LONG-TERM INVESTIGATION OF AEROSOLS AND THEIR IMPACT ON HEALTH IN THE CITIES OF LAHORE AND MULTAN

Tehreem Mustansar

00000119562

Institute of Environmental Science and Engineering
School of Civil and Environmental Engineering
National University of Sciences and Technology
Islamabad, Pakistan
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A thesis submitted in partial fulfillment of the requirements for the degree of

Master of Science in Environmental Science

By

Tehreem Mustansar
00000119562

Institute of Environmental Science and Engineering (IESE)
School of Civil and Environmental Engineering (SCEE)
National University of Sciences and Technology (NUST)
Islamabad, Pakistan

(2019)

THESIS ACCEPTANCE CERTIFICATE

It is certified that the contents and form of the thesis entitled "LONG-TERM INVESTIGATION OF AEROSOLS AND THEIR IMPACT ON HEALTH IN THE CITIES OF LAHORE AND MULTAN" submitted by Ms. Tehreem Mustansar (Reg # 119562) has been found satisfactory for the requirements of the degree of Master of Science in Environmental Science.

Supervisor: ____________
Dr. M. Fahim Khokhar
IESE, SCEE, NUST

Head of Department: _________
Dr. Muhammad Arshad
IESE, SCEE, NUST

Principal: ________________
Dr. Tariq Mahmood
SCEE, NUST

CERTIFICATE

It is certified that the contents and form of the thesis entitled

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Submitted by

Tehreem Mustansar

has been found satisfactory for the requirement of the degree

Supervisor: ______________
Dr. Muhammad Fahim Khokhar
Professor
IESE, SCEE, NUST

Member: __________
Dr. Muhammad Arshad
Associate Professor
IESE, SCEE, NUST

Member: __________
Dr. M. Zeeshan Ali Khan
Assistant Professor
IESE, SCEE, NUST

DEDICATION

I dedicate this thesis to my family for their endless support, encouragement, prayers and patience.

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All the praise and respect for Almighty Allah, who is the ultimate source of all knowledge and wisdom gifted to mankind.

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Contents

List of Abbreviations

μg/m^3	Microgram per Cubic meter
AAE	Absorption Angstrom Exponent
AEC	Aerosol Extinction Coefficient
AERONET	AErosol RObotic NETwork
AOD	Aerosol Optical Depth
AOT	Aerosol Optical Thickness
ALRI	Acute Lower Respiratory Infections
ArcGIS	Arc Geographic Information System
BC	Black Carbon
BLH	Boundary Layer Height
CAMS	Copernicus Atmosphere Monitoring Service
C-CARGO	Climate Change and Atmospheric Research Group
CCN	Cloud Condensation Nuclei
COPD	Chronic Obstructive Pulmonary Disease
CVDs	Cardiovascular Diseases
DALYs	Disability Adjusted Life Years
DB	Deep Blue
DHIS	District Health Information System

D_p	Particle Diameter
DT	Dark Target
ECMWF	European Centre for Medium-Range Weather Forecasts
EMR	Electromagnetic Radiation
EOS	Earth Observation System
ER	Emergency Room
H	Height
HAs	Hospital Admissions
HRA	Health Risk Assessment
HRAPIE	Health Risk Assessment of Air Pollution in Europe Project
HTVs	Heavy Transport Vehicles
IGP	Indo-Gangetic Plain
IHD	Ischaemic Heart Disease
Lat	Latitude
Lon	Longitude
LUMS	Lahore University of Management and Sciences
MCTK	MODIS Conversion Toolkit
MODIS	Moderate Resolution Imaging Spectro-radiometer
MRT	Modified Minimum Reflectance Technique
NASA	The National Aeronautics and Space Administration

OPD	Out-patient Department
Pak-EPA	Pakistan Environmental Protection Agency
Pak-NEQS	Pakistan National Environmental Quality Standards
PAQI	Pakistan Air Quality Initiative
PM	Particulate Matter
PMF	Positive Matrix Factorization
PMD	Pakistan Meteorological Department
ppbv	Parts per billion by volume
RH	Relative Humidity
RR	Relative Risk
SBP	Statistical Bureau of Pakistan
VOCs	Volatile Organic Compounds
WHO	World Health Organization

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Abstract

Since Pakistan is devoid of a ground-based air quality network, monitoring urban air quality by using satellite data can facilitate with updated information about air quality, thus having vast implications for national policy decisions. AOD from MODIS-Terra was used to study the aerosol trend over Lahore (31.5546° N, 74.3572° E) and Multan (30.1984° N, 71.4687° E) districts from the year 2013 to 2017. In addition, continuous 12-hour sampling of Particulate Matter (PM) (10 and 2.5 microns) was carried out for three months from January to March 2017 in the highly polluted urban cities of Lahore and Multan. In order to test the statistical significance of trend in AOD, the Mann-Kendall seasonal trend analysis was performed. Mass concentrations of PM, and AOD AERONET, located in Lahore, were used to validate AOD observations from MODIS – Terra and Aqua, and determining an empirical relationship, which was further improved by introducing weather parameters. The resultant short-term morbidity in the form of hospital admissions attributable to $PM_{2.5}$ was estimated by using population health data, the concentration response coefficients recommended by the WHO, the actual measured exposure, and baseline exposures (or counter-factual) for the months of January, February, and March 2017. During the last five years (2013 – 2017), a significant positive trend of AOD was found over Lahore, while the trend over Multan was not significant. PM concentrations were found to be much higher than those recommended by WHO and Pak-NEQS, and a positive association was found between PM and MODIS AOD. Also, MODIS AOD when compared with AERONET AOD revealed a significant correlation (R) of 0.76 and 0.89 with Terra and Aqua respectively. Moreover, hospital admissions (respiratory diseases) attributable to $PM_{2.5}$ were also found to be substantial during the selected time period.

Chapter 1

1. Introduction

1.1. Background

Air pollution has become a grave concern with high levels in many parts of the world. The sources of particulate matter pollution in air include the agriculture and transport sectors, production of energy from coal, wood burning for cooking in households and inefficient use of energy including bio-fuels, open waste burning, biomass burning and forest fires, sand and desert dust.

According to data released by WHO in 2018, nine out of ten people in the world are exposed to dangerous levels of air pollutants. Consequently, 4.2 million deaths around the world can be attributed to outdoor air pollution in a year, and 3.8 million to indoor air pollution, making a total of 7 million deaths worldwide in a year. It has also been reported that three billion people worldwide still do not have access to clean fuels for in their homes for the purpose of heating and cooking (WHO, 2018).

Asia and Africa are home to most of the developing countries of the world where 90% of the deaths related to air pollution occur. Elevated levels of air pollution in the developing regions of the world has emerged as a global contemporary environmental issue, particularly in South Asia, having negative impacts on the daily life and health of the population. Asia has been reported to have the highest mean exposure to air pollution (Lelieveld et al., 2018).

The impacts of $PM_{2.5}$ on heath have been investigated in many epidemiological studies around the world (Gurung et al., 2017), and both acute (Bell et al., 2008) and chronic exposure to ambient atmospheric pollution has been linked with health burden. Fine particles are notorious as they are able to travel deep inside the lungs and cause damage to the pulmonary and cardiovascular system resulting in life threatening health outcomes such as stroke, Cardiovascular disease (CVD), lung cancer, Chronic Obstructive Pulmonary Disease (COPD), and respiratory infections such as Lower and Upper Respiratory Tract Infections and Pneumonia (Li et al., 1997).

1.2. Particulate Matter (PM) Air Pollution

PM is defined as a suspension of tiny particles of various sizes and liquid droplets in the air. The different components that make up this mixture include soil or dust particles, sulfates and nitrates as acids, organic substances, and metals.

The health implications of PM typically depend upon size and elemental composition (Shao et al., 2018), with more health impacts coming from the smaller particles; particles with a diameter <10 µm are called PM_{10} or 'inhalable coarse particles, and with a diameter <2.5 µm are called $PM_{2.5}$ 'fine particles' (Kim et al., 2015). Figure 1.1 shows the size distribution of aerosols (US EPA, 2008).

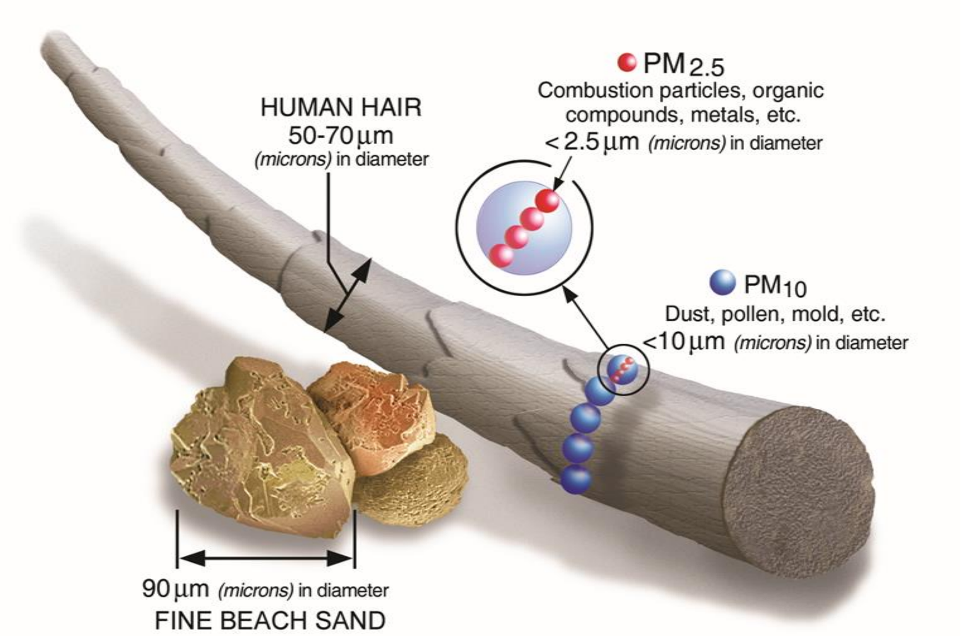


Figure 1.1: Particulate Size Distribution adapted from US EPA, 2008.

Particulate matter is typically divided into two categories: Primary and Secondary. A primary particle is the one which has a direct source whereas a secondary particle is formed when a primary particle gets oxidized or transformed in the atmosphere through interaction with gaseous precursors such oxides of sulfur and nitrogen and Volatile Organic Compounds (VOCs). The acids that are formed due to this process tend to form tiny droplets by attracting water vapor. Figure 1.2 shows the transformations of PM/aerosols in air:

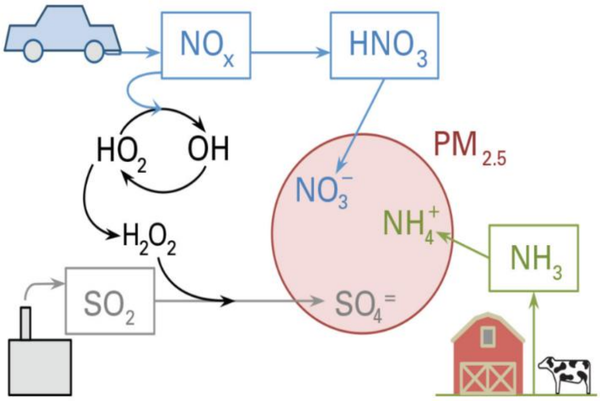


Figure 1.2: Particulate Matter transformations in air (Holt et al., 2015)

The sources of PM_{10} include dust, fly ash, coal, metal oxides of crustal elements, and mechanical disruption.

1.2.1 Environmental and Health Effects of Aerosols/Particulate Matter

The earth-atmosphere system has a delicate energy balance which is strongly impacted by fluctuation in atmospheric aerosol's concentrations, the balance of solar radiation, greenhouse gases, and the land surface properties (Papadimas et al., 2008).

The health impacts of air pollutants can result due to both acute and chronic exposure (WHO, 2016). This exposure can manifest itself in the form of pathophysiological responses including respiratory and cardiovascular morbidity such as an increase in respiratory symptoms i.e. aggravation of asthma, resulting in an increased number of hospital admissions. If the exposure and health condition persists, it can eventually lead to death. In scientific estimations of the health burden due to air pollution, mortality has been identified as a less sensitive marker than hospital admissions (Wong et al., 2002).

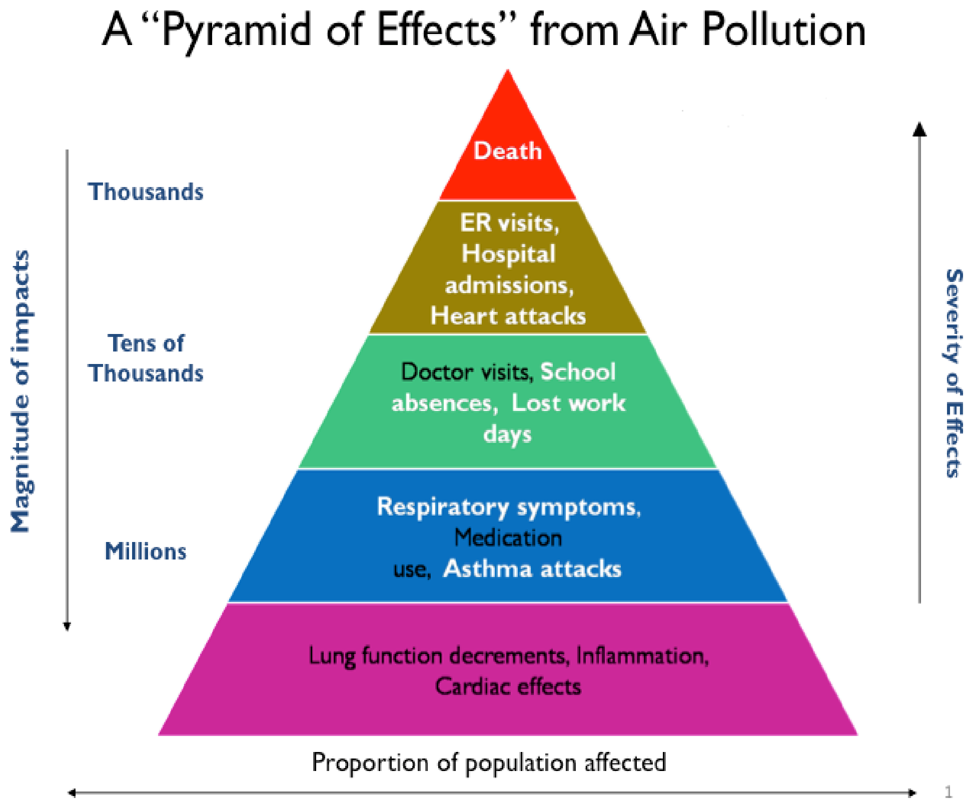


Figure 1.3: The image depicts the pyramid of effects from air pollution. $PM_{2.5}$ can penetrate the human blood-stream, resulting in pathophysiological responses such as inflammation and eventually leading to hospital admissions and clinical outcomes such as heart attacks and death (EPA, Benefits Mapping and Analysis Program, 2018).

1.3. Remote Sensing: Monitoring Air Pollution from Space

In order to observe the atmosphere or the earth surface from a distance i.e. out of space (space-borne) by means of satellites or from the air (air-borne) via aircrafts, the technique of remote sensing is used.

The sun is a source of electromagnetic radiation (EMR) which passes through the atmosphere twice. Firstly, when it comes from the sun to the earth, and secondly when it is reflected by the earth and detected by the satellite or sensor. When passing through the atmosphere the EMR interferes with the atmospheric constituents resulting in a phenomenon known as “atmospheric effects” which can be used to extract useful data about the atmosphere.

In Pakistan, dearth of real-time monitoring and ground based stations has created a huge gap in air quality data which can only be monitored via satellite observations. Setting up a ground based monitoring network is expensive because it requires the purchase and establishment of automated instruments and expensive software and the launch of a permanent monitoring station. They are present in developed regions of the world such as the United States, Australia, Europe, and some parts of Asia, in order to measure the mass concentrations of ambient particulate matter or aerosols.

The drawback, however, of ground based observations is that they are point measurements and they cannot be used to study the global and regional aerosol distribution or trends since they do not provide the required coverage. On the other hand, satellite data measures aerosol optical depth, and can observe changes and transport of aerosols over vast areas (Engel-Cox et al., 2004).

Aerosols must be routinely monitored in order to study and understand their spatial and temporal patterns and how they affect the climate and health of the population on global, regional, as well as local scales.

1.3.1 Aerosol Optical Depth

Aerosol Optical Depth (AOD) is a satellite product which is the most widely used PM proxy. It is dimensionless and quantifies the extinction of light which is a result of the interference of light with PM present in the vertical atmospheric column. AOD is proportional to particulate pollution (Gupta et al., 2013).

In other words, when light coming directly by the sun is blocked by aerosol particles such as smoke, pollution, haze, or dust by either scattering or absorption of light, in a column of the atmosphere over the location that is being observed; the satellite is able to measure the difference or extinction of light in the form of AOD.

1.4 Health Risk Assessment

When humans are exposed to harmful chemicals in a polluted environmental media in the present, past, or future, it is bound to affect their health in some way. In order to estimate the probability and nature of such impacts, an environmental health risk assessment (HRA) is carried out.

