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ORIGINAL ARTICLE

Potential hotspot modeling and monitoring of $PM_{2.5}$ concentration for sustainable environmental health in Maharashtra, India

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Abstract

Modern human civilization has suffered from the disastrous impact of COVID-19, but it teaches us the lesson that the environment can restore its stability without human activity. The government of India (GOI) has launched many strategies to prevent the situation of COVID-19, including a lockdown that has a great impact on the environment. The present study focuses on the analysis of $PM_{2.5}$ concentration levels in pre-locking, lockdown, and unlocking phases across ten major cities of Maharashtra (MH) that were the COVID hotspot of India during the COVID-19 outbreak; phase-wise and year-wise (2018–2020) hotspot analysis, box diagram and line graph methods were used to assess spatial variation in $PM_{2.5}$ across MH cities. Our study showed that the $PM_{2.5}$ concentration level was severe at pre-lockdown stage (January–March) and it decreased dramatically at the lockdown stage, later it also increased in its previous position at the unlocking stages, i.e., $PM_{2.5}$ decreased dramatically (59%) during the lockdown period compared to the pre-lockdown period due to the shutdown of outdoor activities. It returns to its previous position due to the unlocking situation and increases (70%) compared to the lockdown period which illustrated the ups and downs of $PM_{2.5}$ and ensures the position of different cities in the AQI categories at different times. In the pre-lockdown phase, maximum $PM_{2.5}$ concentration was in NAV (358) and MUM (338), and PUN (335) and NAS (325) subsequently, whereas at the last of the lockdown phase, it becomes CHN (82), NAG (76), and SOL (45) subsequently. Hence, the restoration of the environment during the lockdown phase was temporary rather than permanent. Therefore, our findings propose that several effective policies of government such as relocation of polluting industries, short-term lockdown, odd–even vehicle number, installation of air purifier, and government strict initiatives are needed in making a sustainable environment.

Keywords $PM_{2.5}$ · Sustainable · Hotspot · Lockdown · COVID-19

Introduction

The whole world is now facing a serious threat from COVID-19, which was first identified in Wuhan City, China, in December 2019, and spread around the world in a very short time. This condition was primarily referred to as Wuhan pneumonia due to its concentration in the area. Later, however, the International Committee on Virus Taxonomy officially renamed the virus as corona virus acute respiratory syndrome 2 (SARS-COV-2). The disease is very infectious, and the spread of nature from China to other countries has been very rapid (Kodge 2021). WHO (2021a) declared it a global pandemic on 12 March 2020 making it the fifth largest pandemic after the 1918 Spanish flu, 1957 Asian flu, 1968 Hong Kong flu, and 2009 flu pandemic. COVID-19 is now a global threat to public health (Das et al. 2020). The changing nature of this pandemic has had an impact on the natural environment system and more than billions of people are living. According to the United Nations, this pandemic is a social, human and economic crisis for the world. The impact on the global scenario is very pitiful, with more than 83,910,386 confirmed cases and 1,839,660 worldwide deaths until 4 January 2021 (WHO 2021b). Among all the countries, many European and American countries are facing much worse conditions (Kumar et al. 2020). The USA takes the first position on confirmed cases as well as death tolls so far, but as an Asian country, India is also very

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significantly affected by its population density (Kumar et al. 2013) and takes second place in the global scenario (WHO 2021b).

The first confirmed case in India was identified by a student from the Southern State of Kerala on 30 January 2020 who was a student at Wuhan University. Keeping in mind the rapid expansion of the novel corona virus Indian Government has taken some initiatives to prevent the rapid spread of corona virus. First, 14 h of self-quarantine curfew come into effect on 22 March 2020 in the name of *Janata Curfew* (Government of India). After that, the Government of India declared a complete lockdown of the entire human population of the country for 21 days, from 25 March to 14 April, to break the COVID-19 chain. This lockdown strategy was further renewed three times as a second (15 April–3 May), third (4th May–17th May), and fourth (18th May–31st May) phase, respectively. India reached its peak in confirmed cases during September 2020 after which the curve gradually declined. Till now as of 5th January, India reported 10,356,844 confirmed cases and 149,850 death tolls (WHO 2021b) throughout the country.

The preventive measures adopted by the central government of India during the lockdown period are physical distancing, wearing a mask, improving room ventilation, and cleaning or sanitizing hands every time they do and touch anything. All kinds of strict measures are taken to limit the spread of this global pandemic. The lockdown of all actions affects all parts of society as well as the environmental and economic sectors (Das et al. 2021). The poor strategy of Indian government pushes the migrant workers in a difficult condition during lockdown period (Pal et al. 2021b). COVID-19 lockdown has been introduced for social distances, reduction of travel, closure of all outdoor activities during this period, including factories, industries, transport facilities, in particular, several anthropogenic actions; such reduction of economic activities has led to a decrease of anthropogenic emissions that resulting radical changes in environmental pollution as well as air pollution in India (Zhang et al. 2020; Sharma et al. 2020; Kumar et al. 2020). Hence, addressed public health policies made indirect health benefits through lower levels of air pollution (Son et al. 2020). Approximately, half of the population has been affected by this lockdown, which has been imposed on at least 89 countries that place serious restrictions on global economic activity resulting in a reduction in air pollution (Air pollution 2021). The Central Pollution Control Board (CPCB 2020) report shows that air pollution levels have decreased significantly during several phases of lock-up in India (Das et al. 2021). Lockdown periods are productive for the environment to regain its normal condition as well as its natural glory by reducing the amount of emitted pollutants produced by many anthropogenic activities. air quality Index was significantly improved at all parts of the world especially major pollutants such as $PM_{2.5}$ and PM_{10} were observed maximum reduction (40–60%) in a metropolitan city of India (Chowdhuri et al. 2022); the maximum and average temperature also significantly associated with the reduction of ambient air pollutants (Chakrabortty et al. 2021) that denotes that there is a notable reduction in air temperature due to improvement of air quality (Pal et al. 2021a). Pal et al. (2022) show how the strict lockdown influence in reducing the air pollutant and improve the air quality of four megacities of India. A distinctive study by Saha et al. (2021) estimated that how the air pollution got dramatic change in Delhi after unlocking India. In this study, we will find that these dramatic changes in air pollution are mainly $PM_{2.5}$ concentrations in ten cities of Maharashtra State, recorded as having the highest COVID-19 cases among all the states of India with the reference of previous years.

Substantial reductions in air pollution have been recorded throughout the world during this lockdown period. Many polluted cities such as Beijing, Delhi as well as developed cities such as New York, Paris, and Sydney are experienced dramatic improvement in air quality and reduced 46% particulate matter (Karuppasamy et al. 2020). Northern Italy also experienced a high reduction in NO_2 from January to March 2020 (Das et al. 2021). (Hashim et al. 2021) established the fact that there is about an 8% $PM_{2.5}$ reduction in Bagdad. China has also experienced a significant reduction in $PM_{2.5}$ due to the closure of industry and transportation (Wang et al. 2020). Therefore, several studies (Li et al. 2017; Zhu et al. 2020; Paital 2020; Venter et al. 2020; Jain et al. 2021) have ensured the variability of $PM_{2.5}$ in a global scenario during the COVID-19 situation which is very significant. Earlier, many studies were conducted based on $PM_{2.5}$ concentration in several cities in India (Guttikunda and Kopakka 2014; Guttikunda et al. 2014; Nagar et al. 2019; Chowdhury et al. 2019; Mahesh et al. 2019; Das et al. 2021). But till now very few studies have been conducted on the concentration of $PM_{2.5}$ during the COVID-19 period (Chauhan and Singh 2020; Sharma et al. 2020; Singh and Chauhan 2020; Mahato et al. 2020).

India's average $PM_{2.5}$ concentration level was 75 to over 85 µg per cubic meter in 2019 (Hindustan Times, 2020) which was 7.5 to 8.5 times greater than the WHO's (2005) clean air guidelines (10 µg/m^3) resulting in more than billions of people suffering under the risk of $PM_{2.5}$ (Chowdhury and Dey 2016). According to the Hindustan Times report, 980,000 premature deaths were recorded in India in 2019. As a result, GOI adopted several initiatives to reduce $PM_{2.5}$ such as National Clean Air Program launched in 2019 to achieve a 20–30% reduction in emission of $PM_{2.5}$ and other measures like LPG use and promotion of electric vehicles. Several government initiatives have tried to decrease $PM_{2.5}$, but all these policies become unsuccessful due to the substantial growth of urbanization and economic activities throughout the country. Among them road dust, thermal power plant, coal combustion, and vehicular and industrial emission are the major source of $PM_{2.5}$ in the Northern plain (Kulshrestha et al. 2009; Chakraborty and Gupta 2010; Villalobos et al. 2015); whereas in western India especially Maharashtra significantly affected due to industries, waste burning, household and marine sources (Shah and Nagpal 1997). The aforementioned research studies show that the COVID-19 phase brings dramatic changes in environmental restoration throughout the world as well as in India rather than implementing man-made policies. The commercial state of Maharashtra also gets the same benefit from it. Very few studies are available to analyze the air quality of Maharashtra (MH) as well as the concentration of $PM_{2.5}$ despite the harsh air quality of the MH state in the last few years (Hindustan Times, 2019). More than 11 crores of MH people breathe toxic air that does not meet the WHO's allowable limit (10 µg/m^3) of clean air (airpollution.io). The present study focuses on $PM_{2.5}$, a major pollutant due to its size, which can easily penetrate the human body and pose a serious health risk (WHO 2018). This scientific study will help to understand and analyze the variability of the concentration of $PM_{2.5}$ in the most vulnerable commercial state of Maharashtra during pre-locking, lockdown, and unlocking periods. This state was mostly affected by COVID-19 and, faced with the worst effect, passes through a strict lockdown period resulting in a temporary reduction of $PM_{2.5}$.

Materials and methods

Study area

Maharashtra state is located in the north-central part of India with altitudinal extension of 15°33′46″ N to 22° 02′13″ N and 72°38′45″ E to 80°53′17″ E latitude. The state shared its boundary with many Indian states such as Gujrat and Madhya Pradesh in the north, Chhattisgarh and Telangana in the East, and Karnataka and Goa in the South (Fig. 1). The Arabian Sea is situated on the entire western coast and different hills are located here (Kodge 2021). It is the most populous and progressive state of India and is notably famous as an industrial and commercial hub as well as the financial capital of India (Pagar 2015). The state with an area of 3.08 lakh Km^2 is situated in the western part of Peninsular India. The monsoon type of climate is very suitable for the population density in this region and makes it the most developed state of India. Demographically, this state ranked 3rd with a population of 11, 23.72,972 as per the 2011 census, and population density is 365 person/km^2.

