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Atmospheric Environment

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

Plugging the ambient air monitoring gaps in India's national clean air programme (NCAP) airsheds

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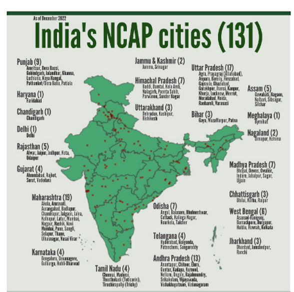
HIGHLIGHTS

- Defined 104 airsheds to represent 131 non-attainment cities under NCAP.
- Defined the minimum number of monitors required in the airsheds.
- Conducted high-resolution meteorological modelling to determine minimum filter sampling frequency per airshed.
- Examples of hybrid networks to reduce monitoring costs.

GRAPHICAL ABSTRACT



ARTICLE INFO

Keywords:
India
Air quality
Ambient monitoring
Hybrid network
Source apportionment
NCAP

ABSTRACT

Building an effective clean air action plan for a city's air pollution problem requires an extensive network of monitoring stations to represent spatial and temporal patterns and an understanding of the sources contributing to the problem. In India, the National Clean Air Programme (NCAP) was launched in 2019 to develop clean air action plans for 131 non-attainment cities, which includes conducting source apportionment studies and establishing emission baselines. As of February 2023, only 39 cities have completed the apportionment studies. In this paper, we present the essential resources needed to strengthen the ambient air monitoring networks, for designing a representative airshed size, sampling size, and sampling frequency, to effectively track the progress made in the cities for better air quality. The NCAP cities were grouped into 104 airsheds (5.3% of the national area), collectively representing a total of 164 cities and a total population of 295 million (21% of the national total). Of these airsheds, 73 contain only one city; 18 contain two cities, and nine contain three cities. Four airsheds – Delhi, Mumbai, Indore, and Chandigarh contain 10, 8, 5, and 5 cities respectively. To measure and analyse particulate matter pollution, a total of 2118 sampling sites are recommended for the 104 airsheds. Cities could consider hybrid monitoring networks by complementing existing regulatory monitoring network with a high-density network of low-cost/sensor-grade monitors. An airshed level air quality management plan, an enhanced monitoring network, and consolidation of information on emission sources, are crucial for optimizing the clean air efforts under NCAP.

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https://doi.org/10.1016/j.atmosenv.2023.119712
Received 14 March 2022; Received in revised form 3 March 2023; Accepted 8 March 2023
Available online 15 March 2023

1. Background

India has some of the worst urban air pollution in the world, which is responsible for an estimated 1.2 million premature deaths caused by outdoor $PM_{2.5}$ pollution levels (Balakrishnan et al., 2019; HEI, 2022). Much of this pollution, around 80%, can be attributed to fossil fuel combustion and resuspended dust (Guttikunda and Ka, 2022; McDuffie et al., 2021). In response to this alarming situation, India's Ministry of Environment Forests and Climate Change (MoEFCC) launched the National Clean Air Programme (NCAP) in 2019, aimed at reducing ambient PM pollution levels in 131 non-attainment cities from 24 states and union territories (CPCB, 2019). The first batch of 102 non-attainment cities exceeded the national ambient standards for either $PM_{2.5}$, PM_{10} or NO_2 for five consecutive years. Over the next two years, this list was integrated with top 10 Indian cities on World Health Organization (WHO)'s most polluted list and some more cities showing an increasing trend in these pollutant concentrations. The programme in 2019, required these cities to prepare action plans to reduce the PM pollution levels by 20–30% by 2024, relative to 2017 levels (CREA, 2023; Ganguly et al., 2020). In 2022, the target was revised to reduce PM pollution levels by 40% by 2026. Maharashtra has the highest number of non-attainment cities with 19, followed by Uttar Pradesh, the most populous state in the country, with 17.

One of the critical components of NCAP is the establishment of the ambient air monitoring networks and conducting source apportionment studies. These initiatives are among the top priorities of the program's 16 key components (Ganguly et al., 2020). For both the initiatives, improving the monitoring capacity and enhancing the measurement protocols remain the most important measures. This was planned through the development of institutional capacity of pollution control boards (PCBs) and the implementation of upgraded guidelines for emissions and pollution monitoring, including integration of new sensor technology. Additionally, an air information cell and National Knowledge Network (NKN) were established to collate and coordinate data flows to support short-term pollution alerts, long-term air quality management, and development of clean air action plans (CPCB, 2019).

As of February 2023, the central pollution control board (CPCB) operated and disseminated real time air quality information from 438 continuous monitoring stations covering 231 cities with at least one station. Delhi (40), Mumbai (21), Hyderabad (14), Bengaluru (10), and Ahmedabad (9) top the list of cities with the most number of operational stations. Of the 231 cities, 178 cities have only one station and 19 cities have two stations, which is not a representative sample for regulatory and research grade urban air pollution analysis. The total monitors count translates to 0.31 per million population, which is the lowest among the big countries - China (1.2), the USA (3.4), Japan (0.5), Brazil (1.8) and most European countries (2–3) (Brauer et al., 2019; Pant et al., 2018). In addition to the continuous stations, CPCB also operated 883 manual stations in 379 cities to collect 24 h average pollution levels for up to 104 days in a year. Kolkata (21), Chennai (11), Delhi (10), and Hyderabad (10) top the list of cities with the most number of operational stations. Similar to the continuous stations, 45% (172 cities) had only one manual station. A summary of the number of stations by state as of February 2023 is presented in Table 1 and a full list by city is included in the Supplementary Material. The data from the manual stations, along with the continuous stations, is a direct input for calculating the air quality index (AQI) and publish pollution alerts in a daily bulletin (CPCB, 2023). The gap between the minimum required and operational number of stations is still significant, but cities are employing various strategies to meet the design objectives of NCAP, including the use of a mix of continuous monitoring stations, manual monitors, and low-cost sensors (Brauer et al., 2019).

All the cities submitted a preliminary clean air action plan using available information and with proposals to conduct new studies (Ganguly et al., 2020). While 50 cities had at least one study with information on emission loads and source contributions, only 25 cities incorporated this information in their approved clean air plans. Cities with no information were expected to conduct pollution load and source apportionment studies. A total of 70 regional academic institutes of repute are conducting various studies, with administrative support from the NKN, the CPCB, and the state PCBs. According to the Portal for Regulation of Air Pollution in Non-Attainment Cities (PRANA), operated by the CPCB, as of February 2023, 39 cities have completed one round of source apportionment studies, 48 cities are conducting a study, 42 cities are planning a study, and two cities have no status update (CPCB, 2019). A summary of the status and associated institutions is included in the Supplementary Material.

Improving the ambient air monitoring network is critical for gaining a comprehensive understanding of a city's pollution levels and establishing an accurate framework to support source apportionment studies. Plans for expanding these networks should consider factors such as airshed size, required sampling size and frequency, and site selection. When it comes to determining the appropriate sample size and airshed designations, there are several factors to consider beyond thumb rules and scientific definitions. For example, urban areas with a high concentration of pollution sources and higher density of people and commercial activities, may require a larger sample size and a larger airshed designation than rural areas with fewer pollution sources. Weather patterns can also impact air quality and thus may influence the representative sample size for seasonal source apportionment studies. In addition to these factors, there are specific regulatory requirements for determining an appropriate monitoring network size.

In this paper, we provide an assessment of the resources needed to evaluate and define these factors for each of the non-attainment cities.

Table 1
Status of ambient air monitoring network in Indian states and union territories, as number of operational stations on February 28th, 2023, for (a) manual stations (b) continuous stations and (c) recommended number of stations estimated using CPCB's thumb rules.

States	Manual	Continuous	Recommended
Andaman & Nicobar	2	–	4
Andhra Pradesh	72	10	126
Arunachal Pradesh	2	1	4
Assam	31	9	143
Bihar	8	35	277
Chandigarh	5	3	7
Chhattisgarh	17	14	103
Dadar-Nagar-Haveli & Daman-Diu	6	–	4
Delhi	10	40	77
Goa	18	–	11
Gujarat	24	17	197
Haryana	5	30	123
Himachal Pradesh	25	1	43
Jammu & Kashmir	31	1	91
Jharkhand	10	2	140
Karnataka	30	39	209
Kerala	29	9	115
Lakshadweep	1	–	4
Madhya Pradesh	42	21	303
Maharashtra	80	41	308
Manipur	1	2	25
Meghalaya	10	2	25
Mizoram	19	1	9
Nagaland	9	1	20
Odisha	38	12	169
Pondicherry	6	1	10
Punjab	48	8	125
Rajasthan	39	24	226
Sikkim	9	1	4
Tamil Nadu	55	23	255
Telangana	25	14	97
Tripura	2	2	21
Uttar Pradesh	84	57	558
Uttarakhand	8	3	64
West Bengal	82	14	197
Total	**883**	**438**	**4097**

Our evaluation includes geography, census data, geospatial information, meteorological data, and guidelines established by CPCB to support the planning process.

