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Spatio-Temporal Variation of Particulate Matter(PM_{2.5}) Concentrations and Its Health Impacts in a Mega City, Delhi in India

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ABSTRACT: Rising concentration of air pollution and its associated health effects is rapidly increasing in India, and Delhi, being the capital city, has drawn our attention in recent years. This study was designed to analyze the spatial and temporal variations of particulate matter (PM_{2.5}) concentrations in a mega city, Delhi. The daily PM_{2.5} concentrations monitored by the Central Pollution Control Board (CPCB), New Delhi during November 2016 to October 2017 in different locations distributed in the region of the study were used for the analysis. The descriptive statistics indicate that the spatial mean of monthly average PM_{2.5} concentrations ranged from 45.92 µg m⁻³ to 278.77 µg m⁻³. The maximum and minimum spatial variance observed in the months of March and September, respectively. The study also analyzed the PM_{2.5} air quality index (PM_{2.5}—Air Quality Index (AQI)) for assessing the health impacts in the study area. The AQI value was determined according to the U.S. Environmental Protection Agency (EPA) system. The result suggests that most of the area had the moderate to very unhealthy category of PM_{2.5}-AQI and that leads to severe breathing discomfort for people residing in the area. It was observed that the air quality level was worst during winter months (October to January).

KEYWORDS: Particulate matter (PM_{2.5}), inverse distance weight, AQI mapping, health effect

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Introduction

Clean air is one of the basic requirements of human health and well-being. However, during the process of economic development, air pollution has been and continues to be a significant health hazard worldwide. The driving forces of air pollution include economic development, urbanization, energy consumption, transportation, and motorization.¹

In recent times, air pollution problem is one of the biggest issue in most of the developed and developing countries.^{2–4} According to World Health Organization (WHO), Delhi, the capital of India, topped among the list of most-polluted cities and thus the public has focused its attention on the issue and the government has responded with ever-stronger measures.⁵ In the last few years, many studies have been conducted by different research groups on the air quality issues in Delhi. Panda et al⁶ conducted a study for analyzing the effect of meteorology, long-range transport, boundary layer, and anthropogenic activities on the chemical composition of particulate matter (PM_{2.5}) in Delhi and Bhubaneswar. The results revealed that PM_{2.5} mass is dominated by fossil fuel specifically from coal combustion in Bhubaneswar, whereas vehicular exhaust, fossil fuel combustion along with biomass burning and road dust were the main sources of emission in Delhi.⁶ Maji et al⁷ studied the short-term effects of criteria air pollutants (PM₁₀, SO₂, NO₂, CO and O₃) on daily mortality in Delhi, India. A time-series

model was developed for analyzing the effect of air pollutants on all natural causes of mortality in Delhi. The study revealed that the health burden is associated with local air quality in Delhi.⁷ Liu et al⁸ analyzed the seasonal impact of regional outdoor biomass burning on air pollution in three Indian cities viz. Delhi, Bengaluru, and Pune using HYSPLIT model. The study results suggested that outdoor fires are not the dominant air pollution source in India throughout the year, but post-monsoon fires contribute substantially to high air pollution exposure levels around Delhi.⁸ Pant et al⁹ proposed a review study to determine the exposure to PM in India for future action.

The most common ambient air pollutants encountered in our daily life are PM, sulfur dioxide (SO₂), nitrogen dioxide (NO₂), ozone (O₃), carbon monoxide (CO), and carbon dioxide (CO₂).¹ Although a number of air pollutants (PM, nitrogen dioxides, sulfur dioxide, carbon monoxide, ozone, lead, etc.) are listed as criteria pollutants in most of the country's air quality standards, this study considers PM_{2.5} for analyzing the spatial variations and its health impacts due to limitations of data availability and accessibility. Particulate matter is often implicated as the most significant predictor of the health outcomes among the air pollutants in most of the studies. However, PM is a chemically non-specific pollutant and may originate or be derived from various emission source types. Thus, its degree of



