

Analysis of the Impact of Road Traffic on the Urban Air Quality

Qi Wang

Shandong Jiaotong University

Haixia Feng (✉ fhx76@163.com)

Shandong Jiaotong University

Haiying Feng

Beijing Technology and Business University

Jian Li

Shandong Jiaotong University

Erwei Ning

Shandong Jiaotong University

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Abstract

With a focus on the hot topics of traffic congestion and smog (air quality), in this study, the impact of road traffic on urban air quality was the first quantitatively analyzed based on the aerosol optical thickness (AOD) and geographical weighted regression (GWR) models, including the road network density, road area occupancy, intersection number, and bus network density. The main research conclusions are as follows. There is a strong positive correlation between the peak congestion delay index (PCDI) and air quality. Based on the GWR model, AOD has high correlations with four road network traffic characteristic parameters, and these correlations are much higher than ordinary linear regression, that is, GWR refines the local spatial changes in the AOD and the road parameters. The correlation was mainly positive. The correlation between AOD and the road area occupancy was the highest, and the correlations between PM_{2.5} and the density of the bus network and the number of intersections were higher than those with the road network density. Thus, bus route planning, bus emission reduction, road network planning, and signal timing (intersection) have a greater impact on air quality, especially in areas with traffic jams. This study has a certain guiding significance for traffic planning and traffic control, and it provides support and a basis for traffic planning and control.

1. Introduction

As the largest developing country, China's air quality has always been a focus of research. Air pollution and the processes that generate air pollution exhibit spatial heterogeneity. According to the pollutant analysis results released by Beijing, Jinan, Hangzhou, vehicle exhaust has surpassed coal as the main source of urban air pollution (especially PM_{2.5}). By June 2020, the number of motor vehicles in China had reached 360 million, and traffic congestion had become the norm in many Chinese cities. As a result, the contribution rate of vehicle exhaust pollution to air quality will continuously increase. Its contribution to PM_{2.5}, volatile organic compounds (VOC), etc., were experimentally analyzed (John, 2001; Osada, 2019; Yuanchung, 2019, 2020; Yanzhao, 2019; Wenlong, 2017; Tianzeng, 2018). The influences of the traffic characteristics, traffic sources, traffic flow states, road grade, vehicle type, fuel, terrain, meteorological conditions, and spatial-temporal heterogeneity on exhaust emissions were studied (Abdull, 2020; Ryosuke, 2019; Asokraj, 2018; Jianbing, 2019; Haobing, 2019; Suhong, 2019; Cheol-Heon, 2018; Osada, 2019). Traffic simulations, the OMG volume-source model, cellular automata, sensitivity analysis, and the fault tree model have also been used to study exhaust emissions, diffusion, and their influence on air pollution. (Hitoshi, 1990; Zhao, 2017; Pratama, 2019; Sergio, 2020; Fengchuan, 2019; Pratama et al., 2019). Few studies on the impacts of road network traffic characteristics (e.g., road density, intersection, and bus network density) on air quality have considered the spatial heterogeneity.

Air pollution and the process of producing air pollution exhibit spatial heterogeneity. The geographically weighted regression (GWR) model considering spatial heterogeneity was used to analyze urban air pollutants, and the results revealed that the GWR is better than regression model (Cheng et al., 2017; Hu et al., 2013; Wang et al., 2016). The multi-scale geographically weighted region (MGWR) model was proposed and used to examining the influences of air quality in China's cities (Fotheringham et al, 2017,

2019). The retrieval of the air pollution status based on remote sensing data not only makes up for the lack of observation data, but also reflects the spatial distribution characteristics of the air pollution, so remote sensing inversion has become an important method for studying air pollution. Previous studies have shown that there is a certain correlation between the aerosol optical thickness (AOD) and the concentration of near surface particles, and the AOD product of MODIS (Moderate Resolution Imaging Spectroradiometer) is the most widely used in air pollution research (Chu et al, 2003; Slater et al, 2004; Wang et al, 2003; Gupta et al,2006; Tao, et al,2013). The objective of this study is to quantitatively analyze the impacts of road traffic characteristics on urban air quality based on their spatial heterogeneity.

2. Materials And Methods

2.1 Study area

The main urban area in Jinan (non-administrative boundaries, Fig. 1) was taken as the study area for two reasons: severe haze and traffic congestion. Jinan has been ranked among the cities in China with the worst smog problems, and its annual average PM_{2.5} concentrations were greater than 90 $\mu\text{g}/\text{m}^3$ in 2016 and 2017. The other reason why Jinan was selected as the study area lay in its serious traffic congestion. The Traffic Analysis Report published by AMap showed that Jinan ranked No. 1 among the cities in China in terms of commuter peak congestion in 2016 and 2017, and the peak road network congestion delay index (PCDI) reached 2.28 and 2.14 in 2016 and 2017, respectively. Traffic congestion was eased in 2018 and 2019. In the first quarter of 2020, Jinan had become the "first traffic jam" in China again. As the capital of Shandong Province, Jinan is located in the western-central part of Shandong Province, south of Mount Tai, and crossing the Yellow River in the north.

