitors that can be easily accessed by mobile low-cost sensors, and that includes ground-based remote sensing instrumentation. Placing ground based monitors in the same location as remote sensing instruments can improve the understanding of the relationship between these two different measurement sources. Periodic collocation of portable ENTs with the regulatory-grade air monitors facilitates calibration of the low-cost sensors to foster measurement consistency that aids interpretation, and relates ground-based observations with area-average concentrations measured by satellites. The Surface Particulate Matter Network (SPARTAN)[15] is an example study focused on integrating ground-based and satellite-based measurements, by collocating ground-level monitors with ground-based sun photometers that measure AOD, in order to improve the accuracy of satellite-based estimates of ground-level $PM_{2.5}$ across the surrounding region. In addition, NASA's AERONET, a federation of ground-based remote sensing networks, measures AOD at ground level to ground truth and validate satellite aerosol retrievals.

3.4 Quality Assurance Considerations

The importance of quality assurance planning and execution in air monitoring cannot be overstated. The key quality assurance/quality control (QA/QC) elements in air monitoring involve the establishment of data quality objectives (e.g., data completeness), standard operating procedures (SOPs) for instrumentation and analytical laboratory processes, appropriately trained personnel, data management, and data reporting. Several good sources of information exist for traditional air monitoring practices, including EPA's Air Monitoring Technology Information Center (AMTIC)[16]. For WNTs and ENTs, similar quality assurance principles apply but need to take into account any additional steps required to build confidence in the data (e.g., correction for measurement artifacts). The cost and efforts involved in data collection may be undermined if QA is not treated as essential - examples of common failure points can include the loss of fidelity of integrated $PM_{2.5}$ filter samples through improper handling, an incorrect flow rate leading to erroneous size-selection of particles entering an inlet, and unreliable data from WNTs or ENTs if not demonstrated or calibrated against reference monitors in the LMIC environment. Successful air monitoring requires a rigorous QA/QC system and ongoing training of staff involved in air quality data collection and dissemination.

Auditing of air monitoring is a common practice, involving bringing a well-maintained reference monitor to an air monitoring site and operating the reference monitor side-by-side for a period of time as a point of comparison. Auditors are highly trained in both air quality monitoring as well as quality assurance practices. Audits include not just review of data but how the raw data are being collected, amended, and ultimately finalized However, in the case of dense ENT networks, this approach may be impractical. The best practices for ENT networks have yet to be established -- currently, pilot projects have varied from conducting frequent collocation with reference monitors (most commonly, moving the ENT to be located with the reference monitor)

[15] SPARTAN website: http://spartan-network.org/
[16] AMTIC Quality Assurance Documentation - https://www3.epa.gov/ttnamti1/qalist.html

to exploring virtual calibration schemes that involve making assumptions that the ENT data may be comparable to another location within a certain geographic distance and specific times of day.[17,18]

3.5 Data Management, Dissemination, and Analysis

The goals of air quality data management are to (i) archive data sets for access in perpetuity, (ii) carefully track the data through the quality assurance process, and (iii) communicate and raise awareness about air quality and human health. A data management plan is critically important to a successful monitoring effort, and should be considered while developing the monitoring strategy.

An archive is a long term, redundant data storage system that guarantees the data will be available in the future. In the simplest form, data are recorded in a logbook, entered into a spreadsheet, and replicated electronically. It is critically important to also archive any meta-data about the location, timing, and quality checks needed to interpret the data.

In addition to archiving, a data management plan should include a protocol for data access, defining who has permission to access which datasets. Quality assurance specialists and auditors need to access and edit the data to provide quality flags or corrections. Air quality analysts need broad access to both the pollutant concentrations and meta-data about quality checks or corrections. Programmatic access to the data allows third party developers to build additional tools for visualizing and analyzing the data or creating specialized alerts. Making this data available to academia and other researches (see section "3.7 Research Needs" below) can go far to strengthen understanding of the challenges and solutions in addressing air quality impacts.

Finally, making air quality data available to the public is a powerful way to build awareness and unlock myriad uses of the data for public good. It is important to carefully develop the communication strategy such that people have information that is comprehensible and actionable. For example, the Air Quality Index relates concentrations to a color scale, where each color has recommendations about which sensitive groups should limit exposure. This is discussed further in Chapter 4.

Historically, a data management system would require procurement of computers, software, and services; however, this approach is challenging to set up, expensive to maintain, and difficult to scale as the monitoring network grows. EPA's AirNow International project freely provides information on how to develop a system that includes archiving, data access for practitioners, and public communication (airnow.gov). The features and complexity of AirNow are beyond what is needed by most countries starting a monitoring network, though several pilot projects are underway to better understand how AirNow could meet these needs. A more

[17] Moltchanov, S., Levy, I., Etzion, Y., Lerner, U., Broday, D. M., and Fishbain, B.: On the feasibility of measuring urban air pollution by wireless distributed sensor networks, Sci. Total Environ., 502, 537–547, doi:10.1016/j.scitotenv.2014.09.059, 2015.

[18] Jiao, W., Hagler, G., Williams, R., Sharpe, R., Brown, R., Garver, D., Judge, R., Caudill, M., Rickard, J., Davis, M., Weinstock, L., Zimmer-Dauphinee, S., and Buckley, K.: Community Air Sensor Network (CAIRSENSE) project: evaluation of low-cost sensor performance in a suburban environment in the southeastern United States, Atmos. Meas. Tech., 9, 5281-5292, https://doi.org/10.5194/amt-9-5281-2016, 2016.

lightweight system that takes advantage of open source communities, reduces maintenance complexity using cloud computing, and leverages standardized programmatic interfaces deserves further exploration and development.