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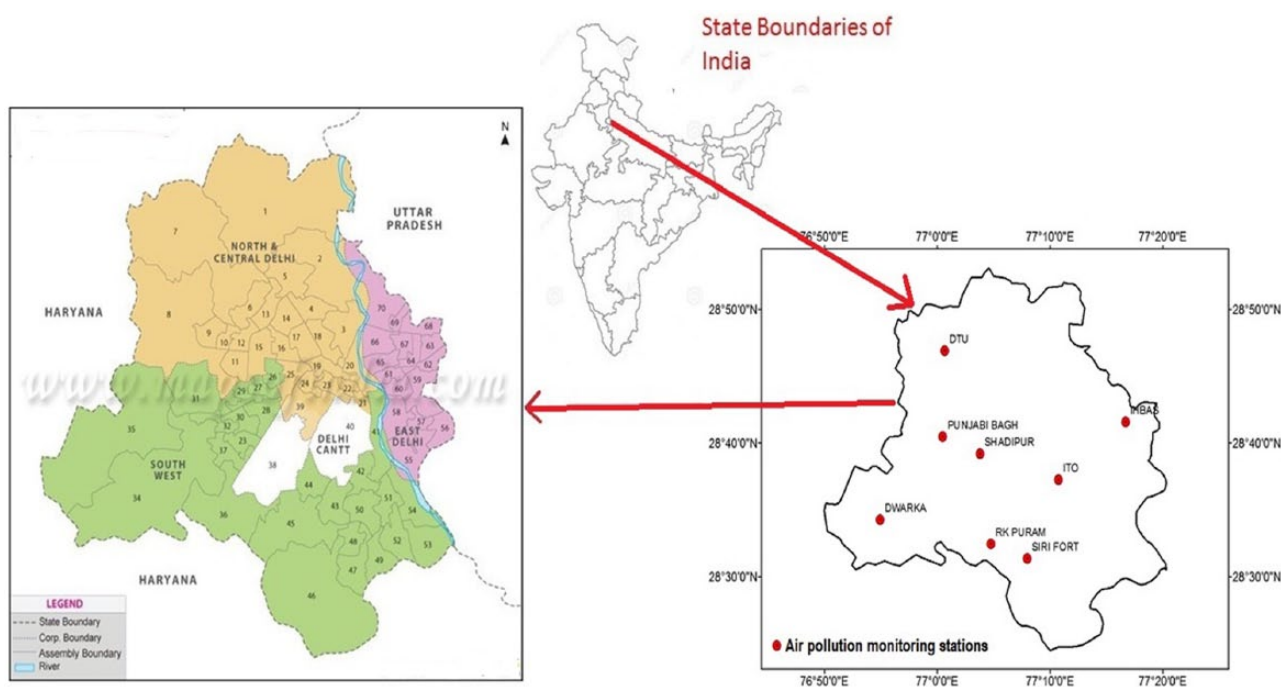


Figure 1. Study area map.

impact may well vary depending on its source and chemical composition. If the impacts of PM could be determined based on source types, the regulation of PM may be implemented more effectively.

Outdoor suspended particulate matter (SPM) is considered to be the most serious pollutant in metropolitan areas, in view of its adverse health effects as a cause of cardiovascular disease, respiratory irritation, and pulmonary dysfunction.⁵ Many time-series studies have explored the acute health effects associated with short-term exposure to airborne particulates.¹⁰ Epidemiological studies have suggested associations of long-term exposure to current air pollution levels and particularly cardio-respiratory health.^{10,11} Particulate matter is used as an indicator for airborne particulates as there are extensive monitoring data for PM_{2.5} in most of the developed nations but at the same time the network of PM_{2.5} monitoring is poorly maintained to obtain the quality and continuous data. Substantial evidence indicate that PM exposure is linked to a variety of adverse effects on mortality (non-accidental all-cause mortality, cardiovascular, and respiratory mortality)¹² and morbidity (hospital admissions, outpatient and emergency-room visits, asthma attacks, acute respiratory infection of young children, etc.).¹³⁻¹⁶ The risk for acute events, including myocardial infarction and stroke has been assessed.¹⁷ The risk for birth outcomes has also been studied, but the evidence is still inconclusive based on the currently available data.^{18,19}

The major sources of air pollution in Delhi are diesel generators and tandoors in restaurants, public transport, combustion of fuels (coal, liquefied petroleum gas, and wood), and power plants.²⁰ Increased combustion of fossils fuel is mainly responsible for the continuous change in the atmospheric

composition.²¹ The size of particles is directly linked to their potential for causing health problems. Small particles less than 2.5 μm in diameter pose the greatest problems because they can get deep into your lungs, and some may even get into your bloodstream. Air pollution also causes environmental effects like visibility impairment, environmental damage, and materials damage. The main objective of the proposed study is to analyze the spatial variations of PM_{2.5} concentrations in a mega city (Delhi) and assessment of health impacts due to exposure to the higher PM_{2.5} concentrations.

