FACTSHEET

AIR QUALITY MONITORING: ADDRESSING DATA SHADOW REGIONS

Only 15 per cent of India's population lives within 10 km of a real-time monitor, leaving 120 crore people in data shadow. Over 64 per cent of districts lack monitoring networks, including 261 districts with populations of over a million . Even in megacities, 22–55 per cent of urban areas lack monitoring coverage.

1. EMERGING AGENDA FOR THE AIR QUALITY MONITORING

The National Clean Air Programme (NCAP) was launched in 2019 with a goal to reduce particulate matter pollution by 20-30 per cent by 2024 and by 40 per cent by 2026. This is a critical step forward to ensure verifiable and measurable improvement in air quality in a timebound manner to have an effective national air quality management system and multi-sector action.

However, central to this strategy is a robust air quality monitoring network to generate credible and reliable data to help track the status of air quality over time, map population exposures, asses the level of non-attainment with respect to the National Ambient Air Quality Standards (NAAQS), the impact of action on air quality to inform the policy action, reduce exposures and verify compliance with the air quality target.

There are no universal design standards for monitoring network to have an absolute idea about the adequacy of the monitoring grid. This varies across countries as the monitoring objectives and capacity vary widely. The governments adopt a broad framework with a varying set of criteria. The criteria are governed by a range of considerations – where the most people live, pollutants they are exposed to, pollutants of concern, pollution challenges in different land-uses, patterns of exposure in the micro environment, and the need for a daily public alert system.

Criteria for establishing monitoring stations: In India too, the Central Pollution Control Board (CPCB), the apex air quality monitoring agency, has adopted population based criteria for designing the monitoring grid. It has specified the number of monitoring stations needed as per different population sizes and land-uses (residential areas, traffic hotspots, industrial areas, urban background sites) to monitor the criteria pollutants for which the NAAQS have been notified. Thus, it selects monitoring sites based on population thresholds, land use patterns, proximity to major pollution sources, and representativeness of urban exposure. Even though the monitoring criteria does not distinguish between rural or urban areas, in practice the network expansion has taken place largely in the urban landscape. Organised rural monitoring is yet to take off. Manual monitoring is implemented under the National Ambient Air Quality Monitoring Programme (NAMP) and real time monitoring under the Continuous Ambient Air Quality Monitoring Stations (CAAQMS).[1]

STATUS OF AIR QUALITY MONITORING IN INDIA

India's air quality monitoring journey began in 1984-85 with the launch of the National Air Quality Monitoring Programme (NAMP) by the Central Pollution Control Board (CPCB). Since then, the network has grown considerably, encompassing over 966 manual monitoring stations as of November 2024 and 562 Continuous Ambient Air Quality Monitoring Stations (CAAQMS) as of May 2025, of which 468 are currently operational.

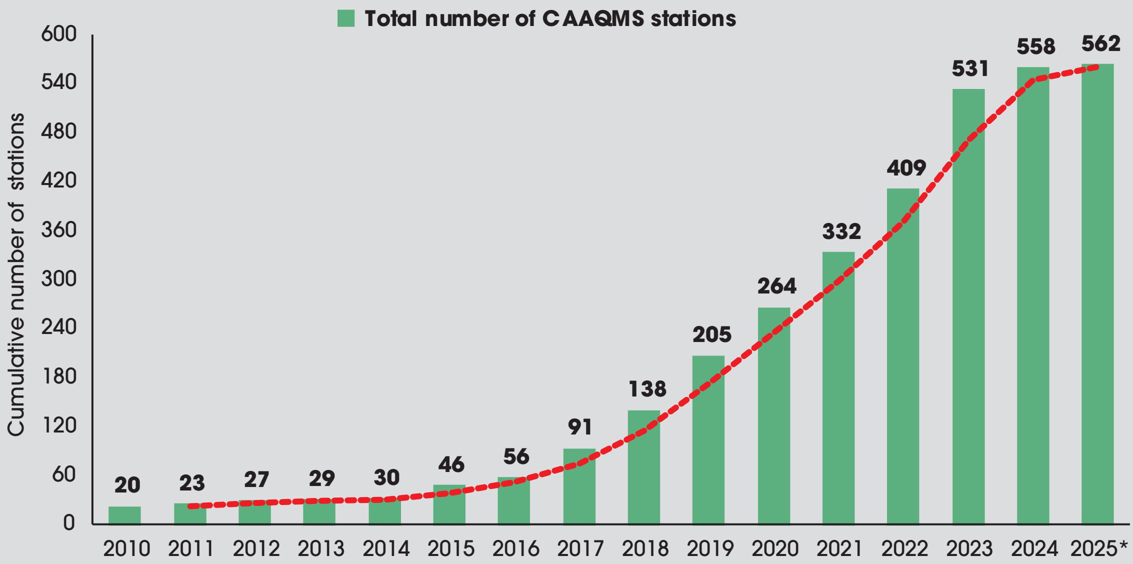
With this expansion, India now operates more than half of the total government-run monitoring stations across Central and South Asia—placing the country at the forefront of regional air quality surveillance.[2]

Expansion of Real-Time Air Quality Monitoring in India: As of 1st May 2025, India has established 562 real-time Continuous Ambient Air Quality Monitoring Stations (CAAQMS) across 294 cities and towns, spanning 27 states and 5 Union Territories. This marks a more than 25-fold increase since 2010, reflecting a significant scale-up in the country's air quality monitoring infrastructure.

The growth has been especially notable in recent years. In 2023 alone, 122 new stations were added, followed by 27 more in 2024, and an additional 4 new stations in early 2025. While this expansion marks significant progress, it is important to note that the official station count includes dysfunctional or inactive monitors, which complicates the assessment of how many stations are actually operational and consistently reporting data. *(See Graph 1: Growth in real time (CAAQMS) stations 2010-2025).*

Real-time air quality monitors operate continuously, recording data at hourly or even minute-level intervals. This high temporal resolution provides critical insights into pollution variability throughout the day, enabling the identification of exposure patterns, diurnal peaks,

GRAPH 1: GROWTH IN REAL TIME (CAAQMS) STATIONS 2010-2025

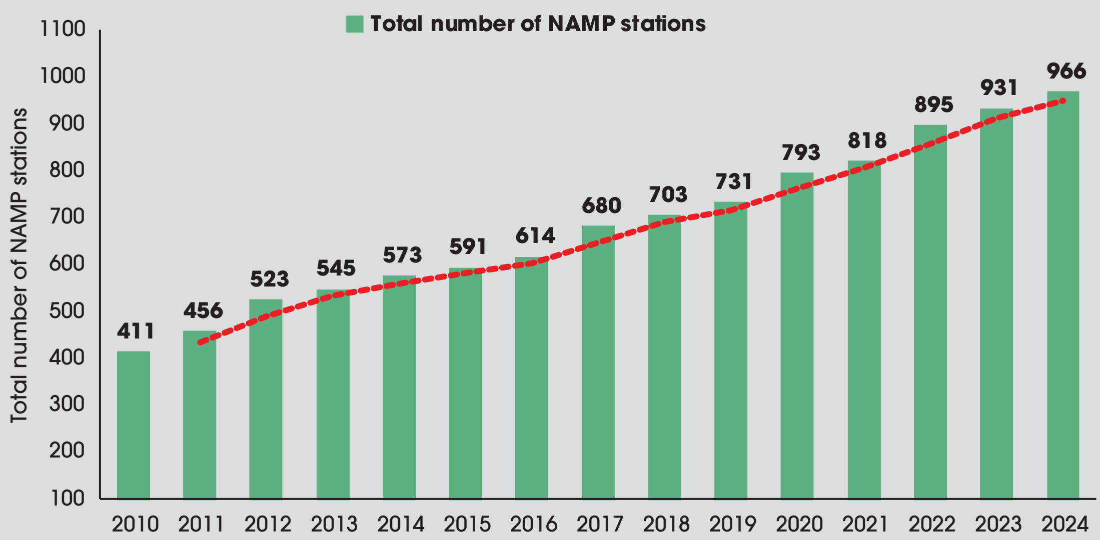


Source: World Bank International Debt Statistics and pollution episodes—particularly in densely populated or traffic-congested areas. Real-time monitors, with their continuous and consistent data output, provide a far more reliable spatial reference for identifying coverage gaps particularly for highly variable pollutants like PM2.5, which are sensitive to local traffic, meteorological changes, and emission hotspots. Their fixed locations and high-frequency measurements make them ideal for assessing real-time exposure and pollution dynamics across urban landscapes.

Growth in Manual Air Quality Monitoring Network: In parallel with the rise in real-time monitoring infrastructure, India's manual air quality monitoring network has more than doubled since 2010. According to the Central Pollution Control Board (CPCB), as of 19 November 2024, there are 966 operational manual monitoring stations across 419 cities and towns, spanning 28 states and 7 Union Territories.

As reported in the CPCB's Annual Report 2022–23, there were 910 functioning manual stations covering 389 cities and towns across 28 States and 7 UTs during 2022–23. In the 2023–24 period alone, approximately 56 new manual stations were added, extending the network to 30 additional cities. *(See Graph 2: Growth in manual (NAMP) stations 2010-2024).* Manual monitoring stations typically collect 24-hour average samples only twice a week on consecutive days, which limits their ability to capture short-term fluctuations and rapidly changing pollution dynamics. Manual monitors, which collect data only intermittently, lack both the temporal depth and spatial granularity required for precise gap analysis. By serving as stable spatial anchors, real-time monitoring stations allow for accurate and consistent mapping of underserved areas, helping to pinpoint population clusters that fall outside the effective reach of current monitoring networks.

GRAPH 2: GROWTH IN MANUAL (NAMP) STATIONS 2010-2024



Source: CSE analysis of CPCB data

As the NCAP programme has integrated the performance linked funding for air quality management under the 15th Finance Commission Grant that means cities can access funds for clean air action only after demonstrating improvement in particulate pollution – the focus on regulatory monitoring has deepened. The non-attainment cities have to report verifiable changes in air quality to access the grant and also to qualify for the Swachh Vayu Sarvekshan for ranking. This is not possible without local data. Since the launch of the NCAP programme in 2019, monitoring network has expanded considerably. The real time continuous monitors have increased 2.74 times, and manual monitors have increased 1.32 times. This expansion also includes the investments that the state governments have made outside the orbit of the NCAP funding to add new monitors. *(see BOX: Status of air quality monitoring in India).*

The monitoring focus is on monitoring of the criteria pollutants for which the NAAQS have been adopted. In practice, the key focus is on the particulate (PM2.5 and PM10), nitrogen dioxide (NO_2) and Sulphur dioxide (SO_2) and on a limited scale ozone and carbon monoxide. Of the 12 pollutants for which NAAQS have been notified, not all have been taken up for regular monitoring everywhere. Some of these include benzene, arsenic, ammonia etc.