2. Definitions, methods, and data

2.1. Airshed size

The concept of airshed management is not new for India, but never officially internalised for air quality management. For example.

1. The central electricity authority (CEA) maintains and records information across India in five electricity zones: northern, southern, western, eastern, and north-eastern. All states within each zone pool their real-time information on demand and supply and maintain individual load dispatch centres to share information.
2. India's climate is divided into six zones: (a) mountainous north covering the Himalayan range, (b) humid subtropical covering most of the IGP and the northeast, (c) tropical wet and dry areas of the Central and East India covering the Deccan plateau, (d) tropical wet which is most of the regions west of the Ghats, (e) arid regions covering the desert, and (f) semi-arid regions between the Ghats and plateau. Each of these zones is unique in their land-use and annual precipitation profiles.
3. Similarly, India is divided into 10 biogeographic zones, 20 water basins, and 24 land-use categories. The last category is very fragmented with no smooth boundaries to define zones.
4. The India Meteorological Department (IMD) maintains 36 subdivisions. These are drawn along the district boundaries with similar geographical patterns in temperature, precipitation, and landcover classification. The daily reports for each of these subdivisions include short-term (1–2 days) dust, thunder, lightning, and storm alerts and long-term (10 days to a month) meteorological predictions to help the local farmers.

In India, it is a challenging to accurately analyse urban air pollution due to the proximity of several cities that are interdependent commercially and economically. Drawing a line based on city administrative boundaries can limit the sources to only local road transport, rail transport, waste management, road dust, greening, and domestic cooking. Sources that are often missed are the large and medium-scale industrial sources located outside the city boundaries and thus also fall outside the regulatory and enforcement responsibilities of city administrations. For instance, Delhi's daily power consumption ranges from an average of 3000 MW–6000 MW during peak hours, but the total generation capacity within the city is less than 15% of this amount (Guttikunda and Calori, 2013; Guttikunda et al., 2023). Most of the power generation is from coal-fired thermal power plants located within a radius of 100 km. Additionally, there are 800 coal and biomass-fired brick kilns operating outside the Delhi's administrative boundary but contribute to Delhi's air quality problems. Similar challenges exist in a cluster of cities on the Indo-Gangetic Plain (IGP) and Central India.

The concept of defining an airshed is crucial for urban air quality management. Typically, an airshed is defined as a geographic area where the movement of emissions and pollution is largely influenced by local meteorological conditions and topography and the boundaries are defined in a way to include all the influential sources in the immediate vicinity of the city's administrative boundary. While this definition is a subjective assessment, the defining factor in determining the size is the inclusion of all major contributing sources in the vicinity of the city. The goal is, irrespective of the administrative jurisdiction, to include all the area and point sources that can likely contribute to local air pollution and to minimize the contribution of long-range regional transport which is defined as boundary influence.

2.2. Recommended number of monitors

Thumb rule for determining the representative area of a continuous air monitoring station is a radius of 2 km. This can be lower in areas with obstructions such as tall buildings and trees or higher in areas with open spaces, mostly outside the city limits. However, the cost and technical limitations make it impractical to place a monitoring station every 9 km^2 (Brauer et al., 2019; Pant et al., 2018). The CPCB provided guidelines in 2003 (Table 2) for determining the minimum number of monitoring stations in a region for reporting levels of particulate matter (PM), sulfur dioxide (SO_2), nitrogen dioxide (NO_2), and carbon monoxide (CO) as well as other oxidants, as a function of population density. While the ambient air quality guidelines were last updated in November 2009, the amendment do not account for the expanding polluted areas nor the need for more monitoring to represent the changes (Guttikunda and Ka, 2022). To address the growing density of urban activities, in addition to the estimates based on Table 2, a correction factor has been introduced to account for urban population density by factoring in the urban area and urban population shares in the airshed.

2.3. @Sampling frequency

To effectively monitor ambient air quality, continuous data is necessary to understand the pollution levels throughout the year and to prepare an air quality management plan, it is necessary to not only understand the pollution levels but also the chemical composition and source contributions to the pollution (Johnson et al., 2011; Yadav et al., 2022). Collecting samples at all monitoring sites every day would be ideal, but the technical, personnel, and financial constraints are very high. Therefore, the frequency of sampling is optimized using information on the seasonality in weather and pollution levels. For example, a tropical city like Bengaluru which experiences consistent weather cycles over seasons can reduce the sampling frequency and still provide a representative source apportionment assessment for the year, compared to a city like Delhi or any other city on the IGP which experience significant variations across season (Guttikunda et al., 2019a, 2023).

Table 2
Recommended number of ambient air quality monitoring stations – based on the protocols introduced in 2000 (CPCB, 2003).

Pollutant	Population in the airshed	Number of stations
Suspended particulate matter (SPM)	<100,000	4
	100,000 to 1,000,000	4 + 0.6 per 100,000 population
	1,000,000 to 5,000,000	7.5 + 0.25 per 100,000 population
	>5,000,000	12 + 0.16 per 100,000 population
Sulfur dioxide (SO_2)	<100,000	3
	100,000 to 1,000,000	2.5 + 0.5 per 100,000 population
	1,000,000 to 10,000,000	6 + 0.15 per 100,000 population
	>10,000,000	20
Nitrogen dioxide (NO_2)	<100,000	4
	100,000 to 1,000,000	4 + 0.6 per 100,000 population
	>1,000,000	10
Carbon monoxide (CO) and Oxidants	<100,000	1
	100,000 to 5,000,000	1 + 0.15 per 100,000 population
	>5,000,000	6 + 0.05 per 100,000 population

2.4. @Data resources

To support the process of designing an ambient air monitoring network, we utilized the databases listed in Table 3. The process started with identifying a representative airshed for each city using information on urban-rural classifications, land-use information, and known emission sources inside and immediately outside the city boundary. The airshed size was established by starting with the administrative boundary of the main city and expanding to include satellite cities and any high-density diffuse and point sources nearby. To classify the airshed area and the population as urban and rural, we utilized the human settlements layer (Pesaresi et al., 2015). The population density data was utilized to calculate the minimum number of sampling sites required for each airshed (CPCB, 2003) and the modelled meteorological data was utilized to calculate the sampling frequency.

3. @Results

3.1. @City backgrounds and airsheds

A summary of the proposed airshed sizes for 131 NCAP cities is included in Table 4 (Column D). For mathematical ease during the emissions and pollution analysis via chemical transport modelling, the range of the number of grids is maintained to a nearest 10. The smallest airshed is 20 × 20 grids in the mountain state of Himachal Pradesh and the largest airshed is 100 × 100 grids for Delhi with 8 other Tier-2 and Tier-3 cities in the immediate vicinity. The most common airshed size is 30 × 30 grids for the Tier-2 and Tier-3 cities, with the main city boundary covering 25–40% of the area. All the grids have uniform size of 0.01° (~1.1 km). A GIS formatted composite of these airsheds with the grid information is included in the Supplementary Material.

Some airsheds include more than one NCAP city (Column B) - 73 airsheds contain only one city; 18 airsheds contain two cities, nine airsheds contain three cities. Four airsheds – Delhi, Mumbai, Indore, and Chandigarh airsheds are covering 10, 8, 5, and 5 cities respectively. Along with the airshed sizes (Column D), Table 4 includes information on total airshed population (Column E), urban shares of the built-up area (Column F) and urban shares of the airshed population (Column G). Some airsheds also include cities not on the non-attainment list (Column C) - together, these 131 NCAP non-attainment cities were grouped into 104 airsheds, collectively representing 164 cities and a total population of 295 million. Delhi, Mumbai, and Kolkata airsheds host more than 20 million inhabitants.

Assam's Silchar and West Bengal's Haldia airsheds displayed least number of grids with built-up area and designated urban population. Haldia airshed hosts one of India's largest oil refinery plants with access to a port. Overall, average share of urban area in the 104 airsheds is 23%, with 16 cities above 40% and Pune recording the highest of 60%. Overall, average share of urban population in the 104 airsheds is 62% with 13 cities above 80%. The population of 295 million represents 21% of the national total and airsheds cover 5.3% of the national land area. The designated urban population of 200 million inhabits 1.4% of the national land area at the rate of 4400 persons/km^2. Mumbai has the highest urban population density of 14,000 persons/km^2.