The impacts of outdoor air pollution on human health are dependent upon a multitude of factors such as the level of concentration, the intensity and period of exposure, the chemical composition of a particular pollutant, the mixture of pollutants present, and the existing health, gender, and age of the individuals.

In order to quantify the local effects of a certain air pollutant, the HRA incorporates the latest scientific evidence that has established the pathological response in humans to air pollution, with the available local information about the incidence of disease and exposure of the population to the concerned pollutant.

Monitoring of air pollution is often used as a baseline when population exposure is estimated resulting from a hypothetical change in pollutant concentrations or emissions. Moreover, when technological innovations and policy changes in the future have to be considered, and the resultant concentration changes need to be estimated, air quality modelling is needed.

1.4.1 Measures of Disease Association

Relative Risk (RR) is defined as the scale of an association between disease and exposure on two groups in the population: the exposed relative to the unexposed.

Relative risk =1: no risk. It is derived from epidemiological studies, usually from meta-analysis.

Number of attributable cases of disease is the difference in the number of cases or incidence/rate of disease at two exposure levels:

1. The measured exposure over a specified period of time, and

2. The baseline exposure

For example, calculation of the difference between the existing disease incidence and that of a time in the past or a projected future incidence. The total health risk can also be calculated relative to zero exposure or any assumed threshold value (WHO Regional Office for Europe, 2014).

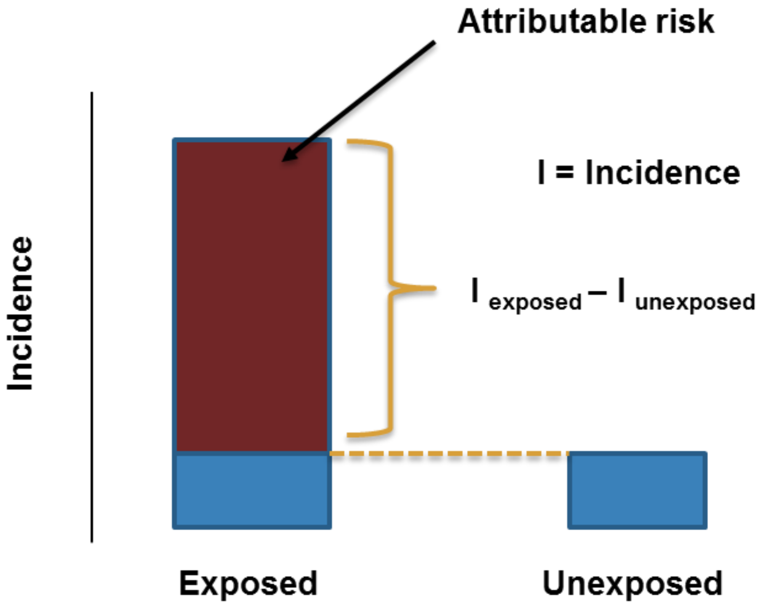


Figure 1.4: Attributable Risk in terms of incidence of disease and exposure (WHO Regional Office for Europe, 2014).

1.5 The Present Study

1.5.1 Study Area

Continuous ground- based measurements of PM_{10} and $PM_{2.5}$ were conducted in Lahore and Multan, Punjab, Pakistan.

Lahore is the 2nd most populous city (lat: 31°32′59″N lon: 74°20′37″E, inhabitants are about 10.2 million) and host various types of industries including power generation, textile, pharmaceutical, steel manufacturing, foundries and huge number of cottage industry. A high number of vehicles and the resulting road congestion is a grave issue in Lahore. As per the Punjab Bureau of Statistics (2015), between the period 2005-2014, there were a total of 13.48 million registered vehicles in the province of Punjab, and out of these, four million vehicles were registered from Lahore (Batool et al., 2018).

Multan is the fifth most populous city located in South Punjab (lat: 30.1984° N, lon: 71.4687° E, inhabitants are about 2.5 million). Industries include cotton production and processing, fertilizer, large scale textile units, oil and sugar mills, cosmetics, glass manufacturing, flour mills, and power generation projects. It is also known for its cottage industries and intricate handicrafts (carpets and ceramics). It is an emerging metropolis and is the most developed city in Southern Punjab, located near the highly arid region of Bahawalpur-Cholistan, thus being influenced by dust springing from that region.

The predominant for poor air quality in Multan are industrial and vehicular emissions. In 2010, the total number of vehicles were estimated to be 77,658 in Multan. 68% of the total number of vehicles were motorcycles/scooters. Station wagons, jeeps and motor cars were estimated to be around 14% and constituted the second highest share.

The growth rate of registered vehicles in Multan was recorded to be around 13% per year for the past 25 years in 2010. Delivery vans and other vehicles' growth rate was recorded to be 17% and 24% respectively. The motor cars, station wagons and jeeps growth rate was found to be 12% while the motorcycles or scooters' growth rate was 13.5%.

The combination of natural sources of pollution and anthropogenic ones favors the manifestation of high concentrations of ozone and particulate matter (Vuillermoz et al., 2013).

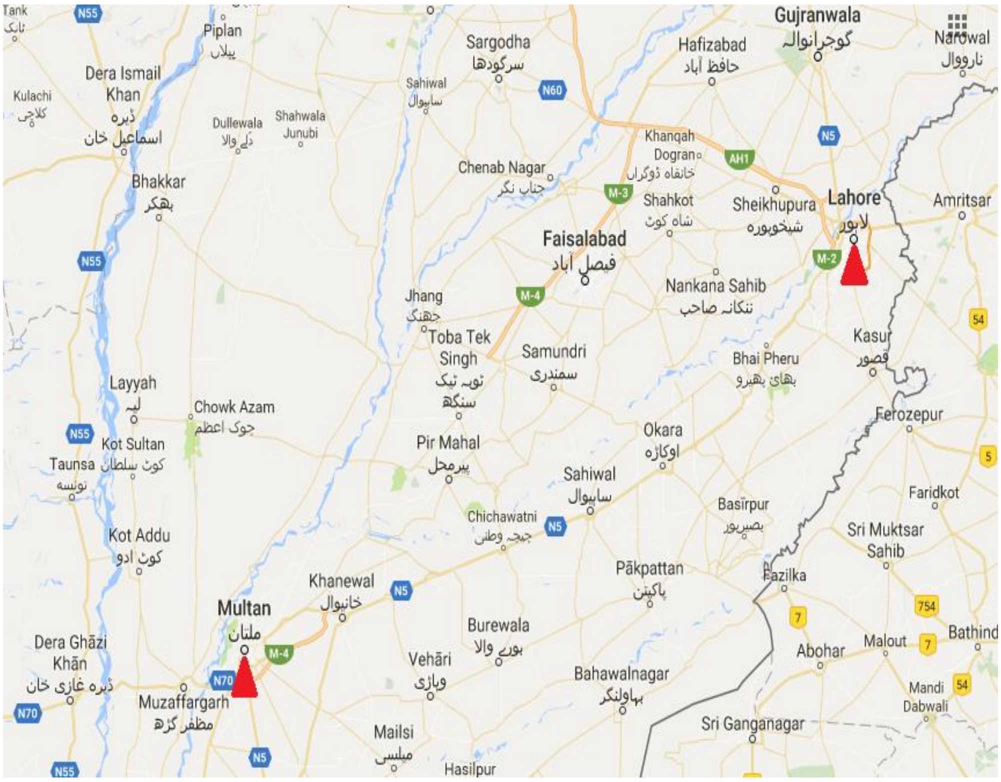


Figure 1.5: Red triangles are exhibiting the proposed monitoring locations within districts of Lahore and Multan

1.6. Objectives of the Study

- To investigate the effect of ambient RH and BLH on the relationship between ground-based PM and AOD.
- Estimate long-term PM by using AOD as proxy.
- Estimate the human health impacts of PM in Lahore and Multan by estimating the morbidity (hospital admissions).

1.7. Significance of the study:

A massive and diverse aerosol burden is observed in the Indo-Gangetic Plain (IGP) located in South Asia (Fig. 1.6). A multitude of factors is responsible including regional meteorology, unique location, topography, social and economic development, emission sources and anthropogenic activities (Banerjee et al., 2015; Singh et al., 2017b, Singh et al., 2017a).

In Pakistan, maximum AOD values are observed over Punjab which is the most populated and industrialized (Figure 1.7). High levels of air pollution strongly correlate with high AOD thus increased risk to human health, while good air quality is represented by low levels of AOD.

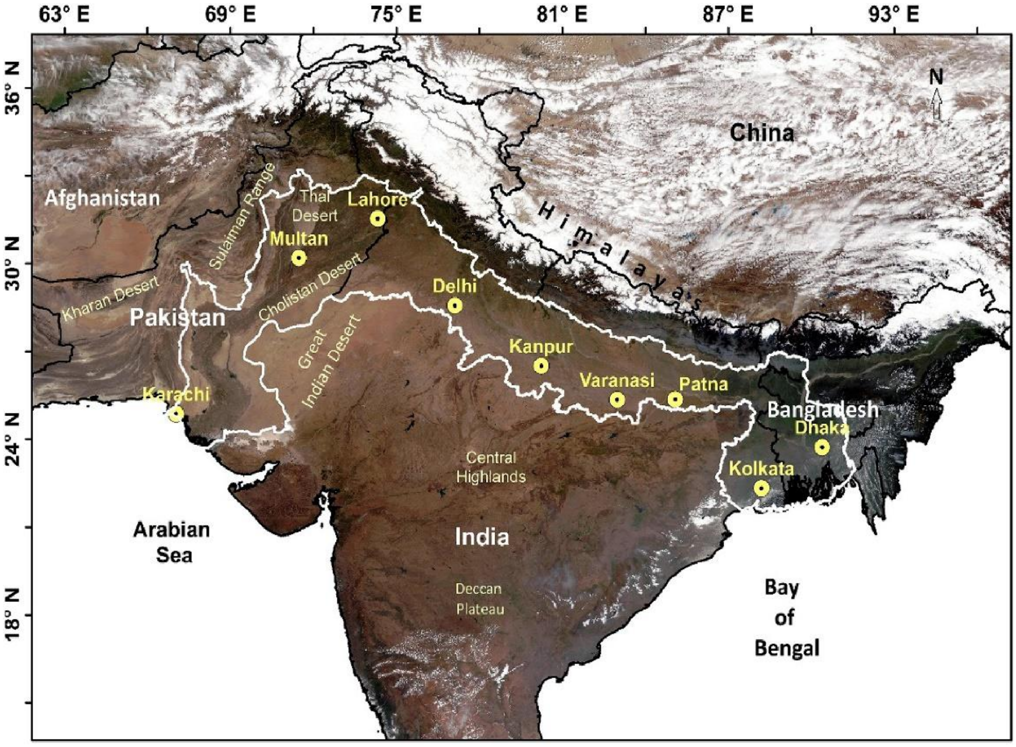


Figure 1.6: The Indo-Gangetic Plain (Kumar et al., 2018)

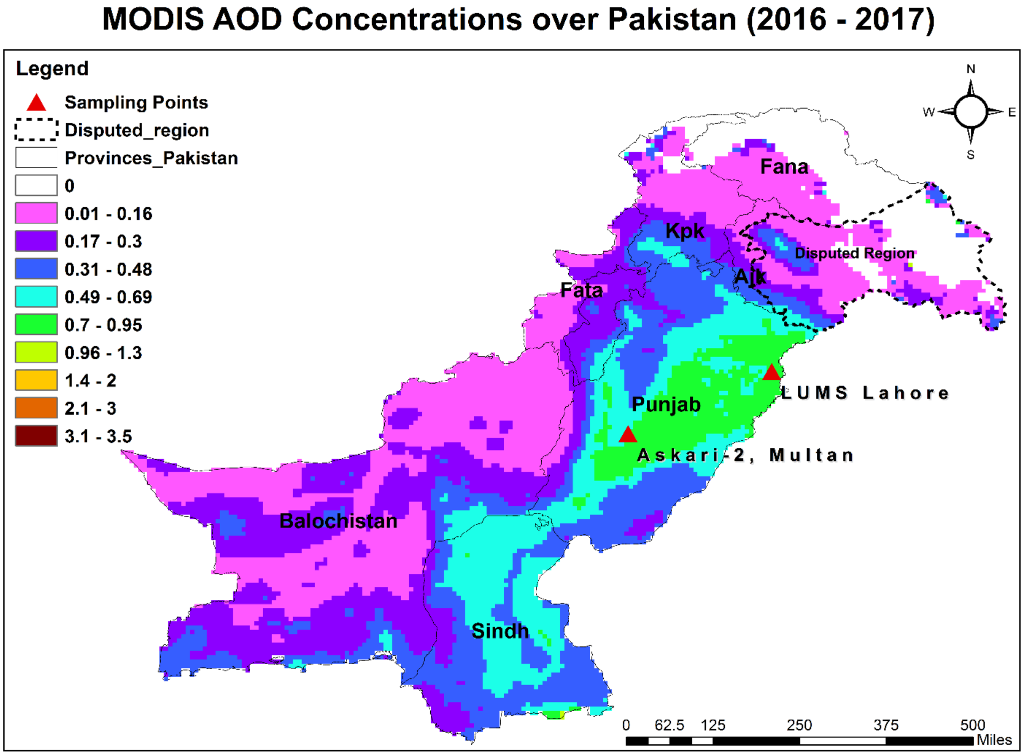


Figure 1.7: Map showing the mean annual Aerosol Optical Depth (AOD) observations over Pakistan for the Period of 2016 to 2017 over Pakistan.

1.7.1 Sustainable Development Goal (SDG) 3.9

Reliable research is needed in order to achieve the sustainable development goals. The one that is particularly relevant to this study is SDG 3.9:

"By 2030, substantially reduce the number of deaths and illnesses from hazardous chemicals and air, water and soil pollution and contamination."

Chapter 2

Literature Review

2.1. Aerosols in the Atmosphere

A complex mixture of both liquid and solid particles suspended in the air are known as aerosols. They are also denoted as particulate matter (PM) and can be responsible for poor air quality and population exposed to higher levels of aerosols can experience negative and serious damage to their health (Gupta et al., 2013, Evans et al., 2013 Kumar et al., 2015a).

The global energy budget can be significantly impacted by aerosols as they influence the solar radiation by causing its extinction through scattering and absorption (Schulz et al., 2006) or by acting as nuclei on which water can condense and form, and by affecting the cloud optical properties (Seinfeld et al., 2016). Aerosols can also considerably lower visibility (Han et al., 2012), impact the oxidation capacity of the air (Rastogi & Patel, 2017), and decrease the crop yield (Burney & Ramanathan, 2014).

The aerodynamic diameters of aerosol particles can range from less than one nanometer which are molecular clusters to those of 10 nm or larger which can be sea salt and wind-blown dust. The clustering of molecules happens due to homogenous nucleation which results in particles that grow to a diameter of several nanometers at the small end of the spectrum (Bellouin & Haywood, 2015).

Nuclei mode particles also known as ‘Aitken’ range from 10 to 100 nm in diameter. They often comprise of ‘primary particles’ which are emitted by combustion processes directly into the atmosphere (Bellouin & Haywood, 2015).

The particles of the submicron mass are mostly the 'accumulation mode particles.' It mostly consists of secondary particles that have been formed by chemical transformations in the atmosphere. These particles tend to accumulate in varying sub-modes, according to the chemical mechanism of their formation. These particles mostly comprise of organics, nitrates and sulfates (Bellouin & Haywood, 2015).

Lastly, mechanical processes lead to the production of coarse-mode particles (Bellouin & Haywood, 2015).

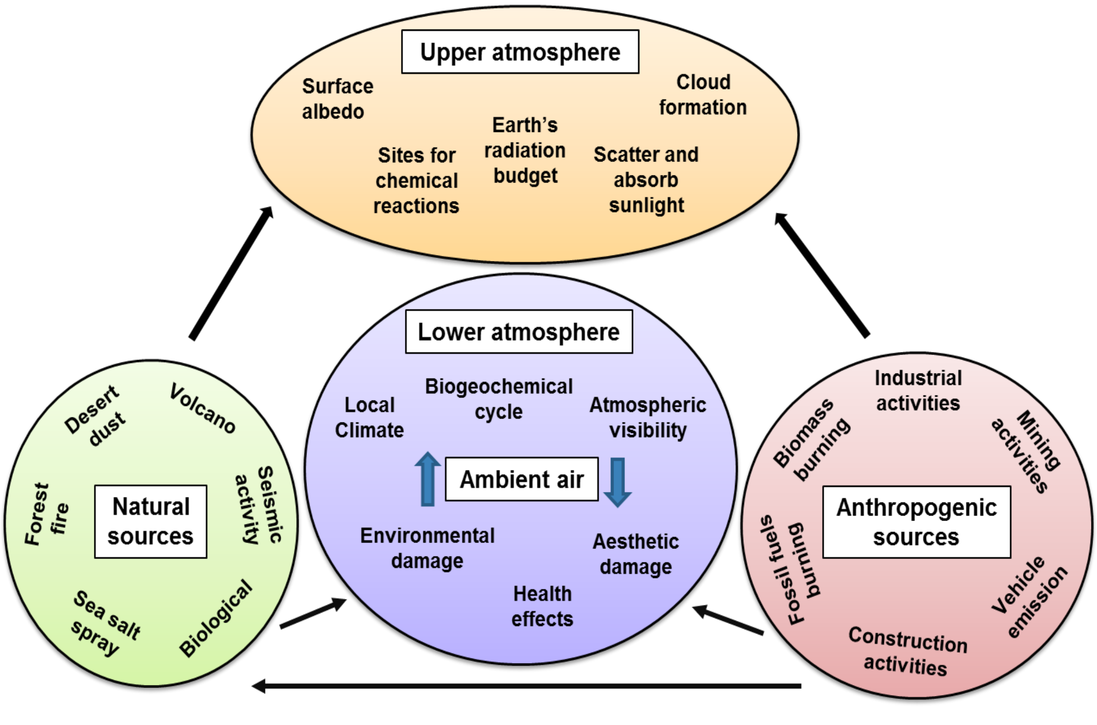


Figure 2.1: Sources and effects of Aerosols. Adapted from Mukherjee et al., 2017.