Maharashtra state has suffered from a huge amount of $PM_{2.5}$ concentration due to its industrial, transportation, and construction activities (Fig. 2). A report in The Times of India https://timesofindia.indiatimes.com/city/mumbai/articleshow/83445637.cms) (12 June 2021) shows that the aforementioned cities are significantly polluted and ranked top of the order in pollution levels before the lockdown stage due to excessive vehicle exhaust and waste burning throughout the cities. Therefore, the continuous burning of fossil fuels releases several air pollutants to the atmosphere and makes the atmosphere vulnerable to the inhabitants. Thus, ten important cities located in this state experience severe unhealthy air quality conditions most of the time.

(i) Aurangabad (AUR) city is situated in the hilly uplands of the decantrap region with 19.8762° N latitude and 75.3433° E longitude. It is the fourth most populous city of MH having a population of more than 11 lakh. The city is most popular due to its textile industry and is also known as the city of Gates.

(ii) Chandrapur (CHN), this city is popularly known as the geological museum and black gold city of MH due to its geological pattern and availability of coal. It is located at the confluence of the Zarpat and Irai Rivers with 19.9615° N latitude and 79.2961° E longitude.

(iii) Kalyan (KAL) is the neighboring city of Mumbai situated at 19.2403° N latitude and 73.1305° E longitude and is also a part of the Mumbai Metropolitan Region. It is the 9th biggest city in MH. $PM_{2.5}$ concentration is very alarming in this region in recent years.

(iv) Mumbai (MUM) metropolitan region ranked 6th in the world (Pacione 2006) and is popularly known as the financial capital of India with a population of more than 20 million and a density of 3850 per Km^2(Kumar et al. 2020). According to a Greenpeace report, Mumbai is the 37th most polluted city in India (Hindustan Times 2020). It is located at the coastline of the state in the 19.0760° N latitude and 72.8777° E longitude.

(v) Nagpur city is the winter capital of MH. It is the third-largest city of MH and the 13th largest city in India based on population (Oxford Economic report) which was 24.1 lakh as of the 2011 census. This city is very significant in industrial development and is located at 21.1458° N latitude and 79.0882° E longitude.

(vi) Nashik is known as the Wine capital of India and is situated on the bank of the Godavari River; its absolute location is 19.9925° N and 73.7898° E. This city is significantly vulnerable to air pollution as well as $PM_{2.5}$ concentration. Most of the residents are facing breathing problems due to its unhealthy and poor air quality.

(vii) Navi Mumbai is the largest planned city in India situated in the western part of the state with an absolute location of 19.0330° N and 73.0297° E. The majority of the time, the atmosphere is unhealthy.

(viii) Pune is located at 18.5204° N latitude and 73.8567° E longitude with a dense population. The city is suf-

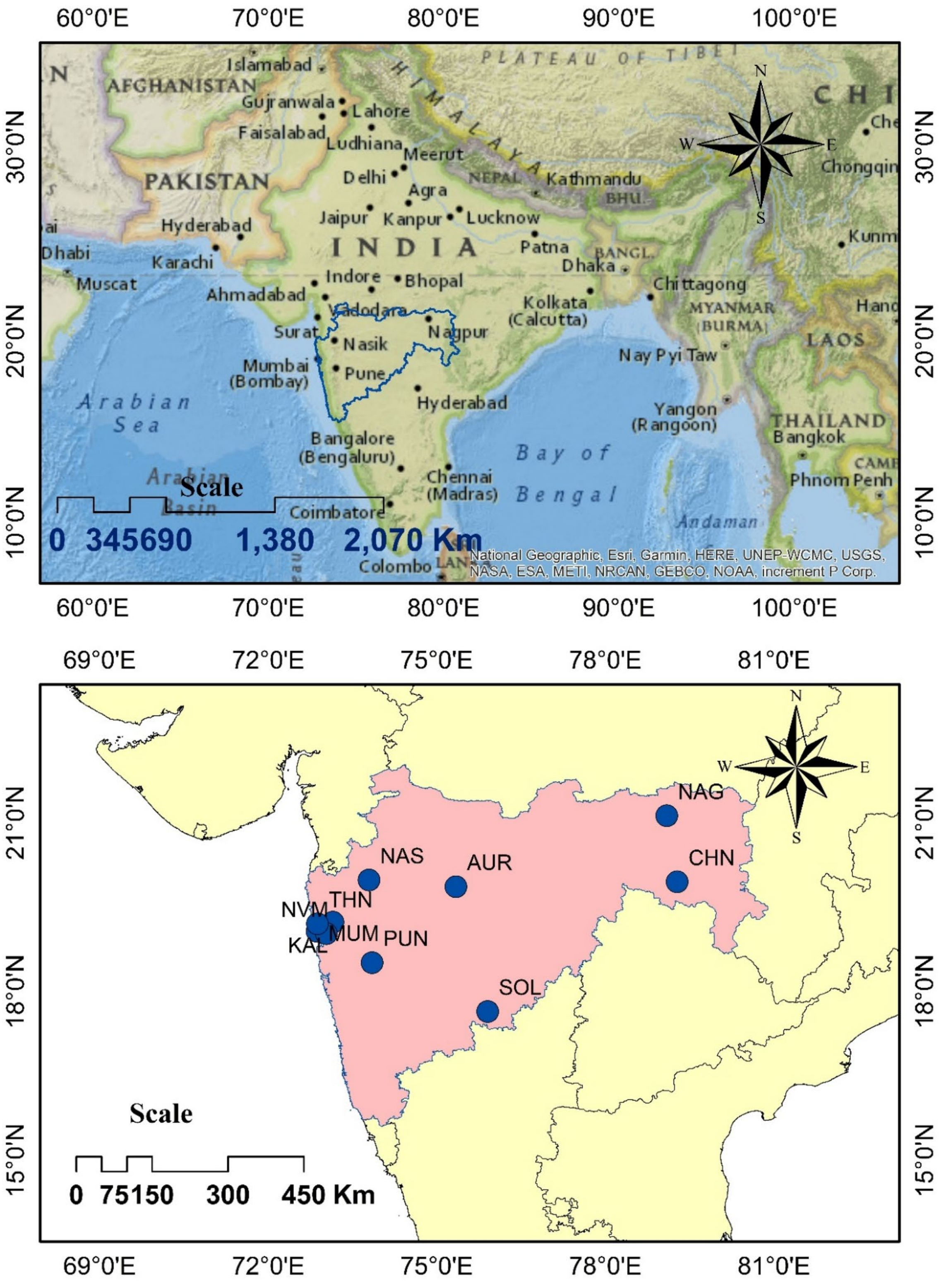


Fig. 1 Location map of study area

fering from unhealthy and moderate air conditions because of its huge transportation and manufacturing industry which are the key sector of this city.

(ix) Solapur is the south-western city of MH, located at the 17.6599° N latitude and 75.9064° E longitude sharing a

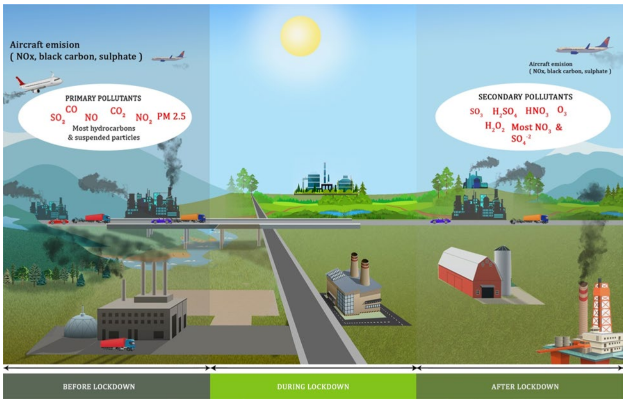


Fig. 2 Environmental pollution during different phases of lockdown period

close border with Karnataka. This city has a population of 9.51 lakh as of the 2011 census.

(x) Thane is a part of the Mumbai Metropolitan Region (MMR) which is situated in the north-western part of MH and close to Mumbai city. The city is characterized by more than 18 lakh population as of the 2011 census and the population density is 13000/Km^2.

Data source

The delineation of $PM_{2.5}$ concentration has been done based on hourly data provided by Central Pollution Control Board (CPCB). These data are collected to analyze the spatio-temporal variation in $PM_{2.5}$ throughout ten important cities of MH. It also helps in the hotspot analysis of each city. The hourly data are classified into three categories for the year 2020 such as before lockdown (1st January–15 March), lockdown period (25th March–31st May) and after lockdown, which means unlock situation (1st June–30th June, 1st October–31st December) which are collected from CPCB (https://app.cpcbccr.com/AQI_India/). The yearly data of 4 months (March to June) for the years 2018, 2019, and 2020 have also been collected to compare the variability of $PM_{2.5}$ concentration during the lockdown period with the previous year. All these data can help to assess the actual trend of $PM_{2.5}$ concentration in pre-lockdown, during the lockdown and unlock period in India.

Methods

Spatial interpolation of $PM_{2.5}$ throughout the cities

Different kinds of interpolation methods are available to analyze data such as Natural Neighbor Method, Nearest Neighbor Method, Kriging Method, Moving Average Method, Polynomial Regression Method, and Inverse Distance Weighted Method which are used by the different scholars in their studies (Rukundo and Cao 2012; Apak and Atay 2013; Ma et al. 2019; Das et al. 2021; Ruidas et al. 2021, 2022a, b). Musikavong and Gheewala (2017) have proposed that the Kriging method can be a more efficient spatial analysis tool at the national level; whereas the method is appropriate and mostly used spatial analysis tool at the regional level (Zhang and Tripathi 2018). Therefore, in this study, IDW method has been used to analyze the spatial concentration of $PM_{2.5}$ with the help of Arc GIS 10.4. This method is performed in this finding with the help of the following equation:

$$Z_0 = \frac{\sum_{i=1}^{S} \frac{Zi}{d_i^k}}{\sum_{i=1}^{S} \frac{1}{d_i^k}} \tag{1}$$

where the values of the unknown point pointed by Z_0, z_i stands for the observed value at i point, d_i refers to the distance between point i and 0, s represent the no. of known points provided in assessment and k stands for specified power (Guan and Wu 2008).