Materials and Methods

Study area

The air quality in Delhi, the capital of India, according to a WHO survey of 1600 world cities, is the worst of any major city in the world.²² Pollution in Delhi, which spikes during winter, hit almost 30 times the WHO's safe limits²³ in the second week of November 2016, with the concentration of harmful PM_{2.5} particles topping 700 $\mu\text{g}/\text{m}^3$ (micrograms per cubic meter).²⁴ Air pollution in India is estimated to kill 1.5 million people in 2012 and also the fifth largest killer in India.²⁵ India has the world's highest death rate from chronic respiratory diseases and asthma, according to the WHO reports.²⁵ Delhi (shown in Figure 1) was selected for analyzing the spatio-temporal variations of PM_{2.5} concentrations. The latitude and longitude of the study area ranges from 28°24'30.46"N to 28°53'4.24"N and 76°49'58.50"S to 77°20'15.86"S, respectively. The state of Delhi is characterized by weather extremes. Both summer and winter are severe with June being the hottest month and January the coldest.²⁶ The annual rainfall is around 700 mm. Maximum rain occurs

Table 1. Air pollution monitoring stations.

STATION ID	LOCATION	LATITUDE (N)	LONGITUDE (E)	LANDUSE TYPE
1	Shadipur	28°39'12.069"N	77°3'42.057"E	Residential and industrial
2	R K Puram	28°32'25.985"N	77°4'52.68"E	Residential cum commercial
3	IHBAS	28°41'33.315"N	77°16'31.85"E	Residential cum commercial
4	DTU	28°46'51.12"N	77°0'38.436"E	Residential and industrial
5	Dwarka	28°34'18.982"N	76°54'59.444"E	Residential
6	Sirifort	28°31'22.424"N	77°7'49.238"E	Ecologically sensitive
7	Punjabi Bagh	28°40'26.223"N	77°0'24.311"E	Residential cum commercial
8	ITO	28°37'4.947"N	77°10'42.265"E	Residential cum commercial

IHBAS: Institute of Human Behaviour and Allied Sciences; DTU: Delhi Technological University; ITO: Income tax office.

during July to August. The latitudes and longitudes of Delhi range from 28°24'17" to 28°53'00"N and 76°50'24" and 77°20'37" E, respectively. The city is 216 m above the mean sea level (MSL). The city is surrounded by other major growth centers of adjoining states such as Haryana and Uttar Pradesh, and thus the geographical location of this city influences the weather conditions of Delhi. Thus, the significant variations in the climate in the specified geographical region may influence the PM_{2.5} concentrations. The population in Delhi was 16 779 294 in 2011 as per Census-India.²⁷ The population density of National Capital Territory (NCT) of Delhi grew substantially from 1176 to 11 297 people per square kilometer of land area between 1951 and 2011 as per Census-India.²⁷

Methods

In Delhi's air quality-monitoring network, continuous data are rarely available for all the monitoring stations for long-term study. Thus, this study considered a specified time period and pollutants based on the availability of continuous data for a limited number of monitoring stations. For analyzing the spatial distribution, the PM_{2.5} concentrations monitored by the Delhi Pollution Control Committee (DPCC) and Central Pollution Control Board (CPCB), New Delhi at eight sampling locations (shown in Figure 1) distributed in the study area were selected. The latitude and longitude of each monitoring location along with the landuse type are shown in Table 1. Particulate matter concentration monitored during November 2016 to October 2017 was used for this study.

The spatial distributions of PM_{2.5} status was studied in Delhi using geographic information system (GIS) tool. An inverse distance weighting (IDW) interpolation method²⁸ was used to predict the PM_{2.5} concentrations at unknown points in the study area. The IDW interpolator assumes that each input point has a local influence that diminishes with distance. It weights the

points closer to the processing cell greater than those further away. The IDW interpolation technique calculates the value for an unknown location using the following equation

$$Z_j = \frac{\sum_i \frac{Z_i}{d_{ij}^n}}{\sum_i \frac{1}{d_{ij}^n}}$$

The prediction performance of the model was evaluated using root mean square error (RMSE) value. The RMSE can be determined as

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (X_{obs,i} - X_{model,i})^2}{n}}$$

PM_{2.5} data

Particulate matter_{2.5} data monitored by DPCC, New Delhi's Air Quality Monitoring Network (AQMN) at eight monitoring stations located in Delhi region for 1 year (November 2016 to October 2017) were used for the study. Daily data of all the PM_{2.5} concentrations were downloaded from the website of the DPCC, New Delhi's air quality network system data mart. Particulate matter concentrations have been monitored using the gravimetric sampling method at all the locations. However, the quality control of data has not been reported in the website and not known to the authors. This study used the deterministic approach (IDW method) for spatial analysis of PM_{2.5} concentrations in Delhi. The IDW method was used for spatial analyses in the area in each of the 12 months. Particulate matter concentrations for each sampling location are summarized in Table 2. The monthly mean of spatial data and annual means of each station are

Table 2. PM_{2.5} concentrations at various locations from November 2016 to October 2017.

