Atmospheric Environment 222 (2020) 117120

Contents lists available at ScienceDirect

Atmospheric Environment

journal homepage: http://www.elsevier.com/locate/atmosenv

Ambient air pollutant monitoring and analysis protocol for low and middle income countries: An element of comprehensive urban air quality management framework

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HIGHLIGHTS

- Status of urban air pollution in LMIC.
- Challenges and issues of air quality management in LMIC.
- Air quality monitoring protocol in LMIC.
- Source apportionment protocol in LMIC.

ARTICLE INFO

Keywords:
Urban air quality management
Wireless low cost sensor based monitoring
Satellite-based monitoring
LMIC
Protocol

ABSTRACT

Rapid urbanization along with industrial growth is one of the major causes of elevated air pollution levels in urban areas of low and middle income countries (LMICs). They are further associated with adverse health impacts within urban ecosystems. In order to manage and control deteriorating urban air quality, an efficient and effective urban air quality management plan is required consisting of systematic sampling, monitoring and analysis; modelling; and control protocols. Air quality monitoring is the essential and basic step that develops foundation of any management plan. The present research article describes a comprehensive methodology for establishing a systematic and robust air quality monitoring network in LMICs and strengthening the effectiveness and efficiency of urban air quality management frameworks. It also describes step-by-step procedures for chemical characterization of both organic and inorganic constituents of ambient particulate matter along with molecular markers, which are essential to identify the corresponding sources of particulate matter, an integral part of air pollution monitoring protocol. Additionally, it discusses the need for coupling low cost wireless sensor-based stations with a limited number of manual and conventional real time ambient air monitoring stations in order to make it cost effective, yet robust. The article demonstrates that satellite-based remote sensing monitoring calibrated with ground level measurement has the potential for regional scale air quality monitoring that captures transport of transboundary pollution.

1. Introduction

Elevated level of urban air pollution affecting public health is one of the major worries throughout the world (Pope and Dockery, 2006; WHO, 2014; Hankey and Marshell, 2017; Wang, 2018; Schiavon et al., 2018; Lancet Planet Health, 2019). The problem is more complex and severe in developing countries when compared to the developed world due to the fast growth in population and associated growth of urbanisation (Baldasano et al., 2003; UN, 2007; Mannucci and Franchini, 2017). This leads to rapid development in motorized transport, industrial and commercial sectors which further lead to high energy consumption (Gulia et al., 2015). It has been reported that the coarser and finer fractions of PM (i.e. PM_{10} and $PM_{2.5}$) frequently violate the prescribed standards (ADB, 2014; Worobiec et al., 2011). Further, the air

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https://doi.org/10.1016/j.atmosenv.2019.117120
Received 12 December 2018; Received in revised form 30 October 2019; Accepted 6 November 2019
Available online 20 November 2019

pollution related health burden has been estimated to be greatest in low- and middle-income countries (LMICs) in the South-East Asia and Western Pacific Regions. In the recent past, WHO has estimated that 92% of the world's population has experienced high exposure levels when compared with WHO limits. Nearly 90% of air-pollution-related deaths (i.e., ~5 million) occurred in LMICs (WHO, 2014). In one of the studies, it is reported that PM_{10} levels are found to exceed the national annual average standards in seven out of ten Asian countries (CAA,2011). Outdoor air pollution is much more significant in terms of public health risk, contributing 2.1 million premature deaths in Asia annually (Lim et al., 2012). Outdoor air pollution has been identified as among the top 10 health risks worldwide and among the top five risks in the developing countries of Asia (ADB,2010).

Efficient and effective air quality management planning is the need of the hour for the LMICs to obtain acceptable air quality. For example, Schiavon et al. (2015) estimated that implementing certain traffic restrictions alone would decrease the benzene concentrations by 43% lower than the concentrations induced by the whole vehicle fleet in Verona, Italy. However, majority of the LMICs are still in the process of formulating air quality management plans (AQMP) (Naiker et al., 2012; Gulia et al., 2015). The success of any AQMP depends upon the integration and linkage between its key components i.e., policy objectives, monitoring network, emission inventory, source apportionment, air quality modelling, health exposure assessment, control strategies and public participation (Longhurst et al., 1996; Gokhale and Khare, 2007; Gulia et al., 2015; 2017). The role and importance of above key components depend upon the pollution problem, its sources and climatic condition. Gulia et al. (2017) have reviewed and compared the success stories of some of the management plan of developed countries and discussed how control strategies have helped to reduce pollution levels in those countries.

The present study emphasises on air quality management issues with special focus on the monitoring and analysis protocol in LMICs of the Asian (India, Bangladesh, Srilanka, Nepal, Bhutan and Vietnam) and African region (Ghana, Nigeria and Kenya) where persistent high levels of ambient PM is one of the major issues (Gulia et al., 2015; Khare and Khanna, 2016). The present study includes a comprehensive review of air quality management practices being followed in LMICs with respect to pollution load, sources, air quality monitoring and source apportionment studies. The study proposes a PM monitoring and analysis protocol which LMICs may adopt in order to strengthen their AQM planning for better air quality.

1.1. *Air quality monitoring techniques*

Air quality monitoring is the basic component of any AQMP as it helps decision makers in making informed decisions. Monitoring helps in addressing concerns related to the magnitude of emissions that need to be reduced; the areas that require control actions; and also evaluating the efficiency of past controls/management actions. Further, analysis of chemical characterization of monitored PM on filter paper identifies the sources and their contribution using source apportionment principles (six city source apportionment study - CPCB, 2010; Pant and Harrison, 2012; Pant et al., 2015; Khare and Khanna, 2016). However, a competent AQMP can only be designed using monitoring data from a robust integrated air quality monitoring network (AQMN). An integrated AQMN includes a combination of different monitoring approaches such as manual conventional method; continuous real time and sensor based monitoring stations. The design of any AQMN may include these types of monitoring approaches in combination especially for LMIC where budget is always a limiting factor as long as quality levels are maintained. Hence, the low cost sensors can be more appropriate for LMICs (M. Kumar et al., 2015; P. Kumar et al., 2015; Moltchanov et al., 2015). The comparative analysis of different types of AQMNs indicates merits and demerits of each monitoring method which can be supplemented by integrating them while designing the AQMN. For example, manual and continuous stations are generally located away from curbside and major traffic intersection areas (*pollution hotspots*) due to space constraints, electricity supply, safety issues, etc. They are spread thinly within a particular city and can provide a comprehensive time-series data in desired resolution, but at limited locations. This makes it difficult to compile representative and reliable information for a city or area as a whole, and therefore, it is not possible to form a large scale view of concentration trends. However, the deployment of a network of properly calibrated low-cost wireless sensors can easily tackle this shortcoming by providing high tempo-spatial resolution of pollutant concentrations data. The calibration of sensor should be performed in environmental conditions where the measurements are made. It can be done through co-locating with reliable measurement techniques with well-defined quality assurance protocols. Calibration in the lab is not sufficient (Pinder et al., 2019). Sensors do not require space as they can easily be mounted on street light poles.

