



**ASSESSMENT OF HEALTH RISK LEVEL ASOCIATED WITH
EXPOSURE TO PARTICULATE MATTER LESS THAN 2.5
MICRONS IN KIGALI, RWANDA.**

by

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College of Science and Technology

School of Science

Master of Atmospheric and Climate Science



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DECLARATION

I, MUHIRE Jean Baptiste with registration number 216100658, a master's student from University of Rwanda in Atmospheric and Climate science, College of Science and Technology (CST), School of Science, Department of Physics.

The undersigned, hereby declare that this thesis entitled “**Assessment of health risk level associated with exposure to particulate matter less than 2.5 microns in Kigali, Rwanda.**” under the supervision of Prof. Bonfils SAFARI and Dr.KWISANGA Christian is my original work and has never been presented or submitted by someone else for any academic award in any university or institution of higher learning, and that any work done by others or by myself previously has been acknowledged and referenced accordingly.

Signed by: MUHIRE Jean Baptiste

Date:.....

CERTIFICATION

This is to certify that the Master’s dissertation entitled “*Assessment of Health Risk Level Associated with Exposure to Particulate Matter Less Than 2.5 Microns in Kigali, Rwanda*” was carried out by Jean Baptiste MUHIRE in partial fulfillment of the requirements for the award of a Master’s Degree in Atmospheric and Climate Science at the University of Rwanda, College of Science and Technology.

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ABSTRACT

Particulate matter, particularly PM_{2.5}, plays a significant role in global air pollution and is a major contributor to serious health issues in both humans and animals. In Rwanda, rapid economic growth in recent years has adversely affected air quality, with PM_{2.5} becoming a key factor influencing urban pollution, particularly in Kigali. As a result, PM_{2.5} pollution has emerged as a critical environmental concern.

This study focuses on mapping PM_{2.5} concentrations in Kigali using nonlinear regression models, with the goal of assessing hourly PM_{2.5} levels, confirming the Air Quality Index (AQI), and identifying areas with high pollution levels over a five-year study period. Remote sensing data, alongside ground-based meteorological measurements, were utilized to estimate PM_{2.5} concentrations across various regions in Kigali. Both nonlinear and linear regression models were applied to predict PM_{2.5} levels and assess the associated health risks.

Although linear regression models are more commonly used, nonlinear models were chosen for their higher correlation with ground-level observations, resulting in more accurate PM_{2.5} concentration estimates. Additionally, the use of MISR AOD data in the nonlinear regressions provided more reliable results compared to MODIS AOD data.

In summary, the nonlinear regression model, which integrates remote sensing and meteorological data, offers a robust method for estimating PM_{2.5} concentrations in Kigali. This approach is crucial for addressing the city's air pollution challenges. The findings revealed that PM_{2.5} pollution is primarily driven by industrial emissions, vehicle exhaust, and agricultural waste. To mitigate the growth of air pollution, strategies such as improving land use planning, enhancing industrial zoning, promoting healthier lifestyles, and expanding the use of renewable energy sources are recommended.

Keywords: PM_{2.5} concentration, Aerosol Optical Depth (AOD), Remote Sensing, MODIS AOD, MISR AOD, Nonlinear Regression, Air Quality Index (AQI), Health Risk, Kigali Air Pollution.

LIST OF ABBREVIATION AND ACRONYMS

AAQS	Ambient Air Quality Standard
AOD	Aerosol Optical Depth
AQCC	Air Quality Control Company
AQCS	Air Quality Controls
AQI	Air Quality Index
GIS	Geographic Information System
NASA	National Aeronautics and Space Administration
HH&E	Human Health and Environment
IC	Institutional Control
MISR	Multi-angle Imaging Spectrometer
PM _{2.5}	Particulate Matter with an aerodynamic diameter of 10 microns or less
MODIS	Moderate Resolution Imaging Spectroradiometer
PBLH	Planetary Boundary Layer Height
PM ₁₀	Particulate Matter with an aerodynamic diameter of 10 microns or less
QA	Quality Assurance
RH	Relative Humidity
PM	Particulate Matter
RL	Risk Level
RM	Regression Model

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CHAPTER 1. GENERAL INTRODUCTION

1.1. Background of the study area.

Rwanda is one Africa nation situated in eastern part of the continent and its capital city is Kigali, it is located in east part of Africa.

Rwanda has covered by hills, forest, rivers, valleys and its great number of citizens are definitely use, fuel, water, solar, charcoal and wood energy in their daily activities which high highly affect environment and air quality as well. This nation is surrounded by countries named as Burundi, Kenya, Tanzania, Uganda and the Democratic Republic of the Congo (DRC), on the side of its coordinates, it is lies at 30°00 Longitude East and 02°00 Latitude South.

Most of Rwanda's regions are in elevation dominated by savanna grassland in the east and highlands in the west and several lakes all over the country, its climate is described by four main seasons in every year namely two dry seasons and rainy seasons.

Weather in this nation is characterized by the normal temperature of 20⁰C temperature and it can vary higher or less depending on daily hours and even the topography. The average ranging of temperatures found in year in this century is (20°C - 30°C) specifically regions around east part get higher temperature compared to other parts all over the nation. The cooler temperatures are mainly found in higher elevation part like Northern or western part, the temperature may even reach around 15⁰C.

Again, Rwanda has Kigali as a capital city where a big number of populations are concentrated by around 1,200,000 inhabitants, this capital has been proved to have a fast population growth ;this raise of population and the coherent increases the rate of motor vehicles which causes destruction of air quality in that city.

Since Kigali is urban area, it is full of different pollutants for instance motorcycles, vehicles, high-usage of mopeds, industries, high usage of stoves but Kigali should not be necessity bound with air pollution in the area of strongest emission that is why topographic and meteorological conditions are reliable in influencing the continuous changing of air quality as well as climate this determines the analysis of the urban temperature and air quality.

So the mentioned issue should need a mathematical modeling of air pollutants in order to evaluate the variation of air pollution air pollution and even facilitate in prediction of future weather.

Residents of Kigali city access to electricity from water energy sources though the greater number of residents use other nonrenewable sources of energy like fuel, gasoline, and so on that use of nonrenewable sources emit harmful gases into atmosphere while on the side of rural areas a greater number of population are still struggling with the use of electricity.

The following map shows a study area of this thesis report which is extracted from Rwanda.

