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PERSPECTIVE

# Systematizing the approach to air quality measurement and analysis in low and middle income countries

**Shahzad Gani[1,2,*], Pallavi Pant[3], Sayantan Sarkar[4], Neha Sharma[4], Sagnik Dey[5,6,7], Sarath K Guttikunda[8], Krishna M AchutaRao[5,6], Jostein Nygard[4] and Ambuj D Sagar[6,*]**

1 Institute for Atmospheric and Earth System Research/Physics, University of Helsinki, Helsinki, Finland
2 Helsinki Institute of Sustainability Science, University of Helsinki, Helsinki, Finland
3 Health Effects Institute, Boston, MA, United States of America
4 India Air Quality Management Team, Environment, Natural Resources and Blue Economy Global Practice, The World Bank, New Delhi, India
5 Centre for Atmospheric Sciences, Indian Institute of Technology Delhi, New Delhi, India
6 School of Public Policy, Indian Institute of Technology Delhi, New Delhi, India
7 Centre of Excellence for Research on Clean Air, Indian Institute of Technology Delhi, New Delhi, India
8 Urban Emissions, New Delhi, India
* Authors to whom any correspondence should be addressed.

**E-mail:** shahzad.gani@helsinki.fi **and** asagar@iitd.ac.in

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## 1. LMICs and the air pollution challenges

Air pollution is the leading environmental risk factor for human health; it is responsible for millions of deaths annually and tens of millions of years of life lost—a majority of them in low- and middle-income countries (LMICs) [1, 2]. Despite recognition of the outsized impact of air pollution on human health and productivity globally, limited progress has been made in tracking and tackling it in most LMICs [3–5]. In fact, more than 100 countries around the world, almost all LMICs, do not even have $PM_{2.5}$ monitoring, and in many cases, data generated through air quality monitoring programs is not publicly available [6, 7]. Although several factors can be seen as contributing to the limited progress, four factors possibly are key: (a) the lack of understanding of the state of air pollution across a country or region, (b) a full appreciation of the national/regional/local social and economic impacts of air pollution, (c) the relative dearth of capacity and resources to capture, digest, and use air pollution-related knowledge to develop clear policies and approaches to mitigate air pollution, and (d) the interplay of diverse sources and atmospheric processes that drive air pollution, which makes mitigation of the problem that much more complex [8].

## 2. Changing scientific and technical landscapes

Globally, the fields of air pollution science and management are rapidly evolving and our understanding of the role of sources and atmospheric processes in driving air pollution is constantly improving. This is especially relevant for many LMICs that have diverse topographies, sources, population densities, and meteorological conditions. Many of these countries are still in a nascent stage of understanding trends in air quality, associated sources, and the underlying atmospheric regimes across regions, both in terms of geographic airsheds and across urban and rural areas [8].

Air pollution measurement tools and techniques have advanced significantly in recent years: conventional, reference-grade air quality monitors and instruments for pollutant characterization have improved substantially and the use of low-cost monitors and satellite-derived estimates is also expanding, adding to the arsenal of tools available to understand air pollution trends and patterns. There have also been major advances in analytical techniques that have increased the scope of what we can learn from the various measurement data streams. Furthermore, experiences from countries and regions around the world—particularly from East Asia, Europe, and North America—offer important lessons on how to operationalize air quality measurement systems and use the data effectively to inform air quality management planning, operation, and policymaking. Taken together, advances in air pollution science, technology, and data analytics and lessons from numerous global experiences—including from other LMICs—provide an opportunity for many countries to take a leapfrog approach, rather than following the ad-hoc and evolutionary path undertaken by many of the pioneering countries.

## 3. A systematic approach to air quality measurement and analysis

Accordingly, we propose here an air quality measurement and analysis system (AQMAS) framework as a systematic and comprehensive approach to guide the efforts of LMICs to put in place the key activities and actors to underpin the development of the knowledge base regarding the state of air pollution and use this knowledge to address air pollution. A suitably designed AQMAS can also pave the way for scientific advances in the areas of atmospheric science, technology, and other disciplines such as public health. Such an approach is particularly relevant for LMICs since it will allow them to utilize resources and capacity to engage efficiently and effectively with the air pollution problem.