In this study, December 26, 2017, was chosen for the following main reasons. (1) Traffic conditions: on Dec 26, 2017, the traffic congestion in Jinan was severe and all of the major traffic arteries, such as Jingshi Road, Beiyuan Road, and the main roads in Jinan, were experiencing longer severe congestion. (2) Weather: it was sunny with northeast winds of $< 3 \text{ m/s}$, which is favorable for remote sensing data. (3) Air quality: the air in Jinan was mildly polluted, with a mean PM_{2.5} value of 85 $\mu\text{g}/\text{m}^3$. The traffic, weather, and air quality in the study area on December 26, 2017, were the most consistent with the study requirements.

2.2 Data

In total, monitoring data from 11 air quality monitoring stations in the study area (<https://www.aqistudy.cn>) and two stations that were deployed by two research teams were utilized. The distribution of the monitoring stations was shown in Fig. 2.

Two types of remote sensing data were used in this study: MCD19A2 AOD products and landsat8 OLI images. MCD19A2 is the official 1 km resolution AOD products of MODIS, and it is produced using the aerosol algorithm in MAIAC (the multi-angle atmospheric correction algorithm). Compared with the 10 km

and 3 km resolution MOD04 aerosol products, the MCD19A2 has a higher resolution (study area located in H27V05). The column number of the Landsat8 image of Jinan was 12235. Both datasets were collected on December 26, 2017.

Roads less than 3 m wide were excluded from the road network in the study area. The network of public transport routes in the study area is shown in Fig. 2.

As a measure of the number of hours of peak congestion delay, the Peak Congestion Delay Index (PCDI) is an indicator used to evaluate the degree of urban congestion, which typically has peaks at 7:00–9:00 in the morning and at 17:00–19:00 in the evening. It is a visual representation of a city's traffic operations, and it reflects the exhaust emissions. The PCDI was obtained from China's Major Urban Transport Report released by AMap.

2.3. Methods

2.3.1 Air quality distribution based on MCD19A2

The MCD19A2AOD products used in this study were taken on December 26, 2017. The AOD data for the different orbits (there are 4 tracks in the daily AOD data) were combined into the daily AOD, and the AOD in the study area is shown in Fig. 3.

2.3.2 Gridding

Using the gridding tool, the study area was divided into 1 km x 1 km grids (Fig. 4), with less than 1 km remaining on the northern and eastern sides of the study area being excluded from the gridding). The AOD, road network density, road area ratio, and number of intersections in each grid were calculated.

2.3.3 GWR-based analysis of the impact of the road network traffic characteristics on the urban air quality

Geographically weighted regression (GWR) is a spatial analysis technique that is widely used in geography and related disciplines involving the analysis of spatial patterns, and it can be used to quantify spatial heterogeneity. It has a higher accuracy because the local effects of spatial objects (i.e., the spatial heterogeneity) are taken into account.

$$y_i = \beta_0(u_i, v_i) + \sum_{k=1}^p \beta_k(u_i, v_i)x_{ik} + \varepsilon_i,$$

where $\beta_0(u_i, v_i)$ is the coordinates of sample point i ; $\beta_k(u_i, v_i)x_{ik}$ is the k th regression parameter at sample point i ; and ε_i is the error correction term.

The GWR analysis was based on the spatial correlation test of PM2.5 distribution in the study area. The spatial autocorrelation analysis tool in ARCGIS (the Moran's Index I) was used for the analysis. Moran's index I is mainly used to measure the spatial distribution characteristics of the data throughout the entire region.

The Moran's index I distributions of PM2.5 was 0.49 in the study area, the distributions of the PM2.5 was closely correlated, had obvious spatial clustering characteristics, and was heterogeneous, which makes them suitable for GWR analysis.

2.3.4 Correlation analysis

The correlation between the PCDI in each quarter for the past five years (2016 to Q1 2020) and the PM2.5 (the average values of each quarter in Jinan) was analyzed, and the fitting diagram is shown in Fig. 5.

The correlations between PM2.5 and the gridded density road network, the road area occupancy, the number of intersections, and the network density of the bus lines were analyzed (linear regression), and the results revealed that their correlations were all low.

3. Results

3.1 Traffic and air quality

As can be seen from Fig. 5 the correlation coefficients between the PCDI and the PM2.5 has R^2 values of up to 0.4962 (R 0.70). The data were paired separately and the F Test was conducted in the two groups of data when $p < 0.05$, i.e., the samples was variance congruent. Then the t-Test was conducted using the two-sample equal variance hypothesis. With $\alpha = 0.05$, all $p < 0.05$, that was, the fitted linear equation passed the significance test. The results demonstrate PM2.5 is positively correlated with PCDI. According to the source analysis of PM2.5 in Beijing, Jinan, and Hangzhou, exhaust gases surpassed coal combustion as the main source of PM2.5 pollution in cities, that is, traffic (exhaust) has a large impact on urban air quality, especially in traffic jams. However, the correlations between AOD and the gridded density road network, the road area occupancy, the number of intersections, and the network density of the bus lines (linear regression) were all low, so the GWR model considering spatial heterogeneity was used.

3.2 Single-parameter impact analysis

The AOD model with road network density, road area occupancy, number of intersections, and bus network density were constructed separately based GWR. The contrast between the input parameters in the GWR output tool is shown in Table 1.