What to monitor? It is understood from the global experience as well as the national experience, that not all pollutants get equal priority. The design and expansion of the monitoring network density usually recognize the gravity of health risks from different pollutants and their dominant contribution to the air quality. This is because the relative importance of different pollutants changes over time due to changes in economic activities, changing mix of pollution sources, new scientific information on health impacts of pollutants, and impact of air pollution control efforts on specific pollutants. The monitoring grid design is changed to reflect that. While monitoring capacity is limited for some pollutants, it is expanded for others to better reflect changing risk levels. For instance, in India, the monitoring of total suspended particulate matter (TSPM) was discontinued in 2009 when NAAQS were revised and the focus shifted towards tightening of the standards for tinier and more harmful PM10 and PM2.5. The NAAQS is undergoing the next round of revision currently. That is may indicate further changes in the grid.

This is consistent with what has been noticed in the western countries. The monitoring of NO^2, ozone and particulates have drawn considerable attention for ambient monitoring. But Sulphur di-oxide (SO_2) and air borne lead, which dominated the older grid design, have now reduced in significance as their concentration in the ambient level have reduced significantly. Their monitoring is confined to the more relevant industrial areas/sources and thermal power plants. Thus, the focus on priority pollutants will require continuous evaluation for future expansion of monitoring.

Address data gaps: Yet another challenge is to ensure credible and high quality data for all kinds of compliance requirements. This has to ensure there are no data gaps, there are not too many outliers and anomalous data etc. The current monitoring network faces the challenge of inadequate data generation, lack of data completeness and poor quality control of monitoring. This makes air quality trend assessment difficult to establish compliance with clean air targets. Credible and consistent data are needed to meet the legal method of compliance as defined by the CPCB. For instance, for the short-term daily standard, CPCB allows exceedances on up to 2 per cent of the days in a year, which means that concentrations may cross the 24-hour limit on roughly 7 days per year without being classified as non-compliant.[3] This demands consistent generation of quality data to establish compliance. For instance, the regulations in the USA require that the data submitted to the US Environmental Protection Agency (EPA) through the Air Quality System are complete and consistent across time, with strict quality assurance and quality control checks applied. Once validated, these data are aggregated across years to evaluate long-term patterns.

Refine the standardized methods for air quality assessment: There is yet another challenge that the monitoring expansion will have to consider – that is adoption of standardized data analytic method for reporting compliance. As air quality management is becoming more performance based, the performance indicators for air quality performance will require well defined scientific methods for estimating short term and long terms air quality trends, standardized calculation of time averaging of the data (24 hours, 8 hours, annual) for different pollutants, among others. The CPCB has already established a protocol for usage of data from the manual monitors for estimating time averaging values for each pollutant and the minimum data requirement (eg. at least two days per week etc). However, such detailed protocol has not been established for the continuous real time monitoring for longer term trend analysis and data validation process. Real time data is primarily used for issuing daily alert based on the national air quality index and 24 hours averaging without adequate data cleaning techniques.

This will have to be addressed immediately, as the cities that are expanding their monitoring grid and including more continuous monitoring stations need this protocol. In fact, cities have begun to report their compliance with the NCAP air quality targets by combining data from both manual and real time monitors without a standardize protocol which is also not scientific. There is no established uniform protocol for data analytics for reporting air quality trends (both short and long term) based on real time data to establish compliance with the air quality targets under the NCAP. This makes trend reporting highly variable and not comparable.

Furthermore, it is also necessary to define the method of estimating the air quality trends to establish compliance with the air quality targets under the NCAP. India currently evaluates compliance on a single-year basis. This involves year-to-year comparisons of annual averages and seasonal analysis, often presented in NAMP and CPCB's annual report. Manual monitoring stations operating under NAMP provide 104 observations annually (two 24-hour samples per week), which are averaged to calculate annual and seasonal values. Continuous Ambient Air Quality Monitoring Stations (CAAQMS), introduced more recently, allow for higher-resolution analysis and real-time reporting through the National Air Quality Index. However, long-term trend reporting in India remains largely descriptive, focusing on annual averages without the statistical stability provided by rolling averages.

This approach makes the system more sensitive to annual variability for example, a single year of high levels due to unusual weather patterns, crop-residue burning, or episodic firework activity may categorize a location as non-compliant, even if the long-term trend is more stable. Conversely, one relatively clean year could mask longer-term exposure risks. In other words, the absence of a multi-year averaging mechanism weakens the robustness of compliance determination. Thus, along with the annual estimation, also co-join and adopt rolling averages.

For instance, by relying on a multi-year average, the US Environmental Protection Agency (EPA) ensures that compliance determinations reflect sustained air quality conditions rather than isolated peaks or unusual years. The monitor with the highest design value in a given area is used as the "design value monitor," and that value becomes the basis for determining the area's attainment status. Trend analysis is performed by comparing successive design values across three-year periods, which allows EPA to track whether air quality is improving, declining, or remaining stable in a given area. This rolling three-year approach smooths out year-to-year variability from weather or short-term events and provides a more robust signal of whether regulatory and policy interventions are effective. In addition, trend reporting ensures that progress can be tracked consistently across the country, allowing comparisons between regions and identifying where air quality improvements are lagging. Thus, three-year averages are used to smooth out anomalies and compliance decisions are explicitly tied to population centers and vulnerable groups (via census-based designations such as Metropolitan Statistical Areas and Core-Based Statistical Areas).

To improve robustness and comparability, it is necessary to focus on a multi-year compliance averaging system to reduce the effect of anomalies and ensure consistency in trend assessment in addition to the annual tracking. Incorporate population and exposure-based siting criteria, especially for vulnerable groups (children, elderly, low-income communities). Standardize trend reporting through rolling averages and percentile-based indicators, rather than relying only on annual means. Combining population and exposure-based considerations with traditional population thresholds would improve monitoring representativeness and public health protection.

Rationalizing monitors for compliance reporting and for proper representations of different exposures and land-uses: Yet another area that requires some attention is to have guidance on the selection of monitors that will be considered for reporting trends for compliance with the clean air targets and impact of action. There is no clear strategy for identifying the monitors to be used for compliance purpose, or to assess the background level. Currently, irrespective of the number of monitors in a city – that may vary widely between three stations in one city to 40 in another – the cities average out the data from all stations without paying adequate attention to the siting of the monitors. There is no explicit rule on the representations of the stations. For instance, under the U.S. regulatory framework, compliance with the NAAQS is guided by the procedures outlined in 40 CFR Part 58, which establishes the requirements for air quality monitoring networks. These provisions define how monitoring stations are located, how their data are used to assess attainment or non-attainment, and how trends are reported over time.[4]

The USEPA requires that monitors be located according to population exposure, emission source impact, background levels, and regional transport considerations. For example, monitors may be placed near roadways to capture traffic-related exposure, or in residential and urban background locations to represent the air quality experienced by the general population. The siting is informed by Census Bureau designations such as Metropolitan Statistical Areas, Core-Based Statistical Areas, and Combined Statistical Areas, which help USEPA align monitoring with real population centers. The regulations do not use a "buffering" method in the sense of drawing fixed-radius coverage around monitors; instead, they require networks to be distributed in such a way that they provide adequate spatial representation of exposure for the population within these urban and regional statistical areas. For compliance assessment, USEPA designates certain monitors within each network as regulatory monitors. Data from these stations are collected, validated, and then used to calculate design values for each pollutant. Continued monitoring is required to ensure pollution levels remain within limits.

Monitoring grid needs to address vulnerable population: Equally important is the need to protect vulnerable groups such as children, the elderly, and residents of low-income or high-exposure neighborhoods who are more susceptible to the adverse health impacts of air pollution. Therefore, station siting should be risk- and exposure-driven, ensuring that the locations selected truly reflect areas where people are most affected and where pollution levels are likely to be highest, rather than relying solely on population density as a criterion. In India, population exposure is considered mainly through population thresholds for siting[5], but compliance and trends are not directly weighted by vulnerable population exposure.

1.1 ADDRESSING DATA SHADOW AREAS

As India is moving towards performance linked funding as well as a compliance framework that requires verifiable improvement in air quality over time while facing the need to reduce exposures for a vast population that are not within the ambit of monitoring, it is necessary to think through the monitoring strategy to address this challenge. Currently, the monitoring grid is not adequate to capture the country-wise population exposures.

It therefore becomes necessary to understand the regions where real-time, reliable air quality information is unavailable, inconsistent, or technically compromised. The pollution levels in these areas go unmeasured and therefore unaddressed, which can have health and environmental consequences that may be underestimated or overlooked. In such areas monitoring infrastructure is limited or is uneven.

Currently, the monitoring stations are largely clustered in metropolitan centers or sparse distributed in industrial zones, peri-urban belts, and along key transport corridors. Also, even where stations are installed, technical issues, wrong sighting, poor calibration, and gaps in real-time data generation and integration can render the measurements non- reproducible, inconsistent or unusable. Furthermore, financial and administrative challenges hinder the expansion, maintenance, and central integration of monitoring data into national policies.

As a result, a large part of the population—especially in underdeveloped or emerging urban regions and rural and suburban areas—remain "invisible" to national air quality assessments. Only a limited amount of data is available on air pollution trends in many cities, and there is a significant gap in our understanding of spatio-temporal patterns of air pollutants at the local, regional, and national level, which is hampered by data shadows- the areas without any real-time monitoring. Yet reliable data is needed to meet the needs of the highly exposed groups across all regions while also generating data in the controlled areas.

While building the case for credible and reliable data across population groups to assess exposures and inform policies, it is also important to be mindful of the fact that it is also not feasible and affordable to create high density regulatory monitoring network across the vast national population base. Given the cost of each continuous real time monitor – that can exceed Rs 1-3 crore, – it can be quite prohibitive.