The largest airshed is Delhi (100 × 100 grids) covers 10 cities – besides Delhi, two cities from Uttar Pradesh (Ghaziabad and Noida) and one from Haryana (Faridabad) and 6 others (Fig. 1a). Delhi's air quality is the most studied in India and receives a lot of media attention (Adhikary et al., 2021; Guttikunda et al., 2023; Yadav et al., 2022). Other commercially and industrially active satellite cities are Bhiwadi, Greater Noida, Gurugram, Manesar, Palwal, and Sonipat, collectively referred as the National Capital Region (NCR) of Delhi.

Mumbai (Fig. 1b) plays a central role in India's economic and commercial portfolio and after Delhi, is the second most studied cities in India for air pollution problems. The Indian Institute of Technology in Mumbai, anchored CPCB's six-city study and developed a library of source chemical profiles for Indian cities (CPCB, 2011; Yadav et al., 2022). The Greater Mumbai's airshed includes Badlapur, Navi Mumbai, Thane, Ulhas Nagar, and Vasai Virar from the NCAP list and Kalyan and Karjat which are industrial hubs outside the main city. Due to constant commercial and personnel movement between these areas, it is difficult to delineate these cities. The 19 non-attainment cities in Maharashtra were clubbed into 13 airsheds covering a total of 23 cities (all within the state).

Kolkata's airshed contains its twin city Howrah as well as its neighbouring cities Barrackpore which hosts a coal fired thermal power plant. This airshed includes 700 coal and biomass fired fixed-chimney brick kilns. Unlike Mumbai and Delhi, only 61% of the airshed population is accounted in the 50% of urban grids, which means a large fraction of the airshed population is in the rural areas with limited access to urban amenities such as waste management and consistent clean cooking fuel access. Other airsheds in West Bengal are Asansol including Ranigunj and Durgapur cities and Haldia, just south of Kolkata airshed.

Uttar Pradesh, the most populated state in the country, with 17 non-attainment cities, hosts 15 airsheds. Only the cities of Noida and Ghaziabad are absorbed into the Greater Delhi airshed. The Lucknow, Varanasi, and Kanpur airsheds have an estimated population of 6.4, 4.6, and 4.1 million and collectively 38 million in the 15 airsheds.

A group of 13 airsheds are in proximity in the Indian states of Himachal Pradesh, Uttarakhand, Punjab, and Chandigarh. During the winter months, a majority share (40–50% on an annual basis) of the $PM_{2.5}$ pollution in these airsheds can be attributed to sources outside the boundary (Guttikunda et al., 2019b). The largest airshed here is Chandigarh, which includes the cities of Dera Bassi and Parwanoo from the NCAP list and 2 others (Panchkula and Kalka).

3.2. @Number of monitoring/sampling sites

Using the guidelines in Table 2, we estimated that India requires at least 4000 continuous monitoring stations – 2800 in the urban areas and 1200 in the rural areas, to truly represent the air quality trends (Pant et al., 2018) (see Supplementary Material for recommended number of

Table 3
Source and use case of open GIS databases.

Field	Database	Design component
Emissions	Air Pollution knowledge Assessment (APnA) city program (Guttikunda et al., 2019b; UEinfo, 2019)	Airshed size
Population	Census-India database at the district level (Census-India, 2011) and Landscan of Oakridge National Laboratory (Rose et al., 2019) were used to create 0.01° resolution population database for the city airsheds. The raw databases are available at 30 s spatial resolution.	Airshed size and number of sampling sites
Global Human settlement (GHS)	GHS layer of Landsat satellite imagery was used to designate the city airshed grids and the gridded population as urban and rural (Pesaresi et al., 2015).	Airshed size and number of sampling sites
Meteorology	Weather Research and Forecasting (WRF) model with inputs from NOAA's National Centres for Environmental Prediction (NCEP) (Kalnay et al., 1996) was used to build all the necessary 3-dimensional meteorological fields, such as wind speeds, wind directions, temperature, relative humidity, pressure, precipitation, mixing layer heights, and surface threshold velocities (and others) at 1-h temporal resolution for base year 2018	Sampling frequency

Table 4
Characteristics of airsheds designated for NCAP non-attainment cities. B = cities included in the airshed from the NCAP list; C = cities included in the airshed, but not on the NCAP list; D = airshed size in grids of equal size (0.01°); E = total airshed population (in million); F = fraction of grids designated as urban using built-up area information from (Pesaresi et al., 2015); G = fraction of population in the urban grids; H, I, J, K = number of continuous monitoring stations recommended for tracking PM, SO_2, NO_2, and Others respectively.

	State/UT	Airshed	B	C	D	E	F	G	H	I	J	K
1	Andhra Pradesh	Anantapur			30 × 30	0.6	8%	60%	10	6	8	2
2	Andhra Pradesh	Chitoor			30 × 30	0.5	8%	50%	9	5	7	2
3	Andhra Pradesh	Eluru		Hanuman Junction	30 × 30	0.7	8%	50%	10	6	8	2
4	Andhra Pradesh	Kadapa			30 × 30	0.5	6%	62%	9	6	8	2
5	Andhra Pradesh	Kurnool			30 × 30	0.7	10%	65%	10	6	9	3
6	Andhra Pradesh	Nellore			30 × 30	0.8	15%	66%	12	7	9	3
7	Andhra Pradesh	Ongole			30 × 30	0.5	9%	54%	9	5	7	2
8	Andhra Pradesh	Rajahmundry			30 × 30	1.4	25%	55%	17	9	10	4
9	Andhra Pradesh	Srikakulam			30 × 30	0.7	8%	41%	10	6	8	2
10	Andhra Pradesh	Vijayawada	Guntur	Tenali	50 × 50	3.1	23%	65%	22	11	10	6
11	Andhra Pradesh	Vishakhapatnam		Anakapalle	50 × 50	2.9	18%	68%	20	11	10	6
12	Andhra Pradesh	Vizianagaram			30 × 30	0.9	9%	47%	12	8	10	3
13	Assam	Guwahati	Byrnahati	Dispur	40 × 30	1.7	36%	73%	18	9	10	4
14	Assam	Nagaon			30 × 30	1.2	47%	20%	36	8	10	3
15	Assam	Nalbari			30 × 30	0.9	31%	56%	11	8	10	3
16	Assam	Sibsagar			30 × 30	0.5	19%	32%	12	5	7	2
17	Assam	Silchar			30 × 30	1.1	14%	18%	19	8	10	3
18	Bihar	Gaya			30 × 30	1.6	18%	30%	19	9	10	4
19	Bihar	Muzaffarpur			30 × 30	2.7	42%	30%	35	11	10	6
20	Bihar	Patna			60 × 40	7.0	38%	46%	43	17	10	10
21	Chandigarh	Chandigarh	Dera Bassi, Parwanoo	Panchkula, Kalka	50 × 40	2.9	40%	76%	23	11	10	6
22	Chhattisgarh	Korba			40 × 40	0.9	11%	58%	12	7	10	3
23	Chhattisgarh	Raipur	Bhillai	Durg	60 × 30	3.2	29%	76%	22	11	10	6
24	Delhi	Delhi	Faridabad, Ghaziabad, Noida	Greater Noida, Gurugram, Palwal, Manesar, Sonipat	100 × 100	32.8	43%	79%	101	20	10	23
25	Gujarat	Ahmedabad		Gandhi Nagar	50 × 50	7.9	40%	79%	38	18	10	10
26	Gujarat	Rajkot			30 × 30	1.5	24%	80%	16	9	10	4
27	Gujarat	Surat		Hazira	50 × 50	5.8	23%	61%	30	15	10	9
28	Gujarat	Vadodara			30 × 30	2.6	34%	82%	21	10	10	5
29	Himachal Pradesh	Kala Amb			30 × 30	0.4	7%	29%	9	5	7	2
30	Himachal Pradesh	Nalagarh	Baddi		30 × 30	0.3	20%	62%	9	5	7	2
31	Himachal Pradesh	Paonta Sahib			20 × 20	0.2	12%	53%	7	4	5	2
32	Himachal Pradesh	Sunder Nagar			20 × 20	0.2	22%	63%	8	4	6	2
33	Jammu & Kashmir	Jammu			30 × 30	1.3	47%	65%	19	8	10	3
34	Jammu & Kashmir	Srinagar			30 × 30	2.1	56%	77%	23	10	10	5
35	Jharkhand	Dhanbad			60 × 40	3.8	23%	39%	28	12	10	7
36	Jharkhand	Jamshedpur		Bokaro, Jaropokhar		2.2	12%	61%	16	10	10	5

