Original Article

Spatiotemporal Modeling of Airborne Fine Particulate Matter Distribution in Isfahan

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Abstract

Aims: Urban expansion has caused lots of problems such as air pollution, which endanger the health of residents. In this research, the spatiotemporal trend of atmospheric fine particulate matter ($PM_{2.5}$) of Isfahan was studied and modeled using distributed space–time expectation–maximization (D-STEM) software in 2017. **Materials and Methods:** This software uses a flexible hierarchical space–time model that can deal with multiple variables and massive loads of missing data. Model estimation is based on the expectation–maximization algorithm. The effects of confounder variables such as holidays, altitude, average temperature and relative humidity, rainfall, wind speed, and direction were considered in the modeling. The hourly measured ambient $PM_{2.5}$ concentration data were obtained from seven air pollution monitoring stations installed in different zones of Isfahan and operated by the department of environment. **Results:** The distribution map of the pollutant demonstrated two polluted areas located in southwest and southeast regions of the city that are high traffic and densely populated area. $PM_{2.5}$ concentration was significantly increased ($P < 0.05$) with an increase in land elevation by a coefficient of 0.93; conversely, it decreased significantly ($P < 0.05$) with every increase in wind speed by a coefficient of −0.226. **Conclusion:** Given the spatiotemporal correlations between air pollutant data, it is necessary to incorporate these correlations into model to obtain more accurate estimates. Using the statistical models and methods to manage the data, time, and volume of calculations in spatiotemporal estimations, the D-STEM program gives more accurate estimates of the desired parameters. Presenting models and maps for every desired time period are another feature of this software that can be useful in health programming and environmental management. Vehicular traffic had a significant effect on the increasing trend of the pollutant level in urban areas; however, the effects of atmospheric phenomena such as dust storms and thermal inversion cannot be ignored.

Keywords: Air pollution, particulate matter, spatial-temporal modeling

Introduction

Today, with the rapid expansion of cities and industries, the growth of motor vehicles, and as a result, excessive use of fossil fuels, we are witnessing a steep rise in air pollution.[1] In some cases, inappropriate geographical location also contributes to this exponential trend of pollutants. In 2014, the World Health Organization estimated that air pollution annually results in nearly seven million premature deaths worldwide, more than twice the previous estimates.[2] In another side, it imposes a significant increase in cost to the communities. A research showed that exposure to particulate $matter_{2.5}$ ($PM_{2.5}$) in the Middle East and North Africa has an increasing cost from 62 to 141 billion USD during 1990 to 2013.[3]

PMs, especially fine particles ($PM_{2.5}$), have been considered as one of the critical measures of air pollution. Studies have shown that exposure to polluted air in pregnant women is a risk factor for preterm labor.[4] Children whose mothers were exposed to $PM_{2.5}$ during pregnancy were more likely at the risk of infection.[5] Numerous extensive studies have shown the essential role of PM in the malfunction of the cardiovascular

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system.[6,7] Some reports have confirmed the adverse effects of PM on cancer risk, genetic mutation, and DNA damage.[8,9] In addition, the strong contribution of this pollutant in respiratory problems has also been confirmed.[7,10] The results of some similar research in Iran are in line with these results, e.g., a study in Ahvaz city revealed that PM_{10} concentration over 20 g/m^3 is accounted for 13% of all respiratory mortality during 2009.[11,12] In Mashhad, 4.24% of nonaccidental total mortality, 6.23% of cardiovascular mortality, and 8.76% of respiratory mortality are due to the exposure to more than 10 μg/m^3 PM_{10} concentrations.[13] For megacity of Tehran, these statistics are 4.6%, 6.8%, and 9.53% for nonaccidental total mortality, cardiovascular, and respiratory mortality, respectively.[12] Another research showed a great association between the rate of mortality and the high concentration of PMs due to fuel's burning and also dust storm of dried lands.[11,14]