2.1.1. Cloud Condensation Nuclei (CCN)

Aerosols are important to the atmosphere because in the absence of them, clouds cannot be formed. Clouds Condensation Nuclei (CCN) are the particles in atmosphere which grow in size as a result of super-saturation while the water droplets start to condense over their surface. Aerosols act as favorable ground base for the formation of clouds under constructively humid circumstances. Marine stratus clouds have supersaturations in the range of 0.1-0.5%, the least CCN particle thickness is 0.05-0.14 μm. The concentration of CCN over a region depends on the level of pollution in that environment, for instance urban centers may have higher number of CCN and may reach to many thousands cm^{-3} while in marine environment, range is only few to 100 cm^{-3}. Typically, a CCN has a life time of about 7 days which means that it may get involved in 5-10 cloud evaporation/activation cycles before it finally reaches the Earth surface in the form of rain (Andreae & Rosenfeld, 2008).

The CCN particles are identified by determining the number of soluble particles it contains which relies on the chemical structure and is a function of the particle size (Andreae & Rosenfeld, 2008). Shortwave radiation is reflected more when it comes into contact with polluted clouds hence having a greater cooling effect on the Earth-atmosphere system. Due to this day-time cooling effect of aerosols as compare to the night-time warming in urban areas, the green-house effect or warming is somewhat compensated (Alizadeh-Choobari et al., 2017).

Table 2.2: Terminology Relating to Atmospheric Particles

Aerosols	Tiny particles spread in atmosphere
Dusts	Solid particles' suspension delivered by power-driven breaking down of materials, for example, pulverizing, crushing, and impacting; Dp > 1μ
Fog	Thick cloud layer of water droplets hanging in atmosphere and reducing visibility up to 1km.
Fume	The compact particles created by compression from vaporize condition, for the most part after volatilization from softened substances, and regularly joined by a compound response, for example, oxidation; frequently the material included is poisonous; Dp < 1 μ

Hazes	An aerosol that hinders vision and may comprise of a mixture of water droplets, pollutants, and dust; Dp < 1 μm
Mists	Liquid or tiny water droplets that are suspended in the air near or at the surface of Earth, distinguishable from fog as they will seem more transparent, or visibly moving downwards in the form of rain or water droplets floating or falling. Dp > 1 μ

2.2. History of Aerosol Measurements

Visibility was the first phenomenon that prompted the initial studies on aerosols. The British scientist, John Aitken, in 1880, was the first to come up with the idea that aerosol particles were responsible for the formation of fog and clouds by acting as the condensation nuclei for water vapor (Bellouin & Haywood 2015).

Later in the twentieth century, scientists linked increased aerosols with acid rain and an upsurge in human respiratory diseases, thereby identifying the need to reduce emissions of aerosols, their precursors, and improve air quality (Davidson et al., 2005). Around the same time, an introduction of simple aerosol representations were seen in climate models as well as weather forecasts, and scientists began the quantification their impact on the Earth’s energy balance (Bellouin & Haywood 2015).

As the interest in aerosol properties in the troposphere grew, climatologies were established over time catering to the vast interests of scientists in this new field. Air quality networks were established such as the Clean Air Status and Trends Network of the United States Environmental Protection Agency and the European Monitoring and Evaluation Programme which provide aerosol surface concentrations, their climatology and chemical composition (Kulkarni et al., 2011; Bellouin & Haywood 2015).

Furthermore, across the lower atmosphere aerosol size and composition as well as the vertical profiles and microphysical properties are observed via dedicated aircrafts with sophisticated instruments which can give a regional snapshot (Kulkarni et al., 2011). Moreover, at selected locations across the world installation of networks of remote sensing instruments has taken place. One such example is the Aerosol Robotic Network (AERONET), which is a network of sun photometers providing column-integrated measurements of AOD, or the extinction of visible or near-infrared radiation in a column of the atmosphere by aerosols, and it can also be utilized to estimate the aerosol size (Hoff & Christopher, 2009).

In the late 1990s, aerosol distributions of AOD were seen in a global context with the launch of dedicated satellite instruments (Hoff & Christopher, 2009). In a more recent development, vertical distributions of aerosols were observed using lidars either on satellite platforms, aboard aircrafts or installed on the ground (Lee et al., 2009; Hoff & Christopher, 2009; Bellouin & Haywood 2015).

Apart from the improved observation of aerosols from space and the ground, the development of numerical models which take into account the data from satellite observations, ground based measurements, meteorological data, and centennial simulations for climate projects, can provide daily aerosol forecasts (Hoff & Christopher, 2009). Numerical models are also very diverse in terms of computational speed and the number of aerosol species as well as characteristics they have the capability of representing (Hoff &Christopher, 2009; Bellouin & Haywood 2015).

2.3. Difficulties in Aerosol Measurements

There are certain difficulties associated with retrieving the exact climatology of aerosols required for a particular purpose or application, despite the diverse sources of data available.

Aerosols vary greatly in their size and chemical composition. There is also an uneven distribution of their sources worldwide. Their removal from the atmosphere occurs primarily by means of precipitation that is spatially inhomogeneous, and to a lesser degree, through turbulence. Therefore, aerosols tend to have a relatively less residence time typically ranging from 1 to 2 weeks in the troposphere (Kulkarni et al., 2011).

As a result, and unlike greenhouse gases like carbon dioxide which are well-mixed, there is immense variation in the aerosol concentrations in time and space, as well as both vertically and horizontally. However, well-mixed aerosol plumes have also been identified in observations both horizontally and vertically, with aerosol mass and number varying by magnitude, within a few kilometers, and a few hundred or even a few tens of meters, respectively.

2.4. Guidelines and Standards for Particulate Matter

The concentrations of particles with aerodynamic diameters less than 2.5 and 10 µm, called Particulate Matter ($PM_{2.5}$ and PM_{10}), respectively, are routinely monitored and reported by air quality networks. Air quality regulations are set up nationally by many countries that impose thresholds, and guidelines have been provided by the World Health Organization, on the daily mean as well as the annual mean of PM concentrations.

Table 2.2: Pakistan Environmental Quality Standards (Pak-NEQs) (Pak-EPA, 2005) and World Health Organization (WHO Fact Sheet, 2018) ambient air standards.

	Pollutant	Pakistan NEQS ($\mu g/m^3$)	WHO ($\mu g/m^3$)
24-hour mean	PM_{10}	150	50
Annual mean		120	20
24-hour mean	$PM_{2.5}$	35	25
Annual mean		15	10

2.5. Air Pollution and Aerosols:

Aerosols or particulate matter is an element of air pollution that is most certainly associated with adverse health outcomes (Anderson et al., 2012). In 2010, ambient air pollution accounted for about 3.1% (2.7-3.4%) of the global Disability Adjusted Life Years (DALYs) and was ranked as the 9th risk factor worldwide (Lim et al., 2012).

Smaller particles have a more severe effect on health as they tend to reach the alveoli without any obstruction while larger particles get trapped in the upper respiratory tract. Therefore, epidemiological studies have reported that particles that have an aerodynamic diameter of less than 2.5 microns have greater effects on health (Schwartz et al., 1996; Franklin et al., 2007).

$PM_{2.5}$ is commonly used as an indicator of an amalgamation of pollutants coming from a myriad of sources and diverse environments; these can include the contribution to ambient air pollution (particulate) from wind-blown dust, transportation, industrial sources, biomass burning, active smoking, coal and wood for cooking (Pope et al., 2011).

2.6. Ground Based PM Concentrations

Between December 2005 and February 2006, the ground-based mean $PM_{2.5}$ mass concentration over Lahore was 209 µg m^{-3}, which was about 14 times the annual mean of New York City and 20 times higher than the WHO guideline value (Biswas et al., 2008).

From November 2005 to December 2007, the $PM_{2.5}$ mass concentrations were measured by Lodhi et al., (2009) at a residential colony located in an urban area in Lahore, Pakistan. A higher load of $PM_{2.5}$ was found in the winter, which ousted the summer, spring, fall and monsoon season loads by four times in the year-long measurements. Lodhi et al., (2009) also used the Positive Matrix Factorization (PMF) model to estimate the sources of $PM_{2.5}$ in Lahore which included vehicular emissions, industrial emissions, soil/ road dust, and secondary aerosols. It was also noted that Lahore city was affected by transboundary air pollution during winter (especially SO_4^{2}) which was one of the reasons for increased $PM_{2.5}$ concentrations many times in conditions of low mixing height. The elevated concentrations of sulfate particles also contributed towards the formation of haze and fog during humid and stagnant wind conditions thereby reducing visibility and leading to increased incidence of respiratory diseases.

In the months of March and April 2010, the 24 hour average PM_{10} was monitored by Alam et al., (2011) for the cities of Rawalpindi, Peshawar and Lahore which was 448 µg m^{-3}, 540 µg m^{-3}, and 198 µg m^{-3}. For the city of Karachi, the values were reported at three sites which were 270 µg m^{-3}, 461 µg m^{-3} and 88 µg m^{-3}. The concentrations of $PM_{2.5}$ were also monitored for the same cities which were 140 µg m^{-3}, 91 µg m^{-3}, and 160 µg m^{-3} for Rawalpindi, Lahore and Peshawar respectively, and for the three sites in Karachi, it was 151 µg m^{-3}, 185 µg m^{-3}, and 60 µg m^{-3}.

In addition, Alam et al., (2011) calculated the $PM_{2.5}/PM_{10}$ ratio which was low, suggesting the dominance of coarser particles from sources such as the re-suspension of road dust, traffic, and other combustion sources. It was also found that the $PM_{2.5}$ and PM_{10} maximum concentrations at all sampling locations exceeded the WHO guidelines by two to ten times.

2.7. Aerosol Optical Depth

For the purpose of understanding the potential climatic implications in the present and future, it is imperative to understand variance of aerosols with respect to time and space. Concerning the above mentioned objectives, and for monitoring different climatic properties including aerosols, a group of various satellites including Earth Observation System (EOS) were launched by NASA. The Moderate Resolution Imaging Spectroradiometer (MODIS) is a sensor aboard two satellites known as Terra (2000) and Aqua (2002). Both of these pass the equator at different times.

The spectral range of MODIS is quite wide, "0.41 μm to 14.5 μm in 36 channels or bands, with 2330 km wide swath having spatial resolution of 1 km or less as per band requirement". For retrieval of aerosol information by using MODIS observations several algorithms were developed by combining its swath, MODIS' spatial resolution, and spectral bands. Some of these algorithms are primarily required for retrieving properties of land and ocean, while others are used for retrieval of aerosols' properties. In order to do that, a specific methodology is designed and products are extracted from a particular family of algorithms, to retrieve aerosol properties obtained from interaction with visible wavelength or brighter surfaces over land (Kaufman et al., 1997) such as urban areas or areas lacking vegetation.

Consequently, a modification was seen in Collection 6 of the MODIS AOD data which was the Deep Blue algorithm (DB). The "Deep Blue (DB) algorithm" of MODIS was essentially established to obtain AOD over bright desert surfaces with a resolution f 10 km, also by utilization of deep blue wavelengths where surface reflectance of land is lesser as compared to greater wavelengths. In DB algorithm Surface reflectance is estimated using Minimum Reflectance Technique (MRT) (Hsu et al., 2006).

2.8. AOD Composition over Pakistan

By studying the AERONET data over the stations of Karachi and Lahore, (Alam et al., 2012) found an association between the Absorption Angstrom Exponent (AAE) and the Extinction Angstrom Exponent (EAE) essentially indicating the comparative high amount industrial and mineral dust aerosol over urban cities, Lahore and Karachi. Over Lahore, they also found low values of Single scattering albedo (SSA) (0.83 to 0.91) compared to Karachi (0.88 to 0.97) which is indicating that aerosol with an absorbing nature are more dominant over Lahore station relative to Karachi.

2.9. Predictive Modeling- AOD to PM

The aerosol optical depth derived from satellites and the surface concentrations of aerosols measured in the form of mass concentrations of $PM_{2.5}$ and PM_{10}, have been analyzed, and significant correlations have been observed (Li et al., 2005; Zheng et al., 2014). The measurement of AOD from satellites has a precision of ±20%, and even in the most careful studies the prediction or derivation of $PM_{2.5}$ from AOD has a precision of ±30% (Hoff & Christopher, 2012).

Such correlations are partially dependent upon models which estimate the surface concentrations from vertical column satellite data and are highly impacted by the relative humidity (RH) and the vertical distribution of aerosols as well as the mixing height (Zheng et al., 2014). MODIS AOD, on board both Terra and Aqua satellites, when compared with ground-based PM concentrations, has yielded varying results across the globe, with the R-pearson values correlation or coefficients ranging from 0.2 to above 0.6 for PM_{10} and 0.12 to above 0.9 for $PM_{2.5}$ (Zeeshan & Oanh, 2014).

2.10. Health Risk Assessment

Ambient air pollution has become a leading population health risk factor, as identified by the Global Burden of Disease (GBD) study 2015, particularly in low and middle income states (Forouzanfar et al., 2016; Cohen et al., 2017), with Asia reported to have the highest mean exposure to air pollution (Lelieveld et al., 2018).

Air pollution exposure, whether long-term (chronic) or short-term (acute) can result in negative health outcomes in the population (Pascal et al., 2013; Schnell et al., 2015; Wang et al., 2015). For example, in the United States (Donora, Pa) and Europe (London and Meuse Valley) in the twentieth century, recurring episodes of debilitating air pollution with high PM concentrations caused and amplified diseases, and resulted in deaths, of hundreds to thousands of people. The drastic increase in morbidity and mortality demonstrated how severe an effect air pollution can have on health (Hassanvand et al., 2015).

One of the major challenges faced when attempting to assess the air pollution impacts on health impacts, whether in local or global epidemiologic studies, is the dearth of exposure estimates that are representative (Cohen et al. 2004). In some areas of the world, extensive ground-based monitoring networks can be found, while a substantial part of the globe remains uncovered. This is true for many of the developing countries with high air pollution levels and burgeoning populations. Ground-based observations, albeit considered a gold standard for health risk assessments, are sparse, and represent only point values in heterogeneous areas of the world, hence a very limited spatial extent (Chen et al. 2006). Contrary to ground monitors, observations from satellites provide global coverage and area-integrated values, thus giving useful information for global health studies.

Due to the highly variable and diverse nature of PM, it is often used as a proxy indicator of the overall air quality of an area, mostly urban. The results describe the disease burden in the population due to PM pollution and also the indirect effects of other correlated pollutants, and sometimes the socio-economic burden is also estimated (Martuzzi et al., 2003).

The health implications of PM typically depend upon size and elemental composition (Shao et al., 2018), with the smaller particles (less than 2.5 microns) having more health impacts (Schwartz et al., 1996) (Franklin et al., 2007); particles with a diameter <10 μm are called PM_{10} or 'inhalable coarse particles, and with a diameter <2.5 μm are called $PM_{2.5}$ 'fine particles' (Kim et al., 2015). Fine particles can easily pass through the respiratory tract as the upper respiratory tract can only trap coarse particles. The ciliary action of the lungs which is responsible for the removal of larger particulates cannot remove $PM_{2.5}$ due to their smaller size and deeper deposition in the alveoli; moreover, the larger surface area of $PM_{2.5}$ particles causes a greater accumulation of toxins such as heavy metals and organic compounds (Li et al., 1997; Khawaja et al., 2012).

A common estimate of an exposure-response association is obtained by carrying out a meta-analysis of the results of various epidemiologic studies (Martuzzi et al., 2003). Even very low concentrations of particulate pollution can result in adverse health effects in sensitive individuals. No safe threshold has yet been established below which there is no manifestation of negative health outcomes.

Only small concentration ranges of PM are covered by the literature produced on the health impacts of ambient particulate pollution. For example, existing studies have only considered the concentration of $PM_{2.5}$ roughly ranging from 5 $\mu g/m^3$to 30 $\mu g/m^3$, whereas the levels of $PM_{2.5}$ recorded in the developing world are much higher. There is probably a non-linear association between the risk of disease and $PM_{2.5}$ (Lim et al., 2012).