While action can always roll even without local data in all regions – as enough is known about the harmful impacts of air pollution and the multi-sector solutions are well understood, – local exposure measurements help to calibrate the action to reduce exposures. This is the reason why globally, hybrid and multi-dimensional monitoring system has begun to emerge to address this problem.

1.2 TOWARDS MULTI-DIMENSIONAL AIR QUALITY MONITORING

Globally, efforts are being made to adopt a multidimensional monitoring system to leverage not only the regulatory monitoring but also to leverage the alternative monitoring methods including high density sensor network that can be deployed across vulnerable population groups for community scale exposure assessment and also the top down satellite based mapping of pollution to complement the regulatory monitoring.

This approach calls for a more rationalized distribution of monitors to ensure representativeness, along with the affordable deployment of new-generation technologies to address data gaps in exposure assessment. This, in turn, requires the integration of a hybrid monitoring framework—combining standardized and certified air sensor networks with satellite-based monitoring under appropriate protocols to achieve maximum and cost-effective population coverage in support of targeted action.

Countries are adopting such multi-dimensional air quality monitoring systems that is combining and layering regulatory monitors with high density sensor monitoring based monitoring networks and satellite based monitoring. In fact, some of the Chinese cities have three-dimensional monitoring that includes a regular monitoring network, a vertical observation network and a high-density sensor monitoring network.

India needs a similar framework for multi-dimensional air quality monitoring approaches. The CPCB needs to define the scope of its application of sensor based monitoring and satellite based assessment, quality control protocols for each data system, and Internet of Things (IoT).

For instance, satellite-derived aerosol products such as Aerosol Optical Depth (AOD) can serve as a proxy for ground-level pollution. Remote sensing techniques estimate pollution levels by analyzing AOD, which reflects the extent to which particles in the atmosphere absorb or scatter light.

Similarly, as regulators begin to adopt sensor-based monitoring, systems will have to be developed for validation of ground-level sensor-based data, compare and correlate data from regulatory monitors and sensor devices.

However, at this stage, the Central Pollution Control Board (CPCB), with respect to the sensor based monitoring, has issued an advisory to all State Pollution Control Board (SPCBs) in 2022.[6] This states that, air quality data generated by any technology (including low-cost sensors) other than the ones specified in the National Air Quality Standards, is not used for regulatory purposes as its accuracy, linearity, reliability and long-term performance are not yet fully established. Ministry of Environment, Forest and Climate Change (MoEF&CC) has constituted a committee for the development of a network of air quality monitoring to frame operational modalities, protocol and guidelines for air quality monitoring and also to optimize the CAAQM requirements.

It has further sought a pilot study for sensor evaluation to develop guidelines for air quality measurements. Until that time, data cannot be used for public information and Air Quality Index (AQI) generation. However, SPCBs can examine its use for other applications such as qualitative assessment of dust control measures at construction sites. Currently, thus, only those air quality measurement methods are allowed that have been notified under the National Ambient Air Quality Standards of 2009.[7] In light of this Bureau of Indian Standards (BIS) has set up a panel to define the system of certification of sensor-based low-cost monitoring devices.

It is however, important to note that the integration of satellite-based estimates and sensor based exposure assessment require reliable groundbased measurements for more accurate, precise, and complete information and to provide better understanding of local and regional air quality. The alternative systems cannot happen in exclusion of the regulatory monitors as these will be needed for network level calibration and prescribe a standard method. Also, using just sensor devices and satellite data may cause circular reference error, as even satellite data needs support of ground-level monitoring for validation. Thus, a strategically located network of regulatory-grade monitors is needed to support a denser network of sensor devices.

It is also important for India to track the global development in leveraging alternative monitoring method to address data gaps, and also support citizen science and crowd-sourcing under their open government data initiatives. For instance, the US Congress enacted Crowdsourcing and Citizen Science Act in 2016 which encourages government agencies to make data collected through crowd-sourcing or citizen science projects available to the public. It obligates agencies to notify participants as to expected modes of use and dissemination of the data, and directs agencies to publicly promote citizen science initiatives to encourage broad participation. The UN Environment Programme (UNEP) is also working towards developing affordable air quality monitoring networks to create real-time air quality databanks and also integrate data from satellites, air quality reference monitors (where available), and measurements from sensor networks.[8]

Thus, multi-dimensional monitoring is critical to address the data shadow areas and exposures of a vast majority and the highly exposed groups for a strong air quality action.

1.3 SUMMARY NEXT STEPS

Against the backdrop of these emerging challenges with respect to air quality monitoring and data gaps, the Centre for Science and Environment (CSE) has carried out a simple and a straight forward assessment of a single parameter of geographic and population coverage to understand the extent to which the current network covers the population spread in the country. This brings out the under-monitored regions and population and quantifies both the geographic area and population falling within and outside the effective influence zones of existing CAAQMS. This buffer-based geospatial analysis using high-resolution population data and monitoring station locations simply highlights the vast population that is still outside the ambit of monitoring. While it is strongly reiterated that action does not await data, at the same time data on population exposures in vulnerable areas are critical to calibrate the action to reduce risks for the local population as well as to improve the regional air quality that impacts local pollution in cities.

This analysis has been carried out to highlight the need for not only further reforms needed in the regulatory monitoring systems to make it more robust and to enable credible performance linked air quality management and funding, but also to improve data generation for a larger population groups who are also highly exposed. Under the NCAP programme it is necessary to develop a multi-dimensional or hybrid monitoring system. Such a system will require several approaches:

i) This requires further reforms in the regulatory monitoring system to develop create protocols for further rationalization of the siting of the monitoring stations to be representative of the land-uses, regional background, hotspots among others that will be utilized compliance reporting. Define the methods for data analytics for real time data and data validation to establish long term and short term trend in air quality to report compliance with clean air targets – including data averaging method, annual and rolling averages, protocol for data completeness, etc.

ii) Establish the framework or multi-dimensional monitoring system to integrate satellite based pollution mapping of all data shadow areas as well as the areas under regulatory monitors and the sensor based monitoring network at a community scale to complement the regulatory monitoring. This is needed to refine the interventions, and reduce exposures for all groups of population that are vulnerable and face high exposures. This can help to bring a lot more granularity in air quality assessment to strengthen system while enable action at a regional scale .

iii) Define the framework for integration and interface of all these data bases to inform action. This will require an open data system that is accessible.

2. UNDERSTANDING DATA SHADOW AREAS

To understand the value of the multi-dimensional monitoring systems, the Centre for Science and Environment has carried out a focused analysis of the distribution of regulatory monitors to understand the nature of the data shadow areas.

While air quality monitoring strategies have several dimensions to consider including population coverage, exposure assessment, representativeness of land-use, pollution hotspots, capability of monitoring different pollutants, and data quality, among others, this factsheet has focused on a single parameter of coverage. To what extent the current network covers the population spread in the country? This aims to understand the under-monitored regions and population. This approach aims to quantify both the geographic area and population falling within and outside the effective influence zones of existing continuous ambient air quality monitoring stations (CAAQMS). This is a buffer-based geospatial analysis conducted using high-resolution population data and monitoring station locations.

This concept of buffer zones is used to represent the extent to which a monitoring station can reliably indicate surrounding air quality. Based on international best practices and scientific studies, buffer distances of 2 km, 3 km, 5 km, and 10 km were selected to reflect different scales of representativeness.[9]

For population estimation, the analysis relied on the Gridded Population of the World, Version 4, Revision 11 (GPWv4.11), developed by the Socioeconomic Data and Applications Center (SEDAC). This raster dataset provides spatially explicit population data at a 100-meter resolution for the year 2020, enabling a granular and geographically consistent assessment of population distribution across India. Its fine scale allows for precise quantification of the population residing within each buffer zone.

In major metropolitan areas such as Delhi, Mumbai, and Bengaluru, where stations are often located close to one another, buffer zones tend to overlap significantly. To avoid overestimation of coverage due to this overlap, all buffer zones were first merged into a single, unified polygon layer. This ensured that overlapping areas were not double-counted when calculating the total population and area covered. The remaining unbuffered portions—representing the data shadow zones—were derived by subtracting the unified coverage area from the total geographic extent of the city or state.

All spatial analysis and raster operations were carried out using ArcGIS. It is important to note that exact coordinates of monitoring stations are not publicly available; hence, approximated locations were used based on available metadata. Moreover, the population data used reflects the 2020 estimates and may not fully account for rapid population shifts in peri-urban areas post-COVID. Nevertheless, this method offers a robust and scalable framework for evaluating spatial coverage, estimating unmonitored populations, and guiding decisions on network expansion priorities.

However, investment constraints are a persistent reality. Thus, monitoring expansion should not only be based on buffer outcomes but also on spatial distribution of pollution, health burden, vulnerability of communities, and availability of supportive infrastructure. In high-priority zones like the Indo-Gangetic Plain, even low-cost sensor networks and mobile monitoring vans can provide much-needed granularity and fill short-term gaps until permanent stations can be installed. While regular network audits—merging or relocating redundant stations will ensure resources focus on emerging pollution hotspots.

While the gaps in monitoring infrastructure across India are evident, quantifying the extent of these data shadows requires a systematic spatial analysis. To understand how much of the population and area fall outside the influence of real-time air quality monitors, and to identify priority areas for network expansion, this study applies a buffer-based geospatial approach.

