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Air Quality Measurement and Analysis Systems

Global Perspectives and Approach for India

"School of Public Policy,
Indian Institute of Technology Delhi"
"Environment, Natural Resources and Blue Economy Global Practice, The World Bank"

March, 2022

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भारत सरकार के प्रमुख वैज्ञानिक सलाहकार
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FOREWORD

White Paper on "Air Quality Measurement and Analysis Systems: Global Perspectives and Approach for India"

It goes without saying that the air pollution is a major scourge of life in India and numerous other countries, despite many policies and actions intended to manage this problem. It also does not need to be highlighted that a comprehensive understanding of air quality – the nature of pollutants, their sources and chemistry, and their distribution over space and time – is necessary to mitigate the problem. And this information is not possible without a systematic measurement of air quality and analysis of the data to yield knowledge that is crucial for policy-making and, indeed, even for our citizens.

This is why this White Paper on "Air Quality Measurement and Analysis Systems: Global Perspectives and Approach for India" developed by the Indian Institute of Technology (IIT) Delhi and The World Bank is particularly important. This document is the result of a set of discussions last year in a workshop jointly organized by the School of Public Policy, IIT Delhi and the World Bank, that brought together a number of global and national scientists, practitioners, and policy-makers to understand global approaches and effective practices to manage air quality and then to use this understanding in the national context to develop a way forward for India to put in place a systematic and comprehensive approach for Air Quality Measurement and Analysis. It was my pleasure to have delivered the closing remarks at the workshop and then engage in an enthusiastic interaction with the participants.

I am delighted to see this White Paper as an outcome of that workshop and subsequent discussions that lays out in a clear and compelling fashion an approach to use cutting-edge science and technology to support the policy process and citizen engagement on the air pollution issue and also advance air pollution science. I very much believe that the detailed and robust approach outlined in this document can serve as a guide for decision makers across the country, and potentially even in other developing countries that are embarking on their efforts to manage air quality. It also serves as a model of a partnership between an academic institution and an international agency to understand how science and technology can contribute to the addressing of major societal challenges. I hope the other readers of this White Paper will find it as interesting and useful as I did.

K. VijayRaghavan

(K. VijayRaghavan)

Dated : 24th January, 2022

In memory of Professor Kirk Smith

A champion of clean air for all
and the AQMAS approach

Preface

In January 2021, the Indian Institute of Technology Delhi and the World Bank organized a symposium to outline the approach for and contours of a modern **air quality measurement and analysis system** (AQMAS) for India, drawing on knowledge about the opportunity offered by existing and emerging measurement technology, and strategies for effectively building institutional infrastructure. This White Paper and the selection of participants for the symposium were based on discussions among the organizers and a background note that was circulated among the participants in advance. The symposium, which was spread over five days, brought together leading domestic and international scholars and practitioners to better understand and draw lessons from different elements of air quality monitoring planning and implementation across a range of efforts to collect and integrate new knowledge to address the problem of air pollution.

This White Paper draws on the background note, presentations by symposium participants, and discussions among the organizers. It synthesizes all this experience and knowledge to propose a framework for systematically thinking about a modern AQMAS for India, advances the discussion on building and planning such a system, and highlights key objectives and those elements that need to be thought through for such an undertaking. The lessons from the global and local perspectives outlined here could help design an effective system for India in the 21st century. It is believed that the establishment of a suitable system tailored to the local context could substantially support policy making and, in the long run, help mitigate a major health and environmental problem. It should, however, be noted that recommendations on its actual design are not included.

In an effort to strengthen the White Paper, a consultation was held in December 2021 involving participants from central and state governments, civil society, and academia. The goal of this meeting was to gain an understanding of and support for the draft AQMAS White Paper, and based on its key recommendations, identify ways of integrating an advanced AQMAS within India's air quality management endeavors.

The White Paper is intended to inspire policy makers, regulators at national and state levels, researchers, and civil society groups to design and develop an integrated, systematic approach and implement a state-of-the-art AQMAS to support India in achieving clean air.

Executive summary

BACKGROUND

The significant, complex, and evolving nature of air pollution and its significant societal and health impacts have received considerable attention in the past few years amongst policy makers, the academic world, and the general public alike.

India's response to its serious air pollution has evolved, although the development of adequate and effective responses is complex given the scale and multifaceted nature of the problem. There are multiple benefits in having access to high-quality, spatially- and temporally-resolved data, not only in terms of advancing policy making but also in increasing knowledge of the nuances of the problem, and informing public awareness and discourse. The relative paucity of high-quality data and analyses related to the sources of and trends in air pollution has historically hindered effective policy making in India, and although there has been an increasing focus on improving its measurement and management, much remains to be done

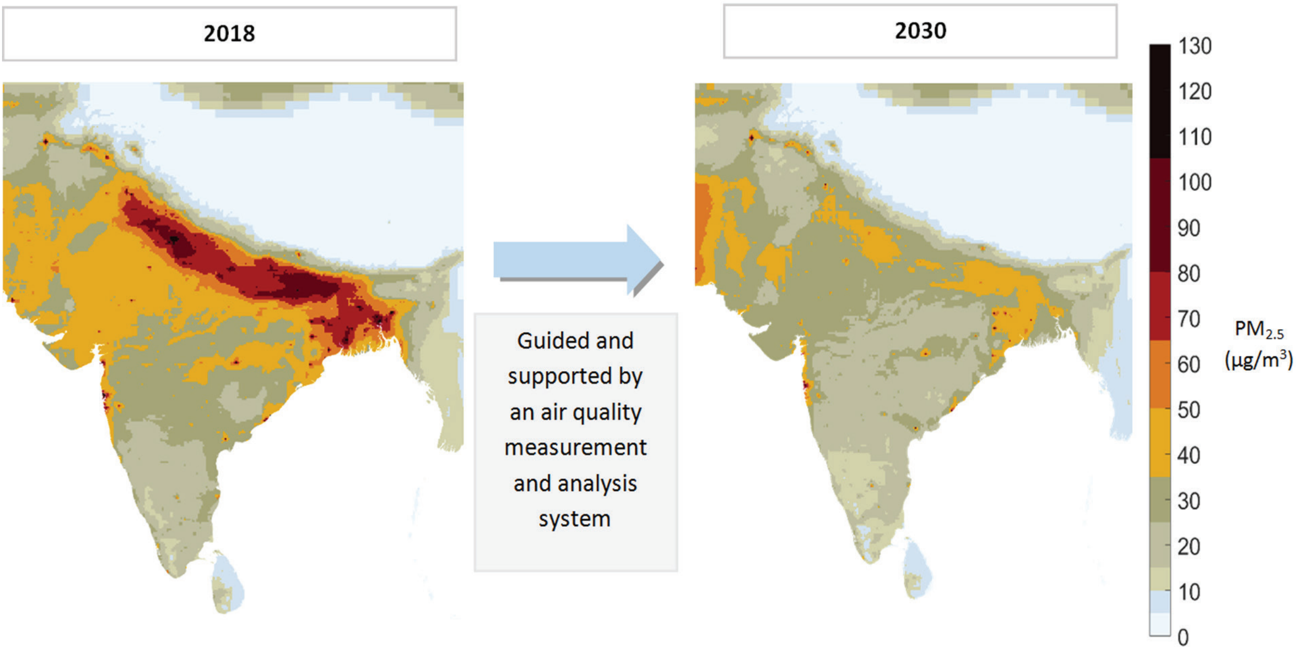
"As India's response evolves further, it must take a long-term perspective to meet both the targets outlined in the National Clean Air Programme (NCAP) for 2024, and the National Ambient Air Quality Standards or the WHO's Interim Target 1 for fine particulate matter ($PM_{2.5}$), respectively 40 and 35 micrograms per cubic meter (µg/m^3), and subsequently the more ambitious WHO Interim Targets 2 and 3 by 2030–2040. Meeting these targets would allow India to eliminate the heavy $PM_{2.5}$ cloud in the critically polluted Indo-Gangetic Plain and further substantively improve air quality throughout the country by 2030 (Figure ES 1)"

[1] WHO has established an Air Quality Guideline for annual mean concentrations of fine particulate matter ($PM_{2.5}$) of 5 µg/m^3. It has also established four Interim Targets for achieving the Guideline – Interim Target 1, 35 µg/m^3; Interim Target 2, 25 µg/m^3; Interim Target 3, 15 µg/m^3; and Interim Target 4, 10 µg/m^3

[2] Fine particulate matter ($PM_{2.5}$) has a diameter of 2.5, respectively 40 and 35 micrograms per cubic meter (µg/m^3), and subsequently the more ambitious WHO Interim Targets 2 and 3 by 2030–2040.

[3] A microgram is 1 millionth (10^{-6}) of a gram

Figure ES 1: Annual fine particulate matter concentrations in 2018 (left) and projected concentrations for 2030 (right), micrograms per cubic meter



Source: Analyses as part of the development of the World Bank's *Air Pollution and Public Health in South Asia Flagship Report* (in press)

Achieving such ambitious yet necessary air quality targets will require a systemic, scientific, and sustained approach. It is suggested that a key ingredient for success is the establishment of an air quality measurement and analysis system (AQMAS) that would help develop a detailed and comprehensive understanding of India's air pollution issues, thereby providing solid evidence and an analytical basis for deliberations and action.

Such a system would, among other benefits, help:

(i) systematically expand and strengthen the country's existing monitoring and air quality management network;

(ii) underpin the science needed to deepen the understanding of local characteristics of air pollution and assess current and future social, health, and economic impacts;

(iii) establish localized targets and sub-targets;

(iv) better identify critical and cost-effective polices and action needed to achieve national and local targets;

(v) provide public information critical to engaging citizen groups with air quality issues.

