EXPLORING THE AIR QUALITY INDEX (AQI) AND THE RELATIONSHIP BETWEEN AEROSOLS AND HEAT INDEX (HI)

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EXPLORING THE AIR QUALITY INDEX (AQI) AND THE RELATIONSHIP BETWEEN AEROSOLS AND HEAT INDEX (HI)

A thesis submitted in partial fulfillment of the requirements for the degree of

Master of Science in Environmental Science

BY

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THESIS ACCEPTANCE CERTIFICATE

It is certified that the contents and form of the thesis entitled “EXPLORING THE AIR QUALITY INDEX (AQI) AND THE RELATIONSHIP BETWEEN AEROSOLS AND HEAT INDEX (HI)” submitted by Ms. Fatima Malik (Reg # 276843) has been found satisfactory for the requirements of the degree of Master of Science in Environmental Science.

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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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Fatima Malik

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LIST OF ABBREVIATIONS

$\mu g/m^3$	Microgram per Cubic meter
AQI	Air Quality Index
AOD	Aerosol Optical Depth
AOT	Aerosol Optical Thickness
ArcGIS	Arc Geographic Information System
ATL	Aerosol Type Land
BC	Black Carbon
BrC	Brown Carbon
BLH	Boundary Layer Height
C-CARGO	Climate Change and Atmospheric Research Group
CO	Carbon Monoxide
HI	Heat Index
km^2	square kilometer
Lat	Latitude
Lon	Longitude
MCTK	MODIS Conversion Toolkit
MODIS	Moderate Resolution Imaging Spectro-radiometer
NASA	The National Aeronautics and Space Administration
OC	Organic Carbon
Pak-EPA	Pakistan Environmental Protection Agency

Pak-NEQS	Pakistan National Environmental Quality Standards
PM	Particulate Matter
RH	Relative Humidity
SSA	Single Scattering Albedo
USPCAS-E	U.S.-Pakistan Center for Advanced Studies in Energy
UVAAI	Ultra Violet Absorbing Aerosol Index
WHO	World Health Organization

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ABSTRACT

Clean air is a necessity for healthy life, a bad air quality infers heavy threat to both environment and human health. Major cities around the globe are facing the problem of declining air quality, which has adverse impacts not only on the human health but also ecosystem and economy. According a recent study by WHO, nine out of ten people in the world are exposed to the deteriorating air quality and high levels of air pollutants. Pakistan is amongst the many Asian countries which are undergoing serious air pollution problems. Levels of dust and smoke in Pakistan are twice the world average and five times higher than the levels in developed countries. Lack of efficient monitoring and control measures of air pollution has made Pakistani cities more vulnerable as compared to the developed world and in the region. Due to lack of ground-based air quality monitoring networks in Pakistan, satellite data is one alternative which provides information about air pollution on regular basis. Aerosol Optical Depth (AOD), Aerosol Type Land (ATL) from MODIS-Terra and Aqua is used in this study to compute the seasonal aerosol trends over Islamabad, for the years 2015-2019. Furthermore, to signify the issue of deteriorating air quality, ground-based monitoring for $PM_{2.5}$ and PM_{10} was carried out at IESE, NUST for the period of December 2019 – March 2020. Particulate matter concentrations exceeded the National Environmental Quality Standards (NEQS) levels on frequent basis. In case of PM concentrations, winter was most polluted and spring was found comparatively cleaner in Islamabad. Absorbing fine aerosols especially dust and smoke contributed the most to aerosols during the study time period. Based on the PM concentrations, AQI was calculated for the study area which showed maximum AQI during winter months. Temperature and relative humidity data was provided by USPCASE, NUST for the calculation of Heat Index. A significant relation between MODIS AOD and Heat Index data was identified.

Chapter 1

INTRODUCTION

1.1. Background

Clean air is a basic necessity for healthy life, a decline in air quality causes serious threats not only to the human health but also to the environment. Majority of the cities around the globe are undergoing the problem of worsening air quality, which has grave impacts on human health, ecosystem and economy (Shahid et al., 2019). Combustion of fossil fuel, atmospheric dust, agriculture, and biomass burning are considered as major contributors of air quality. Moreover, exposure to air pollution increases the risk of heart diseases, cerebrovascular diseases , chronic obstructive pulmonary diseases (COPD) and many other lower respiratory tract infections (LRIs) (Lelieveld et al., 2018).

According to data released by WHO, nine out of ten people in the world are exposed to the deteriorating air quality and high levels of air pollutants. Consequently, 4.2 million deaths around the world can be attributed to the outdoor air quality in a year and 3.8 million to indoor air pollution, making a total of 7 million deaths worldwide. Furthermore, it has also been reported the around three billion people around the world still lack the access to clean fuels for the domestic heating and cooling (WHO, 2018).

Asia and Africa despite being the home to most of the worlds developing countries, faces around 90% of deaths due to air pollution (Lelieveld et al., 2018). Over the last decade, the Asian countries have undergone considerable growth in development and urbanization coupled with motorization and increase in energy use. Intense industrial activities, increasing population and uncontrolled use of motor vehicles are posing serious environmental impacts in the region (Colbeck et al., 2010).Atmospheric particulate pollution has become a serious global environmental problem, not only in East Asia like China, but also in South Asia like Pakistan (Ahmed et al., 2013).

Smoke and dust levels in Pakistan are twice the world average and five times higher than that recorded in developed countries. Therefore, studying air quality of different cities on regular basis, helps not only to evaluate the impact on human health and environment but also to establish a baseline that will help in highlighting the possible sources of air pollution (Shahid et al., 2019).

Foremost causes of air pollution in Pakistan are rapid urbanization, economic growth, and unplanned industrialization. Moreover, in urban areas of Pakistan, major sources of fine particulates are automobiles exhaust, combustion of biomass/ fossil fuels, power plants and industrial emissions (Rasheed et al., 2015). Urban air pollution in Pakistan is a serious challenge and it causes significant damage to human health and ecosystem. Furthermore, lack of efficient monitoring and control measures of air pollution has made Pakistani cities more vulnerable as compared to the developed world and even the neighboring countries (M. Z. Shahid et al., 2015).

Pakistan is one of the most urbanized yet polluted country in South Asia. Studies showed that urban cities like Lahore and Karachi are listed as the most polluted cities worldwide because of high particulate concentration levels (Shahid et al., 2016). Moreover, Islamabad, the federal capital of Pakistan, is a city with small and medium light industry but due to increase in vehicular load over the last decade, air pollution has emerged as a serious issue (Ahmed et al., 2013).

In addition, there has not been any systematic study on the chemical composition of atmospheric particulate matter although some investigations about element analysis have been carried out in Islamabad (Lv et al., 2019).

1.2. Sources of Air Pollution in Pakistan

Pakistan is amongst the many countries which are being affected by air pollution. Rapid industrialization, urbanization, population boom and vehicular load are found to be the major contributors of air pollution in Pakistan (Colbeck et al., 2010). The major sources of particulate matter pollution in air include the agriculture and transport sectors, production of energy from coal, and inefficient use of energy including bio-fuels, biomass burning, sand and desert dust.

The hazardous impacts of air pollution become worse during the winters due to dense persistent fog especially in the months of December, January, and February (DJF). It has been reported that the average concentration of both PM_{10} and $PM_{2.5}$ increased about two times during intense fog days. Aerosols intensify fog formation in low temperature and high humidity conditions (Bulbul et al., 2018).

Like the rest of the world, industrial emissions, burning of solid waste and agricultural residues, waste disposal, and vehicular emissions tend to affect the air quality of Pakistan. The vehicular usage frequency has enhanced over the last two decades which ultimately has made a considerable contribution to air pollution. Industries using furnace oil as a fuel source are a main source of air pollution. Moreover, the burning of crop waste is also a major contributor to air pollution and smog formation. More than 50,000 tons solid waste is generated on daily basis in Pakistan. A huge mass out of this solid waste is incarcinated which release particulate matter (PM) and toxic gases like CO, SOx, and NOx and deteriorate the atmosphere (Marvila et al. 2019).

Many Government departments and international organizations have identified degradation of ambient air quality as a major environmental concern in Pakistan. As part of the 5-year plan for 2005–2010, the Pakistani Government published the Pakistan Clean Air Program (PCAP) for improving ambient air quality. The PCAP highlighted vehicular emissions, industrial emissions, burning of solid waste and natural dust as major sources of urban air pollutants in Pakistan and proposed a number of short and long-term measures that require action at all levels of government (Colbeck et al., 2010).

Atmospheric aerosol or particulate matter (PM) is chemically complex and a dynamic mixture of solid and liquid particles. The major sources of these particles are combustion generated particles, sea salt spray, dust, vehicles exhaust, industrial stacks, construction activities, fossil fuel combustion and biomass burning (Dutkiewicz et al., 2009). There are limited studies available regarding chemical nature of atmospheric aerosol in Pakistan region (Shahid et al., 2019).

The World Bank (2006) estimated an annual environmental degradation cost of about Rs. 365 billion or 6% of GDP for Pakistan. Estimated environmental health cost due to urban particulate matter pollution in the country is around Rs. 65 billion causing about 22,000 premature deaths among adults and 700 deaths among young children (Rasheed et al., 2015).

1.3. Air Pollution Monitoring

Globally air quality monitoring is being carried out either by using ground-based observations or through satellite instruments. As no proper air quality monitoring network exists in Pakistan due to lack of financial and technological resources, therefore, satellites observation can fill this gap by providing continuous observations across the globe (Khokhar et al., 2016). A wide variety of satellite instruments for air quality measurement are available like MODIS onboard Aqua and Terra satellite. 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 both, regional, as well as local scales.

In the last 5 years, the capabilities of National Aeronautics and Space Administration (NASA) earth observing satellites and the technological tools to share and use these images have advanced sufficiently to enable the use of satellite imagery in conjunction with ground-based data for air quality monitoring. Satellite data can add synoptic information, visualization, and validation to ground-based air quality data modeling.

1.4. Remote Sensing of Atmospheric Pollutants

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.

The drawback, however, of ground-based observations is that they are point measurements and 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).

1.5. 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.

1.6. Atmospheric Aerosols

Atmospheric aerosols play an important role in the Earth energy balance system as they act as a seed for cloud/fog formation which results in precipitation. Moreover, an increase in aerosol concentration causes negative impacts on various natural processes such as suppression of precipitation rate, reduced visibility and also causes serious health impacts.

Atmospheric aerosols have a distinct variation in their size and chemical composition and are suspensions of solid, liquid, and mixed particles (Putaud et al; 2010). These aerosols exert some direct and some indirect effects on the whole system. The direct effects include their ability to scatter and absorb solar radiation where the indirect effects include their ability to change cloud properties and precipitation patterns.

Atmospheric aerosols came into the atmosphere either as a primary particle or as secondary pollutant. 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).

Aerosols cause smog, air pollution and various impacts on cloud microphysics, global carbon, sulfur, nitrogen, and hydrological cycles in both direct and indirect ways. Different types of aerosols have diverse properties on the symbol and extent of aerosol radiative forcing. Black Carbon (BC) is considered as an absorbing aerosol that contributes to global warming and the extent of its impact varies in different parts of the world. Suspended dust particles alter the propagation of short and long wave radiation through atmospheric scattering and absorption methods and warm the atmosphere due to absorption.

Aerosols also have impacts on social aspects like human health and ecological processes. Satellite remote sensing is an emerging field for global atmospheric monitoring of different parameters and their impact on climate, such as aerosols. Various studies have been conducted to explore aerosol trends and their effects at both the global and regional scales by utilizing satellite instruments (Khokhar et al., 2016).

1.6.1. Environmental and Health Impacts of Aerosols:

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 persist, it can eventually lead to death. Based on scientific evidences, the health burden caused by air pollution, mortality has been identified as a less sensitive marker than hospital admissions (Wong et al., 2002).

1.7. Particulate Matter

PM stands for particulate matter (also called particle pollution): the term for a mixture of solid particles and liquid droplets found in the air. However, some particles such as dust, dirt, soot, or smoke, are large or dark enough to be seen with the naked eye. Whereas others are so small they can only be detected using an electron microscope. Particle pollution includes:

- **PM_{10}:** inhalable particles, with diameters that are generally 10 micrometers and smaller; and
- **$PM_{2.5}$**: fine inhalable particles, with diameters that are generally 2.5 micrometers and smaller.