By making data programmatically available and/or participating in an open data projects, governments can foster various uses of the data that are outside its direct purview but reinforce its mission to provide cleaner air the public, as well as make use of these tools themselves. Programmatic access to data is the ability for data to be shared seamlessly with other computer programs or users. The benefits of making data publicly programmatically accessible is that it allows the data to be fused into other applications much more easily and in a timely manner. Most commonly, programmatic access is given by sharing the data in a predictable format through an Application Programming Interface (API).

Several air quality projects that ingest open air quality data exist around the world and can be utilized by both air quality agencies and the public. A number of air quality analysis software tools are freely available, such as the openair package in the R statistical system (openair-project.org). The non-profit OpenAQ project can automatically upload air quality data, store it in their archive it, and make it publically accessible on their webpage with analysis and visualization tools. The OpenAQ community of developers, researchers, and practitioners are constantly creating new data analysis tools that are freely available (openaq.org). Some monitoring equipment vendors also offer proprietary cloud-based solutions for storing and visualizing data. It is important to consider the reliability and long-term availability of these options.

3.6 Research Needs

A driving research question regarding alternative approaches for observational data in LMICs is - what is the achievable data quality, and under what circumstances? For sensor technology, there are many unknowns regarding how sensors will perform under the full dynamic range of concentrations and air pollution mixtures. The orders-of-magnitude increase in the number of sensors and associated data sets will lead to fundamentally different ways of how the measurements may be conducted and data utilized, which require targeted research for their application in LMICs. Additionally, research is needed to understand the potential use of multiple data types in concert (e.g., satellite data, sensor data) and quantifying uncertainty. LMICs should consider all these recommendations when an ENT or satellite remote sensing applications are proposed, special care must be considered when reliability of the information is not known or cannot be proved.

Air Monitoring in Peru – Technical Challenges

Many LMIC presenters at the Filling the Gaps meeting described challenges with successfully implementing air monitoring that came after the initial regulatory-grade monitors were procured. A presenter from Peru described that no more than five cities (Lima, Arequipa, La Oroya, Ilo y Tacna) had reliable air monitoring, while other cities had limited monitoring and frequent gaps in data. Technical challenges included maintenance of equipment, lack of standard operating procedures and training, inconsistent data management, and an overall insufficient air monitoring budget. As a result, only Lima and Arequipa had data reported to the public online in a reliable fashion. New investment is supporting Peru to improve its air quality monitoring capacities and infrastructure.

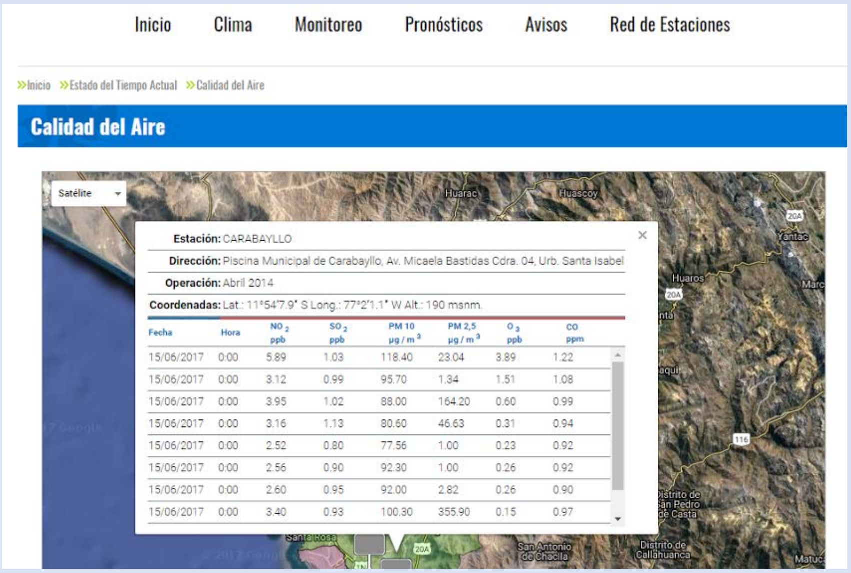

Figure 3.3. Image of the Peru air monitoring data system.

Filling the Gaps: Chapter 4
Sustainable and Successful Monitoring:
The Human and Institutional Dimension

4.0 Introduction

The main focus of this document is on the technical aspects of ambient air quality measurement and characterization, but early consideration should be given to the human dimensions needed to fill the air quality data gaps in LMICs and ensure the sustainability of data and data collection systems over time. The challenge of improving access to high quality data in LMICs is not solely a technical one. There are a number of additional considerations that require planning and investment to ensure sustainability and integration into a broader air quality management program. These considerations include establishing the necessary legal authorities, resourcing human and financial needs, and central coordination to enable AQ monitoring networks to achieve their objectives; ensuring proper investment and accountability for staff and equipment; acquiring, training and retaining qualified staff; establishing relationships with private and academic partners to both optimize training and expertise, and to help establish local, regional and international communities of practice that transcend any local shifts in staffing or governments; and finally communicating effectively within government and to the public about air quality issues.

4.1. Establishing Legal Frameworks, Authorities and Resourcing for Success

Legal Frameworks and government ownership: As mentioned in Chapter 2, to achieve long term sustainability of air monitoring programs, the responsible government agency must have a clear legal mandate to conduct the work. This responsibility varies, with the national government taking the lead in some countries, while in others municipal or provincial governments have the authority and mandate for monitoring. If such authority does not exist, work should begin immediately to establish these authorities, roles and responsibilities. The authority should be very clear not only regarding authority for monitoring, but also for data ownership, management and sharing, as well as responsibility and accountability for financing, validating and reporting of data over time. A well-crafted and inclusive legal framework is an important underpinning of a successful, long term monitoring network.

