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Case Study

Ambient air pollution in selected small cities in India: Observed trends and future challenges

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ABSTRACT

Exposure to ambient air pollution is a major threat to human health in most Indian cities. Recent studies have reported that more than three-quarters of the people in India are exposed to pollution levels higher than the limits recommended by the National Ambient Air Quality Standards in India and significantly higher than those recommended by the World Health Organization. Despite the poor air quality, the monitoring of air pollution levels is limited even in large urban areas in India and virtually absent in small towns and rural areas. The lack of data results in a minimal understanding of spatial patterns of air pollutants at local and regional levels. This paper presents particulate air pollution trends monitored over one year in three small cities in India. The findings are important for framing state and regional level policies for addressing air pollution problems in cities, and achieve the sustainable development goals (SDGs) linked to public health, reduction in the adverse environmental impact of cities, and adaptation to climate change, as indicated by SDGs 3.9, 11.6 and 11.b.

1. Introduction

Rising levels of air pollution are a global concern, and they are caused by many factors, such as increasing urbanization, industrial pollution, traffic emissions, agriculture, and energy usage [1]. Lim et al. [2] reported the significant effect of air pollution on global mortality. The 2017 data from the Global Burden of Disease study [3] provide new evidence regarding the significant effects of air pollution globally, placing it among the top ten risks confronted by human beings. Most cities worldwide cannot comply with the pollutant standards and have reported measurements that far exceed them, resulting in millions of premature deaths [1]. At the forefront of pollutants which exceed concentration limits are coarse and fine particulate matter (PM), defined as particles with a nominal average diameter less than 10 μm (PM10) and 2.5 μm (PM2.5), respectively. The World Health Organization (WHO) report regarding ambient air pollution suggests that the annual mean concentration of PM2.5 or PM10 has increased by more than 10% between 2010 and 2016 in at least 280 cities worldwide [4].

In India, almost the entire country's population resides in areas that exceed the WHO Air Quality Guidelines, and the majority of the population resides in areas where even the less stringent limits set by the Indian National Ambient Air Quality Standard (NAAQS) [5] for PM are exceeded [6]. Air quality modeling by WHO indicates that the median exposure to PM2.5 in India is 66 $\mu g/m^3$ with lower and upper bounds of 45 $\mu g/m^3$ and 97 $\mu g/m^3$ [7].

Despite the poor air quality, the monitoring of air pollution levels is limited even in large urban areas in India and virtually absent in small towns and rural areas. The Central Pollution Control Board of the Government of India and its companion state-level boards currently maintain 92 PM2.5 and 573 PM10 monitoring stations. These numbers are insignificant for a country with a land area of 3.3 million km^2 and a population of over 1.3 billion, 34% of whom live in urban areas. Even on this sparse network, the availability of PM2.5 data is extremely limited as the National Air Quality Monitoring Program monitored only sulfur dioxide, nitrogen dioxide, and PM10 data before 2015. Real-time high-resolution pollutant concentration maps do not exist currently because they require a large amount of data, computing facilities, and high costs. This lack of data leads to a minimal understanding of spatial patterns of air pollutants at the local as well as regional levels, and hampers the ability of planners and administrators to assess the impact of interventions on air quality designed to meet SDG 11 requirements to "reduce the adverse per capita environmental impact of cities, including by paying special attention to air quality …."

Most of the air pollution data in India are from cities with populations greater than one million. According to the 2011 census of India [8], about 230 million of India's urban population lives in towns and cities with populations less than one million. The cities selected for the present study, Bulandshahr, Nainital, and Patiala, have populations of 223,000, 41,400, and 410,000, respectively, per the 2011 census of

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Table 1
Locations and data recording periods of the pollution monitors for cities considered in this study.

Serial number	City	Location	Active from	Active until
1,203,180,177	Patiala	Fountain Chowk	September 1, 2018	October 31, 2019
1,203,180,102	Patiala	PUDA Office	September 1, 2018	October 31, 2019
1,203,180,101	Patiala	Adalat Bazaar	September 1, 2018	October 31, 2019
1,203,180,023	Bulandshahr	Kala Aam Chouraha	September 1, 2018	October 31, 2019
1,203,180,063	Bulandshahr	Ganga Nagar	September 1, 2018	October 31, 2019
1,203,180,037	Nainital	Mall Road	August 14, 2018	July 7, 2019
1,203,180,059	Nainital	Mallital	August 14, 2018	July 7, 2019

India [8]. Ambient air pollution data for these cities are extremely sparse and limited. In recent years, relatively low-cost monitors have become available for measuring ambient particulate concentrations. For a duration of approximately 5 months, i.e., from September 17, 2018 to February 10, 2019 (the months with the worst pollution in northern India), we used these low-cost monitors to measure particulate levels in the above mentioned three cities.

Lack of air quality studies for urban areas other than large metropolitan areas is a global problem, particularly in low to middle-income countries (LMICs). In LMICs, almost all air quality studies deal with large or metropolitan cities [9,10]. There are hardly any studies from Asia and Africa dealing with small cities [11,12]. Most air quality studies come from high-income countries (HICs), and recently from China [13]. Even in HICs, most of the studies deal in detail with large cities [14–16].

The main objective of the work reported here is to understand what is happening with the air quality in small cities and towns and to establish methods and procedures to do more comprehensive studies in the future. This work is part of a larger project with the goal to provide local administrators and planners the capability to evaluate the impact of interventions designed to improve air quality, and attain sustainable development goals in line with India's Smart City program goals. The cost for individual cities and towns to install and maintain a conventional air quality monitoring and assessment program runs into crores of rupees, and requires having staff with specialized training. The present work serves to demonstrate that air quality assessment in small cities can be done with low-cost sensors, and so serves as the first step in developing and providing relatively inexpensive solutions for cities in LMICs to achieve SDG goals to substantially reduce the number of deaths and illnesses from air pollution (SDG 3.9), reduce the adverse per capita environmental impact of cities (SDG 11.6), and improve their ability to mitigate and adapt to climate change (SDG 11.b).

2. Methodology

2.1. Use of low-cost air quality monitors

Our solution to overcome the lack of air quality data is to adopt low-cost methods for robust pollution monitoring. Although these methods tend to yield data of somewhat lower accuracy compared to conventional high-cost, air quality monitoring systems, they can be deployed in a significantly higher number of locations simultaneously, thereby enabling high-resolution assessment mapping of city pollution when resources are limited. Recent work by Genikomsakis and colleagues [17] has demonstrated that low-cost sensors work very well for collecting fine-grained spatio-temporal PM2.5 profiles in urban areas.

Compared with analytical instruments for measuring air pollutants, the sensors used in this study are less expensive and easier to deploy, operate, and manage. Retrieving data from the sensors is straightforward, and their automatic operation enables a widespread deployment. Data collected from the sensors can be managed, processed, and analyzed centrally, as well as shared with all the stakeholders.