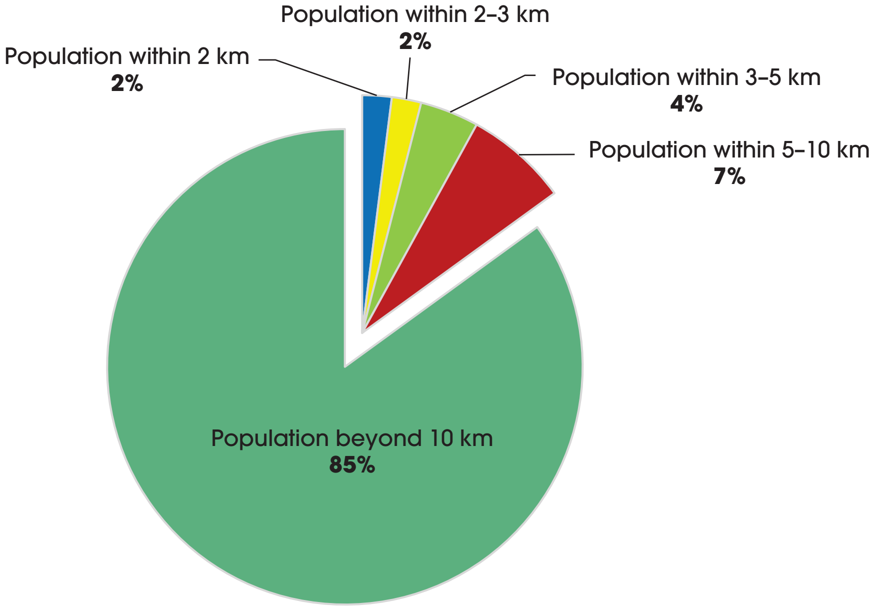
3. THE KEY FINDINGS

3.1. THE NATIONAL MONITORING LANDSCAPE AND GAPS

India's real-time ambient air quality monitoring network provides limited population and geographical coverage, leaving a vast majority of people and regions in data shadow. Analysis shows that only 15 percent of India's population lives within a 10 km radius of a real-time monitoring station, while an overwhelming 85 percent, about 120 crore people remain outside this network and thus lack timely access to AQI-based health alerts *(see Graph 3: Population coverage of real-time ambient air quality network (CAAQMS) for 2024-25).*

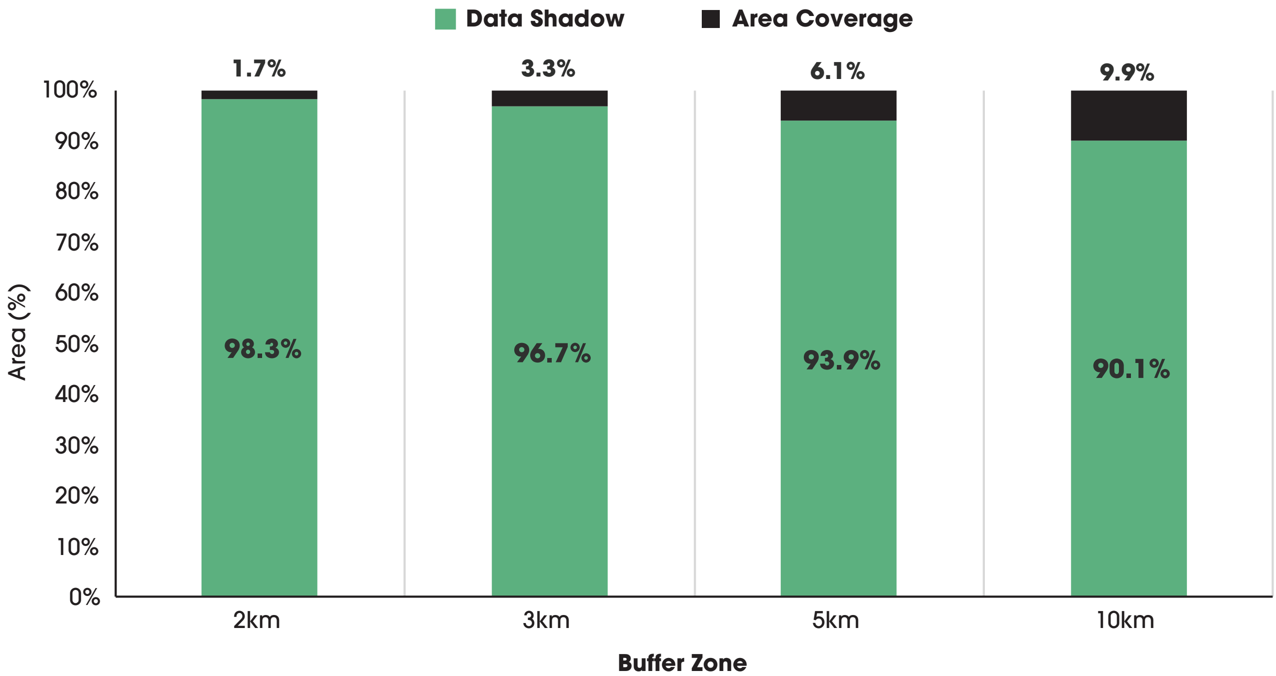
Population distribution within different buffer zones highlights the steep drop in coverage at finer spatial scales: Only about 2 percent of people live within 2 km of a monitoring station, another 2 percent within 2–3 km, around 4 percent within 3–5 km, and just 7 percent within 5–10 km of monitoring site. The geographical reach of the network is even more restricted. Within the closest 2 km buffer, monitoring stations cover barely 1.7 percent of India's land area, leaving 98.3 percent unmonitored. Coverage expands only slightly with distance—3.3 percent within 3 km, 6.1 percent within 5 km, and at the widest 10 km buffer, just 9.9 percent of the country's area is covered. In other words, even under the broadest zone of influence, more than 90 percent of India's landmass remains outside the scope of real-time air quality monitoring *(see Graph 4: Data shadow and area coverage of real-time ambient air quality network for 2024-25).*

GRAPH 3: POPULATION COVERAGE OF REAL-TIME AMBIENT AIR QUALITY NETWORK (CAAQMS) FOR 2024-25



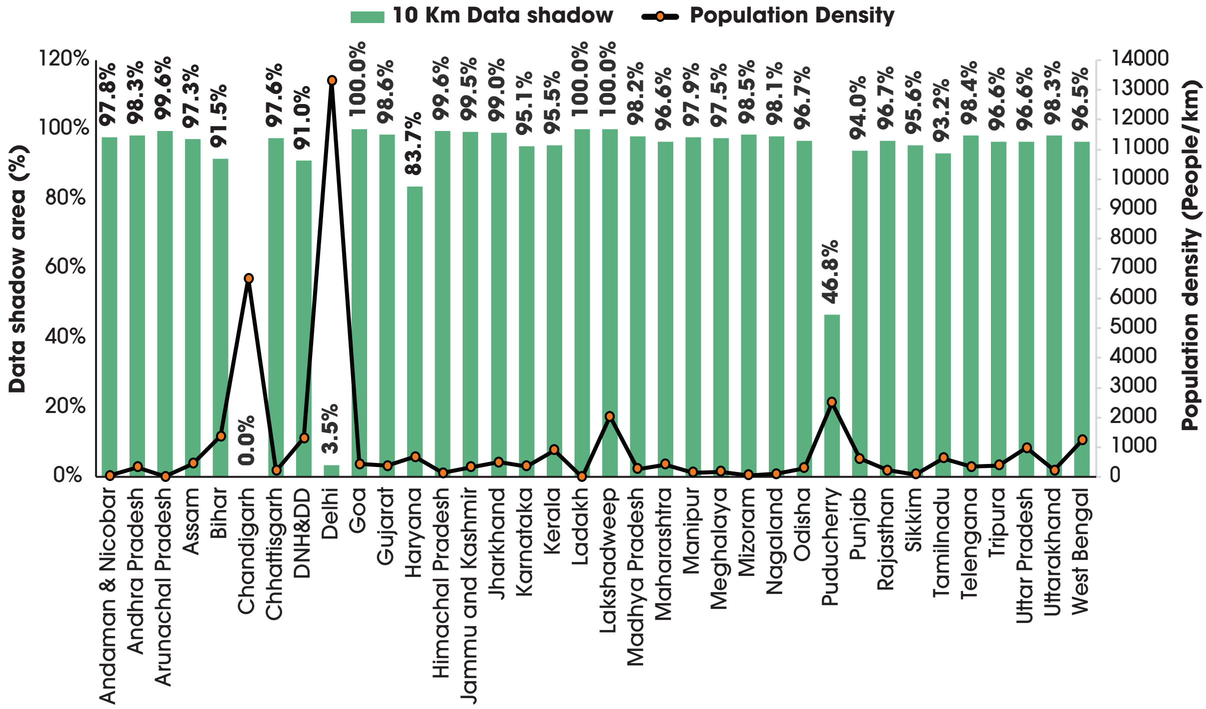
Note: Population estimates are based on the 100mx100m spatial distribution of population in 2020 developed by the by the Socioeconomic Data and Application Center (SEDAC) - Gridded Population of the World (GPW), version 4, revision 11 (GPWv411) for year 2020. Monitoring locations are approximation based on information available from CPCB website and publications, it is not exact geographical co-ordinate of the stations as that information is not publically available.
Source: CSE analysis