(continued on next page)

Table 4 (*continued*)

	State/UT	Airshed	B	C	D	E	F	G	H	I	J	K
					40 × 40							
37	Jharkhand	Ranchi			40 × 40	1.9	20%	58%	17	9	10	4
38	Karnataka	Bangalore			60 × 60	11.7	50%	81%	50	20	10	12
39	Karnataka	Devanagere			30 × 30	0.9	12%	65%	12	7	10	3
40	Karnataka	Gulburga			30 × 30	0.8	10%	71%	11	7	9	3
41	Karnataka	Hubli-Dharwad			30 × 30	1.3	18%	77%	14	8	10	3
42	Madhya Pradesh	Bhopal			40 × 40	2.6	23%	86%	19	10	10	5
43	Madhya Pradesh	Gwalior			30 × 30	1.4	17%	71%	15	9	10	4
44	Madhya Pradesh	Indore	Dewas, Ujjain	Mhow, Pitampura	80 × 80	5.5	11%	51%	26	15	10	9
45	Madhya Pradesh	Jabalpur			40 × 40	1.9	15%	75%	16	9	10	4
46	Madhya Pradesh	Sagar			30 × 30	0.5	8%	61%	9	6	8	2
47	Maharashtra	Akola			30 × 30	0.8	10%	64%	11	7	9	3
48	Maharashtra	Amravati			30 × 30	0.9	10%	74%	12	8	10	3
49	Maharashtra	Aurangabad			40 × 40	1.9	16%	73%	16	9	10	4
50	Maharashtra	Chandrapur			30 × 30	0.7	12%	73%	11	7	9	3
51	Maharashtra	Jalgaon			30 × 30	0.8	10%	66%	11	7	9	3
52	Maharashtra	Jalna			30 × 30	0.6	7%	51%	9	6	8	2
53	Maharashtra	Kolhapur	Sangli		60 × 40	3.9	23%	47%	26	12	10	7
54	Maharashtra	Latur			30 × 30	0.8	10%	60%	11	7	9	3
55	Maharashtra	Mumbai	Badlapur, Navi Mumbai, Thane, Ulhasnagar, Vasai Virar	Kalyan, Karjat	80 × 80	25.1	21%	78%	67	20	10	19
56	Maharashtra	Nagpur			40 × 40	3.6	28%	88%	23	12	10	7
57	Maharashtra	Nashik			40 × 40	2.6	29%	75%	20	10	10	5
58	Maharashtra	Pune		Pimpri-Chinchwad, Hinjewadi	40 × 40	6.8	60%	86%	40	17	10	10
59	Maharashtra	Solapur			30 × 30	1.1	16%	79%	13	8	10	3
60	Nagaland	Dimapur			30 × 30	0.5	22%	80%	10	5	7	2
61	Nagaland	Kohima			30 × 30	0.2	5%	54%	7	4	6	2
62	Orissa	Angul	Talcher		40 × 40	0.7	11%	39%	12	7	9	3
63	Orissa	Balasore			30 × 30	0.8	8%	36%	12	7	9	3
64	Orissa	Bhubaneswar	Cuttack, Kalinga Nagar		40 × 40	3.2	21%	60%	22	11	10	6
65	Orissa	Rourkela			30 × 30	1.2	16%	56%	15	8	10	3
66	Punjab	Amritsar		Tarn Taran	40 × 40	2.2	38%	69%	21	10	10	5
67	Punjab	Jalandhar		Phagwara	40 × 40	1.9	44%	65%	22	9	10	4
68	Punjab	Khanna	Gobindgarh		30 × 30	0.7	37%	69%	14	7	9	3
69	Punjab	Ludhiana		Philaur	40 × 40	2.7	45%	78%	23	11	10	6
70	Punjab	Naya Nangal		Una	30 × 30	0.5	29%	65%	11	5	7	2
71	Punjab	Pathankot/Dera Baba	Damtal		30 × 30	0.7	30%	70%	13	7	9	3
72	Punjab	Patiala			60 × 40	1.8	22%	48%	19	9	10	4
73	Rajasthan	Alwar			30 × 30	0.9	18%	67%	13	7	10	3

(*continued on next page*)

Table 4 (*continued*)

	State/UT	Airshed	B	C	D	E	F	G	H	I	J	K
74	Rajasthan	Jaipur			40 × 40	4.5	54%	90%	31	13	10	8
75	Rajasthan	Jodhpur			40 × 40	1.9	26%	83%	17	9	10	4
76	Rajasthan	Kota			30 × 30	1.1	25%	83%	14	8	10	3
77	Rajasthan	Udaipur			30 × 30	1.4	27%	71%	16	9	10	4
78	Tamil Nadu	Chennai			50 × 50	10.9	44%	83%	46	20	10	12
79	Tamil Nadu	Madurai		Singrauli	30 × 30	2.1	27%	86%	18	10	10	5
80	Tamil Nadu	Thoothukudi			40 × 40	0.9	11%	66%	12	7	10	3
81	Tamil Nadu	Trichy			30 × 30	1.8	31%	78%	18	9	10	4
82	Telangana	Hyderabad	Patancheru, Sangareddy		80 × 50	9.0	36%	85%	39	20	10	11
83	Telangana	Nalgonda			30 x 30	0.4	6%	44%	8	5	7	2
84	Uttar Pradesh	Agra			40 × 40	3.7	22%	66%	23	12	10	7
85	Uttar Pradesh	Allahabad			40 × 40	3.7	31%	49%	28	12	10	7
86	Uttar Pradesh	Anpara			40 × 40	0.8	15%	65%	12	7	9	3
87	Uttar Pradesh	Bareily			30 × 30	2.4	25%	63%	20	10	10	5
88	Uttar Pradesh	Firozabad			30 × 30	1.5	11%	43%	15	9	10	4
89	Uttar Pradesh	Gajraula			30 × 30	0.8	16%	43%	13	7	9	3
90	Uttar Pradesh	Gorakhpur			30 × 30	2.3	44%	60%	24	10	10	5
91	Uttar Pradesh	Jhansi			30 × 30	0.9	17%	72%	13	8	10	3
92	Uttar Pradesh	Kanpur		Unnao	40 × 40	4.0	23%	70%	24	13	10	8
93	Uttar Pradesh	Khurja		Bulandshahr	30 × 30	1.2	14%	32%	16	8	10	3
94	Uttar Pradesh	Lucknow		Barabanki	60 × 60	6.4	22%	54%	32	16	10	10
95	Uttar Pradesh	Meerut			30 × 30	2.5	42%	73%	23	10	10	5
96	Uttar Pradesh	Moradabad			30 × 30	2.0	29%	51%	21	10	10	5
97	Uttar Pradesh	Raebareli			30 × 30	1.1	7%	27%	14	8	10	3
98	Uttar Pradesh	Varanasi			40 × 40	4.6	52%	57%	37	13	10	8
99	Uttarakhand	Dehradun			30 × 30	1.1	31%	82%	15	8	10	3
100	Uttarakhand	Kashipur			30 × 30	1.0	22%	46%	16	8	10	3
101	Uttarakhand	Rishikesh		Haridwar	30 × 30	0.8	20%	75%	12	7	9	3
102	West Bengal	Asansol	Durgapur	Ranigunj	60 × 40	3.6	26%	43%	27	12	10	7
103	West Bengal	Haldia			40 × 40	2.2	11%	7%	34	10	10	5
104	West Bengal	Kolkata	Barrackpore, Howrah		60 × 60	20.4	50%	61%	82	20	10	17

monitors by state (Table 1) and district). Using the same guidelines, and population and urban-rural classification data for year 2020, we estimated the minimum number of monitoring stations and subsequently minimum number of sampling sites necessary for an ideal source apportionment study in the proposed 104 airsheds (Table 4 – Columns H–K). For the 104 airsheds, a total of 2118 sampling sites are recommended to measure and analyse PM pollution. In case of SO_2 and NO_2, the concentrations tend to be higher at the sources and quickly disperse and transform into secondary aerosols as the gases move through the region. In case of CO and other oxidants the variability in the concentrations is more uniform, resulting in the need for even lesser number of monitoring stations. For the 104 airsheds, a total of 985, 977, and 509 stations are recommended for SO_2, NO_2, and CO respectively.