Legal authority is necessary, but not sufficient, to launch successful AQ monitoring networks. Experience has shown that governments who take 'ownership' of this authority and strive to embed their environmental goals throughout other governmental policies – including coordination of environmental policies with other sectoral policies as discussed in the next section – are best able to design networks that are tailored to national needs, ensure adoption of procedures and enforcement across sectors, and more effectively implement monitoring plans.

Resources: The most basic demonstration of government ownership of AQ monitoring objectives is shown with financial resources in support of network costs. While it may be tempting to take advantage of opportunities to purchase equipment with international donor resources, experience has shown that it can be short-sighted to deploy this equipment without long-term dedicated funding for staff to operate the equipment, quality assure and validate the data and perform analysis that can help make the case for further investment in AQ monitoring (i.e. demonstrate the benefits of action). Other critical costs for AQ monitoring network include long-term operations and maintenance costs to ensure that equipment is supplied with annual budgets for consumables and ongoing equipment calibration and maintenance.

This necessarily requires that countries commit internal resources and that such funding is allocated across government ministries/agencies to encourage coordination/collaboration and avoid duplication.
While this undertaking may seem cost-prohibitive at first, LMICs should explore various funding models that have enabled regular national budget allocations for AQ monitoring in other countries. For example, permit fees for selected industries can be a source of revenue to those ministries that ensure compliance; resources for data analysis can be enhanced through academic collaborations utilizing grant resources; health benefits assessments can demonstrate potential health sector savings that might make the business case for prioritizing air quality monitoring in national budgets.

4.2. Administrative Coordination and Processes

Cross-Governmental and Cross-Sectoral Coordination: The responsibility to address air quality at the national level is typically spread across several ministries and authorities, such as Ministries of Environment, Transportation, Energy, Meteorology, and state and city-level agencies. At the same time, officials charged with delivering jobs, stimulating economic growth and promoting competitiveness are becoming increasingly concerned about the effects of environmental quality and climate change on their country's economic future (World Bank 2016 and ClimateWorks, 2014). However, these officials are primarily focused on issues related to their core mandate and can often be less aware of the impact or significance of linkages to air quality. Establishing a dialogue and relationships within each country across governmental authorities is critical to understanding roles and responsibilities, fostering coordination and collaboration and leveraging resources. It is critical that the central government enable AQ monitoring programs to identify those investments that will advance urgent development priorities and reduce the health and social impacts of air pollution.

In addition to stakeholder engagement, communications and outreach (See Section 5.4), it may be helpful to develop communication and advocacy materials directed toward specific government actors to provide information on how their work is affected by air quality impacts – for example, public health costs such as illness, reduced lifespans, and reduced economic development. For example, the Ministries of Labor or Finance are focused on foreign direct investment, yet much of that investment could worsen trends in urbanization, congestion and air quality, if not planned to prioritize cleaner processes. It may also be helpful to conduct national-level cost-benefit analyses, where necessary data is available, in order to allow governments to better evaluate air quality risks and enable them to appropriately prioritize the issue. It is also helpful to integrate air quality concerns with other related issues such as climate change so that governments can address these issues more efficiently and effectively. Policies should be integrated into high-level mandates and made as resilient as possible to political shifts. Though national environmental agencies are a natural home for air quality management activities, it is critical that partnerships are built with public, private and academic institutions to access additional skills and resources. This approach can help ensure sustainability over time, because governmental institutions can be subject to electoral and policy changes.

Multi-sectoral data collection, decision-making and policy and standard setting have historically been difficult for LMICs because they require = coordination across governmental sectors. Through the establishment of air quality management cooperation (at various levels) that enables cross-sectoral, cross-institutional data collection, resource allocation, training and capacity building, LMICs can assign roles and responsibilities with lines of authority that trace back to the central government, yet take advantage of individual areas of expertise that contribute to broader AQM goals. Combined, these can contribute to improved sustainability and success in the long term.

Procurement Arrangements: It is important that LMICs address supply chain obstacles to successful air quality monitoring, including lack of access to suppliers of products needed for AQ monitoring, lack of vendors qualified to provide training in their countries, or regulatory barriers. Rules should be avoided that limit procurement options, such as single supplier restrictions for a whole country's monitoring program, which can slow supply chains or restrict flexibility. Regional suppliers can bring down costs, not only for initial purchases, but also for repairs, supplies and consumables. The recommendations outlined in Section VI, can be very useful for identifying specifications for equipment, but will not help if a country is unable to procure these options because of restrictive purchasing guidelines or a lack of vendors that carry highly rated products.

Standards that specify minimum quality standards are helpful to avoid the purchase of unreliable equipment. However, a balance must be reached so that quality standards are not so specific that very few suppliers qualify. One possibility is to establish nationally appropriate quality standards and a process of vendor certification. Countries should also consider developing standard contracting guidance, such as what elements might be included and how long to maintain support for various monitoring approaches. It is also important to ensure that spare parts, consumables and expertise related to repair and maintenance are available at a reasonable cost and within a reasonable timeframe.