Isfahan is the third most populous city of Iran, having nearly two million population which resulted in high vehicular traffic.[15] Besides this, the presence of large industrial settlements around the city and its geographical and meteorological status have led to serious air pollution.[16] Mapping the special and temporal patterns of air pollutants and identifying the critical points are fundamental in the compilation of air pollution control strategies. Numerous statistical methods have been applied for analyzing, modeling, and mapping of air pollutants worldwide, including time series,[17] land use regression,[18-20] and space–time model,[21-23] using various software such as GIS, AirQ+, and R (Stem Package, INLA). However, the application of a novel method adopted with new software for data analysis can be noteworthy. In this context, the distributed space–time expectation–maximization (D-STEM) software, as a statistical tool for the analysis of environmental space–time data sets, has been developed in the MATLAB (The Math Works, Inc. 2010) language in 2014. This software, with some significant potential such as dealing with a massive load of data sets with lots of missing data, handling multivariate space–time data, and considering spatial correlation, can be helpful for the researchers. The present study attempted to investigate the daily dispersion pattern of $PM_{2.5}$ pollutants for 6 months (autumn and winter 2017) in Isfahan using a spatiotemporal model by the D-STEM software. This software has advantages of working with missing data and preparing maps of the distribution of the pollutants for every desired time, which can help health authorities in exposure assessment and environmental managers in the air pollution control program.

Materials and Methods

Study area

This is an ecological study which conducted in the Isfahan city one of the most populated and industrialized cities of Iran. It is located at 32°39'08'' N and 51°40'28'' E and 1570 m above the sea level. It leads to the desert in the north and east and to the Zagros Mountains in the west and south.[15] It is generally temperate and semi-arid region with an annual average temperature of 16.6°C and rainfall of 125 mm. The most precipitation lasts 7 months from November to May, with the highest in March and December. The Zayandeh-Rood River, which originates from the Zardkouh Bakhtiari Mountains, is one of the most important causes of population growth, as well as the expansion of industrial settlements and consequently the generation of various pollutant emission sources.

Air pollution data and studied variables

Hourly ambient $PM_{2.5}$ concentrations were obtained from seven active air quality monitoring stations located in different sites of the city (Ahmadabad Sq., Azadi Sq., Valiasr St., Roodaki St., Ostandari St., Khajoo St., and Elyaderan St.), which administered by the Isfahan Department of Environment. Given the volume of missing data in studies in Europe (<47%) which implemented this software[21,24] and comparing with the present study (<11%), all stations were eligible for modeling and none of them reached the exclusion criteria. We used variables of holidays/workdays, altitude of the air monitoring stations, and meteorological variables (means of temperature, relative humidity, rainfall, wind speed, and wind direction) to get better estimates and maps. The holiday variable was extracted from the official calendar. For the altitude of stations, we used station coordinates and Google Maps information. The amounts of meteorological variables were extracted from the data file obtained from the Isfahan Meteorological Office. The data referred to September 22, 2016, to March 20, 2017, according to autumn and winter in Isfahan.

Software and statistical model

In spatiotemporal models, estimates are obtained for different days in the study period and the entire study area. When multivariable spatiotemporal datasets are desired, it preferred to use models that can incorporate the correlation between variables into the computation. The parametric statistical model implemented in the D-STEM software is based on latent space–time random variables. The latent spatial random variables are modeled as Gaussian random fields with a Matern correlation function. In this software, model parameters are estimated by the maximum likelihood approach through the expectation–maximization algorithm. In environmental researches, missing data are the rule rather than the exception. In D-STEM, missing data, however, are handled perfectly, without the need for data imputation or interpolation.[25] The result of model estimation consists of the values of the estimated parameters and their variance–covariance matrix. Finally, the estimated model is used to dynamically map pollutant over the geographic area of interest. The following general univariate model implemented in D-STEM:

$$y_{PM}(c;t) = \mu(c;t) + \omega(c;t) + \varepsilon(c;t)$$

Where y(c; t) is the observation at time t and spatial location c; μ(c; t) and ω(c; t) are the fixed and random effect models, respectively. The measurement error ε(c; t) is a zero-mean Gaussian process uncorrelated over space and time with variance σ^2.[26]

Results

The map of the Isfahan and the locations of the air pollution monitoring stations in the city are shown in Figure 1, and the geographical coordinates, altitude (m), percentage of missing data, and mean $PM_{2.5}$ pollutants for air quality monitoring stations of Isfahan are given in Table 1.