ELEMENTS, STATE, AND TRAJECTORY OF AN AIR QUALITY MEASUREMENT AND ANALYSIS SYSTEM

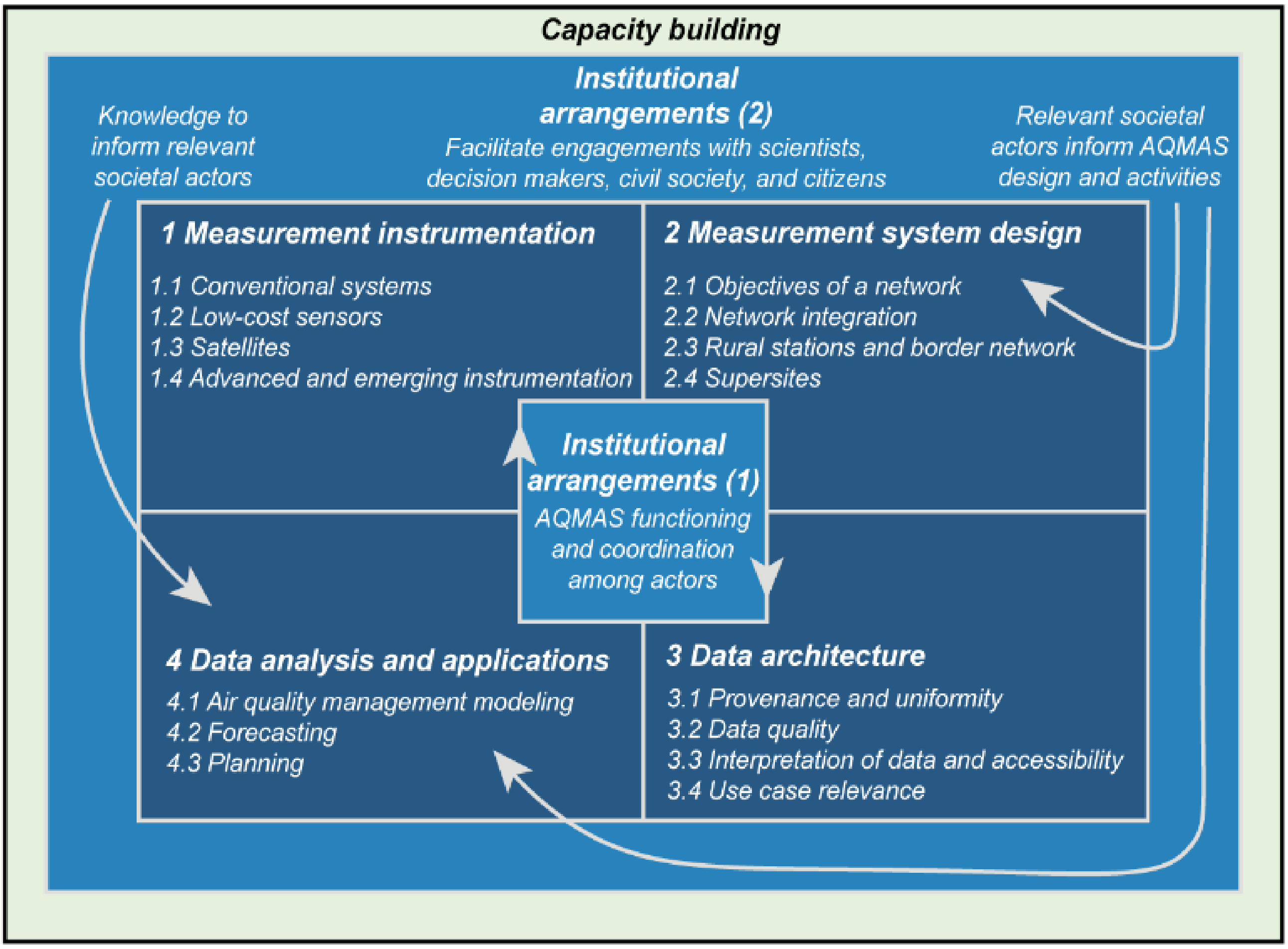
A well-designed AQMAS for India should have a comprehensive, systematic approach, and, while learning from global experience in terms of recent technological and analytical advances, strive to expand the country's air quality monitoring infrastructure, and strengthen coordinated institutional arrangements by fully understanding and reflecting local needs.

While designing an effective AQMAS, the following five key elements need to be considered.

1: A network of state-of-the-art, complementary, and integrated measurement instrumentation should be established to carry out ambient air quality sampling, source apportionment, emission inventories, and air quality modeling.

2: The design of the system should allow for hybrid

Figure ES 2: An air quality measurement and analysis system (AQMAS)



approaches to air quality monitoring and modeling in which instrumentation such as low-cost sensors, regulatory stations, and satellite and remote sensing can be combined and organized in ways that meet specific policy objectives.

3: The data architecture and access, coupled with analytical support, should allow for the optimal utilization of the system by a wide variety of users. Global experience from China, the European Union, and the United States point towards the need for a system that generates transparent, reliable, accessible, and quality-assured data to support policy making and research.

4: A system for data analyses and application should be developed to enable air quality management planning to achieve the country's air quality targets. The data architecture and application system should enable the systematic collection, analysis, and communication of data to support policy making, planning, scientific research, and ensure citizen engagement.

5: Establishing effective institutional arrangements is key to the optimal functioning of an AQMAS. Such arrangements should ensure the functioning and enhancement of interaction among actors within the system, and between the system's actors and external policy makers, scientists, and civil society. Additionally, both individual and institutional capacity building are critical for a well-functioning AQMAS.

LEAPFROGGING OPPORTUNITIES

Over the past decade, a growing number of countries have invested heavily in technology, monitoring infrastructure, research, and analysis as a means of better understanding and managing air quality and responding to questions and challenges that are increasingly complex and connected. Today, there is a wealth of knowledge and experience on building and implementing AQMAS from developed and middle-income countries and regions, including China, the European Union, Mexico, the Republic of Korea, and the United States, that offer India an opportunity to leapfrog to an effective system in a relatively short period of time.

A strong AQMAS could make India a leader in air pollution science and public health diplomacy in South Asia and beyond. In addition, a suitably designed system could also support the country's climate-change science and policy goals. To achieve this, however, India will have to allocate adequate resources and design an institutional and planning mechanism across sectors that is well coordinated and aligned with its goals of reducing air pollution and mitigating climate change. India will also need to put in place adequate data governance systems to support and enhance the engagement of scientists, civil society organizations, and citizens. India's experience in building such a system could also, in the future, offer a resource-efficient template for other countries building their own.

DESIGNING FOR THE FUTURE

When designing an AQMAS, it is important to consider future needs and ensure that elements are built in to ensure that the system remains relevant and effective in supporting air quality monitoring, planning, and regulatory and policy decision making. To achieve this, the system must have a long-term, multi-decadal perspective, and a well-defined strategy for upgrading and adjusting it in a continuously evolving technological and scientific landscape. Careful and systematic planning and implementation that helps put a system in place that will stand the test of time by delivering value both in the short and longer term – and which will also be a role model for other developing countries – is desirable. A key component of such a well-designed system is that it focuses on a systems approach towards instrumentation, thus enabling the integration of different technologies and scales of monitoring. The system must also develop and adopt standardized methods for data collection, storage, access, and usage. Furthermore, it should enable knowledge and information sharing between key institutions responsible for policy and regulatory decision making and foster scientific research. Continued investment in human resources and capacity development is a key to ensuring that the needed capacities and skills to implement and expand the system over multiple decades are established.

An AQMAS should:

(i) balance knowledge development with continued practical application;

(ii) be used to design city- and particularly state- and region-wide air quality management (AQM) policy plans and monitor progress regularly;

(iii) provide needed knowledge about wheretoput resources most cost-effectively;

(iv) provide the basis for scientific-based AQM.

As India increases its efforts to tackle the growing challenge of air pollution, it should establish and operationalize an AQMAS immediately, starting, for example, in highly polluted areas such as the Indo-Gangetic Plain (IGP).

1. Background: India and the Air Pollution Challenges

1.1 State of Air Pollution in India

Air pollution remains a major cause of morbidity and mortality in India. The latest analysis by the India State-Level Disease Burden Initiative indicates that air pollution caused 1.67 million deaths in 2019[4]. Although the scale of air pollution issues has been recognized for quite some time, progress in tackling them has been limited, and in many cases, uneven. Between 1990 and 2019, for example, as a result of changes in exposure – increased exposure to higher ambient (outdoor) $PM_{2.5}$ and ozone (O_3) concentrations, and reduced populations exposed to household air pollution (Table 1.1) – the death rate associated with household air pollution fell by 64 percent, while, at the same time, the death rate from ambient air pollution increased by more than 100 percent. Progress is needed – and can, in fact, yield significant health benefits.

While in 2018/19 the annual average $PM_{2.5}$ concentrations across India were high at 76–91 μg/m^3 (Table 1.1), the IGP experienced the highest levels of often around 100 μg/m^3 (Figure 1.1) or higher, 2–3 times India's own $PM_{2.5}$ standard of 40 μg/m^3 and 20 times more than the current World Health Organization (WHO) Guideline of 5 μg/m^3.

Table 1.1 India's air pollution and population

Air pollution and health indicators:	**1990**	**2019**
$PM_{2.5}$ exposure mean (range) (μg/m^3)	71.5 (36.2–126)	83.2 (76.1–90.7)
O_3 exposure mean (parts per billion[6])	48.9 (48.7–49)	66.2 (66–66.3)
Population exposed to household air pollution (range) (percent)	85.3 (84.6–86)	60.7 (59.4–62)
Estimated deaths due to air pollution (million)	1.33	1.67
Other indicators:		**2020/21**
Population (billion)		1.3
Continuous ambient air quality monitoring stations (number)[7]		335
Manual monitoring stations under the National Air Quality Monitoring Progamme (number)[8]		804
Non-attainment cities (PM_{10} criteria in 2017) (number)		122

Source: Pandey et al. (2020; https://doi.org/10.1016/S2542-5196(20)30298-9) and State of Global Air (2020).

[4]Pandey et al., 2020 (https://doi.org/10.1016/S2542-5196(20)30298-9).
[5]Upadhyay et al., 2018 (https://doi.org/10.1016/j.envpol.2018.07.085); Venkataraman et al., 2018 (https://doi.org/10.5194/acp-18-8017-2018); Chowdhury et al., 2019 (https://doi.org/10.1073/pnas.1900888116).
[6]Throughout this White Paper, billion = 10^9
[7]The data is from official website for Continuous Ambient Air Quality Monitoring Stations, Central Pollution Control Board –https://app.cpcbccr.com/ccr/#/caaqm-dashboard-all/caaqm-landing
[8]The data is from Central Pollution Control Board website –https://cpcb.nic.in/about-namp/

Although a number of factors can be seen as contributing to this situation, ranging from the diversity of the spatial and temporal patterns in pollution levels and sources across India to limited financial resources, two factors play key roles:

1: the lack of detailed understanding of the state of air pollution across the country; and

2: the relative dearth of capacity to capture, digest, and use data to develop clear policies and approaches to mitigate air pollution.

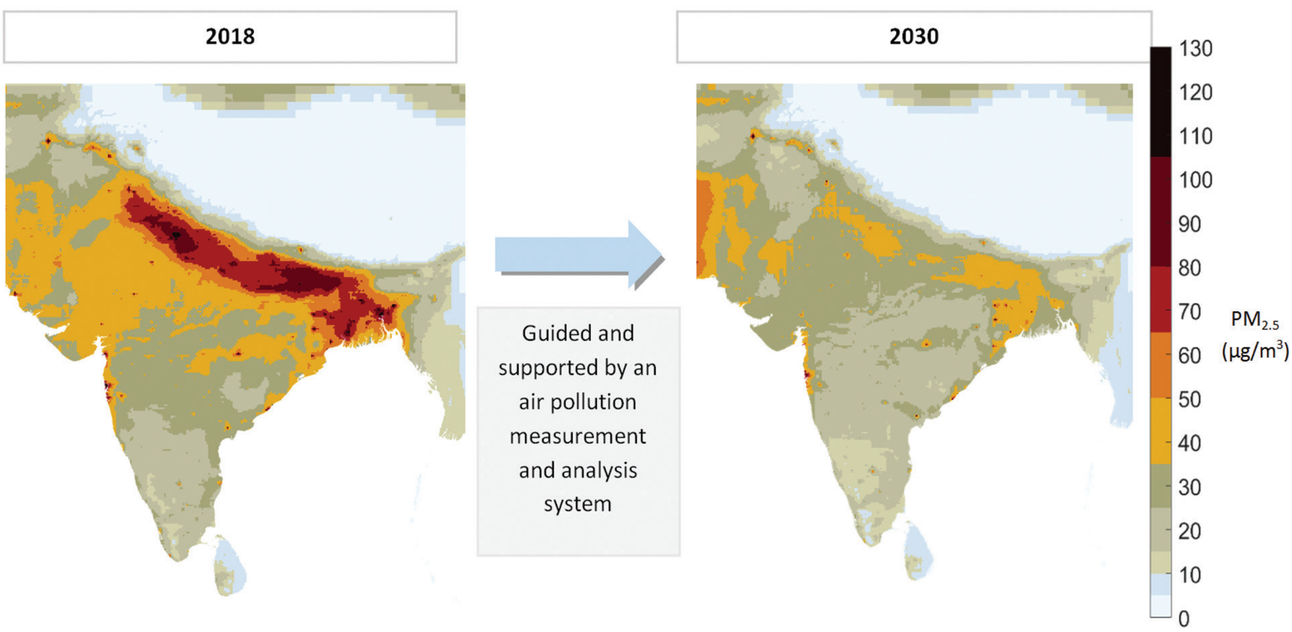
Most of the discussion, therefore, is dominated by geographical areas such as the Delhi National Capital Territory (NCT) that have a wider and reasonable level of official and unofficial coverage of pollution monitors and also the best understanding of air pollution sources.