GRAPH 4: DATA SHADOW AND AREA COVERAGE OF REAL-TIME AMBIENT AIR QUALITY NETWORK FOR 2024-25



Source: CSE analysis

GRAPH 5: STATE-WISE DATA SHADOW AREA AND POPULATION DENSITY



Source: CSE analysis

3.2. STATE LEVEL MONITORING LANDSCAPE

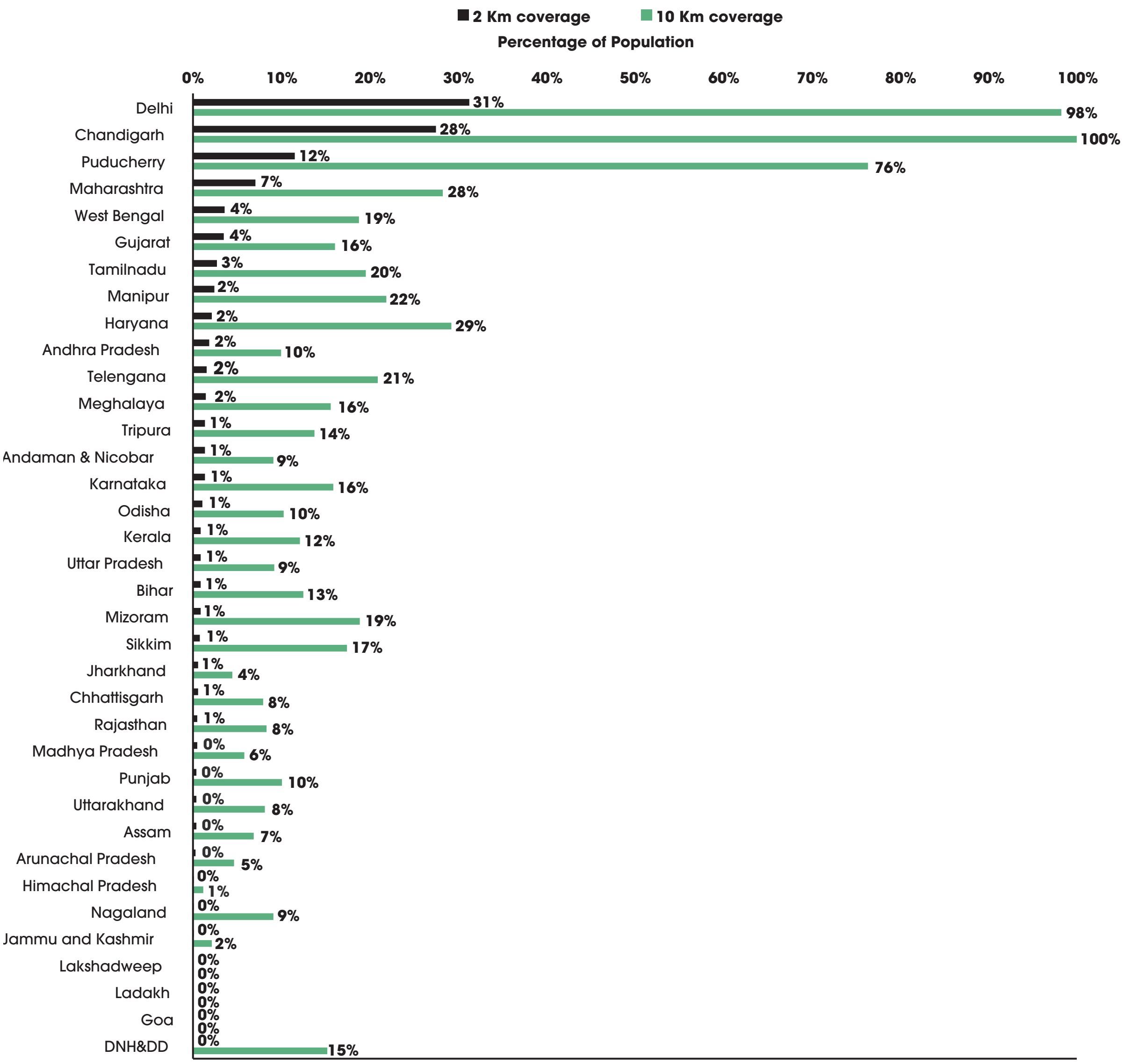
The state-level assessment further exposes the uneven and inadequate spread of real-time air quality monitoring network. While Chandigarh achieves complete coverage, with its entire population living within 10 km of a monitoring station, and Delhi follows closely with only 3.5 percent data shadow, the picture across most states and Union Territories is starkly different. Goa, Ladakh, and Lakshadweep have no real-time stations at all, leaving their populations in total data shadow.

Overall, 28 states and UTs record data shadow areas above 95 percent, meaning the overwhelming majority of their populations remain outside the effective monitoring zone. Puducherry performs relatively better, with 46.8 percent data shadow, but even here more than half of the population is left unmonitored. This contrast is particularly striking in states like Uttar Pradesh, West Bengal, and Kerala, where very high population densities coexist with data shadows exceeding 95 percent. Similarly, Haryana records an 83.7 percent gap despite being moderately populated, underscoring that monitor placement does not always align with where people live. Bihar, with 92 percent data shadow, also exemplifies how some of the most densely populated and vulnerable regions remain critically underserved *(see Graph 5: State-Wise Data Shadow Area and Population Density).*

When population coverage is examined, only a handful of regions stand out. Delhi and Chandigarh provide the most extensive access, with nearly their entire populations covered within 10 km. In Delhi, nearly one-third of residents (31 percent) live within 2 km of a station, reflecting its exceptionally dense monitoring grid. Puducherry also fares relatively better, with three-quarters of its population within 10 km, though only 12 percent live within 2 km of a monitor.

By contrast, in Maharashtra, West Bengal, Tamil Nadu, Haryana, Manipur, and Telangana, less than 10 percent of the population falls within 2 km

GRAPH 6: STATE-WISE POPULATION COVERAGE OF REAL-TIME AMBIENT AIR QUALITY NETWORK FOR 2024-25

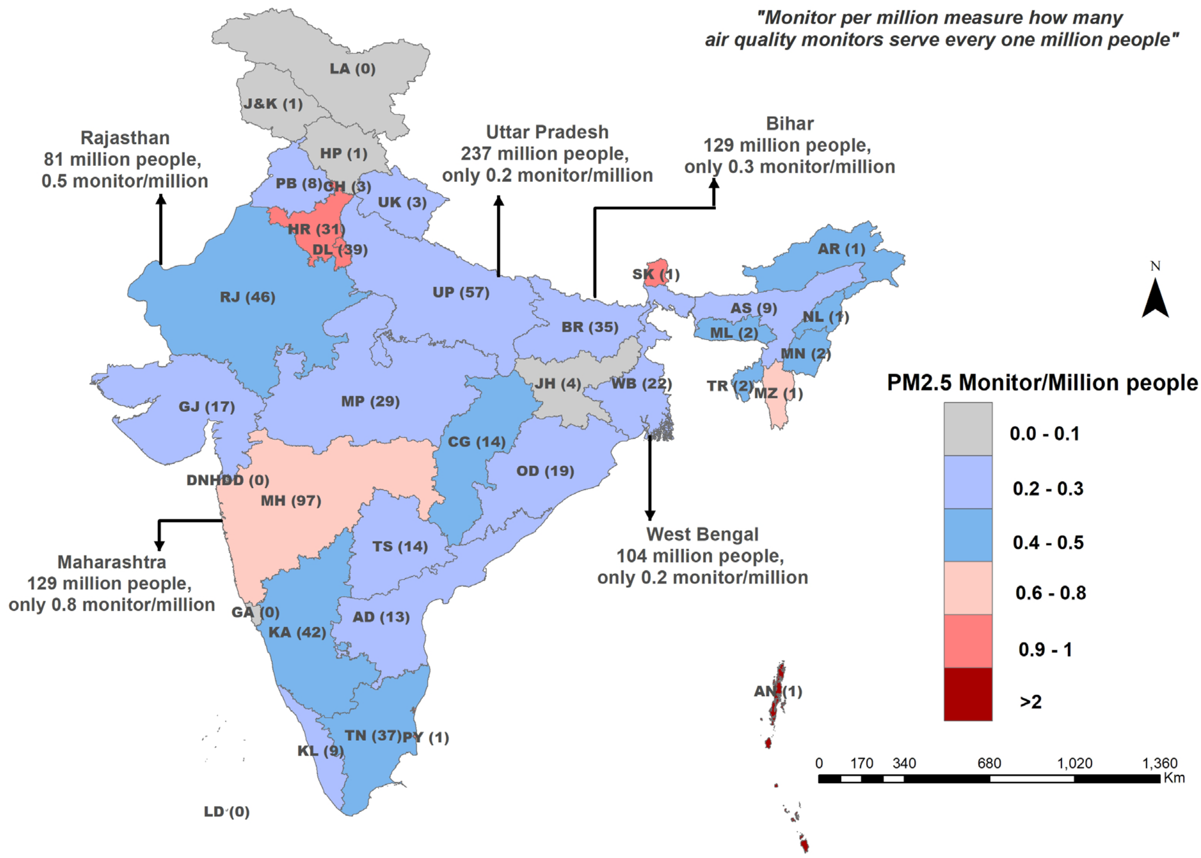


Source: CSE analysis

of a monitor, and only about 20–30 percent within 10 km, exposing the uneven reach of monitoring networks beyond metropolitan hubs. States like Arunachal Pradesh, Nagaland, Assam, Punjab, Madhya Pradesh, Himachal Pradesh, and Uttarakhand perform far worse, each covering less than 1 percent of their population within 2 km and under 10 percent within 10 km. Dadra & Nagar Haveli & Daman & Diu stands as a special case: while it lacks its own monitors, about 15 percent of its population benefits indirectly from proximity to the Vapi monitor in neighboring Gujarat *(see Graph 6: State-wise population coverage of real-time ambient air quality network for 2024-25).*

Monitor density underscores another dimension of inequity in air quality network. Chandigarh leads with 3.98 monitors per million people, followed by the Andaman & Nicobar Islands at 2.8 and Delhi at 1.99 reflecting robust neighborhood-level coverage despite their relatively small size. Mid-range

MAP 1: NUMBER OF REAL-TIME MONITORS PER MILLION POPULATION



Number within brackets represent number of real-time monitoring stations in particular state and UTs.