At the most fundamental level, the objective of an AQMAS is to ensure that adequate and appropriate knowledge pertaining to air pollution levels, sources, and dynamics is available to policy makers and other key stakeholders. Accordingly, an AQMAS has four key components (a) measurement instrumentation that perform ambient air quality monitoring in a complementary and integrative fashion, (b) measurement system design, (c) data architecture and access coupled to analytical support for optimum utilization across user types, and (d) data analysis and applications for modeling, forecasting, and planning including source apportionment and cost effectiveness analysis. We use the term 'system' since all four interconnected elements are necessary for the achievement of the above-mentioned objective. We detail these elements below.

### 3.1. Measurement instrumentation

In an AQMAS, the key instrumentation and infrastructure should work in a complementary and integrative fashion. Instrumentation can include:

(a) Conventional reference grade measurement stations for the measurement of criteria pollutants at strategically located sites.
(b) Advanced instrumentation and infrastructure including comprehensive air quality measurement stations to improve understanding of local air-pollution characteristics and phenomena[9], as well as source apportionment and emissions inventories.
(c) Satellite, remote sensing, and modeling systems that are rapidly evolving with ongoing improvements in instrumentation, algorithms, and applications with broad air quality and climate change applications[10].
(d) Low-cost sensor networks, which can be valuable in situations of high spatial and temporal variability in pollution concentrations and when absolutely accurate measurements may not be required[11].

### 3.2. Measurement system design

Data from the instruments and infrastructure described above can be used for monitoring air quality, identifying sources, and advancing scientific understanding of air pollution processes. However, specific objectives might be best achieved by utilizing different combinations of the instrumentation types, depending on the local context. Cities, regions, and countries are increasingly adopting hybrid approaches for air quality monitoring [12], source identification, and modeling involving a combination of regulatory stations, low-cost sensors, and high-cost instrumentation in fixed, mobile, and satellite platforms that can help achieve an optimum spatial and temporal coverage required to understand air pollution sources and exposure over various parts of the country. Such systems and high-end instrumentation can complement each other to provide highly spatially and temporally resolved air pollution information. Furthermore, when coupled with the growing number of algorithms linking satellite retrievals of particulate matter, gaseous pollutants, and other environmental data, the sources and the pool of information can be significantly enhanced in the coming years and decades.

### 3.3. Data architecture

A systems approach requires harmonized methods and processes, data compilation, and reporting procedures. Well-designed data architecture ensures appropriate processing, archiving, and accessibility of data generated from different streams. Furthermore, a range of actors are involved in the process of translating measurements into actionable information and knowledge through analytical efforts including modeling, source analysis, exposure analysis, atmospheric dynamics, and chemistry. It is necessary to have active interactions among experts to ensure the analysis system is dynamic and provides the best possible

[9] Examples include non-linearity of the atmospheric chemistry, chemical regimes including the critical role of secondary vs primary particulate matter, and changes in sources [9, 10].

[10] For example, satellite derived estimates of $PM_{2.5}$ are helping scientists conduct large-scale air quality and health studies. Furthermore, combining satellite data with on-ground measurements (monitoring) and models can be used to fill data gaps (e.g.in locations without ground-level monitors), improve model simulation, and enhance capacity of monitoring and management of air pollution [11].

[11] Such networks are typically deployed in locations where installation of a conventional network can be expensive or where the network can substantively enhance the air quality monitoring capacity in remote and rural areas. Deployment of such sensor networks can also be valuable for citizen education and citizen engagement.

information for decision-making. It is also important to ensure that the data generated through an AQMAS is credible and consistent. As such, detailed quality assurance and quality control procedures and chain of command are critical within the system; this includes equipment testing and verification as well as periodic internal and third-party data checks and validation.

### 3.4. Data analysis and applications

The various data streams from an AQMAS can be used for policy, science, and citizen engagement applications. Effectively applying and using data can help improve policymakers' and administrators' understanding of past, present, and future air quality scenarios and inform air quality monitoring planning as well as stakeholder engagement. Air quality modeling can also help predict the outcomes of air quality policy interventions and allow decision makers to consider the impacts of specific policies during the decision-making process. The science of air quality modeling and forecasting, which is an important application of an AQMAS data stream, has made significant strides globally. Forecasting methods are increasingly combining satellite data with chemical transport models and reanalysis data to produce air quality forecasts at regional and global scales [13, 14]. Countries, cities, or in some cases, researchers, are also investing in their own fit-for-purpose air quality forecasting and modeling tools [15, 16], or adapting global models for local use [17–19]. Data from such systems, coupled with strategic communications, can also provide citizens usable and timely information, enabling them to limit their exposure to ambient air pollution [20].