On the other hand, for regional scale monitoring, the deployment of low-cost sensors, manual and continuous ambient air quality monitoring stations (CAAQMS) would be very expensive and challenging to maintain, given the large number of sensors required. In that case, a satellite-based remote sensing monitoring approach can be more effective. Remote sensing-based retrieval of satellite data; (RSSD) of air pollutants is one of the foremost techniques for regional scale monitoring and to evaluate the impact of transport of transboundary air pollution. It provides a regional level pollution profile and is not affected by any local sources. The information extracted from satellite data gives vertical profile in varying conditions (Dey et al., 2012). The RSSD can provide long time series of pollutant, which is very useful to conduct epidemiological studies (Kumar et al., 2008). With multiple validation and inter-comparison network, remote sensing information has emerged with much more reliability and provides scope of extensive application in multi-dimensional scientific fields. There are numerous examples of successful application of satellite retrieved O_3, NO_2, and AOD in identifying trans-boundary movement, aerosol source and receptor relationships, variation in particle morphology and in computing radiative impacts both in total organic aerosol and at surface in LMICs (Kumar et al., 2015a; Banerjee et al., 2015; Rastogi et al., 2016; Thompson et al., 2014, Marais et al., 2014; Hersey et al., 2015; Knippertz et al., 2015). Although, retrieval of a pollutant's microphysical properties from satellite-based sensors is a relatively new and developing field, it still provides a generic description of exiting atmospheric profiles which are often well linked to ground-based measurements.

The RSSD fundamentally poses three basic constraints: cloud effects, surface reflectance and molecular scattering. In principle, retrieving of aerosol properties depends on the reflected radiation (Lee et al., 2009; Ackerman et al., 1998; Kokhanovsky et al., 2009). Therefore, validation of RSSD with ground-based measurement must be part of the AQMN (Knippertz et al., 2015; Alvarado et al., 2019). The RSSD improves accuracy in areas where surface-based measurements are also available. However, where high quality ground-level measurements are absent, satellite estimates of ground level $PM_{2.5}$ values should be assigned a higher uncertainty and may not be useful to support AQM planning.

It is inferred that the scale and objective of monitoring should be predefined before designing the AQMN. Table 1 compares the suitability and application of different air quality monitoring techniques.

1.2. *Air pollution issues in LMIC*

The LMICs are often characterized by rapid and extensive growth in infrastructure sectors likes transport, construction, industry etc., which has led to higher emission of pollutants. For example, in India, the annual average PM_{10} and $PM_{2.5}$ concentrations are reported to be 232.1 $\pm$ 131.1 μg m^{-3} and 118.3 $\pm$ 81.7 μg m^{-3}, respectively, which is 3–4 times higher than the specified national ambient air quality standards (NAAQS) of 60 μg m^{-3} and 40 μg m^{-3}, respectively in Delhi city (Khare and Khanna, 2016). Similarly, PM levels in most LMIC citeis exceed the

Table 1
Comparison of different monitoring techniques.

Parameters	Manual	Continuous	Sensor	Remote Sensing
Monitoring methods	Gravimetric, Chemical method	Light Scattering, Chemiluminous	Light Scattering	Satellite Image Processing
Suitable for	Validation and calibration	Urban scale and high temporal variability	With high spatial heterogeneity	Regional scale monitoring, Transboundary air pollution transport
Application	Regulatory purposes, Validation and calibration of other monitoring techniques Research and Development, Source apportionment	Regulatory purposes, air quality management, Public information system	Air quality management in urban areas especially where space is constrained like traffic intersection; Calibration should be performed in conditions where the measurements are made. Means co-locating with reliable measurement techniques with well-defined quality assurance protocols. Calibration in the lab is not sufficient.	Remote areas; Accuracy improves in areas where surface-based measurements are also available. However, where high quality ground-level measurements are absent, satellite estimates of ground level $PM_{2.5}$ values should be assigned a higher uncertainty.
Pollutant can be monitored	Most gaseous, PM_{10} & $PM_{2.5}$,	All gaseous pollutant, different size PM, Online real time level, air quality index, early warning system	Most of the pollutants	Aerosol Optical Depth (AOD) which can convert in to PM, NOx, SO_2, Ozone
References:	CPCB, 2013; CAA, 2016; USEPA, 2018; EANET, 2013	CPCB, 2011; USEPA, 2018; EANET, 2013	Kumar et al., 2015a; Chatto et al. (2016); Aguiar et al. (2015); Gao et al. (2015); Moltchanov et al. (2015)	Dey and Tripathi (2014); Upadhyay et al. (2018);

specified ambient air quality standards many fold (ADB, 2014; WHO, 2018). The monitoring practices in these countries are different in terms of principles, instrumentations, maintenance protocol of instruments, knowledge of skilled manpower, etc. As a result, comparisons of pollution levels across these developing nations using monitored data from these instruments may be misleading due to variation in monitoring approach. Therefore, the air quality index (AQI) measured by single monitoring sites of the US Embassies located in several respective cities has been collected and compared. Based on a recent measurement of year 2018, it has been observed that annual average AQI values were higher in Lahore, Delhi and Dhaka (155–173) when compared with AQI level in Hanoi and Colombo (80–92). The single station data cannot be representative of the whole city due to heterogeneity in the sources, but comparisons across stations may provide useful criteria for understanding general trends between cities. This comparative trend of pollution levels can be different at different time of the year due to variations in wind flow pattern and influence of transboundary pollution. To confirm this general trend in pollution levels across these LMIC, a second common criterion was used, i.e., Environmental Performance Index (EPI) ranking (developed by Yale University for year 2018) which also indicated similar trend of pollution level among the same cities and thus support the observed AQI values. The EPI explains a connection between two important dimensions of sustainable development: (1) environmental health, which rises with financial growth and wealth; and (2) ecosystem vitality, which comes under strain from industrialization and urbanization. Air quality is considered one of the important parameter in calculation of EPI under environment health i.e., 26%. Further, solid fuel burning (10.4%), $PM_{2.5}$ exposure (7.8%) and $PM_{2.5}$ exceedance (7.8%) are considered under air quality for EPI. Additionally, climate and air pollution are considered to be approximately 24% under ecosystem vitality which contribute 60% to total EPI score (epi.envirocenter.yale.edu). Table 2 describes the level of pollution in different LMIC countries.

1.3. Air quality monitoring practices in LMIC

The air quality monitoring systems in a majority of LMICs are at the developing stage and need to be strengthened for better air quality management planning. Additionally, growing AQMNs generate lots of data which leads to issues with accuracy and data management. For example, the monitoring in many cities in selected LMICs have a narrow scope with a limited number of stations and monitor only a few criteria pollutants. Further, data quality, technical manpower for operating monitoring equipment, common regulatory guidelines and quality assurance (QA) and quality control (QC) procedures are also not well defined. Air quality monitoring in these selected countries is being carried out without specific objectives other than meeting regulatory compliance. Therefore, efficient and sustainable AQMNs are needed, but face challenges in terms of technology and finance. Table 3 describes status of air quality monitoring stations in selected LMICs. India houses a very large number of monitoring stations i.e., 836 including manual (703) and CAAQMS (133) which is a vast network compared to other selected LMICs (CPCB,2018). On the other hand, the air quality monitoring networks in selected African countries are insufficient, typically having a few stations operating on a manual basis. An exception is Vietnam, which has 29 CAAQMS including fixed and mobile stations. The selected countries do not follow any criteria in setting up of monitoring stations. Further, air quality monitoring is limited to urban areas

Table 2
Air Pollution Situation in selected LMIC.

LMIC	Area of City (km^2)[c]	Population of city (Million)[c]	AQI[b]	EPI Score[a]	EPI Ranking[a]
Delhi (India)	1483	19	173	30.57	177
Lahore (Pakistan)	1772	11	151	37.5	169
Dhaka (Bangladesh)	1353	16	163	29.56	179
Colombo (Srilanka)	37.31	2.4	92	60.61	70
Katmandu (Nepal)	899	0.9	110	31.44	176
Thimpu (Bhutan)	26.1	0.12	–	47.22	131
Hanoi (Vietnam)	3329	7.82	80	46.96	132
Accra (Ghana)	225	2.27	–	49.66	124
Abuja (Nigeria)	1769	2.4	–	54.76	100
Narobi (Kenya)	696	4.5	–	47.25	130

[a] https://epi.envirocenter.yale.edu/epi-topline, 2018; EPI score and ranking are for country level scoring.
[b] https://airnow.gov/index.cfm?action=airnow.global_summary, (Annual Average, 2018).
[c] http://worldpopulationreview.com/world-cities.