In contrast, when fine particulate matter concentrations are reduced, under the assumption that other confounding factors remain the same, the attributable morbidity and mortality will also decrease, allowing the decision-makers to project the trends and benefits including population health that could result as an outcome of the reduction in particulate air pollution.

In 2016, WHO estimated the attributable pre-mature mortality due to air pollution; out of which 6% was due to lung cancer, 18% was attributed to acute lower respiratory infections (ALRI), and Chronic Obstructive Pulmonary Disease (COPD), and an estimated 58% were due to strokes and Ischaemic Heart Disease (IHD).

Air pollution contributes to the health as well as the economic burden of countries around the world and estimation of its attributable heath impacts can clarify the respective burden (World Bank, 2016) and is the first step towards its abatement. However, very limited information is available for developing regions such as South Asia.

Pakistan has been experiencing an increase in the aerosol concentrations over the years, with maximum concentrations being observed in the winter (Khokhar et al., 2016). Little is known about the effects of $PM_{2.5}$ on health in Pakistan. Only three somewhat significant studies have so far been reported.

Ashraf et al., (2018) calculated the percentage increase in the incidence amongst population of ocular surface diseases during the event of Lahore smog, November 2016, when compared with a set baseline (same month and days of the preceding year). These diseases included irritation in eyes, dry eyes, conjunctival diseases, lid erosion, uveitis, corneal diseases and lacrimation. A significant increase of 60% was found.

Khawaja et al., (2012) reported emergency room visits and hospitalizations for cardiovascular diseases (CVDs) relative to days with the $PM_{2.5}$ concentrations below 50 µg/m^3 and with increments of 50 µg/m^3 up to 300µg/m^3. The hospital admissions were significantly correlated with an increase in concentration of 50 µg/m^3 at every category at the Korangi site, whereas at the Tibet Center site, significant elevations were found above 150mg/m3. Moreover, the emergency Room (ER) visits significantly increased at both sites between $PM_{2.5}$ concentrations of 151 and 200 mg/m^3. The conclusion gained from these results is that hospital admissions for CVDs highly correlate with elevated concentrations of $PM_{2.5}$, while ER visits are associated to a lesser extent.

In Karachi, for the period of one year, during August 2008 – August 2009, Malashock et al., (2018) studied the relation between black carbon (BC) and the outpatient department/emergency room (OPD/ER) visits and hospital admissions (HAs) for CVDs in Karachi. The daily average of BC along with hospital records were analyzed over 0-3 lag days. The range of daily mean BC concentrations was from 1 to 32 µg/m3. Overall results of this study indicated an association between BC and with HAs and ER visits, more so at the Tibet Center, the commercial-residential site, than at Korangi, the industrial-residential site. However, the statistical significance remained low.

Chapter 3

Materials and Methods

3.1. Phases of the Study

This study was divided into four phases namely Data collection, the acquisition and processing of Aerosol Optical Depth datasets, estimation of $PM_{2.5}$ from satellite AOD (MODIS terra) and the influence of meteorological parameters including ambient relative humidity and boundary layer height; lastly, quantification of the respiratory hospitalizations attributable to $PM_{2.5}$, as shown in the flow diagram (Fig 3.1).

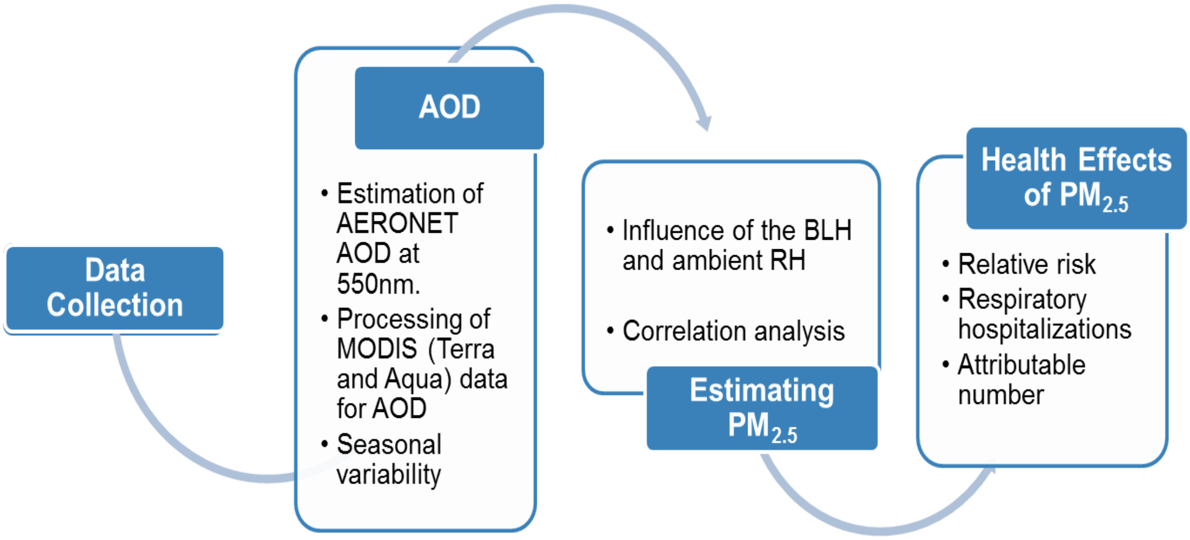


Figure 3.1: All four phases of this study

3.2. Data Collection

3.2.1. Particulate Matter Monitoring Sites: PM_{10} and $PM_{2.5}$

Dual dust samplers in LUMS, Lahore and Askari-2, Multan (Fig 2.2.1) remained operational from January to March 2017. 12-hour samples were taken which constituted one during the day and one during the night.

Figure 3.2: Dual dust sampler at the sampling site in Askari-2, Multan.

AOD at a wavelength of 550 nm over land was used in this study. It is associated with significant radiative effects due to its closeness to the peak of the solar spectrum (Papadimas et al., 2009).

Using the manual by Persson and Grazzini (2005), the daily Boundary Layer Height (BLH) for this study was retrieved from the online portal of ERA-Interim by the European Centre for Medium-Range Weather Forecasts (ECMWF). The average of BLH values at different times of the day was taken: 00:00, 03:00, 06:00, 09:00, 12:00, 15:00, 18:00, and 21:00 to give a representative value.

Table 3.1: Data and data sources for this study

Dataset	**Source**
Ground-based $PM_{2.5}$ and PM_{10}	Dual dust sampler in LUMS, Lahore and Askari-2, Multan
Aerosol Optical Depth (AOD) 550 nm	• Ground-based data from AERONET station Lahore • Satellite observations from MODIS – Terra and Aqua
Daily Relative Humidity (RH)	Pakistan Meteorological Department
Daily Average Boundary Layer Height (BLH)	ERA-Interim by the European Centre for Medium-Range Weather Forecasts (ECMWF)
Health Data	• District Health Information System (DHIS) • Relative risk from HRAPIE
Population Data	Statistical Bureau of Pakistan (2017 census)
Air Quality Data	• Pakistan Air Quality Initiative (PAQI) • Copernicus Atmospheric Monitoring Service (CAMS)

3.3. Operating Software

- Arc Map 10.3.1 (For Data Analysis and Mapping)
- ENVI 5.0 (For Data Preprocessing)
- MODIS Conversion Toolkit (MCTK)
- Panoply (Retrieval of specific attribute of data)
- Hdf Viewer (For processing and viewing hdf format files)
- Java (To run each software)
- Python To generate script for bulk data processing
- FileZilla For Downloading Bulk data
- Pre-Processing using MODIS Conversion Tool Kit (MCTK)
- Notepad++ (To read vector data formats like netcdf, ASCII and CSV files)
- Microsoft Excel/XLSTAT

3.4. Processing and Analysis of Aerosol Optical Depth (AOD)

3.4.1. MODIS AOD

"MODIS (Moderate Resolution Imaging Spectroradiometer)" is the main instrument on satellites Terra (launch in December 1999) crossing equator at 10:30 local daytime and Aqua (launch in May 2002) crossing equator at 13:30 local time. There are 36 spectral bands in which this instrument captures data with the range of wavelength "0.4 µm to 14.4 µm" and at different "spatial resolutions". Spatial resolution varies like 1km, 250m and 500 m for different sensors, having temporal resolution 1 or 2 days. Its swath width is 705 km. (Yan et al., 2016).

The global coverage of aerosol products is being provided by MODIS with moderately high spatial resolution, resulting from "Channels 1 and 3 (visible light) in combination with “band 7(near infrared) based on dark pixel algorithm at a spatial resolution of 10km” (Kaufman et al., 1997). Recently, a “modified Minimum Reflectance Technique (MRT)” is offered by (Wong et al. 2009a, in press) to evaluate AOT for both dark and bright surfaces (e.g. built-up areas and vegetation) at a moderately “high resolution of 500m” with maximum precision, thus avoiding the uncertainties of particle pollution monitoring.

Daily data for the months for time period of 2013- 2017 of Aerosol Optical Depth (AOD) at 550 nm of MODIS satellite was retrieved from NASA’s Goddard Earth Sciences, Information services Center online portal.

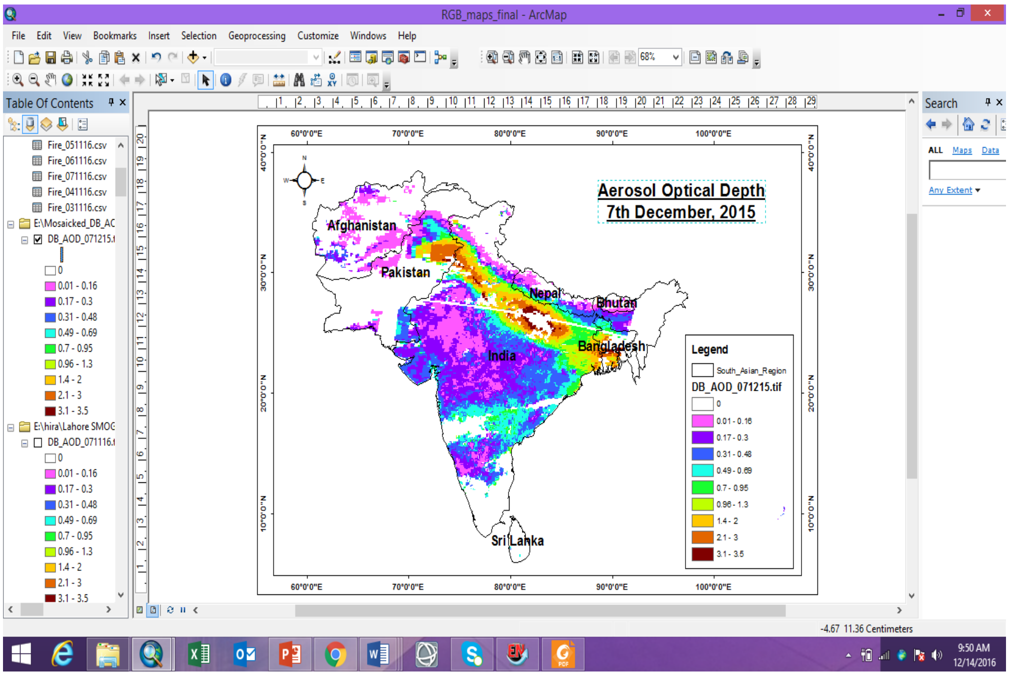


Figure 3.3. Processing of MODIS product Aerosol Optical Depth in ArcMap

3.4.2. AERONET AOD

It is a solar powered remote sensing sun radiometer, which is ground based and weather hardy. It measures direct and diffused radiances of sun and sky with the spectral range of “340 to 1020 nm and 440 to 1020 nm”. It measures not only spectral AOT but also resulting properties of aerosols like “single scattering albedo, phase function and size distribution of aerosol particles. It provides global and near real time measurements of aerosol spectral optical depths”. (Yu *et al.*, 2016)

Three different levels of data are available:

1. Level 1.0 (unscreened)
2. Level 1.5 (cloud screened)
3. Level 2.0 (cloud screened and quality assured)

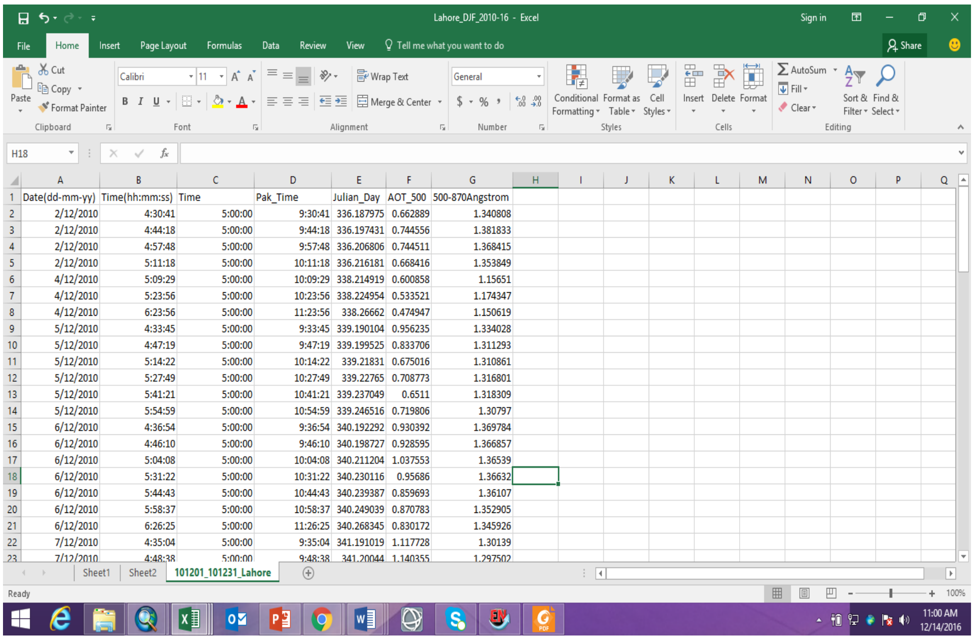
Data products of AERONET are downloaded from the following website “(http://aeronet.gsfc.nasa.gov/)”. Its AOD retrieval accuracy is high having an uncertainty value of 0.01–0.02 (Smirnov et al., 2000). AERONET measurements are considered to be the most effective and reliable tool to validate satellite derived AOD due to its highly improved calibration and monitoring stations’ distribution. (Holben et al., 1998).

AOD is measured by AERONET at different wavelengths. Data used in our dtudy is of sunphotometer level 1.5 at wavelength of 550 nm i.e., AOD$_{500}$ which is cloud masked product and is effective to authenticate aerosol products derived from satellite. Interpolation was done in order to make it analogous with MODIS data using following equation.

$$\mathrm{AOD}_{550\mathrm{nm}} = \mathrm{AOD}_{500\mathrm{nm}}\left(\frac{550}{500}\right)^{-\alpha}$$

……………..Equation 1

It was obtained from the AERONET station in Lahore for the period June 2016 to June 2017.



	A	B	C	D	E	F	G
1	Date(dd-mm-yy)	Time(hh:mm:ss)	Time	Pak_Time	Julian_Day	AOT_500	500-870Angstrom
2	2/12/2010	4:30:41	5:00:00	9:30:41	336.187975	0.662889	1.340808
3	2/12/2010	4:44:18	5:00:00	9:44:18	336.197431	0.744556	1.381833
4	2/12/2010	4:57:48	5:00:00	9:57:48	336.206806	0.744511	1.368415
5	2/12/2010	5:11:18	5:00:00	10:11:18	336.216181	0.668416	1.353849
6	4/12/2010	5:09:29	5:00:00	10:09:29	338.214919	0.600858	1.15651
7	4/12/2010	5:23:56	5:00:00	10:23:56	338.224954	0.533521	1.174347
8	4/12/2010	6:23:56	5:00:00	11:23:56	338.26662	0.474947	1.150619
9	5/12/2010	4:33:45	5:00:00	9:33:45	339.190104	0.956235	1.334028
10	5/12/2010	4:47:19	5:00:00	9:47:19	339.199525	0.833706	1.311293
11	5/12/2010	5:14:22	5:00:00	10:14:22	339.21831	0.675016	1.310861
12	5/12/2010	5:27:49	5:00:00	10:27:49	339.22765	0.708773	1.316801
13	5/12/2010	5:41:21	5:00:00	10:41:21	339.237049	0.6511	1.318309
14	5/12/2010	5:54:59	5:00:00	10:54:59	339.246516	0.719806	1.30797
15	6/12/2010	4:36:54	5:00:00	9:36:54	340.192292	0.930392	1.369784
16	6/12/2010	4:46:10	5:00:00	9:46:10	340.198727	0.928595	1.366857
17	6/12/2010	5:04:08	5:00:00	10:04:08	340.211204	1.037553	1.36539
18	6/12/2010	5:31:22	5:00:00	10:31:22	340.230116	0.95686	1.36632
19	6/12/2010	5:44:43	5:00:00	10:44:43	340.239387	0.859693	1.36107
20	6/12/2010	5:58:37	5:00:00	10:58:37	340.249039	0.870783	1.352905
21	6/12/2010	6:26:25	5:00:00	11:26:25	340.268345	0.830172	1.345926
22	7/12/2010	4:35:04	5:00:00	9:35:04	341.191019	1.117728	1.30139
23	7/12/2010	4:48:38	5:00:00	9:48:38	341.20044	1.140355	1.297502

Figure 3.4: AERONET data preprocessing in Excel

3.4.3 Seasonal Analysis

The seasons, according to the Pakistan Meteorological department, are "winter, spring (pre-monsoon), summer (monsoon), and autumn (post-monsoon)."