Spatial variability in the concentration levels and source contributions is high for Indian cities. For example, previous studies have reported large day-to-day as well as significant seasonal variations in PM in Delhi (Pant et al., 2015; Tiwari et al., 2013). A limited period study in September 2016, using samples collected at 16 locations in Delhi's airshed, followed by chemical composition analysis, suggested that there is significant spatial variability linked to specific sources (see Supplementary Material for details from this study). However, this dataset did not allow for quantification of contributions for specific

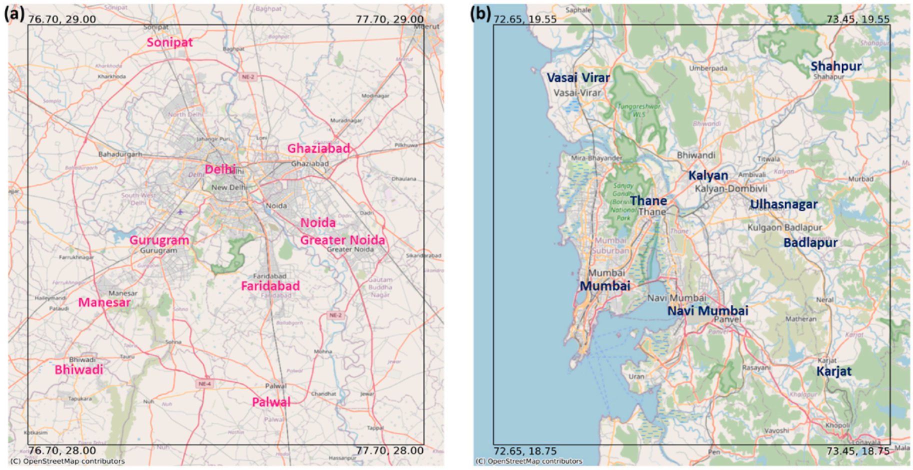

Fig. 1. Proposed airshed size for the city of (a) Delhi (1.0° × 1.0°) and (b) Mumbai (0.8° × 0.8°), with multiple Tier-2 and Tier-3 cities in the immediate proximity. The domain is further disaggregated into 0.01° resolution grids in longitudes and latitudes. Basemap is sourced from OpenStreetMaps

sources, partly due to the demonstrative nature of the experiment with a small sample size (two per site over two days). Heterogeneity in the concentrations and the chemical species is evidence that even 16 sites were not enough to represent the spatial and temporal trends in Delhi's air quality. Using the CPCB guidelines, we recommend at least 77 ambient and source apportionment sampling sites within Delhi and 101 within the airshed. Similar variability is expected in other airsheds, which require more than the nominal 3 to 5 sampling locations to quantify their source mix.

Accounting for the spatial variability in concentration levels and presence of local sources, the number of recommended PM monitoring and sampling sites varies from 7 for Kohima (in Meghalaya) and Paonta Saheb (in Himachal Pradesh) to 101 in Delhi. For the 104 airsheds combined, estimated average number is 20 per airshed. The Tier-1 cities on the NCAP list – Delhi, Kolkata, Mumbai, Bengaluru, Chennai, Patna, Pune, Hyderabad, and Ahmedabad require at least 101, 82, 67, 50, 46, 43, 40, 39, and 38 monitoring locations, respectively, which is 2–5 times their current operational monitoring capacity (Supplementary Material). The recommended number of stations for the 104 airsheds will bring the monitor density up to 7.2 monitors per million persons.

3.3. @Sampling frequency

The variation in weather and pollution levels is stronger in the Northern states as compared to the Southern peninsular states (Guttikunda et al., 2014b). This can be used for some compromise in the number of sampling days. For ease, we grouped the airsheds into eight zones (Fig. 2) – six zones based on the state's temperate conditions

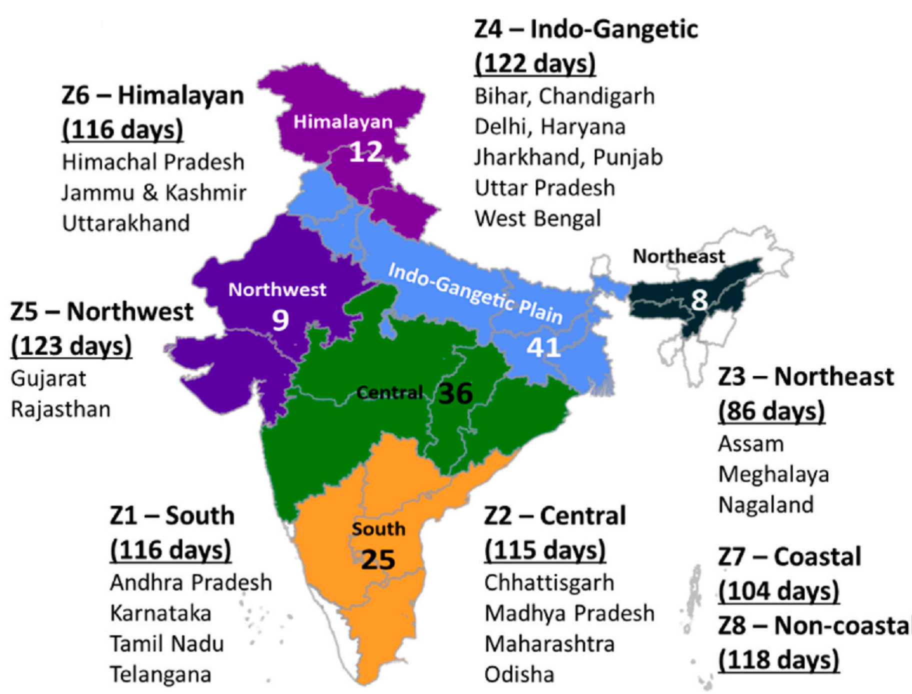

Fig. 2. Grouping of states based on temperate and geographical conditions, number of NCAP cities in each group, and proposed minimum number of sampling days in each group based on meteorological data analysis.

(South, Central, Northeast, Indo-Gangetic plain, Northwest, and Himalayan) and two zones based on the airsheds location (coastal and non-coastal – not shown in the figure). A summary of variations and averages by month in near surface (2m) temperature, near surface (10m) wind speed, precipitation, and mixing heights for all the airsheds is included in the Supplementary Material.

Two parameters that can be used for optimizing the number of samples are ventilation rate (mixing layer height * wind speed) and precipitation rate. Under wet conditions, most of the aerosols are entrained in the rain. Typically, June to September are the wet months (precipitation greater than 100 mm/month) and these months require fewer samples to catch the trend. Higher ventilation rate (greater than 4000 m^2/s) means either the wind speeds are high allowing for long-range transport of pollutants, or the mixing height is high allowing for more vertical mixing. In both the cases, the probability of regional contribution and consequently secondary pollution is high, which requires more frequent sampling to catch the trends. Under low ventilation rates, which is a proxy for stagnant conditions can mean lesser number of samples. Supplementary Material also includes monthly variation in average near surface temperature, but not used in assessing the need for sampling frequency because temperature is an integral parameter which determines the mixing height. Typically, winter months and night times experience lower temperature leading to lower mixing heights and vice versa.

The total number of proposed sampling days varies from 86 for the Northeast states (Z3) to 122 for the Indo-Gangetic Plain (IGP) states (Z4) and 123 for Northwest states (Z5). Least number for the Northeast is mainly because this region receives more than 100 mm of rain for six months and exhibits least variation in the ventilation rates (under 1500 m^2/s). Most number of sampling days for IGP is an indicator of strong seasonality and the need to carry out more sampling to better represent the changes. South India (Z1) is on average hotter than the rest of India and receives more scattered rains in the second half of the year. While the number of sampling days for South and Central India (Z2) are the same, we estimate the need for more sampling in the first half of the year in Z2. In general, coastal regions (Z7) have better ventilation rate due to consistent land-sea breeze and more precipitation compared to the inland cities (Z8), thus needing 14 less sampling days. The land-sea breeze an advantage that coastal cities also benefit from. For example, while the estimated emission load in Chennai and Delhi are similar, the overall $PM_{2.5}$ pollution level in Chennai is half or less of that observed in Delhi (Guttikunda and Calori, 2013; Guttikunda et al., 2014a).

The estimated minimum number of sampling days is only a representative example to reduce the technical and financial burden of the source apportionment studies. Where and when possible, as much sampling and chemical analysis must be conducted to better understand the pollution composition and source contributions (Yadav et al., 2022). The meteorology database is for year 2018 and we did not estimate the same requirement for other years. One factor not considered in the analysis is the influence of regional emission sources. This is important for IGP and Northwest, both with strong seasonal sources such as post-harvest agricultural residue fires in October–November and dust storms in April–May.