In the execution phase and after three iterations, the program converges. Table 2 summarizes the results of the modeling, the β-coefficients, and their confidence intervals. It also demonstrates that $PM_{2.5}$ concentration increases with elevation (β = +0.093), temperature (β = +0.063), and wind direction (β = +0.026). In contrast, the variables of holiday, humidity, rain, and wind speed have a decreasing effect on pollutant concentration (with coefficients of − 0.075, −0.017, −0.083, and −0.226, respectively). In this modeling, only elevation with a 95% confidence interval between +0.071 and +0.115 and wind speed with a 95% confidence interval of −0.344 to −0.110 had a significant impact on pollutant concentration.

Figure 2 represents the monthly trend of pollutant variation for autumn and winter in Isfahan. The most polluted day was on October 1 and the clearest day on November 21. In the most polluted day, the pollutant level was several times higher than the allowed limit (147 mg/m³ at Station 1).

Figure 3 reflects the dispersion map of airborne $PM_{2.5}$ in autumn and winter in Isfahan where the most polluted regions of the city in the east and southwest were clearly demonstrated.

Figure 4 shows the mean dispersion map of $PM_{2.5}$ for autumn and winter. In this map, all city approximately has a borderline situation (pale green area); but also, there are some polluted points in the southwest and in the east of the city.

The pollutant's dispersion map for the most polluted day (October 1, 2016), is shown in Figure 5. On that day,

Table 1: Specifications of Isfahan active stations for September 22, 2016, until March 20, 2017

Station number	Longitude	Latitude	Elevation (m)	Missing data (%)	$PM_{2.5}$ (μg/m³)
1	51,70209	32,66403	1571.8	<1	34.45
2	51,66396	32,62246	1592.8	<6	35.20
3	51,71383	32,68189	1567.9	<2	30.19
4	51,63708	32,63458	1586	<1	34.74
5	51,68014	32,65739	1579	<1	29.42
6	51,68333	32,64249	1571.1	<8	33.29
7	51,63844	32,67798	1582.6	<11	31.75

$PM_{2.5}$: Particulate matters with diameter less than 2.5 micrometer

Table 2: Estimated model parameters, standard deviations, and 95% confidence interval

Variable	Parameter estimation	SD	95% CI
Elevation	+0.093	0.011	+0.071, +0.115
Holiday	−0.075	0.046	−0.165, +0.015
Humidity	−0.017	0.117	−0.246, +0.212
Rain	−0.083	0.053	−0.187, +0.021
Temperature	+0.063	0.158	−0.247, +0.373
Wind speed	−0.226	0.060	−0.344, −0.110
Wind direction	+0.026	0.048	−0.068, +0.120

CI: Confidence interval, SD: Standard deviation

Figure 1: Map of the study area, surrounding mountains and locations of the air pollution monitoring stations in Isfahan (1. Ahmadabad Sq., 2. Azadi Sq., 3. Valiasr St., 4. Roodaki St., 5. Ostandari St., 6. Khajoo St. and 7. Elyaderan St.)