Hotspot analysis of $PM_{2.5}$ throughout the cities

IDW method helps to assess the spatio-temporal as well as spatial variation of $PM_{2.5}$ throughout the ten cities of MH but it does not identify the spatial cluster significantly (Das et al. 2021). Due to this reason, Zhang and Tripathi (2018) state that hotspots can describe the grouping of spatial clusters efficiently. This is very helpful in assessing point density in a particular area as well as it measures the extent of point occurrence to describe the spatial pattern. In this study, the Getis-Ord-Gi* application has been used to identify the hotspot and coldspot which plays a very efficient role (Das et al. 2021). This method has been performed in Arc GIS 10.4 for this study based on the following equations:

$$Gi *= \frac{\sum_{j=1}^{n} wi.jwj - x\sum_{j=1}^{n} wi.j}{\sqrt{\frac{\sum_{j=1}^{n} w2i.j-(\sum_{j=1}^{n} wi.j)2}{n-1}}} \tag{2}$$

where the weight of ith sub-component is represented by w_j, spatial weight between ith and jth components is referred by w_{ij}, x_j is the value of jth component with the n number of features:

$$X^{-} = \frac{\sum_{j}^{n} xj}{n} \tag{3}$$

$$S = \sqrt{\frac{\sum_{j=1}^{n} x2j}{n} - (x^{-})2} \tag{4}$$

The advantage of this Getis-Ord-Gi* application is that it is very easy to perform and understand. Here, high cluster value represents the hotspot and the low cluster value means the coldspot. Therefore, in this study, high and low concentrations of $PM_{2.5}$ mean the hotspot and coldspots, respectively.

Different statistical methods

In the present study, various statistical methods such as box diagram and line graph analysis are also performed for a detailed assessment of $PM_{2.5}$ concentration in ten important cities of MH (Fig. 3). The spatio-temporal maps were prepared based on hourly data of before lockdown, during the lockdown, and during unlocking phases to show the trend of $PM_{2.5}$ at different times. Box diagram of different times depicts the variability of $PM_{2.5}$ in the different periods from January to December in 2020. Line graph of several cities of MH also shows the up and down of the $PM_{2.5}$ curve in a different months of the lockdown period.

Results and discussion

Many studies (Li et al. 2017; Yang et al. 2017; Das et al. 2021) have shown that $PM_{2.5}$ is an important component of the atmosphere that plays a significant role in controlling atmospheric temperature, humidity, and other characteristics at a regional scale. Singh and Chauhan (2020), Berman and Ebisu (2020), Yin et al. (2021), Jephcote et al. (2021) have displayed how worldwide lockdown events due to COVID-19 help to decrease air pollution in a global scenario. Besides, several studies (Singh et al. 2020; Chakrabarty et al. 2020; Laxmipriya and Narayanan 2021) have tried to find out the direct relation between $PM_{2.5}$ and COVID-19-positive cases in different areas. According to the estimation of Wu et al. (2020), about 8% COVID-19 death rate has been increased with the only rise of only 1 $\mu g/m^3$ $PM_{2.5}$. $PM_{2.5}$ also has a great impact on visibility and put adverse effects on the environment and also poses a great impact on human health especially affecting the lung and heart of the human body, making lung cancer like deadly disease (Hu and Jiang 2014) that can increase the mortality and morbidity by weakening the immune system (Glencross et al. 2020).

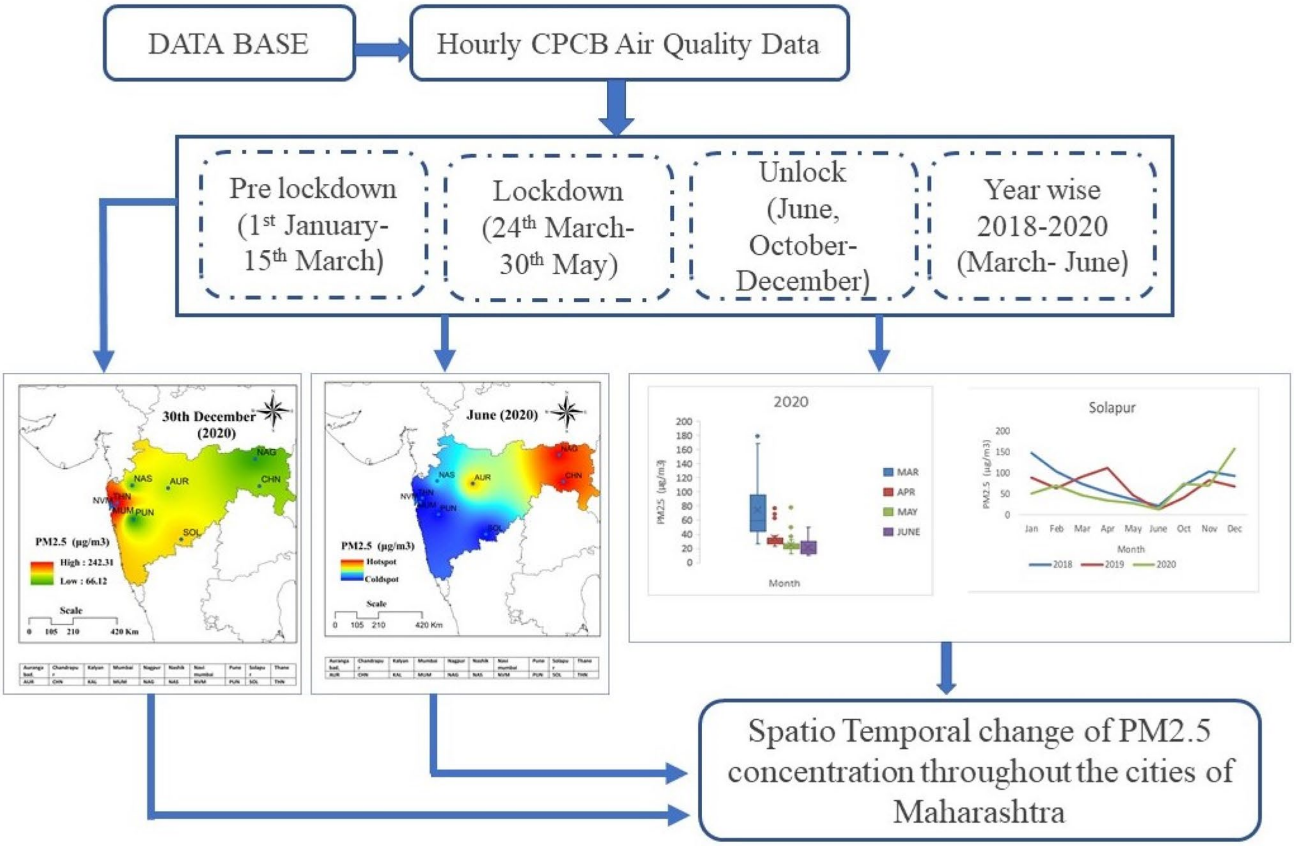


Fig. 3 Methodological frameworks for the study

That is why $PM_{2.5}$ is a very crucial component in measuring the air quality of an area. Routine monitoring is the only way to control this fatal particulate matter. Maximum cities of India are highly vulnerable to $PM_{2.5}$ concentration which makes poor air quality index occurring due to its high population, transportation, and industrial activities. All the ten important cities of MH experienced very high $PM_{2.5}$ concentration in previous years as well as in the current year. But during the lockdown period, MH experienced a dramatic change in $PM_{2.5}$ level. In this study, we are going to find this phenomenon by establishing the relationship between lockdown and lowering of $PM_{2.5}$ concentration across the cities of MH. GOI implemented the lockdown strategy to prevent COVID-19 which has a direct effect on the setting down of $PM_{2.5}$ resulting in a very significant curve line and variation in spatio-temporal context throughout the cities during the different periods of lockdown (Table 1).

Spatial variation of $PM_{2.5}$ concentration throughout the cities in pre-lockdown period

The MH state and its cities are most vulnerable to $PM_{2.5}$ levels during previous years and remain almost the same in the current year, resulting, in adverse effects in a large population of MH. Before implementing the lockdown, the cities of MH, as well as India, were under pre-lockdown stage (1st Jan–15th Mar). During this time, several cities of MH have experienced extremely high $PM_{2.5}$ concentrations compared to the permissible limit of a human body (10 μg/m^3, WHO). Spatial distribution of $PM_{2.5}$ shows that it is mainly concentrated at MMR due to excessive engagement in several economic activities and its surrounding region, whereas it is less at the areas far away from the MMR region based on various activities. During the month of January, maximum $PM_{2.5}$ concentration was in NAV (358) and MUM (338), and PUN (335) and NAS (325) subsequently take their position which picturize the pollution level of cities of MH having an impact upon meteorological phenomenon in regional level. The average $PM_{2.5}$ concentration is also significantly unhealthy for the environment as well as the human body; the highest level concentration in January was mainly concentrated at NAV (248) followed by MUM (236), NAS (190), AUR (142), and PUN (141).