Among various air indicators, particulate matter with a particle size less than or equal to 2.5µm ($PM_{2.5}$) and particulate matter with a particle size less than or equal to 10µm (PM_{10}) are the main components of air pollutants that can enter the body and affect human health, causing ischemic heart disease, chronic obstructive pneumonia, and other diseases (Su et al., 2021).

1.7.1. Sources of Particulate Matter

These particles come in many sizes and shapes and can be made up of hundreds of different chemicals. Some are emitted directly from a source, such as construction sites, unpaved roads, fields, smokestacks, or fires. Most particles form in the atmosphere as a result of complex reactions of chemicals such as sulfur dioxide and nitrogen oxides, which are pollutants emitted from power plants, industries and automobiles (EPA, 2021).

Particulate matter is one of the significant pollutants with adverse health impacts like premature mortality, lungs, and cardiovascular diseases. Particulate matter consists of various organic and inorganic species with both natural and anthropogenic origin. Fine particles ($PM_{2.5}$) are composed of constituents like elemental carbon, organic carbon compounds, sulfates, nitrates, ammonium, heavy metals, H+ and condensed metal vapors (Rasheed et al., 2015).

The major components of PM are sulfate, nitrates, ammonia, sodium chloride, black carbon, mineral dust, and water. While particles with a diameter of 10 microns or less, ($\leq PM_{10}$) can penetrate and lodge deep inside the lungs, the even more health-damaging particles are those with a diameter of 2.5 microns or less, ($\leq PM_{2.5}$). $PM_{2.5}$ can penetrate the lung barrier and enter the blood system. Chronic exposure to particles contributes to the risk of developing cardiovascular and respiratory diseases, as well as of lung cancer. $PM_{2.5}$ is very small in size, and its residence time is longer as compared to PM_{10}, which makes it more convenient to penetrate in lungs, becoming part of blood circulation and reaching to other organs and causing more toxicity (Mehmood et al., 2018).

Particulate matter (PM) is a mixture of solid and liquid droplets in the atmosphere. Some major sources of these particles are combustion generated particles, sea salt spray, dust, vehicles exhaust, industrial stacks, construction. Pakistan is among the topmost polluted countries of South Asia. The PM concentration in Pakistan exceeds the safe limits of WHO on regular basis as in other countries of South Asia. Pakistan was ranked as the second most polluted country in South Asia in the 2018 World Air Quality Report (Air, 2018).

Air quality measurements are typically reported in terms of daily or annual mean concentrations of PM_{10} particles per cubic meter of air volume (m^3). Routine air quality measurements typically describe such PM concentrations in terms of micrograms per cubic meter ($\mu g/m^3$) (Smith, 2020).

Due to lack of proper information and inadequate law practices, monitoring and management of PM are not among the top priority in Pakistan. Moreover, very little literature and reports regarding PM pollution in Pakistan could be found (Mehmood et al., 2018).

1.8. Objectives of the Study

Objectives of the current research are:

1. To quantify the concentration of PM_{10} and $PM_{2.5}$ over the study area and calculate AQI for Islamabad.
2. To identify spatial and temporal variations of aerosol over the Islamabad and its relationship with heat index (HI).

1.9. Significance of the Study

Air pollution is increasing with every passing day all over the world because of urbanization, industrialization, and ecological degradation particularly in emerging nations like Pakistan, India, and China. Elevated degrees of contaminants are not only harming the cultural heritage but are also dangerous for human health particularly in metropolitan regions, where higher concentrations have made breathing extremely difficult (Shahid et al., 2019).

This study will provide an understanding of the prevailing conditions of aerosols over Islamabad and will also characterize these aerosols by exploring their optical properties. The study will provide not only the concentrations of particulate matter but will also measure AQI of Islamabad. Moreover, this research also focuses on the relationship between aerosols and Heat index (HI). The resultant datasets of PM, AOD, ATL will provide a base for any decision-making system to abate air pollution and economic losses in the fields of health, road traffic and road accidents, and agriculture. It will also improve the skills of students in the handling of remotely sensed data and geoinformatics techniques. Results of the study will be made public and shared with all concerned departments and common people through journal publications and institutional web pages.

Chapter 2

LITERATURE REVIEW

2.1. Role of Aerosols in Air Pollution

Aerosol particles in the atmosphere are emitted either directly from various natural and anthropogenic sources (primary aerosol particles) or produced by gas-to-particle conversion processes (secondary aerosol particles). These particles influence the local and global climates directly by scattering and absorbing radiation and indirectly by acting as cloud condensation nuclei (CCN) or ice nuclei (IPCC, 2013).

Aerosol concentrations depend upon factors such as location, atmospheric conditions, annual and diurnal cycles, and the presence of local sources. Usually, the highest concentrations are found in or near urban and industrial areas. The impact of aerosols, both anthropogenic and natural, are of particular concern because of their role in reducing visibility, degrading sunlight at the surface and the resulting consequences on the local climate, animals, and plants lives along with the health of local inhabitants (Alam et al., 2014).

South Asia is very prone to the adverse effects of increasing aerosol amount because of population expansion, rapid urbanization, land use changes, increasing motorized traffic, and growing industrialization within, and adjacent to urban areas. Pakistan, situated in the northwestern part of South Asia, is also affected by the growing aerosol concentration

South Asia is seriously affected by the increasing concentration of aerosols caused by rapid industrialization and urbanization, growing population, land use changes and increase in vehicular load. Similarly, Pakistan situated in the northeastern part of the region is also facing the problem of increasing aerosol concentrations (Ali et al., 2020).

Seasonal variations of aerosols are driven by seasonal variations in both emissions and meteorological conditions. Pakistan has four seasons: cool and dry winter from December through February, hot and dry spring from March through May, the summer rainy season (or monsoon period) from June through September, and the retreating monsoon period of October and November (Shahid et al., 2015).

Alam and his co-workers have reported higher AOD concentration during summers and lower for winters. Their study highlighted that the seasonal variations and regional meteorology could be the prime cause for in consistence spatial distribution of aerosols.

Awais et al., 2018 analyzed the aerosol optical properties using remote sensing over Islamabad and Rawalpindi. Their study found an exponential growth in vehicular load in the twin cities since 2007. However, introduction of latest technologies and emission standard has helped in reducing the emissions.

2.2. Aerosol Optical Depth (AOD)

Aerosol optical depth (AOD) is a measure of the extinction effect of atmospheric aerosols and is widely used as a key parameter for assessing the degree of air pollution. Moreover, aerosols have a profound impact on local, regional, and even global climate as well as atmospheric radiation transmission and water cycles (Li et al., 2021).

Aerosol observation can be generally divided into in situ, surface-based remote sensing and space-borne remote sensing. In situ observations the ambient air can accurately measure the mass concentration, scattering and/or absorbing properties, and more detailed information such as chemical composition, shape, mixing states, hygroscopicity and particle size distribution that determine CCN concentration (JingLi et al., 2022).

For better assessment of the effect of aerosols on environment, their properties should be studied both at provincial and worldwide scales. In this regard, various remote sensing techniques ranging from ground-based to satellite observations, have been developed to provide accurate measurements of AOD and other aerosol properties. The ground-based aerosol robotic network (AERONET) is one of the regularly used networks providing continuous and reliable data on aerosol properties. The MODIS sensors onboard the Terra and Aqua satellites utilize distinct algorithms to provide long-term spatiotemporal characteristics of aerosols at regional and global scales. Advancements in satellite remote sensing of aerosols have simplified the assessment of aerosol properties over a large area with a high number of repeated observations.

A growing body of literature has also reported the use of satellite observations to investigate the indirect effects of spatial and temporal patterns of aerosols, at both regional and global scales. Satellite remote sensing is a powerful tool for monitoring and assessing the global aerosol budget and the radiative effects of aerosols on climate. Moreover, the satellite remote sensing has the benefit of assessing the spatial distribution and properties of aerosols over a large area in a single snapshot. This technique is undoubtedly a unique opportunity to derive regional and global patterns for aerosol distribution and aerosol properties (Ali et al., 2020).

2.3. Ground- Based PM Concentrations

The concentrations of particles with aerodynamic diameters less than 2.5 and 10µm, 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.

Mehmood et al., 2018 reported higher particulate matter pollution in Islamabad during the four seasons of 2017. The maximum days from all seasons have higher $PM_{2.5}$ and PM_{10} values than the NEQSAA and WHO. The positive trend has been observed between PM_{10} and $PM_{2.5}$ mass concentration; however, PM_{10} values remain higher than $PM_{2.5}$ in all sampling days.

Lv et al., 2019 found that both PM_{10} and $PM_{2.5}$ concentrations, as well as the carbonaceous, elemental species and water-soluble inorganic ions in winter are higher than those in summer in three cities, which attributes to more air pollutant emissions because of winter heating and the frequent occurrence of the atmospheric dispersion conditions in winter, as well as stronger wet precipitation in summer.

Bulbul et al., 2018 reported that during foggy days, the ambient air of Islamabad is contaminated with PM_{10} and it also consists of various toxic heavy metals. On most occasions, PM_{10} levels are considerably high as compared to permissible limits of both Pak-NEQS and WHO guidelines. It has been observed that the air quality during fog days was much worse, and elevated levels of particulate matter were observed during the foggy days. The AOD data for non-foggy days were also observed through MODIS satellite, which shows low AOD levels during non-foggy days.

Chishtie et al., 2019 assessed the air quality of twin cities by measuring the concentration of criteria pollutants along with CO_2. 24 hourly sampling was carried out at each location using mobile monitoring lab. Concentrations of SO_2, NOX and O_3 were found within the permissible limits of Pak NEQS and US-EPA. However, higher concentrations of PM_{10} and CO_2 were observed at most of the locations.

Mansha et al., 2011 in their study reported high levels of $PM_{2.5}$ during fall and winter season. The elevated levels during winter season can be attributed to increased coal and biomass burning for domestic heating purposes within the cities as well as the nearby rural areas.

2.4. Air Quality Index (AQI)

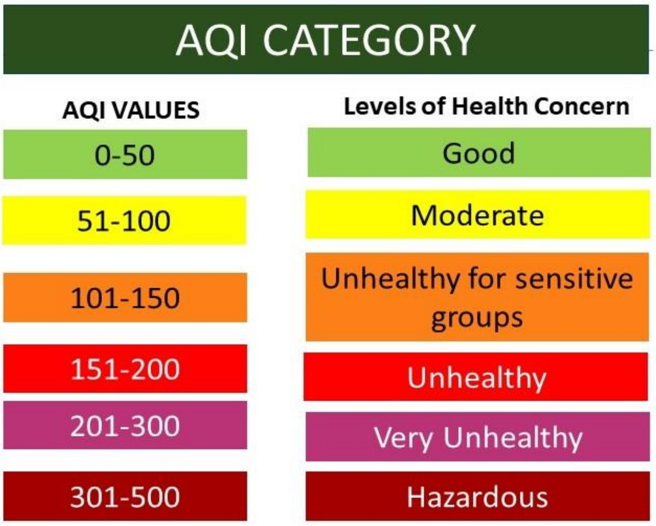
Air Quality index (AQI) is an index used by government offices to impart to the public how polluted the air at present is or forecasted to become. AQI data is obtained by averaging readings from an air quality sensor, which can increase because of vehicle traffic, forest fires, or anything that can increase air pollution.

Calculation of the AQI requires an air pollutant concentration over a predetermined averaging period, obtained from an air model or monitor. Taken together, concentration and time represents the dose of air pollutant. Health effects caused a given dose are established by epidemiological research. Air pollutants vary in potency, and the function used to convert from air pollutant concentration to AQI varies by pollutant (EPA, 2011).

The air quality index (AQI) is a grading scale for reporting the ambient air pollution status monitored at sampling location during a certain monitoring period (e.g., one, 8 or 24 h). The main purposes of AQI are to report and caution the public about the risk of exposure to daily pollution levels and to implement mandatory regulatory measures. The greater the AQI value, higher the level of air pollution and the larger human health risk. The AQI reflects some aspect(s) of air quality related to a particular pollutant and it is generally related with pollutant ranges, quality category descriptors (e.g., good, moderate, poor, or hazardous) and several associated descriptions so it can be used to describe the impact of the pollutants on human health and the environment (Javed et al., 2014).