The seasonal analysis of MODIS AOD was done using the Mann-Kendall trend test which is non-parametric, hence it is applied when the distribution of data is unknown and a trend needs to be detected in a series of values.

2.5. Predictive Modeling – Estimation of PM$_{2.5}$

Assuming that the atmosphere is divided into infinite planes which are parallel to one another, then AOD will be the sum or integral of the Aerosol Extinction Coefficient (AEC) (k_a) at all altitudes or height along the vertical orientation/plane. Therefore, the k_a (λ,Z) describes the AEC at wavelength (λ) and altitude (Z) in equation (2):

$$\tau\,(\lambda) = \int_{0}^{\infty} k_{\mathrm{a}}\,(\lambda, Z)\,\mathrm{d}z \quad \text{.........................} \; (2)$$

Furthermore, when the vertical distribution of k_a (λ,Z) is assumed as in the negative exponent form, and ka,0 (λ) will refer to the AEC at the surface with wavelength (λ), and the scale height of the aerosol is represented by H, the equation becomes (3),

$$k_a(\lambda, z) \approx k_{a,0}(\lambda)\, e^{\frac{-Z}{H}} \quad \text{.........................} (3)$$

Consequently, when equation (3) is substituted into equation (2) we will get equation (4). The ka,0 (λ) can be calculated from Height (H) and AOD, and atmospheric BLH can approximately replace H in the equation. Hence, we arrive at the vertical correction, AOD/BLH, which will represent the aerosol optical extinction at the surface (Zheng *et al.,* 2013; Liu et al., 2005).

$$\tau(\lambda) = k_{a,0}(\lambda) \times H \text{..........................} (4)$$

- Where τ is AOD
- λ is wavelength = 550 nm
- $k_{a,0}$ is the AEC at surface
- H is the scale height (BLH)

Generally RH influencing factor can be expressed as follows (Equation 4) (Im *et al.,* 2001; Li *et al.,* 2005; Z. F. Wang *et al.,* 2010; Zheng *et al.,* 2013)

$$f(RH) = 1/(1.0-RH/100 \qquad \text{………………….} (4)$$

2.5.1. Correlation Analysis

Firstly, the relationship between ground-based PM observations from January to March 2017 with MODIS AOD (both Terra and Aqua) was estimated.

Subsequently, the influence of the ambient RH and BLH was considered, and a correlation analysis was done for the RH corrected $PM_{2.5}$ ($PM_{2.5} \times f(RH)$) and the vertically corrected AOD (AOD/BLH).

2.6. Air Pollution - Health Risk Assessment

The air pollution health risk assessment was conducted in accordance with the flow chart in Fig 2.6. The model (tool or health function) is specified in section 2.6.3.

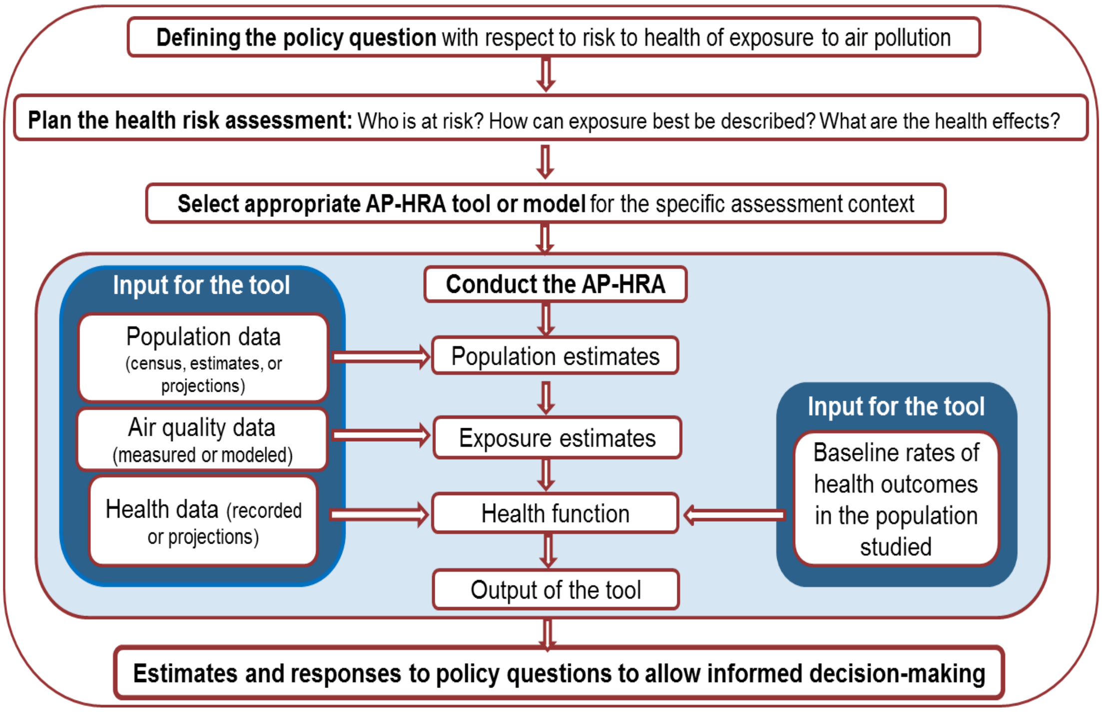


Figure 3.5: Tools required and process for the air pollution health risk assessment; adapted from the WHO Regional Office for Europe, 2014a

The population data was from the 2017 census by the Statistical Bureau of Pakistan (SBP); the PM exposure for the study period was from the ground- based observations of PM_{10} and $PM_{2.5}$ in Lahore and Multan, that were done as part of this study; the baseline PM exposure data was from 1) Pakistan Air Quality Initiative 2) CAMS modeled data 3) Pak NEQs and 4)WHO guidelines; the baseline health data available on a monthly basis, from the District Health Information System (DHIS).

2.6.1. Baseline Incidence

Incidence measures the probability of occurrence of new cases of a particular health outcome in a population within a specific time interval. We calculated the total respiratory hospitalizations per 100,000 population (equation 6).

Baseline Incidence rate (per 100,000 per month) = (Total admission/district population) *100000 ……………………........ (6)

2.6.2. Exposure Assessment (estimating ∆X)

The burden attributable to the total $PM_{2.5}$ concentration is of limited interest because some $PM_{2.5}$ is from natural sources and cannot be reduced. Instead, burden of disease is generally assessed in relation to an arbitrary scenario, also known as the baseline or counter-factual exposure, which can be the WHO guideline value, a level without human-made $PM_{2.5}$, or the lowest concentration observed in epidemiological studies.

ΔX is the change in $PM_{2.5}$ levels, and was calculated using four baselines or counterfactual datasets.

1. Pak NEQS
2. WHO guideline
3. CAMS modeled data
4. Pakistan Air Quality Initiative (PAQI) data

2.6.3. Respiratory Hospitalisations Attributable to Short-Term Exposure

Within this region we analyzed the number of respiratory hospitalizations attributable to short-term exposure to smoke using the equation (7):

Attributable number = (Risk in exposed – Risk in unexposed) x Population

$$= \text{Baseline incidence x } (e^{\beta \Delta X} - 1) \text{ x Population} \qquad \ldots\ldots (7)$$

$e^{\beta \Delta X}$ is the relative risk associated with a ΔX µg/m^3 change in PM$_{2.5}$ concentration. β is a coefficient defining the relationship between a 1 µg/m^3 increase in PM$_{2.5}$ and a health outcome of interest. It is derived from epidemiological studies.

Table 3.2: Diseases that were considered as part of the respiratory spectrum, the baseline incidence rates, and the counter-factual baselines considered

Month	City	Pneumonia <5 - Total Admission	Pneumonia >5 - Total Admission	Asthma - Total Admission	Chronic Obstructive Airways - Total Admission	Pulmonary Tuberculosis - Total Admission	Total Admission	Total District Population 2017	Baseline Incidence (per 100,000 per month)	Monthly $PM_{2.5}$ average concentrations baseline (PAQI)	Monthly $PM_{2.5}$ average concentrations	CAMS Baseline	WHO	NEQs
Jan-17	Lahore	1464	908	520	264	215	3371	11,126,285	30.29762405	162	227.0301196	46.8364	25	35
	Multan	359	224	1302	114	111	2110	4,745,109	44.46683943		144.9469817	56.1799	25	35
Feb-17	Lahore	1915	845	384	200	477	3821	11,126,285	34.34210071	107	117.6689329	52.7122	25	35
	Multan	267	202	1433	112	93	2107	4,745,109	44.40361644		147.8394118	63.0929	25	35
Mar-17	Lahore	781	343	327	232	181	1864	11,126,285	16.7531211	89	121.2373611	47.3185	25	35
	Multan	170	271	1628	127	83	2279	4,745,109	48.02840146		103.4589712	59.2928	25	35

Table 3.3: HRAPIE concentration response coefficients

Health Outcome	**Age group**	**Estimate per 10µg/m3**	**β-coefficient**
All-cause mortality	ALL	1.0123 (1.0045 - 1.38153)	0.0012 (0.0004 - 0.002)
CVD Hospitalisation	ALL	1.0091 (1.0017 - 1.0166)	0.0009 (0.0002 - 0.0016)
Respiratory hospitalisation	ALL	1.019 (0.9982 - 1.0402)	0.0019 (-0.0002 - 0.0039)

Chapter 4

Results and Discussion

4.1. Concentrations of Particulate Matter during the Study Period

4.1.1. PM_{10} and $PM_{2.5}$ Concentrations over Lahore

The maximum concentrations have been observed in the end of January and start of February 2017. The box-plot depicts the daily average concentrations in Lahore. The upper and lower bounds show the maximum and minimum values, the third quartile is depicted by the top of the box, the first quartile is depicted by the bottom of the box, the line in the middle shows the median, and the plus sign shows the mean.

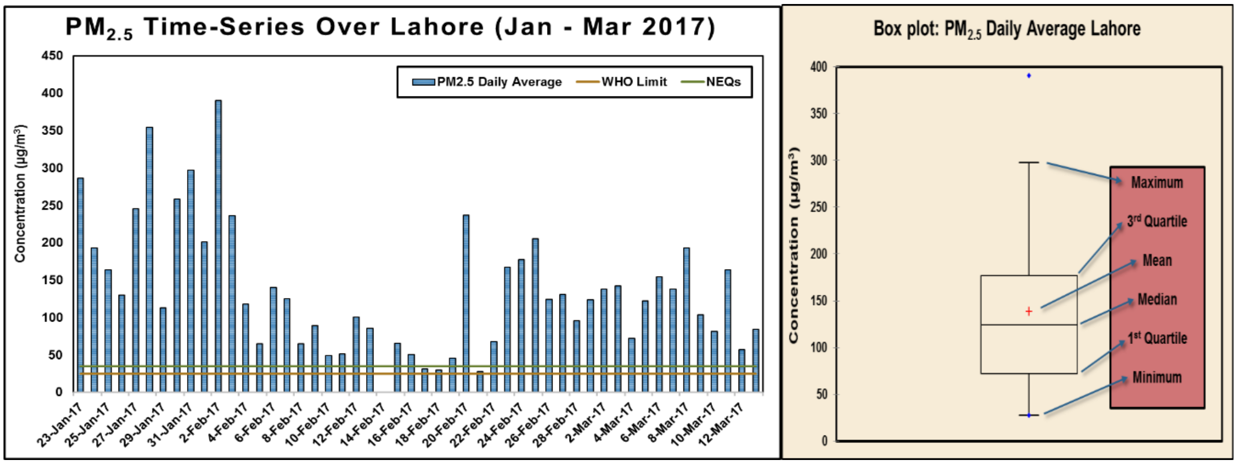
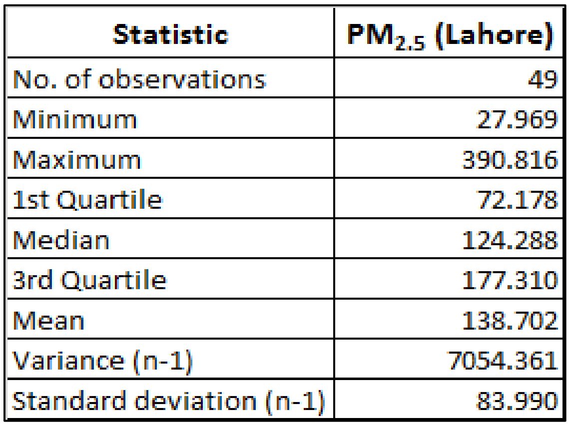


Figure 4.1: Bar Graph shows $PM_{2.5}$ Time Series over Lahore (Jan – Mar 2017), Right Box Plot Shows the $PM_{2.5}$ Daily Average over Lahore

Table 4.1: Statistical Values of Box Plot of $PM_{2.5}$ over Lahore



Statistic	$PM_{2.5}$ (Lahore)
No. of observations	49
Minimum	27.969
Maximum	390.816
1st Quartile	72.178
Median	124.288
3rd Quartile	177.310
Mean	138.702
Variance (n-1)	7054.361
Standard deviation (n-1)	83.990

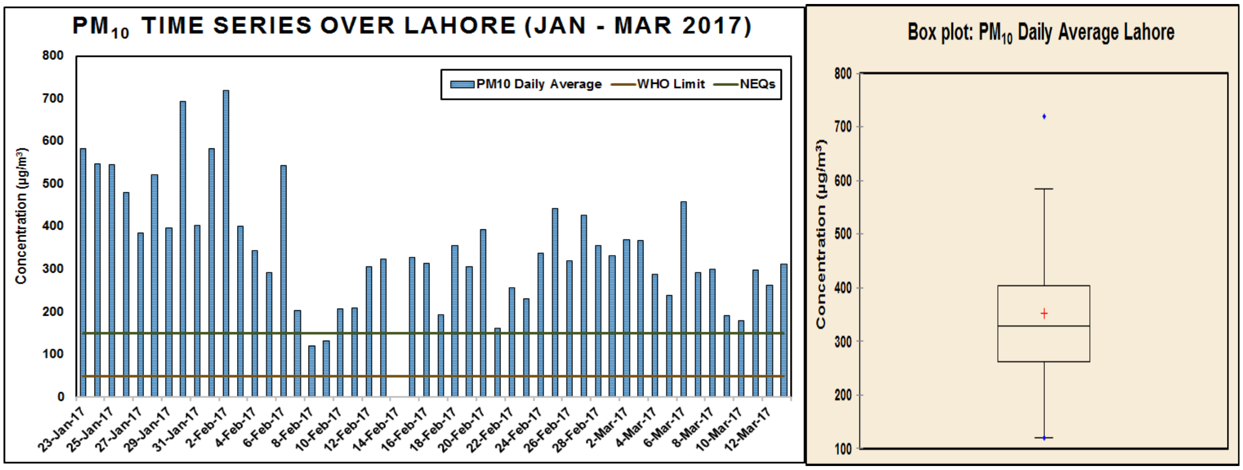
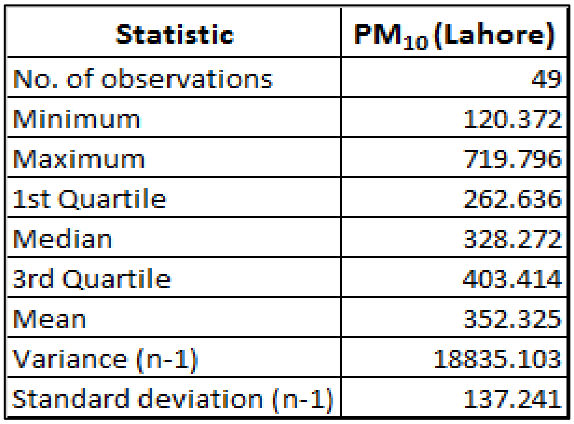


Figure 4.2: Bar Graph shows PM_{10} Time Series over Lahore (Jan – Mar 2017), Right Box Plot Shows the PM_{10} Daily Average over Lahore

Table 4.2: Statistical Values of Box Plot of PM_{10} over Lahore



Statistic	PM_{10} (Lahore)
No. of observations	49
Minimum	120.372
Maximum	719.796
1st Quartile	262.636
Median	328.272
3rd Quartile	403.414
Mean	352.325
Variance (n-1)	18835.103
Standard deviation (n-1)	137.241

During the study period, both PM_{10} and $PM_{2.5}$ frequently exceeded the NEQS as well as WHO standards in Lahore. The mean concentration of $PM_{2.5}$ over Lahore was 138.7±84 (Table 4.1), and the mean concentration of PM_{10} was 352.3±137.2. It was observed that wind speed and temperature during this time was low leading to a stable temperature inversion and the accumulation of PM.