4.3. Technical Capacity Building, Training, and Program Sustainability

Sustainable, long-term air quality monitoring in LMICs requires staff with specific technical skills. It also requires that government agencies retain those staff over a reasonable period of time and have succession plans in place to manage staff turnover. For new programs, it is imperative to build upon existing pools of talent and leverage skills that are already in place. A good initial step for a new air measurement program is to assess the existing capacity. This might include those within the relevant government agencies, but should also include potential partners in academia and the private sector. This process necessarily should cast a wide net, be participatory and inclusive, including all national stakeholders with practical skills related to air quality monitoring. This skills mapping could be reflective of the principal sectors associated with key emission sources, such as transportation, industry, household, agriculture, and municipal solid waste as well as ministries or offices with key roles in monitoring or enforcement of potential regulations.

Assessment of skills and capacities at the local level can serve as a basis for building coordinated regional programs. Over time, these programs can enable knowledge sharing and continuing education via south-south exchange or through international development partners.

Box 5.1: A Process for National And Regional Skills Mapping

Because air quality impacts many sectors, and many of those sectors – in turn – affect the quality of air, investing in national level coordination of air quality monitoring and other aspects of air quality management (AQM) could enhance sustainability of AQM efforts over the long term. One potential national level coordinating structure would be the creation of a national focal point mapping exercise to coordinate policy, inventory reporting and other monitoring requirements. With respect to air quality monitoring, such a coordination body could:

- Establish a national team of experts who have knowledge and skills on air quality management.
- Conduct a coordination workshop with the expert team to define responsibilities for data collection based on an analysis and understanding of what is feasible and practical, given the existing organizational structures.
- Discuss and coordinate functional and technical areas of expertise among existing national and regional programs, projects or initiatives related to air quality monitoring.
- Conduct technical visits to local expert institutions including government labs, academic institutions or other institutions that host monitoring, analytical or data analysis capacity.

Based on an understanding of various skills and capacities, a national air quality monitoring action plan can lay out individual roles and responsibilities for a comprehensive air quality monitoring program, including a definitive list of equipment, monitoring protocols, quality assurance and data management expectations and maintenance plans. The plan should also define resources and staffing to support AQ monitoring activities. Finally, the plan will evaluate the existing equipment and identify gaps, and the needs for additional capacity building on both the technical and institutional levels.

Regional and International Coordination. After a comprehensive national-level skills mapping has been conducted and a coordinated national plan is established within a group of countries, enhanced regional cooperation is possible with different countries bringing their individual strengths to support regional collaboration. This regional collaboration could include the creation of a shared platform for training, support and exchange between countries. For example, remote sensing may be a particular area of expertise in one institution in one country, whereas emission inventory development or a specific type of analytical chemistry may be the specialty of another country. While local resources are necessary to support local training, international or regional agreements may be able to support additional training in areas where various countries have specialized skills. Donor institutions may find it beneficial to be able to offer training and resources regionally, in addition to what is offered to a subset of countries on an individual basis.

An example of how such a process might be carried out in a typical developing country is provided in **Box 5.1**, which demonstrates some key steps in both national and regional exercises to establish and communicate focal points of local expertise that exist. Such an exercise enables local, national and regional governments and other support structures – such as regional collaborations or aid agencies – to allocate resources to build on existing strengths and identify capacity gaps that need to be addressed.

Staff retention is also a problem for many LMICs where training and capacity building often results in new opportunities for entry level staff to seek other opportunities in industry or out of country. Increased collaboration with independent research institutions or academic partnerships – as described in the Box 5.1 example – can further embed critical skills within a country's core capacities and ensure a pipeline of qualified individuals to address potential turnover challenges.

4.4. Effective Communication and Stakeholder Engagement

As pointed out in the prior paragraphs, successful program implementation requires investments in human and financial resources by high-level government officials, coordination of sometimes conflicting mandates across government sectors, understanding and support of policy directives by affected industries, and understanding and support by the public. Effective communication is needed to reach these various audiences, and planning and budgeting for communication and public involvement is important. A well thought out communication strategy can enhance program success and therefore should accompany technical work.

Internal Communications: A key theme emerging from experience with LMICs is that internal government communication is as important as public awareness raising. Environmental ministries must do more to share knowledge and key messages across government ministries – finance, health, energy, transportation etc. - about air pollution and health, availability of known solutions, and the benefits of clean air for development priorities. Sustainability of air measurement and management programs requires significant collaboration and cooperation across ministries, and communicating effectively can bolster those efforts.

Data sharing may be a particular concern on the part of governments due to potential implications of sharing data that may show high pollution levels. Effective communications planning can go a long way to mitigate these concerns (see below). Sharing data can build broader support for addressing air quality and also create stronger demands on authorities to take action to address air pollution emissions.

Public Communication: Effective communication is important for any environmental agency action, but it is especially critical in situations where new data may signal a public health threat, or even when new equipment is installed in a public area. Consideration must be given to the timing of data release, (it is best to release important data to the public as quickly as possible) and what is known regarding data quality, but also to what an environmental agency may want to say regarding public health, actions the agency is taking and actions the public may take to protect themselves. Governments must also be prepared to explain any relevant limitations on the use of data, especially data that has not been quality assured. For this reason, data sharing agreements should be carefully written and explained to avoid public confusion. Governments may also be called upon to explain data provided to the public from outside organizations who may be conducting their own monitoring. Some government agencies are concerned about how the public will react to certain data, but these concerns can be mitigated by careful planning and messaging. As more air quality measurements become available, serious consideration needs to be given to the ways in which data will be communicated to the public, setting clear expectations and being prepared to respond to a wide range of questions that the data will motivate, whether that data is provided by the government, or released by others.