Air quality index (AQI) is divided into 6 groups ranging from 0 to 500: good (0-50); moderate (51-100); unhealthy for sensitive individuals (USG) (101-150); unhealthy (151-200); very unhealthy (201-300) and hazardous (301-500) as shown in figure 2.1. According to Clean Air Act, AQI has been categorized for five major "criteria" pollutants: ground-level ozone, particulate matter, carbon monoxide, sulfur dioxide, and nitrogen dioxide (figure 2.2).

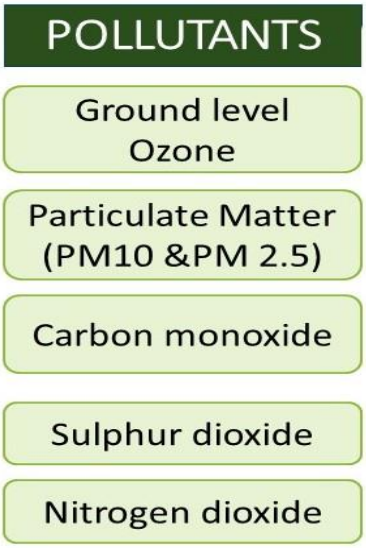
In this study, the AQI related to PM pollutants proposed by US-EPA was used to describe the air quality status. The AQI was calculated by relating PM mass concentrations to the relevant standards (US-EPA, 2012).



AQI CATEGORY

AQI VALUES	Levels of Health Concern
0-50	Good
51-100	Moderate
101-150	Unhealthy for sensitive groups
151-200	Unhealthy
201-300	Very Unhealthy
301-500	Hazardous

Figure 2.1 Categorization of Air Quality Index
Source: (EPA,2012)



POLLUTANTS

- Ground level Ozone
- Particulate Matter (PM10 &PM 2.5)
- Carbon monoxide
- Sulphur dioxide
- Nitrogen dioxide

Figure 2.2 Criteria Pollutants for AQI
Source: (EPA,2012)

2.5. Heat Index (HI)

The heat index, also known as the apparent temperature, is what the temperature feels like to the human body when relative humidity is combined with the air temperature. This has important considerations for the human body's comfort (NWS, 2011)

When the body gets too hot, it begins to perspire or sweat to cool itself off. If the perspiration is not able to evaporate, the body cannot regulate its temperature. Evaporation is a cooling process. When perspiration is evaporated off the body, it effectively reduces the body's temperature. When the atmospheric moisture content (i.e., relative humidity) is high, the rate of evaporation from the body decreases. In other words, the human body feels warmer in humid conditions. There is direct relationship between the air temperature and relative humidity and the heat index, meaning as the air temperature and relative humidity increase (decrease), the heat index increases (decreases).

Table 2.1 Classification of Heat Index based on its effect on human body

Source: (NWS,2011)

Classification	**Heat Index**	**Effect on the body**
Caution	**80°F - 90°F**	**Fatigue possible with prolonged exposure and/or physical activity**
Extreme Caution	**90°F - 103°F**	**Heat stroke, heat cramps, or heat exhaustion possible with prolonged exposure and/or physical activity**
Danger	**103°F - 124°F**	**Heat cramps or heat exhaustion likely, and heat stroke possible with prolonged exposure and/or physical activity**
Extreme Danger	**125°F or higher**	**Heat stroke highly likely**

Based on the effect on the human body, heat index has been classified into 4 categories i.e., caution, extreme caution, danger and extreme danger as shown in table 2.1. The heat index was developed in 1979 by Robert G. Steadman. The heat index contains presumptions about the human weight and height, clothing, measure of physical work, individual heat tolerance, exposure to daylight and ultraviolet radiation and wind speed.

In Canada, the similar humidex is used in place of the heat index. While both the humidex and the heat index are calculated using dew point, the humidex uses a dew point of 7 °C (45 °F), whereas the heat index uses a dew point of 14 °C (57 °F).

Chapter 3

METHODOLOGY

3.1. Study Area

Islamabad, the federal capital of the country is located in the north eastern part of Pakistan. Islamabad is located at 33°26′N and 73°02′E at the foot of the Margalla Hills with more than 2 million residents and covers an area of 906 km^2. Moreover, the city falls in a semi-arid zone and face very humid and hot summers followed by monsoon and cold winters. The climate of Islamabad has a typical version of humid subtropical climate, with four seasons: winter (December – February), pre-monsoon (March - June), monsoon (July - September) and post-monsoon (October and November).

In this study, sampling of PM was carried out at the Institute of Environmental Science and Engineering (IESE), NUST which is located in sector H-12, Islamabad. The sampling site is selected based on its unique feature as it is surrounded by one busiest road of Islamabad, namely the Kashmir Highway and also near to IJP road and Peshawar Road.

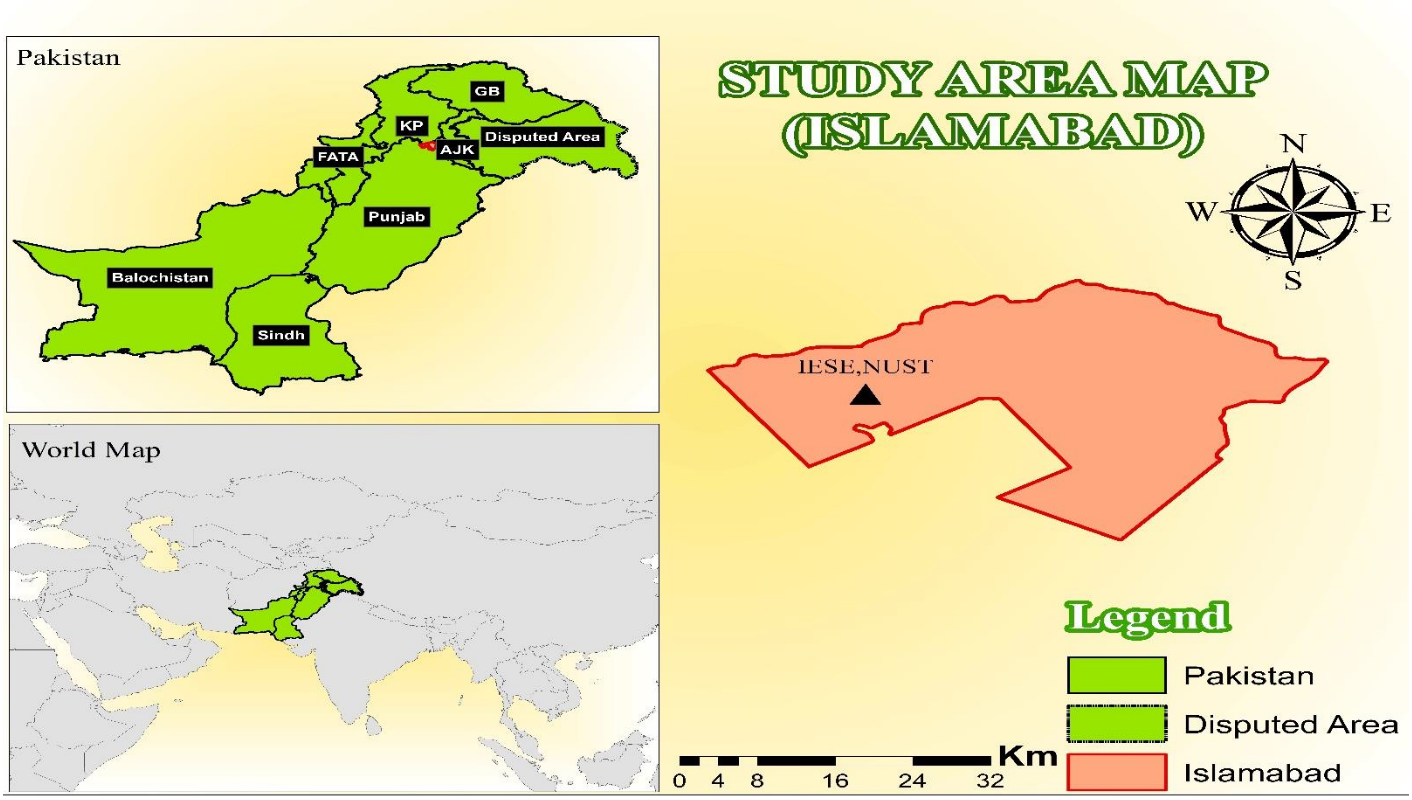


Figure 3.1 Study Area Map

3.2. Datasets

The study was divided into four phases starting from data collection from various satellite and ground-based instruments. Aerosol optical depth was then estimated from Modis (TERRA and AQUA). The aerosols were then characterized into various categories and in the last. Following datasets are used in the current study. Satellite data was downloaded from LADDS Web. Data was pre-processed in ENVI before final analysis. Pre-processing includes

- Geo-referenced Mosaicking
- Layer Stacking
- Extraction over Study Area

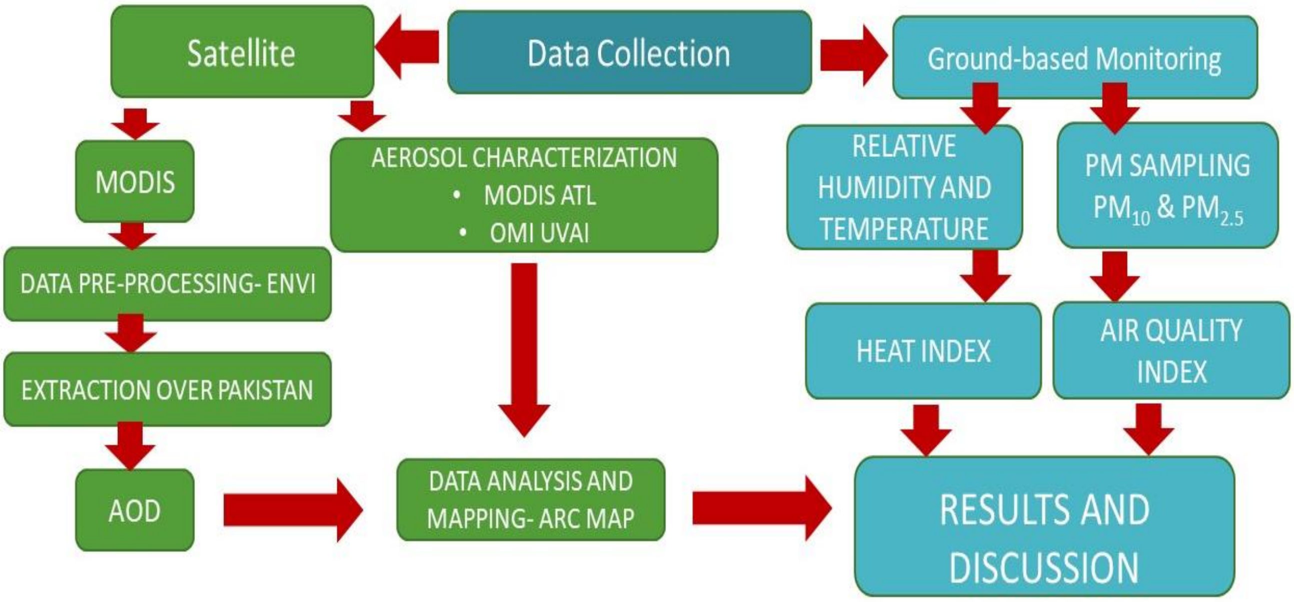


Figure 3.2 Flowsheet for Methodology

3.3. Aerosol Optical Depth Data Processing and Analysis

3.3.1 MODIS Aerosol Optical Depth

The Moderate Resolution Imaging Spectroradiometer (MODIS) sensor on board Terra (launched December 1999) and Aqua (launched May 2002) earth observation system satellites with the multispectral data of 36 bands span visible, near infrared and far infrared portion of the spectrum. It has 1km, 500m, 250m multi-resolution sensors and cover the entire globe. Its revisit time is 12 hours and has a swath width of 705 Km (Jensen, 2009). However, the coarse spatial resolution (10x10 km) of MODIS AOT values as obtained from the NASA algorithm cannot provide detail spatial difference for local/urban scale aerosol monitoring.