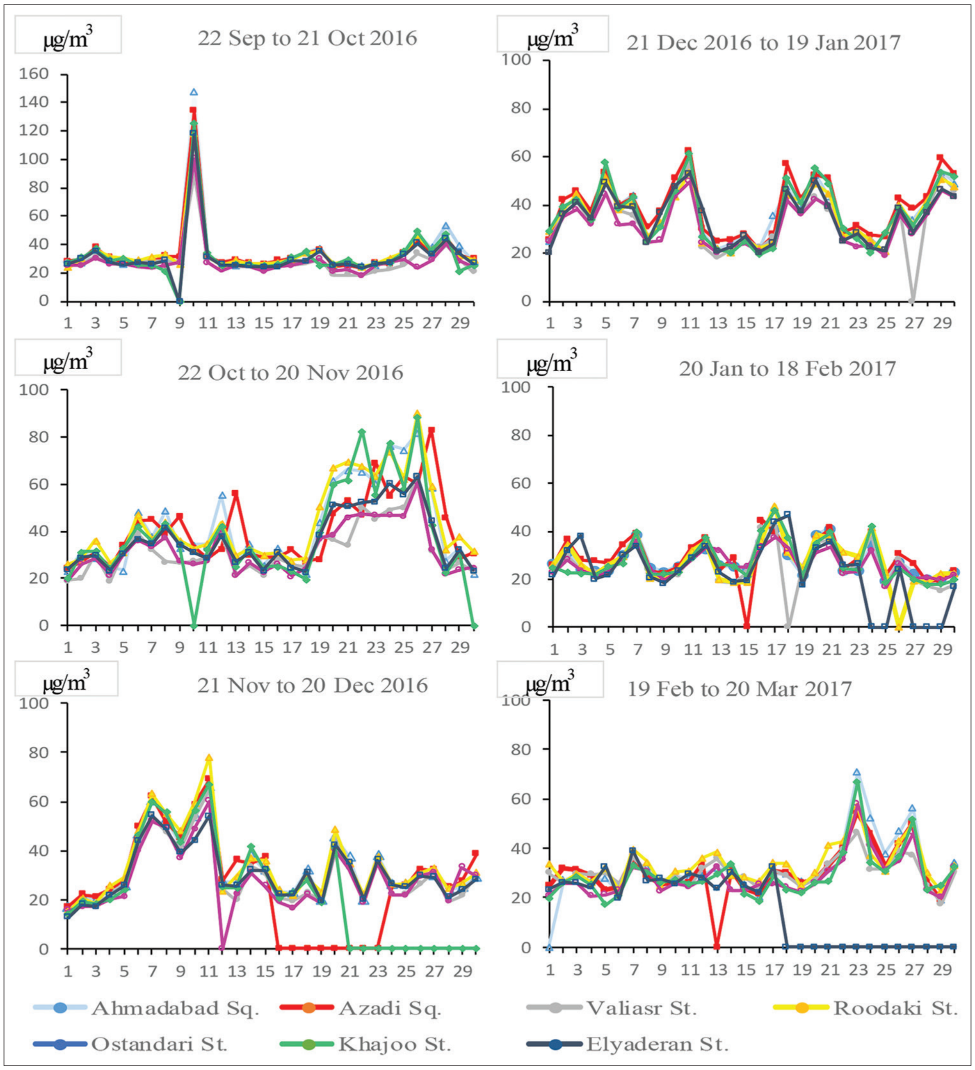

Figure 2: The trend of changes in $PM_{2.5}$ (μg/m^3) for Isfahan in autumn and winter 2016–2017

presumably, the prevailing wind from the dry parts of the north and northeast of the province has created a dust phenomenon (due to the lack of sufficient moisture in those lands). All the air pollutant monitoring stations reported unhealthy conditions for all population. This is clearly evident in the figure showing the monthly trend of $PM_{2.5}$ from September 22 to October 21 [Figure 2]. Further, the reddish-brown critical points in the southwest, southeast, and narrow strip in the northwest in Figure 5 clearly reflect this event.