A knowledgeable public can be a powerful and permanent advocate for air quality solutions. Excellent resources are available to those who want to conduct a public participation campaign, including the USEPA online Public Participation Guide. Public participation should be fully integrated in air pollution measurement and data efforts, as well as air quality management more broadly.

As with ambient monitoring, a communication strategy will evolve differently depending on the desired goals. Example goals include raising public awareness of the health burden of air pollution so they support control programs, alerting the public to a specific air quality threat, promoting widespread adoption of a new technology, convincing government managers to support program development and implementation programs, or informing affected industry about a new regulatory requirement.

Communications planning: A written communication plan can serve to organize the various components of a communication strategy. A written plan can include a summary of the action, including background information as needed. The plan can also help a communication team strategize about potential incoming questions in advance, so staff can be prepared with answers. The written plan should include three to four key messages, as well as anticipated reactions from the various audiences and key points of contact who can answer any questions that arise.

Regardless of the audience, in developing a communication plan, there are some questions that should be explored: Who will benefit from knowing about air quality? If an action is being proposed, who can benefit from actions your agency may take? Who might be harmed or bear some cost? Who could stop the project from being successful? Who else might be affected?

Similarly, when developing key messages, some basic principles apply. First, keep it simple. Translate complex concepts into ideas and messages that can be easily understood. Make any message short, easy to explain, easy to understand, and easy to remember. Do not try to do too much. Too many concepts can be confusing, and lose the audience's attention. Be consistent. Whatever information is provided must not conflict with other information that may have been given previously. Repeat often. Use local knowledge to determine the people to whom the public listens. Engage different messengers to different audiences, and take advantage of different venues or media to reinforce the message.

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World Bank and ClimateWorks, 2014. *Climate-smart Development: Adding up the benefits of actions that help build prosperity, end poverty and combat climate change*. The World Bank, Washington, DC and the ClimateWorks Foundation, San Francisco, CA.

Filling the Gaps: Chapter 5
Recommendations

5.0 Introduction

Measurement recommendations will necessarily vary by country capacity. Recognizing that significant variation exists with respect to air quality monitoring capacity among different LMICs, this paper has presented a typological framework in Chapter 2 that groups country capacity into five separate types. Current air quality monitoring capacity in many LMICs is representative of the Type I, II or III descriptions (e.g. either no ongoing monitoring or limited monitoring programs with gaps; see expanded information on characteristic features of each country type in Section III). Given this distribution, the recommendations provided focus on these first three stages of monitoring network development. Ideally, detailed guidance will describe actions, protocols and methods for each interim level of monitoring that LMICs achieve now and into the future – enabling them to proceed systematically along a path deepening their level of engagement at each step. The ultimate goal is air quality monitoring characterized by routine, high-quality monitoring networks capable of supporting comprehensive air quality management planning.

Monitoring objectives also vary, and drive network design. It is also important to recognize that while recommendations for air quality monitoring should be appropriate to a country's capacity, they also must be appropriate to the specific monitoring objectives. The various monitoring objectives that LMICs cite as the most common reasons for establishing routine air quality monitoring networks were also presented in Section III. Among those objectives were (i) baseline assessment and evaluation against regulatory standards (including compliance monitoring), (ii) raising public awareness/public information, (iii) source apportionment or source attribution, and (iv) exposure monitoring and health assessment. As indicated, other objectives exist as well, such as research, model validation, AQM accountability and others.

A common progression of objectives and capacity defines a progression for building AQ monitoring programs. It is not uncommon for typical monitoring objectives in LMICs to closely follow the level of monitoring engagement (i.e. Type I countries are most likely to be focused on assessment of baseline conditions, Type II countries may add the objective of public awareness, and Type III countries will be concerned with multiple objectives that also include source attribution, etc.). Thus the recommendations have been presented below to serve the *baseline assessment* or *evaluation against standards* objectives but also in a way that is appropriate for Type I countries. Recommendations for *raising public awareness* have been presented in a way that is appropriate to Type II countries that have already established routine regulatory-grade $PM_{2.5}$ measurements at a site or two - and therefore may have satisfied some aspects of their baseline assessment objective. These countries may need to shift focus more toward network design issues to ensure that observations are fit for purpose in informing a disparate public living across many different neighborhoods in a city. Similarly, it would not be uncommon for Type III countries to be interested in objectives related to *source attribution* or *exposure assessment,* which will require measurements of other pollutants and new analytical methods. The authors acknowledge that not all countries will follow the same path and some may need to make adjustments to fit their particular monitoring objectives].

5.1 Measurement Recommendations by Country Type

As outlined in previous chapters, the choice of measurement approaches will be highly dependent on the situation on-the-ground and can evolve over time as that situation changes.

5.1.1 Recommendations: Type I countries

Type I countries are establishing a new air quality monitoring system. The objectives of many Type I countries are typically to understand baseline air quality conditions for fine particle pollution (PM2.5), which is the principle driver of the burden of disease associated with air pollution, and to assess the severity of pollution problems relative to local or national standards or global guidelines. Many monitoring technologies are available to meet these goals, so the first step is often to develop a detailed air quality monitoring plan addressing the issues listed below.