MODIS provides global coverage of aerosol products with moderately high spatial resolution, which are derived from Channels 1 and 3 (visible light) in conjunction with band 7(near infrared) based on dark pixel algorithm at a spatial resolution of 10km (Kaufman et al., 1997). Recently, Wong et al. (2009, in press) presented a modified Minimum Reflectance Technique (MRT) to derive AOT over both bright and dark surfaces (e.g., urban and vegetated areas) at a relatively high resolution of 500m with high accuracy, thus avoiding the uncertainties of particle pollution monitoring.

3.3.2 MODIS Aerosol Type Land MODIS

Aerosol Type Land (ATL) data was extracted from MODIS atmospheric level 2 data product MOD04 collection 6. Data was extracted and georeferenced using MODIS Reconversion Tool kit (MCTK) using ENVI 5 software. Then extracted data was mosaicked using same software. After all pre-processing data was analysed on ArcGIS 10.2 and mapped over study area. ATL basically provide information regarding distribution of aerosol types over area of interested. Collection 6 basically provide categories of aerosol types each type is designated by numerical number. Aerosol Type as cited by (Levy et al., 2013b);

1 = Continental,
2 = Moderate Absorption Fine
3 = Strong Absorption Fine
4 =Weak Absorption Fine
5 = Dust Coarse

3.3.3 Categorization into Smoke, Dust, and Sulphates

For this type of categorization, two products were required. Ultraviolet aerosol absorbing index (UVAAI) data product of Ozone Monitoring Instrument (OMI) and carbon monoxide (CO) total column's data of Measurement of Pollution in The Troposphere (MOPITT), both datasets were retrieved from Goddard Earth Sciences Data and Information Services Center (GIOVANNI) for the same study time period. OMI was launched back in July 2004 on the

NASA satellite EOS Aura which has a swath width of 2600 km and a nadir pixel size of 13 x 24 km^2 . It has a temporal resolution of one day. OMI generates various datasets of different atmospheric parameters at a wavelength range of 270 to 550 nm with a spectral resolution of 0.45 nm in ultraviolet and 0.63 nm in visible range (Veihelmann et al., 2007).

For the current study, OMAERUVd UV aerosol index product was retrieved and processed. If the value of aerosol index is less than 0.8, the aerosols are non-absorbing sulphates and if the value is more than 0.8, the aerosols are dust and are of absorbing nature. MOPITT is an instrument boarded on TERRA satellite and it estimates the CO columns globally. MOPITT is active since March 2000 and provides CO total column data in raster format. The data was processed in ArcMap together with the UVAAI product from OMI. If the CO total column is more than 2 * 10^18 and UVAAI is more than 0.8, it means the aerosols are actually smoke particles, where the dust in CO total column is less than 2 * 10^18 and UVAAI is more than 0.8.

3.4. Particulate Matter Sampling

PM sampling was carried out by low volume samplers and quartz filter papers installed at IESE rooftop. 12-hourly day and night sampling was carried out twice a week. A total of 13 samples of PM_{10} and $PM_{2.5}$ were collected during the period of December 2019 to March 2020. Particles in the PM_{10} and $PM_{2.5}$ were then collected on the filter during the specified 24-h sampling period. Each sample filter was weighed before and after sampling to determine the net weight (mass) gain of the collected sample (40 CFR Part 50, Appendix M, US EPA).

3.4.1 Gravimetric Analysis

The $PM_{2.5}$ and PM_{10} mass were determined by gravimetry. Gravimetric analysis of the filters was performed by weighing sample filters before and after sampling period. Quartz filter papers were equilibrated in a temperature and relative humidity-controlled chamber for 24 hours and then weighted using an electronic balance (CPA-26P, Sartorius, German). The mass difference attributed to the total PM mass.

3.5 Computing Air Quality Index (AQI)

The air quality index is a piecewise linear function of the pollutant concentration. At the boundary between AQI categories, there is a discontinuous jump of one AQI unit. To convert from concentration to AQI this equation is used:

$$\mathbf{AQI} = \frac{I_{high} - I_{low}}{C_{high} - C_{low}} (C - C_{low}) + I_{low}$$

Where:

I = the Air Quality Index,

C = the pollutant concentration,

C low = the concentration breakpoint ≤ C

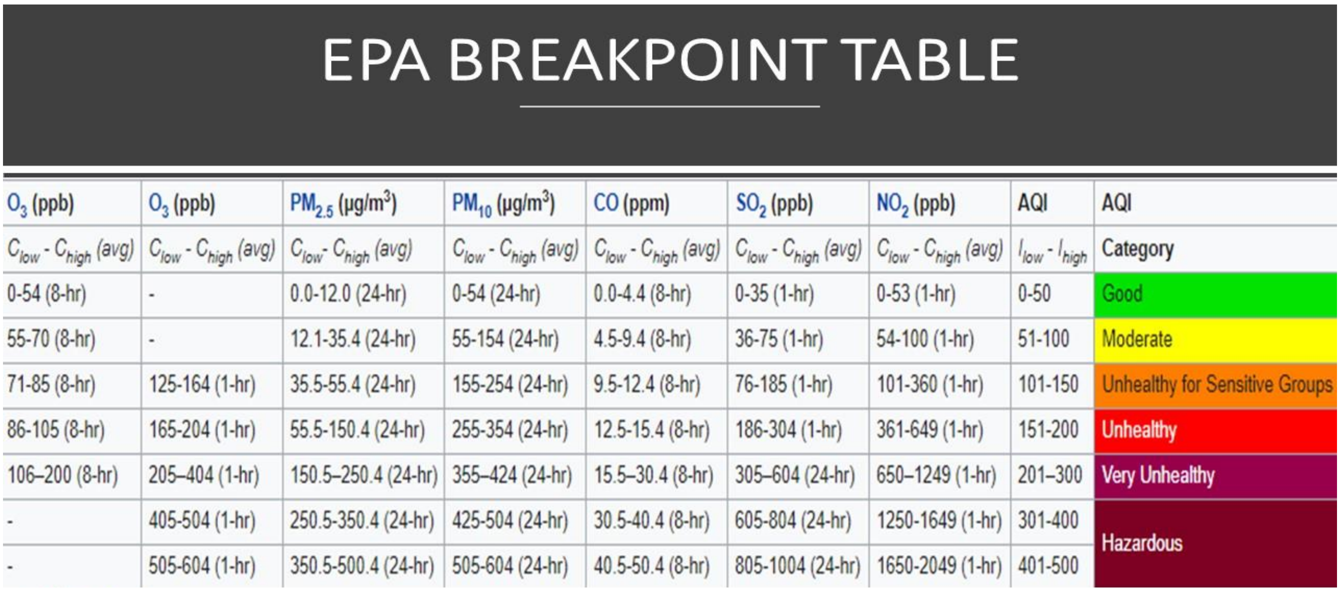
C high = the concentration breakpoint ≥ C

I low = the index breakpoint corresponding to C low

I high = the index breakpoint corresponding to C high

Table 3.1 EPA Breakpoint table for PM concentrations

Source: (EPA, 2012)



EPA BREAKPOINT TABLE

O_3 (ppb)	O_3 (ppb)	$PM_{2.5}$ (µg/m^3)	PM_{10} (µg/m^3)	CO (ppm)	SO_2 (ppb)	NO_2 (ppb)	AQI	AQI
C_{low} - C_{high} (avg)	C_{low} - C_{high} (avg)	C_{low}- C_{high} (avg)	C_{low} - C_{high} (avg)	C_{low} - C_{high} (avg)	C_{low} - C_{high} (avg)	C_{low} - C_{high} (avg)	I_{low} - I_{high}	Category
0-54 (8-hr)	-	0.0-12.0 (24-hr)	0-54 (24-hr)	0.0-4.4 (8-hr)	0-35 (1-hr)	0-53 (1-hr)	0-50	Good
55-70 (8-hr)	-	12.1-35.4 (24-hr)	55-154 (24-hr)	4.5-9.4 (8-hr)	36-75 (1-hr)	54-100 (1-hr)	51-100	Moderate
71-85 (8-hr)	125-164 (1-hr)	35.5-55.4 (24-hr)	155-254 (24-hr)	9.5-12.4 (8-hr)	76-185 (1-hr)	101-360 (1-hr)	101-150	Unhealthy for Sensitive Groups
86-105 (8-hr)	165-204 (1-hr)	55.5-150.4 (24-hr)	255-354 (24-hr)	12.5-15.4 (8-hr)	186-304 (1-hr)	361-649 (1-hr)	151-200	Unhealthy
106–200 (8-hr)	205–404 (1-hr)	150.5–250.4 (24-hr)	355–424 (24-hr)	15.5–30.4 (8-hr)	305–604 (24-hr)	650–1249 (1-hr)	201–300	Very Unhealthy
-	405-504 (1-hr)	250.5-350.4 (24-hr)	425-504 (24-hr)	30.5-40.4 (8-hr)	605-804 (24-hr)	1250-1649 (1-hr)	301-400	Hazardous
-	505-604 (1-hr)	350.5-500.4 (24-hr)	505-604 (24-hr)	40.5-50.4 (8-hr)	805-1004 (24-hr)	1650-2049 (1-hr)	401-500	

3.6 Calculation of Heat Index (HI)

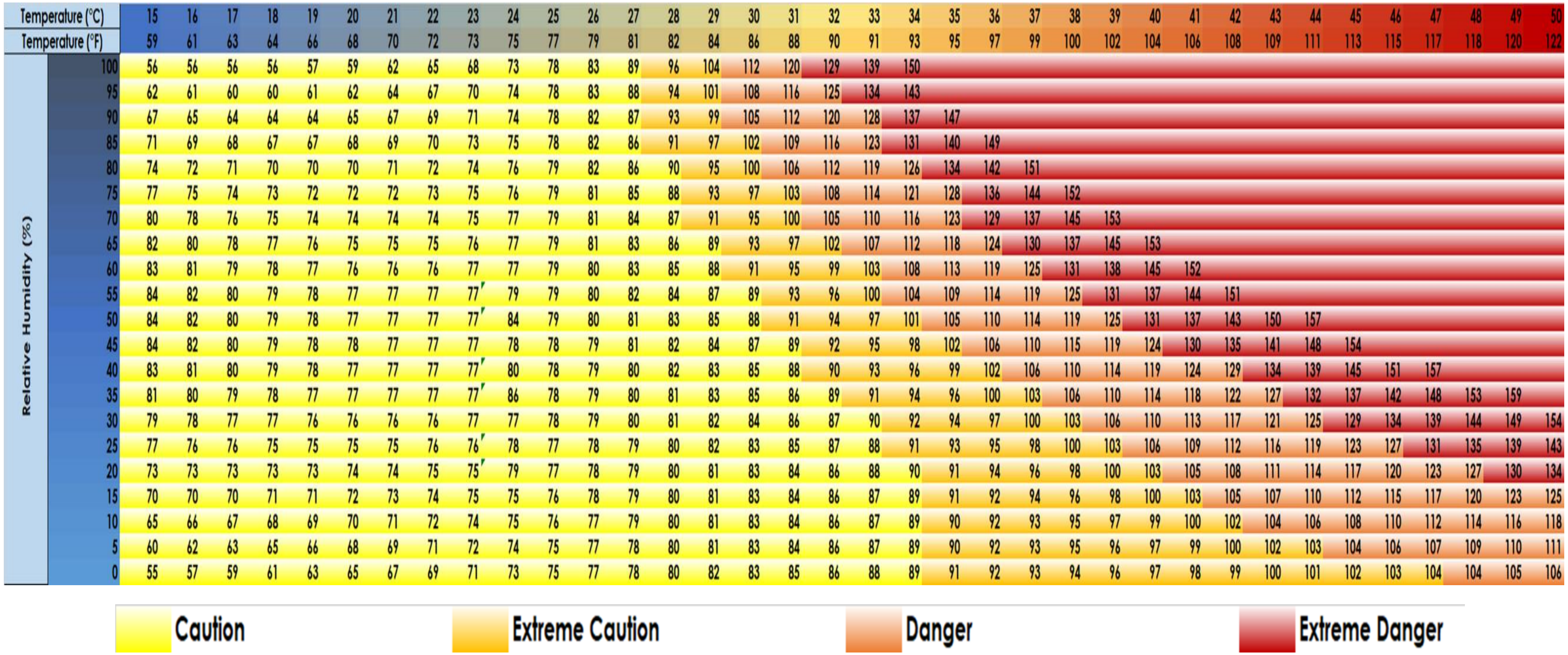
The following equation is used for the calculation of Heat Index. Based on the calculations general matrix chart has been developed, which makes it easier for the lay public to calculate HI and understand its effects on the human body (figure 3.2).