The particular monitors used for collecting the data reported herein are commercial units that use such low-cost sensors. The monitors range in price from Rs. 15,000 to Rs. 25,000, and have an operational and maintenance cost of about Rs. 5000 for about 200 days of operation per year. They are portable and can be mounted outdoors provided that a power source is available for the continuous measurement of ambient PM2.5 and PM10 concentrations. The technical specifications of these monitors are as follows:

Measurement

- Measurement parameters: PM2.5, PM10 in μg/m^3
- Range of PM2.5: 0–999 μg/m^3
- Range of PM10: 0–1999 μg/m^3
- Minimum resolution of $<$0.3 μm
- Relative error Maximum of $\pm$10% and $\pm$ 10 μg/m^3

Power

- Power voltage: 220 V
- 3000 mAh rechargeable battery, 6–8 h of battery backup

Tested and Calibrated

- Beta attenuation monitor (BAM)

The operating principle of the sensors in these monitors is based on laser light scattering. A small fan draws in a stream of ambient air passing through a detection chamber. The PM in the air scatters the coherent light from the laser. A photodetector converts the scattered light into an electrical signal, which is then amplified and processed. The processing entails using existing correlations to calculate particulate concentrations in real time. The monitors were calibrated against a Beta Attenuation Monitor (BAM) by the vendor.

2.2. Locations of air quality monitors within each city

We installed seven particulate concentration monitors in the three selected cities. Three of the monitors were installed in Patiala, and two each in Nainital and Bulandshahr. The locations of the monitors and the time for which they were active are shown in Table 1. The locations were selected to encompass a range of urban morphologies: central, high-traffic, commercial zones; peripheral, low-traffic, residential zones; and densely populated old-city areas with a relatively low volume of motorized traffic. Fig. 1 shows the locations of the three cities on a map of India. Figs. 2, 3 and 4 show the location of each monitor on the maps of the three cities.

3. Results

3.1. Overview of pollution data

Our analysis was based on data collected from September 1, 2018 to October 31, 2019 in Bulandshahr and Patiala, and from August 14, 2018 to July 7, 2019 in Nainital. The monitors were set to record a reading every minute and then upload the data to the server every 10 min. For this study, the data were averaged every 30 min. Table 2 presents the mean of PM2.5 and PM10 (averaged for all the monitors in each city) and the corresponding standard deviations. The data shows that the city of Bulandshahr reported the highest level of pollution for both

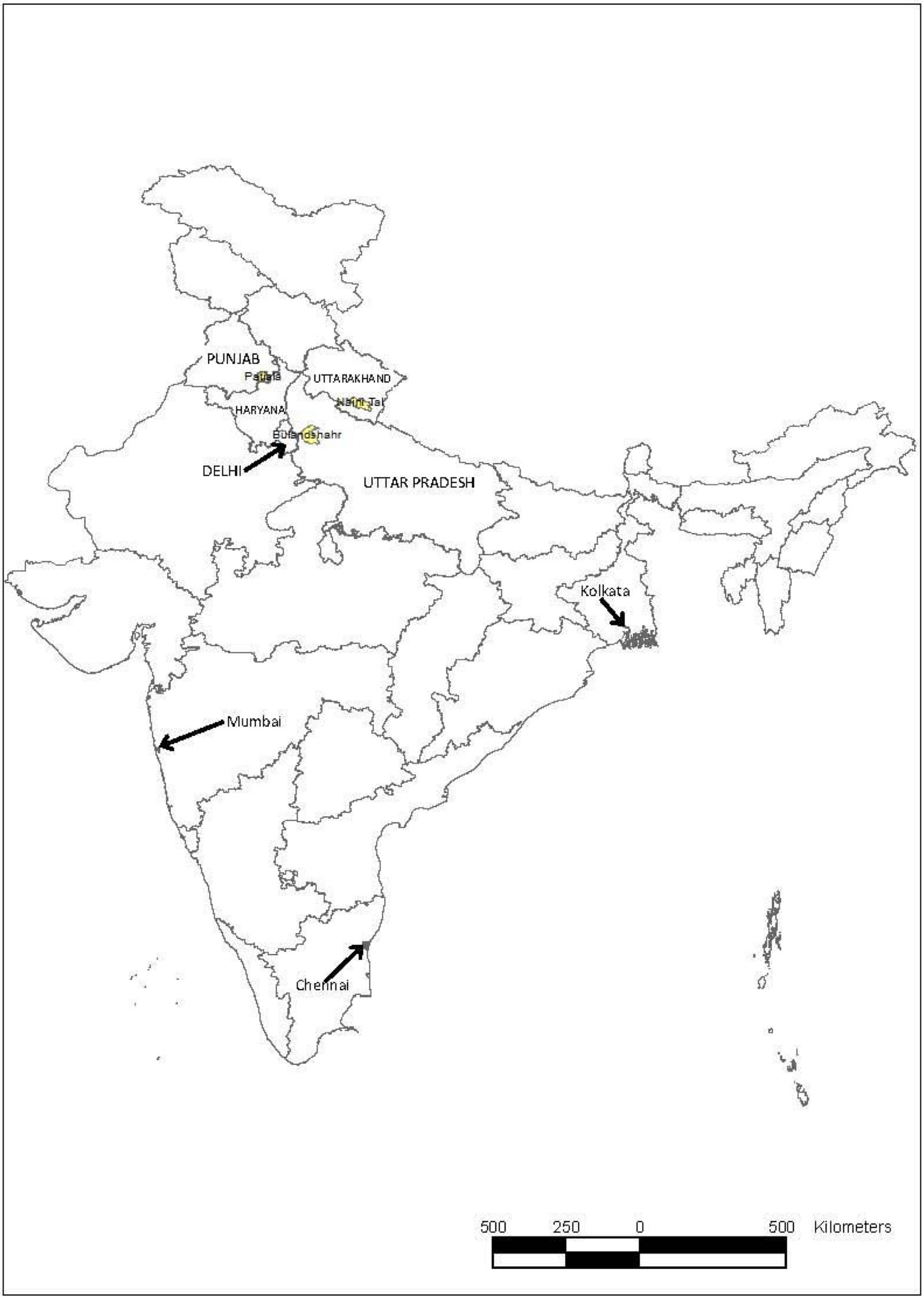

Fig. 1. Locations of Patiala, Bulandshahr, and Nainital.