SL. NO.	STATIONS	NOVEMBER, 2016	DECEMBER, 2016	JANUARY, 2017	FEBRUARY, 2017	MARCH, 2017	APRIL, 2017	MAY, 2017	JUNE, 2017	JULY, 2017	AUGUST, 2017	SEPTEMBER, 2017	OCTOBER, 2017	ANNUAL MEAN $\pm$ SD
1	Shadipur	265.81	204.88	143.89	148.21	120.07	121.91	145.67	71.14	51.50	60.05	69.05	178.23	131.70 $\pm$ 64.32
2	R K Puram	275.69	203.67	200.70	139.52	92.99	129.53	119.17	72.29	41.43	49.17	71.33	176.90	131.03 $\pm$ 71.71
3	IHBAS	244.83	240.81	117.79	81.68	61.25	227.05	107.81	67.87	40.76	95.86	73.56	158.60	126.49 $\pm$ 73.50
4	DTU	383.43	290.99	206.37	160.22	116.84	108.14	104.92	68.11	38.42	40.24	60.29	197.00	147.91 $\pm$ 106.15
5	Dwarka	213.66	162.18	135.91	110.20	291.54	120.36	104.58	163.59	55.85	62.78	73.60	165.92	138.35 $\pm$ 67.47
6	Sirifort	347.96	230.84	244.29	264.23	85.22	107.57	94.15	55.91	34.74	36.44	54.36	140.50	141.35 $\pm$ 104.51
7	Punjabi Bagh	298.98	242.01	180.78	128.60	96.04	105.65	62.34	57.81	37.42	38.81	55.78	160.45	122.06 $\pm$ 84.09
8	ITO	199.80	250.75	170.08	103.37	86.85	77.30	105.33	116.05	67.24	65.10	86.78	147.47	123.01 $\pm$ 57.96
Monthly mean $\pm$ SD		278.77 $\pm$ 63.19	228.27 $\pm$ 38.38	174.98 $\pm$ 41.87	142 $\pm$ 55.6	118.85 $\pm$ 72.2	124.69 $\pm$ 44.24	105.5 $\pm$ 23.3	84.09 $\pm$ 37.13	45.92 $\pm$ 11.24	56.06 $\pm$ 19.67	68.09 $\pm$ 10.84	165.63 $\pm$ 18.16	

IHBAS: Institute of Human Behaviour and Allied Sciences; DTU: Delhi Technological University; ITO: Income tax office.

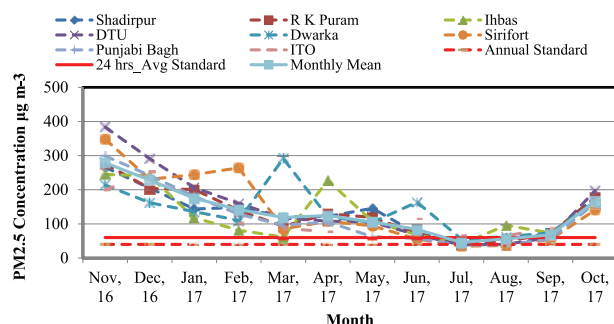


Figure 2. Monthly average concentrations of PM_{2.5} at different monitoring stations.

also shown in Table 2. The results indicate that the monthly mean PM_{2.5} concentrations of eight locations varied from $45.92 \pm 11.24 \mu\text{g m}^{-3}$ in July 17 to $278.77 \pm 63.19 \mu\text{g m}^{-3}$ in November 16 during the study period. The higher value of standard deviation indicates that the spatial variations of PM_{2.5} concentrations are significant, and thus the mapping is very useful for assessing the health impacts. The annual mean PM_{2.5} concentrations were found to be 131.70 ± 64.32 , 131.03 ± 71.71 , 126.49 ± 73.50 , 147.91 ± 106.15 , 138.35 ± 67.47 , 141.35 ± 104.51 , 122.06 ± 84.09 , and $123.01 \pm 57.96 \mu\text{g m}^{-3}$, respectively for monitoring station 1 to 8. Thus, the lowest annual mean was observed at Punjabi Bagh, whereas the highest was observed at Delhi Technological University (DTU). The monthly mean of spatial data of eight stations are also shown in Figure 2. The results (shown in Figure 2) suggest that the monthly spatial mean values of PM_{2.5} concentrations exhibit a decreasing trend from November 16 to July 17, and an increasing trend from September 17 to October 17. That is, the concentrations were relatively higher in winter months compared to summer and monsoon months.