Table 1
GWR Model input comparison table

Dependent Field	Explanatory Field	R ²	R ² Adjusted
AOD	Road network density	0.6075	0.4814
	Road occupancy rate	0.6484	0.5155
	Number of intersections	0.6162	0.4912
	Density of the public transport network	0.6304	0.5075

As can be seen from Table 1, the PM_{2.5} based on the GWR model analysis was closely correlated with the road network density, road area occupancy, and the number of intersections. That is, PM_{2.5} has strong heterogeneities, so the GWR model was used to refine the characterization of the AOD distribution and the local spatial variation in the road network in the study area. The regression parameters for each variable were positive or negative, i.e., each factor had a facilitating or inhibiting impact on air quality in the different regions. However, based on the median of the regression coefficients for each variable, it is clear that the road network density, road area occupancy, and number of intersections had significant impacts on the regional AOD, and they were positively correlated.

The road area occupancy was exhibited the highest correlations with AOD, i.e., during traffic congestion, the road occupancy area had the greatest impact on the air quality in the region. AOD was better correlated with the density of the bus route network than with the density of the road network, which means that buses had a greater impact on the urban AOD, and reducing pollution from buses is important for reducing urban AOD concentrations. AOD was more significantly correlated with the number of intersections than with the density of the road network, i.e., the setting of the traffic lights (traffic signals) within the regional road network. The number of intersections and the network of bus routes had significant impacts on the exhaust emission (i.e., the regional air quality).

3.3 Parameter autocorrelation analysis

In this study, four parameters were selected to analyze the impacts of the road network density, the road area occupancy, the number of intersections, and the bus route network density on urban air quality in a congested environment, and all four parameters had significant impacts on the air quality in the corresponding areas. To avoid multicollinearity among the variables, the correlations between the four parameters themselves were analyzed before constructing the multi-parameter GWR model (Table 2).

Table 2
Correlation coefficient R^2 of parameters

	Road network density	Road occupancy rate	Number of intersections	Density of the public transport network
Road network density	1			
Road occupancy rate	0.924	1		
Number of intersections	0.8999	0.7891	1	
Density of the public transport network	0.2392	0.2463	0.2685	1

As can be seen from Table 2, the three parameters, including the road network density, the road area occupancy, and the number of intersections, were significantly correlated. In particular, the correlation coefficient between network density and road area occupancy was 0.924, but the correlation between road area occupancy and intersections was weaker (0.7891). The correlations between the bus route network density and the other three parameters were less significant (less than 0.3). Thus, road area occupancy and bus route network density were used to construct the GWR model, and the variance inflation factor (VIF) of the independent variables test was determined for the two variables (i.e., road area occupancy and bus route network density). $VIF = 1.33$, i.e., the collinearity between the independent variables was small, but meets the requirements of the regression analysis, and thus, the GWR model-based results are credible.

4. Discussion

4.1 Error analysis based on the GWR model

The standard deviations of the AOD models constructed based on the GWR in the study area is shown in Fig. 6.

As can be seen from Fig. 6, fewer grids had standard deviations of greater than 2.5 or less than -2.5. The AOD model constructed based on GWR has three grids with large errors, Fig. 7.

As can be seen from Fig. 7, the types of ground cover within the seven error-prone grids are complex, i.e., a large error exists in the model constructed based on GWR under complex surface conditions. The reasons for this are as follows. The complex surface conditions were prone to lower remote sensing inversion AOD accuracies, leading to large estimation errors. Second, for the complex surface conditions, the calculation accuracy of the road network characteristic parameters was lower.

4.2 Spatial-temporal deduction of the remote sensing data

Although remote sensing data can retrieve the spatial distribution characteristics of the AOD (air pollution) well, it is instantaneous data, that is, it can only represent the spatial distribution of the satellite transit time. However, the AOD and traffic exhaust emissions are always changing, so the AOD retrieved by remote sensing has the problem of time scale deduction. To ensure the correspondence of the time scale, the observation data corresponding to the response time of the satellite transit time are generally used for research. In order to reduce the time scale error, in this study, the correlation analysis between the PCDI and the air quality was based on the average value. Therefore, the GWR analysis was conducted using the daily mean value of the AOD and the road network density, road area occupancy rate, intersection number, and bus network density.

The AOD data from MODIS generally contain data for more than three orbits each day (each orbit time is different). The AOD data are commonly missing on days with heavy pollution or very little pollution, e.g., from January 1 to 10, 2017, the air pollution in study area was serious, and the MCD19A2AOD in Jinan is all no data. Thus, the algorithm of the AOD needs to be further improved.

The correlations between the PCDI and the AOD were positive, that is, the more congested the traffic is, the stronger the relationship between the PCDI and air pollution is. Thus, the results of this study provide a significant reference for traffic planning and air quality control in congested areas.

4.3 Scale problem

In addition to spatial heterogeneity, spatial scale is also an important feature of geographical phenomena. Fotheringham et al. developed the multi-scale geographically weighted regression (MGWR) model to study the influence of different scales on air quality. To reduce the impact of the different scales on the analysis, in this study, the gridded study area (i.e., the 1 km grid) was selected to match the 1 km resolution the AOD product.

Haiying et al. constructed the difference index (DI) (red band and near-infrared band based on Landsat8 data to monitor the DI concentration (30 m resolution)(Feng, et al, 2018). The AOD (1000 m), DI (30 m) and the road network in study on December 26, 2017 were shown Fig. 8.

The difference index of the 30 m resolution can better retrieve the relationships between the roads, road network, and air quality, but the difference index of the 30 m resolution lacks a strict theoretical basis, that is, a higher classification of the remote sensing products is a direction for future research.