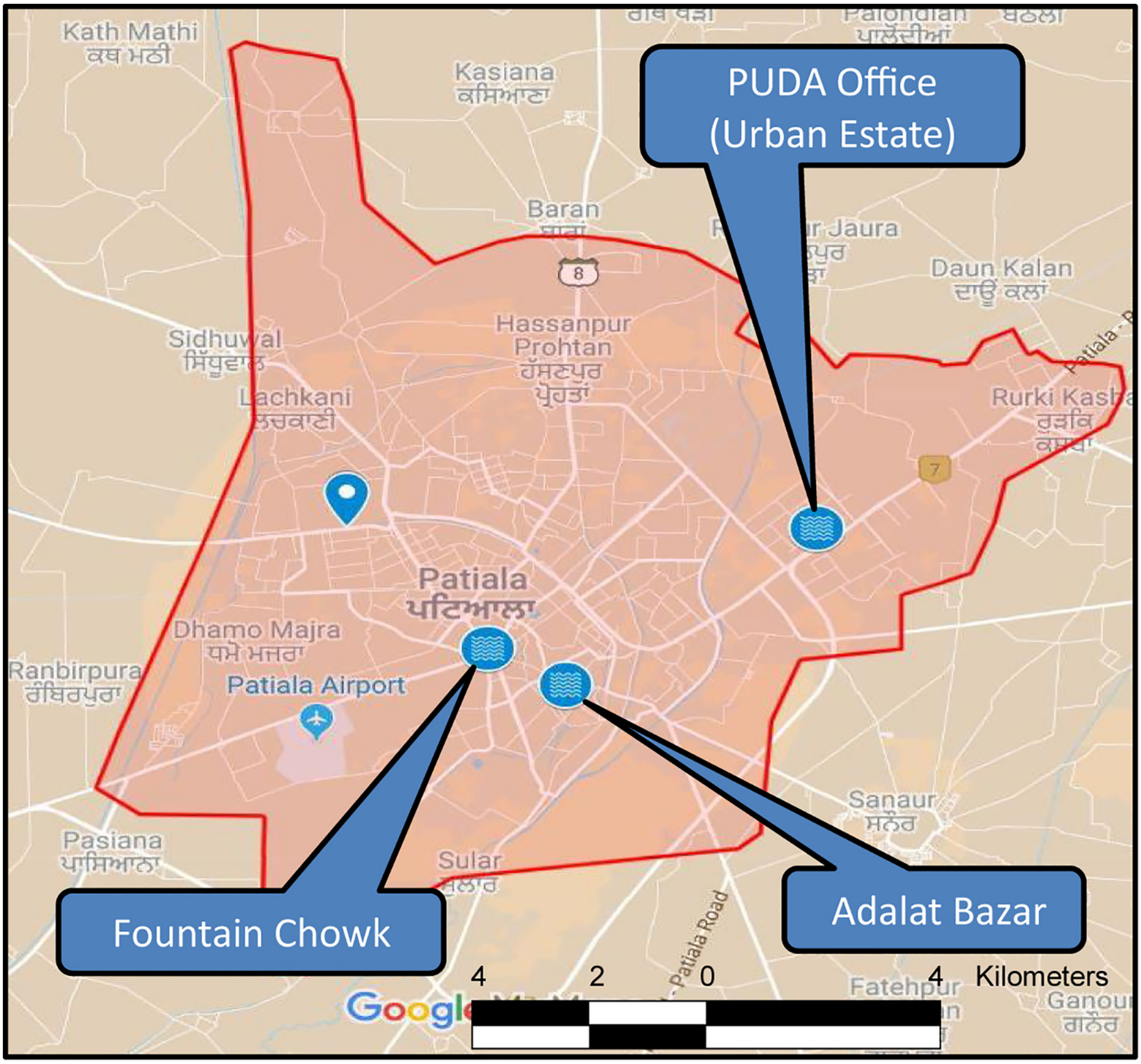

Fig. 2. Locations of air quality (particulate concentration) monitors in Patiala.

PM2.5 and PM10, followed closely by Patiala. Nainital reported the lowest PM2.5 and PM10 pollution levels among the three cities. This is interesting because Bulandshahr, the city with the highest pollution levels, is closest to the large urban city of New Delhi and its satellite towns and cities, whereas Nainital, the city with the lowest levels of PM pollution, is distant from Delhi and isolated in the foothills of the Himalayas at an elevation of approximately 2000 m above the mean sea level.

Figs. 5, 6 and 7 show the monthly mean variations of PM for the full duration of the study for Patiala, Bulandshahr, and Nainital, respectively. For both Patiala and Bulandshahr, the PM2.5 and PM10 levels increased steadily from September to December of 2018, and then decreased steadily from December 2018 to late July 2019, and then rose steadily again until the end of our observation period in late October 2019. The periods of increase can be attributed to the winter season in northern India. Meanwhile, for Nainital, no such pattern was observed. For all 14 months of observation, the PM pollution levels in Patiala and Bulandshahr were significantly higher than the safe limits provided by the NAAQS. The PM pollution level in Nainital was within the safe limit for the 11 months of observation. Per the NAAQS, the time-weighted daily average safe limits for PM2.5 and PM10 are 60 and 100 μg/m^3, respectively; the corresponding time-weighted annual average safe limits are 40 and 60 μg/m^3, respectively.

3.2. Monthly mean comparison of the three cities

The three cities are located between about 200 to 300 km from each other and have different immediate environments. Hence, it is important to analyze the variation in PM pollution levels with respect to each city. Figs. 8 and 9 show a comparison of the monthly means for PM2.5 and PM10, respectively. Both the PM2.5 and PM10 levels were the highest for Bulandshahr for all but 3 of the 14 months of the observation period, followed by Patiala and Nainital. The PM2.5 and PM10 levels in Bulandshahr were higher than the daily average safe limit per the NAAQS. For Patiala, the PM2.5 level was at the safe limit only in September 2018, March 2019, and April 2019, whereas it was significantly above the safe limit for the remaining 11 months of observation. For Nainital, both the PM2.5 and PM10 levels were well within the daily average safe limit throughout the observation period.

3.3. Daily mean comparison of the three cities

To understand the daily changes in PM concentrations in ambient air, a comparative analysis of daily mean data for each city is presented in Figs. 10 and 11. Patiala and Bulandshahr exhibited similar rise and fall patterns for the PM2.5 and PM10 concentrations. This indicates that for