## 4. Enabling an effective AQMAS

Suitable institutional arrangements are required for the optimal functioning of an AQMAS, both from the point of view effective measurement and analysis and ensuring its societal relevance in an LMIC. Furthermore, both individual and institutional capacity building are also critical for the sustainability of an AQMAS.

### 4.1. Institutional arrangements

It is particularly important to set up institutional arrangements that facilitate coordination and ensure responsiveness among the actors involved in the four activities described above, across geographic or institutional scales. For example, measurements may well be organized at local, state, and national levels but some of the analysis may take place in a more centralized fashion. Furthermore, institutional arrangements to enhance interactions between AQMAS actors and external stakeholders (policy makers, civil society, citizens, and scientists) are key. Such interactions will allow both societal needs to shape the design and focus of the AQMAS, and equally importantly, allow for the reliable data and relevant analyses to inform and support policymaking, citizen engagement, and scientific research. This could happen, for example, through online portals that share data in a usable format and through regular formal or informal platforms and events that bring together air pollution analysts, policy makers, administrators, scientists, civil society, journalists, and others.

### 4.2. Capacity building

It is important to note that two kinds of capacity building are relevant for the smooth and effective functioning of an AQMAS: one, that of the actors relevant to the individual components of the AQMAS and, two, of the institutions to promote both interactions and coordination among these actors as well as interactions between AQMAS and external actors. Developing local technical research capacity is critical to support and sustain implementation of locally implemented air quality related policies and regulations. Thus, investments in developing and maintaining such capacity should be seen as an integral part of an AQMAS approach. International experience shows, for example, the importance of combining structured training courses with on-job training to gain sufficient capacity and skills required for various components of an AQMAS.

An optimal AQMAS requires proper functioning of individual components of the system, but also for the various components to work together as a part of a synergistic system. In addition to the financial and logistics support required to operate such a system, there needs to be effective and efficient coordination across an AQMAS to ensure that high quality and user-friendly data streams are available to all users, and that the data streams can be optimally used to achieve the various objectives of the AQMAS.

In the long-term, the ability to sustain and improve an AQMAS is critical to derive optimal value from it, and will require a well-trained, engaged, and dynamic ecosystem. To achieve such an ecosystem, long-term and continuous capacity building of individuals and institutions across all components of the AQMAS must be a key consideration.

The components and organization of an AQMAS are presented in figure 1.

## 5. Illustrating an AQMAS process and its potential implementation

The authors are currently working with key stakeholders in India including government ministries, central and state pollution control boards, academia, civil society, and others to outline the approach for, and contours of, a modern AQMAS for India. In this context, we have drawn on the AQMAS framework outlined above to (a) bring together representatives from government agencies, academia, and civil