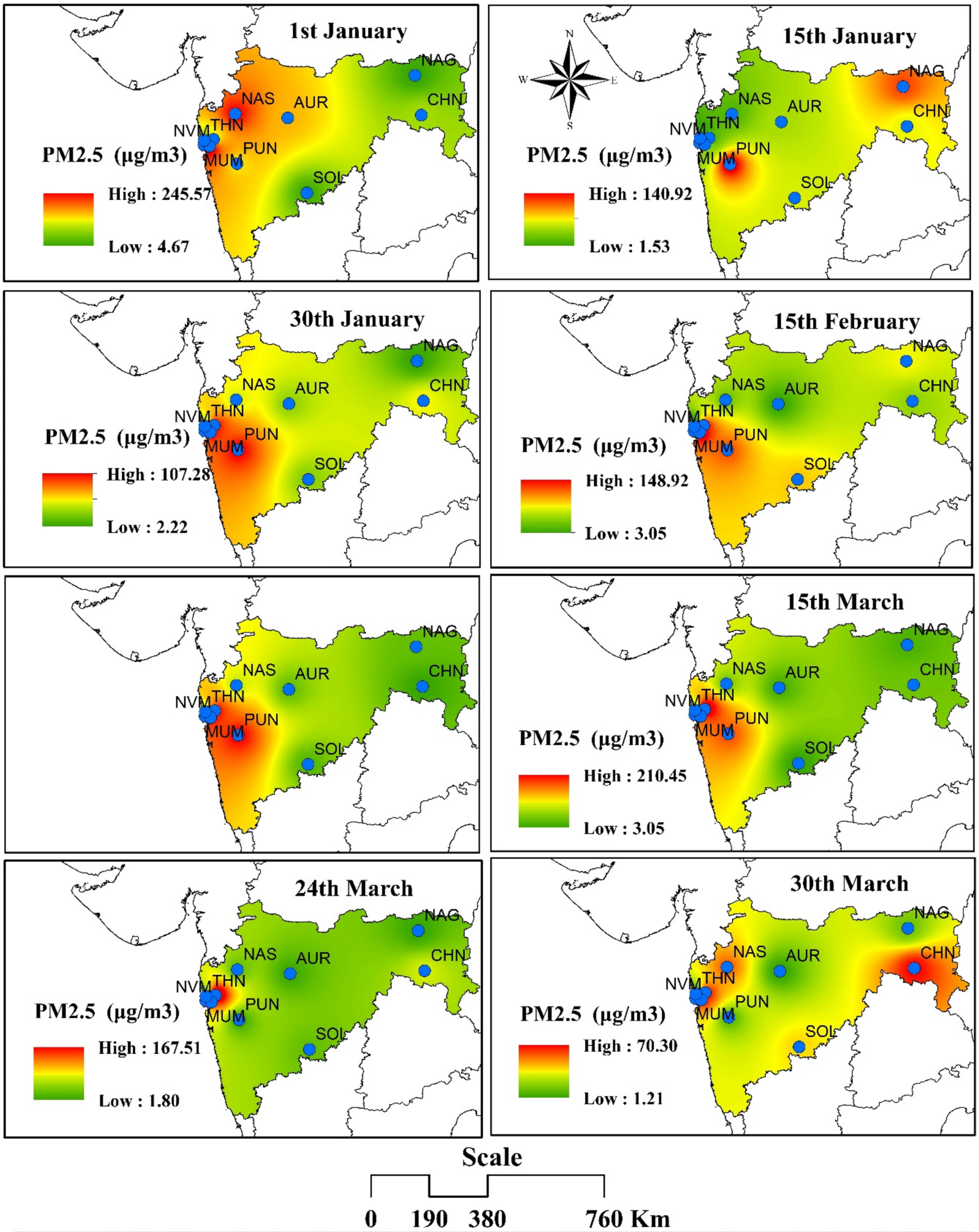
Table 1 Temporal concentration level of $PM_{2.5}$ on various time periods

Different phases of lockdown (2020)	Time period	PM2.5 concentration (μg/m3)
Before lockdown	1st January to 15th March	109
I Phase	24th March to 14th April	57.27
II Phase	15th April to 3rd May	42.38
III Phase	4th May to 17th May	42
IV Phase	18th May to 31st May	35.72
Unlock I	1st June to 30th June	19
Unlock V	1st October to 31st October	72
Unlock VI	1st November to 30th November	99
Unlock VII	1st December to 31st December	110

In the month of February, maximum $PM_{2.5}$ concentration is identified at PUN (372) than NAV (337), KAL (325), and MUM (309); whereas the highest average concentration was recorded in this month at KAL (225) and NAV, MUM and PUN also take a position in the top with 223, 222, and 210 μg/m^3, respectively. Around half of the days of March fall under pre-lockdown phase (Fig. 4), and in this month, minor decrease of $PM_{2.5}$ was recorded, but after adopting lockdown from 24th March, it significantly decreases where average $PM_{2.5}$ in the first week of January was 142 μg/m^3 then it declined to 32 μg/m^3 in the first week of May.

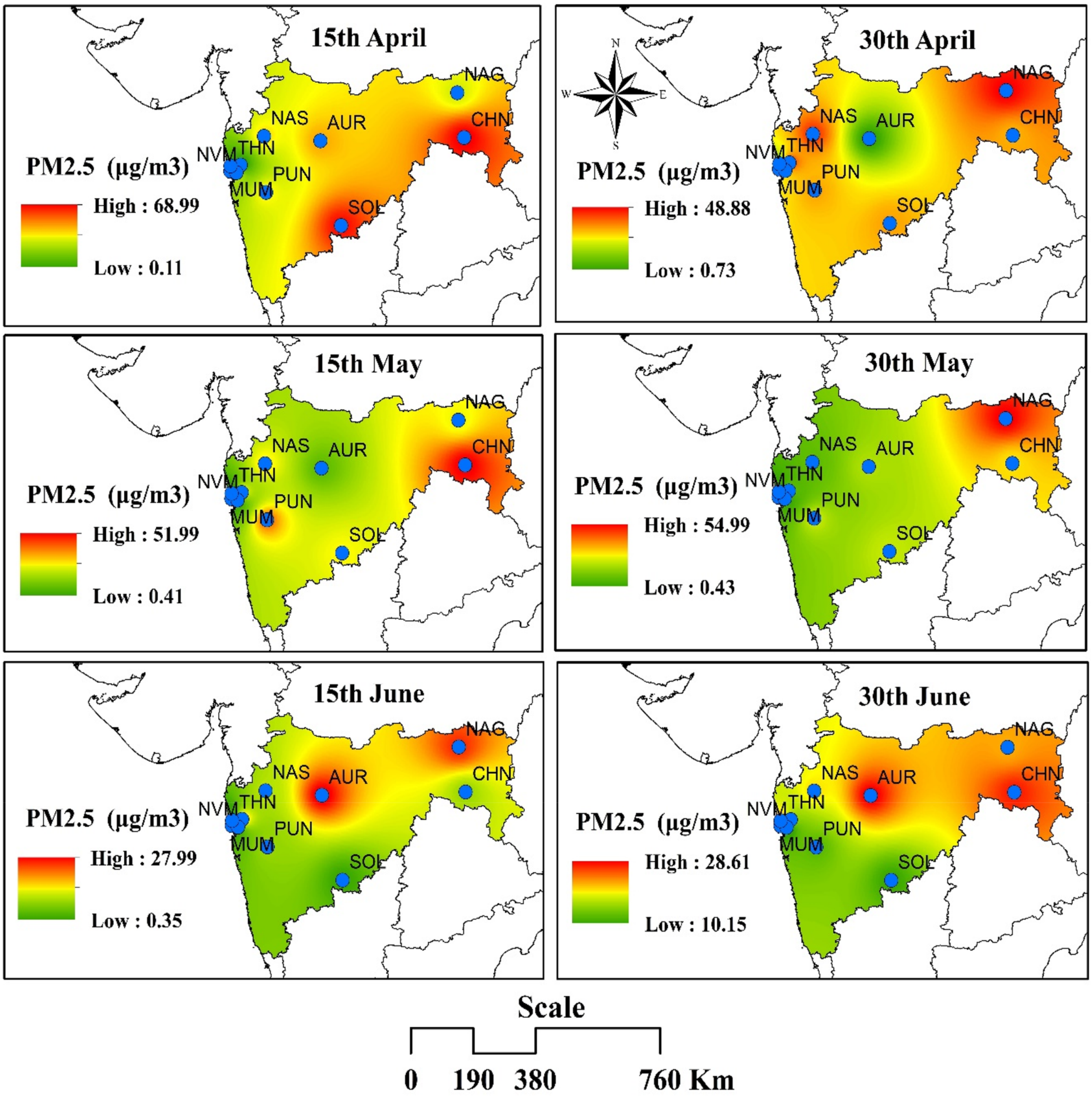
Spatial variation of $PM_{2.5}$ concentration throughout the cities during the lockdown period

This lockdown period serves as a very crucial time for the environment to repair her disease which occurs due to anthropogenic activities. It was identified that there was a significant change in air pollution after enactment of lockdown from 24th March which stayed up to 31st May; that involves shutting down of all the industries, outdoor activities, and stagnation of transport vehicles leading to a dramatic decline in $PM_{2.5}$ level, helping the state population to breath better air. All the cities of MH experienced low $PM_{2.5}$ concentration during that period which provides a very healthy condition for human beings with sequential changes such as about 50% decrease at the end of March, 65% at the end of April, and 74% at the end of May compared to before lockdown period. The mean $PM_{2.5}$ throughout the cities was 74 μg/m^3 on 24th March 2020 then it was 26 μg/m^3 on 30th May (the last day of the lockdown period). The decline of spatial variation of $PM_{2.5}$ across the cities (Figs. 4, 5) was remarkable when the mean $PM_{2.5}$ was so high in pre-lockdown situation but in this period, it became very low. At the end of April, $PM_{2.5}$ concentration was recorded at KAL (80) followed by THN (73) and MUM (68), whereas in May, it was highest at CHN (82), NAG (76), and SOL (45); therefore, the mean $PM_{2.5}$ concentration (μg/m^3) was 47 at KAL at the end of April and 35 at CHN at the end of May; this situation may be the first time in state history. The transmission of several infectious diseases was significantly restricted due to improvement in air quality (Manoj et al. 2020).



Aurangabad.	Chandrapur	Kalyan	Mumbai	Nagpur	Nashik	Navi mumbai	Pune	Solapur	Thane
AUR	CHN	KAL	MUM	NAG	NAS	NVM	PUN	SOL	THN

Fig. 4 Spatial variation of $PM_{2.5}$ concentration (January–March)