$$HI= c_1+ c_2T+ c_3R + c_4TR + c_5T^2 + c_6R^2 + c_7T^2R + c_8TR^2 + c_9T^2R^2$$

where

- HI = heat index (in degrees Fahrenheit)
- T = ambient dry-bulb temperature (in degrees Fahrenheit)
- R = relative humidity (percentage value between 0 and 100)

c1 = -42.379 **c2** = 2.04901523 **c3** = 10.14333127 **c4** = -0.22475541 **c5** = -6.83783*10-3
c6 = -5.481717*10-2 **c7** = 1.22874*10-3 **c8** = 8.5282*10-4 **c9** = -1.99*10-6



Temperature (°C)		15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50
Temperature (°F)		59	61	63	64	66	68	70	72	73	75	77	79	81	82	84	86	88	90	91	93	95	97	99	100	102	104	106	108	109	111	113	115	117	118	120	122
Relative Humidity (%)	100	56	56	56	56	57	59	62	65	68	73	78	83	89	96	104	112	120	129	139	150																
	95	62	61	60	60	61	62	64	67	70	74	78	83	88	94	101	108	116	125	134	143																
	90	67	65	64	64	64	65	67	69	71	74	78	82	87	93	99	105	112	120	128	137	147															
	85	71	69	68	67	67	68	69	70	73	75	78	82	86	91	97	102	109	116	123	131	140	149														
	80	74	72	71	70	70	70	71	72	74	76	79	82	86	90	95	100	106	112	119	126	134	142	151													
	75	77	75	74	73	72	72	72	73	75	76	79	81	85	88	93	97	103	108	114	121	128	136	144	152												
	70	80	78	76	75	74	74	74	74	75	77	79	81	84	87	91	95	100	105	110	116	123	129	137	145	153											
	65	82	80	78	77	76	75	75	75	76	77	79	81	83	86	89	93	97	102	107	112	118	124	130	137	145	153										
	60	83	81	79	78	77	76	76	76	77	77	79	80	83	85	88	91	95	99	103	108	113	119	125	131	138	145	152									
	55	84	82	80	79	78	77	77	77	77	79	79	80	82	84	87	89	93	96	100	104	109	114	119	125	131	137	144	151								
	50	84	82	80	79	78	77	77	77	77	84	79	80	81	83	85	88	91	94	97	101	105	110	114	119	125	131	137	143	150	157						
	45	84	82	80	79	78	78	77	77	77	78	78	79	81	82	84	87	89	92	95	98	102	106	110	115	119	124	130	135	141	148	154					
	40	83	81	80	79	78	77	77	77	77	80	78	79	80	82	83	85	88	90	93	96	99	102	106	110	114	119	124	129	134	139	145	151	157			
	35	81	80	79	78	77	77	77	77	77	86	78	79	80	81	83	85	86	89	91	94	96	100	103	106	110	114	118	122	127	132	137	142	148	153	159	
	30	79	78	77	77	76	76	76	76	77	77	78	79	80	81	82	84	86	87	90	92	94	97	100	103	106	110	113	117	121	125	129	134	139	144	149	154
	25	77	76	76	75	75	75	75	76	76	78	77	78	79	80	82	83	85	87	88	91	93	95	98	100	103	106	109	112	116	119	123	127	131	135	139	143
	20	73	73	73	73	73	74	74	75	75	79	77	78	79	80	81	83	84	86	88	90	91	94	96	98	100	103	105	108	111	114	117	120	123	127	130	134
	15	70	70	70	71	71	72	73	74	75	75	76	78	79	80	81	83	84	86	87	89	91	92	94	96	98	100	103	105	107	110	112	115	117	120	123	125
	10	65	66	67	68	69	70	71	72	74	75	76	77	79	80	81	83	84	86	87	89	90	92	93	95	97	99	100	102	104	106	108	110	112	114	116	118
	5	60	62	63	65	66	68	69	71	72	74	75	77	78	80	81	83	84	86	87	89	90	92	93	95	96	97	99	100	102	103	104	106	107	109	110	111
	0	55	57	59	61	63	65	67	69	71	73	75	77	78	80	82	83	85	86	88	89	91	92	93	94	96	97	98	99	100	101	102	103	104	104	105	106

Figure 3.3 General Matrix Chart for HI

Chapter 4

RESULTS AND DISCUSSION

4.1. Aerosol Optical Depth (AOD)

According to IPCC 2007 report, aerosols play a significant part in affecting the global climate change and a key role in processes linked to solar and thermal radiative transfer in the atmosphere, water cycle and precipitation processes. Some of the major sources of aerosols in Pakistan are seasonal biomass burning, smoke and dust storms in addition to industrial and vehicular emissions (Alam et al., 2011; Kaufman et al., 2005). AOD is a dimensionless quantity that characterizes the absorption and scattering effect of particles from sunlight. The value of AOD can be derived directly by a sun photometer on ground or indirectly from the reflected radiations of earth detected by satellite sensors.

Seasonal variations of aerosols are caused by variations in both emissions and meteorological conditions. Pakistan experiences four seasons: cool and dry winters from December through February, pre monsoon from March through May, the monsoon period from June through September and the retreating monsoon period of October and November. According to NOAA’s Earth System Research Laboratories, a value of 0.01 AOD means a very clear atmosphere and 0.4 AOD indicates a very hazy atmosphere (NOAA 2005). Yearly mean maps of aerosol optical depth (AOD) over the study area during the seasons of pre-monsoon, monsoon, post-monsoon, and winter for the period 2015-2019 are shown in the figures 4.1.

Results showed maximum aerosol concentration in the monsoon period and minimum levels in winter season. Changes in precipitation, prolonged periods of elevated temperature, surrounding infrastructure development and vehicular emissions are the drivers of increase in AOD levels over the study area. High speed winds and frequent dust storms during summer season also contributes to the emission of dust aerosols in the atmosphere.

Moreover, the exponential increase in AOD is attributed to high relative humidity during monsoon which causes hygroscopic growth of atmospheric aerosols. Higher relative humidity indicates the hygroscopic growth of water-soluble aerosols, whereas lower relative humidity indicates dominance of coarser aerosol particles. The atmospheric boundary layer height, which is maximum during summer season and minimum during winter also plays a significant role in the inclusion of aerosols in the atmospheric column. Therefore, a deeper boundary layer height accompanied by a strong convection and hygroscopic growth of aerosols results in higher AOD concentration during the monsoon period. Enhanced level of aerosol over the study area during the summer months especially monsoon can be clearly seen as identified by previous studies (Pradeep et al., 2020) (Ali et al., 2020) (Tariq et al., 2021) (Bulbul et al., 2018)

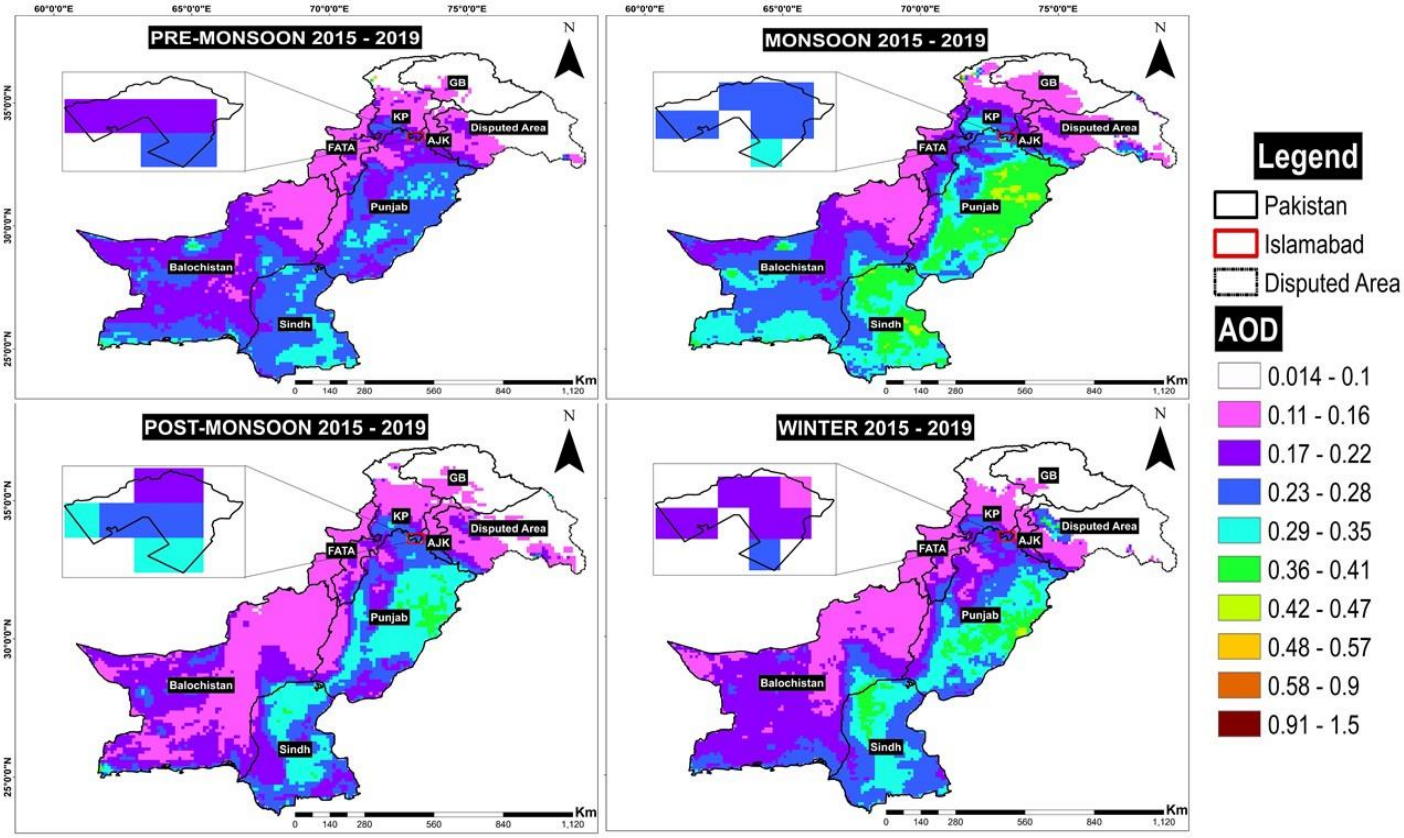


Figure 4.1 Trend of AOD over study area during pre-monsoon, monsoon, post-monsoon, and winter seasons of 2015-2019

Meteorological conditions such as precipitation, surface temperature, wind speed and relative humidity plays a critical role for aerosol characterization in any region. The mean AOD values over Islamabad for each season (pre-monsoon, monsoon, post-monsoon, and winter) during 2015- 2019 are **0.464**, **0.703**, **0.493**, **0.403** as shown in table 4.1. Islamabad, being in the semi-arid zone faces hot and humid summers followed by heavy spells of rain during the monsoon season. Higher relative humidity aided by high temperature intensify the hygroscopic growth of aerosols and gas-to-particle conversion process, producing more secondary aerosols and resulting in higher AOD concentration.