Table 3
The monitoring network of selected countries in LMICs.

LMIC	Total Number of Stations (National Level)	References
India	836 (Mannual-703; CAAQMS-133	CPCB, 2018
Pakistan	70 (Manual & CAAQMS)	–
Bangladesh	11 (CAAQMS)	CASE (2018)
Srilanka	78 (Manual)	–
Nepal	12 (CAAQMS)	Govt. of Nepal (2018)
Bhutan	03 (CAAQMS)	Bhujel et al. (2017)
Vietnam	29 (CAAQM- Fixed and Mobile)	Anh N.T.N (2016).
Ghana	05 (Manual)	Emmanuel K.E. (2016)
Nigeria	05 (Manual)	Fagbeja et al. (2017)
Kenya	05 (Manual)- Sensor based network at 05 locations in Nairobi	Nthusi V (2017)

where *grab* monitoring/sampling is often carried out in response to air pollution complaints. Internationally, there are no common rules for air quality monitoring network design or the number of monitors/samplers required in a city. However, developed countries have set up criteria for deciding the number of air quality monitoring stations based on population. For example, US requires 1–2 monitors for 0.1 million people only in high-pollution areas. Otherwise, the requirement is 1 monitor for 0.5 million (ADB, 2014).

The selected LMICs do not have any sensor based monitoring stations as part of their national regulatory networks. Air quality monitoring based on remote sensing techniques are also not part of national air quality monitoring programs (NAQMP) in LMICs as listed in Table 3. Both sensor and remote sensing based technologies are still in a research and development stage (Dey and Tripathi, 2014; Upadhyay et al., 2018; Mhawisha et al., 2017; Lasko et al., 2018, WMO, 2018). However, the present status of the ground based air pollution monitoring/sampling is that it includes all common criteria air pollutants (Table 4). These air pollutants are PM_{10}, $PM_{2.5}$, SO_2, NOx and CO. However, $PM_{1.0}$ is monitored at a few stations in Nepal, Vietnam and Kenya. In Nepal, PM_{10}, $PM_{2.5}$, and $PM_{1.0}$ are monitored but no information is available on gaseous air pollutant (Govt. of Nepal, 2018).

These selected and many other LMICs are facing many challenges in strengthening their air quality monitoring network. The major hurdles are lack of availability of advanced analytical laboratories; shortage of skilled manpower; absence of regulatory framework/requirements for air monitoring; electricity connection problems; indigenous equipment; and financial problems.

Table 4
Air pollutants monitored at selected LMICs under national air quality monitoring program.

LMIC	Common Pollutants Monitored							
	TSP	PM_{10}	$PM_{2.5}$	PM_1	SO_2	NO_2	CO	O_3
India	–	×	×	–	×	×	×	×
Pakistan	–	×	–	–	×	×	×	
Bangladesh,	–	×	×	–	×	×	×	×
Srilanka,	–	×	×	–	×	×	×	×
Nepal,	–	×	×	×	–	–	–	–
Bhutan	×	×	–	–	×	×	×	
Vietnam	×	×	×	×	×	×	×	×
Ghana,	–	×	–	–	×	×	×	×
Nigeria	–	×	×		×	×	×	–
Kenya	–	×	×	×	×	×	–	–

x = Pollutant being Monitored, '-'Not being Monitored.

2. Ambient air quality monitoring protocol for LMIC

2.1. Protocol for setting up an AQMN

All AQMNs for any LMIC should have the following features to support efficient and effective air quality management planning.

Objective: The AQMN in the LMIC needs to have clearly defined objectives. The monitoring programme should meet the requirements of the region and have specified goals such as regulatory compliance, background monitoring, pollution episode monitoring, health exposure assessment or urban air quality management, awareness raising, effectivity of control strategies etc. It is one of the important components of air quality monitoring programme. The planning, design and establishment of AQMN will vary according to air quality objectives (Sivertsen, 2008; Pinder et al., 2019). It should have legal enforceability and international acceptability.

Network design: There must be some criteria for setting up AQMNs, which can be based on population, area, types of problematic sources or types of receptors. Design should also be aligned with available literature and have proper scaling and representative coverage to establish a database that spans local, regional and global scenarios. The AQMN should be designed in such a way that generated datasets can be utilized effectively for public safety in instances of episodic exposure. It is not necessary to monitor all defined parameters at all locations. Scientifically designed networks should have representative datasets that are based on pre-dominant land use patterns, activities and exposures. In all cases, representative locations should be selected in order to satisfy the monitoring objectives such as exposure assessment of human population, impact on receptors, local, regional or global movement of pollutants, etc. The land use pattern is considered as one of the major factors in establishment of ambient air stations. Further, the type of stations and parameters should be decided based on the purpose of the data use.

Dynamic Process: There is always a need to review the existing monitoring networks and improve the performance by incorporating more advanced instruments in the system or changing the location. Many times, the primary air polluiton issue in a city can shift from one pollutant to another following the adoption of stricter air pollution control measures. For example, the problems of high ambient concentrations of lead (Pb), and SO_2 in India have largely been solved due to reduction of Pb and sulphur (S) in transport fuels, respectively. However, air pollution problems have simply shifted from SO_2 and Pb to elevated NOx levels following implementation of compressed natural gas strategies in the Delhi public transport system (Narain and Krupnick, 2007).

Learning from Success Stories: It maybe concluded that of the current process of establishing monitoring stations in most LMICs is a random process, based on space and logistical availability. There are no common guidelines available that define the criteria for selecting location or number of stations required in a particular populated area. It is suggested that LMICs should take lessons from developed countries where AQMNs are designed, developed and function through common guidelines such as those developed by the US EPA's Office of Air Quality Planning and Standards (AIRNow, 2011). Or as in the UK, where over 300 air quality monitoring stations are operating though common guidelines (DEFRA, 2013). The European Union's countries manage their AQMN through the European Topic Centre on Air Pollution and Climate Change (EEA, 2014). LMICs should follow the standard guidelines available from countries where such successful AQMNs are operational, and customize their own AQMNs based on the available resources, population, landuse type, sources etc.

Integration of different monitoring technologies: Based on the AQ monitoring objectives and resource availability, the AQMN can integrate available monitoring techniques of manual, continuous, low-cost sensor and remote sensing. The continuous exponential growth in urbanization and associated sectors such as industries, transport etc.

without proper air quality management in LMICs has led to increased air pollution problems of increased complexity. New pollutants are being introduced in the atmosphere. For example, problem of $PM_{2.5}$, benzene and NOx have increased in last decade in Delhi and many other Indian cities (Khaiwal et al., 2006). In view of this, the Ministry of Environment, Forests and Climate Change (MoEF&CC) has included these pollutants in the national ambient air quality standard (NAAQS) along with a few more pollutants (MoEFCC, 2009). It is not possible to monitor all these pollutants through manual monitoring, so continuous ambient air quality monitoring has been introduced in the country. Therefore, integration of different monitoring techniques in a smart AQMN is necessary.