15th April

30th April

15th May

30th May

15th June

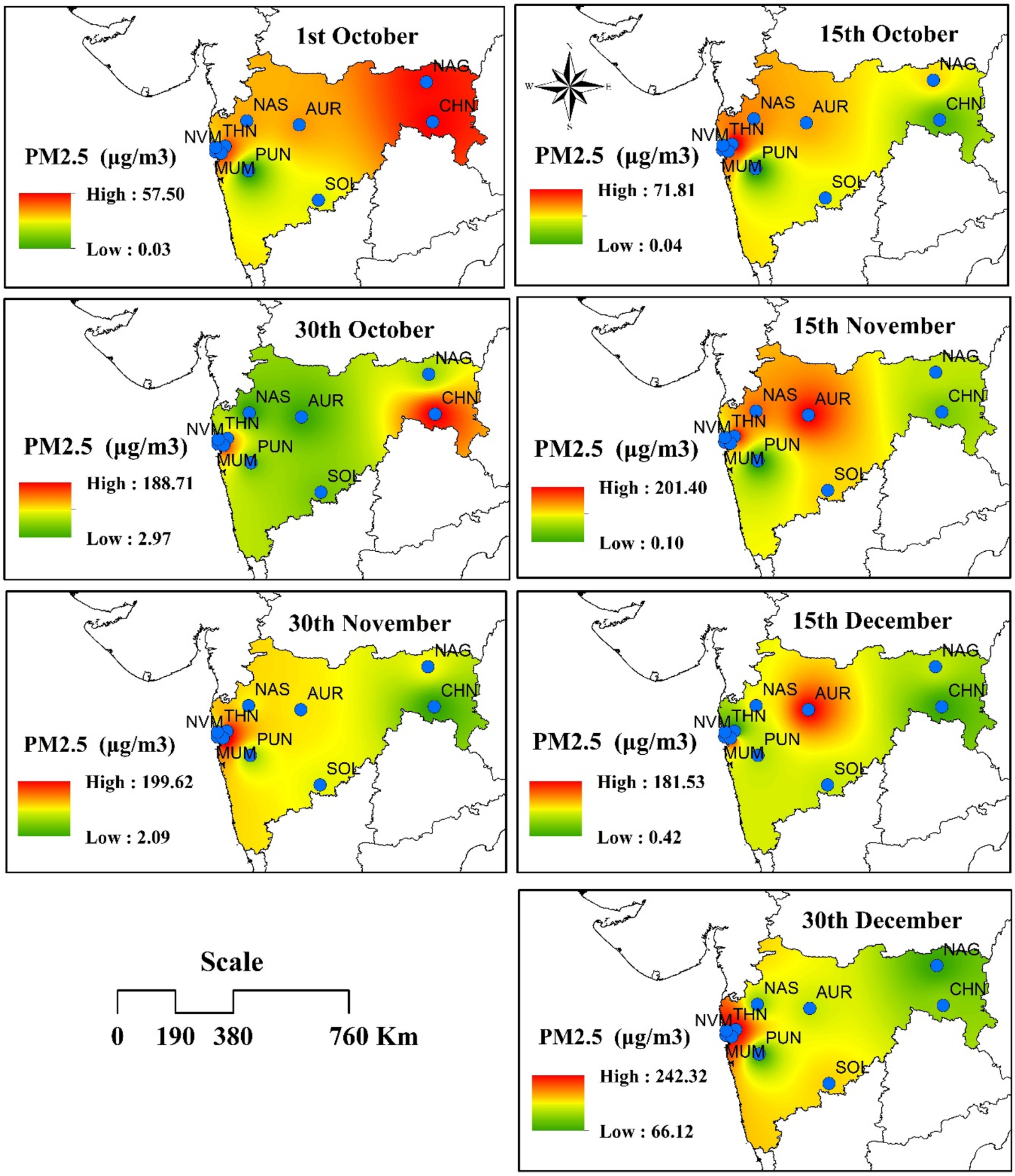
30th June

Aurangabad.	Chandrapur	Kalyan	Mumbai	Nagpur	Nashik	Navi mumbai	Pune	Solapur	Thane
AUR	CHN	KAL	MUM	NAG	NAS	NVM	PUN	SOL	THN

Fig. 5 Spatial variation of $PM_{2.5}$ concentration (April–June)

Spatial variation of $PM_{2.5}$ concentration throughout the cities in unlock period

Although the lockdown situation gives a great opportunity to the environment to rejuvenate its sustainability, it has a significant impact on human civilization pointedly economic activities of several regions. The same situation has occurred in the cities of India as well as MH state because of the closedown of industrial activities which are the strength of MH. Hence, GOI started to open up all the activities step by step. The process of partial unlocking occurred in various stages by GOI from 1st June to 31st December (Unlock I–VII). During this time period, the cities were gradually reaching their previous situation of air condition during lockdown (Figs. 5, 6). During the unlock I (June), the $PM_{2.5}$ concentration was very low because the effect of lockdown in nature was still present at that time. The mean $PM_{2.5}$ concentration in June was 19 µg/m^3 which represents a very good condition of the atmosphere. But later it gradually increases across the cities and reaches the previous situation of lockdown because all the outdoor activities started again. The maximum average $PM_{2.5}$



Aurangabad.	Chandrapur	Kalyan	Mumbai	Nagpur	Nashik	Navi mumbai	Pune	Solapur	Thane
AUR	CHN	KAL	MUM	NAG	NAS	NVM	PUN	SOL	THN

Fig. 6 Spatial variation of $PM_{2.5}$ concentration (October–December)

concentration in the month of June was recorded at THN (29) followed by AUR (28) and NAG (26), and then in the month of December (Unlock VII), it was maximum at KAL (238) followed by NAV (211) and SOL (159), became worse and unhealthy environment like before COVID-19 phase.

Changes occurring in AQI among cities of MH during different stages of lockdown

Although $PM_{2.5}$ concentration level decreases at a significant rate during these three phases. CPCB calendar also shows dramatic changes in AQI among several cities of MH and change in their position at AQI categorical division based on the range of concentration (24 h) of before lockdown, lockdown, and unlock stages in India. The air quality index for pollutants is categorized in six by the System of Air Quality and Weather Forecasting (SAFAR) such as good, satisfactory, moderate, poor, very poor, and severe as 0–50, 51–100, 101–200, 201–300, 301–400, and 401–500, respectively. According to WHO (2018) air pollution database, Mumbai is the fourth most polluted megacity in the world. Before the lockdown period, the $PM_{2.5}$ concentration level across ten cities of MH was so high and it resembled the previous year's hazardous condition in AQI which was very harmful for the human population to survive. Several cities during the pre-lockdown phase were under the poor category and most of them were under the moderate category, only a few cities were under the satisfactory category mentioned in Table 2. The huge amount of manufacturing industry, construction activities, and a large number of traffic is held responsible for this kind of situation.

The lockdown phase served as a gift to the environment to heal and overcome its previous situation. Several cities of MH that fell under the poor category during the pre-lockdown stage have recovered themselves very well and take a position in the good to the satisfactory category as well as no cities of MH fall under the poor category which is a very good sign for the environment as well as a human population which is shown in Table 3.

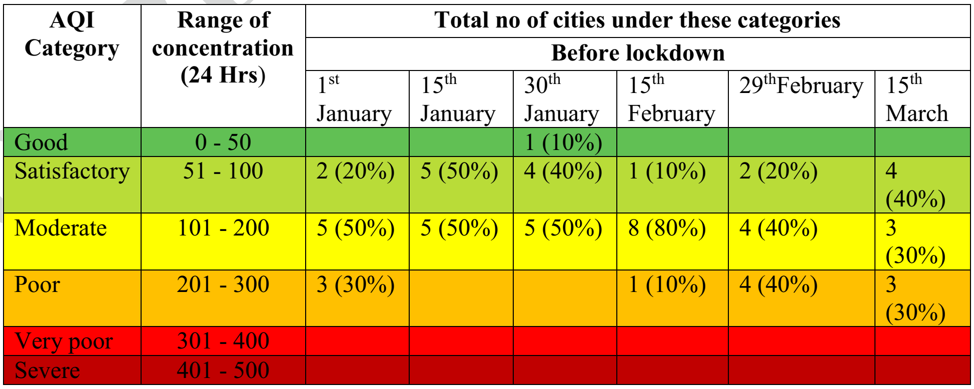
After the lockdown, GOI started to unlock to heal the economy of India but it became a curse for the environment which leads to the substantial increase in $PM_{2.5}$ level that was responsible for poor AQI. Table 4 displays that several cities which were earlier positioned in the good to satisfactory category stepped down their position and reach the spot of moderate to poor AQI again.

Therefore, before the lockdown situation, the lockdown situation and unlock situation experienced ups and downs in the average $PM_{2.5}$ concentration level in different months of the year 2020 (Fig. 7). These situations are slightly related to COVID-19 because at that time, MH was the hotspot of India in the COVID-19 outbreak and suffered from a huge impact of it.

Comparison of $PM_{2.5}$ concentration levels during the month of March–June (2018–2020)

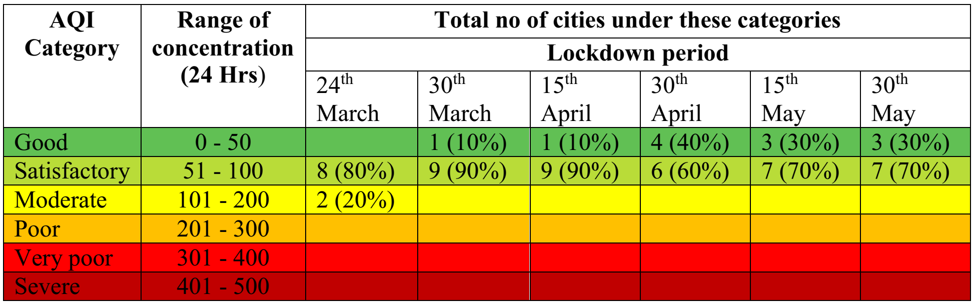
Previous years are the evidence of high $PM_{2.5}$ concentration from which we can easily understand the trend and

Table 2 Number of cities under AQI categories on $PM_{2.5}$ in before lockdown



AQI Category	Range of concentration (24 Hrs)	Total no of cities under these categories					
		Before lockdown					
		1st January	15th January	30th January	15th February	29th February	15th March
Good	0 - 50			1 (10%)			
Satisfactory	51 - 100	2 (20%)	5 (50%)	4 (40%)	1 (10%)	2 (20%)	4 (40%)
Moderate	101 - 200	5 (50%)	5 (50%)	5 (50%)	8 (80%)	4 (40%)	3 (30%)
Poor	201 - 300	3 (30%)			1 (10%)	4 (40%)	3 (30%)
Very poor	301 - 400						
Severe	401 - 500						

Table 3 Number of cities under AQI categories on $PM_{2.5}$ during lockdown



AQI Category	Range of concentration (24 Hrs)	Total no of cities under these categories					
		Lockdown period					
		24th March	30th March	15th April	30th April	15th May	30th May
Good	0 - 50		1 (10%)	1 (10%)	4 (40%)	3 (30%)	3 (30%)
Satisfactory	51 - 100	8 (80%)	9 (90%)	9 (90%)	6 (60%)	7 (70%)	7 (70%)
Moderate	101 - 200	2 (20%)					
Poor	201 - 300						
Very poor	301 - 400						
Severe	401 - 500						

Table 4 Number of cities under AQI categories on $PM_{2.5}$ in unlock stages

AQI Category	Range of concentration (24 Hrs)	Total no of cities under these categories								
		Unlock time								
		15th JUN	30th JUN	1st OCT	15th OCT	30th OCT	15th NOV	30th NOV	15th DEC	31st DEC
Good	0 - 50	9 (90%)	8 (80%)		4 (40%)			1 (10%)		
Satisfactory	51 - 100	1 (10%)	1 (10%)	6 (60%)	5 (50%)	4 (40%)	1 (10%)	5 (50%)	3 (30%)	2 (20%)
Moderate	101 - 200		1 (10%)	4 (40%)	1 (10%)	6 (60%)	7 (70%)	4 (40%)	7 (70%)	4 (40%)
Poor	201 - 300						1 (10%)			4 (40%)
Very poor	301 - 400									
Severe	401 - 500									