Results and Discussion

Spatial analysis

This study examined IDW method for prediction of PM_{2.5} concentrations at the un-sampled locations in the study area. The performances of the fitted models were examined based on the RMSE values (shown in Table 3). The RMSE values seem to be high. This may be due to less number of sampling locations. However, the predictions can be used for estimating the PM_{2.5} exposure level. The spatial distribution maps were derived using the IDW model for each month during the study period. The analysis was done using Geostatistical Analyst module of ArcGIS software, version 10.3. The spatial distributions of PM_{2.5} concentrations are presented for each month in Figure 3. The monthly spatial maps (shown in Figure 3) indicate that the spatial distributions of PM_{2.5} concentrations do not have uniform patterns with month. However, the spatial patterns were found to be uniform in few months due to uniform influences of meteorological

Table 3. RMSE values for each month.

MONTH	RMSE ERROR
November, 2016	66.69
December, 2016	39.29
January, 2017	39.72
February, 2017	60.26
March, 2017	69.79
April, 2017	48.82
May, 2017	28.37
June, 2017	40.07
July, 2017	12.57
August, 2017	18.11
September, 2017	11.82
October, 2017	19.46

factors (wind speed [WS], temperature, and precipitation; shown in Figure 3) with the assumptions of constant emission factors. It is also obvious from Figure 3 that the monthly mean of PM_{2.5} concentrations exceeded the 24-h average standard ($40 \mu\text{g/m}^3$)²⁹ and annual average standard ($60 \mu\text{g/m}^3$)²⁹ concentrations in the entire study area in each month except in July and August. The influences of local meteorological factors such as WS, temperature, and precipitation may be reason for the observed distribution patterns. The correlation analyses of PM_{2.5} concentration with three meteorological factors (temperature, precipitation, and WS) were conducted to understand the role of meteorological factors on the concentration level of PM_{2.5}. The monthly average meteorological data during the same period (November 2016 to October 2017) was retrieved from online sources (<https://www.weatheronline.in/weather/maps/city?>). These are represented in Figure 4. The correlation analyses results (shown in Table 4) indicated that PM_{2.5} had significant negative correlations with WS and precipitations. To understand the actual reason of the observed pattern, region-wise emission sources need to be studied.

PM_{2.5}-air quality index maps for estimation of health impacts

The Air Quality Index (AQI) is an indicator for reporting daily air quality. It tells how clean or unhealthy the air is and provides recommendation for populations that may be sensitive to excess pollution. During the last two decades, a number of AQI determination methods have been developed worldwide.³⁰ This study uses the U.S. Environmental Protection Agency's (EPA) AQI system for determining the AQI. The PM_{2.5}-AQI was determined as