5. Conclusions

Based on the AOD retrieved from remote the sensing data and GWR models, in this study, the impacts of four road network traffic characteristic parameters on air quality were the first quantitatively analyzed, including the road network density, road area occupancy, intersection number, and bus network density. The main research conclusions are as follows. There is a strong positive correlation between the PCDI and air quality. Based on the GWR model, AOD has high correlations with the road network density, road area occupancy, intersection number, and bus network density, and these correlations are much higher

than ordinary linear regression, that is, GWR refines the local spatial changes in AOD and the road traffic parameters. The regression parameters of the four variables have positive and negative effects, that is, the influence of each factor on air quality in the different regions can promote or inhibit, but positive correlations were dominant. The correlation between AOD and road area occupancy was the highest, and the correlations between the AOD and the density of the bus network and the number of intersections were higher than that between the AOD and the road network density, that is, bus route planning, bus emission reduction, road network planning, and signal timing (intersection) have greater impacts on air quality. The accuracy of the AOD models based on GWR was low under the conditions presented in the table. This study has certain guiding significance for traffic planning and traffic control, and provides support and basis for traffic planning and control, especially in areas with traffic jam.

Declarations

Author Contributions:

Haixia Feng was involved in the research design and finalized the paper; Erwei Ning was involved in software and validation, Jian Li and Haiying Feng analyzed the data; Qi Wang gave useful comments which improved the paper.

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Conflicts of Interest:

The authors declare no conflict of interest.