Previous studies have also reported significantly high concentrations of particulate matter in Lahore (Biswas et al., 2008; Lodhi et al., 2009; Alam et al., 2011). During monsoon and post-monsoon, precipitation is high leading to lower values of particulates in the atmosphere and during winter the particulate pollution is highly elevated due to low wind speed, thereby stable atmospheric conditions, a low inversion layer (Tiwari et al. 2013). Similar pattern was observed in this study. Lahore also remains a victim of transboundary air pollution (Lodhi et al., 2009). Lahore also has the highest traffic bulk compared to other districts in the province (Batool et al., 2018).

4.1.2. PM_{10} and $PM_{2.5}$ Concentrations over Multan

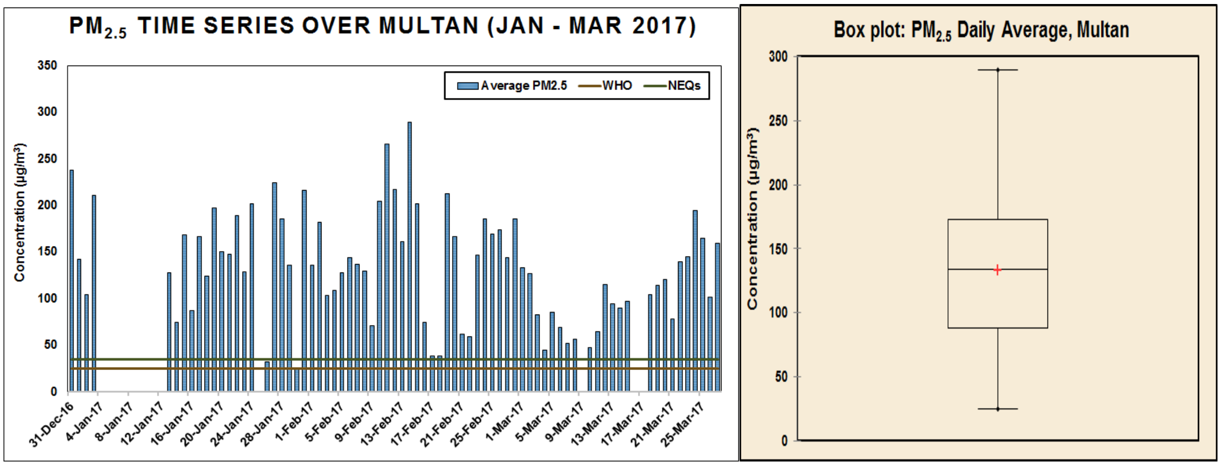


Figure 4.3: Bar Graph shows $PM_{2.5}$ Time Series over Lahore (Jan – Mar 2017), Right Box Plot Shows the $PM_{2.5}$ Daily Average over Multan

Table 4.3: Statistical Values of Box Plot of $PM_{2.5}$ over Multan

Statistic	$PM_{2.5}$ (Multan)
Nbr. of observations	74
Minimum	24.876
Maximum	289.626
1st Quartile	87.996
Median	134.278
3rd Quartile	173.022
Mean	133.842
Variance (n-1)	3440.953
Standard deviation (n-1)	58.660

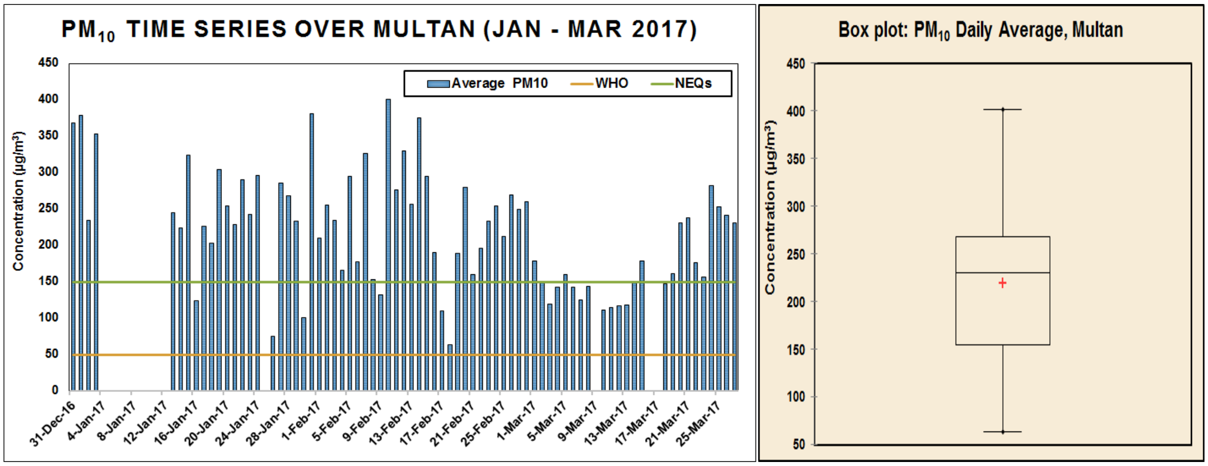


Figure 4.4: Bar Graph shows PM_{10} Time Series over Multan (Jan – Mar 2017), Right Box Plot Shows the PM_{10} Daily Average over Multan

Table 4.4: Statistical Values of Box Plot of PM_{10} over Multan

Statistic	PM_{10} (Multan)
Nbr. of observations	74
Minimum	63.417
Maximum	401.125
1st Quartile	154.145
Median	229.842
3rd Quartile	268.425
Mean	219.598
Variance (n-1)	6289.346
Standard deviation (n-1)	79.305

Both PM_{10} and $PM_{2.5}$ frequently exceeded the NEQS as well as WHO standards in Multan. During the study period, the mean concentration of $PM_{2.5}$ over Multan was 133.8±58 (Table 4.1), and the mean concentration of PM_{10} was 219.6±79. The high concentrations in Multan were most likely due to stable atmospheric conditions, construction activity near the sampling site, and transport of dust from nearby arid regions (Alam et al., 2011: Vuillermoz et al., 2014).

4.1.3. PM_{10} and $PM_{2.5}$ Day/Night Concentrations in Lahore

The Day/Night ratio for $PM_{2.5}$ in Lahore was found to be 0.85 indicating that $PM_{2.5}$ remained high during night time. This is a heavily industrialized city. At night-time, the industries burn dirty fuels, and Heavy Transport Vehicles (HTVs) are allowed to pass through. PM_{10} concentrations were also higher during the night with a ratio of 0.97 typically due to construction activities.

Due to the incoming solar radiation during the day, as the land and air is heated, there is greater turbulence and a deeper boundary layer, hence a quick dispersion and dilution of aerosols. However, at night, temperature inversion can trap the pollutants in the lower atmosphere.

Lahore is also reported to have the highest traffic volume in the province (Batool et al., 2018).

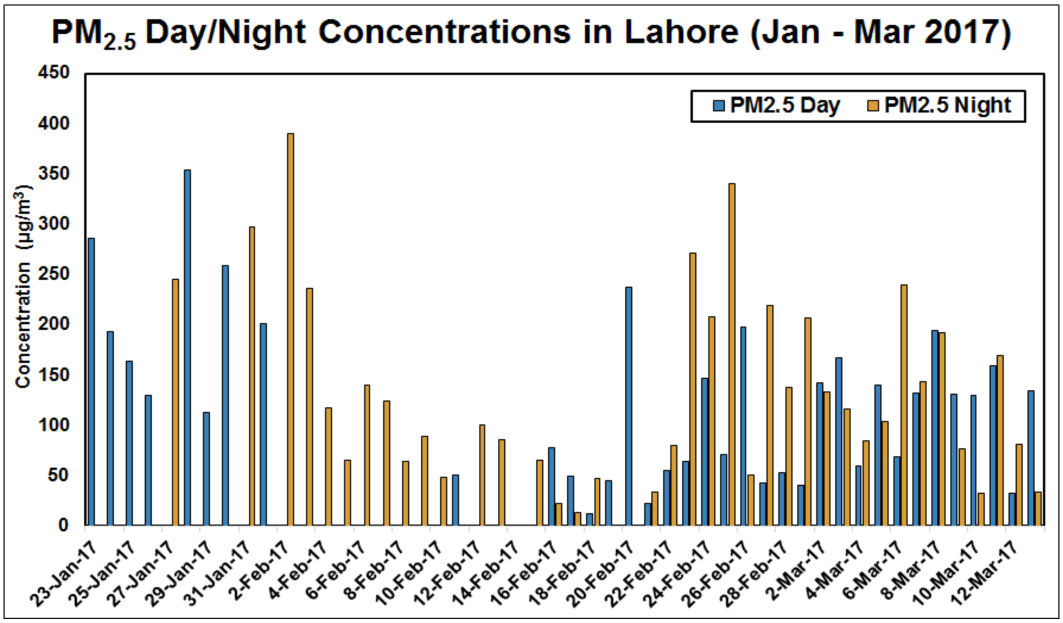


Figure 4.5: PM$_{2.5}$ Day and Night Concentrations in Lahore for the Period of Jan – Mar 2017

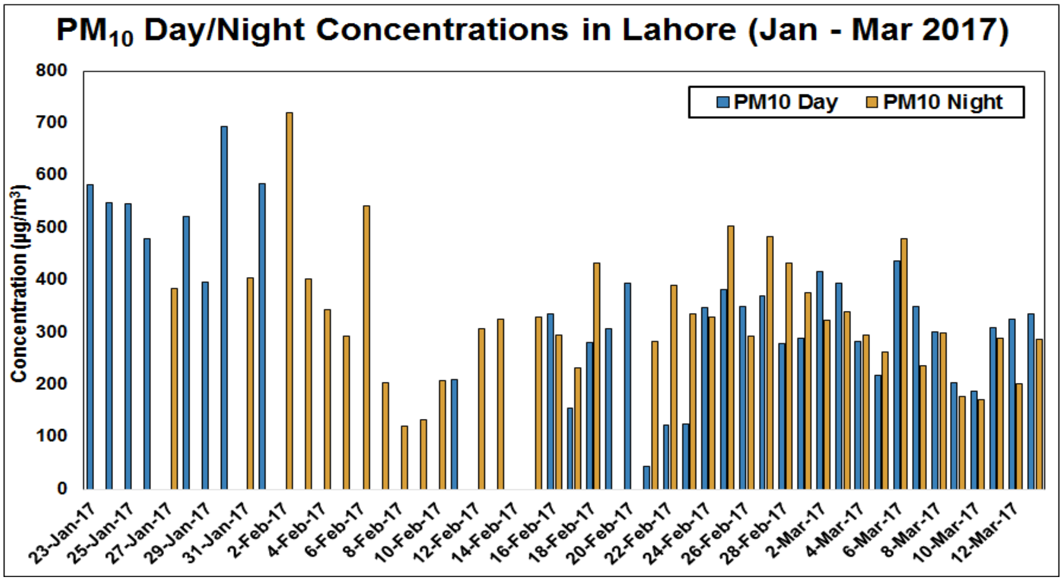


Figure 4.6: PM$_{2.5}$ Day and Night Concentrations in Lahore for the Period of Jan – Mar 2017

4.1.4. PM$_{10}$ and PM$_{2.5}$ Day/Night Concentrations in Multan

An opposite trend was observed in Multan where the Day/Night ratio for PM$_{2.5}$ and PM$_{10}$ in Multan was found to be 1.47 and 1.40 respectively, thus both the PM$_{2.5}$ and PM$_{10}$ concentrations were higher during the day.

PM$_{2.5}$ was higher due to the higher vehicle load during day time in Multan as compared to night as there is no such night restriction. Also, there are less factories, and mostly people operate during day time.

In case of PM$_{10}$, construction activities of Garrison Public Library and Pearl Continental Housing Colony were going on near the sampling site during the study period, and dust from the nearby Cholistan Desert were contributing factors for the elevated concentrations (Vuillermoz et al., 2014).

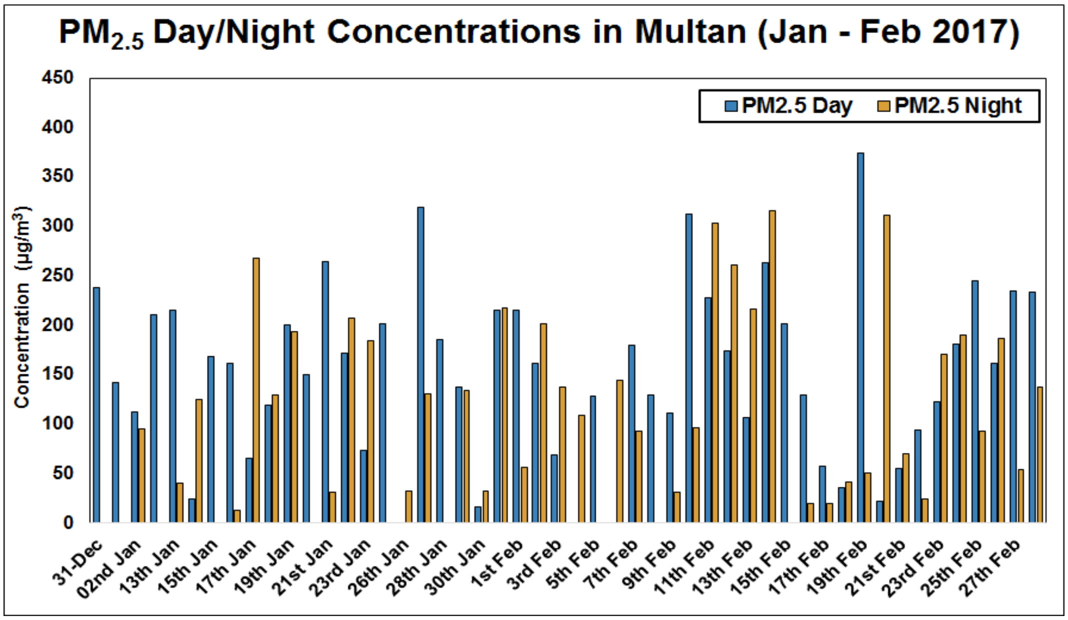


Figure 4.7: PM$_{2.5}$ Day and Night Concentration in Multan for the Period of Jan – Feb 2017

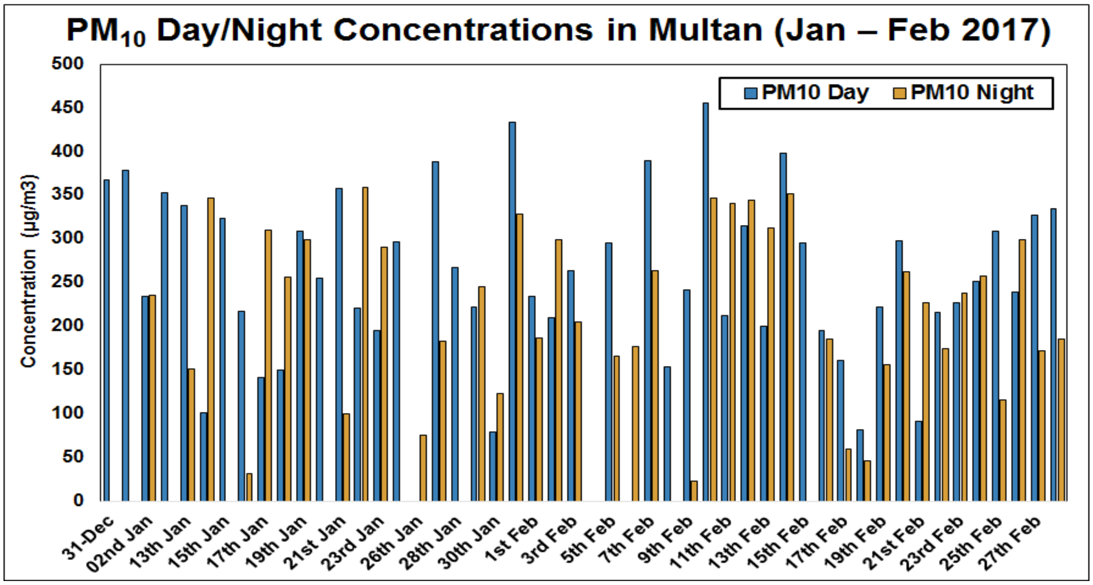


Figure 4.8: $PM_{2.5}$ Day and Night Concentration in Multan for the Period of Jan – Feb 2017

4.2. Aerosol Optical Depth

4.2.1. Validation of MODIS AOD with AERONET AOD - Lahore

Validation of Terra MODIS AOD with AERONET AOD showed a correlation of 76% which is highly significant. While Aqua MODIS AOD yielded an even better correlation of 89%. This is due to the difference in overpass time of the two satellites. Terra passes the equator at about 1000 hours while Aqua passes the equator at about 1330 hours, hence they pass over Pakistan around the same time. During noon, the aerosols in the atmospheric boundary layer are well-mixed, hence allowing a better association between ground-based AERONET AOD, and satellite based MODIS AOD.