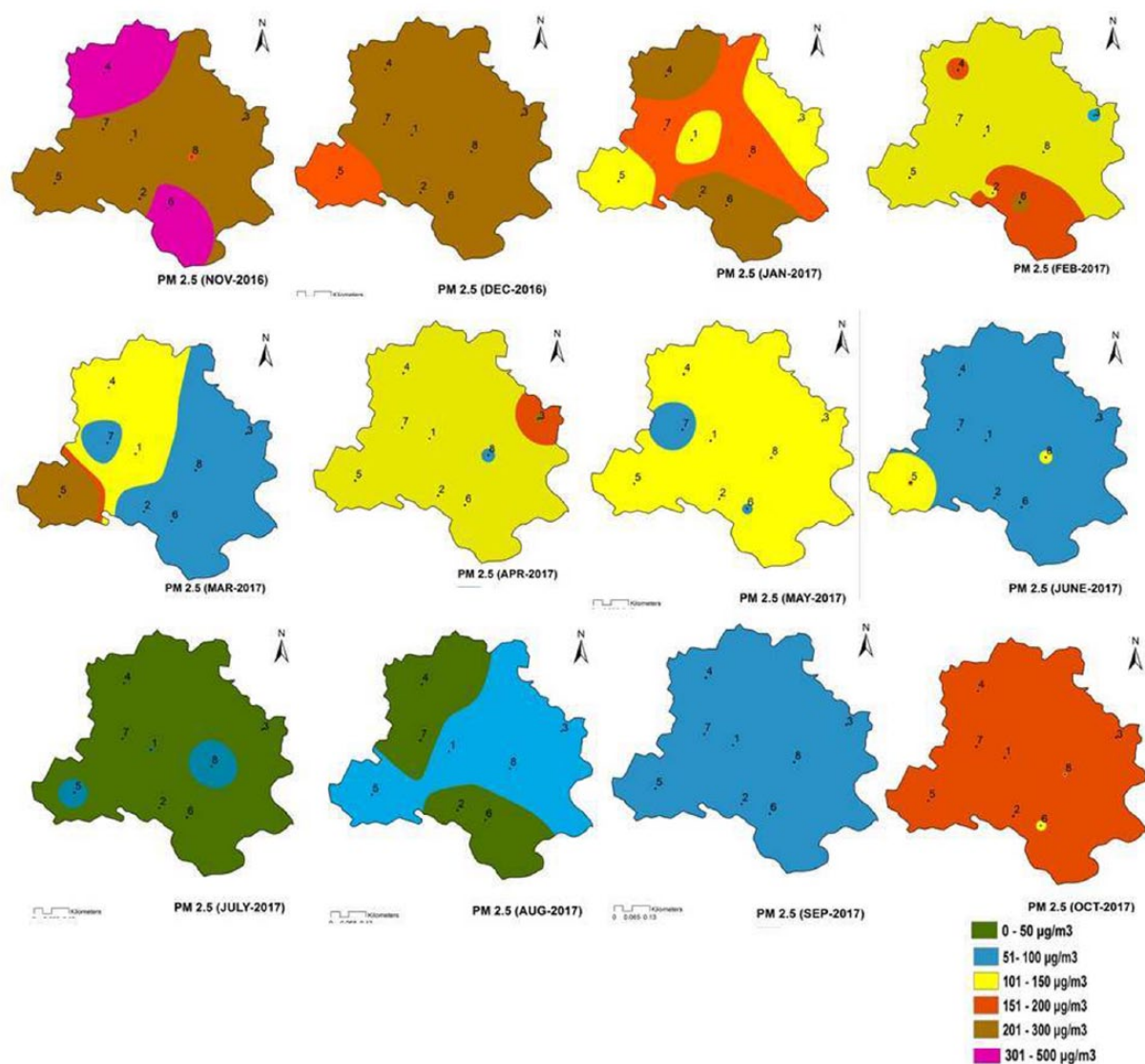


Figure 3. Spatial distributions of PM_{2.5} concentrations during November 2016 to October 2017.

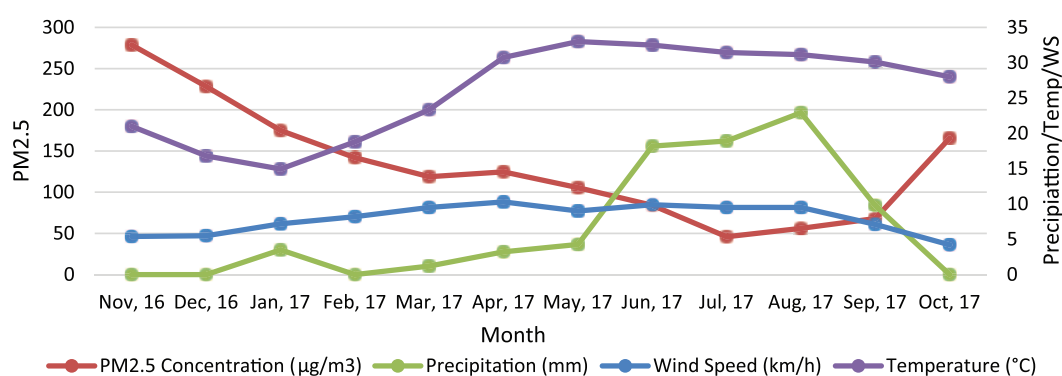


Figure 4. Meteorological data vs PM_{2.5} concentrations.

$$I_p = \frac{(I_{HI} - I_{LO})}{BP_{HI} - BP_{LO}} (C_p - BP_{LO}) + I_{LO}$$

where I_p represents the Index for PM_{2.5}, C_p is the rounded concentration of PM_{2.5}, BP_{HI} is the breakpoint that is greater than or equal to C_p , BP_{LO} is the breakpoint that is

less than or equal to C_p , I_{HI} is the PM_{2.5}-AQI value corresponding to BP_{HI} , and I_{LO} is the PM_{2.5}-AQI value corresponding to BP_{LO} .