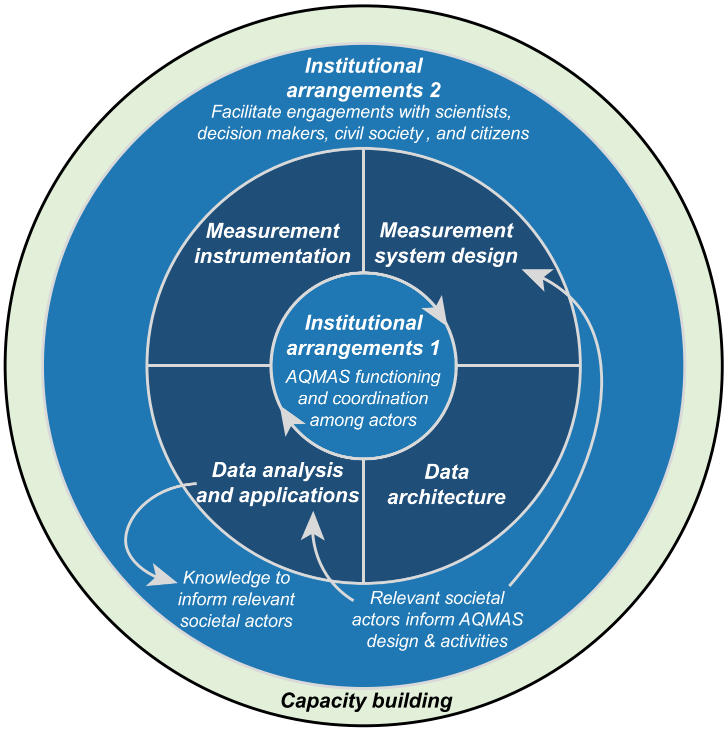


**Figure 1.** The components and organization of an AQMAS.

society to develop an understanding of key objectives for air quality measurement and analysis in India, (b) convene leading Indian and international scholars and practitioners to learn about the latest advances in air quality measurement instrumentation and from experiences of air quality monitoring programs within India and in other countries/regions (e.g. US, Europe, South Korea, China), (c) draw on the expertise of data scientists to outline suitable data collection, storing, retrieval, and analysis approaches, (d) identify gaps in existing measurement and data infrastructure, governance, and capacity in the Indian context. These steps are intended to help design an AQMAS that caters uniquely to the Indian context.

Given that air pollution is a problem across urban and rural parts of India, an air pollution measurement network's coverage needs to be designed accordingly. We are envisaging a systematic approach to instrumentation and their placement for India that might use satellite-derived air pollution data and existing ground-based observations to optimally place low-cost and reference grade instrumentation across the country and obtain spatially- and temporally-resolved urban and rural air quality information across major air sheds. Furthermore, a few strategically located supersites across the country (e.g. Indo-Gangetic Plain, coastal, high-altitude, etc) with state-of-art instrumentation and continuous source profiling capabilities could advance air pollution science and inform policymaking at the regional and national level. Sustainable operations of such as system in India will require sustained funding and long-term and continuous capacity building of personnel who can design measurement networks, install, and operate instrumentation, enable accessible and usable data architecture, analyze data, and facilitate coordination among the key actors (including users)—these capacity needs point towards the necessity of developing training programs for a range of personnel. The effectiveness of the AQMAS will require coordination across key government agencies (such as Central and State Pollution Control Boards, Ministry of Environment, Forest and Climate Change, Ministry of Health and Family Welfare, Ministry of Earth Sciences, Indian Space Research Organization, and Office of the Principal Scientific Advisor) as well as with civil society, academics, and other key stakeholders in the country—this function potentially could be carried out by a government entity or through a public–private partnership. While an effective AQMAS for India will require allocation of significant resources, we hope that a systematic process to design and develop an AQMAS will help to efficiently utilize, and perhaps even incentivize, domestic and international financing that support India's air quality and related goals.

## 6. Conclusion

Given the complexity of the air pollution problem and the challenge of addressing this problem in LMICs, we believe that a systematic approach—as outlined above—can greatly facilitate planning and implementation of efforts to attain clean air goals.

While the design of an AQMAS for an LMIC can benefit from decades of global experiences, it ultimately needs to be designed in the context of the individual country or region and take into consideration available resources and technical capacity as well as heterogeneity in terms of pollution levels and associated impacts. While financial or capacity constraints may prevent a country from implementing a full version of an AQMAS as defined by its local context and needs, the approach proposed here still provides a roadmap to add components and capacity over time. At the same time, we believe that a systematic approach of this kind will allow for a more effective and efficient use of the limited financial and human resources available in LMICs—and in doing so, potentially also increase the support available for efforts to engage with the air pollution problem over time.

We believe that there exists great potential for such a leapfrog approach, taking advantage of existing knowledge and experiences. There is no reason why LMICs (and their international partners) should not take heed of this opportunity and work together to realize it.

## Data availability statement

No new data were created or analyzed in this study.

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## Conflict of interests

SS, NS, and JN are employed by the World Bank which finances air quality related projects in many countries around the world. PP is employed by the Health Effects Institute which receives funding from the United States Environmental Protection Agency and the worldwide motor vehicle industry as well as philanthropic organizations. The views expressed here are those of the authors and do not necessarily reflect the views of the World Bank, the Health Effects Institute, or its sponsors. The authors declare that they have no conflict of interest.

## ORCID iDs

Shahzad Gani https://orcid.org/0000-0002-6966-0520
Pallavi Pant https://orcid.org/0000-0003-0251-6580
Sagnik Dey https://orcid.org/0000-0002-0604-0869
Sarath K Guttikunda https://orcid.org/0000-0003-4507-5199
Krishna M AchutaRao https://orcid.org/0000-0001-9064-5053
Ambuj D Sagar https://orcid.org/0000-0002-5361-0852

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