To improve the air quality in India, a long-term perspective must be taken to meet both the targets outlined in the National Clean Air Programme (NCAP) for 2024, and the National Ambient Air Quality Standards or the more ambitious World Health Organization's (WHO) Interim Target 1 for $PM_{2.5}$ and subsequently the WHO Interim Targets 2 and 3 by 2030–2040. Meeting these targets would allow India to eliminate the heavy $PM_{2.5}$ cloud in the critically-polluted IGP and substantively improve air quality throughout the country by 2030 (Figure 1.1).

1.2 The Complexities of the Air Pollution Challenges

The complexity of the air pollution challenges in India can be illustrated through the patterns of primary and secondary $PM_{2.5}$ concentrations throughout the country. While primary $PM_{2.5}$ is mainly emitted

Figure 1.1 Annual fine particulate matter concentrations in 2018 (left) and projected concentrations for 2030 (right), micrograms per cubic meter



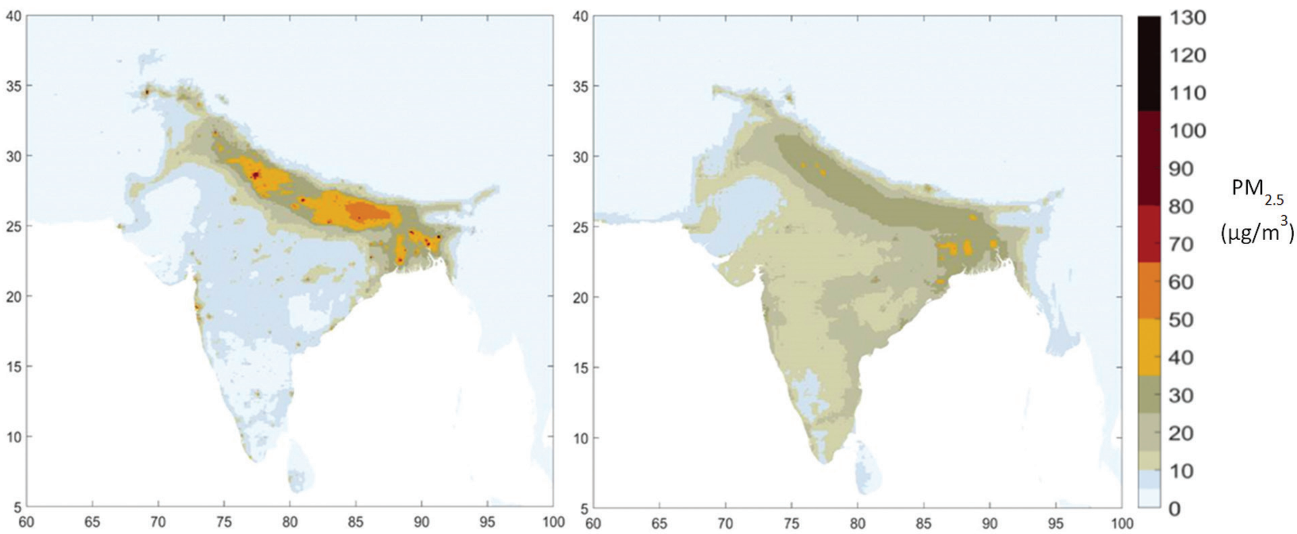
Source: Analyses as part of the development of World Bank's *Air Pollution and Public Health in South Asia Flagship Report* (in press)

[9]WHO has established an Air Quality Guideline for annual mean concentrations of fine particulate matter ($PM_{2.5}$)of10 µg/m^3. It has also established three Interim Targets for achieving the Guideline – Interim Target 1, 35 µg/m^3; Interim Target 2, 25 µg/m^3; and Interim Target 3, 15 µg/m^3.

from such sources as the combustion of solid fuels, urban and rural waste management, large and small industry, transport, and crop residue burning, production of secondary $PM_{2.5}$ is largely linked to ammonia (NH^3) emissions from agriculture, and sulfur dioxide (SO_2) and/or nitrogen oxide (NO_x) emissions from energy production, industry and transport.

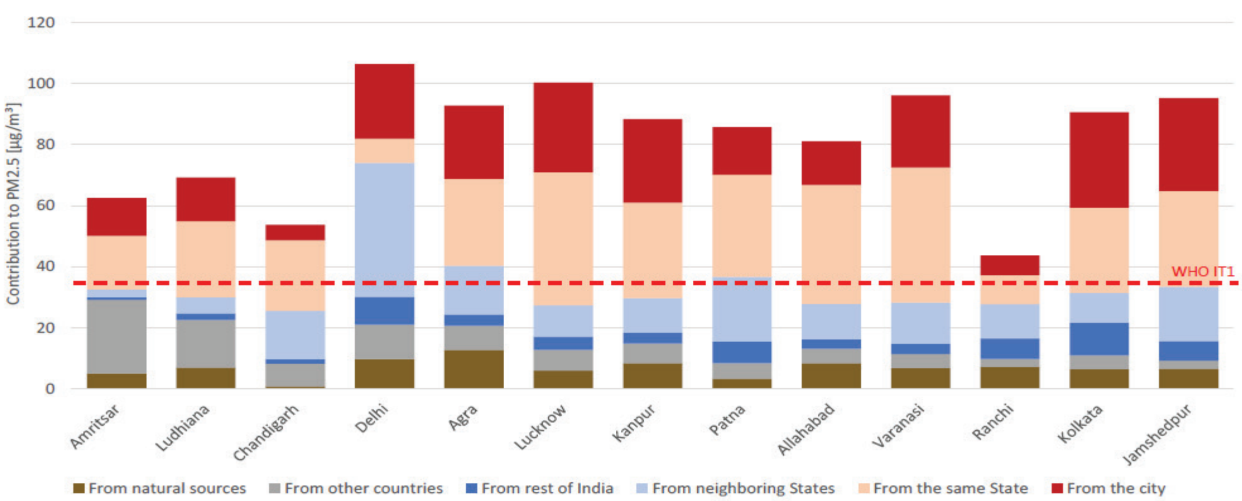
A linked issue is the imbalance between local and regional sources. In many cities and urban agglomerations, for example, only a limited share of the total air pollution load originates locally (Figure 1.3). As a result, any mitigation plans and policies need to target both local and regional sources, as well as clearly defining the geographic scale of interventions.

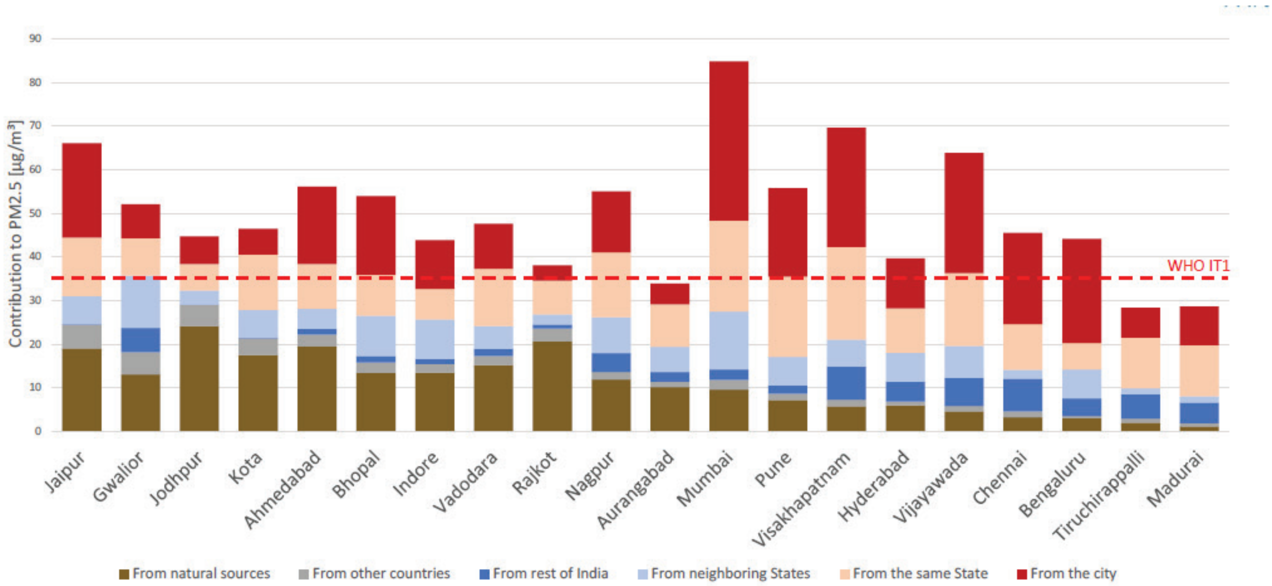
Figure 1.2 Primary (left) and secondary (right) fine particulate matter concentrations in India, 2018, micrograms per cubic meter



Source: Analyses as part of the development of World Bank's *Air Pollution and Public Health in South Asia Flagship Report* (in press)

Figure 1.3 Spatial origin of population-weighted fine particulate matter exposure in cities within the Indo-Gangetic Plain (above) and beyond it (below), 2018, contribution to $PM_{2.5}$ in micrograms per cubic meter





Note: WHO IT1 = WHO Interim Target 1, 35 µg/m³

Source: Analyses as a part of the development of World Bank's *Air Pollution and Public Health in South Asia Flagship Report* (in press)

1.3 Evolving Understanding

Air pollution science and management are rapidly evolving fields both in India and around the world, with the understanding of the role of sources and atmospheric processes in driving air pollution constantly improving. This is critical in India where there are, as mentioned, diverse topographies, sources, population densities, and meteorological conditions. Air pollution measurements are still sparse across much of the country and the discourse is largely focused on the Delhi National Capital Territory that has a relatively wide and reasonable level of official and unofficial coverage of air pollution monitors and some infrastructure to determine sources. Since the launch of India's NCAP in 2019, air quality monitoring across the country has expanded rapidly, but other parts of the air quality management infrastructure remain very limited.