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Figures



Figure 1

Location of the study area Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

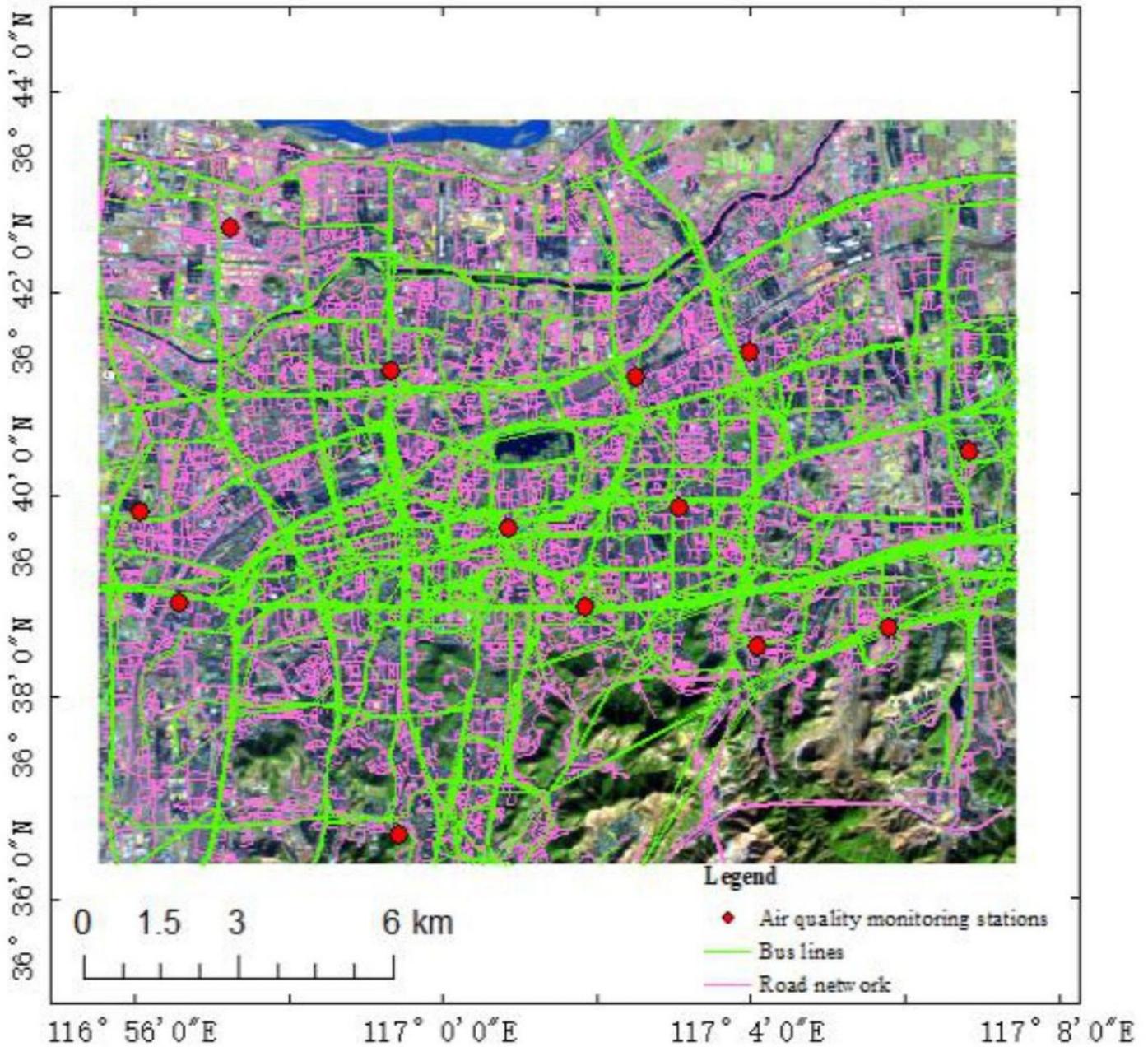


Figure 2