Discussion

The present study is one of the few studies that investigated the spatiotemporal pattern of $PM_{2.5}$ pollutant in the ambient air of Isfahan.[27,28] Using D-STEM model, we mapped the average $PM_{2.5}$ concentration distribution in Isfahan city for 6 months in 2016–2017. Given the capabilities of this software, the map can be plotted for any day or time period during a year. The influence of predictors including holidays, altitude of pollutant monitoring stations, mean temperature, mean wind speed, wind direction, and average relative humidity was also evaluated. With the sake of this software, by applying such predictors in the model, one of the weaknesses of the already applied models was improved.[29] According to the pollutant distribution maps [Figure 3], the southwest of Isfahan, near the Station 1, was the highest polluted area, which is accordance with the results of the Talebi and Tavakkoli research on PM_{10} in the atmosphere of Isfahan.[30] However, when the whole province experiences a very high level of PM due to atmospheric phenomena such as dust storm, the condition exacerbates in this area.

The prevailing wind direction in Isfahan is from the east for 4 months, from June to September with a maximum percentage on July, and from the west for 8 months, from October to May with a peak percentage on January (https://weatherspark.com). Thus, in the cold season, due to pollutant movement from west to east and its accumulation, there are some reddish spots in the southeastern area of the city [Figure 3]. In addition to this, the role of heavy vehicular traffic in this area is undeniable. There are numerous scientific-educational centers as well as