Understanding trends in air quality, associated sources, and the underlying atmospheric regimes across regions, both in terms of geographic airsheds[10] and across urban and rural areas, are, nonetheless, still at a nascent stage. Furthermore, limited data are available regarding local and regional source contributions, especially outside the Delhi National Capital Territory. Drawing on strong international experience in countries and regions with similar economic diversity, population density, variety of anthropogenic pollution sources, and complex air pollution chemistry over large geographic scale as India (Figures 1.1–1.3), it is understood that air quality management can only be effective if it is designed at a large geographic scale or what is being referred to as applied airshed management. To support this, it is understood that an AQMAS must be developed to support such large-scale air quality management.

[10]An airshed is a geographical area where local topography and meteorology limit the dispersion of pollutants away from the area.

1.4 Evolving Response

Air pollution measurement tools and techniques have evolved significantly in recent years. Advancements have been made in conventional, reference-grade air quality monitoring that measures insitu black carbon (BC) and NH_3 with cavity ring-down spectroscopy (CRDS) analyzers. The use of low-cost monitors[11] and satellite-based measurements is expanding, adding to the arsenal of tools available to understand air pollution trends. There have also been major advances in analytical techniques that have increased the scope of what can be learned from the various measurement data streams. Further more, experience from countries and regions around the world — particularly from East Asia, Europe, and North America – offers important lessons on how to operationalize air quality measurement systems and use the resulting data to inform air quality management policymaking and planning.

1.5 Key Role of Data and Analysis

Given that the function of air pollution measurement is to generate knowledge that is useful for societal objectives, other activities beyond just measurement are also needed. These include data management and archiving, data analysis to generate policy- and societally-relevant information, and knowledge dissemination. These elements have to work coherently and seamlessly together to achieve the desired function.

Box 1.1 The importance of high-quality data and analysis: lessons from COVID-19

Worldwide lessons from COVID-19 highlight the importance of high-quality data and analysis for avoiding and controlling major health-related crises.

Data: availability of and access to high quality spatially- and temporally-resolved datasets can help policy makers utilize diverse expertise and stay up-to-date on advances in scientific understanding that have implications for real-time policy making. Easily accessible high-quality datasets can complement the expertise of multiple groups of stakeholders in testing and improving predictive models,aid independent assessments and provide feedback to policy makers in realtime.

Analysis: the ability to monitor the progress of COVID-19 related variables – cases, deaths, variants, etc. – and predict future scenarios accurately helped policy makers control its spread and preemptively increase hospital capacity in expected hotspots.

Science-policy links: COVID-19 highlighted the importance of high-quality data and analysis that supported real-time science-policy links and was instrumental in limiting deaths and suffering. These lessons also motivate the need for building a forward-looking data and analysis system to tackle air pollution – another airborne health hazard with huge public-health costs.

Citizen engagement: COVID-19 has also highlighted the importance of citizen engagement in informing the public about individual-level decisions that enhance and protect the safety and wellbeing of individuals and the population as a whole.

[11]Throughout this White Paper the term low-cost sensors/monitors is used as a common term for all sensors/monitors that are substantially lower in cost than conventional air quality monitors. These devices can provide a more affordable option for monitoring air quality compared to conventional stations. Their cost can range any where from a few hundred to a few thousand US dollars.

2. State and Trajectory of Measurement Technologies and Analysis Systems – a Global Perspective

The key components of an AQMAS (Figure 2.1) are:

1: measurement instrumentation that performs ambient air quality monitoring, sampling, source apportionment, emission inventory, air quality management,and cost effectiveness modeling, working in a complementary and integrative fashion;

2: measurement system design;

3: data architecture and access coupled to analytical support, allowing the optimal utilization of the system by various users; and

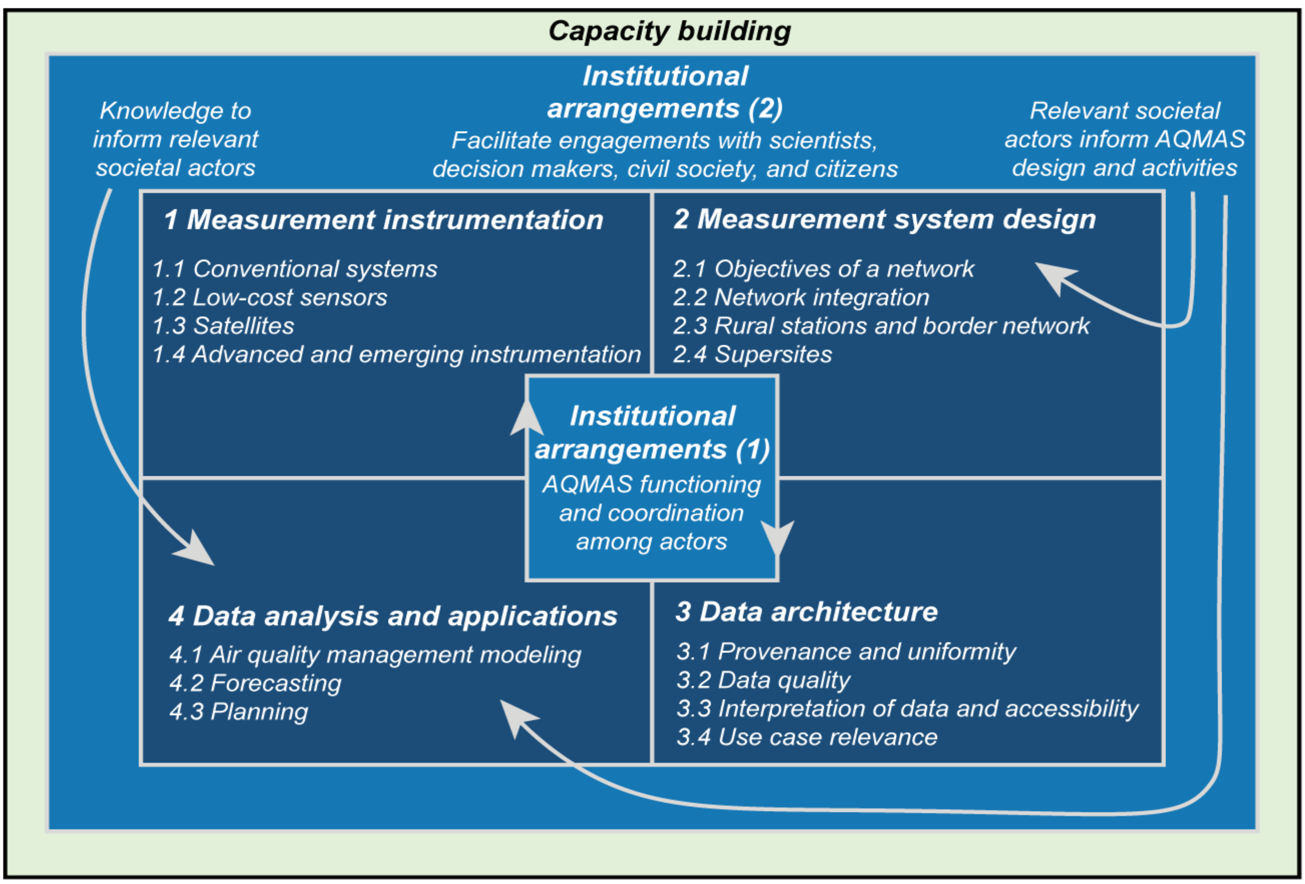
4: data analysis and applications for modeling, forecasting, and planning.

Furthermore, two types of institutional arrangements are required for the optimal functioning of such a system:

1: institutional arrangements to ensure the functioning and enhancement of the interactions among the actors within the system; and

2: institutional arrangements to enhance interactions between the system's actors and external ones – policy makers, civil society organizations, citizens, and scientists.

Figure 2.1 Structure of an air quality measurement and analysis system (AQMAS)



Finally, both individual and institutional capacity building are critical for a well-functioning system.

2.1 Measurement Instrumentation

Instrumentation and infrastructure working in a complementary and integrated fashion include the following.

1) Conventional reference (regulatory) measurement stations.
   a) Measurement of criteria pollutants using regulatory-grade instrumentation;
      i) continued updating of instrumentation, following evolving understanding of air pollution problems, especially the importance of secondary air pollutants and the capacity to monitor them (Annex I–1.4);
      ii) advanced technologies, such as CRDS, in a monitoring system are required to understand and track the gases that form secondary pollutants, for example NH_3, while BC samplers are critical to understand the concentration levels and sources of the finest particles (Annex I– 1.1).
   b) Measurements across areas of high pollutant concentrations, regions with high population densities, sites near significant pollution sources, and, critically, background concentrations to determine regional transport of pollutants (Annex I– 2.3).

2) Satellite, remote sensing, and modeling.
   a) This is a rapidly evolving area with ongoing improvements in instrumentation, algorithms, and applications. A significant amount of data from programs led by the United States' National Aeronautics and Space Administration (NASA), the European Space Agency (ESA), India's National Satellite (INSAT) system, the Republic of Korea's Geostationary Environment Monitoring Spectrometer (GEMS) system etc. are publicly available online and can be accessed for various applications, often for free.
      i) GEMS, for example, provides coverage of 20 Asian countries including India and illustrates the role of an AQMAS in science diplomacy. Such measurement networks have applications for air quality and climate change, and can increase national/international cooperation (Annex I – 1.3).
      ii) Satellite derived estimates of $PM_{2.5}$ are helping scientists conduct air quality and health studies, including work in India, for example the Satellite-Based Application for Air Quality Monitoring and Management at National Scale (SAANS) project.
   b) Using satellite data with on-ground based measurements (monitoring) and models can fill data gaps in, for example, locations without ground-level monitors such as less populated areas, improve model simulation, and enhance capacity of monitoring and management of air pollution (Annex I– 2.2).
   c) Forecasting methods, such as the European Union's COPERNICUS[12] , are increasingly combining satellite data with chemical transport models to produce air quality forecasts (Annex I– 4.2).

3) Low-cost sensor networks.
   a) Valuable in situations of high spatial and

[12]https://www.copernicus.eu/en

temporal variability in pollution concentrations and when absolutely accurate measurements may not be required (Annex I – 1.2).

b) Applied in locations where it is too costly to put a conventional network in place, they may substantively enhance the air quality management capacity of states, including in remote and rural areas (Annex I– 1.2).

c) A push for low-cost sensors should come with reliable standardization methods and improved baseline understanding of local and regional air quality and source contributions (Annex I – 1.2).

d) Such sensors are valuable for education and citizen engagement.

4) Advanced instrumentation and infrastructure.

a) Comprehensive air quality measurement stations with high-end trumentation, typically costing US$135,000–300,000 each, can help advance the science of air pollution, including the non-linearity of atmospheric chemistry, chemical regimes, and changes in sources.

b) Such instruments can also be used for calibration, performance evaluation, and comparability of low-cost sensors and other measurement techniques.

Such instrumentation can be used for:

1: ambient air quality monitoring;

2: source identification;

3: contributing towards AQM planning and operation; and

4: advancing overall AQM science.