The breakpoints for PM_{2.5} concentrations along with the ranges of various PM_{2.5}-AQI category and the possible health consequences are reported in Table 5. These breakpoints (shown

Table 4. Correlation analysis results.

	PM _{2.5}	WS	PRECIPITATION	TEMPERATURE
PM _{2.5}	1			
WS	−0.713**	1		
Precipitation	−0.751**	0.547	1	
Temperature	−0.727**	0.502	0.622*	1

PM: particulate matter; WS: wind speed.

*Correlation is significant at the 0.05 level (two-tailed).

**Correlation is significant at the 0.01 level (two-tailed).

Table 5. Breakpoint concentration of air pollutants defined in U.S. EPA (1999) system.

BREAKPOINTS	AQI	CATEGORY	HEALTH IMPACTS
PM _{2.5} (μG/M ³)			
0-15.4	0-50	Good	Air quality is satisfactory and poses little or no health risk
15.5-40.4	51-100	Moderate	People who are unusually sensitive to ozone or particle pollution may experience respiratory symptoms
40.5-65.4	101-150	Unhealthy for sensitive groups (USG)	People with heart or lung disease, older adults, and children are considered sensitive and therefore at greater risk
65.5-150.4	151-200	Unhealthy	Members of sensitive groups may experience more serious health effects
150.5-250.4	201-300	Very unhealthy	Everyone may experience more serious health effects
250.5-350.4	301-400	Hazardous	The entire population is even more likely to be affected by serious health effect
350.5-500.4	401-500	Hazardous	The entire population is even more likely to be affected by serious health effect

PM_{2.5}: particulate matter less than 2.5 μm; AQI: air quality index.

in Table 5) were used to determine the PM_{2.5}-AQI values using the above equation. The values of I_{HI} , I_{LO} , BP_{HI} , and BP_{LO} were taken from the Table 5, and the C_p was taken from the observed data to calculate the PM_{2.5}-AQI. The probable health impact of a particular region was estimated based on the observed category of PM_{2.5}-AQI.

The PM_{2.5}-AQI values were calculated for each of the monitoring locations in the GIS database. As the breakpoints are defined only for 24-h average concentration, it was assumed that the monthly average of 24-h daily monitored values represents the 24-h average values. The PM_{2.5}-AQI maps were generated using the same interpolation method (IDW) as explained above. The maps are shown in Figure 5, which indicate that the spatial distributions of PM_{2.5}-AQI have uniformity patterns in part of the study regions during a particular season. The results (shown in Figure 5) indicate that the AQI of PM_{2.5} in the region is not under “Good category” in any of the month during November 16 to October 2017. The PM_{2.5}-AQI maps indicate that AQI values range from “Unhealthy” to “Hazardous” category in most of the places in each month except in July to September. In the month of July 2017 and August 2017, part of the region showed the Moderate category of AQI. The population

density in Delhi is 11 297 people per square kilometer, and the entire region shows a higher air pollution exposure level than the permissible level throughout the year. Thus, a huge air pollution-related health burden exists in Delhi.

Conclusion

This study analyzed the temporal and spatial variations of PM_{2.5} concentrations in Delhi, India. The mean value of the spatial PM_{2.5} concentrations was found to be relatively higher in the winter months (October to January) in comparison to that of the summer and monsoon months. The monthly spatial distribution maps of PM_{2.5} indicate that the PM_{2.5} concentrations do not show uniform patterns. However, the spatial patterns were found to be uniform in few months due to uniform influences of local meteorological factors such as WS, temperature, and precipitation. Hence, the correlation coefficients of these parameters and PM_{2.5} were found to be higher and significant. The vulnerable zone or area of highest concentrations was generally found in most of the regions of the study area during winter seasons. The results of AQI maps indicate that AQI values range from Unhealthy to Hazardous category in most of the places in each month except from July to September. In the month of July and August, few areas