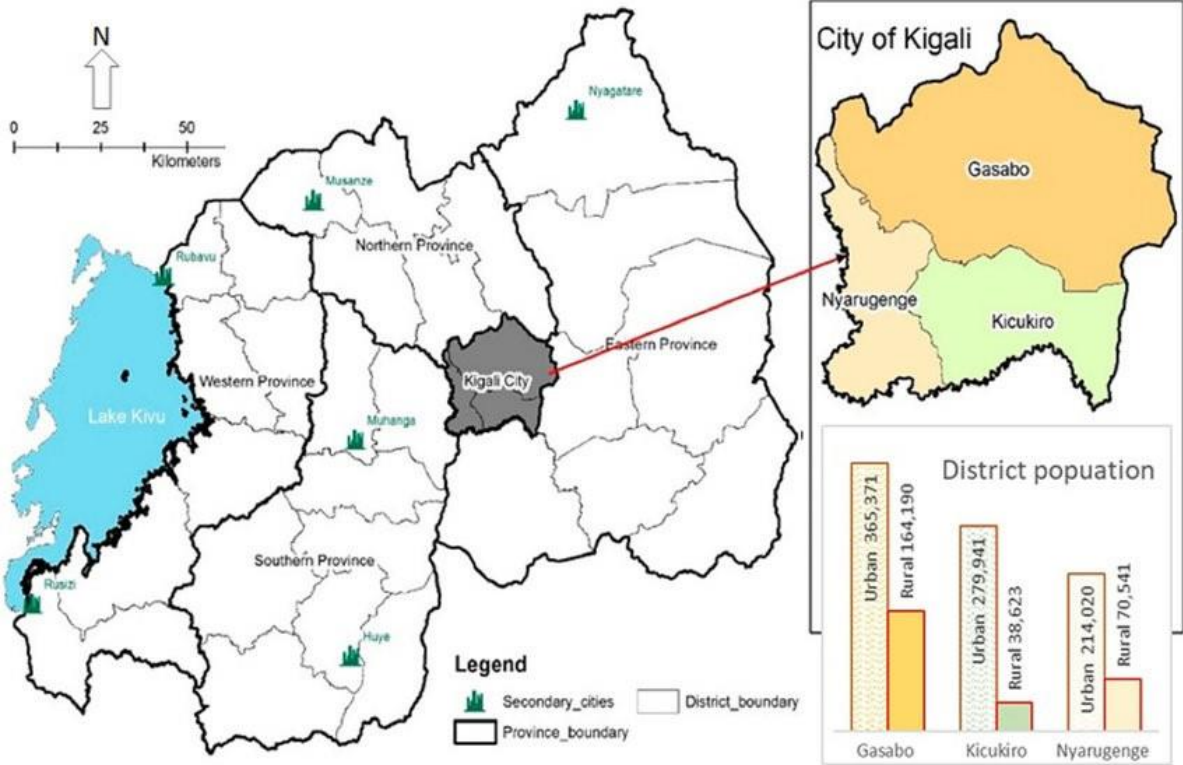


Figure 1:Map of Kigali extracted from map of Rwanda.

In recent decades, Rwanda has been acknowledge to have floods produced by plain heavy rainfall that have destroyed buildings and other properties located in the hilly northern part of nation.

The beginning of heavy rainfall starts and ends in wet and autumn season consequently that growers were confused as to know time to plant and time to harvest. In nowadays the prediction of weather conditions are no longer the problem due to the presence of several meteorological agencies in different regions of the country.

Clarifications given by Rwanda Meteorology Agency (Meteo Rwanda) indicated that within the last 30 years' minimum temperature has increased to three degrees. During a year of 2005 was found to be the warmest among these recent years ago in Rwanda.

Regarding to data recorded the minimum temperature found to be 24.8°C in August and maximum temperature found to be 34.7°C, this recorded temperatures belonged in Capital city, Kigali. In this study area, the report is aimed to assess health risk level in Kigali City based on PM_{2.5} mapping.

1.2.Problem statement

The rapid growth of Kigali's population, coupled with the increasing rate of motorization and industrialization, has led to a significant deterioration of urban air quality (Henninger S. M., 2003). As a result, the exposure to harmful particulate matter (PM_{2.5}, PM₁₀, and PM_{0.1}) in the air has become a major concern for public health. These fine particles, often inhaled through contaminated air, can negatively affect the respiratory system, including the lungs, heart, and brain, contributing to a range of health problems such as chronic respiratory diseases, cardiovascular issues, and premature deaths.

Both short-term and long-term exposure to air pollutants have been linked to an increased risk of mortality and morbidity globally, with urban areas being particularly vulnerable. In Kigali, the rapid economic development, urbanization, and population growth have intensified the concentration of air pollutants, including PM_{2.5}, making air quality an urgent public health issue. Additionally, anthropogenic activities, such as industrial emissions, transportation, and indoor air pollution, contribute significantly to the presence of these harmful particles in the atmosphere.

The presence of PM_{2.5} not only affects human health but also harms vegetation and wildlife, creating a broader environmental concern. These particles, which often carry viruses and bacteria, can lead to the destruction of ecosystems, further compounding the issue.

This study aims to assess the health risks associated with PM_{2.5} exposure in Kigali, with the objective of providing data that can inform government policies and actions to mitigate air pollution. By improving air quality, it is possible to reduce the harmful effects on human health, vegetation, and the environment, ensuring a healthier, more sustainable future for the city.

1.3. Research Objectives

This research aims to achieve one main goal, supported by several specific objectives.

1.3.1. Main Goal

Air pollution, particularly particulate matter (PM), is known to have significant detrimental effects on both human and animal health. The concentration of these fine particles, especially PM_{2.5}, in the atmosphere can lead to a range of health issues, including respiratory diseases, cardiovascular problems, and even premature death. While many pollutants are chemically driven, particulate matter originating from anthropogenic activities also plays a crucial role in deteriorating air quality.

The main goal of this study is to assess the health risk levels associated with PM_{2.5} concentration over Kigali city, with the intention of better understanding the impacts of air pollution on public health.

To achieve this main goal, the following specific objectives will be addressed:

1.3.2. Specific Objectives

To comprehensively assess the health risks of PM_{2.5} exposure, it is essential to analyze various aspects of air quality, including its correlation with human health outcomes. The specific objectives of this research are:

- ✓ **To estimate surface-level PM_{2.5} concentrations in Kigali using meteorological data and Aerosol Optical Depth (AOD):** This objective will involve the integration of ground-based meteorological data and satellite-derived AOD measurements to estimate PM_{2.5} concentrations across different regions of Kigali. The use of these data sources will enable accurate spatial mapping of PM_{2.5} levels, helping to identify areas with the highest exposure.
- ✓ **To compute the Air Quality Index (AQI) for PM_{2.5} levels in Kigali:** The AQI is a critical tool for assessing the quality of air and its potential health impacts. This objective

will focus on computing the AQI for PM2.5 concentrations, providing a standardized measure of air quality in Kigali. By doing so, it will offer a clear understanding of air pollution levels and the associated health risks to the population.