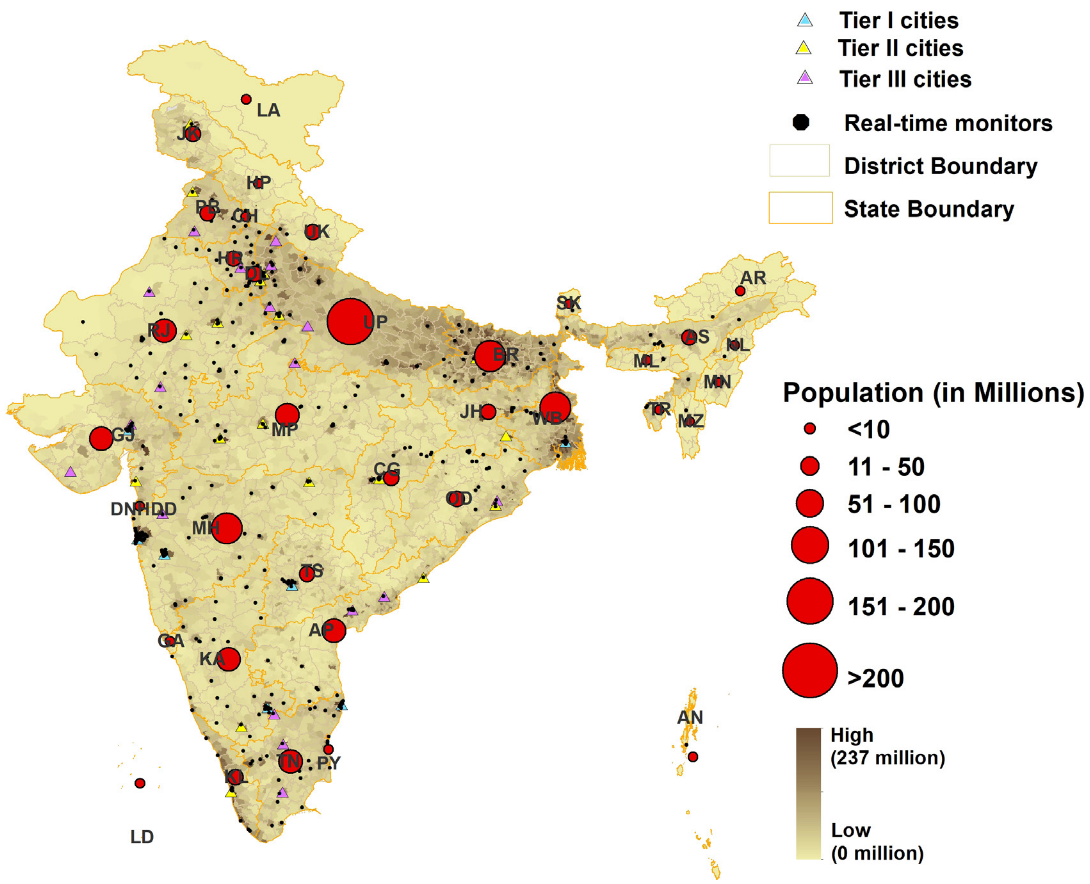
Note: Population estimates are based on the 100mx100m spatial distribution of population in 2020 developed by the by the Socioeconomic Data and Application Center (SEDAC) - Gridded Population of the World (GPW), version 4, revision 11 (GPWv411) for year 2020. Monitoring locations are approximation based on information available from CPCB website and publications, it is not exact geographical co-ordinate of the stations as that information is not publically available.
Source: CSE analysis

states such as Himachal Pradesh (1.08), Sikkim (0.95), and Haryana (0.69) provide moderate access, but in the majority of large, populous states the numbers fall well below one monitor per million inhabitants.

However, Uttar Pradesh, Maharashtra, Bihar, West Bengal, Madhya Pradesh, Tamil Nadu, Rajasthan, and Gujarat, together accounting for more than half of India's population, each operate fewer than one monitor per million residents, leaving millions without adequate surveillance. The worst-off are Lakshadweep, Goa, Ladakh, and Daman & Diu with Dadra & Nagar Haveli, which have no monitors at all, resulting in complete data shadows *(see Map 1: Number of real-time monitors per million population).*

The mismatch between monitoring presence and population distribution is most glaring in densely populated areas. Current CPCB norms prioritize cities with more than one million residents, as well as state capitals and

MAP 2: UNEVEN DISTRIBUTION OF MONITORING STATION IN DENSELY POPULATED AREAS



Note: Population estimates are based on the 100mx100m spatial distribution of population in 2020 developed by the by the Socioeconomic Data and Application Center (SEDAC) - Gridded Population of the World (GPW), version 4, revision 11 (GPWv411) for year 2020. Monitoring locations are approximation based on information available from CPCB website and publications, it is not exact geographical co-ordinate of the stations as that information is not publically available.
Source: CSE analysis

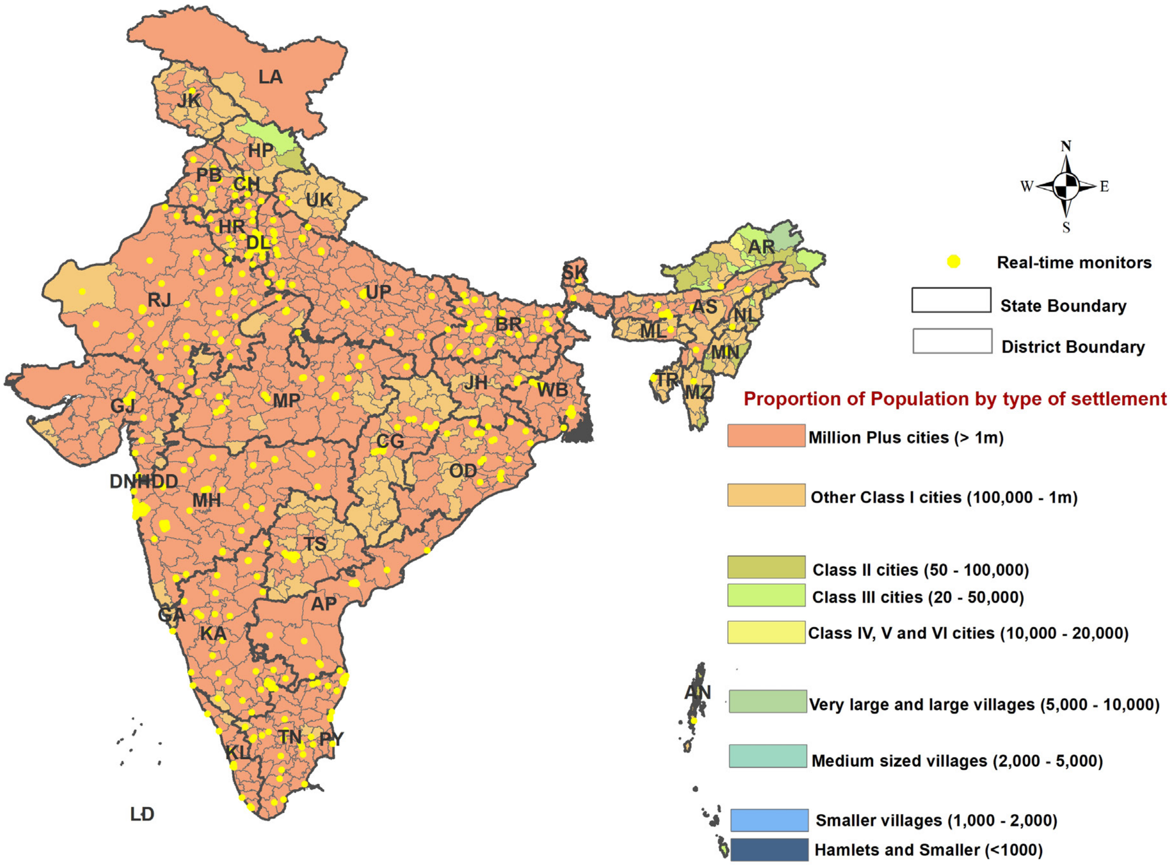
UT headquarters, for station placement.[10] While this ensures coverage in major metros, it leaves peri-urban, semi-urban, and Tier II/III districts largely unmonitored. For instance, Uttar Pradesh and Gujarat cluster their monitors around urban cores, leaving many high-density districts without any coverage. Assam's sparse monitoring network overlooks many of its most densely populated towns, while southern and eastern states such as Tamil Nadu, Telangana, Odisha, Jharkhand, Maharashtra, West Bengal, and Bihar show major gaps across peri-urban belts, despite having population densities comparable to those of major metros. Jammu & Kashmir and Himachal Pradesh, meanwhile, each operate just one station for their entire populations, leaving vast stretches of territory in data shadow *(see Map 2: Uneven distribution of monitoring station in densely populated areas).*

At the district level, the gaps are even more severe. More than 64 percent of India's districts have no real-time monitoring stations at all. Of the 742 districts, 261 with populations exceeding one million remain entirely unmonitored. This includes 148 districts with 1–2 million people, 61 with 2–3 million, 26 with 3–4 million, 18 with 4–5 million, and 5 districts hosting more than 5 million residents. Hugli, South 24 Parganas, and Murshidabad in West Bengal alone each house between 6–8 million people without a single real-time monitor, pointing to one of the most severe surveillance gaps in the country *(see Map 3: Monitoring Void in Million-Plus Districts).*

A population-to-monitor comparison against CPCB's own criteria makes this deficit even clearer. Uttar Pradesh, home to more than 237 million people, should theoretically operate around 391 real-time monitors but has only a fraction of that number. Bihar and Maharashtra face similarly severe shortfalls, each requiring over 200 monitors but managing far fewer. Even states like Madhya Pradesh, Rajasthan, and Tamil Nadu, which appear relatively better placed, still fall short when matched against the required numbers, as coverage remains concentrated in urban pockets. Delhi is one of the few regions meeting or exceeding its target number of stations, but with its population continuing to grow, even here the adequacy of monitoring is fast becoming questionable. This widening gap between demand and actual monitoring infrastructure underlines the urgent need to expand or redistribute stations more equitably across states and districts *(see Graph 7: Air monitoring Gap- Population Vs Pollution Monitoring).*

Detailed analyses for the 2 km, 3 km, and 5 km buffer zones highlighting smaller-scale coverage and remaining data shadows are provided in the Annexures. *(See Annexure)*