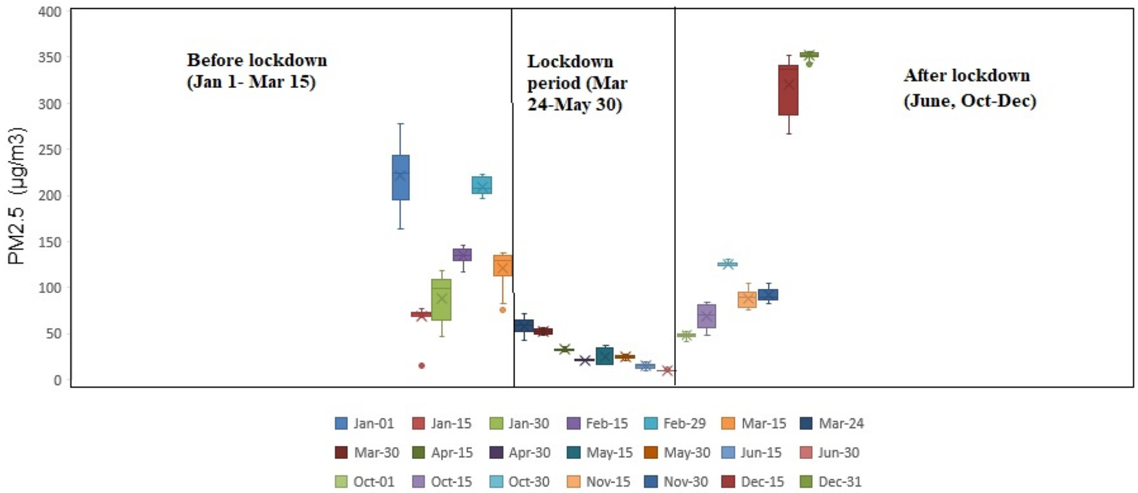


Fig. 7 Situation of $PM_{2.5}$ concentrations before lockdown, during lockdown and unlock stages

compare it with recent times. It ensures that the significant decline in $PM_{2.5}$ only occurred due to the lockdown effect. In this study, we make a comparison among 2018, 2019, and 2020 $PM_{2.5}$ concentration levels during the month of March to June of each year (Fig. 8). This can help to understand the impact of COVID-19 as well as the lockdown on the atmosphere. The mean $PM_{2.5}$ concentration of the earlier 2 years (2018, 2019) was 76 µg/m^3, whereas 39 µg/m^3 in 2020 that represents a significant decline (48%) compared to previous years. The maximum mean $PM_{2.5}$ (µg/m^3) was documented at CHN (187) in 2018, THN (192) in 2019, and KAL (69) in 2020. All the cities experienced a substantial decrease of $PM_{2.5}$ from March to June in 2020 compared to 2018, and 2019. Maximum decrease was occurring at AUR (83%), NAG (78%), CHN (68%), PUN (56%), SOL (56%), MUM (51%), and NAS (29%) compared to the year 2018.

Hotspot analysis of different phases of lockdown

Lockdown was the preventive measure of the COVID-19 situation which is a serious threat to human civilization and its impact on economic activity is very severe. Various industries and many outdoor activities were stopped during this time. Therefore, the $PM_{2.5}$ level drastically changes in different phases of lockdown which depicts different hotspot regions (Fig. 9) of MH across the cities. Basically, 100 AQI and 35 µg/m^3 of $PM_{2.5}$ is the higher limit of satisfactory category by CPCB standard and it is also the permissible value for human health; when it crosses its value, then this area turns into an atmospherically polluted and hotspot region. $PM_{2.5}$ has a notable contribution in making the harsh AQI. Thus, there is a significant relationship between the AQI and hotspot region. These hotspot regions are significantly different

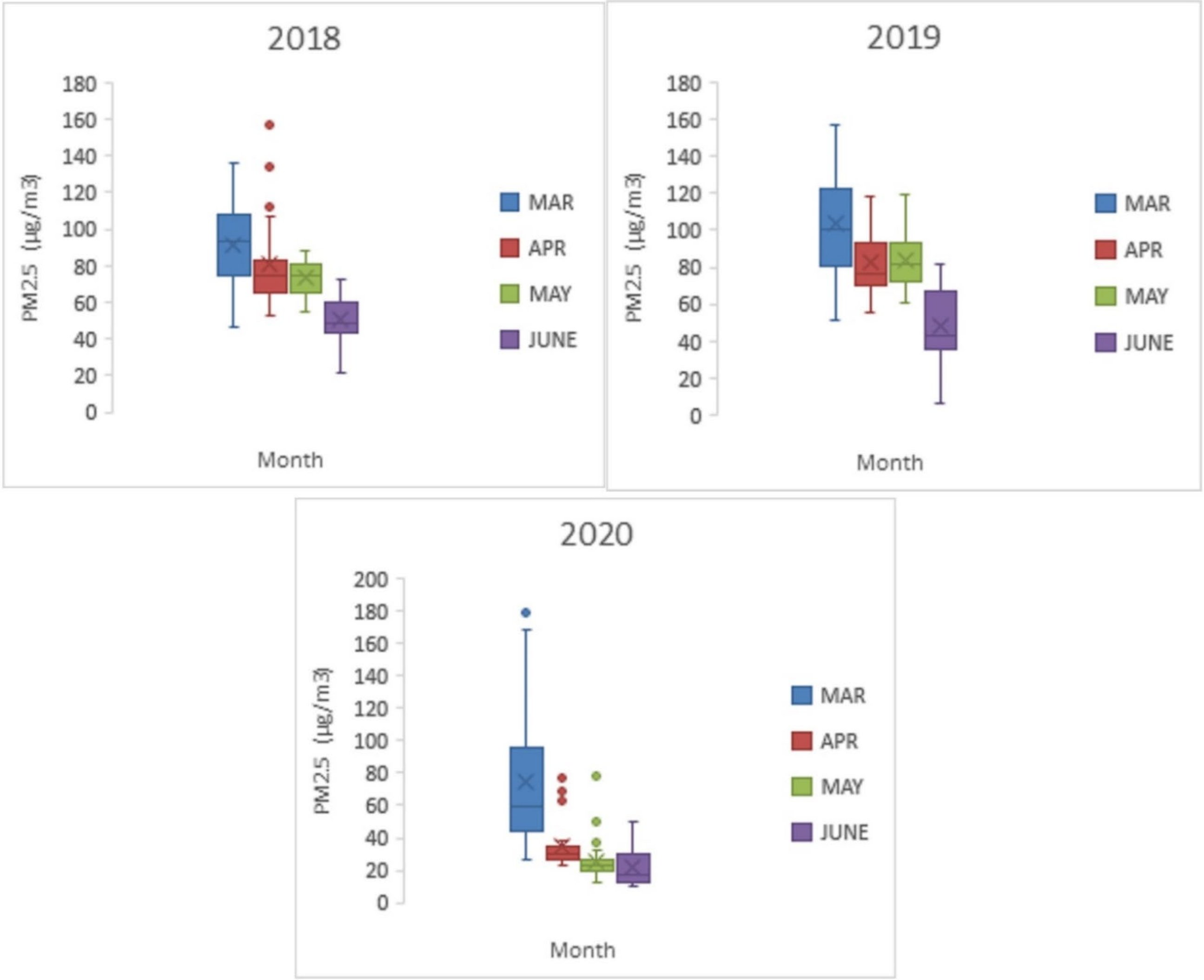


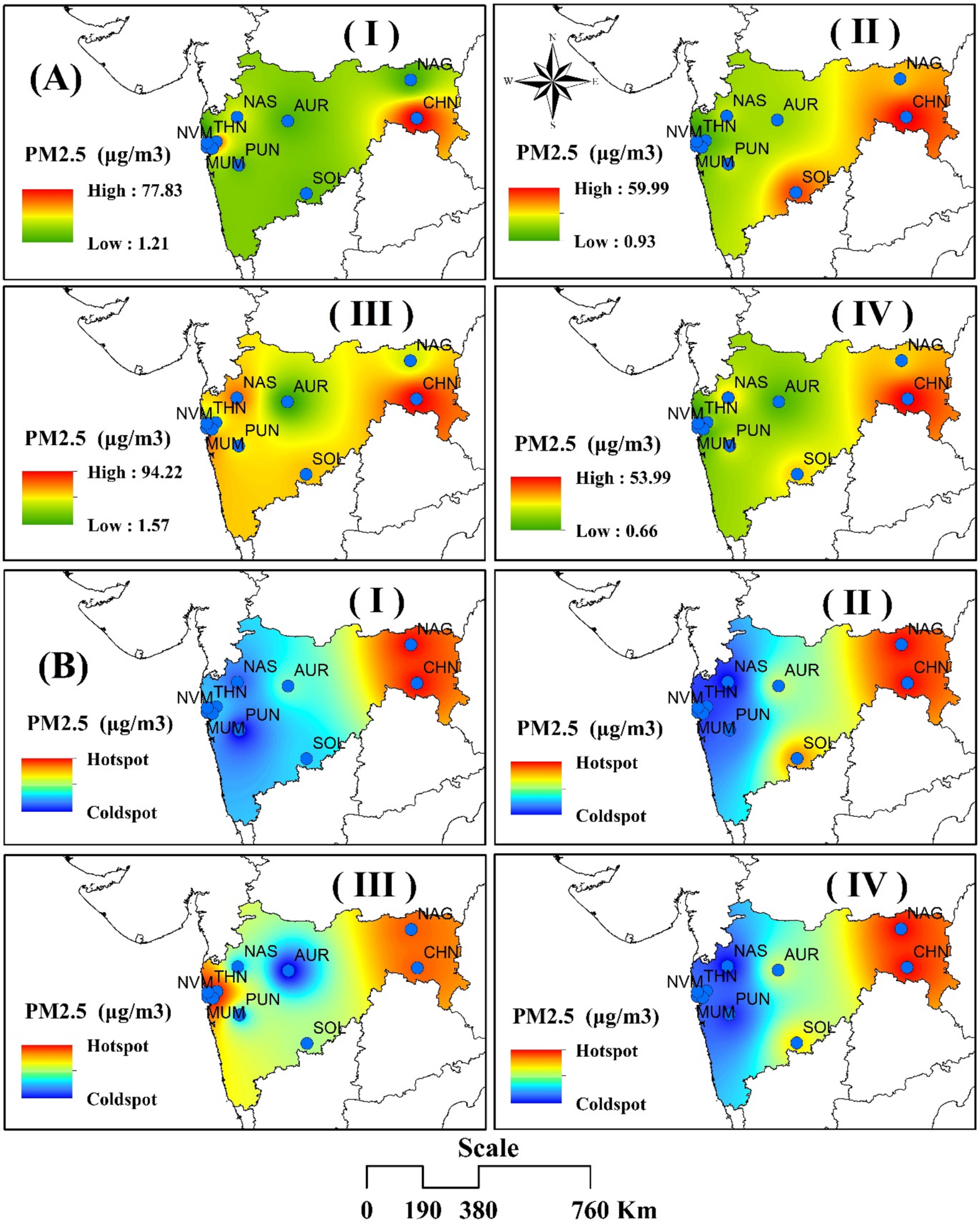
Fig. 8 Average $PM_{2.5}$ concentration during March to June of the year 2018–2020