- ✓ **To identify areas with high levels of air contamination in Kigali:** The spatial distribution of PM2.5 concentrations is key to understanding the areas most at risk. This objective will involve mapping and identifying regions in Kigali that experience high levels of air pollution. Such an analysis will allow for targeted interventions in areas where the public health risk is greatest.

1.4.Hypothesis of the Study

The concentration of PM2.5 in various regions of Kigali is influenced by both anthropogenic and natural sources, with traffic emissions, industrial activities, biomass burning, and meteorological factors being the primary contributors. This variation in PM2.5 levels, depending on factors such as time of day, weekdays vs. weekends, and weather conditions, leads to fluctuating health risks for the population.

It is hypothesized that:

- ✓ The highest concentrations of PM2.5 in Kigali are found in regions with high traffic density and industrial activity, particularly during rush hours and weekdays.
- ✓ Areas affected by biomass burning and weather conditions (such as fog or mist) will show significant variations in PM2.5 levels compared to areas primarily impacted by industrial and vehicular emissions.
- ✓ Fluctuations in PM2.5 concentrations throughout the day and week are directly linked to an increase in respiratory and cardiovascular health risks in the affected populations.
- ✓ Implementing effective air quality monitoring and policy measures can reduce PM2.5 levels and, in turn, decrease the health risks associated with long-term exposure to particulate matter in Kigali.

1.5. Scope of the study

This thesis focuses on assessing PM2.5 pollution in Kigali, Rwanda, using a nonlinear regression model to map its concentration across the city. The study will be conducted within Kigali, considering areas with varying urbanization and pollution sources. It will analyze data from 2019 to 2024, focusing on hourly and daily variations in PM2.5 levels, especially during rush hours and weekends. The research will estimate PM2.5 concentrations using remote sensing and meteorological data, with the aim of identifying regions with high and low air quality. Health risks associated with PM2.5 exposure will be assessed through the Air Quality Index (AQI). The study will exclude other pollutants like PM10 and will not address environmental impacts on vegetation. The goal is to identify areas and times with the highest health risks due to air pollution in Kigali.

CHAPTER 2: LITERATURE REVIEW

2.1. GENERAL REVIEW ABOUT AIR POLLUTANTS

In recent years, cities in developing countries, such as Kigali, Rwanda, have been facing significant increases in air pollution levels. This growing concern has resulted not only in physical and psychological health problems for their populations but also in broader environmental issues, such as contributing to climate change. The increase in particulate matter (PM) pollution, particularly PM_{2.5} (particles with a diameter of 2.5 micrometers or smaller), has emerged as a pressing issue, as these fine particles are capable of penetrating deep into the human respiratory system. The health risks associated with PM_{2.5} exposure are extensive, leading to respiratory and cardiovascular diseases, as well as premature mortality (Pop, 2015).

Air pollution in cities like Kigali is primarily driven by both anthropogenic and natural sources. Anthropogenic sources are the dominant contributors, including motor vehicle emissions, industrial activities, biomass burning, and construction activities (Cui et al., 2018). These sources are exacerbated by rapid urbanization, increasing vehicular traffic, and the growth of industrial sectors. In Kigali, the transportation sector, combined with expanding economic activities, has significantly increased PM levels. Although natural sources, such as wildfires and dust storms, can contribute to PM concentrations, their impact is typically less significant than that of human-made sources in urban environments (Gurjar et al., 2016).

The health consequences of long-term exposure to PM_{2.5} are well-documented. Studies have shown a strong link between PM_{2.5} exposure and the development of chronic respiratory diseases, such as asthma and chronic obstructive pulmonary disease (COPD), as well as lung cancer (Chen et al., 2018). Furthermore, PM_{2.5} exposure is associated with an increased risk of cardiovascular diseases like heart attacks and stroke (Pope et al., 2015). Beyond the physical health impacts, air pollution has also been implicated in contributing to mental health issues. Recent studies suggest that long-term exposure to air pollutants, especially fine particulate matter, can lead to anxiety, depression, and cognitive impairments, particularly in urban areas with high pollution levels (Xu et al., 2020).

To address the growing concern of air pollution, particularly PM_{2.5}, it is crucial to monitor and assess pollution levels accurately. In cities like Kigali, where ground-level monitoring infrastructure may be limited, satellite-based measurements, such as Aerosol Optical Depth (AOD), are increasingly used to estimate PM concentrations. These satellite observations, combined with meteorological data such as wind speed, temperature, and humidity, allow for the estimation of PM_{2.5} concentrations in regions where traditional air quality monitoring is sparse (van Donkelaar et al., 2016). By using these methods, researchers can estimate the spatial distribution of PM_{2.5} across different areas of the city and identify regions most at risk.

Nonlinear models, which provide complex estimations based on multiple input variables, have become essential tools for air pollution monitoring and health risk assessments. These models can integrate ground-based measurements, satellite data, and meteorological conditions to predict the concentration of PM_{2.5}. The advantage of using nonlinear models lies in their ability to handle the complexity of the relationship between environmental factors and air pollutant concentrations, making them particularly useful in urban areas like Kigali, where pollution sources and their effects can vary greatly (Zhang et al., 2016).

In addition to the health effects, air pollutants like PM_{2.5} also contribute to broader environmental degradation. These particles can damage vegetation, impair agricultural productivity, and affect local climates. Fine particulate matter can influence cloud formation, precipitation patterns, and the overall radiation balance, which in turn can contribute to climate change (Geng et al., 2017). The environmental impacts of air pollution, particularly from PM_{2.5}, are interconnected with health effects, as they create a cycle where deteriorating ecosystems and altered climate patterns exacerbate the adverse health outcomes associated with air pollution.

Addressing the health risks posed by PM_{2.5} and other air pollutants requires a comprehensive understanding of their sources, distribution, and the health outcomes associated with exposure. In cities like Kigali, where the effects of rapid urbanization and economic development are leading to increasing levels of air pollution, understanding these dynamics is essential. By integrating satellite data, meteorological information, and advanced modeling techniques, it is possible to create effective strategies to mitigate air pollution and its associated health risks. As the research continues to evolve, these insights will be crucial for informing urban planning decisions,

improving air quality policies, and protecting public health in rapidly growing cities across the world (Zhang et al., 2016).