Air quality monitoring is a basic - and one of the key - components of any AQMP. Therefore, AQMNs should be smart and objective oriented in order to provide accurate information on pollution level and its possible sources, enabling the foundation of an efficient and effective AQMP. The AQMN should consist of monitoring stations designed to fulfil the requirements of each successive component of the AQMP. Typically, LMICs own customised monitoring objectives will evolve over time. It is expected that the following types of air quality monitoring may meet the most common objectives:

i) Monitoring station for regulatory compliance as per specified national standards;
ii) Source specific monitoring station (Industrial, Traffic Intersection, etc.)
iii) Source apportionment study (PM_{10}, $PM_{2.5}$ sampling);
iv) Population health exposure assessment (residential and sensitive receptors),
v) Background pollutant concentrations (very useful for dispersion modelling),
vi) Transport of transboundary air pollution
vii) Urban impact station and rural station

The availability of sufficient budget for effective and efficient AQM planning is one of the major constraints for LMICs. Therefore, establishment of monitoring network and selection of monitoring approaches must include costs related to data management, analysis and communication, which can be prioritised based on the requirements of the country and available resources.

It is suggested that LMIC may focus more on low-cost sensor-based networks to monitor criteria air pollutants. The data generated from these sensors can be easily accessed through a common server and used for air quality index calculations and to further disseminate AQ information to the public. The network can easily cover a large area while avoiding space and budget constraints. LMICs should also focus on development of air quality sensors suitable for respective local climatic conditions, which is one of the constraints for reliable performance. Generally, these sensors are factory calibrated and perform accurately in a controlled environment but may not perform with same accuracy in the ambient environment. Therefore, it is suggested to develop a field calibration protocol for these sensors by comparing with reference monitoring station manual/CAAQMS. Researchers have presented various field calibration methods of these sensors which can be used by LMICs (Moltchanov et al., 2015; Aguiar et al., 2015; Gao et al., 2015; WMO, 2018).

The monitoring program should also include remote sensing applications for air quality monitoring to cost-effectively cover the regional and national scales. Satellite-based remote sensing is more global and open access in nature hence this approach, coupled with limited number of sensors and manual stations, can be more cost effective and reliable. Manual monitoring data and sensor-based data are necessary to validate satellite data. Further, the suitability of monitoring techniques should be evaluated based on different criteria such as cost, space requirement, accuracy etc. (Fig. 1).

Evidence presented in this paper suggests that low-cost sensor-based monitoring can be a suitable complement to regulatory grade monitors subject to in situ calibration requirements. Data management and accuracy of the generated data tend to be lacking in most LMICs. There should be a strong team having expertise in all monitoring techniques, instrumentation and data statistics to manage the overall program. The quality control and assurance of the monitoring should be managed through common national guidelines.

3. Source apportionment protocol for LMIC

Source Apportionment (SA) studies quantify the contribution of individual sources to particulate mass loadings based on source profiles and receptor characteristics with the nature of pollutants. There is a large variation in the physio-chemical characteristics of PM, which are based on the difference in intensities of the sources in different regions. Based on outcomes of 149 SA studies conducted in 51 countries, 25% of $PM_{2.5}$ mass is contributed by traffic, 15% by industrial activities, 20% by domestic fuel burning, 18% from natural dust and salt and the rest from unspecified anthropogenic sources (Karagulian et al., 2015). Source categories also have diverse characteristics in terms of their chemical composition. For instance, two coastal cities in south Asia, Mumbai and Chennai, have observed high contributions from marine sources; whereas Delhi has observed dominance of crustal and vehicular sources in PM_{10} and $PM_{2.5}$, respectively. In Karachi, major sources contributing to $PM_{2.5}$ are vehicular/industrial oil burning (39.7%), vehicles (18.5%), road dust (16.1%), steel industry (13.3%) and secondary aerosols (12.4%) (Mansha et al., 2012). Recent studies regarding the characterization of PM_{10} and $PM_{2.5}$ in Nepal have shown that the dominant sources are anthropogenic sources from the southern side of the Himalayas, which are responsible for constituting light-absorbing aerosol hazes, or Asian brown cloud (Decesari et al., 2010; Marinoni et al., 2010).

There have been a huge number of studies in LMICs regarding the $PM_{2.5}$ mass concentrations, but the number of SA studies to identify the source contributions to the mass is comparatively less. Consequently, approaches for conducting SA have not been developed at a similar pace and the majority of studies still focus only on inorganic constituents, which are emitted from a large number of sources, rather than incorporating source-specific organic molecular markers for source identification (Khare and Khanna, 2016; Xu et al., 2015; Crilley et al., 2014;

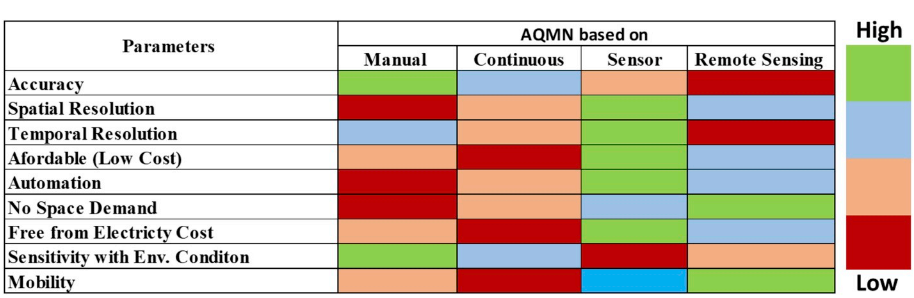

Fig. 1. Suitability for monitoring technique for LMICs.

Pant and Harrison, 2012; Sheesley et al., 2011; Stone et al., 2010; Gustafsson et al., 2009; Simoneit, 1999).

There have been only limited source apportionment studies with a focus on $PM_{2.5}$ and its associated effect on health, visibility and climate change in LMICs (Khanna et al., 2018, 2015; Chen et al., 2015; Kong et al., 2015; Pipal et al., 2014; Kirillova et al., 2013). Considering the large variations in source contributions due to spatio-temporal heterogeneity, a comprehensive spatio-temporal source apportionment study protocol is required including detailed physio-chemical analysis of the PM as a function of their size in all AQMPs. Source profiles are the characteristics of emission sources with each chemical species articulated as a mass fraction of the total mass emitted.

Historically, SA conducted in LMICs have focused primarily on only inorganic components which are not source-specific. It has been observed that many source tracers/signatures used in LMICs differ significantly when compared with source tracers/signatures used in Western countries. The majority of the studies have used USEPA SPECIATE source profiles owing to the lack of locally prepared source profiles. This situation has improved owing to the development of region-specific source profiles for some sources in select regions; however, these need to be further strengthened to capture the variability in different regions. Inter-comparison of traditional SA studies with those conducted in LMICs have shown that there are considerable differences in the results due to different sampling locations based on topographic, territorial and urban planning-based factors; sampling methodology; seasonal variations; and variations in analytical instrumentation and methodology used.

The receptor models like Chemical Mass balance (CMB) estimates source contributions based on the degree to which source profiles can be combined to reproduce ambient concentrations. Statistical-based receptor models like Positive Matrix factorization (PMF) and Principal Component Analysis (PCA) estimate source contributions based on correlations between characterised data and do not require source profiles. Both these types of models require specification of input data uncertainty and calculates standard errors for source contribution estimates. There is need for the formulation of a framework for SA studies in LMICs which takes into consideration the key issues presented above. SA studies are used to identify the sources and quantify their contributions, which will allow policy makers to frame control measures and policies based on them. Hence, there's a need to include SA studies as a part of NAQMP, which is not the case for any LMIC. Central Pollution Control Board (CPCB), India has formulated a Standard Operating Procedure for conducting SA studies; however, it needs to be elaborated more with specific recommendations.