MAP 3: MONITORING VOID IN MILLION-PLUS DISTRICTS



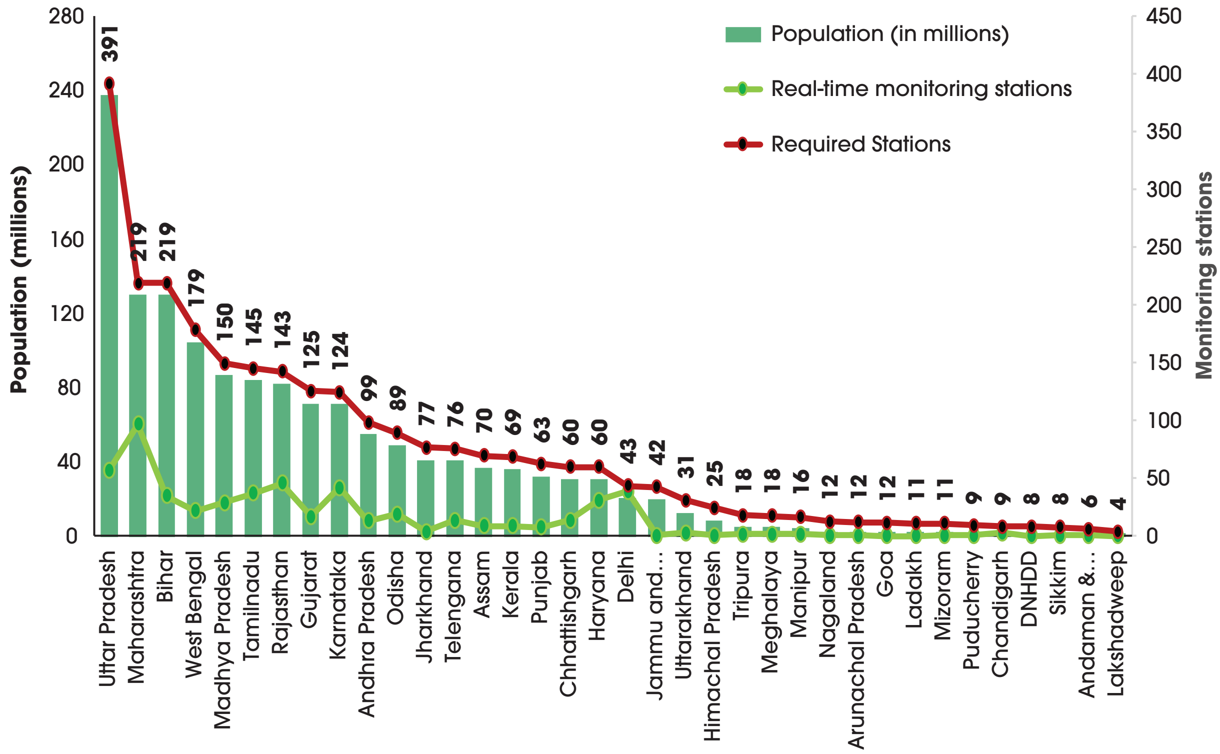
Note: Population estimates are based on the 100mx100m spatial distribution of population in 2020 developed by the by the Socioeconomic Data and Application Center (SEDAC) - Gridded Population of the World (GPW), version 4, revision 11 (GPWv411) for year 2020. Monitoring locations are approximation based on information available from CPCB website and publications, it is not exact geographical co-ordinate of the stations as that information is not publically available.
Source: CSE analysis

3.3. CITY-LEVEL OVERVIEW

Across India's six largest metropolitan regions - Delhi, Mumbai, Bengaluru, Kolkata, Chennai, and Hyderabad, a buffer analysis reveals significant gaps in real-time monitoring coverage. The spatial spread of monitors in these megacities is uneven, leaving large sections of densely populated urban areas without adequate surveillance.

At the hyper-local scale (2 km), only 9–32 percent of each city's land area falls within a monitor's reach, meaning that between two-thirds and nine-tenths of the city remains in data shadow. Even when the buffer is extended to 5 km, substantial blind spots persist: 22–55 percent of urban areas across the six metros are left unmonitored, with rapidly growing suburban zones the most affected. Mumbai performs best at the immediate 2 km scale, with 32 percent coverage, while Hyderabad fares the worst at just 9 percent. By the 5 km buffer, Kolkata and Chennai achieve the strongest reach (77–78 percent), but Hyderabad continues to lag behind, covering less than half of its area

GRAPH 7: AIR MONITORING GAP- POPULATION VS POLLUTION MONITORING

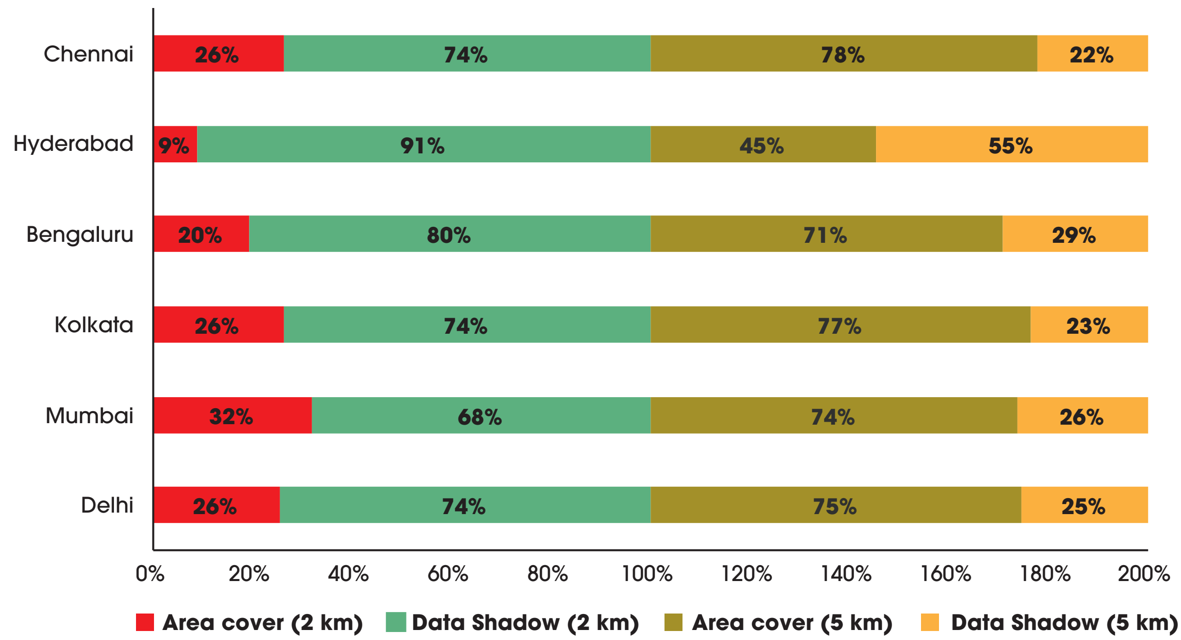


Source: CSE analysis based on CPCB monitoring criteria

(45 percent). These findings underscore the urgent need to both expand and redistribute monitors to ensure equitable city-wide coverage *(see Graph 8: Monitoring Coverage and Data Shadows in India's Six Megacities).*

- **Delhi:** Covers 26 percent of its area within 2 km (74 percent data shadow) and 75 percent within 5 km (25 percent shadow), leaving peripheral districts under-served.
- **Mumbai:** Leads in 2 km coverage (32 percent) and achieves 74 percent by 5 km, but northern suburbs remain poorly monitored.
- **Kolkata:** Matches Delhi and Chennai in 2 km coverage (26 percent) and reaches 77 percent at 5 km, though eastern and western peripheries still face gaps.
- **Chennai:** Covers 26 percent at 2 km and leads all cities at 5 km with 78 percent, yet southern and central fringes remain under-served.
- **Bengaluru:** Records only 20 percent coverage at 2 km and 71 percent at 5 km, leaving northern, eastern, and southern outskirts in data shadow.
- **Hyderabad:** Suffers the weakest reach overall, with just 9 percent coverage at 2 km and 45 percent at 5 km, highlighting widespread blind spots across both core and peripheral wards. *(see Map 4: Spatial Distribution of Real-Time Air Quality Monitors and Data Shadow Areas)*

GRAPH 8: MONITORING COVERAGE AND DATA SHADOWS IN INDIA'S SIX MEGACITIES



Source: CSE analysis

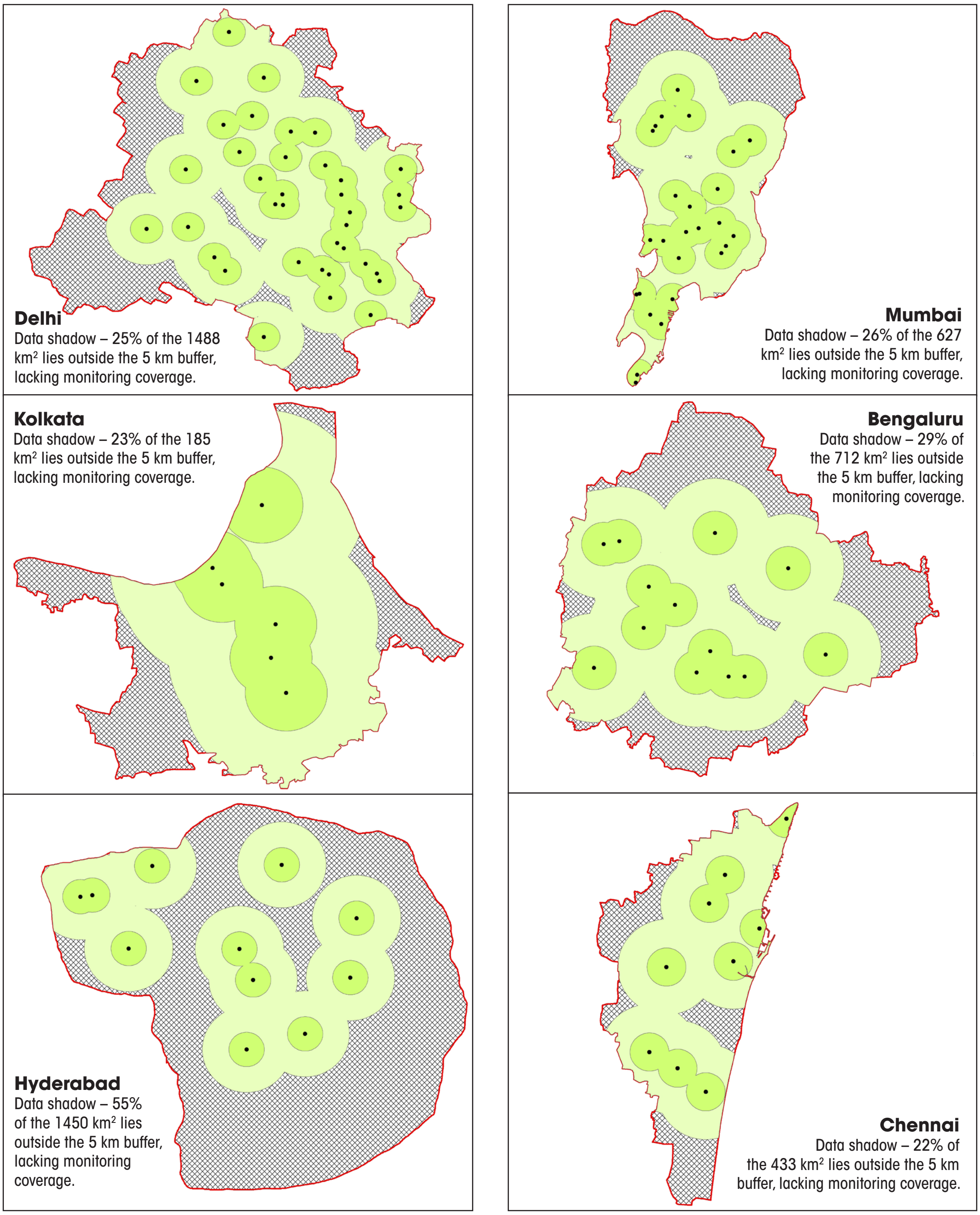
A closer look at Delhi highlights how this imbalance plays out in practice. The majority of monitors are concentrated in central and southern districts, leaving the southwestern, northwestern, and peripheral areas significantly under-monitored. These outer zones are home to rapidly expanding populations and high exposure risks but remain largely invisible in the city's monitoring network.