4. @Discussion

The success of the NCAP largely depends on the availability of accurate and comprehensive information on the status of air pollution in the cities. This can be used to track progress towards the goal of reducing 40% of PM pollution by 2026, compared to 2017 levels. A summary of the level of efforts necessary for plugging the ambient air quality monitoring needs for NCAP is presented in Table 5. The long-term data collection and analysis will require a significant amount of resources and expertise from (a) setting up air quality monitoring stations across the country, (b) collecting and analysing air samples for source apportionment, and (c) developing models to estimate the levels of pollutants in areas where monitoring stations are not available.

Table 5
Summary of status and requirements for ambient air monitoring network in India under NCAP.

Field	Data
Total number of non-attainment cities	131
Total number of designated airsheds	104
Airshed with the most number of cities	Delhi (4 NCAP + 6 Others)
Area covered by all the airsheds	5.3% of national total
Total airsheds population	295 million
Population covered by all the airsheds	21% of national total
Median population size in the airsheds (min-max)	1.4 (0.2–32.8) million
Average % of urban population in the airsheds	62%
Airsheds with 80% urban population	13
Airsheds with above one million population	64
Monitoring status in India (as of Feb 2023)	
Total number of manual stations	438
Total number of continuous stations	883
Monitors per million	0.31
Monitoring requirement in all airsheds	
Total number of PM monitors	2118
Total number of SO_2 monitors	985
Total number of NO_2 monitors	977
Total number of CO and other monitors	509
Airsheds with the most number of PM monitors	Delhi (101), Kolkata (82)
Anticipated PM monitors per million	7.2

4.1. @Framework for periodic assessment of source contributions

The last comprehensive source apportionment study in India was conducted by CPCB in 2006 for six cities, and the findings were made public in 2011 (CPCB, 2011; Pant and Harrison, 2012; Yadav et al., 2022). Despite the establishment of capacity to conduct similar studies at multiple institutions, no further multi-city studies have been conducted since, resulting in a significant information gap for NCAP. As of February 2023, more than 70 institutions are coordinating source apportionment across NCAP cities and in some cases for the first time (details in the Supplementary Material). However, one drawback of this program is the lack of provision to update information after NCAP. The current studies are designed as one-time exercises conducted by regional academic and research institutions, with no means to repeat and quantify air quality changes in the future. To sustain and improve these efforts, a national framework is necessary to establish protocols for periodically conducting receptor studies and emission inventories.

As of February 2023, CPCB operates at one manual monitoring station in 379 cities. These stations use high volume samplers to collect $PM_{2.5}$ and PM_{10} filters, which are only subjected to gravimetric analysis to determine the 24 h average concentrations, to calculate the air quality index, and to assess compliance attainment. However, with some modifications to the sampling technique, the same network can be utilized to collect filters required for ionic, elemental, and carbon analysis to support periodic source apportionment studies for all cities beyond NCAP. This expansion would require a systematic increase in laboratory facilities at state PCBs and regional research institutions.

In January 2023, the Delhi of pollution control committee (DPCC) launched a real-time source apportionment program, which is designed to monitor, analyse, and conduct receptor modelling every hour (DPCC, 2023). While sampling and analysis from one location is not a representative size and the capital cost of the equipment is large, the methodology is unique and provides instantaneous results for short-term pollution alerts and feeds the long-term policy dialogues with continuous data.

Source apportionment exercises require the use of appropriate source profiles to reproduce the total mass on the ambient filter for all the elements, ions, and carbon species (Watson, 1984; Yadav et al., 2022). In the absence of local profiles, generic profiles can be used with caution. If not selected to represent the local sources, can lead to misleading results. For example (CPCB, 2011), and (DPCC, 2023) list domestic liquified petroleum gas (LPG) combustion as the major contributor to ambient $PM_{2.5}$ pollution (see Supplementary Material for a summary), which goes against the conventional wisdom of promoting LPG as the cleanest fuel for urban and rural cooking in India (Harish and Smith, 2019; Mani et al., 2020). This is a result of overemphasizing one profile or missing other key sources in the vicinity of the sampling site. Every effort must be made to develop emission inventories and source profiles of local and influential sources.

4.2. @Expansion of the monitoring network to rural areas

According to the reanalysed $PM_{2.5}$ concentrations, India's annual $PM_{2.5}$ averages have at least doubled between 1998 and 2020 (Fig. 3) (Guttikunda and Ka, 2022, 2022van Donkelaar et al., 2021). On India's AQI scales, pollution over IGP moved from poor to very poor and severe conditions and over Central India it moved from moderate to poor conditions. At the administrative level, number of districts complying with India's annual ambient standard of 40 μg/m^3 dropped from 440 to 255 (out of 640 districts as per Census-India, 2011) and number states dropped from 29 to 21 (out of 36, including union territories). Traditionally, these increases are observed over the cities. However, in the reanalysis fields combined with satellite retrievals, it is evident that similar trends are occurring in areas beyond urban boundaries. Total population complying with the national annual average standard of 40 μg/m^3 dropped from 60.5% to 28.4% (Fig. 3c–d), with most of this change coming from non-urban areas, especially over IGP. In the same period, the population exposed to poor, very poor, and severe AQI levels (above 90 μg/m^3) increased from 0.0% to 17.8%. In 2020, only 2 out of 640 districts complied with the World Health Organization (WHO)'s new guideline of 5 μg/m^3. All the efforts to monitor air quality in India are concentrated in the cities and any information on the air quality trends in the rural areas is only coming from the reanalysis fields. Given the proximity of the rural areas to the growing number of urban centres and the deteriorating air quality in the rural areas, for NCAP to succeed, efforts to monitor and analyse pollution levels must expand to the rural areas.

4.3. @Framework for a hybrid monitoring network

The current ambient monitoring network (Table 1) is limited in its capacity to represent the spatial air quality trends in India. Of the current 438 regulatory monitors (as of February 2023), 40 are in Delhi and another 30 in Delhi's satellite regions, making the National Capital Region (NCR) of Delhi the most monitored region in India. Similar networks are necessary in all the cities and across the rural India, not only to study the compliance levels, but also to study the sectoral, regional, and meteorological influences on urban air quality.

The capital and operational cost of a reference-grade monitoring network is high, which can be complemented with the use of a calibrated low-cost sensor network (Brauer et al., 2019; Robinson et al., 2019; Zheng et al., 2018). In a hybrid network, a combination of reference-grade monitors and calibrated sensors are interspersed to plug the operational gaps and monitor hyperlocal pollution hotspots within a city. Data from a large network of reliable sensors can also be integrated with satellite-measurements and modelled outputs, to support generation of spatially continuous information on pollution levels in an airshed.

An example comparison for setting a reference-grade monitoring network vs. a hybrid monitoring network for different combinations is presented in Table 6 for Lucknow, Hyderabad, and Mumbai. On average, the network size of a hybrid network can be doubled, at 70% of the capital and operational costs of using only reference-grade monitors. For direct comparison, these calculations were limited only to $PM_{2.5}$ ambient monitoring, using Met-ONE Beta Attenuation Monitor (BAM) as reference in operation at the US Embassy's across the world. We did not consider the full-range continuous monitoring station capable of monitoring all the criteria pollutants (including gaseous species) and meteorological fields, with capital costs of 10–30 times of a single BAM.

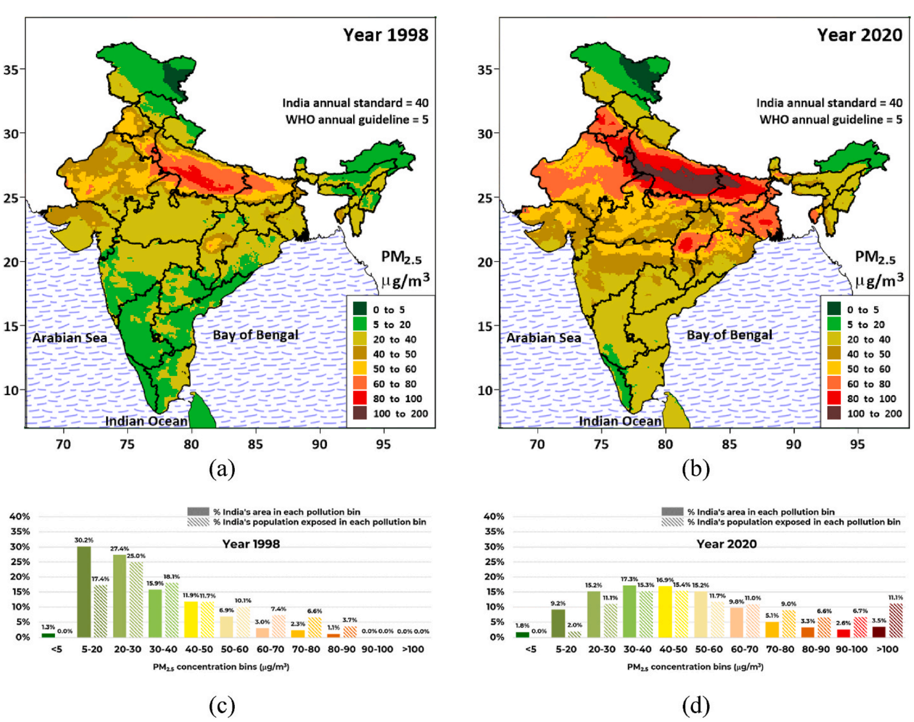

Fig. 3. Summary of reanalysed annual $PM_{2.5}$ concentrations (a) 1998 and (b) 2020 and summary of % India's area and % India's population exposed to various $PM_{2.5}$ pollution bins (c) 1998 and (d) 2020 (Guttikunda and Ka, 2022, van Donkelaar et al., 2021).