The following features should be incorporated in the protocol for conducting a source apportionment study for LMICs:

(1) Formulate monitoring plan: The monitoring network plan requires basic details about the area and a qualitative knowledge of the sources in the surrounding regions. The use of low-cost sensors may help in identification and selection of the SA monitoring sites by studying the spatial variations in the area and finding representative sites – residential, industrial, and commercial, etc.
(2) Preparation of emission inventory: Emission inventories are an essential input to dispersion models that estimate air pollutants concentrations downwind of the emission source. Receptor models require only qualitative information about the sources; however, dispersion models require quantitative information regarding source emission factors and activity data. There is a need to validate the receptor model results with dispersion models to assess whether they align in terms of source estimations. This comparative analysis can help quantify the emissions from the unidentified sources.
(3) Chemical characterization for samples and source profiles: Source profiles are envisioned to characterise a type of source rather than individual emitters. There is a need to create region-specific source profiles as the source characteristics vary a lot depending on the origin of sources, particularly soil/road dust, vehicular emissions due to different fuel qualities, coal characteristics (sulphur content based on region from where it has been mined), combustion sources, etc. A large number of studies have used the SPECIATE source profiles which are not representatives of sources in LMICs and hence tend to either over-predict or under-predict the source contributions.
(4) PM Mass Reconstruction/Mass Closure: Reconstructed mass is a weighted sum of species (i.e, Carbon content, elements and ions). PM mass reconstruction applies multipliers to several of the measured species to estimate unmeasured components. This is used to identify and correct potential measurement errors as part of data validation efforts and understand temporal and spatial variations of chemical composition which help in estimating source contributions.
(5) Source Contribution Estimation: The receptor models like Chemical Mass balance (CMB) estimates source contributions based on the degree to which source profiles can be combined to reproduce ambient concentrations. Statistical-based receptor models like Positive Matrix factorization (PMF) and Principal Component Analysis (PCA) estimate source contributions based on correlations between characterised data and do not require source profiles.
(6) Sensitivity Analysis and Validation: Source contributions from receptor models should be validated with those from dispersion model to compare the inclusion of all sources. Discrepancies between the source contributions estimated by two models should be reconciled

The use of low-cost sensors may help in identification and selection of the SA monitoring sites by studying the spatial variations in the area and finding representative sites – residential, industrial, and commercial, etc. There is a need to validate the receptor model results with dispersion models to assess whether they align in terms of source estimations. (Watson, 1979; Core et al., 1981; Ryan et al., 1988; Watson and Chow, 2000; Watson et al., 2000). This comparative analysis can help quantify the emissions from the unidentified sources. There is a need to create region-specific source profiles as the source characteristics vary a lot depending on the origin of sources, particularly soil/road dust, vehicular emissions due to different fuel qualities, coal characteristics (sulphur content based on region from where it has been mined), combustion sources, etc. It is also necessary to include the secondary pollutants formed in the atmosphere by the reaction of primary pollutants after they're emitted.

An efficient monitoring network as part of air quality management plan must be strengthen through the legislative norms/act. The implementation of robust integrated AQMN needs prior permissions regarding space, electricity, security and safety which can only be provided through a strong legislative norms. The below section discussed the legislative norms enforced in LMICs for overall environmental management.

4. Legislative status of LMIC for air pollution management

Increasing air pollution levels and lack of sufficient management practices has attracted the attention of legislators trying to establish strict regulations to control increasing air pollution. In LMICs, the formulation of legislation for air pollution control has been gradual and only a few countries have been able to enact their own laws. Of the selected LMICs reviewed for this article, India has a separate act for air pollution control; however, in other LMICs, the air pollution control laws are mostly under umbrella Environmental Legislation (see Table 5). In India, air quality standards have been introduced under the Air (Prevention and Control) Act of 1981. Due to larger public concern, a separate National Green Tribunal has been set up in India to deal with

Table 5
Status of legislation for air pollution control in LMICs.

LMICs	Applicable Legislation for Air Pollution Control
India	The Air (Prevention and Control of Pollution) Act, 1981, National Green Tribunal, 2010 Environment Pollution Control Authority, 1999
Pakistan	The Environment Protection Ordinance, 1983
Bangladesh	Bangladesh Environment Conservation Act , 1995,
Srilanka	National Environmental Act, 1980
Nepal	Environmental Act 1996 and Regulation 1997,
Bhutan	No specific Act for Air Pollution Control
Vietnam	Environmental Law, 2014,
Ghana	Environmental Protection Agency Act 1994
Nigeria	Environmental Impact Assessment (EIA) Act. 2004
Kenya	Environmental Management and Co-Ordination Act, 1999

environmental violations.

5. Conclusion

The paper has reviewed and discussed the problem of air pollution levels in LMICs and challenges being faced in developing smart AQMNs. The problem of air pollution is a serious concern in urban areas of LMICs especially high PM levels. Based on the existing AQMNs and also keeping in mind the available resources in LMICs, this article has prepared a protocol for monitoring and assessment of air quality in these countries. The key conclusions of the study are as follows:

1. LMICs should develop AQMNs based on robust and sustainable criteria, which should be documented in a guideline document that may serve as a reference for other countries having similar conditions.
2. AQMNs in LMICs should be goals/target specific, dynamic in nature and internationally acceptable.
3. AQMNs should not have single monitoring approach, rather they should integrate different monitoring/sampling techniques with a major focus on field-calibrated low-cost sensors.
4. RSSD – when coupled with limited number of ground based monitoring stations – are a cost-effective and reliable option for regional scale assessment of transboundary pollutant sources.
5. Source apportionment studies are essential for efficient and effective AQMP. The AQMN should be designed to allow for source apportionment analysis of key air pollution sources.
6. Chemical profiling of sources in LMICs needs to be developed to improve the accuracy of SA studies which are at present based on the available sources profiles in developed countries.
7. LMICs should invest in State-of-Art laboratories to analyse and characterise particulate matter for source apportionment analysis, to enable identification of sources and development of management strategies to reduce pollution level.
8. There is need for well-funded AQMP programs that include not only monitoring, but resources for the other elements of AQM planning like data management, communication, and control strategy development etc.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.atmosenv.2019.117120.

References

Ackerman, S.A., Strabala, K.I., Menzel, W.P., Frey, R.A., Moeller, C.C., Gumley, L.E., 1998. Discriminating clear sky from clouds with MODIS. J. Geophys. Res.: Atmosphere 103 (D24), 32141–32157.

Alvarado, M.J., Mcvey, A.E., Hegarty, J.D., et al., 2019. Evaluating the use of satellite observations to supplement ground-level air quality data in selected cities in low- and middle-income countries. Atmospheric Environment. https://doi.org/10.1016/j.atmosenv.2019.117016.

ADB, 2010. Key Indicators for Asia and the Pacific, 41st Edition. Asian Development Bank, Mandaluyong City.

ADB, 2014. Improving Air Quality Monitoring in Asia: A Good Practice Guidance, Final Report. Asian Development Bank, Mandaluyong City, Philippines. Asian Development Bank, 2013. http://cleanairasia.org/wp-content/uploads/portal/files/improving_aqmt_in_asia.pdf. (Accessed 9 December 2018).

Aguiar, E.F.K., Roig, H.L., Mancini, L.H., de Carvalho, E.N.C.B., 2015. Low-cost sensors calibration for monitoring air quality in the federal district—Brazil. J. Environ. Prot. 6, 173–189. https://doi.org/10.4236/jep.2015.62019.

AIRNow, 2011. Local Air Quality Conditions and Forecasts. http://www.airnow.gov/index.cfm?action=topics.about_airnow. (Accessed 5 November 2011).

Anh, N.T.N., 2016. Perspective Air Quality System in Vietnam. Centre for Environmental Monitoring, Vietnam Environment Administration. http://cleanairasia.org/wp-content/uploads/2016/09/02_Regional-Perspective-AQ-Systems_Vietnam.pdf. Accessed on August 18.