For Delhi and by extension, other megacities, strengthening the monitoring framework requires not only scaling up the number of stations but also addressing their spatial distribution. Underserved zones, particularly those with dense populations or major emission sources, demand urgent prioritization. A well-distributed network would allow for more representative data, timely alerts, and targeted interventions.

The situation in Delhi is emblematic of a broader pattern across India's urban centers: monitoring networks are dense in select urban cores while leaving peripheral, high-density belts in data shadows. Addressing this imbalance will require a more rational and scientifically grounded design, one that aligns station placement with population exposure, local emission profiles, and spatial representativeness rather than administrative convenience.

Real time Monitor | 2km Buffer | 5km Buffer | Data Shadow

MAP 4: SPATIAL DISTRIBUTION OF REAL-TIME AIR QUALITY MONITORS AND DATA SHADOW AREAS



Note: Monitoring locations are approximation based on information available from CPCB website and publications, it is not exact geographical co-ordinate of the stations as that information is not publically available. 9304524577
Source: CSE analysis

4. NEXT STEPS

This is a simple and a straight forward assessment of a single parameter of geographic and population coverage to understand the extent to which the current network covers the population spread in the country. This brings out the under-monitored regions and population and quantifies both the geographic area and population falling within and outside the effective influence zones of existing CAAQMS. This buffer-based geospatial analysis using high-resolution population data and monitoring station locations simply highlights the vast population that is still outside the ambit of monitoring. While it is strongly reiterated that action does not await data, at the same time data on population exposures in vulnerable areas are critical to calibrate the action to reduce risks for the local population as well as to improve the regional air quality that impacts local pollution in cities.

Under the NCAP programme it is necessary to develop a multi-dimensional or hybrid monitoring system. A robust monitoring system is critical for improving performance linked air quality management and funding. Such a system will require several approaches:

i) This requires further reforms in the regulatory monitoring system to develop create protocols for further rationalization of the siting of the monitoring stations to be representative of the land-uses, regional background, hotspots among others that will be utilized compliance reporting. Define the methods for data analytics for real time data and data validation to establish long term and short term trend in air quality to report compliance with clean air targets – including data averaging method, annual and rolling averages, protocol for data completeness, etc.

ii) Establish the framework or multi-dimensional monitoring system to integrate satellite based pollution mapping of all data shadow areas as well as the areas under regulatory monitors and the sensor based monitoring network at a community scale to complement the regulatory monitoring. This is needed to refine the interventions, and reduce exposures for all groups of population that are vulnerable and face high exposures. This can help to bring a lot more granularity in air quality assessment to strengthen system while enable action at a regional scale.

iii) Define the framework for integration and interface of all these data bases to inform action. This will require an open data system that is accessible.

ANNEXURES

ANNEXURE 1: STATE WISE DATA SHADOW AREA (NOT COVERED) BY REAL TIME MONITORING STATION WITHIN 2KM, 3KM, 5KM AND 10KM BUFFER

Data Shadow Area (in Percentage)					
Sl No	Name	2Km	3Km	5Km	10Km
1	Andaman & Nicobar	99.8%	99.6%	99.3%	97.8%
2	Andhra Pradesh	99.9%	99.8%	99.5%	98.3%
3	Arunachal Pradesh	100.0%	100.0%	99.9%	99.6%
4	Assam	99.9%	99.7%	99.3%	97.3%
5	Bihar	99.6%	99.1%	97.7%	91.5%
6	Chandigarh	74.2%	49.8%	10.4%	100.0%
7	Chhattisgarh	99.9%	99.7%	99.3%	97.6%
8	Daman and Diu and Dadra and Nagar Haveli	100.0%	100.0%	99.5%	91.0%
9	Delhi	73.4%	51.3%	21.2%	3.5%
10	Goa	100.0%	100.0%	100.0%	100.0%
11	Gujarat	99.9%	99.8%	99.5%	98.6%
12	Haryana	99.2%	98.2%	95.2%	83.7%
13	Himachal Pradesh	100.0%	100.0%	99.9%	99.6%
14	Jammu and Kashmir	100.0%	100.0%	99.9%	99.5%
15	Jharkhand	99.9%	99.9%	99.7%	99.0%
16	Karnataka	99.8%	99.5%	98.6%	95.1%
17	Kerala	99.7%	99.4%	98.5%	95.5%
18	Ladakh	100.0%	100.0%	100.0%	100.0%
19	Lakshadweep	100.0%	100.0%	100.0%	100.0%
20	Madhya Pradesh	99.9%	99.8%	99.5%	98.2%
21	Maharashtra	99.7%	99.4%	98.7%	96.6%
22	Manipur	99.9%	99.7%	99.3%	97.9%
23	Meghalaya	99.9%	99.7%	99.3%	97.5%
24	Mizoram	99.9%	99.9%	99.6%	98.5%
25	Nagaland	99.9%	99.8%	99.5%	98.1%
26	Odisha	99.8%	99.7%	99.1%	96.7%
27	Puducherry	96.4%	91.4%	78.6%	46.8%
28	Punjab	99.8%	99.5%	98.6%	94.0%
29	Rajasthan	99.8%	99.7%	99.1%	96.7%
30	Sikkim	99.8%	99.6%	98.9%	95.6%
31	Tamilnadu	99.7%	99.3%	98.1%	93.2%
32	Telengana	99.9%	99.8%	99.4%	98.4%
33	Tripura	99.8%	99.5%	98.8%	96.6%
34	Uttar Pradesh	99.8%	99.5%	98.8%	96.6%
35	Uttarakhand	99.9%	99.8%	99.6%	98.3%
36	West Bengal	99.7%	99.5%	98.8%	96.5%

ANNEXURE 2: STATE WISE AREA COVERAGE BY REAL TIME MONITORING STATION WITHIN 2KM, 3KM, 5KM AND 10KM BUFFER

Area coverage (in Percentage)					
Sl No	**Name**	**2Km**	**3Km**	**5Km**	**10Km**
1	**Andaman & Nicobar**	0.2%	0.4%	0.7%	2.2%
2	**Andhra Pradesh**	0.1%	0.2%	0.5%	1.7%
3	**Arunachal Pradesh**	0.0%	0.0%	0.1%	0.4%
4	**Assam**	0.1%	0.3%	0.7%	2.7%
5	**Bihar**	0.4%	0.9%	2.3%	8.5%
6	**Chandigarh**	25.8%	50.2%	89.6%	100.0%
7	**Chhattisgarh**	0.1%	0.3%	0.7%	2.4%
8	**Daman and Diu and Dadra and Nagar Haveli**	0.0%	0.0%	0.5%	9.0%
9	**Delhi**	26.6%	48.7%	78.8%	96.5%
10	**Goa**	0.0%	0.0%	0.0%	0.0%
11	**Gujarat**	0.1%	0.2%	0.5%	1.4%
12	**Haryana**	0.8%	1.8%	4.8%	16.3%
13	**Himachal Pradesh**	0.0%	0.0%	0.1%	0.4%
14	**Jammu and Kashmir**	0.0%	0.0%	0.1%	0.5%
15	**Jharkhand**	0.1%	0.1%	0.3%	1.0%
16	**Karnataka**	0.2%	0.5%	1.4%	4.9%
17	**Kerala**	0.3%	0.6%	1.5%	4.5%
18	**Ladakh**	0.0%	0.0%	0.0%	0.0%
19	**Lakshadweep**	0.0%	0.0%	0.0%	0.0%
20	**Madhya Pradesh**	0.1%	0.2%	0.5%	1.8%
21	**Maharashtra**	0.3%	0.6%	1.3%	3.4%
22	**Manipur**	0.1%	0.3%	0.7%	2.1%
23	**Meghalaya**	0.1%	0.3%	0.7%	2.5%
24	**Mizoram**	0.1%	0.1%	0.4%	1.5%
25	**Nagaland**	0.1%	0.2%	0.5%	1.9%
26	**Odisha**	0.2%	0.3%	0.9%	3.3%
27	**Puducherry**	3.6%	8.6%	21.4%	53.2%
28	**Punjab**	0.2%	0.5%	1.4%	6.0%
29	**Rajasthan**	0.2%	0.3%	0.9%	3.3%
30	**Sikkim**	0.2%	0.4%	1.1%	4.4%
31	**Tamilnadu**	0.3%	0.7%	1.9%	6.8%
32	**Telengana**	0.1%	0.2%	0.6%	1.6%
33	**Tripura**	0.2%	0.5%	1.2%	3.4%
34	**Uttar Pradesh**	0.2%	0.5%	1.2%	3.4%
35	**Uttarakhand**	0.1%	0.2%	0.4%	1.7%
36	**West Bengal**	0.3%	0.5%	1.2%	3.5%

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8. UNEP
9. 2 km buffer - captures a station's immediate zone of influence, typically representing neighborhood-scale exposure.
   3 km buffer - extends this reach slightly, identifying nearby pockets still underserved.
   5 km buffer - reflects a broader municipal or peri-urban scale, helping visualize intermediate gaps in monitoring coverage.
   Finally, the 10 km buffer - encompasses a citywide scale, identifying major regions such as suburban clusters or industrial belts that lack any real-time monitoring infrastructure.
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India's air quality monitoring has grown rapidly, yet vast regions and millions remain in "data shadows" without reliable information on the air they breathe. This report reveals the scale of these blind spots and their risks to public health and governance. Bridging these gaps is essential not only for accountability under national programmes but also to protect vulnerable communities. The findings call for urgent action: redistributing monitors, adopting hybrid systems with sensors and satellites, and making open data central to policy. Closing these gaps is key to advancing equitable, evidence-based clean air action across the country.

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