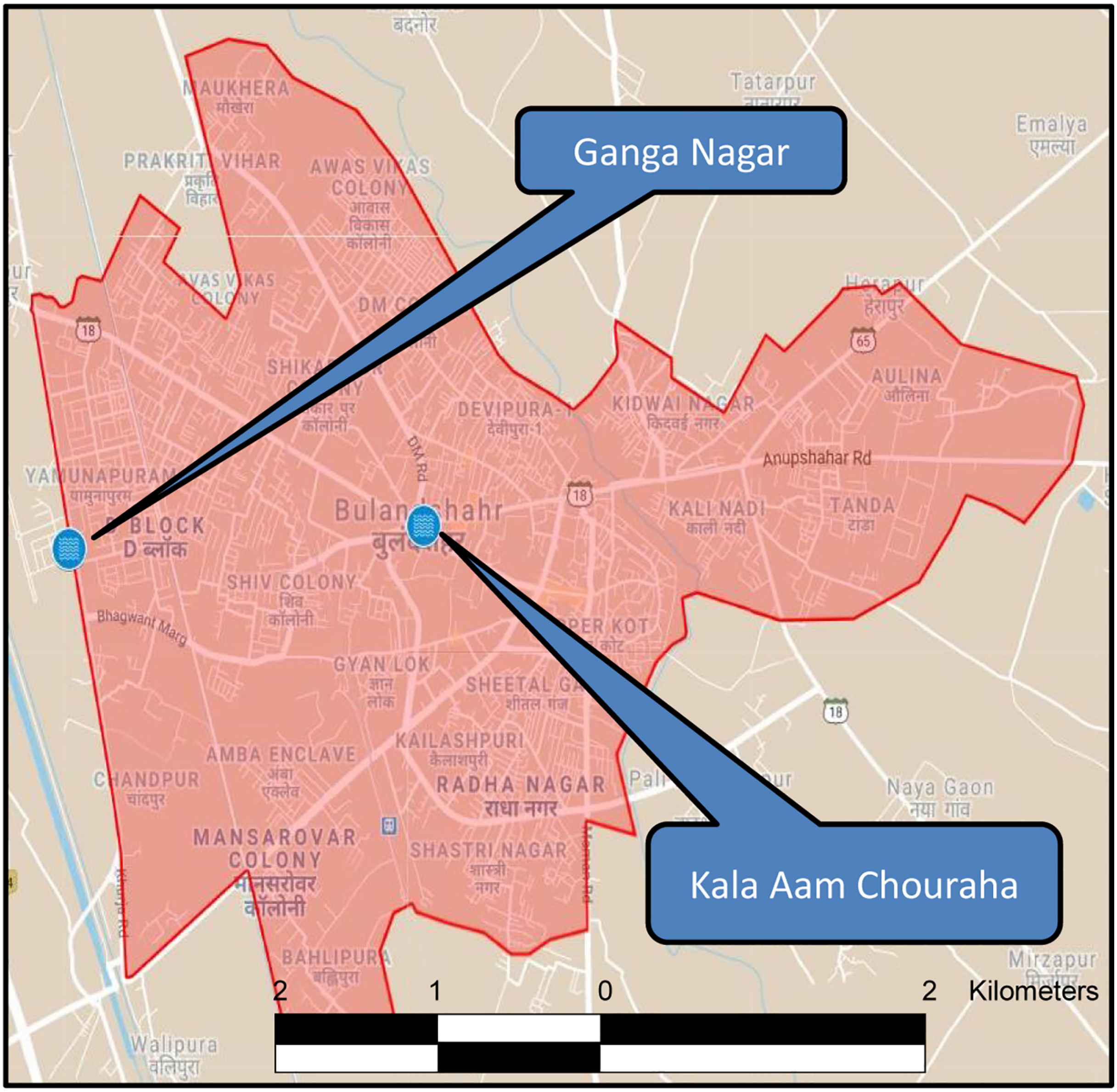

Fig. 3. Locations of air quality (particulate concentration) monitors in Bulandshahr.

cities located in the northern Indo–Gangetic Plains region of India, a regional pattern of particulate pollution exists that dominates the local environment, at least for the winter and early spring seasons during which the data reported herein were collected. This pattern is consistent with the data collected from the monitors located in multiple locations in the National Capital Region of Delhi [18]. The PM concentrations in Nainital showed a different pattern, likely attributable to its geographical location in the foothills of the Himalayas. For almost all of the 423 days of available data for Patiala and Bulandshahr, the PM pollution levels exceeded the NAAQS safe limits, whereas for Nainital, the particulate concentration levels were within the safe limit except for a few days.

3.4. Diurnal comparison of the three cities

Diurnal analysis allows us to determine the pattern of PM concentration variation in ambient air. The recorded data for each half-hour for each day were averaged over the entire observation period; they are graphically depicted in Figs. 12 and 13 in terms of PM2.5 and PM10, respectively. The diurnal variation of particulate concentrations in Patiala and Bulandshahr exhibited similar cycles. In Patiala and Bulandshahr, the PM concentration levels reached the maximum in the mornings, from approximately 6 AM to 9 AM, and the minimum in the afternoons, between 1 PM and 4 PM. Compared with Patiala, the PM levels in the ambient air were consistently higher in Bulandshahr; they are significantly higher than the NAAQS daily average safe limit in both the cities. However, the trend observed for Nainital differed; the maximum level of PM concentration was observed in the evening, whereas the minimum concentration was observed at night. The levels of particulate pollution remained within the NAAQS safe limits for the full diurnal cycle in Nainital.

That the PM2.5 and PM10 levels were high in the first half of the day and lower in the second half suggests that the particulate pollutants descended at night when the temperature was lower and rose as the temperature increased during the day, reaching a peak at mid-afternoon. This may be because a large proportion of the PM2.5 particles are volatile substances that tend to break down and rise as the ambient