from the previous year's situation because their opposite situations are there. Most of the time, hotspots are located in the western part and decrease towards the eastern part of the state but during the lockdown, opposite situations have been seen. $PM_{2.5}$ concentration zone changes in this time, and in unlock situations, these hotspots also tend to achieve the previous condition. Lowering $PM_{2.5}$ creates an impact on the regional climate and cools down the temperature of the cities of MH. It is clear from some previous work of researcher's temperature has a great impact on the COVID-19 outbreak. This low level of $PM_{2.5}$ may be the cause of the COVID-19 outbreak in these cities of MH because low $PM_{2.5}$ levels are slightly responsible for regional climate change that could accelerate the outbreak of COVID-19. Several researchers (Comunian et al. 2020; Zoran et al. 2020; Paital and Agrawal 2021) have tried to find out the relation between $PM_{2.5}$ concentration and the spreading of COVID-19 in different areas.

Hotspot analysis of different years from 2018 to 2020 (March–June)

The hotspot of any region means the large concentration of any particular matter in a particular region. In this study, hotspot analysis has been done to identify $PM_{2.5}$ concentration hotspots throughout the cities of MH state. MH is known as the hotspot of our commercial activity, but in recent years, it became a hotspot for COVID-19 outbreak due to the large number of COVID-19 cases found in the cities of MH.

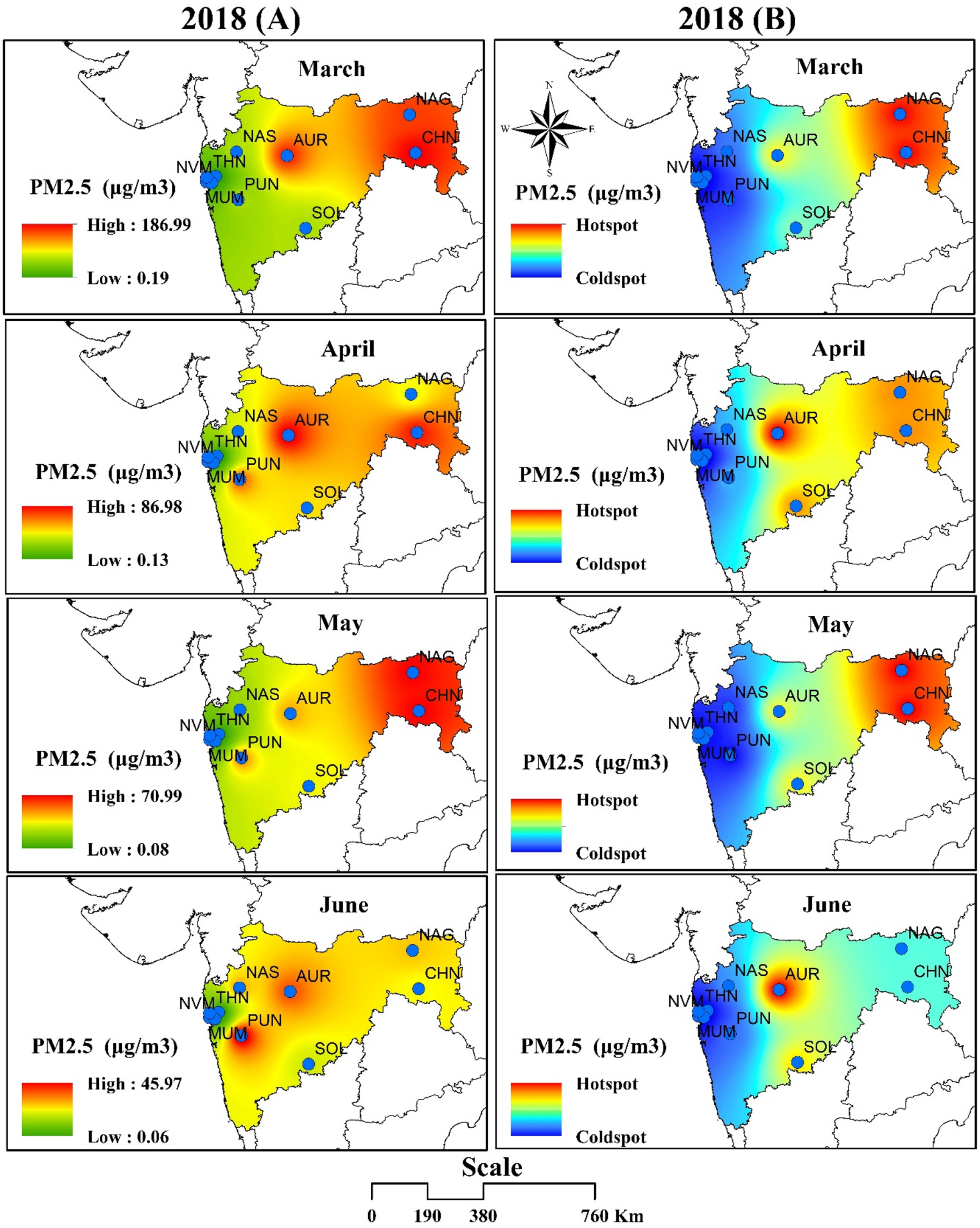
In this present study, hotspot analysis method has been used to compare the $PM_{2.5}$ concentration of the previous year 2018 and 2019 for the months of March to June with



Aurangabad,	Chandrapur	Kalyan	Mumbai	Nagpur	Nashik	Navi mumbai	Pune	Solapur	Thane
AUR	CHN	KAL	MUM	NAG	NAS	NVM	PUN	SOL	THN

Fig. 9 **A** Spatial distribution and **B** hotspot of PM$_{2.5}$ during different phases of lockdown

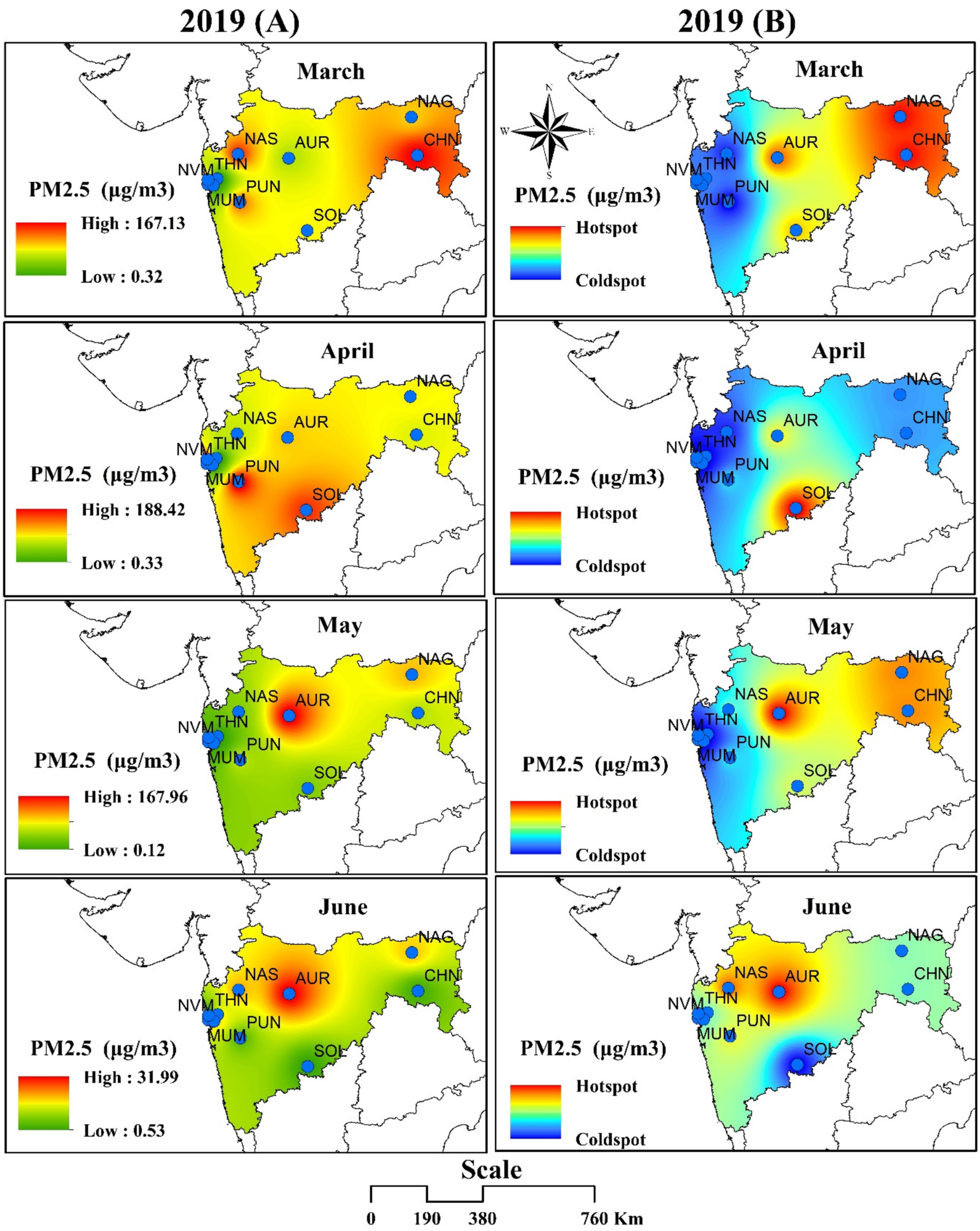
recent 2020 because these months were very vulnerable during 2020. From the hotspot analysis of the year 2018 (March–June), it is clear that the main concentration of hotspots in MH state developed in MMR due to its various outdoor activities (Fig. 10). The same situation occurred during the year 2019 here spatial concentration of PM$_{2.5}$