Each of these four objectives needs to be given adequate attention and the achievement of any objective requires different measurement-system designs that canutilize different combinations of the instrumentation from the above categories, depending on the national context.

2.2 Measurement System Design

The instrumentation can be organized in different ways to meet specific policy objectives. Satellite and remote sensing, and modeling approaches, for example, are useful for obtaining highly spatially resolved information on air pollutants. On the other hand, spatially sparse, conventional reference instrumentation provides more reliable and better temporally resolved air quality data.

In addition, data from a combination of the instruments and approaches listed above can be utilized for identifying sources andpreparing emission inventories. The organization of these instruments also affects the quality and reliability of the emission inventories and air quality models that can be built using the various data streams obtained from them (Annex I – 1.4).

Experience from China, Europe, India, the United States, and elsewhere highlights the importance of source identification networks in parallel with ambient air quality monitoring networks. These source identification networks require specialized instrumentation such as:

(i) gravimetric samplers deployed in a network, from which samples are collected for chemical composition analyses in an air quality laboratory. These should not be confused with filter samplers from which samples are collected and analyzed for ambient air quality concentration levels;

(ii) online/real time source monitors; and

(iii) analytical instruments in a laboratory used for chemical composition analyses (Annex I– 1.4 and 2.4).

Another way of organizing instrumentation is in supersites – sites with a combination of concentration and source instrumentation, which may have different levels of advancement, and also have other instrumentation. Availability of co-located information on various parameters directly or indirectly related to air quality makes it possible to develop high quality insights into the dynamics of air pollution processes. Supersites bring together ambient air quality monitoring and enable source apportionment analyses, the building of emissions inventories, the improvement of air quality models, and more. The ability to facilitate advanced source identification, knowledge creation, and innovation in the integration of monitoring and analysis of data from a range of different measurement technologies makes supersites increasingly relevant (Annex I - 2.4).

There are many ways of organizing instrumentation spending depending on specific policy needs. Generally, cities/countries are increasingly adopting hybrid approaches for air quality monitoring and modeling involving a combination of regulatory stations, low-cost sensors, and high-cost instrumentation on fixed, mobile, and satellite platforms that can help obtainthe optimum spatial and temporal coverage required to understand air pollution sources and exposure over various parts of a country. In addition, there is a need for harmonized methods and processes, data compilation, and reporting procedures for emission inventories, as well as guidelines for source apportionment analyses to ensure that data across cities are comparable (Annex I– 2.2).

2.3 Data Architecture

Given the various data streams generated by the instrumentation discussed in the previous section, well-designed data architecture ensures appropriate processing, archiving, and accessibility of data. 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, and analysis of atmospheric dynamics and chemistry. Active interaction among experts is necessary to ensure the analysis system is dynamic and provides the best possible information for decisionmaking (Annex I – 3.3). The Convention on Long-range Transboundary Air Pollution (CLRTAP) is a good example – it has adopted a well-defined data management framework that emphasizes understanding the origins of air pollution while maintaining the quality and uniformity of data. It ensures that any data used for regulatory purposes or for informing the wider public undergo stringent validation and a third-party verification process (Annex I– 3.1).

2.4 Data Analysis and Application

The science of air quality modeling and forecasting has made significant strides globally. Applying and using data effectively can help improve a policy maker's understanding of past, present, and future air quality scenarios and inform air quality management planning, assessing monitoring needs, and engaging stakeholders. Air quality modeling can help develop management scenarios and enable decision makers to assess impacts of certain policy decisions. Advanced tools that combine dispersion modeling and cost effectiveness analysis have enabled developed nations, such as European Union Member States, to prioritize clean air measures and take sustained, informed action. Applying models can further help advance development of nested planning – at regional, state, and city levels. Air quality forecasting efforts can help for governments, particularly state ones, respond to air quality emergencies. Advances in predictive analytics, coupled with strategic communications, can provide citizens with usable and timely information that can help limit their exposure to high levels of ambient air pollution. Based on relevant international air quality management experience and drawing on today's accumulated knowledge about data application in air quality management modeling and planning, experience over the last decade shows that it is more than possible to achieve ambitious and specific air quality targets based on identified locations, sectors, and measures (Annex I– 4.1, 4.2 and 4.3).

2.5 Integrating Science, Decision Making, and Citizen Engagement

Reliable and accessible data from an AQMAS, available publicly in a usable format, can be useful for researchers, policy makers, and citizens in general (Annex I– 3.3). An effective system can therefore help progress science, facilitate effective decision making, and help with increasing awareness and local policy buy-in by having communications and citizen engagement components. Such a system can also help build and expand educational programs for citizens, both to inform them about air pollution – levels, sources, etc. – and build local buy-in and consensus around emissions reductions from key sources (Annex I- 3.4).

A well-designed system offers the opportunity offsetting up super sites with comprehensive and state-of-art instrumentation. The data and knowledge from these super sites can be used to answer policy-relevant questions with meaningful engagement from both researchers and regulatory bodies. Furthermore, a dynamic system can promote innovation and entrepreneurship, especially in the arena of instrument design and development, creating opportunities for indigenous business development and manufacturing in India, for example of low-cost sensors and internet-of-things (IoT) solutions for monitoring networks.

Finally, publicly available data on air quality can be used for the development of course materials for university students, and such research training opportunities as Master's and PhD theses, and can ultimately feed into the process of developing and expanding the talent base (Annex I– 3.3).

2.6 Institutional Arrangements and Capacity Building

Given the wide range of functions and actors involved in an AQMAS, it is particularly important that concerted efforts are made to facilitate cross-departmental coordination and communication across organizations and between individuals. There need to be, for example, formal or informal platforms and events that bring air pollution analysts, policy makers, scientists, civil society, journalists, and others together. This coordination and communication among and across organizations and between individuals is required to ensure that various linked functions of a system are fulfilled. Furthermore, such institutional arrangements ensure an effective system that is dynamic and continuously evolving as the air pollution landscape, technologies, and other factors change.

International experience also shows the importance of combining structured air quality management training courses with on-the-job training to develop sufficient capacity and skills. Developing local technical research capacity, particularly within states, is critical to support the implementation of locally implemented air quality management policies and regulations (Annex I– 1.1, 1.4, 2.1 and 4.3). It is important to note that two kinds of capacity building are relevant for an AQMAS– that of the actors relevant to the individual components of the system and of institutions to promote:

1: interaction and coordination among these actors; and

2: interaction between the system and external actors.

Box 2.1 Integrating industrial continuous emissions monitoring systems with an AQMAS: facilitating better compliance by improving monitoring and analysis

Industries, large and small, are a major source of air pollution across India. To effectively regulate industrial emissions, Indian states still rely heavily on quarterly monitoring of pollution through manual sampling and testing in National Accreditation Board for Testing and Calibration Laboratories (NABL) and/or United States Environmental Protection Agency (US EPA) accredited laboratories. This system only allows authorities to monitor air pollution three to four times a year. Adopting and integrating an effective real-time emissions monitoring regime based on continuous emissions monitoring systems (CEMS) with anAQMAScould greatly benefit India in tracking pollution from industry and understanding its impact on ambient air pollution levels, as well as on public health.

To improve monitoring of air pollution from industry, the Ministry of Environment, Forests and Climate Change (MoEF&CC) and the Central Pollution Control Board (CPCB) issued a directive in February 2014 asking 17 categories of highly polluting industry to install continuous emissions monitoring systems and continuous effluent quality monitoring systems (CEQMS), and transfer the data collected directly to the Central Pollution Control Board and their respective state pollution control boards (SPCBs) or pollution control committees (PCCs). Subsequently, the same directive was made applicable, as relevant, to grossly polluting industry (GPIs) in the Ganga Basin. Overall, nearly 4,000 companies have installed continuous emissionsand/or effluent quality monitoring systems and supply data to Central Pollution Control Board under this initiative. It is important to note that, besides this, since February 2014 many states have asked various other red category industries[13] , beyond the 17 categories, to install real-time monitors and transfer the data to the respective State Pollution Control Boards.

Despite these efforts, several implementation challenges, including but not limited to improper calibration and performance testing of equipment, inaccurate installation of devices, and infrequent data transmission, have led to issues with data availability, quality, accuracy, and reliability. Overall, despite the installation of many continuous emissions monitoring systems in 17 highly polluting categories of industry, their data has not graduated into a mainstream regulatory tool.

Looking ahead, given that the installation of continuous emission monitoring systems is now ubiquitous across the most highly polluting industries in the country, there is an opportunity to improve the existing status of their data, and integrate them with a larger AQMAS. This could enable regulators, policy makers and the public to remaininformed about the impact of industrial emissions on air quality and design targeted policies for pollution reduction.

[13]For a definition of industries in the red category,
see https://cpcb.nic.in/openpdffile.php?id= TGF0ZXN0RmlsZS9MYXRlc3RfMTE4X0ZpbmFsX0RpcmVjdGlvbnMucGRm

3. India and Leapfrogging Opportunities

Over the last few decades, countries and regions around the world have utilized various approaches to air quality monitoring and management, with many of them developing their monitoring infrastructure in a piecemeal fashion. India has the opportunity to learn from the current experience and set up an AQMAS that addresses multiple policy goals, is built for the local context, and helps achieve clean air for all. Such a system could potentially also serve as a model for other resource-constrained countries.

3.1 A Big-picture Perspective

3.1.1 Learning from Others' Experience

Given the state of global understanding of air pollution science, India has the opportunity to learn from the experience of other countries and regions – China, the European Union, Mexico, South Korea,the United Kingdom, and the United States –that have spent enormous resources on this problem over the last half-century and continue to do so. India also has the possibility of designing a system that builds on existing infrastructure and efforts to optimize the use of ground-based and remote-sensing data to meet various objectives.

A strong AQMAS could make India the leading player in air pollution science and public health diplomacy in South Asia and beyond. In addition, a suitably designed system could also support climate-change science and policy. Global experience shows that recent advances in monitoring science and technology provide an opportunity to inform integrated air and climate-change policy and planning. Improved planning to achieve a clean air scenario for both $PM_{2.5}$ and ground-level O3 targets, for example, could help prioritize action that yields substantial climate benefits through significant reductions in both greenhouse gases and short-lived climate pollutants. In addition, planning and achieving clean air scenarios could also substantially reduce premature mortality from high levels of pollution.

For this to happen, it is crucial that there is:

1: a continued strong and ambitious commitment, with both resources and a systematic approach, to the development of a state-of-the-art AQMAS, drawing on lessons from global experience;

2: coordination across relevant government agencies;

3: strong support for air pollution science and policy research – with systematic links to policymaking across thematic areas; and

4: suitable data governance to support and enhance the engagement of scientists, civil society organizations, and citizens.

3.1.2 Taking an Integrated, Systemic Perspective

An AQMAS, being a system,can achieve its objectives fully if all its individual pieces work, and all of them work together. For such a system, systemic thinking would mean considering the various instrumentation, data streams, uses, knowledge flows, and actors individually, but also their connections and how they could all work together. A system is as good as its weakest link and therefore consideration must be given to all the individual pieces and the links between them.