Table 4.1 AOD Concentrations over Islamabad retrieved from MODIS Observations

SEASONS	2015	2016	2017	2018	2019	MEAN
Pre-Monsoon	0.608618	0.514	0.482	0.517	0.372	**0.464**
Monsoon	0.609	0.685	0.701	0.738	0.781	**0.703**
Post-Monsoon	0.462	0.589	0.595	0.418	0.401	**0.493**
Winter	0.399	0.508	0.313	0.403	0.393	**0.403**

4.2. CHARACTERIZATION OF AEROSOLS

Aerosol characterization was carried out using the following datasets:

1. MODIS ATL product
2. UV index and CO columns

4.2.1 MODIS Aerosol Type Land

To investigate the types of aerosols, present over the study area, MODIS product named MOD04 level 2 collection 6 with subset Aerosol Type over land (ATL) was used. MODIS ATL product was downloaded using NASA's ladsweb repository and further processing was carried out using ENVI, ENVI IDL and ArcMap. MODIS aerosol types were categorized into four types includes: Continental, Weak, Moderate and Strong absorption fine.

The resultant rasters show a complete dominance of strong absorption fine aerosols over the study area during monsoon, post monsoon and winter season. However, moderate to strong absorption fine aerosols were seen during pre-monsoon. The raster output of the product is as shown in Figure 4.2.

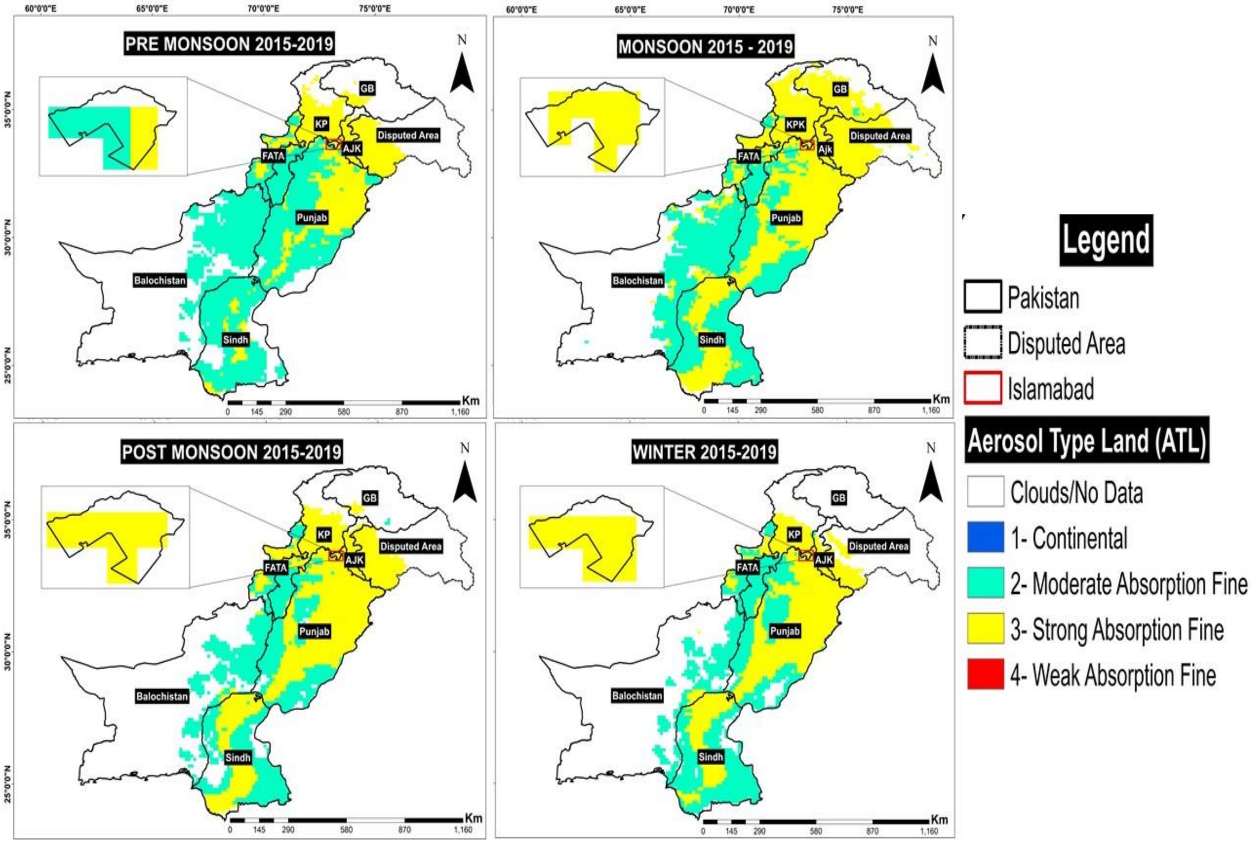


Figure 4.2 Trend of ATL over study area during pre-monsoon, monsoon, post-monsoon, and winter seasons of 2015-2019

The analysis presented in fig 4.2 showed that moderate to strong absorption fine aerosols are predominant over Islamabad during 2015 – 2019. Absorbing aerosols, caused by vehicular and industrial emissions, comprises of black carbon (BC), brown carbon (BrC) or absorbing organic carbon (OC), and dust. Moreover, they cause positive radiation balance anomaly in the climate system which leads to atmospheric warming. Due to these aerosols the air quality deteriorates, hydrological cycle gets disturbed and snow albedo changes (Li et al., 2022).

4.2.2 Aerosol Characterization by UV index and CO columns data

To further observe the types of aerosols following data products were used:

- **UV INDEX**

This index detects the presence of UV-absorbing aerosols such as dust and soot. It is sensitive to carbon and mineral containing aerosols which indicates the presence of absorbing aerosols and is insensitive to surface types. Positive index indicates the presence of absorbing aerosols (smoke, dust) whereas negative index shows the presence of non-absorbing aerosols. However, in case of clear sky/ Rayleigh scattering conditions the values of UVAI are close to zero.

- **CO COLUMN**

Aerosol types are further characterized by using OMI-UVAI combined with MOPITT CO total column multispectral data product. Carbon Monoxide is considered since it is a good precursor for emissions resulting from biomass burning and industrial activities. The output rasters generated from analyzing UV index and CO columns are shown in figure 4.3. As the result shows, the incidence of smoke aerosol types gradually increases during post-monsoon and winters. However, during pre-monsoon and monsoon the windspeed and dust storms increases which consequently results in the rise of dust aerosol type in that period.

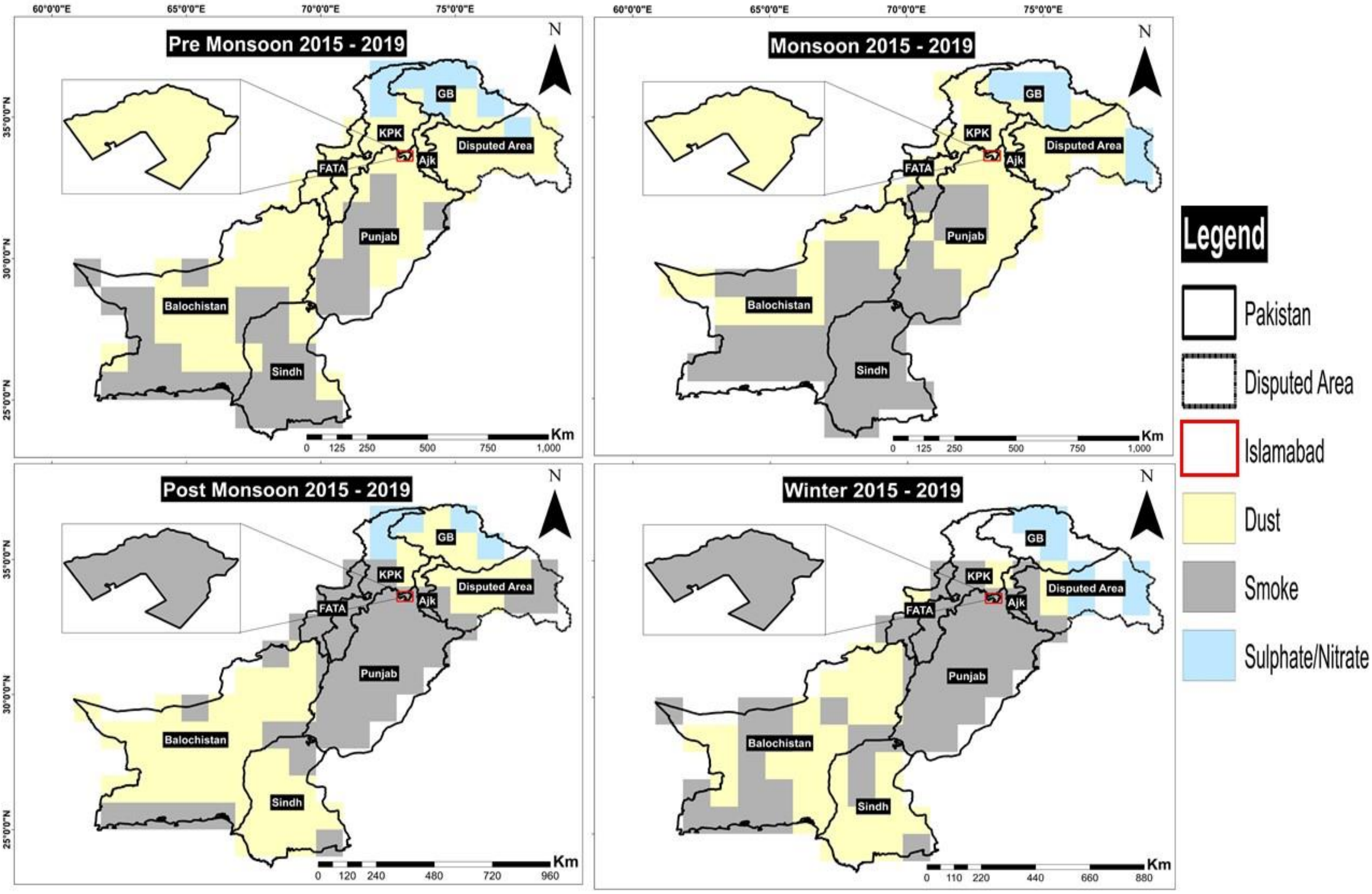


Figure 4.3 Aerosol characterization with CO and UVAAI

4.3. MEASUREMENT OF PM$_{10}$ AND PM$_{2.5}$ CONCENTRATIONS

The study also had a special focus on the ground data collection of PM$_{10}$ and PM$_{2.5}$ during the period of December 2019 to March 2020 over the capital city of Pakistan. Continuous monitoring was carried out by low volume samplers for PM$_{10}$ and PM$_{2.5}$ installed over IESE rooftop, Nust, Islamabad. The sampling was carried out twice a week for 12 hours (day and night) and quartz filters (Whatman international limited) were used to collect samples because of their high collection efficiency and ability to withstand high temperature. Filters were weighed both before and after the sampling, moreover, based on the weight of filters and volume of the sampler PM concentrations were calculated.

During the study period, both $PM_{2.5}$ and PM_{10} concentrations exceeded the limits of NEQS and WHO standards in Islamabad as shown in figure 4.4 (a & b). Maximum concentrations have been observed during the winter months (December-February), however, a gradual decrease in concentrations was observed during the month of March (early spring).