2.2. INTRODUCTION TO AIR POLLUTANTS

Air pollution, particularly particulate matter (PM), is one of the most pressing environmental concerns of the current decade. PM is typically classified into three categories based on particle size: PM₁₀, PM_{2.5}, and PM_{0.1}, with PM_{2.5} being the most dangerous due to its ability to penetrate deep into the lungs and even enter the bloodstream. These fine particles are primarily a result of anthropogenic activities, and their growing levels are of particular concern in rapidly developing countries like Rwanda (Sanja Grgurić & Josip Križan, 2013).

PM_{2.5} particles, whose diameters are equal to or less than 2.5 μm, are a significant environmental hazard due to their adverse effects on human health. Exposure to these particles has been linked to respiratory problems, cardiovascular diseases, and even premature death (Sfetsos, 2010). Additionally, long-term exposure to PM_{2.5} increases the risk of developing various forms of cancer, especially lung cancer. Vulnerable populations, including children under five, adults, and individuals with pre-existing chronic diseases, are at the highest risk of these harmful health effects (Hillier, 2013).

In developing countries, particularly in cities like Kigali, indoor air pollution also poses a serious threat. The reliance on solid fuels for cooking, heating, and lighting contributes significantly to the rise in air pollutant levels. While outdoor air pollution is often the primary concern in urban environments, indoor air pollution can lead to severe respiratory diseases and premature death (Hillier, 2013). The World Health Organization (WHO) estimates that 1.3 million deaths occur annually due to outdoor air pollution, a large proportion of which is caused by fine particulate matter (WHO, 2018).

Air quality monitoring typically relies on ground-based measurements taken from established monitoring stations. However, these stations are limited by their spatial coverage, often unable to provide sufficient data across wide urban areas or regions without monitoring infrastructure (S Grgurić, 2013). To address this issue, satellite-based data has become a critical tool for estimating PM_{2.5} concentrations. Satellite measurements, especially Aerosol Optical Depth (AOD), provide

a global perspective on air quality, which is crucial for understanding the spatial distribution of particulate matter over large areas (Guo et al., 2014).

Despite the advantages of remote sensing, the accuracy of satellite-based data is often lower than that of ground-based measurements. However, combining satellite data with meteorological parameters, such as temperature, wind speed, and relative humidity (RH), allows researchers to improve the estimation of PM_{2.5} concentrations. Nonlinear regression models are particularly useful in this context, as they account for the complex, non-linear relationships between meteorological factors and PM concentrations (Gupta, 2009). These models are capable of capturing the spatial and temporal variability of air pollution in ways that linear models cannot.

In the context of Kigali, the primary sources of PM_{2.5} include vehicle emissions, biomass burning, and industrial activities. These pollutants not only contribute to health risks but also exacerbate environmental degradation, impacting ecosystems, agriculture, and contributing to climate change. Therefore, understanding the distribution of PM_{2.5} and its health impacts is essential for improving air quality and public health.

The aim of this research is to assess the health risks associated with PM_{2.5} exposure in Kigali by using a nonlinear regression model to predict PM concentrations based on satellite data and meteorological factors. The model incorporates variables such as temperature, wind speed, wind direction, relative humidity, and AOD, which collectively influence PM levels in the atmosphere. This approach allows for a more accurate prediction of PM_{2.5} concentrations, which is critical for policy-making and public health interventions aimed at reducing air pollution and mitigating its effects.

The nonlinear regression model proposed in this study is based on the general form of equations used by Liu et al. (2005). The model provides a mathematical representation of the relationship between the independent variables and PM_{2.5} concentration, offering a powerful tool for understanding air pollution dynamics in Kigali. By integrating satellite-based AOD data with ground-based meteorological observations, the model can estimate PM_{2.5} concentrations at locations where direct measurements are not available.

In conclusion, this study seeks to enhance the understanding of air pollution patterns in Kigali and improve the accuracy of health risk assessments related to PM_{2.5} exposure. The findings will provide valuable insights for policymakers in developing strategies to reduce air pollution, improve air quality, and protect public health in rapidly growing urban environments.

2.3. AIR POLLUTANTS AND PARTICULATE MATTER CLASSIFICATION

2.4.1 AIR POLLUTANTS AND ITS CAUSES

Air pollution is the contamination of the indoor or outdoor environment by various chemical, physical, or biological agents that alter the natural characteristics of the atmosphere (Gilbert, 2013). This definition underscores the idea that the degradation of air quality occurs when pollutants are present in the atmosphere, leading to significant health and environmental consequences. Air pollutants can exist in many forms—gaseous, particulate, or biological—and they interact in complex ways, contributing to both short-term and long-term health risks for humans, animals, and ecosystems.

The most commonly recognized air pollutants include carbon dioxide (CO₂), nitrogen oxides (NO_x), particulate matter (PM₁₀, PM_{2.5}, and PM_{0.1}), ammonia (NH₃), ozone (O₃), carbon monoxide (CO), and sulfur dioxide (SO₂). Each of these pollutants has distinct sources, chemical properties, and impacts on air quality. Particulate matter, for instance, is classified based on its size and can be divided into PM₁₀ (particles with a diameter of 10 micrometers or less), PM_{2.5} (particles with a diameter of 2.5 micrometers or less), and PM_{0.1} (ultrafine particles). These fine particles are especially dangerous as they can be inhaled deep into the lungs, causing respiratory and cardiovascular diseases, and even leading to premature death (WHO, 2018).

The primary sources of air pollution can be broadly categorized into anthropogenic (human-made) and natural sources. The anthropogenic sources are the leading contributors to the rising levels of air pollution, particularly in urban areas. Activities such as transportation, industrial emissions, agriculture, and power generation are significant contributors to the contamination of the atmosphere. For example, vehicles release large amounts of nitrogen oxides (NO_x) and carbon monoxide (CO) into the air, while industrial facilities and power plants emit sulfur dioxide (SO₂) and carbon dioxide (CO₂), which contribute not only to local pollution but also to global climate

change. Agricultural activities, including crop burning and the use of fertilizers, release ammonia (NH_3) and other pollutants into the air, affecting both air quality and soil health (Sanchez et al., 2016).

In addition to anthropogenic sources, there are natural sources of air pollution that also play a role in the contamination of the atmosphere. Volcanic eruptions, for example, release large amounts of sulfur dioxide (SO_2) and ash into the atmosphere, which can travel long distances, affecting air quality and visibility. Dust storms, particularly in arid regions, can carry dust particles over vast distances, contributing to increased levels of particulate matter in the air. Even the biological processes of living organisms, such as the emission of methane (CH_4) by animals and the decay of organic matter, can contribute to air pollution (Tian et al., 2019).