3.1.3 Encompassing Multiple Objectives through an Air Quality Measurement and Analysis System

The key objectives of a forward-looking system should be:

1: linking the system with policymaking to provide a good overview of the air that people breathe in various parts of the country and underpin the data and analysis needed for science-driven policymaking to reduce air pollution and its impacts;

2: linking the system to air quality management planning and operation to ensure cost effective implementation, including direct links with monitoring and evaluation for the NCAP, decisions related to air quality management allocated funds under the 15th Finance Commission, the Commission for Air Quality Management for the National Capital Region and Adjoining Areas, etc.;

3: linking the system to research priorities and cutting-edge science to support scientific research to increase understanding of sources and atmospheric processes that drive air quality and thereby improve its management;

4: setting up data architecture and accessibility so that data can be managed in a way that is easily accessible and useful to various users;

5: informing and engaging citizens throughout the country.

3.1.4 Reconciling Short- and Long-term Needs

A forward looking, dynamic AQMAS needs to be designed based on both short- and long-term needs. In the short term, for example, the system can be used to identify and control air pollution hotspots and for forecasting and alert systems. Given the complexity and the scale of the air pollution problem and the constantly evolving scientific understanding, however, an effective system also needs to take a multi-decadal perspective. Planning, designing, and setting up an effective system requires significant resources and time. Furthermore, it will be cost effective in the long run to have one that can be upgraded and adjusted based on:

1: an evolving understanding of air pollution science, health, and other policy priorities; and

2: improvements and advancements in measurement technologies and analysis systems.

3.1.5 Designing for a Local Context

While an AQMAS for India should learn from decades of global experience, it needs to ultimately be designed for an Indian context. Even within this, it needs to reflect the heterogeneity within the country in terms of pollution levels, associated impacts, personnel/institutional capacity, and financial resources. In a low-cost censor-based network, for example, the sensors should allow for heterogeneity of sources and meteorological variations which may produce shock loads in the data. The local context – district, municipality, urban agglomeration, city, etc. – is important both in terms of the needs and of the practical operation of components of the system. This involves thinking about the suitability of technologies to be used, the workforce needed to operate them, and the information required for engaging and informing citizens.

3.2 Key Elements

3.2.1 Data and Analysis

3.2.1.1 Data Measurement

India's current air quality monitoring system relies on a mix of continuous ambient air quality monitoring stations (CAAQMS) and manual stations operated by the National Air Monitoring Programme (NAMP). Protocols for measuring annual trends of ambient air quality are, however, only present for the NAMP– there is no structured, official method for using continuous ambient air quality monitoring stations' data for establishing long-term trends. The Central Pollution Control Board protocol for manual monitors requires a minimum of monitoring twice a week or 104 days a year. Thus, legal compliance with national ambient air quality standards can be assessed based on data for a minimum of 28.5 percent of the days in a year. This benchmark is low compared to data requirements in high-income nations. This benchmark was not met in 73 percent of $PM_{2.5}$ manual monitors in 2019 when the advent of continuous ambient air quality monitoring stations and other advanced technologies provided more continuous and voluminous data. Globally, there are protocols for using collocated real-time monitors as equivalents of manual monitors and used to fill in data for missed days of manual monitoring. India needs to develop methods to address data gaps, adopt data substitution methods to address them, and integrate data from different technologies. Going forward, it will be important to establish methods for utilizing continuous ambient air quality monitoring stations to help monitor annual trends. To do this, it will also be important to ensure the archiving of real-time ambient air quality data and making it readily available.

Advances in science and technology have reduced the cost of data collection by providing a path from current expensive continuous regulatory-grade monitoring systems, ranging in cost from US$ 200,000 to US$ 300,000, to calibrated sensors capable of providing single pollutant information at a fraction of that cost – US$ 1,000–15,000. While low-cost sensors can help improve the spatial coverage of measurements, they also need to be carefully calibrated as their performance can vary sharply based on air pollution levels/composition and meteorological conditions. These calibrations and performance evaluations are usually performed by co-locating low-cost sensors with reference-grade instrumentation. Furthermore, the reference-grade instrumentation, along with other advanced research-grade instrumentation that provides detailed information about the composition of air pollution, can also be used for online source apportionment analysis, building emissions inventories, and strengthening air quality models. Low-cost sensors, regulatory measurement 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 pollution with other environmental information, the sources and the pool of information could be significantly enhanced in the coming years and decades.

3.2.1.2 Data Archiving and Accessing

Access to properly archived, appropriately formatted, machine-readable, analysis ready, and easily accessible data and meta data is critical for the optimal utilization of an AQMAS by various users. This can only be achieved through collaboration between atmospheric-science, database-systems, and systems-design experts. Availability of data through standardized application programming interface (API) access together with information on meta data, such as device type and location, date and time, raw and processed data point, and data quality can enable a myriad of cross-functional applications. Furthermore, in designing the system, it is important to consider long-term archiving practices, including data storage options, trade-offs between storage strategies and data retrieval time, and strategies for access and security systems.

Finally, it is important that the data available in the public domain meets specific criteria, and data access policies are clearly and publicly defined and maintained.

3.2.1.3 Data Analysis and Air Quality Management

An important element of air quality management is the effective use of information for policy making. Different kinds of analyses, such as source apportionment, exposure apportionment, epidemiological analysis, and analysis of health impacts, are required for different policy and scientific objectives. There are a number of research and policy questions which can be understood better with access to a large pool of information. These include, but are not limited to:

- pollution load assessments for a selected area or city;
- land-use regression analysis for hotspot assessment;
- validation of the chemical transport modeling studies at urban and regional scales;
- interpretation of the satellite retrievals;
- source apportionment of ambient pollution, especially PM2.5 and PM10;
- health impacts assessments;

- what-if scenario analysis for policy support;
- prioritization of interventions based on cost effectiveness, which enables federal, state and cities authorities to optimize limited financial resources.

India's NCAP has emphasized the need for integrating the generation of ambient air quality monitoring data with policy making, including prioritizing a list of actionable measures for air pollution control. An active AQMAS can provide the necessary data support for monitoring and evaluation as states and cities embark on targeted air pollution interventions.

3.2.2 Institutional Architecture

3.2.2.1 Systematic Achievement of Functions

An optimal AQMAS not only requires its individual components to function properly, but also the various components to work together as a part of a synergistic system. In addition to the financial and logistic support needed to operate such a system, it also requires coordination and communication between the various individuals and organizations involved.

3.2.2.2 Coordination

As there are many data and analysis streams in an AQMAS,there needs to be effective and efficient coordination among them to ensure its proper functioning. Such coordination is required to ensure that high-quality and usable data streams are available to all users, and also to ensure that these can be used optimally to achieve the system's various objectives.

3.2.2.3 Strategy and Planning

Leapfrogging and designing a state-of-the-art AQMAS for India will require institutional support for strategy and planning activities to make sure that the country has a forward-looking system. Strategic support is needed for the conceptual design of its various objectives, its functions,and coordination and information exchange between key stakeholders.

3.2.2.4 Stakeholder Links

Linking Air Quality Knowledge to Policy and Planning

Ultimately, information and knowledge obtained through an AQMAS should serve the needs of policy makers, both in the short- and long-term. In the short term, drawing on measurement data to produce air quality forecasts/early warning systems, such a system can be used to design a health-alert system with targeted messaging for the general public as well as healthcare facilities, or for hotspot detection and monitoring. In the longer term, the system can aid identification of key sources of pollution and help design regulatory priorities on an ongoing basis. Data could be used by local leaders, tourism boards, etc. for short-term action as well as by policy makers for long-term policy planning.

Advancing Air Pollution Science

While scientific understanding of air pollution has drastically improved in the last few decades, it remains a continuously evolving field. Scientists are still making breakthroughs in air pollution science and its connection with climate change, toxicology, public health, and more. An AQMAS that prioritizes air pollution science:

- becomes a stakeholder in the evolving science;
- engages scientists who can help better interpret air pollution patterns/trends and help upgrade the system with advances in scientific knowledge and relevant technologies;
- can be used as a tool in global science diplomacy.

Enabling Citizen Engagement

India's NCAP, launched in 2019, has explicitly discussed the need for a better understanding of the air pollution problem not only by increasing the monitoring of ambient air quality but also by establishing an air information cell capable of managing and integrating the information into policy discussions and decisions.

4. Designing for the Future

Effective management of air pollution requires paying attention to all these system elements and ensuring that they are appropriately linked to each other. Furthermore, an AQMAS must be responsive to locallydefined objectives and must take such factors as pollutants of concern, target values for ambient concentrations or relevant metrics, measurement standards, and geographical scope into account. In other words, there is no single universal optimal design for anAQMAS and its design has to be tailored to the local context and needs. Finally, such a system is not just a technical construct as it also has to keep human and organizational aspects in mind if it is to function efficiently. Thus, attention to human and institutional capacity is critical.

Characteristics of an effective AQMAS include:

- ambitious, comprehensive, and systematic approaches that are consonant with the national context and needs;
- clarity of objectives – what functions to serve, what pollutants/chemical entities to measure, definition of geographical coverage, etc.;
- deep and sustained investment with a long-term perspective of decades is required to enable suitable resources for physical infrastructure, instrumentation, staff, training, research, data infrastructure, engagement, etc.;
- integration and coordination across regulatory and research agencies and institutions;
- upgrading and adjustment to reflect the continuously evolving landscape – technological, scientific, social, etc.

In the following sections, wediscuss the key design issues that need to be considered for an effective system.

4.1 Systems Approach to Instrumentation and Placement

The instrumentation and their placement are a critical component of an AQMAS. A systems approach is, however, required to ensure that its various objectives are met. Some of the considerations are:

- understanding the characteristics of an effective ambient air quality monitoring network;
- setting clear objectives for the network being established;
- combining regulatory-grade monitors and calibrated low-cost sensors to increase the efficacy of a network in a city/state and at a regional (airshed) scale;
- learning from experience in integrating ground-based and remote-sensing technologies to develop hybrid networks;
- identifying barriers and lessons learnt from operating such hybrid networks;
- defining a roadmap for integrating emerging technologies, such as CRDS, BC monitors, and standard field-calibrated low-cost sensors,including the development of a standard field calibration protocol, into the network;
- understanding and determining how networks with different functions – monitoring and determining both ambient air quality and sources of pollution – can be collocated at both local and regional, including airshed, scales;
- identifying and building the capacity of institutions and personnel to design, operate, coordinate, and maintain such networks;
- developing clear thinking around how instrumentation and networks support source

apportionment analyses, the building of emissions inventories, improving air quality models, etc.

4.2 Data Architecture

In developing an AQMAS, it is important to consider standardized methods for data collection, storage, distribution/access and usage, as well as resources including systems and personnel. Some of the key design considerations are:

- clarity in who builds and maintains the data infrastructure for a national systems;
- deciding appropriate formats for data and metadata storage;
- ensuring that all instruments and infrastructure making measurements can easily transmit data to this data infrastructure;
- keeping large, long-term datasets securely stored and accessible;
- providing these datasets to multiple users in real-time;
- keeping the data architecture secure while promoting data transparency;
- facilitating multiple analysis systems, such as source apportionment and air quality forecasting, in real-time, as well asensuring that data from manual sampling arealso applied;
- ensuring protocols for data verification and quality assurance/qualitycontrol are established and instituted;
- to make full use of India's current data sources, including ensuring that past and future trends can be fully analyzed, it is critical that data from manual systems, including the NAMP, are also stored, made accessible and used in analyses.