***Choice of monitoring technologies*: LMICs should deploy integrated filter monitoring (e.g. 24-hr collection of particles to filter media, followed by laboratory analysis) or, if near real-time alerts are a higher priority, reference-grade monitors that measure continuously.** Monitoring stations form the foundation of the nation's air quality assessment. Key requirements are (i) reference-grade accuracy, (ii) straightforward operating procedures and calibration, (iii) low maintenance needs, (iv) locally available service and replacement parts, and (v) cost effectiveness. Given that LMICs don't have the luxury to deploy a new monitoring network as monitoring objectives change, an integrated filter approach is recommended. This technique has been refined over decades and is a dependable means of establishing reference grade $PM_{2.5}$ measurements. Additionally, the archived filter samples can satisfy potential source apportionment needs in the future. There are many vendors who make reliable, reference-grade filter monitors available at reasonable cost. The filters need to be prepared (tared for original mass), changed in and out, re-weighed, and their mass recorded for each 24-hr sampling period (e.g., 1 in 6 day samples), which is labor-intensive. There are more sophisticated monitors with automated filter changing mechanisms, which reduces field labor demands. There are also more simplified monitors that have higher labor requirements but less expensive at time of purchase and usually can be maintained using locally trained staff. Though monitors that measure continuously may be a better fit for real-time alerts, these monitor types (e.g., a beta-attenuation monitor) do not provide the ability to measure chemical composition of particles to better understand the contributing sources.

***Network design*: The selection of monitoring locations should be carefully planned to ensure it is aligned with the immediate objectives, and considers potential future goals.** For understanding general air quality conditions in support of public health, monitoring stations should be located in highly populated areas. Monitors sited in residential areas may be more representative of average exposure across a geographic area, compared to monitors sited next to industry or traffic. In order to manage air quality, additional monitoring sites in strategic locations can help to understand the local or regional nature of air pollution sources. For example, placing an air monitoring station in an area at the edge of an urban geographic area and removed from any local sources, representing "background" conditions, can help identify how much pollution is transported into an urban area through long-distance transport versus generated locally. Finally, positioning monitors in areas near sources (e.g., within a hundred meters of a major roadway) can help determine maximum pollution exposure. Publicly available satellite data offer information to guide monitor placement, such as by identifying regions with high concentrations. Beyond these siting considerations, care should be taken to find locations that are accessible at all times, secured against extreme weather, theft and vandalism, supported by reliable electricity, and representative of a broad area rather than a single, nearby emission source. New monitoring programs may only start with one or two reference grade monitors, but can be supplemented with well-calibrated continuous monitors that are placed based on network design considerations and assessment goals.

Quality assurance: **Develop and implement a quality assurance program that sets data quality objectives and standard operating procedures.** These air quality monitoring data will provide the foundational evidence for national environmental policy decisions, guiding the health of citizens and investments in pollution controls. The quality assurance plan ensures that these decisions are guided by reliable information by establishing data quality objectives (DQOs) which determine the minimum performance for monitors in order to achieve the various network monitoring goals. It should also include standard operating procedures, requirements for audits and calibration, and a data management system that protects the data from being lost or altered. The goal is to develop the necessary infrastructure and skilled staff to operate, maintain and calibrate all measurement technologies against regulatory-grade instrumentation.

Data management: Establish a data management process for recording the measurements, storing modifications during the quality assurance process, providing access to the data, and enabling health officials to communicate actionable information to decision-makers and to the public. Section 3.5 provides several options to meet these requirements.

Ongoing maintenance and support: **Achieve continuous operations by securing ongoing and uninterrupted financial and institutional support**. As air pollution conditions vary over time due to industrial development and changing environmental conditions, a long-term commitment to ongoing measurements is needed to understand the evolving state of air quality. Planning - including financial resources and procurement arrangements - should account for, ongoing training of new staff, maintenance, re-supply and repairs of equipment, and continuous support for quality assurance and data management.

5.1.2 Recommendations: Type II countries

Type II countries have an existing air quality monitoring program designed to characterize baseline air quality conditions. This could include a small network of monitoring stations at secure locations and an established quality assurance and data management program that carefully calibrates all monitoring technologies against reference-grade equipment. Type II countries are often interested in extending their capabilities beyond baseline assessment towards raising public awareness. The elements of an air quality monitoring plan include all of the items listed above for Type I countries, with extensions listed below.

Monitoring technologies and network design: **Measurements of $PM_{2.5}$ using an integrated filter-based method (described for Type I countries) should be supplemented with additional reference monitors (e.g., for gases such as NOx and CO) and an expanded network that considers the location of population (e.g. dense residential neighborhoods or environmental justice hotspots), the location of key emission sources (e.g. train**

or bus depots, highways, industrial facilities) and endemic meteorological conditions (e.g. valleys or hills that prevent dispersion, prevailing winds, etc).

Type II countries will generally already possess the technical knowledge (trained staff) needed to integrate various continuous measurement technologies (as described in section IV) into their monitoring networks based upon the data quality objectives that have been established for Type I monitoring objectives. For instance, co-locating untested continuous monitors at one of the existing regulatory sites with reference monitors establishes the performance characteristics of the new technologies with minimal infrastructure costs. If new technologies can meet revised DQOs that include the objective of providing public information on prevailing air quality conditions or other expanded monitoring goals, then those technologies can be used in monitoring networks to provide data to the public and perform other forms of air quality planning support.

Quality assurance: **Existing quality assurance project plans (QAPPs) should be extended to accommodate new monitoring technologies** as they are introduced to the network and existing DQOs should be modified to meet new monitoring objectives. Since most newer technologies have limited information about their appropriate operational conditions, QAPPs updated to include new technologies would need to frame the purpose of their use and ensure reliable performance characterization across the expected range of observed concentrations.

5.1.3 Recommendations: Type III Countries

Type III countries' monitoring goals include quantifying air quality conditions at multiple locations, tracking trends in emissions and concentrations, identifying relative contributions from pollution sources and sectors, supporting regulatory programs, and advancing air pollution knowledge of exposure and health impacts. The air quality monitoring plan should include the elements for Type I and Type II countries, as well as these extensions listed below.