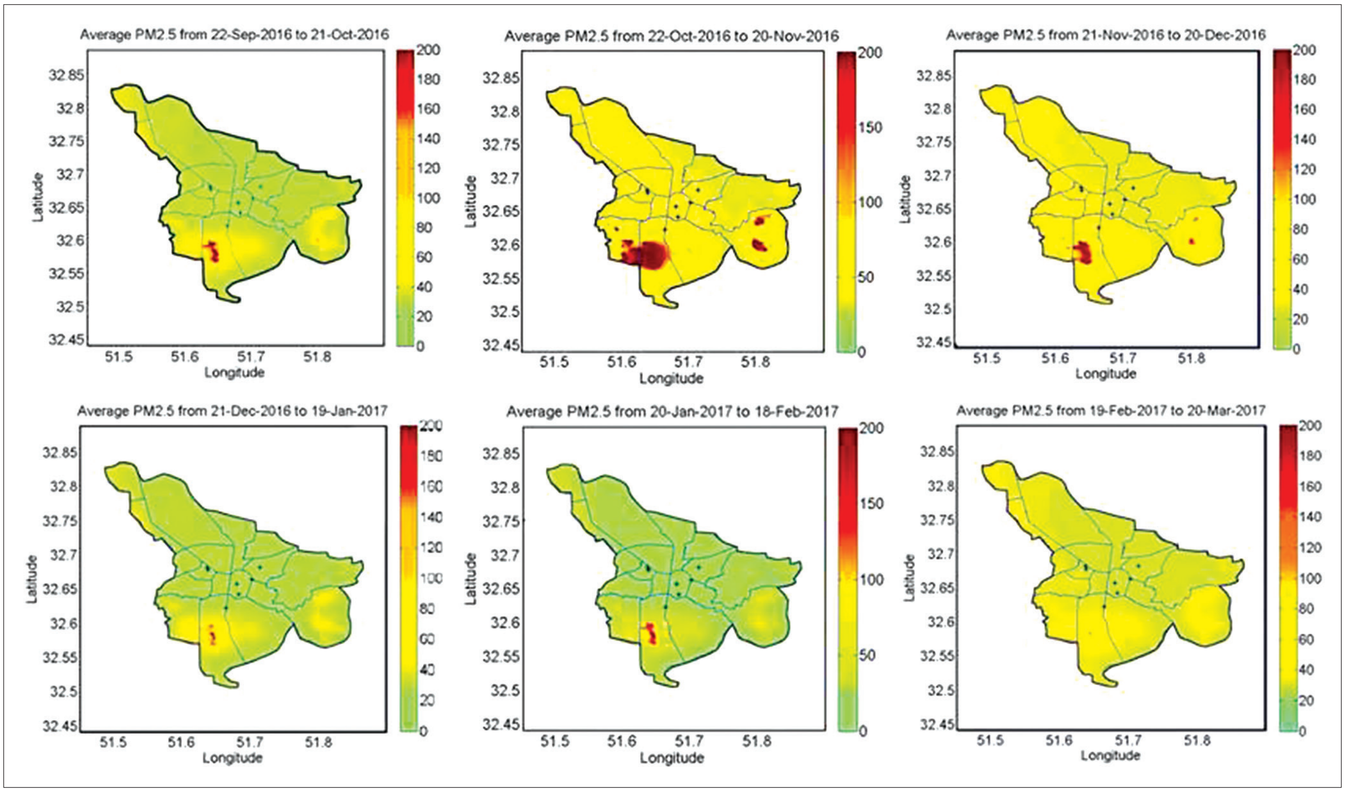

Figure 3: Dispersion map of $PM_{2.5}$ (μg/m^3) for autumn and winter in Isfahan, Iran, 2016–2017 (*monitoring stations)

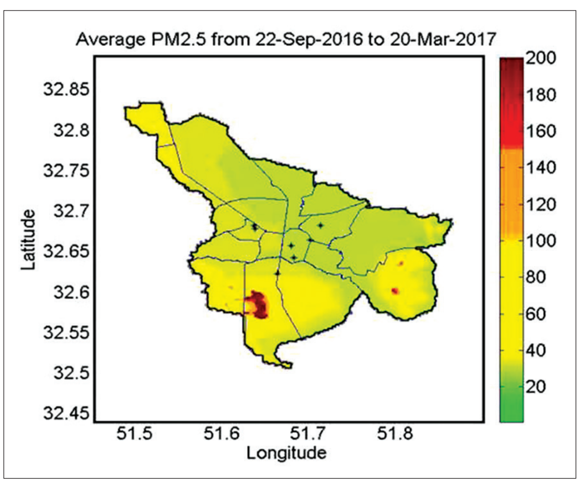

Figure 4: Dispersion map of average $PM_{2.5}$ (μg/m^3) for Isfahan, Iran, on September 22, 2016 until March 20, 2017 (seven monitoring stations are indicated by *in maps)

bus and coach stations in the eastern part of the city. These results were in line with what Jafari *et al.*[27] have obtained in 2017. Using data from four pollutant monitoring stations, they concluded that the $PM_{2.5}$ level was higher in the aforementioned area. However, even for the most polluted days of the year, there were many colored spots in the southwest area on the map. Along with the emissions from motor vehicles, this can be attributed to the emissions from Isfahan Steel Company, Isfahan Oil Refinery, Shahid Montazeri and Isfahan Power Plants, and some other industries which are located in the western of Isfahan. Furthermore, magnificent PM carrying by dust storms from neighboring districts and the activity of the small industries inside the city are considered as the other effective sources of air pollution.

The results showed a higher annual mean of the pollutant in cold months compared to warm months [Figure 2]. The much stability of the atmosphere and occurrence of thermal inversion during the early morning in cold months can be the main reason for the increased concentration of the pollutant in cold months. We also found that wind speed had a significant decreasing effect on air pollution level, which is in line with the results of some European studies.[31,32] In a previous study carried out in Isfahan, the researchers investigated the effect of meteorological variables on pollutants and found that air pressure and wind variables are the effective factors on regulating the concentration of pollutants.[33] Another variable in increasing the level of pollution in our study was the land elevation. In Tables 1 and 2 and also in Figure 3, we can find more polluted areas in the west and south, where the elevation of land increases. However, the altitude of these areas cannot be the main reason for this increase because the height difference of the study area was not considerable. This can be fully interpreted by the two environmental phenomena "eddy circulation" and "building wakes" effect as the west and southwest of the city are surrounded with mountains.[34] This finding was in accordance with the results of other study assessing the NOx concentration in the atmosphere of