Baldasano, J.M., Valera, E., Jimenez, P., 2003. Air quality data from large cities. Sci. Total Environ. 307, 141–165.

Banerjee, T., Murari, V., Kumar, M., Raju, M.P., 2015. Source apportionment of airborne particulates through receptor modelling: Indian scenario. Atmos. Res. 164–165, 167–187. https://doi.org/10.1016/j.atmosres.2015.04.017.

Bhujel, A., Praveen, P.S., Mahapatra, P.S., Adhikary, B., et al., 2017. Ambient air quality monitoring stations in Nepal and Bhutan: bridging the data gap in the hindu kush himalayan region. ICIMOD, GPO box. Kathmandu, Nepal. https://www.researchgate.net/publication/322570534_Ambient_Air_Quality_Monitoring_Stations_in_Nepal_and_Bhutan_Bridging_the_Data_Gap_in_the_Hindu_Kush_Himalayan_Region. Accessed on 18 August.

Clean Air Asia, 2011. Status and Trends in Air Quality Management. Philippines, Pasig City. http://cleanairinitiativeorg/portal/node/3962.

CAA (Clean Air Asia), 2016. Guidance framework for better air quality in asian cities. Pasig city, Philippines. http://cleanairasia.org/ibaq/wp-content/themes/ibaq/pdf/Ambient%20Air%20Quality%20Standards%20and%20Monitor.pdf.

CASE, 2018. Clean Air and Sustainable Environment Project. Ministry of Environment and Forests, Government of the People's Republic of Bangladesh. http://case.doe.gov.bd/index.php?option=com_content&view=article&id=29&Itemid=7.

Chatto, V., Roychowdhury, A., Shukla, S., 2016. Reinventing Air Quality Monitoring: Potential of Low Cost Alternative Monitoring Methods. Technical Report, Centre for Science and Environment, New Delhi, India. https://doi.org/10.13140/RG.2.2.36357.55525.

Chen, P., Kang, S., Li, C., Rupakheti, M., Yan, F., Li, Q., Ji, Z., Zhang, Q., Luo, W., Sillanpää, M., 2015. Characteristics and sources of polycyclic aromatic hydrocarbons in atmospheric aerosols in the Kathmandu Valley, Nepal. Sci. Total Environ. 538, 86–92. https://doi.org/10.1016/j.scitotenv.2015.08.006.

Core, J.E., Hanrahan, P.L., Cooper, J.A., 1981. Air particulate control strategy development. In: Macias, E.S., Hopke, P.K. (Eds.), Atmospheric Aerosol: Source/Air Quality Relationships. American Chemical Society, Washington, DC, pp. 107–123.

CPCB (Central Pollution Control Board), 2010. Air Quality Monitoring, Emission Inventory and Source Apportionment Study for Indian Cities, National Summary Report. The Central Pollution Control Board, New Delhi, India, p. 290. http://www.moef.nic.in/downloads/public-information/Rpt-air-monitoring-17-01-2011.pdf. (Accessed 9 December 2018).

CPCB, 2011. Guidelines for Real Time Sampling & Analyses, Guidelines for the Measurement of Ambient Air Pollutants Volume II. Central Pollution Control Board, New Delhi, India. http://www.indiaenvironmentportal.org.in/files/NAAQSManualVolumeII.pdf.

CPCB, 2013. Guidelines for Manual Sampling & Analyses, Guidelines for the Measurement of Ambient Air Pollutants, vol. 1. The Central Pollution Control Board, New Delhi, India. http://cpcb.nic.in/openpdffile.php?id=UmVwb3J0RmlsZXMvMjdfMTQ1ODExMDQyNl9OZXdJdGVtXzE5Nl9OQUFRTVNfVm9sdW1lLUkucGRm.

CPCB, 2018. Operating Stations under National Air Quality Monitoring Programme. The Central Pollution Control Board, Delhi, Minsitry of Environment, Forest and Climate Change, Govt. of India. http://cpcb.nic.in/monitoring-network-3/. (Accessed 22 December 2018).

Crilley, L.R., Ayoko, G.A., Morawska, L., 2014. First measurements of source apportionment of organic aerosols in the Southern Hemisphere. Environ. Pollut. 184, 81–88. https://doi.org/10.1016/j.envpol.2013.08.015.

Decesari, S., Facchini, M.C., Carbone, C., Giulianelli, L., Rinaldi, M., Finessi, E., Fuzzi, S., Marinoni, A., Cristofanelli, P., Duchi, R., Bonasoni, P., Vuillermoz, E., Cozic, J., Jaffrezo, J.L., Laj, P., 2010. Chemical composition of PM10 and PM1 at the high-altitude Himalayan station Nepal Climate Observatory-Pyramid (NCO-P) (5079 m a.s.l.). Atmos. Chem. Phys. https://doi.org/10.5194/acp-10-4583-2010.

DEFRA (Department of Environment Federation and Rural Affairs), 2013. Air Quality Monitoring Network. http://uk-air.defra.gov.uk/networks. (Accessed 9 December 2013).

Dey, S., Tripathi, S.N., 2014. Remote sensing of atmospheric aerosol. In: Colbeck, Ian, Lazardis, Mihalis (Eds.), Aerosol Science: Technology and Applications. John Wiley & Sons, Ltd. https://www.wiley.com/en-us/Aerosol+Science%3A+Technology+and+Applications-p-9781119977926.

Dey, S., Di Girolamo, L., van Donkelaar, A., Tripathi, S.N., Gupta, T., Mohan, M., 2012. Variability of outdoor fine particulate (PM2. 5) concentration in the Indian Subcontinent: a remote sensing approach. Remote Sens. Environ. 127, 153–161.

EANET, 2013. Technical Manual for Air Concentration Monitoring in East Asia. Atmospheric Research Department, Asia Center for Air Pollution Research. http://www.eanet.asia/product/manual/techacm.pdf.

EEA, (European Environment Agency), 2014. European topic Centre on air pollution and climate change mitigation (ETC/ACM). Available on. http://acm.eionet.europa.eu. (Accessed 5 January 2014).

Emmanuel, K.E.A., 2016. Air quality monitoring & health programme in accra, Ghana. 8EQD/standards, compliance & enforcement division, environmental protection agency, Ghana. Available on. https://cdn.cseindia.org/userfiles/accra-ghana.pdf. (Accessed 17 September 2018).

Fagbeja, M., Olumide, O., Rabiu, B., 2017. An Overview of AQ monitoring and prediction in Nigeria. In: Proceeding of WMO AQ Forecasting Workshop 04-06 Dec 2017. SAWS, Pretoria. https://www.wmo.int/pages/prog/arep/gaw/documents/1_BRabiu_Nigeria_AQ.pdf. accessed on August 18.

Gao, M., Cao, J., Seto, E., 2015. A distributed network of low-cost continuous reading sensors to measure spatiotemporal variations of $PM_{2.5}$ in Xi'an, China. Environ. Pollut. 199, 56–65.

Gokhale, S., Khare, M., 2007. A theoretical framework for the episodic-urban air quality management plan (e-UAQMP). Atmos. Environ. 41, 7887–7894.

Govt of Nepal, 2018. Air Quality Monitoring. Ministry of Forests and Environment, Department of Environment, Govt. of Nepal. http://pollution.gov.np/#/stations?_k=3u312a. accessed on 18th August.

Gulia, S., Nagendra, S.M.S., Khare, M., Khanna, I., 2015. Urban air quality management–A review. Atmos. Pollut. Res. 6, 286–304.