Monitoring technologies and network design: **The monitoring network should be used to identify the sources of poor air quality (source apportionment) by conducting chemical analysis on the filters collected at reference-grade monitoring sites.** After gravimetric $PM_{2.5}$ mass is determined, in order to understand the chemical composition as well as unique chemical tracers that indicate specific emission sources, such as diesel traffic, wood smoke, or power plants. Based on the relative abundance of these tracers, it is possible to quantify the relative contribution from different types emission sources. If multiple measurement sites are strategically located to maximize source apportionment, multiple data sets can be used along with wind information to identify the location of important emission sources. For example, a site representing "background" conditions with no nearby emissions can help determine how much pollution is transported over long distances and not produced locally. Adding in wind information, multiple sites can be used to look at how different chemical components increase or decrease with wind direction and isolate potential source locations causing nearby pollution increases. The wind-directional type analysis can also be applied using PM2.5 monitors that measure continuously, at a faster time resolution (subhourly), and can indicate the location and relative strength of different nearby sources (e.g., industrial facilities, traffic) that may be impacting air pollution.

While the reference-grade monitoring network provides the foundation for regulatory decision-making, **in Type III countries, continuous monitors and potentially newer, lower-cost measurement technologies can fill in the spatial gaps in the network to provide more detailed local conditions, examine variability in exposure, and**

identify emission sources. Satellite remote sensing can also help fill in the spatial gaps by offering observational information across an entire country and beyond. However, satellite data are more complicated to interpret due to observation of an atmospheric column. Integration of these different measurement platforms – reference monitors, new lower-cost monitoring technologies, and satellite remote sensing with collocated ground-based measurements of the atmospheric column – offers the opportunity to capitalize on their unique attributes in order to glean the maximum information from their collective perspectives.

Communication: Broadcast public alerts to protect human health. Development of the robust monitoring and data management system coupled with an increasingly widespread monitoring network affords countries with a tremendous opportunity to improve human health by public engagement. A national air quality awareness program can issue public alerts, such as the Air Quality Index, which provides health warnings via appropriate websites, mobile phones and electronic street signs. These public alerts help protect human health and raise awareness.