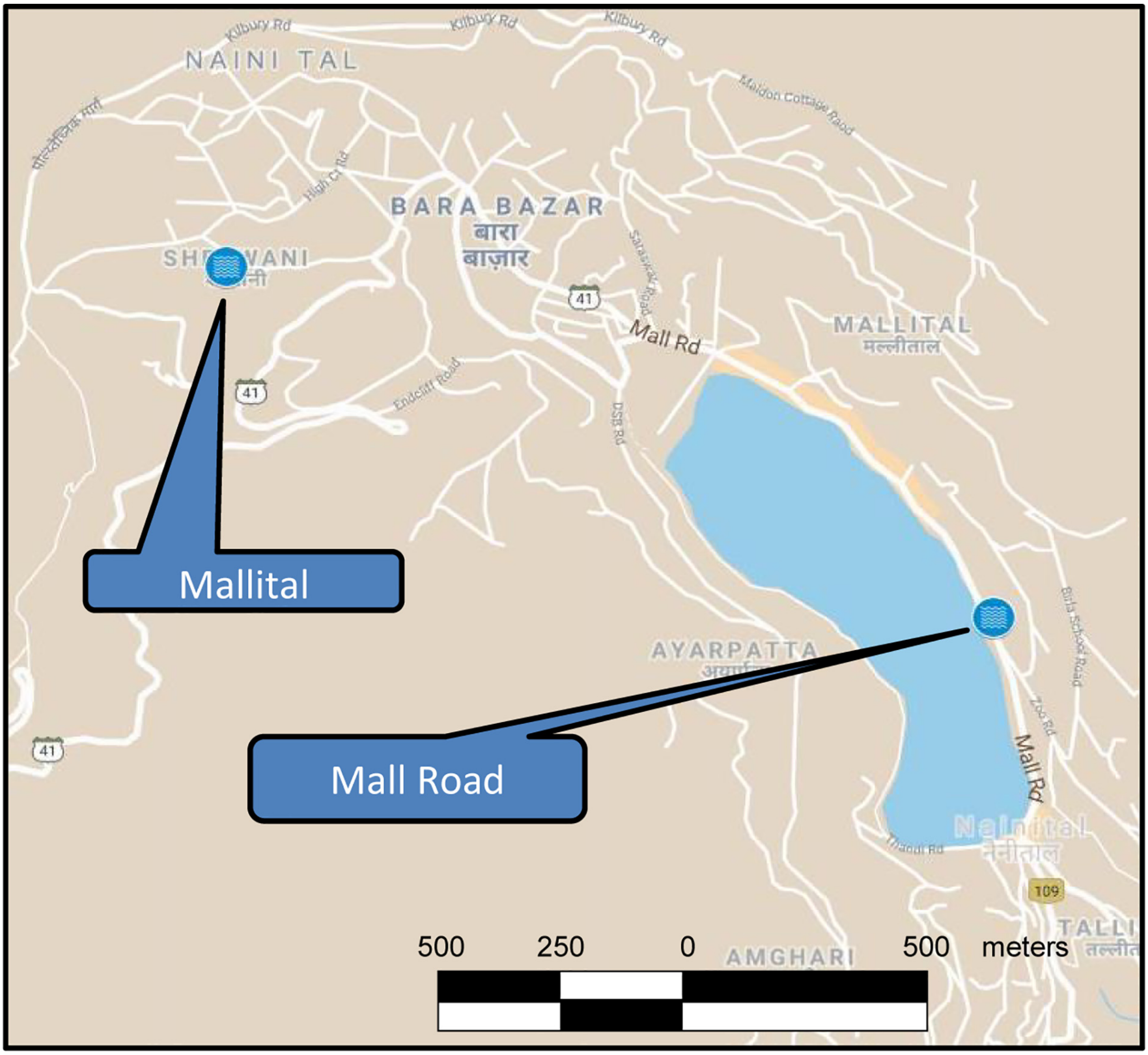

Fig. 4. Locations of air quality (particulate concentration) monitors in Nainital.

Table 2
PM2.5 and PM10 statistics for cities considered in this study.

City	PM 2.5 (μg/m^3)		PM 10 (μg/m^3)	
	Mean	S·D	Mean	S·D
Patiala	105	69	182	102
Bulandshahr	122	78	2254	101
Nainital	27	15	63	25

air temperatures increases. However, our current information regarding the constituents of PM is insufficient to confirm this conjecture.

3.5. PM proportion

To understand PM pollution, it is important to look at the proportion of PM pollutants. Figs. 14, 15 and 16 show the relative proportion of PM2.5 particles and those between PM2.5 and PM10. Patiala and Bulandshahr exhibit similar patterns with PM2.5 averaging 59% and 52%, respectively, of PM10. The percentage of PM2.5 was the highest in September-October of both 2018 and 2019, and the lowest in May 2019. The pattern for Nainital differed; the PM2.5 concentration averaged about 43% of the PM10 concentration.

4. Discussion and conclusion

4.1. Summary of findings

Among the three cities, Bulandshahr exhibited the highest level of PM pollution, followed by Patiala and Nainital. For Patiala, the average level of PM concentration during the 14-month observation period was approximately 105 and 182 μg/m^3 for PM2.5 and PM10, respectively. The levels for Bulandshahr over the same period were approximately 122 μg/m^3 (PM2.5) and 225 μg/m^3 (PM10). These levels were more than twice the average daily safe limit prescribed by the NAAQS. For Nainital, the average levels of PM concentrations were less than 30 μg/m^3 for PM2.5 and less than 70 μg/m^3 for PM10, both well within the average daily safe limit allowed under the NAAQS.

For both Patiala and Bulandshar, the PM2.5 and PM10 levels increased steadily from September to December of 2018, and then decreased steadily from December 2018 to late July 2019, then rose steadily again until the end of our observation period in late October 2019. Nainital did not exhibit any such pattern.

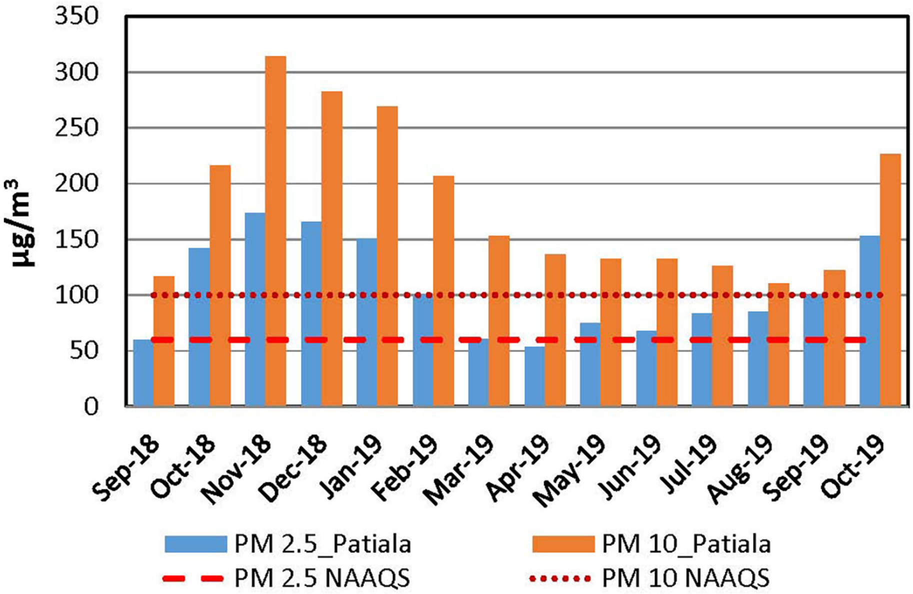

Fig. 5. PM2.5 and PM10 monthly mean variations in Patiala.

Patiala and Bulandshahr exhibited the same monthly and diurnal patterns of the increment and decrement of PM2.5 and PM10 levels. The proportions of PM10 formed by PM2.5 for Patiala and Bulandshahr were similar – varying from about 25% to 90% of PM10. The percentage of PM2.5 was the highest in September-October of both 2018 and 2019, and the lowest in May 2019. For Nainital, the composition of PM2.5 ranged from 13% to 80% of that of PM10, with the highest levels recorded in October 2018 and June 2019.

The PM diurnal variations for Patiala and Bulandshahr exhibited similar patterns. Both cities exhibited the maximum level of PM pollution in the morning from 6 AM to 9 AM and the minimum in the afternoon from 1 PM to 4 PM. However, the diurnal variation trend in Nainital differed as the maximum level of PM pollution occurred in the evening and the minimum at night.