Aurangabad.	Chandrapur	Kalyan	Mumbai	Nagpur	Nashik	Navi mumbai	Pune	Solapur	Thane
AUR	CHN	KAL	MUM	NAG	NAS	NVM	PUN	SOL	THN

Fig. 10 **A** Spatial distribution and **B** hotspot of $PM_{2.5}$ during March–June of 2018

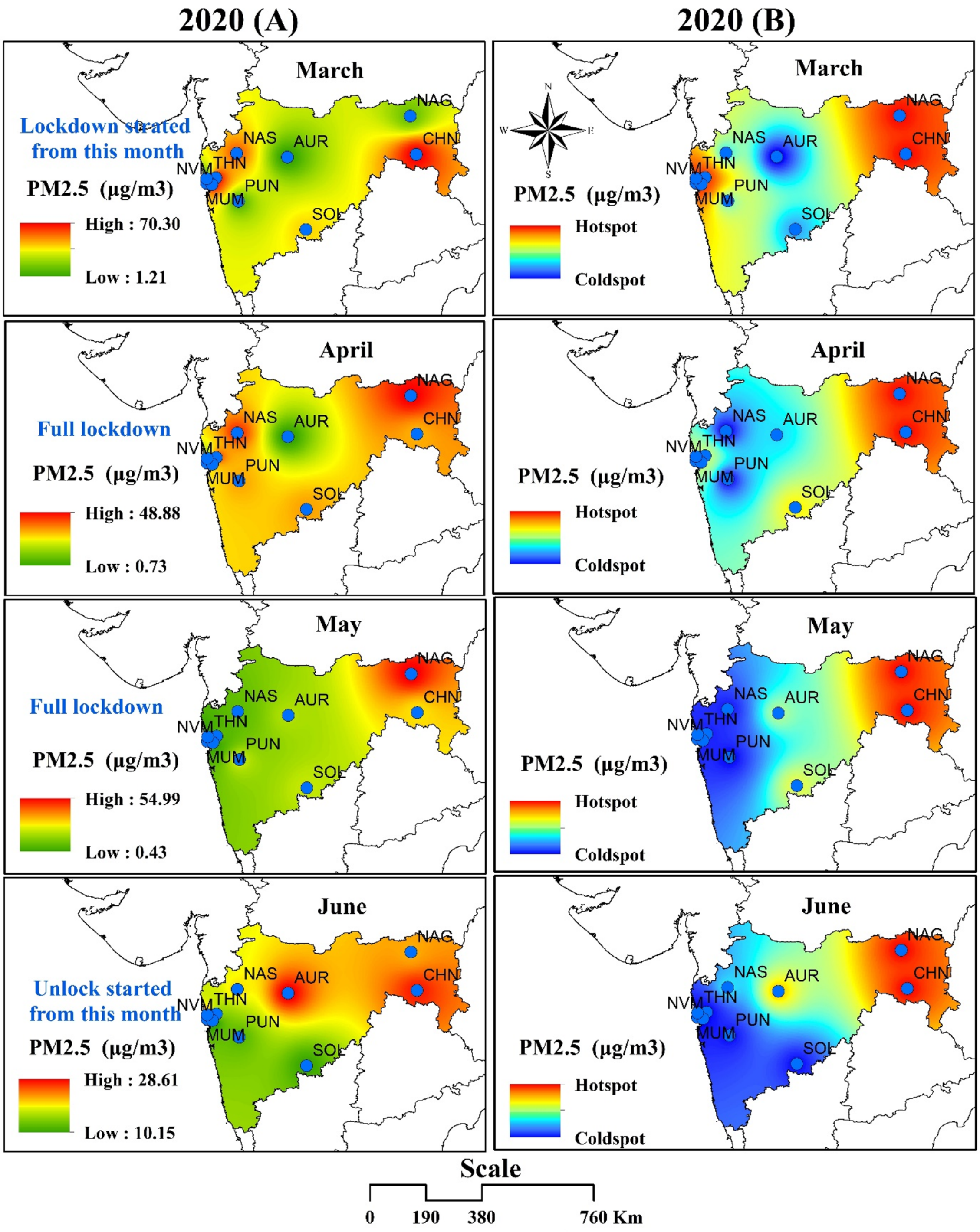
and hotspots were found in the cities of the western part and some cities of the east (Fig. 11). But this situation dramatically changes in the year 2020; hotspots have been shifted towards the central part and eastern part of the state. It also proved that different phases of lockdown were responsible for a decline in the $PM_{2.5}$ level.



Aurangabad.	Chandrapur	Kalyan	Mumbai	Nagpur	Nashik	Navi mumbai	Pune	Solapur	Thane
AUR	CHN	KAL	MUM	NAG	NAS	NVM	PUN	SOL	THN

Fig. 11 **A** Spatial distribution and **B** hotspot of $PM_{2.5}$ during March–June of 2019

Primarily, the hotspot of MH state is concentrated at the surrounding region of MMR which is the western part of the state (NAS, NVM, PUN, MUM, and THN). But from present findings, it can be observed that the hotspot of $PM_{2.5}$ concentration is developed in the cities of the eastern part (NAG, CHN, AUR, and SOL) of the state



Aurangabad.	Chandrapur	Kalyan	Mumbai	Nagpur	Nashik	Navi mumbai	Pune	Solapur	Thane
AUR	CHN	KAL	MUM	NAG	NAS	NVM	PUN	SOL	THN

Fig. 12 **A** Spatial distribution and **B** hotspot of $PM_{2.5}$ during March–June of 2020

because several economic activities were closed down during lockdown resulting in coldspots at the western part of the state (Fig. 12).MMR is the most vulnerable place in $PM_{2.5}$ concentration that is all time hotspot of $PM_{2.5}$ but during the lockdown, it has changed its position. Our study also has shown the variation of $PM_{2.5}$ in adopted ten important cities throughout the entire year of 2018, 2019, and 2020 (Fig. 13).

Fig. 13 Comparison of $PM_{2.5}$ concentration throughout the cities of the year 2018, 2019, 2020 (before lockdown, lockdown, and after lockdown)

Apart from this, the most significant air pollution has notable relation to water resources. Suspended particulate matter can directly influence the water quality of a region because this can easily transfer from one place to another place and settle on water after a consecutive time and then it affects the water body by its chemical composition (Yunus et al. 2020). According to (USEPA), particulate matter can make several changes in the lakes, streams and any water body such as it can acidify the water body by its chemical properties. Particulate matter also brings substantial changes in nutrient balance in the river and coastal water; besides, this atmospheric component plays a significant role in producing acid rain which has a significant impact on the water body by direct mixing of acid water with available surface water (Bilotta et al. 2012).

Therefore, this study with spatial distribution and hotspot analysis of $PM_{2.5}$ can help in easy identification of particulate matter concentration zone and that also helpful in detecting the potential water resource vulnerable zone due to deteriorating nature of air quality more specifically because of $PM_{2.5}$ in a particular area. Our present study shows the $PM_{2.5}$ hotspot zone more significantly and this is directly related to water quality deterioration.

Conclusion

Since the beginning of 2020, COVID-19 has become a global threat to the human population. Because of this serious situation, GOI initiated a lockdown strategy by shutting down all outdoor activities. In response to its natural environment, the atmospheric conditions underwent a dramatic change during this time period and sensible effects also have been seen in cities rather than rural areas. MH government has taken various strategies to overcome the COVID situation that brings several changes in the atmosphere. This study seeks to analyze the ups and downs of the $PM_{2.5}$ concentration of ten major MH cities identified as the hotspot of the outbreak of COVID-19, in three consecutive periods, namely before lockdown, lockdown, and post-lockdown. In this study, we have seen that various MH cities have undergone significant changes in $PM_{2.5}$ levels that could trigger the outbreak of COVID-19 and make this state a hotspot in India. Generally, MH states experienced unhealthy as well as very poor air quality (Chattopadhyay and Shaw 2021); Bashir et al. (2020) and Fattorini and Regoli 2020) showed how air polluted areas become COVID hotspots during this time. Hence, MH faced devastating consequences of it.

This change in the atmosphere varies at different times at different rates. Before the lockdown period, MH was facing very critical condition in $PM_{2.5}$ (μg/m^3) concentration level. Several cities experienced very unhealthy $PM_{2.5}$ levels. The highest average concentration was found in NAV (248) then MUM (236) and NAS (190) subsequently. During the lockdown period, all the ten cities of MH experience a substantial decrease in $PM_{2.5}$ where there was about a 50% decrease at the end of March, 65% at the end of April, and 74% at the end of May compared to before lockdown period. After lockdown or the unlock, stages were opposite to the lockdown period where the cities have experienced a gradual increase in $PM_{2.5}$ concentration level. On 30th May, average, $PM_{2.5}$ concentration across the cities was 26 (μg/m^3) which becomes 130 (μg/m^3) on the 31st December. Therefore, it can be said that there was a significant rise of $PM_{2.5}$ seen in unlock period, although it can also be concluded that a record level of decline in $PM_{2.5}$ concentration has occurred from March to June period of 2020 rather than the years 2018 and 2019.

The hotspot analysis in this study plays a significant role in identifying the highest concentrated $PM_{2.5}$ area in 2020 compared to the previous years in 2018 and 2019. It also shows how the $PM_{2.5}$ hotspot region of cities of MH converts to coldspots during the lockdown period; whereas at the beginning of lockdown (March 2020), some cities such as Navi Mumbai, Thane, Pune, and Mumbai were under hotspots of $PM_{2.5}$ concentration and those places transform into coldspot in June due to lockdown effect; the previous hotspot regions moved from western cities to eastern cities. All the above discussions ensure that although this COVID-19 situation has posed a very serious threat to the human population, it gives time to the environment to overcome its disease and bring sustainability to the environment.

This study ensures that it is very necessary to give the environment time to rejuvenate easily; COVID-19 as a natural power forces us to implement mandatory lockdowns throughout the world that bring change to the environment. But it is not a permanent solution, rather than a temporary one. As a result, the environment reached its previous poor condition gradually after the unlocking phase in the world. Nor is India, as well as the MH state, an exception in this case. GOI has taken several steps to balance the level of pollution in the various cities of the country. But it is not being properly maintained. Until now, many Indian cities are ranked among the top polluted cities in the world by crossing their upper pollution limits. In MH, the concentration of $PM_{2.5}$ is in very serious condition and a large number of people are suffering from critical illness due to its excessive levels. Central authorities need to be more focused, and take more effective and strict preventive measures to overcome this situation.

Data availability Data will be made available on request.

Declarations

Conflict of interest The authors declare that they have no competing interests.

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