4.3 Institutional Architecture

Envisioning, designing, and operating an AQMAS requires institutional architecture which brings together all its various components. Consideration should be given to:

- selecting the ecosystems of institutions, organizations and individuals, for example, the relevant government institutions, academia, and private companies;
- understanding and supporting the expertise critical for developing an effective system – for example, beyond the traditional air quality/ atmospheric science expertise, there is a need for vendors and operators of air quality monitoring equipment and quality assurance/ quality control, data systems experts for designing the architecture, data science experts for data visualization and analysis platforms;
- ensuring uniformity and comparability across systems including standard operating procedures which enable effective coordination across agencies and individuals;
- deciding who gets access to various datasets;
- building capacity to manage monitoring equipment/sites, analyze and visualize data streams, and effect policy change;
- ensuring there are the required resources for building and operating such a system for India.

4.4 Links with Science, Policy, and Citizens

As discussed above, a state-of-the-art AQMAScan further scientific knowledge, be useful for policy makers, and keep citizens informed and engaged. Some of the design elements to consider are:

- establishing clear goals and a roadmap for a system that supports the planning and implementation of advanced air quality monitoring;
- understanding how the system can be leveraged to inform other priorities such as addressing climate change – particularly carbon dioxide (CO_2), methane (CH_4), and BC emission reductions – and public health impacts;

- identifying current best practice for data analysis and integration across multiplein India and globally; crosscutting thematic areas, such as climate change; health impact assessments; urban planning; prioritization of air pollution mitigation action;clean air scenario development;etc.;
- developing a roadmap of air quality management research in India for source apportionment, hybrid modeling coupled with satellite retrievals, chemical transport modeling, and cost-effectiveness analysis;
- translating scientific knowledge into easily understandable formats that can act as direct inputs for policy makers and administrators. For example, further development of AQM guidelines (including ambient air quality monitoring (AAQM), source apportionment, emission inventory, and cost effectiveness) to stimulate technical and managerial advancements in line with global best practices;
- developing a strategic communications strategy for engaging citizens, underpinned by user-friendly dissemination tools/platforms that help make key data and messages easily accessible and comprehendible.

4.5 Capacity Building

In the long-term, the ability to sustain and improve an AQMAS is critical to derivingvalue, and will require a sustained, long-term effort and a well-trained, engaged, and dynamic ecosystem. Capacity building figures strongly across all the four components in this White Paper (Annex I– Capacity and Collaboration Consideration column) combining training courses with extensive on-the-job training. Some of the key considerations to enable continuous capacity building for the sustainable design, functioning, and operation of such a system are:

- building the capacity and capabilities, through personnel training and institutional support, needed to enable cross thematic data analysis, research, and application of, for example, cost-effectiveness. Capacity building in cost-effectiveness analysis and application is seen as one of the greatestneeds in India's air quality management endeavors that can make further good use of the country's strong capacity in atmospheric science in air quality management planning and implementation;
- complementing theoretical learning with practical, on-the-job learning that may be multi-year, for example, capacities in operating collocated networks, operating and making full use of superstations, and developing analytical skills in all elements in the AQMAS process – ambient air quality, sources, emission inventories, air quality management modeling, and the application of analyses in planning and forecasting;
- setting up an advanced system and working on the expansion of capacity in tandem can ensure that the needed capacity to meet the system's requirements over the coming decades is in place;
- supporting local leadership and ensuring the availability of financial resources dedicated to capacity building; sufficient multi-year financial resources for capacity building must be made available and integrated into the financial plans by both the federal and local governments – state, urban agglomerations,etc.;
- tapping into, supporting, and building on ongoing capacity building efforts in India – for example, under the National Carbonaceous Aerosols Programme –Carbonaceous Aerosol Emissions, Source apportionment and Climate Impacts (COALESCE);
- reasonable compensation for any turnover of trained personnel who will understandably be of value on the job market; make use of economic- and social-cost arguments of not substantively improving India's air quality;
- ensuring the capacity-building strategy/plan – training courses, and short- and long-term

on-the-job training – is supported by sufficient funding, and partnerships with the private sector, civil society, and academic institutions.

4.6. Application for Regulatory and Policy Actions and Implementation Support for Air Quality Managementplans

In addition to equipping regulators and policy makers with relevant analyses and data to design regulations and policies that enable coordinated action on air pollution in the medium to long term, an AQMAS should also enable more immediate actions. To achieve this, it is important to consider the following.

- Ensuring that an AQMAS builds on currently used instrumentation and strives to adopt the "best available technology". Harmonization of instrumentation used within the AQMAS should comply with regulatory guidelines and be well calibrated to national standards and adhere to quality assurance/quality control (QA/QC) protocols, to support regulation is important. An actionable, time-bound road map for standardizing our approach to air quality monitoring instrumentation, for example, reference grade, low cos, and data streams such as satellite data used within the framework of an AQMAS should be developed and implemented. In addition, an AQMAS should also allow piloting of new/emerging technology to advance research objectives.
- Creation of a data architecture that can readily disseminate actionable, regulatory-grade data to the appropriate regulatory agencies at the city, state, regional and national levels.
- Regular assessment of air quality targets (short, medium, and long term) and potentially integration with information-technology enabled project management tools that help authorities monitor sectoral action under city/state/regional air action plans.

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Annex I

SUMMARY OF THE SYMPOSIUM

AREA	KEY POINTS MADE	ISSUES TO CONSIDER	CAPACITY AND COLLABORATION CONSIDERATIONS
1. MEASUREMENT INSTRUMENTATION			
1.1 Conventional systems (CRDS,BC, manual stations)	• India is well placed to adopt new conventional monitoring technologies available and applied globally now applied, for both gases and particulate matter (PM) monitoring, and leapfrogging to develop a comprehensive AQMAS. (APT, many) • CRDS is an important technology for tracking gases including ammonia which is a key contributor to secondary particle formation through reactions with sulfur oxides and nitrogen oxides. (MZ, SL) • Semi-automatic monitoring solution that measures aerosols (BC) and traces their source by determining the isotopic delta-carbon signature are also available. (TG) • Despite the complexity of measuring ammonia, the cavity ring-down spectroscopy technology can provide accurate measurement of it, and as a condition for understanding its sources. (MZ, DG)	• Integration of CRDS devices with real-time monitoring stations to track ammonia. (SL, LR) • Test different cavity ring-down spectroscopy technologies to learn about strengths and weaknesses. (APT, MZ) • Integrate an adequate number of BC monitors in air quality management networks to ensure representativeness across the country, including semi-automatic monitoring solutions. (SL, DS, TG) • Prepare station facilities to manage elevated temperatures (> 45°C) during summer. (TG) • Develop state level checks/ calibration mechanisms to ensure quality assurance of data from manual monitors and calibration with continuous ambient air quality monitoring stations. (APT, BSPCB)	• Establishing in-house market and manufacturing of technology, such as licensing and joint ventures. (APT, NK) • Integrating BC and CRDS monitors into the operations and management contracts with the suppliers of continuous ambient air quality monitoring systems procured by state pollution control boards. (APT) • Developing the technical and managerial capacity in the states for third party evaluations and reviews and deploying a skilled workforce for operation and management of manual monitors is crucial. (LM, APT) • Operating capacity for NAMP stations, as well as analytical capacity can be further developed when operating new source apportionment samplers. (LR, LM)

	• Need for separate BC monitoring due to high ad-hoc measured black carbon content in PM2.5 readings is well established. (SL, DS) • Majority of monitors in India are manual (at present 805 in 344 cities, intended 1250). Limited number of days with data (2-3 per week) and limited calibration with online continuous ambient air quality monitoringnetworks. Many of the monitors are old with imprecise readings. (VK)	• Use NAMP stations as a source of providing historical air pollution trends and retain analytical capacity. (SL, LR) • Consider critical performance specifications including accuracy, precision range detection limit, pollutant specificity, noise, multi-site measurement, response time etc. (RV)	• Low technical capacity of state pollution control bards, gaps in data collection, shortage of staff (routine checks, etc.) need to be addressed to improve monitoring capacity to, for example, evaluate progress towards reaching national ambient air quality standards. (BK, ST)
1.2 Low- cost sensors	• Low-cost sensors can substantively enhance the ambient air quality management capacity of states. (VKS, MK, AKG) • Standardization of low-cost sensors deployed by the government is necessary to ensure reliability and instill confidence. (KVR) • To increase technical reliability of low-cost sensors, it may be advantageous to not go with lowest-cost solutions but gradually invest in more reliable solutions. (DW) • Globally, stand-alone low-cost sensors are not used for regulatory monitoring. (RV)	• Pilot low-cost sensor integration with conventional networks. • Deploy low-cost sensors (mini and micro) across a larger area (urban and rural) that can provide real-time measurement [e.g., Stations of Measuring Ecosystem – Atmosphere Relations (SMEAR)] (TP) • Technical standardization for low-cost sensors should be part of the ambient air quality management guidelines to be updated. (KVR)	• Ensuring calibration with conventional networks, as well as building up domestic manufacturing capacity to develop indigenous low-cost sensors is important. • Low-cost sensors cost less (= < US$ 5,000 as opposed to US$ 15,000–40,000 or more for reference grade monitors) and require little or no training to operate. (RV)

1.3 Satellites	• Satellite observations can be used to verify anomalous ground level-based data and modeled data and to establish spatial and temporal pollution trends including pollution impacts. (TH, DL, DG) • Improving air quality management capacities at the regional level is key. GEMS specializes in aerosol optical depth observations over 20 Asian countries, from Japan to Brunei, and India has been invited to participate in both the Pandora Asia Network (PAN) and Pan-Asia Partnership for Geospatial Air Pollution Information PAPGAP programs. (LSC)	• In the short-term, data provided by space agencies (the European Satellite Agency, GEMS, NASA) is free to users and thus can be used for all kinds of measurement. (JB) • Considering India's extensive air quality management challenge, the country should develop a dedicated satellite monitoring system to complement air quality management tailored to its particular air quality needs. (JB)	• Data from satellites, real-time and manual air quality stations should be analyzed and assimilated together. There is a need to enhance technical capacity to develop data algorithms (for example, product developers at the Indian Space Research Organisation) and personnel capacity to ensure seamless coordination across institutions. (PC) • Need for innovative monitoring approaches, such as satellite-based air quality monitoring (should the Indian Space Research Organisationdevelop a satellite for South Asia), high-resolution (hyperlocal) monitoring including land-use regression, low-cost sensors, and mobile monitoring. (PC)
1.4 Advanced and emerg-ing instru-mentation	• Measuring and understanding secondary particle formation and sources, for example, secondary aerosols and ammonia, should be prioritized. (MS) • Both simulated(emission inventory and dispersion modeling) and measured (chemical composition analysis and receptor modeling) source apportionment is needed to establish a complete AQMAS and is as important as air quality monitoring. (CV) • Real-time source apportionment in India also show reliable results, including the importance and high	• Source (dispersion) and receptor modeling should be executed in states that should include establishment of state level laboratories for full-scale chemical speciation analyses. Preferably, larger states with high air pollution concentrations and large varieties of air pollution sources should each establish such a laboratory. (MS) • In addition to research purposes, real-time source apportionment should be applied regularly and be part of state-wide air quality management infrastructure. (SL, LR)	• On-the-job training of state pollution control board staff on both chemical composition analyses and dispersion and receptor modeling is a key. (LR) • As a basis of capacity building, ensuring sufficient investment for innovative technologies for air quality laboratories is necessary to consider. (LR) • Strengthening collaboration between state laboratories and those recognized internationally for performing full-scale chemical composition analyses can help bridging capacity gaps. This is particularly important for states with high air pollution concentrations and a large