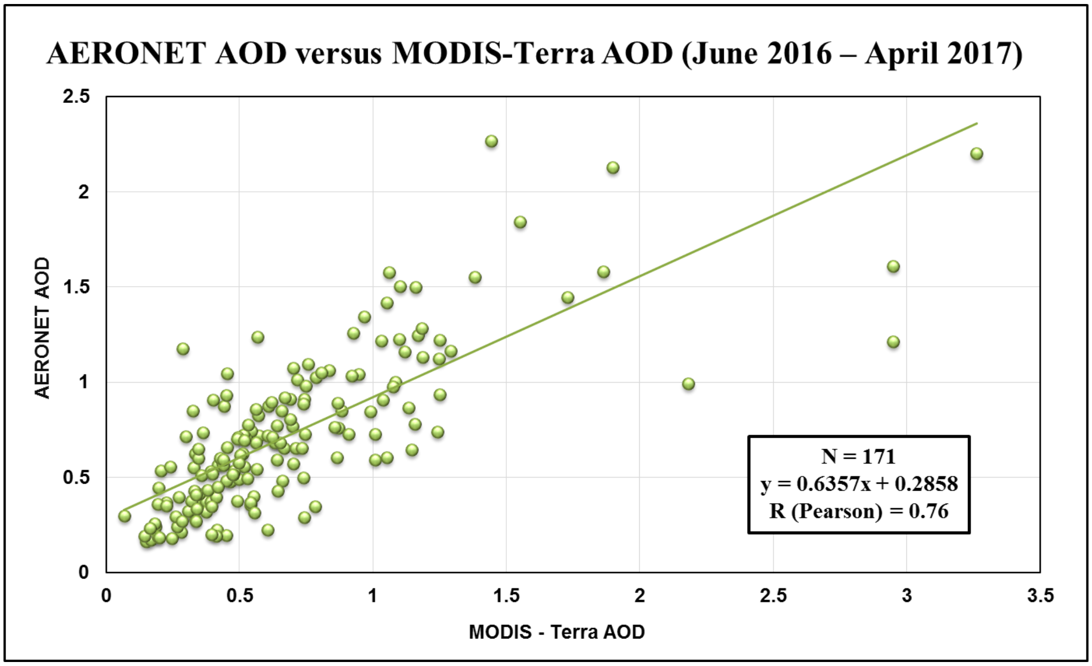


Figure 4.9: Co-relation between AERONET AOD vs MODIS-Terra AOD for a period of June 2016 – April 2017

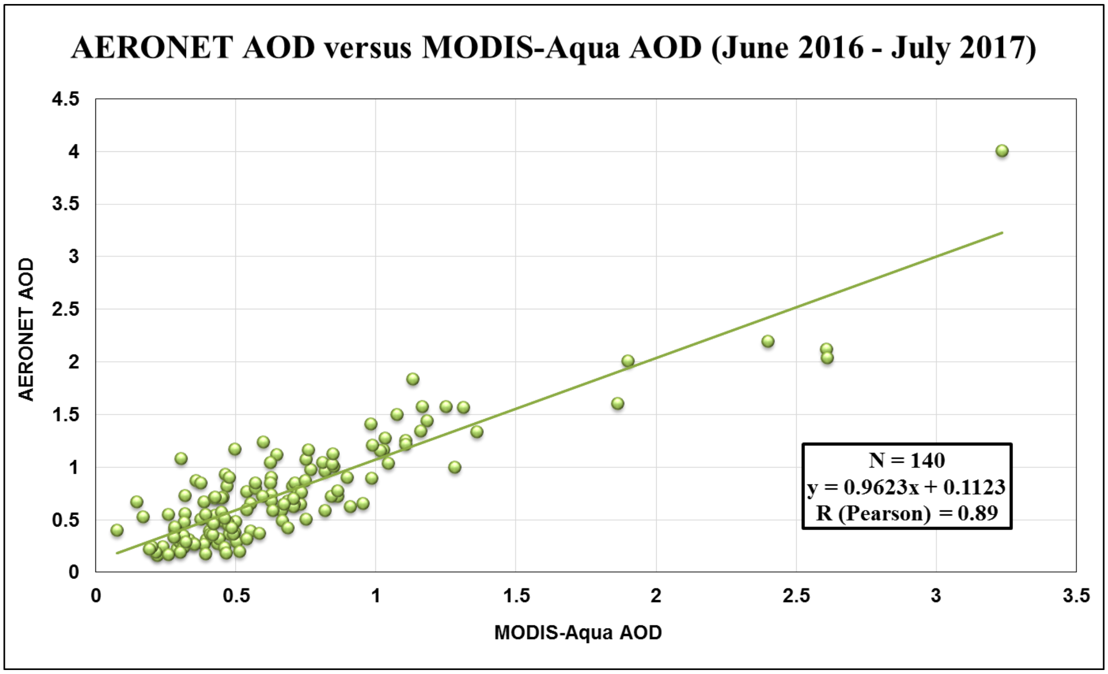


Figure 4.10: Co-relation between AERONET AOD vs MODIS- Aqua AOD for a period of June 2016 – April 2017

4.2.2 Spatial and Temporal Trend of AOD

4.2.2.1. Yearly Trend Analysis over Lahore and Multan

In the yearly maps of AOD for Lahore (Figure 4.11), green color shows the maximum observed concentrations of aerosols and it has progressively increased from 2013 to 2016, with a slight decline in 2017. Similar maps were generated for Multan (Figure 4.12), which also show progressive increase from 2013 to 2017.

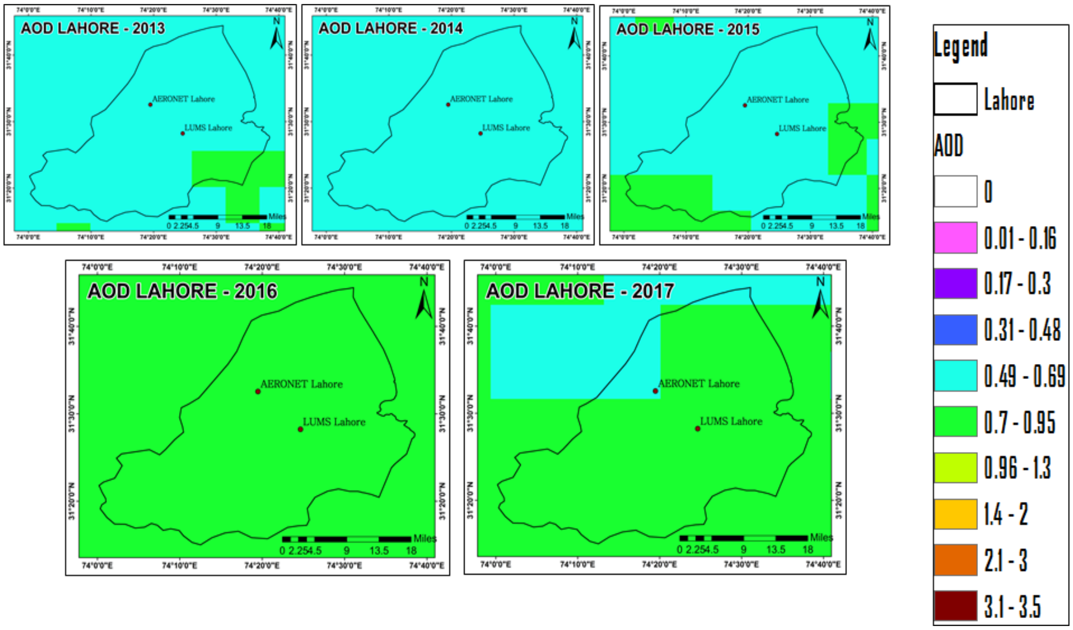


Figure 4.11: Yearly AOD Map over Lahore from 2013 - 2017

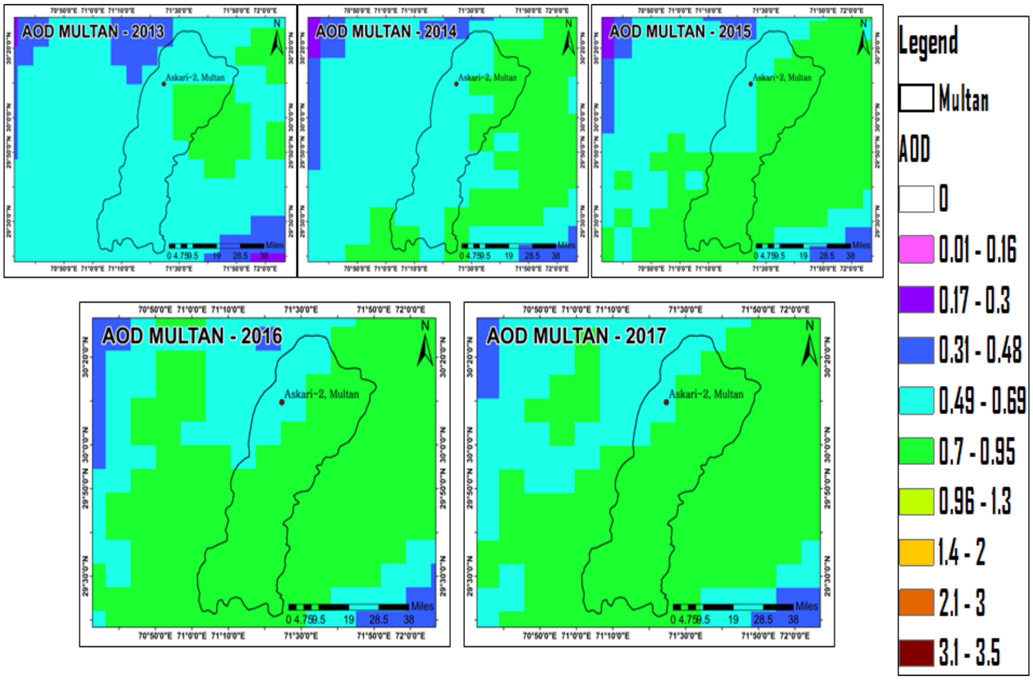


Figure 4.12: Yearly AOD Map over Multan from 2013 - 2017

4.2.2.2. Mann- Kendall Trend Test

In order to ascertain whether an actual trend existed in the AOD of the last five years, we performed the Mann-Kendall seasonal trend analysis with a period of 12. The Mann – Kendall Trend test revealed a significant increase in Lahore, as shown in table 4, with a p-value of 0.034, and relative change of 13%. This can be explained by the fact that Lahore is the capital city of Punjab and a major attraction for people seeking a better quality of life including education, housing, jobs, health care etc. Thus, a massive increase in population, motor vehicles, and industries has been witnessed resulting in poor air quality. The myriad of sources that strongly affect aerosol loading in Lahore are biomass burning, dust, transboundary air pollution, vehicular emissions, and industrial emissions (Lodhi et al., 2009; Alam et al., 2012; Ali et al., 2014; Bibi et al., 2016; Iftikhar et al., 2018).

While the trend in Multan was not significant. The main sources of aerosol emission in Multan (30.19°N, 71.47°E) are crustal and vehicular sources (Alam et al., 2011).

In Lahore (31.54°N, 74.32°E), the main contribution towards aerosol loading comes from the biomass burning, industrial and vehicular emissions, fossil fuel combustion, and transported dusts (Gupta et al., 2013), therefore a sharp seasonality is found in Lahore for the aerosol load as well as type.

Table 4.5: Mann-Kendall Seasonal trend Analysis

City	Absolute Change	Relative change (%)	Yearly change (%)	p-value	Seasonal Mann-Kendall Statistic (S)	Significance
Lahore	0.08 ±0.08	13	1.6	0.034	200	Yes
Multan	0.06 ±0.02	9.7	1.2	0.149	192	No

4.2.2.3. Seasonal Trend Analysis over Lahore and Multan

PMD classifies December, January and February as winter; March, April and May as spring; June, July, August and September as summer; and October and November as autumn. In Lahore, AOD was found to be maximum in winter, followed by autumn, summer and spring. Similarly, in Multan, AOD was found to be maximum in winter, followed by autumn, summer and spring. As Multan and Lahore both lie in the IGP region, winter is characterized by dense fog which occurs recurrently from November to February each year, and high AOD values are observed (Lodhi et al., 2009; Khokhar and Yasmin, 2018).

The summer increase, in spite of the monsoon washout, is due to the fact that unstable atmospheric conditions lead to high wind speed, thereby producing wind-driven dust particles in larger quantities. This is especially true for Multan since it is greatly influenced by dust coming from the Cholistan desert. Other studies also yielded similar results such as Alam et al., (2010) concluded that in southern parts of Pakistan, dust activities in summer, particularly June to August, give rise to high AOD. They also found that maximum AOD values occur in almost all big cities of Pakistan in summer, including Lahore.

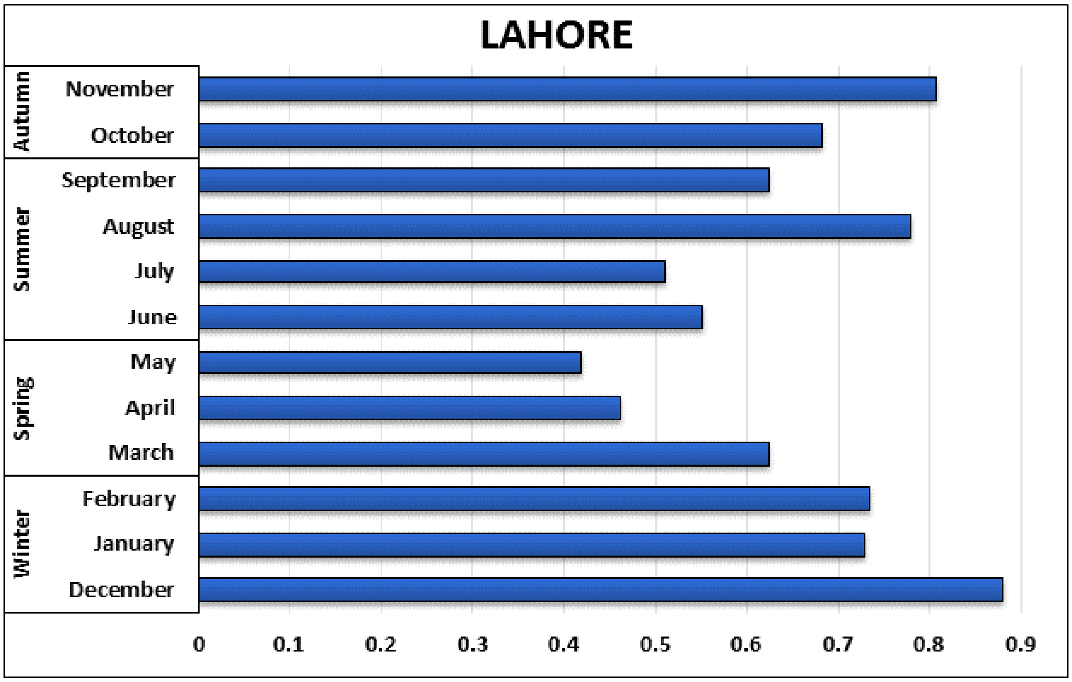


Figure 4.13: Seasonal AOD concentration over Lahore

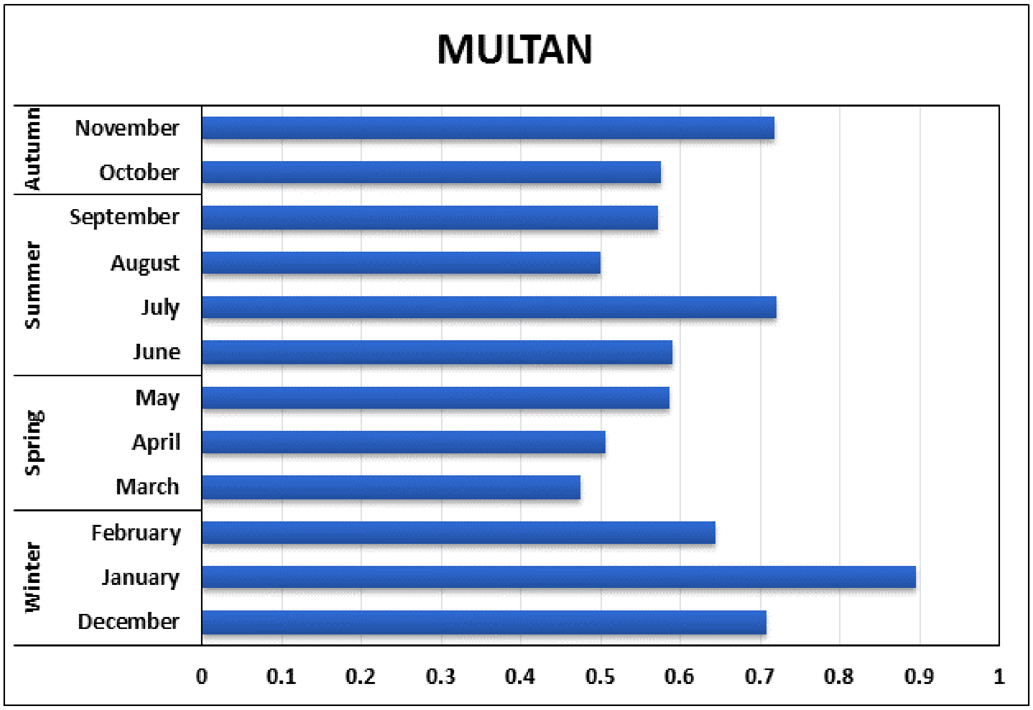


Figure 4.14: Seasonal AOD concentration over Multan

4.3. Predictive Modeling – AOD to $PM_{2.5}$

It was observed that the consideration of relative humidity and boundary layer height in the relationship between AOD and $PM_{2.5}$ improved the correlation significantly in the case of Aqua AOD in Multan and Terra AOD in Lahore.