Air quality monitoring stations, bus lines, and road network in the study area

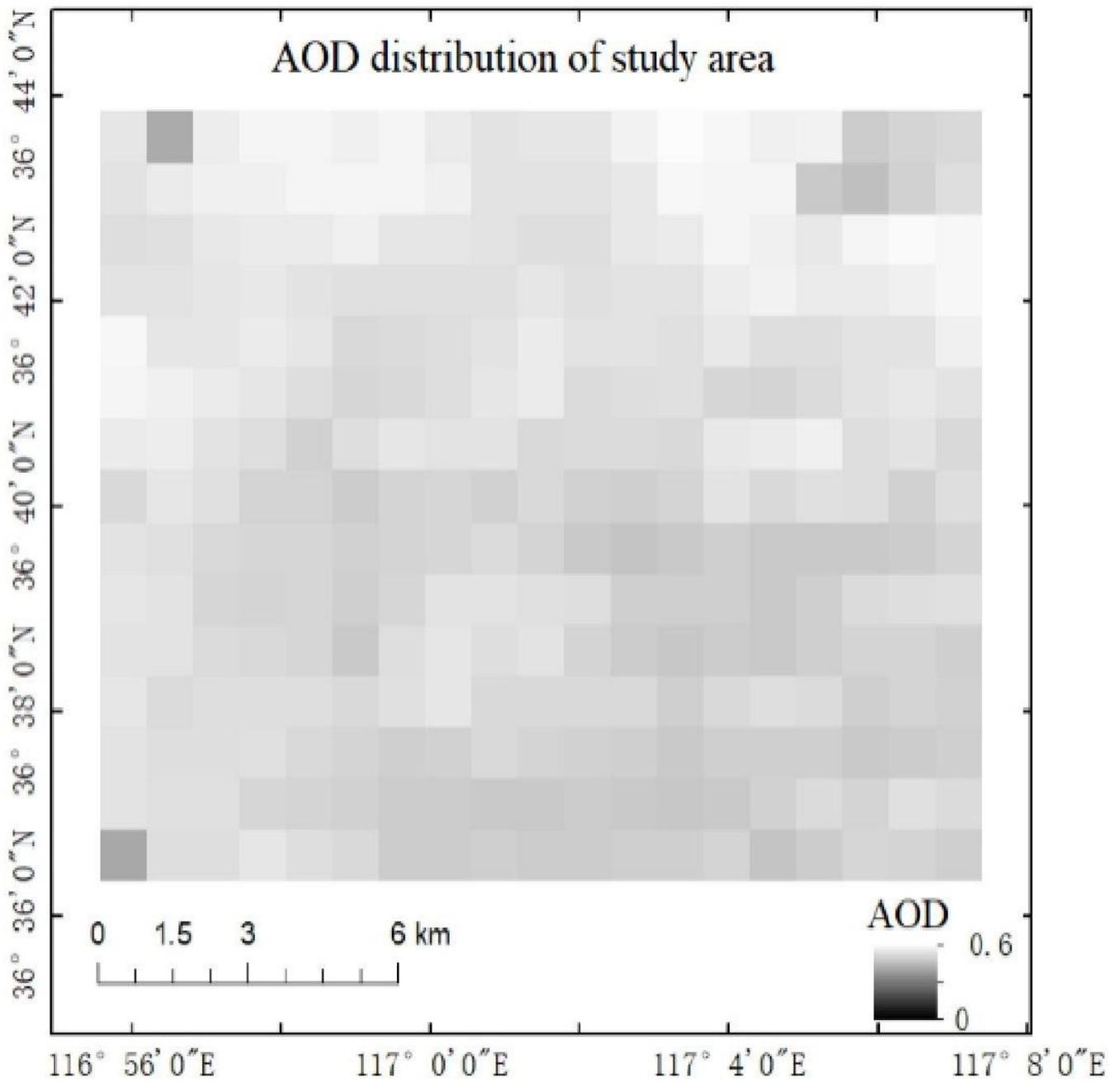


Figure 3

AOD distribution in the study area

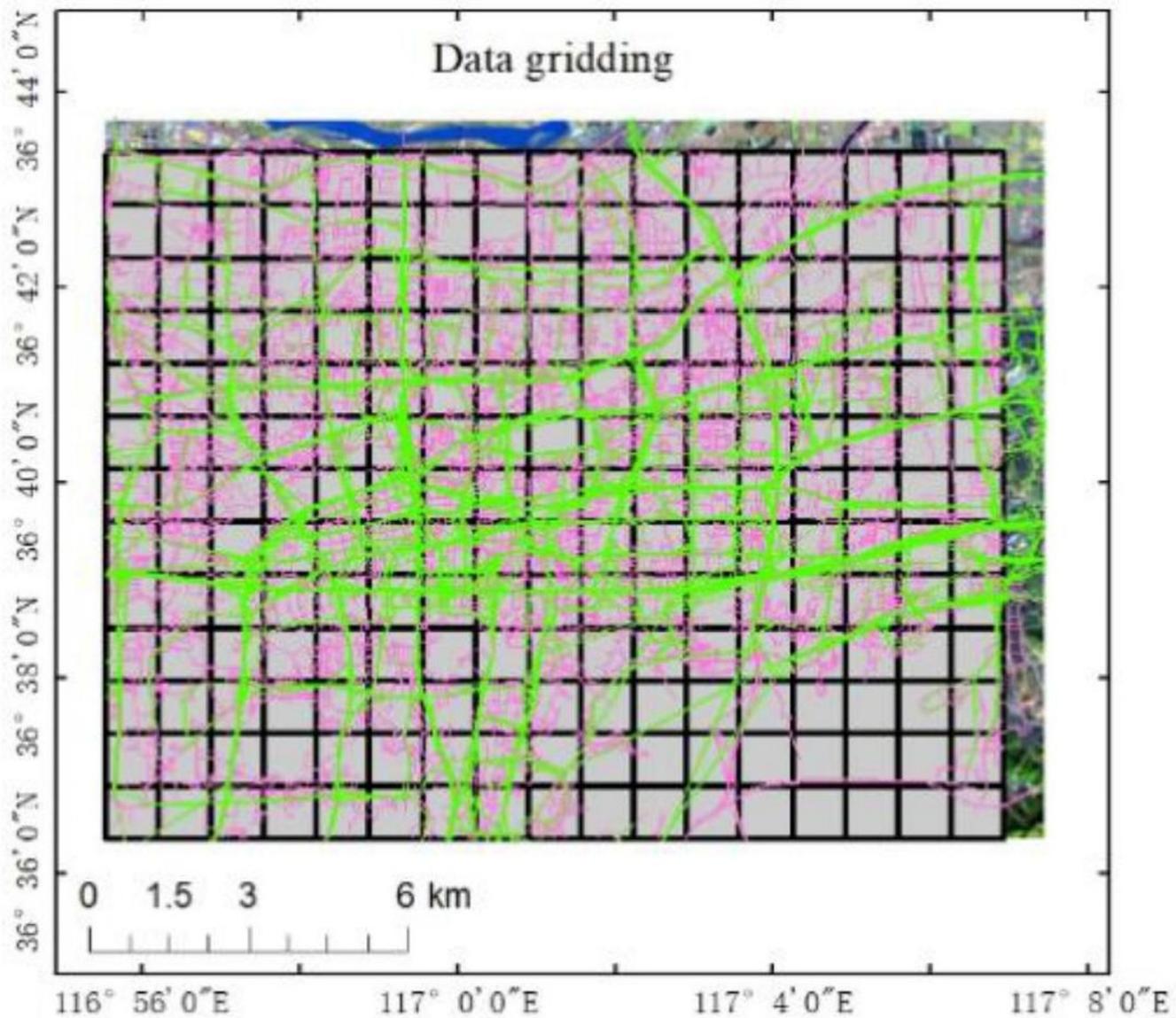