While both anthropogenic and natural sources are responsible for the introduction of pollutants into the atmosphere, the relative contribution of each depends largely on the geographic location and specific environmental conditions. In urbanized areas, anthropogenic sources are typically the primary contributors to air pollution, whereas in rural or semi-arid regions, natural sources like dust storms or wildfires may dominate. In developing countries like Rwanda, rapid urbanization and economic growth, along with an increase in industrial activity and vehicular traffic, have exacerbated air pollution levels, particularly in capital cities like Kigali. These cities often face poor air quality, largely due to rising motor vehicle emissions, industrial discharges, and biomass burning for cooking and heating (Hillier, 2013).

It is essential to understand the sources of air pollutants and their contributions to atmospheric degradation because this knowledge directly informs policies and interventions aimed at mitigating pollution. Accurate air quality monitoring and predictive models, such as regression models, are critical tools for assessing air quality and informing decision-making to improve public health and environmental sustainability. These models help estimate $\text{PM}_{2.5}$ concentrations and other pollutants using data from a variety of sources, including satellite measurements and meteorological observations. By accurately predicting air pollution levels, policymakers can implement effective strategies to reduce emissions, protect vulnerable populations, and improve overall air quality.

2.4.2 PARTICULATE MATTER CLASSIFICATION

All over the world due to different natural phenomena and due to different human activities such as industrialization, urbanization, mining and all other activities that involve combustion, there is the problem of air pollution especially particulate matter.

Particulate matter is a combination of solid particles, liquid droplets and other particles such as soot, or smoke found in air.

Particulate matter are obtained from different sources such as industrial sites, construction sites, unpaved roads, combustion, automobiles and from power plants. This makes some of them visible with our naked eyes such as smokes, dusts and soot and others not visible.

Particulate matter according to the fact that it is not a single pollutants, but a mixture of many chemicals, such as solid and aerosols, and according to their diameter for air quality regulatory purposes, they are classified into three main categories namely PM_{10} , $PM_{2.5}$ and $PM_{0.1}$. Detailed information is discussed below:

- PM_{10} the particulate matter of diameter less than or equal to 10 micrometers: these are rough or coarse particles consisting of large particles and their combination can be visible. They include dust, smoke, soot etc. They cause respiratory problems as they are called inhalable particles.

- $PM_{2.5}$ the particulate matter of diameter not more than 2.5 micrometers: are fine particles and they can enter our blood stream problems and they can lead to cardiovascular problems and can lead to lung diseases and neurological diseases.

- $PM_{0.1}$ the particulate matter of diameter less than or equal to 0.1 micrometers: are the ultrafine particles and they have the same source as $PM_{2.5}$. They come from power plant emissions, wildfires, vehicle exhausts and other combustion activities.

Sometimes we may consider $PM_{2.5}$ and $PM_{0.1}$ as the particulate matter of diameter less than 10 micrometers because their diameters are less than 10 micrometers.

2.5. HEALTH EFFECTS AND REGULATIONS OF PARTICULATE MATTER

2.5.1. Health Effects of Particulate Matter

Particulate matter (PM) has significant health implications, impacting both short-term and long-term health outcomes. PM is categorized based on its size, with PM10 and PM2.5 being the most commonly studied due to their ability to penetrate the respiratory system.

Short-Term Health Effects: Exposure to elevated levels of PM can cause acute respiratory issues, such as asthma attacks, bronchitis, and other respiratory infections. Symptoms can manifest within hours or days of exposure, leading to increased hospital visits and emergency room admissions, particularly among vulnerable populations like children and the elderly.

Long-Term Health Effects: Prolonged exposure to PM is associated with chronic health conditions, including cardiovascular diseases, lung cancer, and reduced lung function. Studies have shown that individuals living in areas with high PM concentrations are at a greater risk of developing these conditions. The World Health Organization (WHO) estimates that millions of premature deaths annually are linked to air pollution, with a significant portion attributed to PM exposure.

Vulnerable Populations: Certain groups are particularly susceptible to the adverse health effects of PM. Children, due to their developing respiratory systems, are at higher risk for developmental issues. The elderly often have pre-existing health conditions that can be exacerbated by PM exposure. Additionally, individuals with chronic diseases, such as asthma or heart disease, are more likely to experience severe health impacts from particulate matter.

2.5.2. Regulatory Framework

Recognizing the health risks associated with particulate matter, governments and international organizations have established regulations and guidelines aimed at reducing PM exposure and improving air quality.

National Regulations: In the United States, the Environmental Protection Agency (EPA) is responsible for setting air quality standards under the Clean Air Act. The National Ambient Air Quality Standards (NAAQS) for PM2.5 and PM10 were established to protect public health.

The EPA periodically reviews these standards based on new scientific evidence, ensuring they remain relevant to current health knowledge.

International Guidelines: The WHO has also developed air quality guidelines that recommend maximum levels for PM exposure. These guidelines are intended to inform policy decisions and help countries establish their own regulations to protect public health. The WHO guidelines suggest that annual mean concentrations of PM_{2.5} should not exceed 5 µg/m³, while the guideline for PM₁₀ is set at 15 µg/m³.

Impact of Regulations: Regulatory measures have shown positive effects on public health. For instance, since the implementation of stricter emissions standards in the U.S. and Europe, significant reductions in PM levels have been observed. This has led to improved air quality and associated health benefits, including decreases in hospital admissions and respiratory-related deaths.

Challenges and Future Directions: Despite progress, challenges remain in effectively regulating particulate matter, especially in rapidly urbanizing regions and developing countries. Factors such as industrial emissions, vehicle exhaust, and indoor air pollution continue to contribute to PM levels. Moreover, the complexity of PM composition complicates regulatory efforts, as different sources and types of PM can have varying health effects.

To enhance regulatory frameworks, continuous monitoring and research are essential. Advancements in technology can aid in better understanding PM sources and health impacts, allowing for more targeted and effective policies. Additionally, public awareness campaigns can educate communities about the risks of PM exposure and encourage practices that contribute to better air quality.

2.6. MODIS DESCRIPTION

In the modern era, technological advancements have significantly altered our perception of various Earth phenomena. One such development is the ability to monitor and analyze land surfaces, cloud cover, the oceans, and the lower atmosphere with unprecedented detail. The Moderate Resolution Imaging Spectrometer (MODIS), a key satellite-based sensor, has played a crucial role in enabling this transformation by providing comprehensive observations of Earth's dynamic systems.