Table 6
Average estimated capital and operational costs of a combination of reference-grade and sensor-grade monitoring network for $PM_{2.5}$ only, for the cities of Lucknow, Hyderabad, and Mumbai. The minimum number of stations is obtained from Table 1.

City	Combination	Name	Reference grade (RG) costs	Sensor grade (SG) costs
	1	Unit cost	INR 2,000,000	INR 50,000
	1	Annual maintain cost	INR 200,000 (10% is standard practice from the manufacturer)	INR 5000 (also assuming replacement after lifetime)
	1	Lifetime	10 years	6 months (best available)
Lucknow	32 RGs (minimum)	10-year costs	INR 128,000,000	
	10 RGs + 22 SGs (hybrid)	10-year costs	INR 40,000,000	INR 23,100,000
	10 RGs + 50 SGs (expanded hybrid)	10-year costs	INR 40,000,000	INR 52,500,000
Hyderabad	39 RGs (minimum)	10-year costs	INR 156,000,000	
	15 RGs + 24 SGs (hybrid)	10-year costs	INR 60,000,000	INR 25,200,000
	15 RGs + 65 SGs (expanded hybrid)	10-year costs	INR 60,000,000	INR 68,250,000
Mumbai	67 RGs (minimum)	10-year costs	INR 268,000,000	
	20 RGs + 47 SGs (hybrid)	10-year costs	INR 80,000,000	INR 49,350,000
	20 RGs + 100 SGs (expanded hybrid)	10-year costs	INR 80,000,000	INR 105,000,000

While the overall costs of a hybrid network are less than a full-scale reference-grade network, caution is required in implementing these programs for multiple reasons (Peltier et al., 2021) – (a) sensors are an emerging technology and their manufacturing, installation, training, and operations is not standardized (b) several sensors are available in the market from as low as INR 5000 to INR 50,000 making it difficult to judge their operational quality (c) there is a considerable amount of uncertainty in the measurements (d) the calibration and quality assurance processes are not standardized (e) because of lack of onsite validation, current sensor technology cannot be used for research purposes without validation from colocation against a reference-grade unit.

Major advantage of a calibrated hybrid network, besides cost cutting, is availability of a larger pool of data which can be immediately used for public awareness, identification of hotspots in the city's airshed, landuse regression analysis to study the movement of pollution, and validation of the technology itself against the reference-grade system to further bridge the gap between limited and recommended amount of monitoring.

4.4. @Consolidation with Bottom-up Emission Inventories

Since the need for instrumentation, personnel, and finances is higher for chemical-analysis based receptor-model studies, the missing gaps can be filled with emission-based studies, which can be conducted at more regular intervals (such as monthly) at lower financial burden. For consolidation of information and results from both the methods, an institutional anchor is necessary to collate information. The air information cell at CPCB and the NKN of academic institutions, are expected to fill this gap. Additional benefits of an operational emissions inventory are:

- An understanding of the sources and their strengths, which can aide in the selection of appropriate source profiles for receptor modelling.
- Results from chemical transport models can aide in the selection of hotspots for representative ambient monitoring and source sampling.
- Regular updates to the emissions inventory based on sectoral activity trends, can aide in the planning of future sampling and source apportionment studies.

5. @Final remarks

To effectively address the issue of air pollution, it is necessary to adopt a comprehensive approach that considers not only the sources within city administrative boundaries but also those beyond them. We recommend an airshed based approach for both air quality management and designing monitoring networks for Indian cities. To accomplish this, 104 airsheds were defined covering not only the 131 NCAP cities, but also another 33 cities in the immediate proximity, which can mutually benefit from working together on a clean air action plan. This approach requires close collaboration and coordination among various government agencies and stakeholders responsible for monitoring and managing air pollution in the region.

The expansion of air quality monitoring infrastructure in the non-attainment cities and rural areas must be top priority for the NCAP. A representative monitoring network in these cities, comprising of at least 2118 particulate monitors, can capture the impacts of all local and regional emission sources that affect the air quality in the respective airsheds. To meet the emerging needs of scientific assessment required by the NCAP, the significant costs associated with augmenting the monitoring infrastructure can be supplemented by using a combination of reference-grade and sensor-grade monitors as a calibrated hyperlocal-hybrid network.

In addition to the monitoring efforts, the need for complementary activities, such as the use of emissions inventories, satellite measurements, and other modelling work, is necessary for tracking the NCAP parameters. Emissions inventories provide important information on source strengths at various times and satellite measurements can provide valuable data on atmospheric concentrations and changes in air quality. By combining these different approaches, the NCAP cities can gain a more comprehensive and accurate understanding of the complex processes driving air pollution and develop effective strategies to address it.

CRediT authorship contribution statement

Sarath Guttikunda: Conceptualization, Methodology, Writing – original draft, preparation, Writing – review & editing. **Nishadh Ka:** Data curation, Methodology, Software, Visualization. **Tanushree Ganguly:** Writing – original draft, preparation, Writing – review & editing. **Puja Jawahar:** Conceptualization, Supervision, Writing – original draft, preparation, Writing – review & editing.

Declaration of competing interest

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

Data availability

Data will be made available on request.

Acknowledgements

This research did not receive any external funding. We would like to acknowledge and express our gratitude to Dr Pallavi Pant from the Health Effects Institute in Boston, USA, for her assistance in evaluating the concept and manuscript at various stages. We would also like to thank the anonymous reviewers for their valuable contributions to this manuscript.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.atmosenv.2023.119712.

References

Adhikary, R., Patel, Z.B., Srivastava, T., Batra, N., Singh, M., Bhatia, U., Guttikunda, S., 2021. Vartalaap: what drives# airquality discussions: politics, pollution or pseudo-science? Proc. ACM on Hum. Comput. Interact. 5, 1–29.

Balakrishnan, K., Dey, S., Gupta, T., Dhaliwal, R.S., Brauer, M., Cohen, A.J., Stanaway, J. D., Beig, G., Joshi, T.K., Aggarwal, A.N., Sabde, Y., Sadhu, H., Frostad, J., Causey, K., Godwin, W., Shukla, D.K., Kumar, G.A., Varghese, C.M., Muraleedharan, P., Agrawal, A., Anjana, R.M., Bhansali, A., Bhardwaj, D., Burkart, K., Cercy, K., Chakma, J.K., Chowdhury, S., Christopher, D.J., Dutta, E., Furtado, M., Ghosh, S., Ghoshal, A.G., Glenn, S.D., Guleria, R., Gupta, R., Jeemon, P., Kant, R., Kant, S., Kaur, T., Koul, P.A., Krish, V., Krishna, B., Larson, S.L., Madhipatla, K., Mahesh, P.A., Mohan, V., Mukhopadhyay, S., Mutreja, P., Naik, N., Nair, S., Nguyen, G., Odell, C. M., Pandian, J.D., Prabhakaran, D., Prabhakaran, P., Roy, A., Salvi, S., Sambandam, S., Saraf, D., Sharma, M., Shrivastava, A., Singh, V., Tandon, N., Thomas, N.J., Torre, A., Xavier, D., Yadav, G., Singh, S., Shekhar, C., Vos, T., Dandona, R., Reddy, K.S., Lim, S.S., Murray, C.J.L., Venkatesh, S., Dandona, L., 2019. The impact of air pollution on deaths, disease burden, and life expectancy across the states of India: the Global Burden of Disease Study 2017. Lancet Planet. Health 3, e26–e39.