5. Discussion

It was interesting that the data obtained from the three cities showed similar daily and long-term patterns of particulate levels, as recorded by different monitors within each city. Furthermore, they were similar between Patiala and Bulandshahr, which are located approximately 330 km from each other but are within the same large-scale geographic feature, i.e., the northern Indo–Gangetic Plains. The magnitude and patterns of variation of particulate concentration levels observed in these two cities were similar to those recorded at multiple locations in the Delhi region [18]. This suggests that the pollution levels in very different size cities may be similar in spite of very different local activity levels because the influence of the wider region may be very large at present. This is something which has not been reported in previous

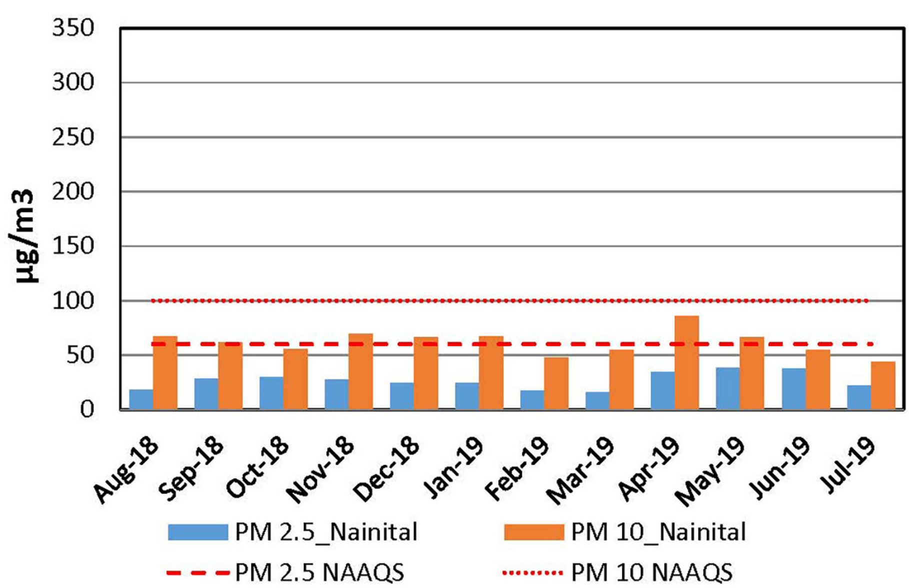

Fig. 6. PM2.5 and PM10 monthly mean variations in Nainital.

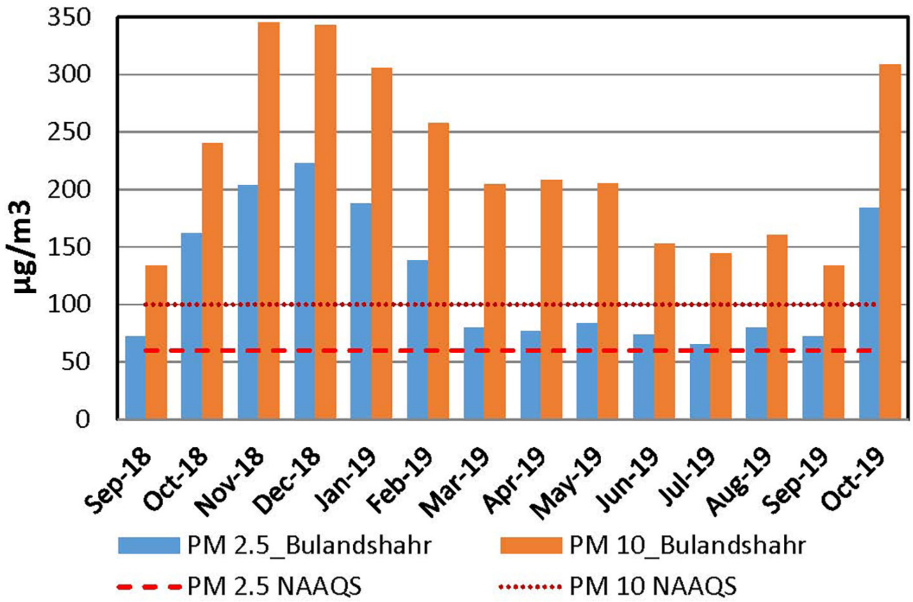

Fig. 7. PM2.5 and PM10 monthly mean variations in Bulandshahr.

studies. It is possible that because of developments in the future, pollution levels may change in different cities and it would be useful to keep track of pollution at different locations. A note of caution here: we do not suggest that pollution in a small city is the same as that in a large city nearby, and so data collection in the large city itself would be sufficient. A much larger and comprehensive data collection and analysis effort is needed to understand the regional effect.

5.1. Future studies

For the next phase of this study, we will collect and integrate pollution monitoring data for a longer period to understand seasonal variation. The number of monitoring locations will be increased across the region to corroborate the validity of the regional similarity of patterns of particulate level concentrations observed in the three small cities investigated in this study. To understand the effects of temperature, humidity, wind, and other meteorological phenomena on pollution, it is necessary to test and validate the contention that variations in PM levels are likely influenced by local and regional climatic conditions.

Owing to the similarity in patterns of PM level variations across different urban morphologies, it is critical to investigate the proportion of pollutants contributed by various sources. For instance, the data herein suggest that motor vehicle traffic may not be a significant contributor of the pollutants to the atmosphere.

The deployment of monitors with low-cost sensors in significant numbers can assist in creating emission inventories of pollutants and detecting pollution hotspots, as well as allowing real-time exposure assessments for designing mitigation strategies. A related goal is to develop a set of policy prescriptions regarding urban layout and land use changes to maximize the attainment of sustainable development goals linked to public health, reduction in the adverse environmental impact of cities, and adaptation to climate change, as indicated by SDGs 3.9, 11.6 and 11.b, under India's smart cities initiative.

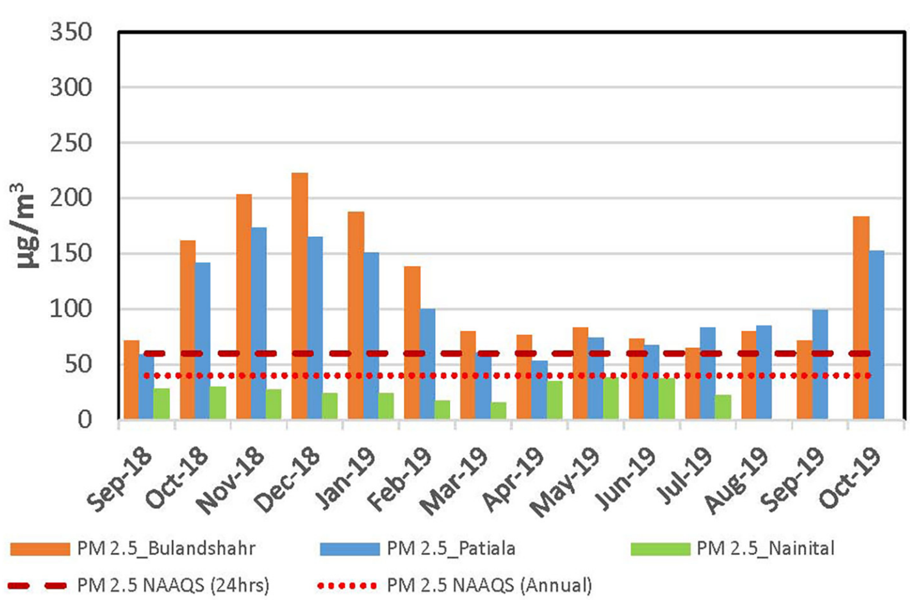

Fig. 8. PM2.5 monthly mean comparison of the three cities.