Figure 4

Gridding of the study area

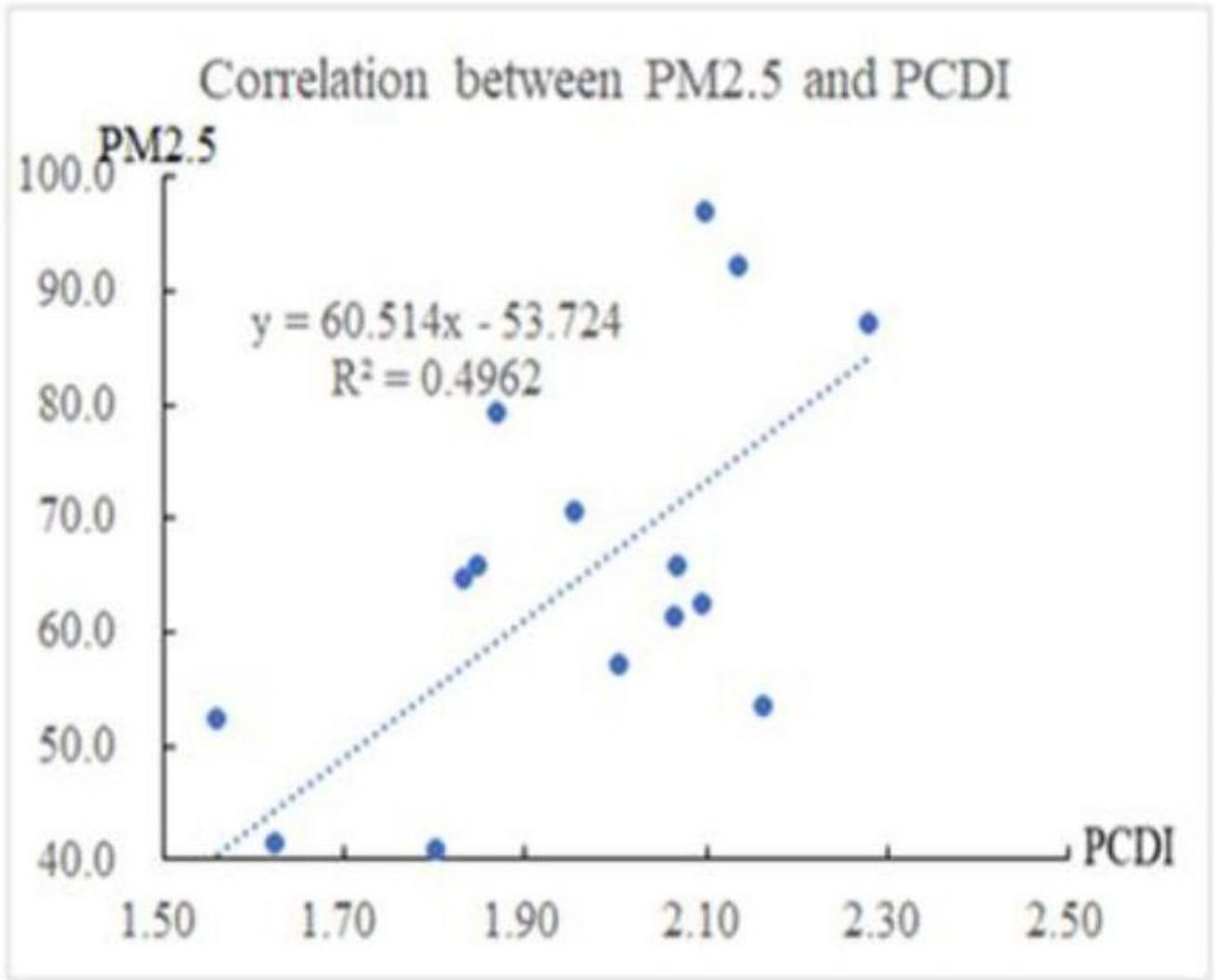


Figure 5

Correlation between PM2.5 and PCDI

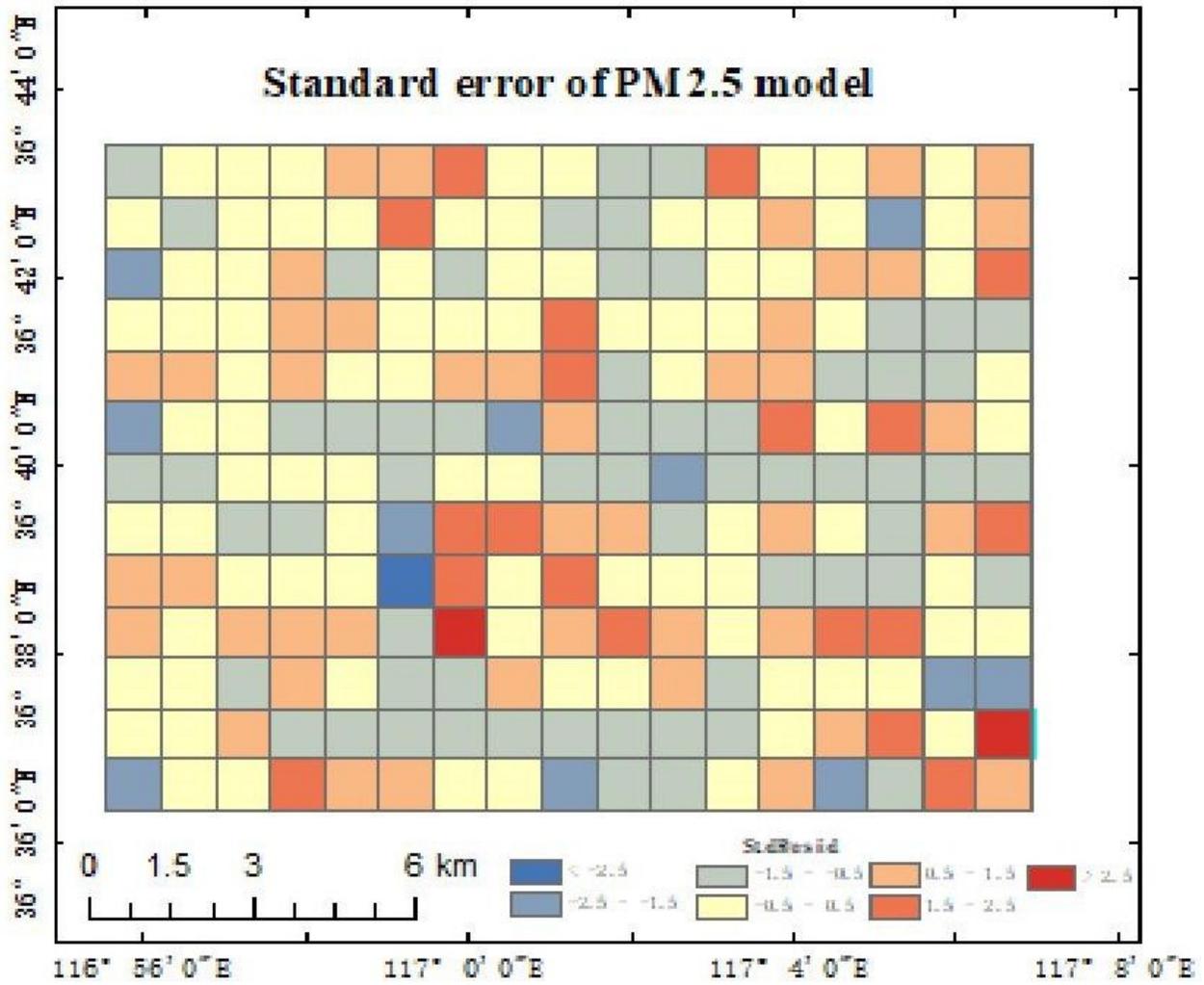


Figure 6