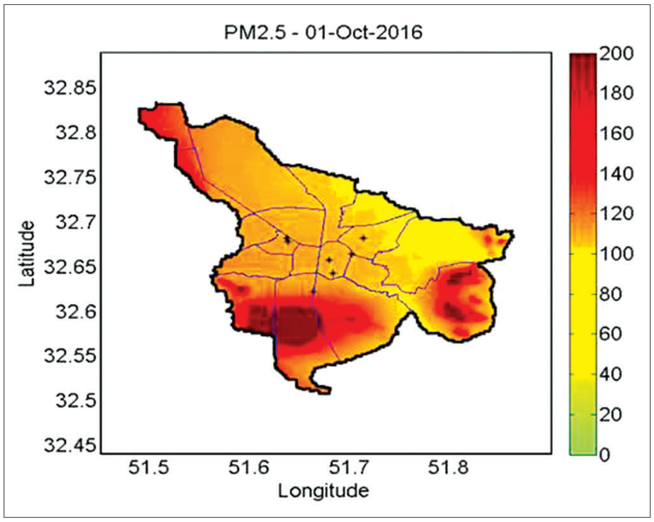

Figure 5: Dispersion map of $PM_{2.5}$ (µg/m³) for the most polluted day (October 1, 2016) in Isfahan, Iran, 2016–2017 (seven monitoring stations are indicated by *in maps)

Tehran[35] and against what Fassò *et al*. have found in their research[21,36] but for different pollutant and geographical location which are so effective in the results.

One of the strengths of the present study is considering seven independent variables affecting the concentration of $PM_{2.5}$, which help to get more exact results. Another notable point is the use of D-STEM software to map airborne fine particulate pollutant. In addition to considering spatial correlations in the form of the exponential correlation function in this model, a measurement error is also considered which is effective in obtaining more accurate coefficients. However, in similar studies, these spatial correlations have been neglected in modeling thanks to low values of Moran's I statistics.[37,38] In the present study, estimation of missing values by the software itself gave the software great flexibility,[26] while in some previous studies, this has been done using replacement methods such as averaging or with the aid of ancillary software.[38,39] The other strength of this study was considering both the random and fixed effects in modeling, while we can see that random effect has been omitted in lots of other surveys for big cities in Iran.[35] In the other methods of data analysis, all the information on the considering period was collapsed and eventually yielded only one map for the entire study period,[40] whereas in this study, it can be drawn a map for each day or period of interest. However, due to the complexity of the database and the need to get acquainted with MATLAB software, the program was less welcomed. The limitation of this study was the low number of pollutant monitoring stations, whereas the more monitoring stations, the more accurate results we can earn. In our study, we used the dataset of only seven stations in comparison to a European study where the number of sensors for $PM_{2.5}$ was significantly higher than our case. The broad set of stations can lead to get more accurate maps.[21]

Conclusion

The present study showed that high traffic areas have an unhealthy condition in terms of air pollution levels, which confirms the major effect of urban transportations on air pollution.

In this study, the D-STEM software and environmental effective variables were used in the modeling in order to obtain more reliable estimates and accurate maps of the PM pollutant status in the city. By implementing facilities such as verified pollutant sensing devices to get more precise and accurate data, and using software like D-STEM which has strengths and advantages that make it more significant than other conventional software in this field (such as working with missing data, preparing maps for every unit of time, taking the correlations into account, etc.), the researchers can provide models and spatiotemporal maps of the distribution of the pollutants, which can be applied for decision-makers in the air pollution control program.

Climatic conditions and natural phenomenon such as thermal inversion of the atmosphere which reduce the dilution and dispersion of the pollutants are not controllable. However, some key actions such as changing commute patterns by the citizen, expansion of public transportation, improving cars and fuel standards, installation of air pollution control devices for the industries, and practical solution in the field of restoration of dry and loose soil around the cities can be solutions for the reduction of air pollution.

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Conflicts of interest

There are no conflicts of interest.

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