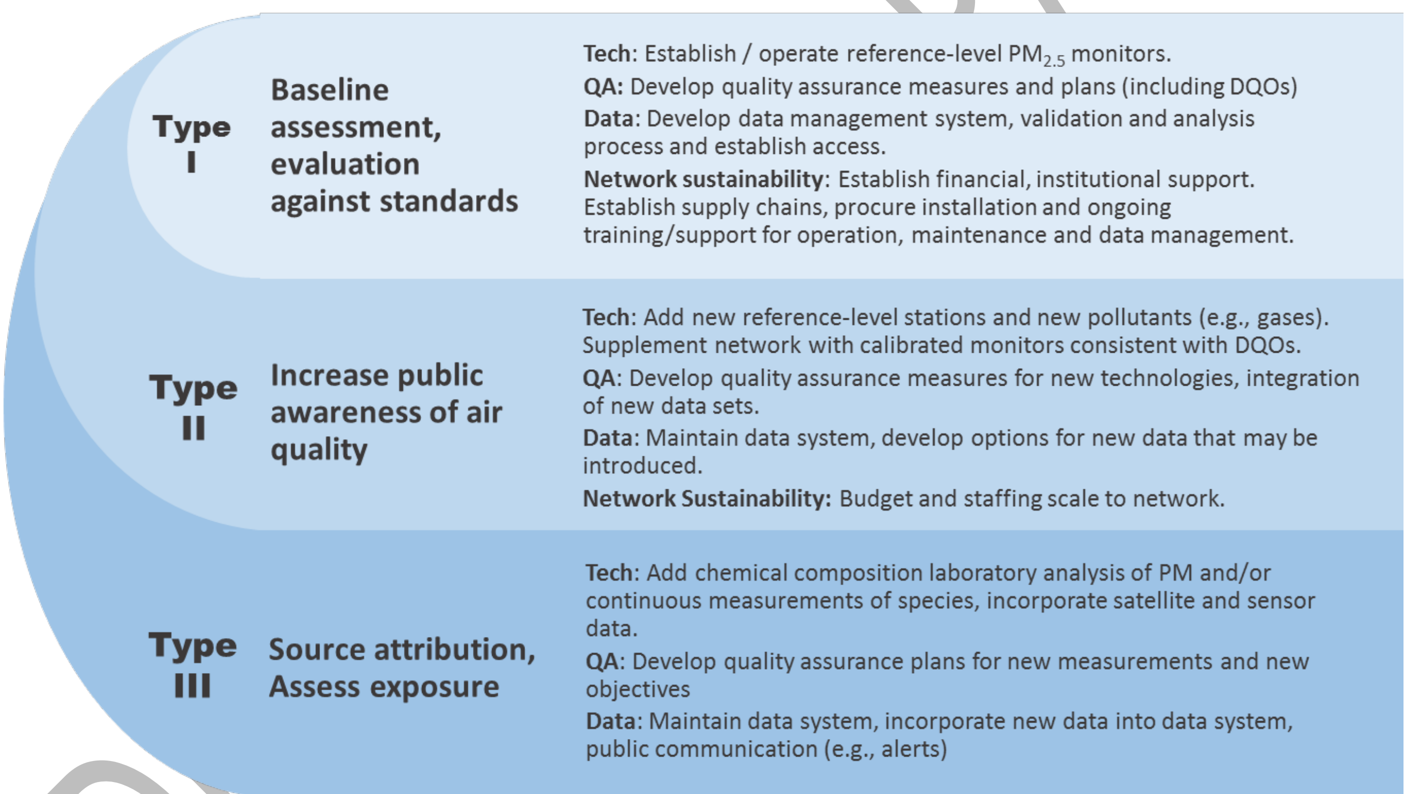

Figure 5-1: Recommendations by Country Type

5.2 Ground-level Monitoring Technology – the Decision Process

As the air monitoring technology landscape becomes more diverse, the selection of the best air monitoring strategy should be closely tied to the desired monitoring objective, but also be workable within the real-world constraints of available resources, infrastructure (e.g., land power availability), security, laboratory capability, and trained personnel. In Figure 5-2 offers an illustrative decision-tree for how to consider technology options given real-world constraints. For example, the common objective of Type I countries is to have accurate measurements to establish a baseline and compare against health-based air quality standards. Therefore, the desired measurement method would be as close to regulatory-grade as possible. Meanwhile, if monitoring is being conducted to meet multiple objectives, which is likely for Type III countries, a variety of measurement technologies may be used in concert. For example, a regulatory-grade monitor might be operated to compare against air quality standards and to serve as the calibration point for other technologies (sensors, satellite remote sensing), which would increase the coverage of air monitoring data for purposes of exposure assessment and air quality communication.

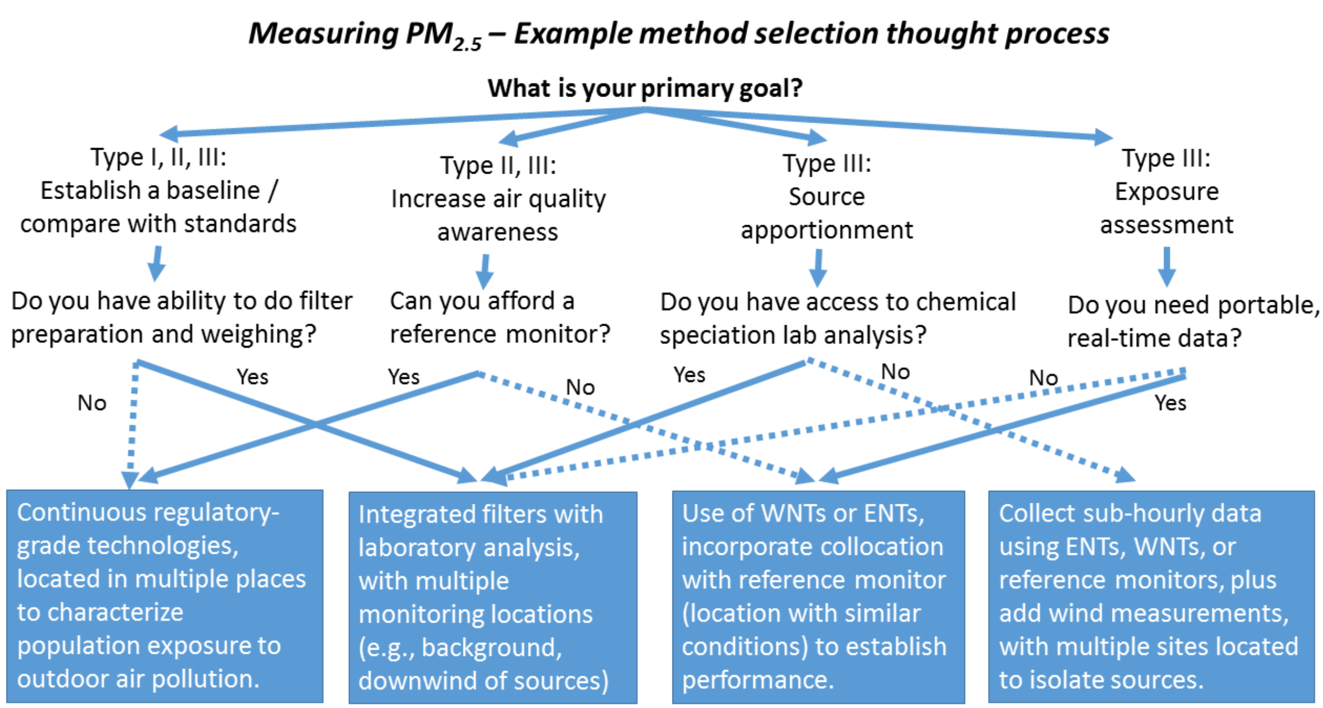

Figure 5-2. Common goals and considerations that drive the selection of an air monitoring approach for a geographic area of interest. Dashed blue lines indicate the "no" options.

5.3 Non-technical Recommendations

To surmount the challenges identified in this document and ensure sustainability of LMIC air quality measurement and the air quality management programs that arise from these measurements, workshop participants identified some additional critical activities for action. Governments, academics, the private sector and civil society should work together to:

1. Build on existing partnerships, programs and expertise to assess the current status of LMIC air measurement programs and capacity;

2. Improve partnerships between governments and universities;
3. Improve engagement with private sector;
4. Capitalize on new technologies (Big data, telecom, Skype, Slack, other IT) to improve communications and community of practice/practitioners;
5. Approach donors and other governments to support a clearinghouse for existing efforts - raising awareness of what is already happening;
6. Improve collaboration between the air quality and health ministries and research communities, focusing in particular on enhancing research in LMICs; and
7. Use available data to make the business case for taking action on air pollution, including to conduct cost-benefit analysis (including health benefits), trends analysis, regional transport analysis and other important assessments.