Standard deviation based on the GWR model

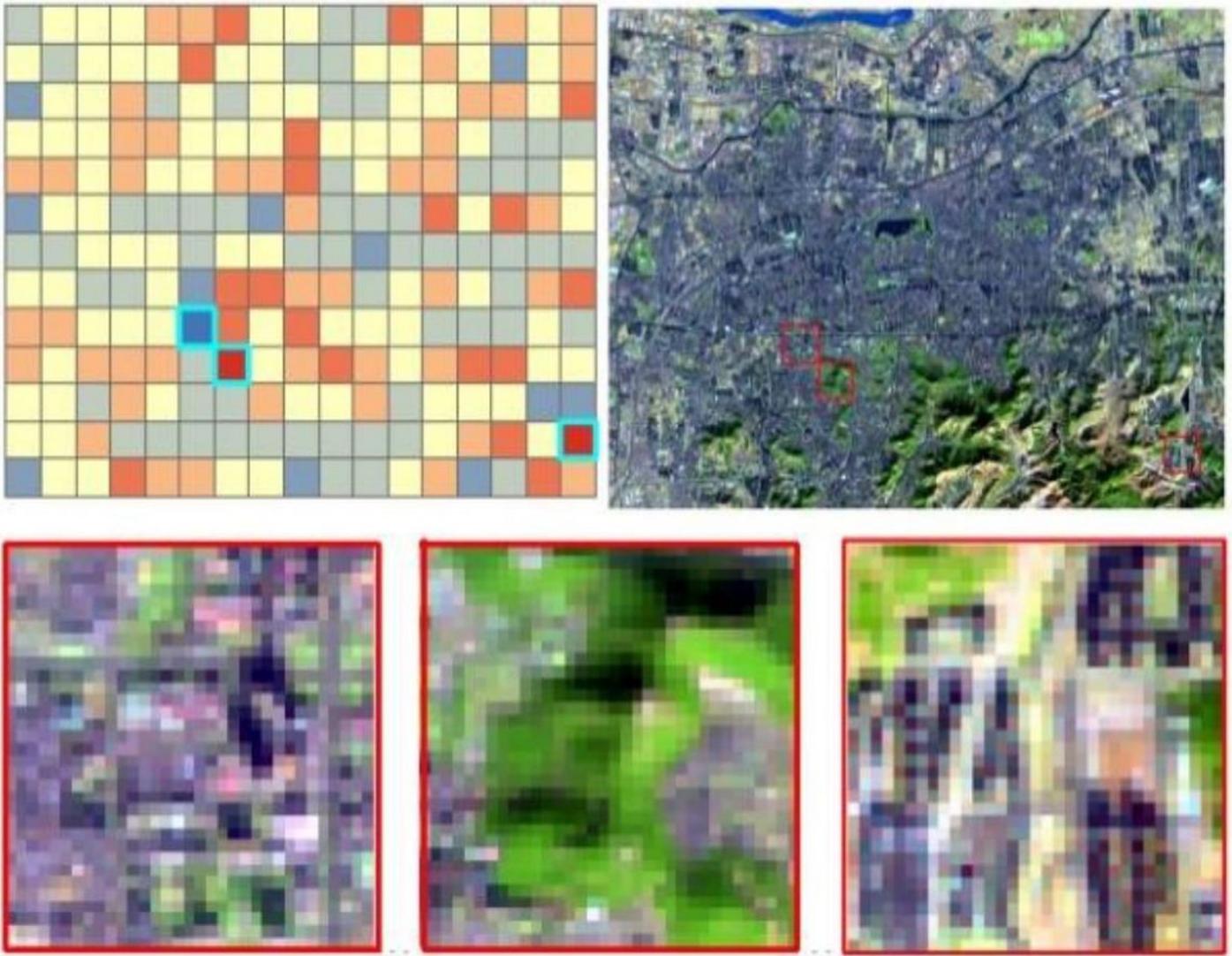


Figure 7

Grid with large error

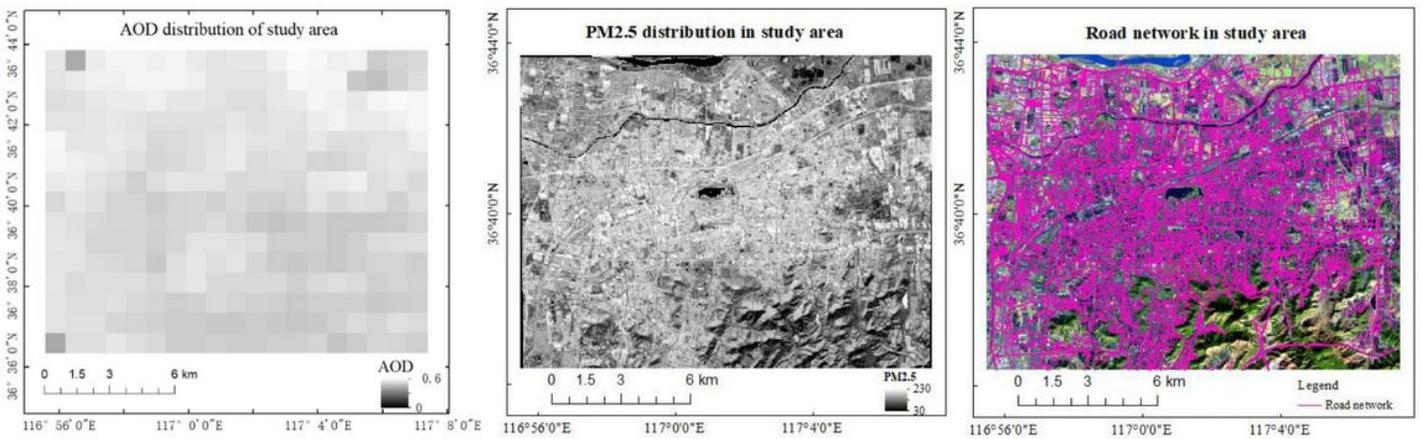


Figure 8

AOD(1000m),PM2.5(30m) and road network in study area