Brauer, M., Guttikunda, S.K., K A, N., Dey, S., Tripathi, S.N., Weagle, C., Martin, R.V., 2019. Examination of monitoring approaches for ambient air pollution: a case study for India. Atmos. Environ. 216, 116940.

Census-India, 2011. Census of India, 2011. The Governement of India, New Delhi, India.

CPCB, 2003. Guidelines for Ambient Air Quality Monitoring. Central Pollution Control Board. Ministry of Environment Forests and Climate Change, Government of India, New Delhi, India.

CPCB, 2011. Air Quality Monitoring, Emission Inventory and Source Apportionment Study for Indian Cities. Central Pollution Control Board, Government of India, New Delhi, India.

CPCB, 2019. National Clean Air Programme (NCAP), Portal for Regulation of Air-Pollution in Non-attainment Cities. Ministry of Environmental Forests and Climate Change, The Government of India, New Delhi, India. PRANA -. https://prana.cpcb.gov.in. (Accessed 28 February 2023). accessed on.

CPCB, 2023. National Air Quality Index (AQI) Bulletin. Central Pollution Control Board, New Delhi, India. https://cpcb.nic.in/AQI_Bulletin.php. (Accessed 28 February 2023). accessed on.

CREA, 2023. Tracing the Hazy Air 2023. Progress Report on National Clean Air Programme (NCAP). Centre for Research on Energy and Clean Air, New Delhi, India.

DPCC, 2023. Real-Time Advanced Air Source Management Network (R-AASMAN). Delhi Pollution Control Committee, Government of Delhi, New Delhi, India. http://raasman.com. (Accessed 23 February 2023). accessed on.

Ganguly, T., Selvaraj, K.L., Guttikunda, S.K., 2020. National Clean Air Programme (NCAP) for Indian cities: review and outlook of clean air action plans. Atmos. Environ. X 8, 100096.

Guttikunda, S., Ka, N., 2022. Evolution of India's PM2.5 pollution between 1998 and 2020 using global reanalysis fields coupled with satellite observations and fuel consumption patterns. Environ. Sci. J. Integr. Environ. Res.: Atmosphere. 2022 (2), 1502–1515.

Guttikunda, S.K., Calori, G., 2013. A GIS based emissions inventory at 1 km × 1 km spatial resolution for air pollution analysis in Delhi, India. Atmos. Environ. 67, 101–111.

Guttikunda, S.K., Dammalapati, S.K., Pradhan, G., Krishna, B., Jethwa, H.T., Jawahar, P., 2023. What is polluting Delhi's air? A review from 1990 to 2022. Sustainability 15, 4209.

Guttikunda, S.K., Goel, R., Mohan, D., Tiwari, G., Gadepalli, R., 2014a. Particulate and gaseous emissions in two coastal cities—Chennai and Vishakhapatnam, India. Air Qual. Atmosph. Health 8, 559–572.

Guttikunda, S.K., Goel, R., Pant, P., 2014b. Nature of air pollution, emission sources, and management in the Indian cities. Atmos. Environ. 95, 501–510.

Guttikunda, S.K., Nishadh, K.A., Gota, S., Singh, P., Chanda, A., Jawahar, P., Asundi, J., 2019a. Air quality, emissions, and source contributions analysis for the Greater Bengaluru region of India. Atmos. Pollut. Res. 10, 941–953.

Guttikunda, S.K., Nishadh, K.A., Jawahar, P., 2019b. Air pollution knowledge assessments (APnA) for 20 Indian cities. Urban Clim. 27, 124–141.

Harish, S., Smith, K.R. (Eds.), 2019. Ujjwala 2.0: from Access to Sustained Usage, Policy Brief No. CCAPC/2019/03. Collaborative Clean Air Policy Centre, New Delhi, India.

HEI, 2022. State of Global Air (SOGA). A Special Report on Global Exposure to Air Pollution and its Health Impacts. Health Effects Institute, Boston, USA.

Johnson, T.M., Guttikunda, S.K., Wells, G., Bond, T., Russell, A., West, J., Watson, J., 2011. Tools for Improving Air Quality Management. A Review of Top-Down Source Apportiontment Techniques and Their Application in Developing Countries. ESMAP Publication Series, The World Bank, Washington DC, USA.

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., Iredell, M., Saha, S., White, G., Woollen, J., Zhu, Y., Leetmaa, A., Reynolds, R., Chelliah, M., Ebisuzaki, W., Higgins, W., Janowiak, J., Mo, K.C., Ropelewski, C., Wang, J., Jenne, R., Joseph, D., 1996. The NCEP/NCAR 40-year reanalysis project. Bull. Am. Meteorol. Soc. 77, 437–471.

Mani, S., Jain, A., Tripathi, S., Gould, C.F., 2020. The drivers of sustained use of liquified petroleum gas in India. Nat. Energy 5, 450–457.

McDuffie, E.E., Martin, R.V., Spadaro, J.V., Burnett, R., Smith, S.J., O'Rourke, P., Hammer, M.S., van Donkelaar, A., Bindle, L., Shah, V., Jaeglé, L., Luo, G., Yu, F., Adeniran, J.A., Lin, J., Brauer, M., 2021. Source sector and fuel contributions to ambient PM2.5 and attributable mortality across multiple spatial scales. Nat. Commun. 12, 3594.

Pant, P., Harrison, R.M., 2012. Critical Review of Receptor Modelling for Particulate Matter: A Case Study of India. Atmospheric Environment.

Pant, P., Lal, R.M., Guttikunda, S.K., Russell, A.G., Nagpure, A.S., Ramaswami, A., Peltier, R.E., 2018. Monitoring particulate matter in India: recent trends and future outlook. Air Qual. Atmosph. Health 12, 45–58.

Pant, P., Shukla, A., Kohl, S.D., Chow, J.C., Watson, J.G., Harrison, R.M., 2015. Characterization of ambient PM2.5 at a pollution hotspot in New Delhi, India and inference of sources. Atmos. Environ. 109, 178–189.

Peltier, R.E., Castell, N., Clements, A.L., Dye, T., Hüglin, C., Kroll, J.H., Lung, S.-C.C., Ning, Z., Parsons, M., Penza, M., 2021. An Update on Low-Cost Sensors for the Measurement of Atmospheric Composition, December 2020. World Meteorological Organization.

Pesaresi, M., Ehrilch, D., Florczyk, A.J., Freire, S., Julea, A., Kemper, T., Soille, P., Syrris, V., 2015. GHS Built-Up Grid, Derived from Landsat, Multitemporal. In: European Commission, Joint Research Centre, JRC Data Catalogue, 1975, 1990, 2000, 2014.

Robinson, E.S., Shah, R.U., Messier, K., Gu, P., Li, H.Z., Apte, J.S., Robinson, A.L., Presto, A.A., 2019. Land-use regression modeling of source-resolved fine particulate matter components from mobile sampling. Environ. Sci. Technol. 53, 8925–8937.

Rose, A.N., McKee, J.J., Urban, M.L., Bright, E.A., Sims, K.M., 2019. LandScan 2018. Oak Ridge National Laboratory, Oak Ridge, TN, p. 2018.

Tiwari, S., Srivastava, A.K., Bisht, D.S., Safai, P.D., Parmita, P., 2013. Assessment of carbonaceous aerosol over Delhi in the Indo-Gangetic Basin: characterization, sources and temporal variability. Nat. Hazards 65, 1745–1764.

UEinfo, 2019. Air Pollution Knowledge Assessments (APnA) City Program Covering 50 Airsheds and 60 Cities in India. https://www.urbanemissions.info.

van Donkelaar, A., Hammer, M.S., Bindle, L., Brauer, M., Brook, J.R., Garay, M.J., Hsu, N.C., Kalashnikova, O.V., Kahn, R.A., Lee, C., Levy, R.C., Lyapustin, A., Sayer, A.M., Martin, R.V., 2021. Monthly global estimates of fine particulate matter and their uncertainty. Environ. Sci. Technol. 55, 15287–15300.

Watson, J.G., 1984. Overview of receptor model principles. J. Air Pollut. Control Assoc. 34, 619–623.

Yadav, S., Tripathi, S.N., Rupakheti, M., 2022. Current status of source apportionment of ambient aerosols in India. Atmos. Environ. 274, 118987.

Zheng, T., Bergin, M.H., Johnson, K.K., Tripathi, S.N., Shirodkar, S., Landis, M.S., Sutaria, R., Carlson, D.E., 2018. Field evaluation of low-cost particulate matter sensors in high- and low-concentration environments. Atmos. Meas. Tech. 11, 4823–4846.