Gulia, S., Nagendra, S.M.S., Barnes, J., Khare, M., 2017. Urban local air quality management framework for non-attainment areas in Indian cities. Science of the Total Environment 319, 1308–1318.

Gustafsson, O., Kruså, M., Zencak, Z., Sheesley, R.J., Granat, L., Engström, E., Praveen, P. S., Rao, P.S.P., Leck, C., Rodhe, H., 2009. Brown clouds over South Asia: biomass or fossil fuel combustion? Science 323, 495–498. https://doi.org/10.1126/science.1164857.

Hankey, S., Marshall, J.D., 2017. Urban form, air pollution, and health. Curr. Environ. Health Rep. 4 (4), 491–503.

Hersey, S.P., Garland, R.M., Crosbie, E., Shingler, T., Sorooshian, A., Piketh, S., Burger, R., 2015. An overview of regional and local characteristics of aerosols in South Africa using satellite, ground, and modeling data. Atmos. Chem. Phys. 15, 4259.

Karagulian, F., Belis, C.A., Dora, C.F.C., Prüss-Ustün, A.M., Bonjour, S., Adair-Rohani, H., Amann, M., 2015. Contributions to cities' ambient particulate matter (PM): a systematic review of local source contributions at global level. Atmos. Environ. 120, 475–483.

Khaiwal, R., Wauters, E., Tyagi, S.K., Mor, S., Grieken, R.N., 2006. Assessment of air quality after the implementation of compressed natural gas (CNG) as fuel in public transport in Delhi, India. Environ. Monit. Assess. 115, 405–417.

Khanna, I., Khare, M., Gargava, P., 2015. Health risks associated with heavy metals in fine particulate Matter : a case study in Delhi city , India. J. Geosci. Environ. Prot. 3, 72–77.

Khanna, I., Khare, M., Gargava, P., Khan, A.A., 2018. Effect of $PM_{2.5}$ chemical constituents on atmospheric visibility impairment. J. Air Waste Manag. Assoc. 68, 430–437. https://doi.org/10.1080/10962247.2018.1425772.

Khare, Khanna, 2016. Case studies of source apportionment from the Indian sub-continent. In: Hester, R.E., Harrison, R.M., Querol, X. (Eds.), Book Chapter 8: Airborne Particulate Matter: Sources, Atmospheric Processes and Health. The Royal Society of Chemistry.

Kirillova, E.N., Andersson, A., Sheesley, R.J., Kruså, M., Praveen, P.S., Budhavant, K., Safai, P.D., Rao, P.S.P., Gustafsson, Ö., 2013. 13C- and 14C-based study of sources and atmospheric processing of water-soluble organic carbon (WSOC) in South Asian aerosols. J. Geophys. Res. Atmos. 118, 614–626. https://doi.org/10.1002/jgrd.50130.

Knippertz, P., Evans, M.J., Field, P.R., Fink, A.H., Liousse, C., Marsham, J.H., 2015. The possible role of local air pollution in climate change in West Africa. Nat. Clim. Chang. 5 (9), 815.

Kokhanovsky, A.A., Curier, R.L., De Leeuw, G., Grey, W.M.F., Lee, K.H., Bennouna, Y., North, P.R.J., 2009. The inter-comparison of AATSR dual-view aerosol optical thickness retrievals with results from various algorithms and instruments. Int. J. Remote Sens. 30 (17), 4525–4537.

Kong, S., Li, X., Li, L., Yin, Y., Chen, K., Yuan, L., Zhang, Y., Shan, Y., Ji, Y., 2015. Variation of polycyclic aromatic hydrocarbons in atmospheric PM2.5 during winter haze period around 2014 Chinese Spring Festival at Nanjing: insights of source changes, air mass direction and firework particle injection. Sci. Total Environ. 520, 59–72. https://doi.org/10.1016/j.scitotenv.2015.03.001.

Kumar, P., Morawska, L., Martani, C., Biskos, G., Neophytou, M., Di Sabatino, S., Bell, M., Norford, L., Britter, R., 2015a. The rise of low cost sensing for managing air pollution in cities. Environ. Int. 75, 199–205.

Kumar, M., Tiwari, S., Murari, V., Singh, A.K., Banerjee, T., 2015b. Wintertime characteristics of aerosols at middle Indo-Gangetic Plain: impacts of regional meteorology and long range transport. Atmos. Environ. 104, 162–175.

Kumar, N., Chu, A., Foster, A., 2008. Remote sensing of ambient particles in Delhi and its environs: estimation and validation. Int. J. Remote Sens. 29 (12), 3383–3405.

Lancet Planet Health, 2019. The Impact of Air Pollution on Deaths, Disease Burden, and Life Expectancy across the States of India: the Global Burden of Disease Study. https://doi.org/10.1016/S2542-5196(18)30261-4, 2017.

Lasko, K., Vadrevu, K.P., Nguyen, T.T.N., 2018. Analysis of air pollution over Hanoi, Vietnam using multi-satellite and MERRA reanalysis datasets. Available on. https://doi.org/10.1371/journal.pone.0196629. (Accessed 1 December 2018).

Lee, K.H., Li, Z., Kim, Y.J., Kokhanovsky, A., 2009. Atmospheric aerosol monitoring from satellite observations: a history of three decades. In: Atmospheric and Biological Environmental Monitoring. Springer, Dordrecht, pp. 13–38.

Lim, S.S., et al., 2012. The Lancet 380, 2224–2260. https://doi.org/10.1016/S0140-6736(12)61766-8.

Longhurst, J.W.S., Lindley, S.J., Watson, A.F.R., Conlan, D.E., 1996. The introduction of local air quality management in the United Kingdom: a review and theoretical framework. Atmos. Environ. 30, 3975–3985.

Mannucci, M., Franchini, M., 2017. Health effects of ambient air pollution in developing countries. Int. J. Environ. Res. Public Health 14 (9), 1048. https://doi.org/10.3390/ijerph14091048.

Mansha, M., Ghauri, B., Rahman, S., Amman, A., 2012. Characterization and source apportionment of ambient air particulate matter ($PM_{2.5}$) in Karachi. Sci. Total Environ. https://doi.org/10.1016/j.scitotenv.2011.10.056.

Marais, E.A., Jacob, D.J., Wecht, K., Lerot, C., Zhang, L., Yu, K., Sauvage, B., 2014. Anthropogenic emissions in Nigeria and implications for atmospheric ozone pollution: a view from space. Atmos. Environ. 99, 32–40.

Marinoni, A., Cristofanelli, P., Laj, P., Duchi, R., Calzolari, F., Decesari, S., Sellegri, K., Vuillermoz, E., Verza, G.P., Villani, P., Bonasoni, P., 2010. Aerosol mass and black carbon concentrations, a two year record at NCO-P (5079 m, Southern Himalayas). Atmos. Chem. Phys. 10, 8551–8562. https://doi.org/10.5194/acp-10-8551-2010.

Mhawisha, A., Banerjeea, T., Broday, D.M., Misrad, A., Tripathi, S.N., 2017. Evaluation of MODIS Collection 6 aerosol retrieval algorithms over IndoGangetic Plain: implications of aerosols types and mass loading. Remote Sens. Environ. 201, 297–313.

MoEFCC (Ministry of Environment, Forest and Climate Change), 2009. National Ambient Air Quality Standards. Government of India, New Delhi, p. 4. Notification number: S. O.3067 (E).

Moltchanov, S., Levy, I., Etzion, Y., Lerner, U., Broday, D.M., Fishbain, B., 2015. On the feasibility of measuring urban air pollution by wireless distributed sensor networks. Sci. Total Environ. 502, 537–547.