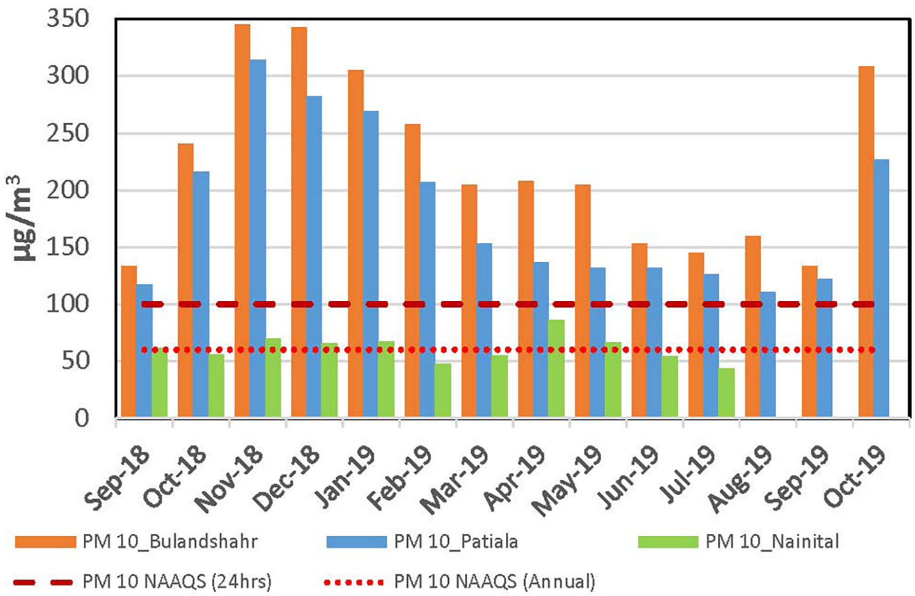

Fig. 9. PM10 monthly mean comparison of the three cities.

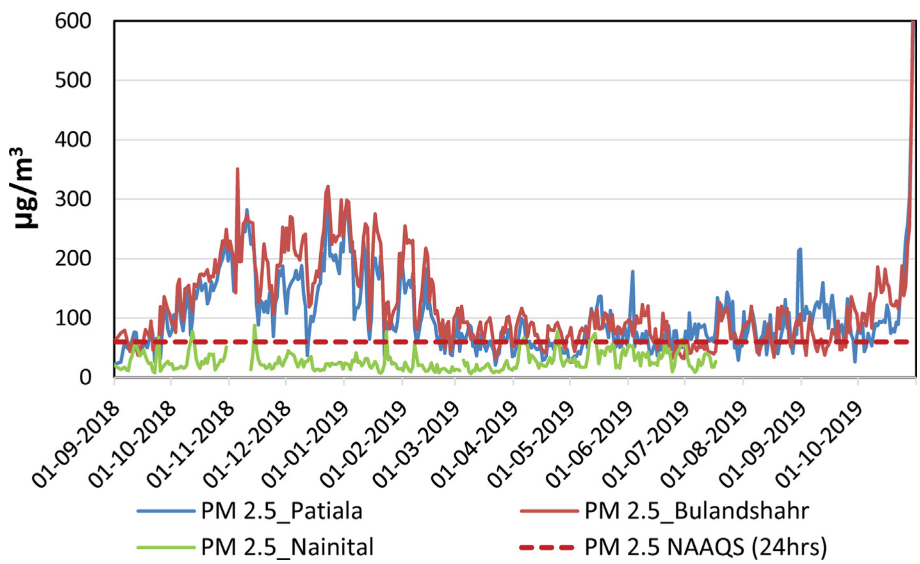

Fig. 10. PM2.5 daily mean comparison of the three cities.

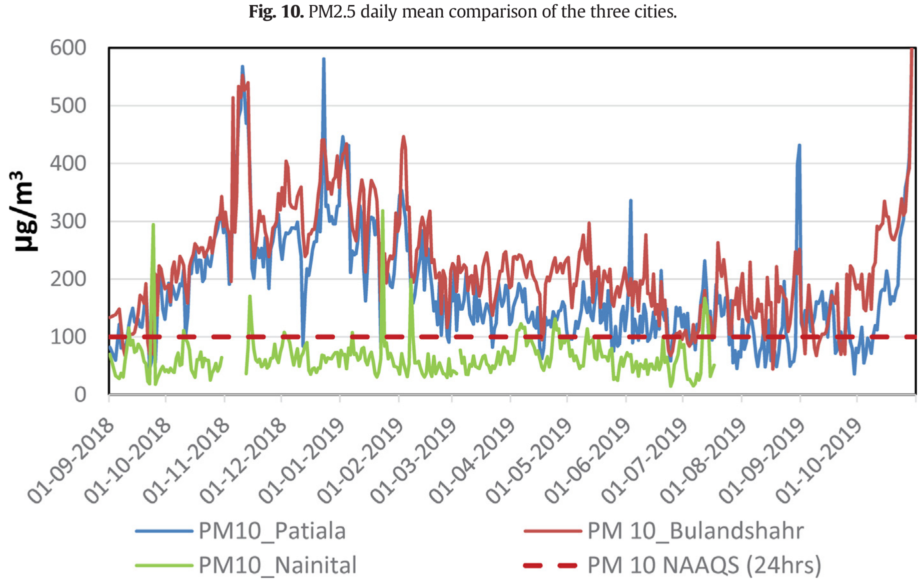

Fig. 11. PM10 daily mean comparison of the three cities.

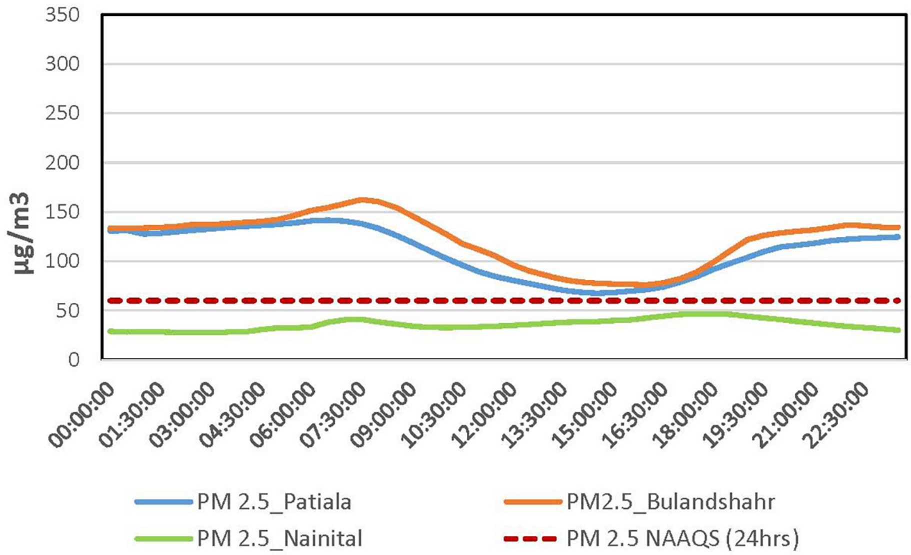

Fig. 12. PM2.5 diurnal comparison of the three cities.