MODIS is an essential tool for understanding global processes, including cloud dynamics, sea and oceanic phenomena, radiation budgets, and atmospheric conditions. This instrument, developed by Santa Barbara Remote Sensing, is equipped with 36 spectral bands that cover a wide range of wavelengths from 0.4 micrometers to 14.4 micrometers (NASA, 2020). These bands allow MODIS to capture detailed information about Earth's surface and atmosphere. MODIS has varying spatial resolutions, with two bands at 250 meters, five bands at 500 meters, and 29 bands at 1 kilometer (NASA, 2020). Furthermore, it has the capability to provide global images every 1 to 2 days, offering frequent and consistent data for various environmental studies.

Launched in 1999, the Terra (EOS AM) satellite, and the Aqua (EOS PM) satellite, launched in 2002, both carry MODIS instruments. These satellites orbit Earth and enable continuous monitoring of environmental processes. One of MODIS' most significant advantages is its ability to observe and track global dynamics, including shifts in land cover, atmospheric conditions, and ocean currents. This makes it a vital tool in climate monitoring, disaster management, and environmental research (Snyder et al., 2014).

However, despite its advantages, MODIS has some limitations. A primary constraint is its reduced effectiveness in observing snow and ice-covered regions. MODIS is capable of monitoring ice at a spatial resolution of 1 kilometer and snow cover at 500 meters (Dozier, 2017). Furthermore, the instrument's performance diminishes in the presence of cloud cover, as clouds obstruct its ability to capture accurate surface measurements. These limitations led to the development of the Visible Infrared Imaging Radiometer Suite (VIIRS), which was launched in 2011 aboard the Suomi National Polar-orbiting Partnership (NPP) satellite. Unlike MODIS, VIIRS has 22 spectral bands and improved capabilities, particularly in observing sea ice at 750 meters and 375 meters resolution (Dozier, 2017).

To ensure the quality and accuracy of MODIS data, the MODIS Characterization Support Team (MCST) is responsible for the calibration, validation, and analysis of the instrument's outputs. Their work guarantees that the data provided by MODIS is reliable for environmental monitoring, climate studies, and policy development (NASA, 2020).

2.7. MODIS OBSERVATION

The observation data used in this study were obtained from the Moderate Resolution Imaging Spectroradiometer (MODIS) instruments aboard two satellites: *Terra* and *Aqua*. These satellites provided valuable aerosol data for the city of Kigali, covering the period from June 2018 to November 2022.

Specifically, the MODIS datasets utilized include the MOD04 product from the *Terra* satellite and the MYD04 product from the *Aqua* satellite, both from Collection 051. These datasets are designed to provide Aerosol Optical Depth (AOD) at a wavelength of 550 nm (AOD550) with a spatial resolution of approximately 10 km × 10 km at nadir. AOD550 is a crucial parameter for assessing aerosol concentrations in the atmosphere, which is important for understanding air quality, climate processes, and their impacts on public health and the environment (Remer et al., 2005; Levy et al., 2013).

The two satellites, *Terra* and *Aqua*, have different overpass times over the equator. The *Terra* satellite typically passes over the equator around 10:30 local solar time (LST), while the *Aqua* satellite has its overpass time around 13:30 LST. These equatorial overpass times, as reported by Guo et al. (2014), are important for understanding the temporal distribution of the data and any potential diurnal variations in aerosol concentrations. Such variations are critical in assessing the overall aerosol load and its daily fluctuations.

For the purposes of this thesis, the aerosol data from MODIS were collected and processed to cover the entire study period. To prepare the data, a Python computer program was developed to execute the necessary algorithms for extracting the required aerosol information. The program was designed to handle large datasets efficiently and process them according to the specifications of the study. The implementation of these algorithms ensured that the resulting data were accurate, robust, and suitable for analysis.

By leveraging MODIS aerosol data from both *Terra* and *Aqua*, this research provides a comprehensive view of aerosol dynamics in Kigali city over the specified time frame. The careful processing and handling of the data ensure that the study is based on high-quality, reliable

information, facilitating a thorough investigation into the atmospheric conditions of the region and their implications for air quality and climate modeling.

CHAPTER3. METHODOLOGY

3.1. DATA COLLECTION

This thesis relies on data from the period 2018 to 2022, divided into three key categories: meteorological data, satellite-based weather observations, and air quality data. Each category contributes valuable insights into the environmental conditions and air quality in Kigali, Rwanda.

Meteorological Data: The meteorological data were sourced from MeteoRwanda, the national service responsible for weather monitoring in Rwanda. The dataset includes daily time-series records of key atmospheric parameters: wind direction, wind speed, air temperature, and relative humidity. Wind direction and speed are essential for understanding the dispersion of pollutants and aerosols, while air temperature influences atmospheric chemistry and the formation of secondary pollutants. Relative humidity is also important for aerosol formation and cloud dynamics, influencing the overall atmospheric stability and pollution processes.

Satellite-Based Weather Observations: Data on Aerosol Optical Depth (AOD) and Planetary Boundary Layer (PBL) Height were collected from the Moderate Resolution Imaging Spectroradiometer (MODIS) on NASA's *Terra* and *Aqua* satellites. AOD measures aerosol concentrations in the atmosphere, which helps assess aerosol pollution's impact on air quality and visibility. PBL height indicates the altitude at which the atmosphere becomes unstable, affecting the vertical dispersion of pollutants. These satellite-derived datasets are crucial for understanding regional aerosol dynamics and pollutant transport, complementing ground-based measurements.

Air Quality Data: Air quality data were obtained from the Rwanda Environmental Management Authority (REMA), responsible for monitoring air quality across the country. This data includes measurements of key pollutants, including particulate matter (PM_{2.5} and PM₁₀), carbon monoxide (CO), sulfur dioxide (SO₂), ammonia (NH₃), ozone (O₃), and nitrogen oxides (NO_x). PM_{2.5} and PM₁₀ are critical indicators of air pollution, with potential health impacts. CO and SO₂ are harmful gases, contributing to air pollution and environmental damage. NH₃ plays a role in particulate matter formation, while O₃ and NO_x are key components of ground-level smog and contribute to respiratory problems.

By categorizing the data into meteorological, satellite, and air quality datasets, this study provides a comprehensive view of atmospheric conditions in Kigali. The combination of ground-based and satellite data enables a detailed analysis of aerosol and air pollution dynamics, helping to better understand the factors influencing air quality in the region.