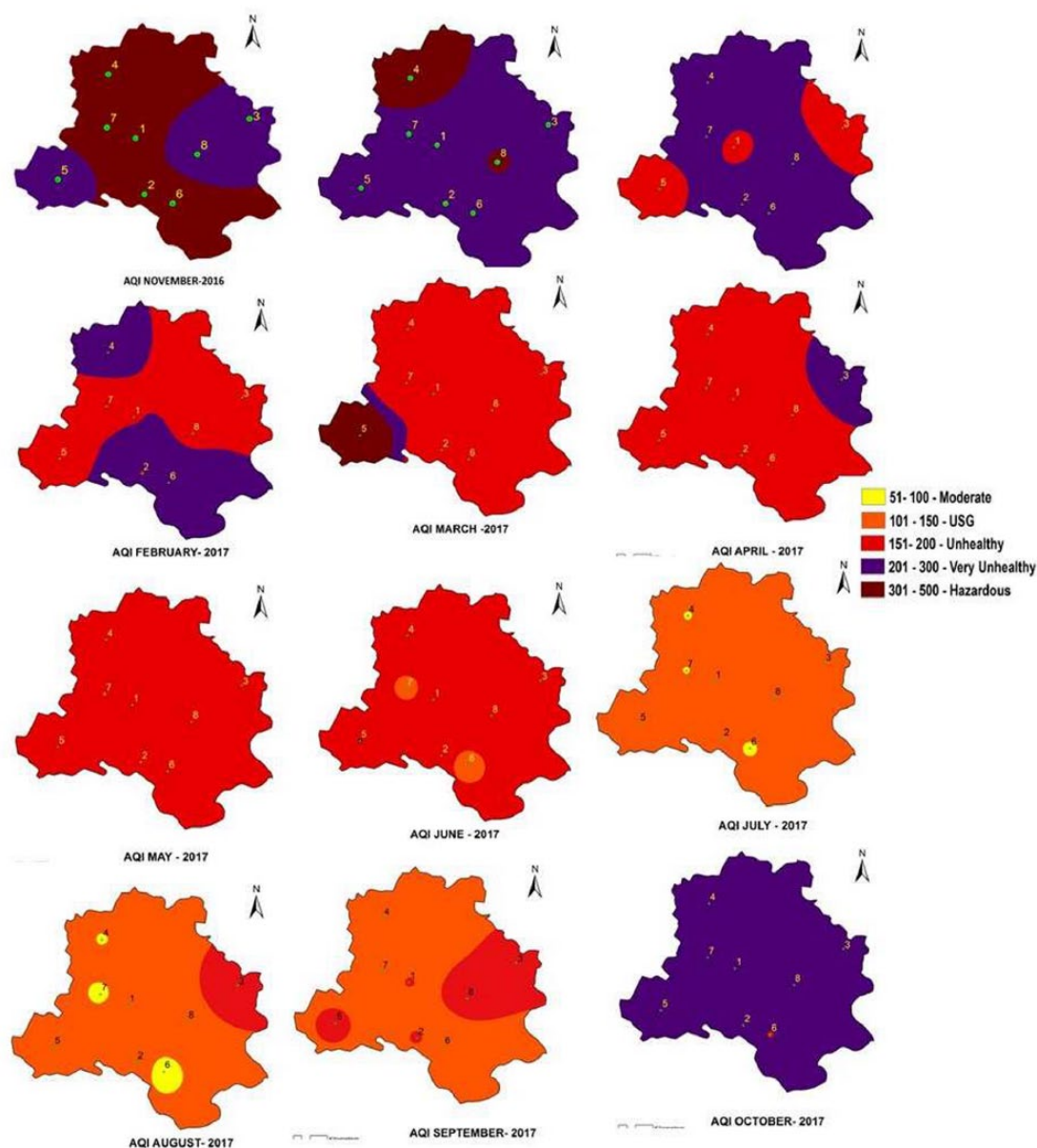


Figure 5. PM_{2.5}-AQI maps for each month.

showed the Moderate category of AQI. Thus, the entire population residing in Delhi is more likely to be affected by serious health effect. As the dispersion of PM_{2.5} depends on the atmospheric conditions and it cannot be changed and thus it is essential to reduce the vehicular emission (identified as major air pollution sources in Delhi in most of past research) by facilitating better public transport system.

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Author Contributions

AKG conceived and designed the experiments. SSB analyzed the data and wrote the first draft of the manuscript. AKG, PBT

and FT contributed to the writing of the manuscript and given critical comments on the draft manuscript. All authors agree with manuscript results and conclusions, reviewed and approved the final manuscript.

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