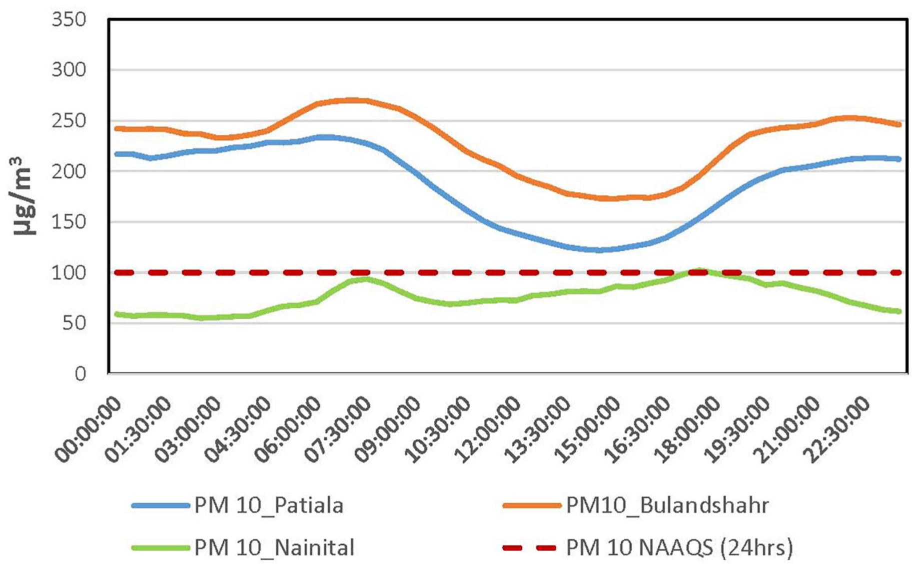

Fig. 13. PM10 diurnal comparison of the three cities.

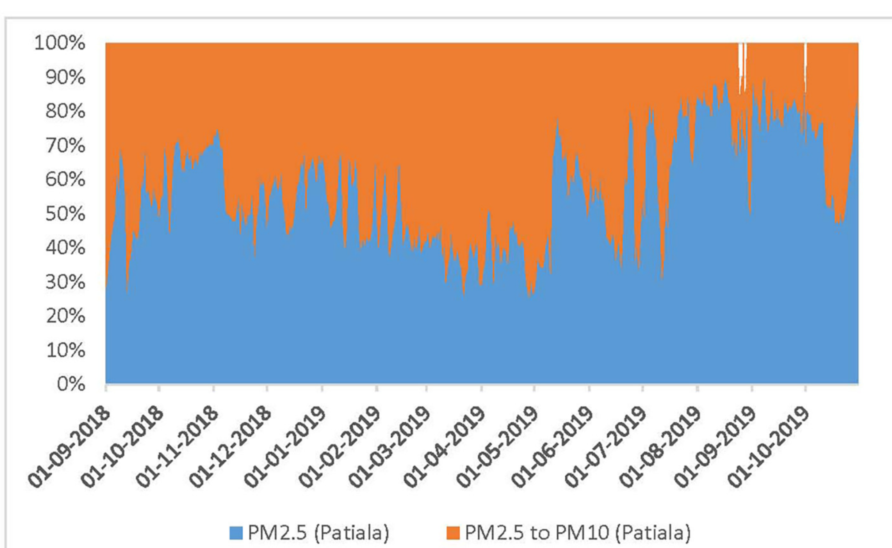

Fig. 14. Percentage distribution of particulate matter in Patiala.

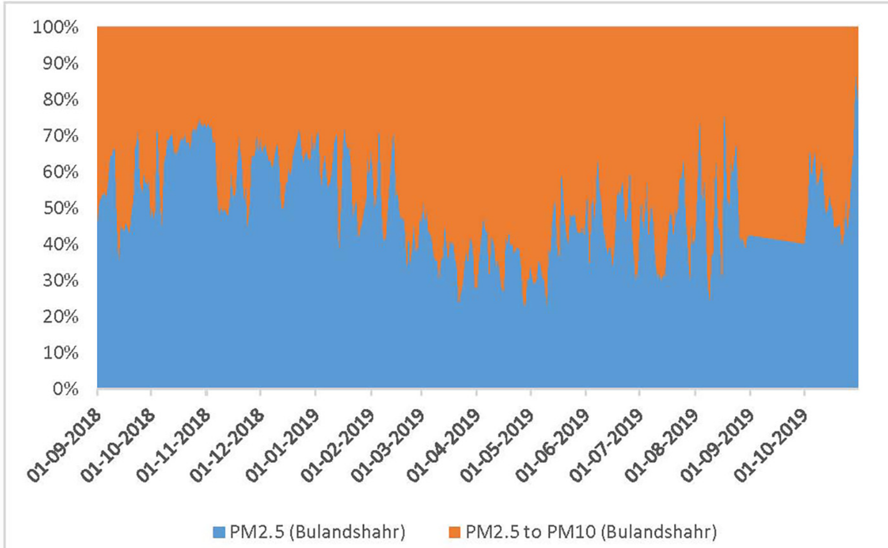

Fig. 15. Percentage distribution of particulate matter in Bulandshahr.

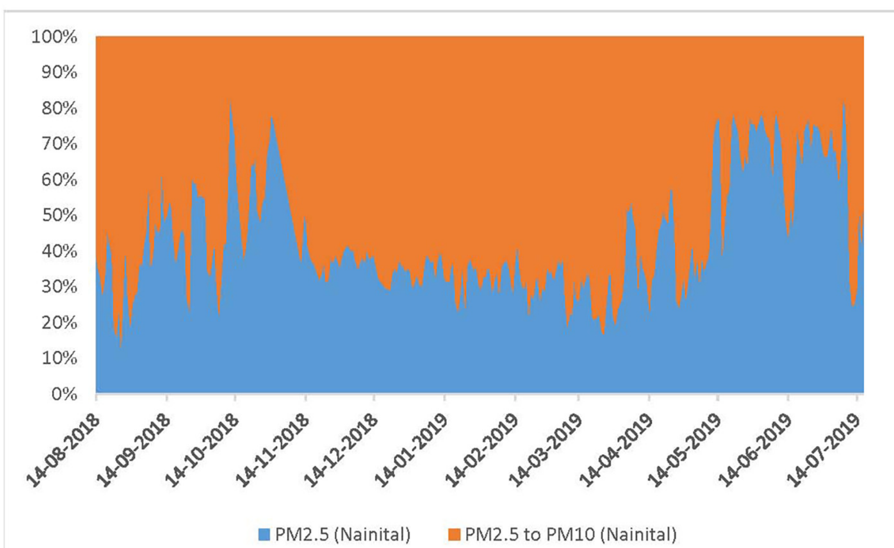

Fig. 16. Percentage distribution of particulate matter in Nainital.

As suggested by one of our reviewers, as part of the next phase of this study, we will also investigate the utility of machine learning and data mining techniques to analyze air quality data from locations across various geographic regions and determine airshed boundaries, which would then allow expansion of the geographic range of air quality monitoring, even with a sparse network of monitors.

Declaration of Competing Interest

None.

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