3.2. DATA EXTRACTION AND PROCESSING

This project relies on long-term, homogeneous climate data to ensure consistency in analyzing climate change impacts. Abrupt changes observed in a homogeneous climate time series are typically caused by variations in weather and climate conditions rather than other factors (Safari, 2012). For this study, several key datasets were collected, extracted, and processed to model air quality and aerosol dynamics in Kigali, Rwanda, over the period from 2018 to 2022. The PM_{2.5} concentrations were obtained from multiple monitoring stations across Kigali, including Gikomero, Jali, Rusororo, Kimironko, and Gacuriro, managed by the Rwanda Environment Management Authority (REMA). These datasets were extracted from REMA's database, and the data for each station were processed to validate both linear and non-linear models of PM_{2.5} variations over time. The extraction process involved retrieving time-series data, which were then cleaned and filtered to address missing values or any inconsistencies. This dataset provided valuable insights into local air quality patterns and how PM_{2.5} concentrations fluctuate across different areas of Kigali.

For the aerosol data, Aerosol Optical Depth (AOD) values were collected from two remote sensing instruments: MODIS (Moderate Resolution Imaging Spectroradiometer) and MISR (Multi-angle Imaging Spectroradiometer). MODIS AOD data were extracted from NASA's Earth Observing System Data and Information System (EOSDIS), while MISR AOD data were sourced from NASA's Atmospheric Science Data Center. These datasets were crucial in understanding aerosol concentrations in the atmosphere and their role in air quality and climate change. After extraction, the data were processed using Python scripts, where any gaps or outliers were identified and corrected through interpolation and data validation methods.

The Relative Humidity (RH) data, along with PM_{2.5} concentrations, were collected from the various monitoring stations over the course of the study period. These datasets were processed using a combination of Python and Excel programs to prepare the data for analysis. The time-series data were first extracted, cleaned, and imputed where necessary to fill missing values. The cleaned datasets were then analyzed to explore the relationship between aerosol concentrations (PM_{2.5}) and meteorological conditions, particularly RH, which can influence aerosol formation and dispersion.

Both the PM and RH data collected at the various stations over the study period were organized and processed using Python and Excel programs. These tools were essential for preparing the data for statistical analysis and for the modeling of aerosol dynamics in Kigali. Python was used to automate data cleaning, processing, and visualization, while Excel was employed for detailed calculations and model validation.

The data extraction and processing steps ensured that all datasets were homogenous, reliable, and ready for use in model validation. By integrating ground-based and satellite data with sophisticated computational tools, this study provides a comprehensive analysis of the air quality and aerosol dynamics in Kigali.

3.3. AIR QUALITY INDEX SCALE

The Air Quality Index (AQI) is a standardized system used to record and communicate daily air quality levels. It indicates how clean or polluted the air is in a specific location and highlights the potential health effects associated with that level of pollution.

The AQI scale helps the public understand the immediate health risks of air pollution, particularly for sensitive groups such as children, the elderly, and individuals with respiratory or heart conditions.

The table below presents the AQI scale, as provided by the U.S. Environmental Protection Agency (US-EPA), which includes AQI values, the level of air pollution, corresponding colors, health implications, and recommended precautions:

Table 1: A table showing AQI, Color, Level of Air Pollution, Health Implications and precaution.

AQI	Level of Air Pollution	Health Implications	precaution
0 - 50	Good	Air quality is considered satisfactory, and air pollution poses little or no risk	None
51 - 100	Moderate	Air quality is acceptable; however, for some pollutants there may be a moderate health concern for a very small number of people who are unusually sensitive to air pollution.	Active children and adults, and people with respiratory disease, such as asthma, should limit prolonged outdoor exertion.
101- 150	Unhealthy for Sensitive Groups	Members of sensitive groups may experience health effects. The general public is not likely to be affected.	Active children and adults, and people with respiratory disease, such as asthma, should limit prolonged outdoor exertion.
151- 200	Unhealthy	Everyone may begin to experience health effects; members of sensitive groups may experience more serious health effects	Active children and adults, and people with respiratory disease, such as asthma, should avoid prolonged outdoor exertion; everyone else, especially children, should limit prolonged outdoor exertion

AQI	Level of Air Pollution	Health Implications	precaution
201-300	Very Unhealthy	Health warnings of emergency conditions. The entire population is more likely to be affected.	Active children and adults, and people with respiratory disease, such as asthma, should avoid all outdoor exertion; everyone else, especially children, should limit outdoor exertion.
300+	Hazardous	Health alert: everyone may experience more serious health effects	Everyone should avoid all outdoor exertion

For the air pollutants data taken from Kigali city, the following table is representing average air pollutants concentrations within the period of 2018 to 2022.

Table 2: Table showing average concentration of air pollutants within the period of 2018 to 2022.

Parameter	PM ₁₀ (micrograms per cubic meter) taken in 24hrs	PM _{2.5} (micrograms per cubic meter) taken in 24hrs	NO ₂ (micrograms per cubic meter) taken in 24hrs	SO ₂ (micrograms per cubic meter) taken in 24hrs	CO(milligrams per cubic meter) taken in 8hrs	O ₃ (micrograms per cubic meter) taken in 8hrs	NH ₃ (micrograms per cubic meter) taken in 24hrs

				24h rs			24hr s
Average observed concentration values	52.712714 32	43.333 29	12.34383	52.7 127 143 2	288.189 6	19.9 5292	65

Meanwhile the Air Quality Index needs to be specific for those mentioned air pollutants, to find their individuals values we need to them by calculating Air Quality Index for each one of the pollutants (PM_{2.5}, PM₁₀, SO₂, NO₂, CO, NH₃ and O₃).

Because we are dealing with concentrations of PM_{2.5} air quality during the mentioned study period. Therefore, we will calculated by using the following equation.

$$\text{Air Quality Index (AQI) for PM}_{2.5} = \frac{(C_{obs} - C_{min})(I_{max} - I_{min})}{(C_{max} - C_{min})} + I_{min}$$

The table below containing parameters of air pollutants measured in microgram per cubic meter except the mentioned otherwise and their observed concentrations in Kigali so as to help us computing a value of AQI.

Table 3 Table showing list of air pollutants measured in micrograms per cubic meter except the stated otherwise and their observed concentrations

parameters measured in microgram per cubic meter	Average Observed concentrat	Index minim	Index maxim	Concentrat ion min (C _{min})	Concentrat ion
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except the mentioned otherwise		ion values (C _{obs})	um (I _{min})	um (I _{max})		maximum (C _{max})
PM ₁₀	24hrs	52.7	50	400	21.7	302.1
PM _{2.5}	24hrs	65.3	50	350	17.3	275.5
NO ₂	24hrs	12.3	100	150	3.6	53.0
SO ₂	24hrs	12.0	0	50	0	46.6
CO(mg/m ³)	8hrs	88.1	50	200	17	200
O ₃	8hrs	19.9	0	100	8.0	57.3
NH ₃	24hrs	65	0	250	0	200

By applying this equation of Air Quality Index (AQI) for PM_{2.5} = $\frac{(C_{obs}-C_{min})(I_{max}-I_{min})}{(C_{max}-C_{min})} + I_{min}$

The result value of Air Quality Index specifically for PM_{2.5} is 105.7; this value represents Air Pollution Level of Unhealthy for Sensitive Groups like Active children, adults, and people with respiratory diseases however to find air quality index of air in areas of Kigali it is essential to note that all pollutants must be considered so as to facilitate in health purposes.