Naiker, Y., Diab, R.D., ZunckelHayes, M.E.T., 2012. Introduction of local Air Quality Management in South Africa: overview and challenges. Environmental Science and Policy 17, 62–71.

Narain, U., Krupnick, A., 2007. The Impact of Delhi's CNG Program on Air Quality. Discussion Paper, Resources for the Future. Washington DC, Available on. http://www.rff.org/files/sharepoint/WorkImages/Download/RFF-DP-07-06.pdf. (Accessed 1 December 2018).

Nthusi, V., 2017. Nairobi Air Quality Monitoring Sensor Network Report - April 2017. Technical Report · May 2017. UNPD. https://doi.org/10.13140/RG.2.2.10240.64009.

Pant, P., Harrison, R.M., 2012. Critical review of receptor modelling for particulate matter: a case study of India. Atmos. Environ. 49, 1–12.

Pant, P., Shukla, A., Kohl, S.D., Chow, J.C., Watson, J.G., Harrison, R.M., 2015. Characterization of ambient $PM_{2.5}$ at a pollution hotspot in New Delhi, India and inference of sources. Atmos. Environ. 109, 178–189.

Pinder, R.W., Klopp, J.M., Kleiman, G., Hagler, G.S.W., Awe, Y., Terry, S., 2019. Opportunities and challenges for filling the air quality data gap in low- and middle-income countries. Atmos. Environ. 215, 116794, 15 October 2019.

Pipal, A.S., Jan, R., Satsangi, P.G., Tiwari, S., Taneja, A., 2014. Study of surface morphology, elemental composition and origin of atmospheric aerosols ($PM_{2.5}$ and PM_{10}) over Agra, India. Aerosol Air Qual. Res. 14, 1685–1700. https://doi.org/10.4209/aaqr.2014.01.0017.

Pope, C.A., Dockery, D.W., 2006. Health effects of fine particulate air pollution: lines that connect. J. Air Waste Manag. Assoc. 56 (6), 709–742.

Rastogi, N., Singh, A., Sarin, M.M., Singh, D., 2016. Temporal variability of primary and secondary aerosols over northern India: impact of biomass burning emissions. Atmos. Environ. 125 (B), 396–403. https://doi.org/10.1016/j.atmosenv.2015.06.010.

Ryan, W.M., West, C.R., Holtz, D.R., Peters, T.A., Cooper, J.A., Ono, D.M., 1988. Reconciliation of receptor and dispersion modeling impacts of PM_{10} in Hayden, Arizona. In: Mathai, C.V., Stonefield, D.H. (Eds.), Transactions, PM_{10}: Implementation of Standards. Air Pollution Control Association, Pittsburgh, PA, pp. 419–429.

Schiavon, M., Ragazzi, M., Rada, E.C., Magaril, E., Torretta, V., 2018. Towards the sustainable management of air quality and human exposure: exemplary case studies. WIT Trans. Ecol. Environ. 230, 489–500.

Schiavon, M., Redivo, M., Antonacci, G., Rada, E.C., Ragazzi, M., Zardi, D., Giovannini, L., 2015. Assessing the air quality impact of nitrogen oxides and benzene from road traffic and domestic heating and the associated cancer risk in an urban area of Verona (Italy). Atmos. Environ. 120, 234–243.

Sheesley, R.J., Andersson, A., Gustafsson, Ö., 2011. Source characterization of organic aerosols using Monte Carlo source apportionment of PAHs at two South Asian receptor sites. Atmos. Environ. 45, 3874–3881. https://doi.org/10.1016/j.atmosenv.2011.01.031.

Simoneit, B.R., 1999. A review of biomarker compounds as source indicators and tracers for air pollution. Environ. Sci. Pollut. Res. Inst. 6, 159–169. https://doi.org/10.1007/BF02987621.

Sivertsen, B., 2008. Monitoring air quality, objectives and design. Chem. Ind. Chem. Eng. Q. 14, 167–171.

Stone, E.A., Schauer, J.J., Pradhan, B.B., Dangol, P.M., Habib, G., Venkataraman, C., Ramanathan, V., 2010. Characterization of emissions from South Asian biofuels and

application to source apportionment of carbonaceous aerosol in the Himalayas. J. Geophys. Res. Atmos. 115, 1–14. https://doi.org/10.1029/2009JD011881.
Thompson, A.M., Balashov, N.V., Witte, J.C., Coetzee, J.G.R., Thouret, V., Posny, F., 2014. Tropospheric ozone increases over the southern Africa region: bellwether for rapid growth in Southern Hemisphere pollution? Atmos. Chem. Phys. 14 (18), 9855–9869.
UN, 2007. World Urbanization Prospects: the 2007 Revision Population Database. Division of the Department of Economic and Social Affairs of the United Nations Secretariat, United Nations, New York.
Upadhyay, A., Dey, S., Chowdhury, S., Goyal, P., 2018. Expected Health Benefits from Mitigation of Emissions from Major Anthropogenic $PM_{2.5}$ Sources in India: Statistics at State Level. https://doi.org/10.1016/j.envpol.2018.07.085.
USEPA, 2018. List of designated reference and equivalent methods. National Exposure Research Laboratory, United States environmental protection agency. https://www.epa.gov/sites/production/files/2018-12/documents/amtic_list_dec_2018_update_1.pdf.
Wang, Q., 2018. Urbanization and global health: the role of air pollution. Iran. J. Public Health 47, 1644–1652.
Watson, J.G., 1979. Chemical Element Balance Receptor Model Methodology for Assessing the Sources of Fine and Total Suspended Particulate Matter in Portland, Oregon. Ph.D. Dissertation. Oregon Graduate Center, Beaverton.
Watson, J.G., Chow, J.C., 2000. Reconciling Urban Fugitive Dust Emissions Inventory and Ambient Source Contribution Estimates: Summary of Current Knowledge and Needed Research. Report No. 6110.4D2. Prepared for US Environmental Protection Agency, Research Triangle Park, NC. by Desert Research Institute, Reno, NV.
Watson, J.G., Chow, J.C., Pace, T.G., 2000. Fugitive dust emissions. In: Davis, W.T. (Ed.), Air Pollution Engineering Manual, second ed. John Wiley, New York, pp. 117–135.
World Health Organization (WHO), 2018. Air Pollution and Child Health: Prescribing Clean Air. WHO/CED/PHE/18.01. https://www.who.int/ceh/publications/Advance-copy-Oct24_18150_Air-Pollution-and-Child-Health-merged-compressed.pdf?ua=1.
World Health Organization, 2014. Methods for Burden of Disease Attributable to Ambient Air Pollution for the Year 2012. Geneva. http://www.who.int/phe/health_topics/outdoorair/databases/AAP_BoD_methods_March2014.pdf?ua=1. (Accessed May 2016).
World Meteorological Organization (WMO), 2018. In: Lewis, Alastair C., von Schneidemesser, Erika, Peltier, Richard E. (Eds.), Low-cost Sensors for the Measurement of Atmospheric Composition: Overview of Topic and Future Applications. WMO, IGAC and UN Environment, Geneva, Switzerland. WMO-No. 1215.
Worobiec, A., Vermaak, S.S.P., Berghmans, P., Winkler, H., Burger, R., Grieken, R.V., 2011. Air particulate emissions in developing countries: a case study in South Africa. Anal. Lett. 44 (11), 1907–1924.
Xu, H., Guinot, B., Shen, Z., Ho, K., Niu, X., Xiao, S., Huang, R.J., Cao, J., 2015. Characteristics of organic and elemental carbon in $PM_{2.5}$ and $PM_{0.25}$ in indoor and outdoor environments of a middle school: secondary formation of organic carbon and sources identification. Atmosphere 6, 361–379.