	share of secondary sources. (SNT)		variety of pollution sources. (LR, APT)[1]
2. MEASUREMENT SYSTEM DESI			
2.1 Objectives of a network	• While establishing an ambient air quality management network, consider different objectives related to (i) public awareness; (ii) compliance; (iii) research; (iv) policy action; and (iv) health effects analysis. (RV, ST) • Clarify if all functions of these objectives should be integrated in one common network or parallel operating networks. Globally, countries are running networks meant, for example, for compliance and public awareness in parallel. (RV, ST) • Under the Health Mission on Climate Change, a sentinel surveillance of acute respiratory illnesses started in Delhi three years ago. An improved, expanded ambient air quality management network can support expanding the study to the rest of the country. (AS)	• Developing guidelines to mandate criteria on geographical representation of ambient air quality managementmonitors (both manual and real time) and uniform standardized criteria in determination of location (including micro-location) of the ambient air quality management network stations. (LR, MA) • Making air quality assurance part of major national and international events, such as sport and conference events. (WZ) • The result of the Health Mission on Climate Change sentinel surveillance work can be linked directly to air quality to enhance the understanding of air quality-health links. (AS)	• Establishing collaboration between strong local leadership, regulatory agencies, local research community, non-governmental organizations to build local capacity and allocating resources for staff. and maintenance are essential for sustaining and monitoring the network. (CW) • Challenges in developing AQMAS go beyond technologies and into systems, institutions. This calls for increased budget allocation, raising citizen awareness, enhancing communication strategies, reducing personnel rate, and ensuring timely maintenance of the system. (SS)

2.2 Network integration (including low low-cost sensors, mobile monitors, satellites, Source apportionment)	• Low-cost sensor networks need to be integrated and calibrated with conventional networks, (for example, through one conventional station in a district). (VK, MK, AKG, KJR) • Using satellite data with on-ground based measurements (monitoring) and models can be used to fill data gaps, improve model simulations, and enhance capacity of monitoring and management of air pollution. (TH, LSC, AR) • Co-location and integration of ambient air quality management and source apportionment networks are realistic and feasible in integrating not only into current the continuous ambient air quality monitoring system expansion but also in the expanding National Air Monitoring Programme monitoring infrastructure. (LR, NK, AKG, SL) • If current Central Pollution Control Board guidelines are followed, an ambient air quality management network up to four times the size of the current one will need to be established (SG). However, when the establishment of a regional ambient air quality management network is considered, the actual number of stations to be deployed may be less	• In a selected number of districts, set up district-wide low-cost sensor networks that are linked to one or more conventional network stations to ensure calibration. (SL, APT) • Should India integrate (i) all ambient air quality monitoring (compliance, Air Quality Index information, other public awareness, etc.) into one combined ambient air quality management network; or (ii) could networks operate in parallel (as do United States compliance networks applying the Federal Reference Method (FRM) and Federal Equivalent Method (FEM) as opposed to AirNow networks)? (APT) • Collaboration between India, NASA, the European Space Agency and GEMS in developing, obtaining and making use of aerosol optical depth-derived data in analytical work and air quality management planning. (DL, LSC, TH) • Design regional/state-wide ambient air quality management and source apportionment networks and integrate one or a few real-time monitors in state-wide combined source apportionment networks. (LR, VK)	• Under the leadership of the Ministry of Environment, Forest and Climate Change, strengthen coordination between relevant departments, including the Ministry of Earth Sciences, the Indian Space Research Organisation, the Central Pollution Control Board, state pollution control boards, the National Physical Laboratory, etc. (APT) • Training (mostly domestic on-job, but also selected skill sets from abroad), experience sharing in operating (including analyzing), and managing (deploying, collecting, and managing) collocated ambient air quality management and source apportionment networks need to be instituted. (LR, SL, NK)

	but strategically located to achieve efficiency. (SL)	• Advancements in air quality monitoring are also being made by the application of drones and portable monitoring solutions. (SS)	
2.3 Rural stations and border network	• Rural stations are needed to address, for example, PM2.5 and other air pollutants travelling across states/regions and as background stations to urban-based monitoring stations. (MA) • Need knowledge about technology access, suitable instruments and technologies, and ambient air quality management network set-ups in complicated and eco-sensitive geographies. (VKS) • Ambient air quality management coverage of rural areas is challenging but these areas must be covered due to high population densities and economic activities. (NK)	• In the amendment of the ambient air quality management guidelines, develop design criteria that include the number of stations needed in rural parts of the country according to population, population density, size of geographic area, economy, etc. (APT) • Consider using data from satellites for designing ambient air quality management networks that include rural areas and those that have complicated geographies. (APT)	• On-the-job training in establishing and developing ambient air quality management networks that include rural parts of districts (limited experience to draw from other countries). New knowledge in combininglow-cost sensors and conventional stations in rural areas is important. (APT) • Contractors for ambient air quality management networks need experience of the operation and maintenance of stations located in rural areas. (NK, SL) • State pollution control boards need to be strengthened to expand monitoring capacity in rural areas. (BK)
2.4 Supersites	• The need for a supersite in each peak (high air pollution concentration) city is self-evident. (WZ, DG) • Supersites are used to combine all aspects of an air quality management infrastructure –ambient air quality management, source apportionment, including real-time, chemical composition analyses, air quality management modeling, reference	• At least one supersite to be established within each of the most polluted states, for example, in the Indo-Gangetic Plain, and other polluted areas throughout India, as China has done. (WZ) • Target could be to establish supersites in 10 cities (integrating state-wide networks) starting out with four sites in 2021–2022. (APT)	• Integration of all air quality management infrastructure operations in one location, drawing upon international supersite experience, from, for example, China, Europe and the United States, can help provide important learning and capacity enhancement. (WZF, VKS)

	sites for low-cost sensor calibration, satellite data, etc. (VKS) • Establishing a supersite in each of the most polluted states is important. Patna, Bihar plans to establish them. (NK, AG)	• Establish system to receive and utilize satellite data for north India in one of the proposed superstations in the Indo-Gangetic Plain. (PC, APT)	
3. DATA ARCHITECTURE			
3.1 Provenance and unifor-mity	• Understanding the origin of reported air quality and processed data is important. All air quality data, metadata (which may be device, location, station specific) and processed data (from data sources and algorithms) must be captured and made available. Ensure proper compliance of data considering uniformity in its usage. (MR[1], LR)	• Guidelines for air quality data management should be established. (MR[1])	• State pollution control boards should consider investing sufficiently in building infrastructure to support data management, for example, dedicated servers, analysis platforms, building data analysis capacity and the workforce, and data dissemination tools. (BK, APT) • Training and certification programs for air quality data assurance should be put in place (including capturing data origin). (APT) • An air information center and a uniform, transparent strategy/ standard operating procedure for sharing data with researchers and the wider public should be established. (VKS, APT) • An agreed path for using air quality data generated from an AQMAS for informing development of policies should be established. (APT)

3.2 **Data quality**	• It is important to ascertain data quality before putting data to use. (MR1, VKS, LR)	• Development and implementation of quality assurance/quality control protocols and systems for third party data verification should be done. (LM)	
3.3 Inter-pretation of data and accessibility	• Regulatory bodies can work with academics, civil society, health researchers to interpret meaning of data collected (applying big-data thinking) which will only be possible with better access to data. Making data available to the public can also help in improving its quality. (APT)	• Raw air quality data should be made easily available and accessible to researchers, and research encouraged. (MR1, APT)	
3.4 **Use case relevance**	• Ascertaining use of data must be done alongside designing an AQMAS. The design of a network should be based on the objective – regulatory use (for example, to reach national ambient air quality standards), exposure and health impact analysis, public awareness, spatial and temporal distribution, etc. (AR, BK, RV) • AQMAS presentations reflected an enormous capacity particularly in atmospheric science. However, application of economic analytical tools, including cost-effectiveness, appeared completely absent. (CV, SNT)	• Expansion of the ambient air quality management network must be done to help collect and use data for multiple purposes. (AG, MA) • Indian leadership (the Ministry of Environment, Forest and Climate Change, etc.) should set specific air quality improvement targets for the next 5–10 years and requestion the Indian science community to determine how to most cost effectively reach these targets. This will stimulate the development of environmental economics (including cost effectiveness) among scientists. (MA, APT)	

4. DATA ANALYSIS AND APPLICATION			
4.1 Air quality management modeling	• How enhanced data management can strengthen atmospheric (including receptor and dispersion) modeling was emphasized. (CV, KJR). However, the limitations of current air quality management modeling to define cost-effectiveness were pointed out. • Air quality modeling is important to bring together satellite-based aerosol optical depth measurements and ground-based monitoring data. (JB)	• Add cost-effectiveness into air quality modeling. (MA)	• Build up new educational programs in environmental economics to strengthen assessment of cost-effectiveness. (SNT, CV)
4.2 Forecasting	• Air quality forecasting is the most important aspect to understand the steps to be taken at the ground levels. (MR2) • Forecasting air quality during high pollution episodes is difficult, as it is a regional phenomenon. Deploying a nested air quality prediction modeling system provides a strong basis for an air quality forecasting system for China. (WZ) • India's Central Pollution Control Board proposes building a forecasting, data dissemination and data sharing policy in collaboration with the Indian Institute for Technology Madras and the India Meteorological Department, starting with 20 cities. (VKS)	• A decision theatre to enable an early warning system for air quality episodes can be developed and early air quality decisions can be taken that will help regulators think of alternative scenarios. (MK, KJR, WZF)	• Physical infrastructure development for a decision theatre, along with technical expertise required to conduct accurate forecasting needs to be assessed and built. (APT, KJR, MK)

	• Copernicus provides global modeling and forecasting capabilities that can be used to build country-scale and city-scale models and forecasting mechanisms. (KJR)		
4.3 Planning	• Air quality measurements are needed from distinct levels (regional, state, district, municipality) to do required nested air quality management planning. (DS) • Global experience is to apply AQMASknowledge at a state level and define non-attainment areas due to the regional scale of air quality management. (ST)	• Apply AQMAS at the regional level (for example, in state air quality management action planning) rather than a at a city level (for example, define non-attainment areas rather than non-attainment cities). (APT)	• Develop the capacity, strengthen and streamline coordination between the Central Pollution Control Board and state pollution control boards, urban local bodies, and local technical partners (such as the National Knowledge Network) to enable full-scale state and regional air quality management action plans and to apply AQMAS to support the development and implementation of such plans. (APT)

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