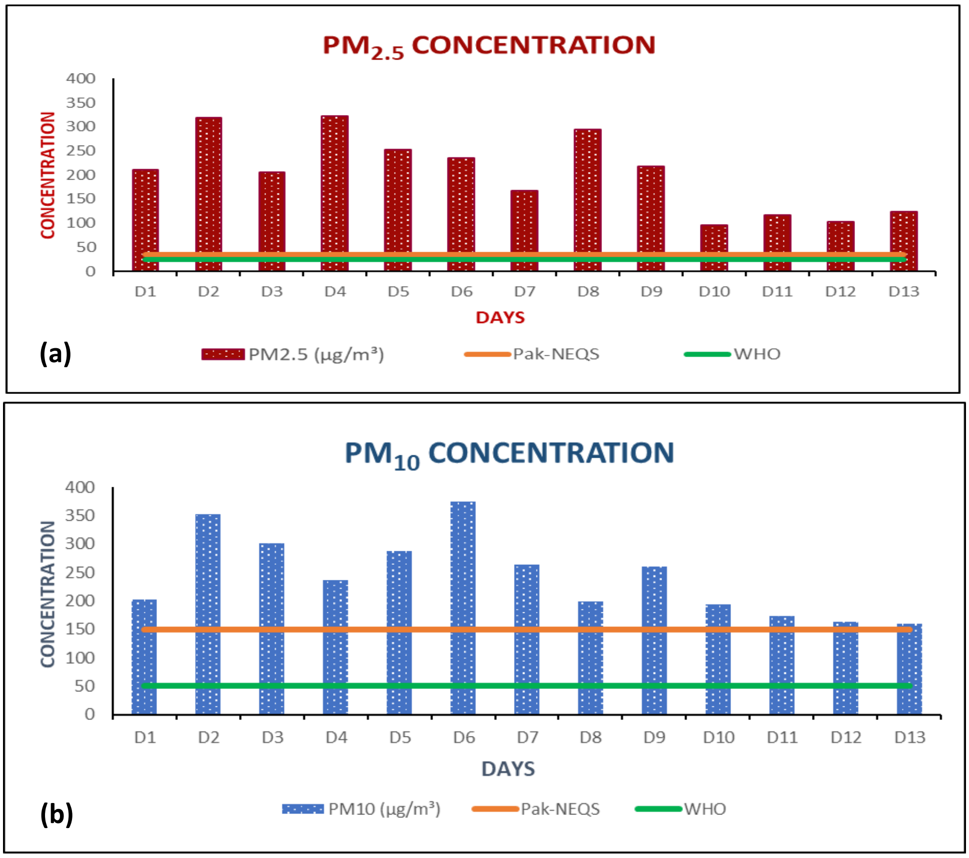


Figure 4.4 (a&b) Average mass concentration (µg/m³) of $PM_{2.5}$ and PM_{10}

Highest concentration recorded for $PM_{2.5}$ during the study period was 323 µg/m³ whereas, the lowest recorded concentration was 97 µg/m³. Similarly, for PM_{10} the highest and lowest recorded concentration was 375 µg/m³ and 159 µg/m³ respectively. The high peaks of PM_{10} and $PM_{2.5}$ observed in December and January is attributed to low temperature inversion layer, winter fog and stagnant atmospheric conditions during winters. Moreover, the higher concentrations can also be caused due to household heating activities, emissions from heavy traffic load on Kashmir highway and other construction activities along the highway during the study period.

4.4. CALCULATION OF AIR QUALITY INDEX (AQI)

AQI is color coded, unitless index developed by EPA which provides information about the air quality and to alert the public about the risk of exposure to daily pollution. AQI is calculated by relating PM mass concentrations to the relevant US-EPA standards (Javed et al., 2014).

The results of the current study showed that AQI for Islamabad during the study period remained between moderate to hazardous. The categorization of air quality with respect to AQI is presented in table 4.2. The AQI for $PM_{2.5}$ remained higher compared to PM_{10} throughout the sampling period. In case of $PM_{2.5}$, December and January were the most polluted months with majority of hazardous and very unhealthy days. On the other hand, AQI for PM_{10} remained comparatively well with a few unhealthy and very unhealthy days in Dec – Feb and moderate to unhealthy levels for sensitive groups in March.

Table 4.2 Categorization of air quality with respect to AQI

DATE	PM 10	AQI (10)	Category
17/12/2019	203	125	Unhealthy for Sensitive Groups
26/12/2019	353	199	Unhealthy
31/12/2019	301	174	Unhealthy
09/01/2020	236	141	Unhealthy for Sensitive Groups
14/01/2020	287	167	Unhealthy
22/01/2020	375	230	Very unhealthy
30/01/2020	264	155	Unhealthy
06/02/2020	198	123	Unhealthy for Sensitive Groups
11/02/2020	260	154	Unhealthy
17/02/2020	94	70	Moderate
25/02/2020	138	93	Unhealthy for Sensitive Groups
03/03/2020	163	105	Unhealthy for Sensitive Groups
11/03/2020	160	103	Unhealthy for Sensitive Groups

DATE	PM 2.5	AQI (2.5)	Category
17/12/2019	211	261	Very unhealthy
26/12/2019	319	369	Hazardous
31/12/2019	206	256	Very unhealthy
09/01/2020	323	373	Hazardous
14/01/2020	253	303	Hazardous
22/01/2020	235	285	Very unhealthy
30/01/2020	167	217	Very unhealthy
06/02/2020	294	344	Hazardous
11/02/2020	218	268	Very unhealthy
17/02/2020	97	172	Unhealthy
25/02/2020	116	167	Very unhealthy
03/03/2020	103	176	Unhealthy
11/03/2020	124	186	Unhealthy

Moreover, AQI for PM_{10} and $PM_{2.5}$ both showed an overall increase in values during Dec-Feb followed by a decrease in end February and March. AQI trend for PM_{10} and $PM_{2.5}$ during sampling period can be seen in figure 4.5.

Biomass combustion for space heating in the suburban areas of Islamabad increases the mass concentration of $PM_{2.5}$ and PM_{10} during winter season. Whereas, lower concentration of $PM_{2.5}$ and PM_{10} in summer than in winter is mainly because of the heavy monsoon rainfall during the months of July and August (Rasheed et al., 2015)(Mehmood et al., 2018).

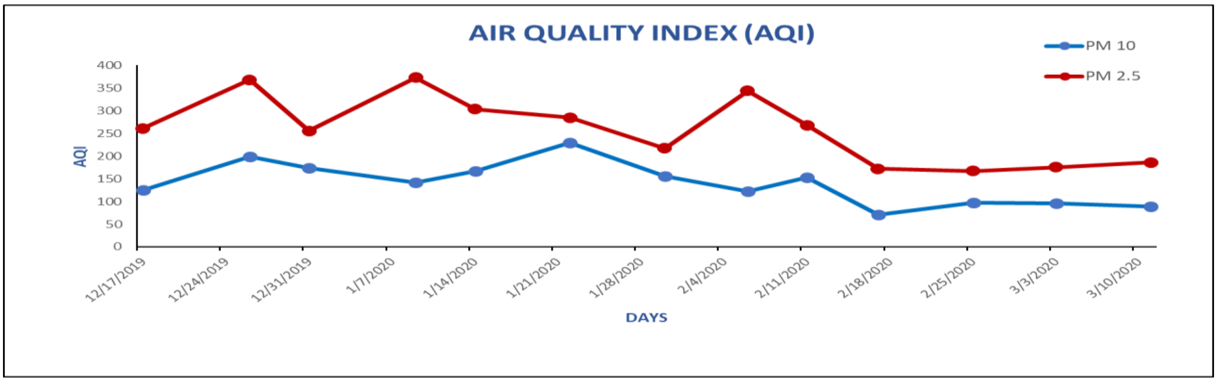


Figure 4.5 AQI trends for $PM_{2.5}$ and PM_{10}

The pie charts in figure 4.6 (a&b) shows the categorization of days with respect to AQI. According to the AQI analysis 43% of the days during PM_{10} monitoring showed unhealthy levels. However, 46% of the total sampling days for $PM_{2.5}$ monitoring showed hazardous levels, which is a cause of concern for the inhabitants of the nearby areas. The higher AQI values in the study area indicate very high levels of air pollution and the greater the danger to human health, hence proper action should be taken to reduce the concentrations of pollutants and thus improving the air quality. Both anthropogenic activities and natural sources contributes to PM pollution. Extensive urbanization, industrialization and vehicular load are found to be the major contributors of high PM levels in the study area.

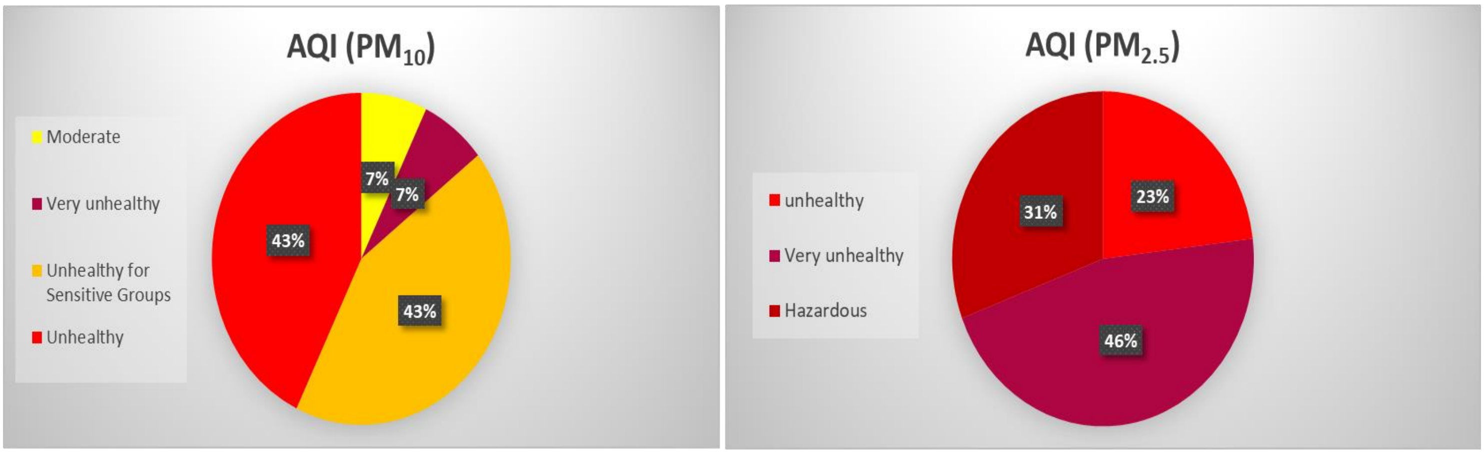


Figure 4.6 Categorization of days with respect to AQI

4.4. HEAT INDEX CALCULATION

Various efforts have been made to quantify the renowned phenomenon known as heat index. According to this, the discomfort that is felt during hot weather depends to a significant degree on the humidity of the air as well as the actual air temperature. The U.S. National Weather Service (NWS) has linked different heat index values to environmental health threats and the NWS uses heat index for its excessive heat warnings and to caution the public (NOAA 2012). The National Weather Service relies on the heat index to let people know how much heat the human body can handle before it becomes dangerous.

Figure 4.7 shows the matrix table of heat index over Islamabad which highlights the severity level of stress during the period 2015-2019. The matrix table was generated using the same formula and color codes as shown in the previous general matrix table proposed by the NOAA National Weather Service.

Heat index of Islamabad during the period of 2015-2019 (figure 4.8) shows an increasing trend towards the end of the April until reaching its first peak in May. The largest spike occurs in June and July and then starts decreasing from September onwards. However, a small dip in July end and August is due to the monsoon period as the air temperature, which is a dominant feature, starts decreasing. The Heat index rise observed in June and July is caused by the increase in air temperature and RH which results in high heat index. This analysis shows how the potential periods for extreme hot events are more likely to take place during the hot and dry season.