Overall, the results, shown in table 4.6, are in harmony with other studies that have been done across the globe and correlated MODIS AOD (on both Terra and Aqua satellites) with PM mass concentrations on the ground. According to Zeeshan and Oanh (2014), the r values from their results have ranged from 0.2 to 0.6 for PM_{10} and from 0.12 to above 0.9 for $PM_{2.5}$.

Table 4.6: Statistics relating to the predictive modeling in the cities of Lahore and Multan

		Terra		Aqua	
City	Parameter	$PM_{2.5}$ (µg/m^3) and AOD	$PM_{2.5}$ x f(RH) and AOD/BLH (m^{-1})	$PM_{2.5}$ (µg/m^3) and AOD	$PM_{2.5}$ x f(RH) and AOD/BLH (m^{-1})
Lahore	Number of observations (N)	26	26	21	21
	R (Pearson)	0.18	0.48	0.27	0.55
	p-value	0.39	0.013	0.24	0.01
	Equation	y = 0.0007x + 0.3434	y = 8E-07x + 0.0005	y = 0.0006x + 0.3992	y = 1E-06x + 0.0005
Multan	Number of observations (N)	36	36	40	40
	R (Pearson)	0.39	0.78	0.18	0.38
	p-value	0.019	< 0.0001	0.26	0.016
	Equation	y = 0.0049x + 0.067	y = 7E-06x - 0.0006	y = 49.509x + 113.35	y = 2E-06x + 0.0005

4.4. Air Pollution Health Risk Assessment

4.4.1. Annual Baseline Incidence Rates and Scenario

In both the cities, Lahore and Multan, the incidence of respiratory diseases has periodically increased from 2010 to 2016, as shown in the figures 4.4.1a and 4.4.1b respectively. OPD stands for the Out-Patient Department where consultation services are provided to the patients and a rudimentary diagnosis is made.

This sharp increase can be attributed to the deterioration of air quality due to the fast paced development of the two cities. They have been sites of huge infrastructure projects without the consideration of environmental consequences and the health of the population.

In 2016, when the smog became unpalatable in winter, the number of respiratory diseases reported were the highest.

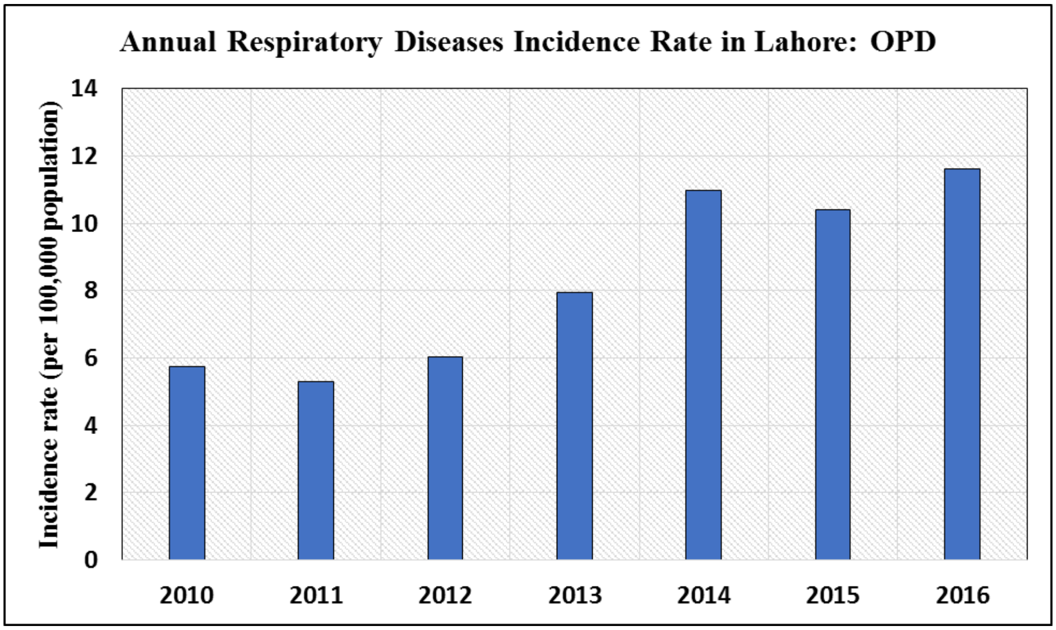


Figure 4.4.1a: Annual Respiratory Diseases Incidence Rate in Lahore: OPD

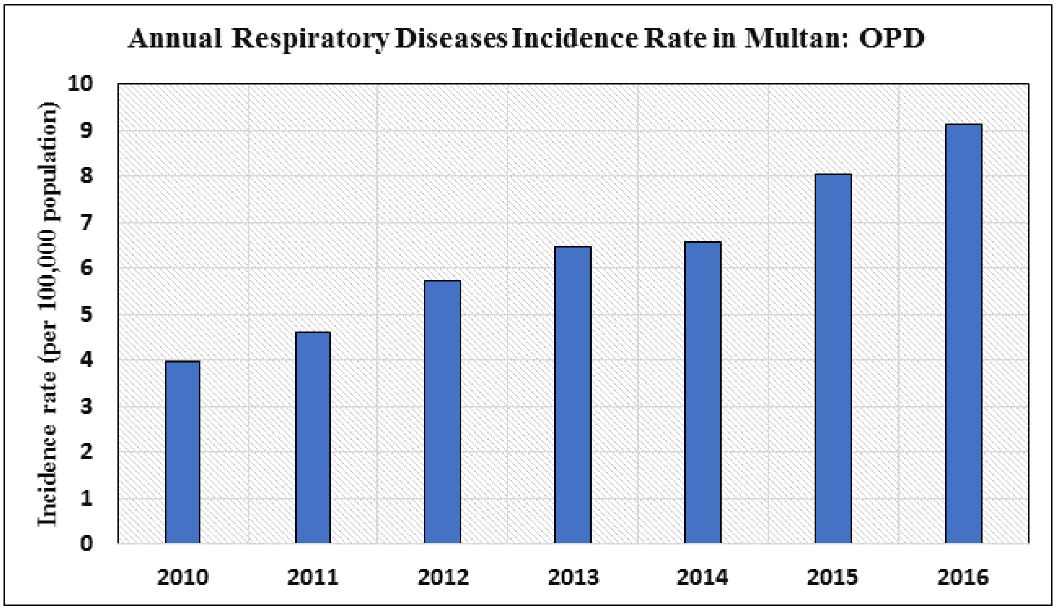


Figure 4.4.1b: Annual Respiratory Diseases Incidence Rate in Multan: OPD

4.4.2. Monthly Baseline Incidence and Scenario

In Lahore district, the number of cases reported in the OPD were highest in October, November and December 2016. In Multan, the incidence was also highest in winter, with the exception of July, when the concentration of dust tends to be very high.

Amin et al., 2015, found that in Multan, Bronchiolitis onset started in October and November, and the most incidence months were December, January and February with minimal cases in June, July and August, with the majority of our study cases i.e. 89 (65.4%) belonged to age group of 1 – 6 months.

In a study of 3,205 patients in the megacity of Karachi, Raza et al., (2012) found that 19.87% of them were suffering from pneumonia, 26.35% from COPD, and 53.77% from asthma. Interestingly, the highest number of HAs for pneumonia, COPD and asthma, were reported in winter (from mid-December to February) while the peak was observed in early spring (March). On the other hand, a significantly less number of cases were reported for summer and autumn, that is May and November respectively. Therefore, the results of this study were able to demonstrate a strong seasonality with the highest number of patients of COPD, Pneumonia and asthma in the winter, and the peak being observed in spring.

There are a number of environmental elements that have been suggested to play a key role in the seasonal pattern such as:

1. Length of daylight or time of exposure to day light

2. The availability and quality of healthcare facilities

3. Gender

4. Precipitation

5. Humidity

6. Temperature

7. Immune suppression

8. Delayed or failure of diagnostics

(Raza et al., 2012; Amin et al., 2015).

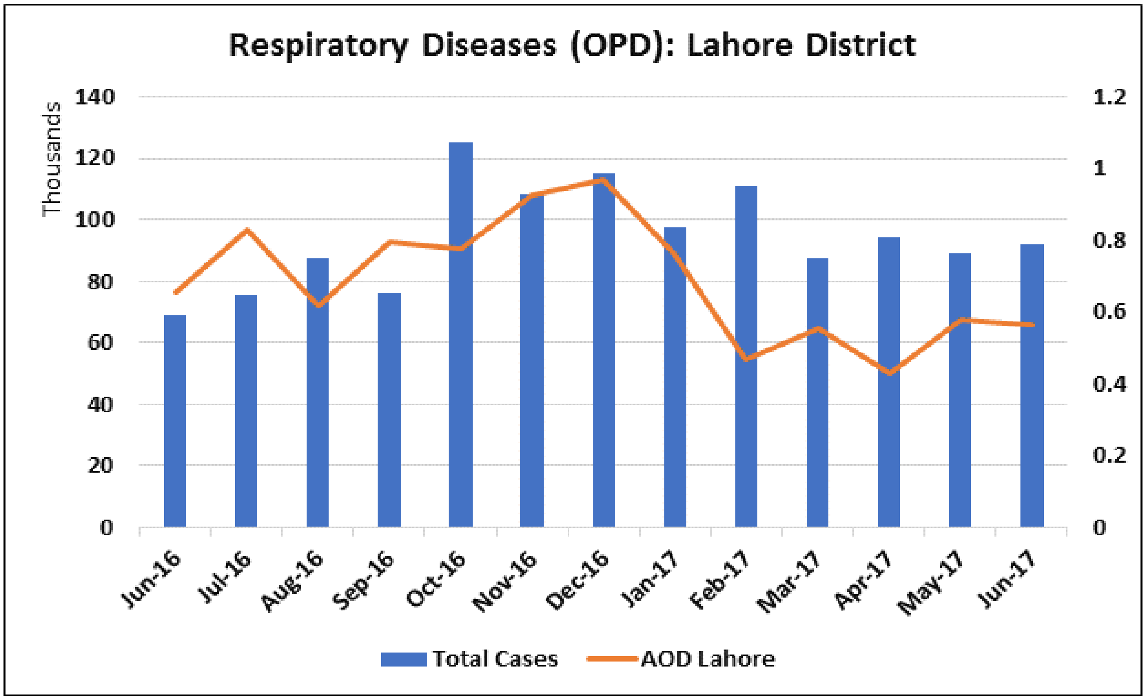


Figure 4.17: Monthly Respiratory Diseases Incidence in Lahore (OPD)

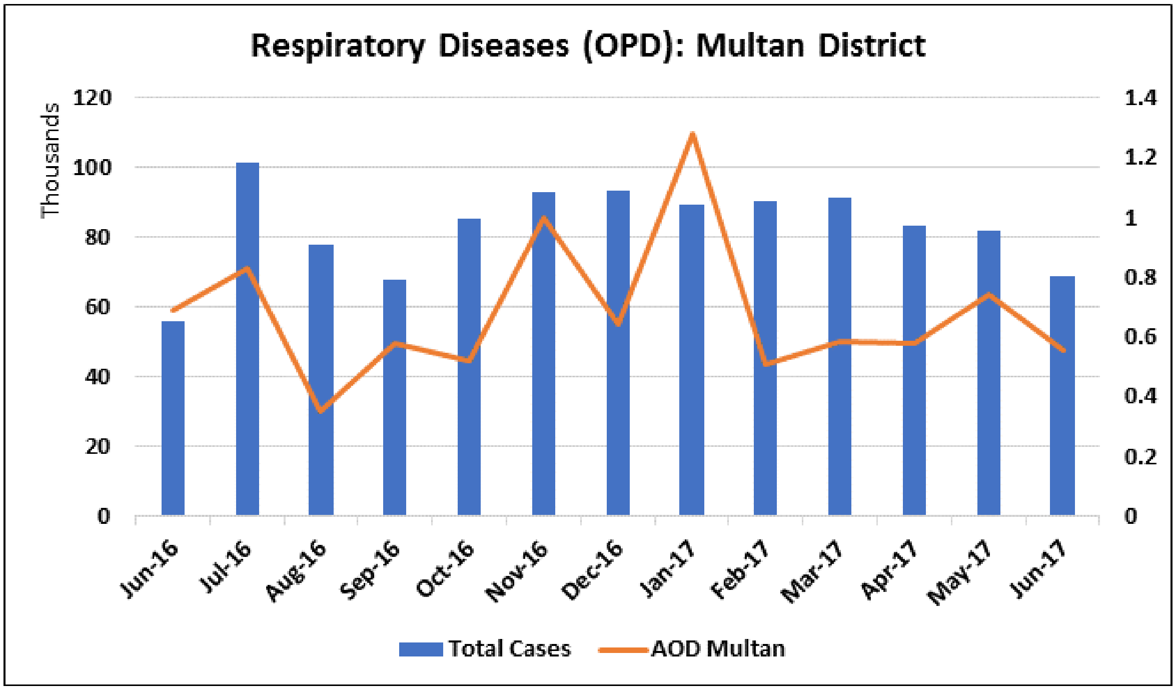


Figure 4.18: Monthly Respiratory Diseases Incidence in Multan (OPD)

4.4.3. Counter-factual and Attributable Number

Table 4.7: The counter-factual and attributable number of respiratory diseases associated with the counter-factual exposure in the cities of Lahore and Multan.

City	Month	Cases	PAQI Baseline	CAMS Baseline	WHO	NEQs
Lahore	Jan-17	Counter-factual	2981	2401	2305	2348
		Attributable number	390	970	1066	1023
	Feb-17	Counter-factual	3743	3381	3209	3270
		Attributable number	78	440	612	551
	Mar-17	Counter-factual	1756	1622	1555	1585
		Attributable number	108	242	309	279
Multan	Jan-17	Counter-factual	n/a	1785	1684	1716
		Attributable number	n/a	325	426	394
	Feb-17	Counter-factual	n/a	1796	1672	1704
		Attributable number	n/a	311	435	403
	Mar-17	Counter-factual	n/a	2097	1966	2003
		Attributable number	n/a	182	313	276

In Lahore, the number of respiratory hospitalizations attributable to $PM_{2.5}$ have been found to be the highest in January followed by February and March. In Multan, the highest number was in February followed by January and March. The attributable number of respiratory hospitalizations computed using the NEQS as baseline were 1853 and 1073; and WHO as baseline were 1987 and 1174, for the cities of Lahore and Multan respectively.

Chapter 5

Conclusions and Recommendations

5.1. Conclusions

Ground based monitoring of particulate matter in the cities of Lahore and Multan from January to March 2017 revealed high concentrations that frequently exceeded the WHO ambient air guidelines. Using the relative risk estimates or the concentration–response functions established by epidemiological cohort studies, and the exposure based on the $PM_{2.5}$ monitored data, the attributable number of respiratory hospitalizations computed using the NEQS as baseline were 1853 and 1073; and WHO as baseline were 1987 and 1174, for the cities of Lahore and Multan respectively. These numbers are substantial and they essentially reveal that the policy makers need to give urgent attention to air pollution abatement.

The seasonal and annual distribution of AOD revealed increasing concentrations over time in Lahore annually, and high aerosol loadings in winter in both Lahore and Multan. This is indicative of the fact that winter fog has indeed become a massive issue in Pakistan. Inter–comparison or validation of MODIS AOD with AERONET AOD over Lahore showed a good agreement, indicating that MODIS AOD can be a good predictor ground based concentrations. The estimated linear relationship of MODIS AOD with ground level $PM_{2.5}$ with the incorporation of the influence of relative humidity and boundary layer height corroborated this finding, and yielded equations that can be used for calculating long-term concentrations of $PM_{2.5}$, which can be extremely useful for future air pollution health risk assessments. It can be concluded that the data from MODIS sensor and other satellites as well can be immensely useful for air quality monitoring and agencies such as EPA.

5.2. Recommendations

In order to improve the debilitating air pollution load in the country and the air quality monitoring data and practices, following recommendations should be considered based on the results from this study:

- Further research needs to be conducted to establish the relationship between satellite AOD and ground based PM.
- Based on the model developed in this study, further research and tool development will greatly enhance the data availability and usefulness to EPA and state and local air quality agencies.
- Air quality monitoring network needs to be established around Pakistan.
- Health data should be publically available.
- Considering the growing population of urban areas in Pakistan and the persistently elevated air pollution load, this study supports and recommends effective air pollution abatement strategies on an urgent basis.
- There needs to be an emphasis on emission reduction policies as well as epidemiological studies to reduce the harmful effect of aerosols.

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