Months	January			February			March			April			May			June			July			August			September			October			November			December		
Dekade	D1	D2	D3	D4	D5	D6	D7	D8	D9	D10	D11	D12	D13	D14	D15	D16	D17	D18	D19	D20	D21	D22	D23	D24	D25	D26	D27	D28	D29	D30	D31	D32	D33	D34	D35	D36
2015	73	72	74	73	74	72	69	75	86	77	94	98	102	102	107	107	114	115	118	113	115	125	117	117	111	117	96	112	99	81	74	75	76	73	73	73
2016	72	71	72	75	73	81	81	68	81	84	93	92	107	109	114	117	124	126	129	125	123	119	115	118	118	115	114	110	102	95	87	80	77	78	76	76
2017	74	77	74	73	76	77	77	78	83	88	100	100	109	117	115	108	120	119	120	119	115	114	120	125	116	119	109	107	106	103	89	83	77	77	75	75
2018	75	75	77	78	77	74	76	87	89	87	99	94	104	108	108	112	119	118	128	125	124	122	112	117	108	102	104	111	96	94	84	81	83	75	73	72
2019	73	75	74	75	71	70	76	80	84	86	99	95	91	102	106	117	120	123	132	120	127	117	122	125	110	118	100	99	96	95	85	74	76	75	69	72

Figure 4.7 Matrix Chart of Heat Index of Islamabad during the period of 2015-2019 on dekadal basis

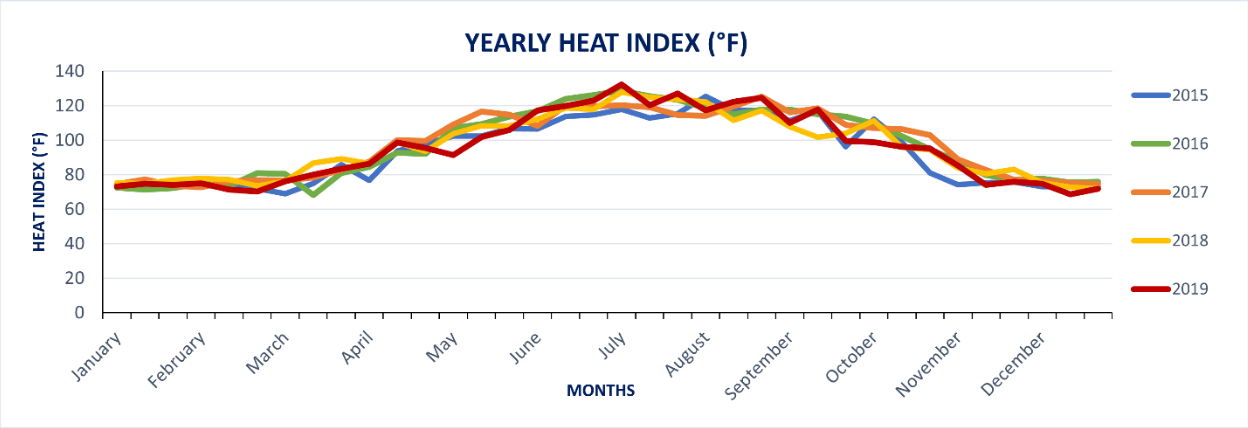


Figure 4.8 Heat Index (HI) of Islamabad during 2015-2019

Pie charts in fig 4.9 shows distribution of days during 2015 -2019 based on heat index matrix table. According to the days count, maximum number of days during 2016 showed high heat index values, thus, posing a severe stress to the people. The rise in heat index during 2016 can be linked to 2015- 2016 EL Niño events. Back in 2016, the country came under severe impact of EL Niño resulting in some unusual and extreme weather events. The severe El Niño of 2015-16 also resulted in marking 2016 as the hottest year on record across the world. Furthermore, the monsoon season was also suppressed by its impact and hence shortened by 30 days (Shahid et al., 2019).

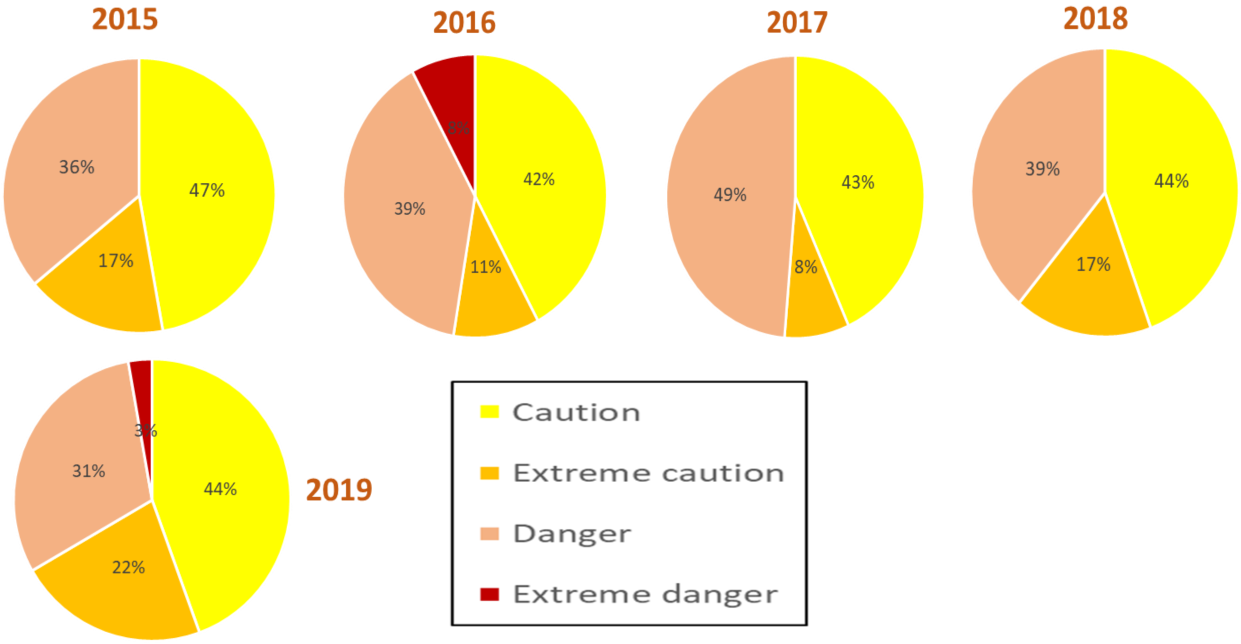


Figure 4.9 Categorization of days with respect to Heat Index

Yearly trends of heat index in Islamabad during 2015-2019 shows that the temperature is lower during the winter months and elevates from late April till July. The maximum surface area temperature along with higher relative humidity is observed during June each year. Monthly data from MODIS derived aerosol optical depth (AOD) for 2015-2019 is also plotted in figure 4.10. Data for each month is plotted in the graph for each respective year. Higher values of AOD are observed in June-August (summer). MODIS AOD started declining after August, which is due to monsoon rains in this month. Yearly trends of AOD are found similar to heat index as shown earlier.

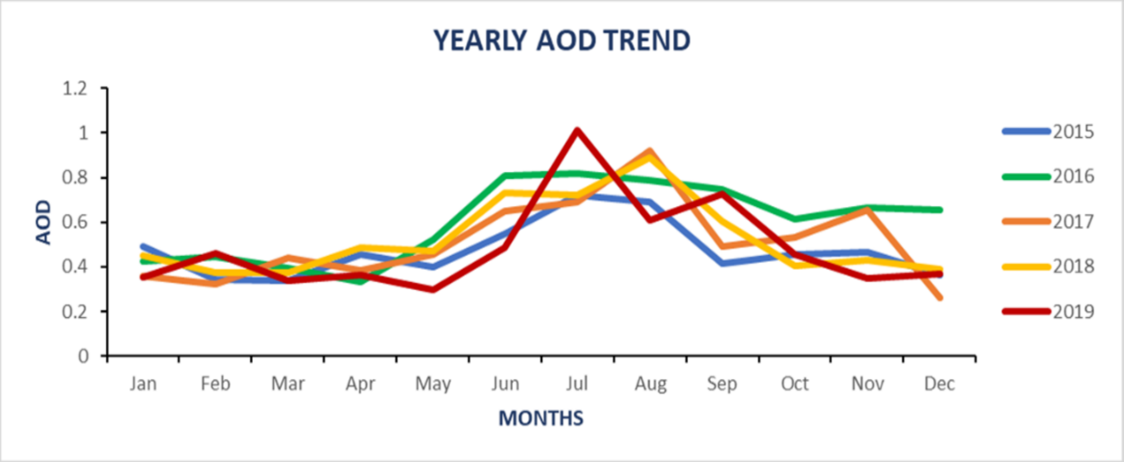


Figure 4.10 AOD over Islamabad during 2015-2019

Figure 4.11 shows a correlation graph plotted for daily values of AOD and HI for 2015-2019. The resultant plot showed a strong correlation between HI and AOD, having a coefficient value of 0.89.

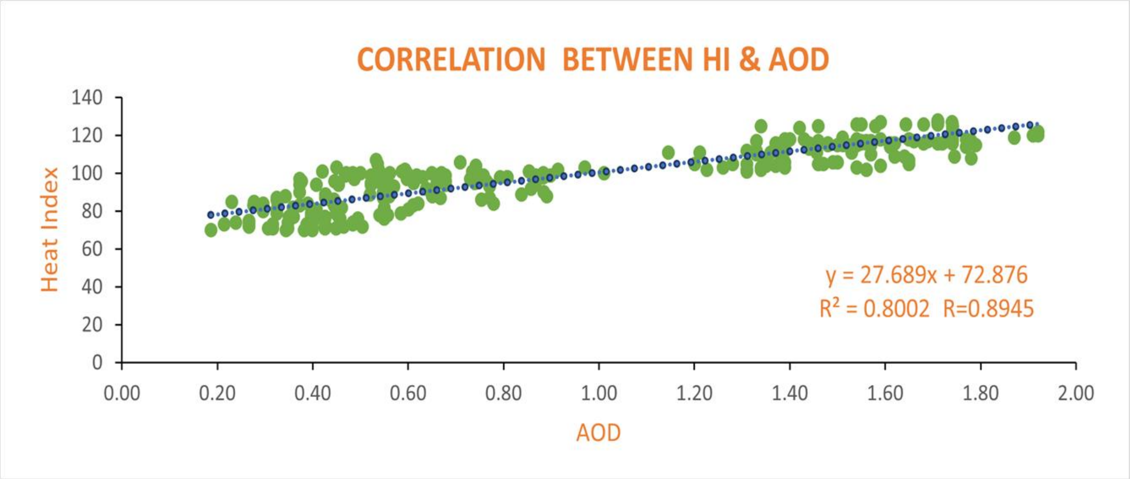


Figure 4.11 Correlation between HI and AOD

Chapter 5

CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusions

Most urban areas in Pakistan are quickly growing because of movement of masses from rural to urban areas, which has resulted in environmental degradation and declining air quality. Many international and government organizations have highlighted the deteriorating air quality issues in significant urban areas of Pakistan. In this study, our aim was to provide an assessment of air quality of Islamabad. Ground-based monitoring of PM in Islamabad revealed higher concentrations of both $PM_{2.5}$ and PM_{10} that frequently exceeded the WHO and Pak-NEQs ambient air guidelines. Calculation of AQI based on PM sampling, showed an increase in AQI values during winter months (December- February). Highest concentration recorded for $PM_{2.5}$ during the study period was 323 $\mu g/m^3$ whereas, the lowest recorded concentration was 97 $\mu g/m^3$. Similarly, for PM_{10} the highest and lowest recorded concentration was 375 $\mu g/m^3$ and 159 $\mu g/m^3$, respectively. Distribution of AOD over study area revealed increasing concentrations during monsoon period, the exponential increase in AOD is attributed to high relative humidity during monsoon which causes hygroscopic growth of atmospheric aerosols. The dominant type of aerosol is medium and strong absorption fine retrieved from MODIS ATL product, which was further confirmed by OMI UVAI combined CO total column data (categorized as smoke and dust). Moreover, the study revealed higher values of HI during summer months and a gradual decrease in HI during winters as the temperature decreases. The Heat index rise observed in June and July is caused by the increase in air temperature and RH which results in high heat index value. The study showed how the potential periods for extreme hot events are more likely to take place during the hot and dry season. A significant relation between MODIS AOD and Heat Index data was also identified as higher AOD values were typically observed during June-August period. Hence, this study highlights the need of a much more comprehensive study to further understand air quality levels and related issues across Pakistan, in particular, urban centers such as Islamabad, Lahore, Karachi, Rawalpindi etc.

5.2. Recommendations

In order to improve the deteriorating air quality condition in the country, 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 Heat Index on wider spatial and temporal scales.
- Air quality monitoring network needs to be established across Pakistan.
- 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.
- This study demands an emphasis on emission reduction policies as well as epidemiological studies to reduce the harmful effect of aerosols on human health.
- Encouraging clean fuel usage and implementing green technologies.
- Afforestation, green belts, and reforestation may help to improve local condition.
- Vehicular load should be decreased by promoting carpooling and electric bikes.
- Strict compliance to PAK NEQS for both industrial and transport sector
- Policies should be made to switch to renewable resources to limit global warming and increasing heat waves.
- Highways and main roads should be constructed away from the residential areas and educational institutes,
- Public should be made aware of the health concerns of air pollution by educating them about the Air Quality Index and also create awareness about Heat Index as well.

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