3.4. REGRESSION ANALYSIS

The primary step within the modeling process is to decide the model structure to predict $PM_{2.5}$ concentrations as the subordinate variable. Various regression models were created, and compared in this research to assess the $PM_{2.5}$ concentration utilizing the satellite-measured data.

These models were made by joining the meteorological parameters as well as AOD data. Most of past studies centered on the single-variable linear regression between $PM_{2.5}$ concentrations and AOD data measured by distinctive satellite sensors.

The linear regression model was utilized as the primary step in this research to examine the direct relationship between AOD and $PM_{2.5}$, and evaluate the plausibility of utilizing AOD parameters to create more complex models.

A linear regression model to predict $PM_{2.5}$ is given by

$$[PM_{2.5}] = a + b (AOD) \quad (2)$$

Where a and b are constants gotten from mean values of particulate matter less than 2.5 micrometer and Aerosol data (AOD).

3.4.1 Comparison of actual $PM_{2.5}$ concentration from surface measurements and predicted values from equation1 and equation2.

Depending on the average monthly aerosol optical depth data obtained from the Moderate Resolution Imaging Spectroradiometer (MODIS) on account of NASA that gives terra data.

The values of particulate matter less than 2.5 microns predicted from that linear equation show a good relation between satellite-derived $PM_{2.5}$ and surface $PM_{2.5}$.

The table below shows a statistics of $PM_{2.5}$ concentration predicted by that mentioned linear model with regarding to different seasons of year.

Table 4: The table showing a statistics of PM_{2.5} concentration predicted by that mentioned linear model with regarding to different seasons of year.

season	Equation	Value of a	Value of b	Correlation coefficient r	Root mean square error
Spring	1	0.6	2.1	0.70	17.8
Summer	1	0.8	-3.2	0.65	32.3
Autumn	1	1.2	-1.6	0.73	14.5

On behalf of this root mean square error (RMSE) which is ranging between 14.5 to 32.3, this range value explains the difference between the statistical equation's predicted PM values and actual values of PM concentration.

3.5 THE RELATIONSHIP BETWEEN RELATIVE HUMIDITY AND HYGROSCOPIC GROWTH FACTOR

The aerosol hygroscopic growth factor, $f(RH)$, defines the growth of the aerosol extinction cross-section or scattering coefficient with RH, aerosol hygroscopic growth depends on relative humidity (RH).

Several methods have been used to derive this factor to correct the AOD-PM_{2.5} equation, e.g. $f(RH) = 1/(1 - RH)$ and $f(RH) = \log(1+RH)$ (Kang, 2014).

Here are graphs relationship between the hygroscopic factor $f(RH)$ and RH.

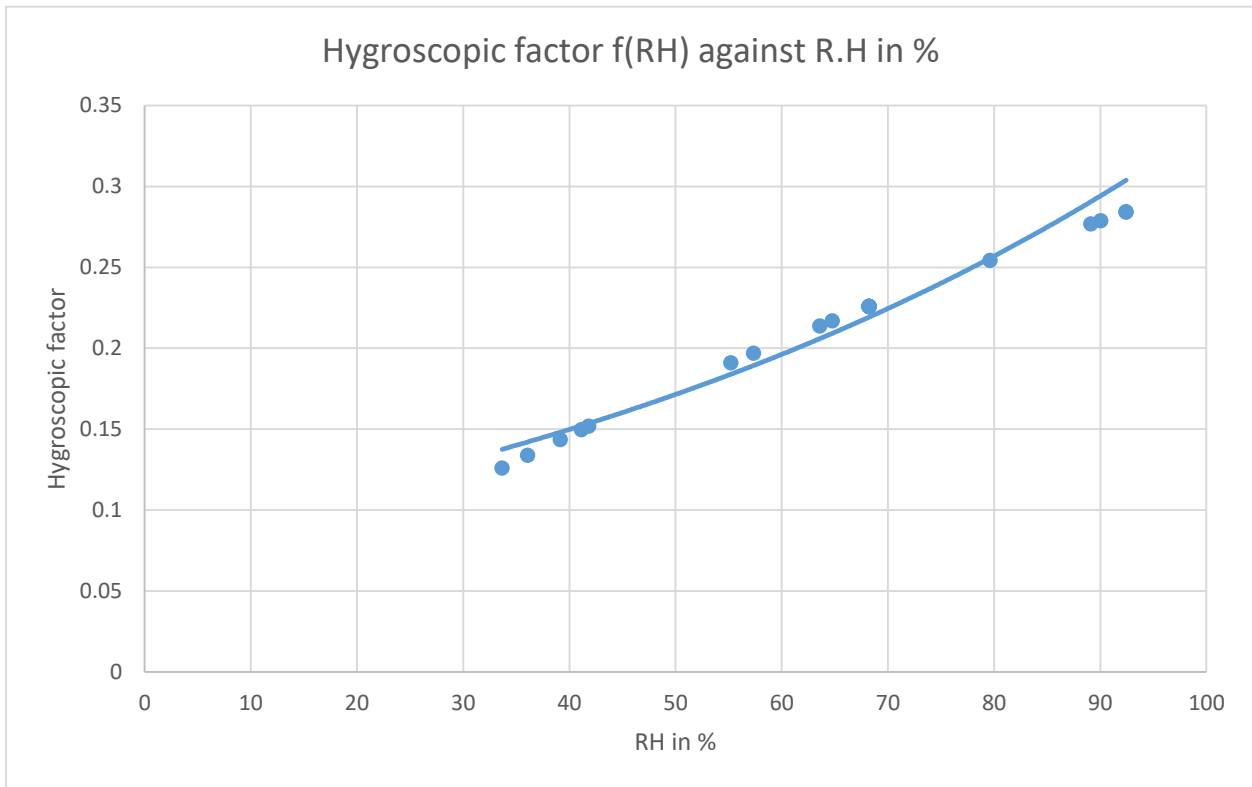


Figure 2: Figure showing a relationship between the hygroscopic factor $f(RH)=1/(1-RH)$ and RH in %.

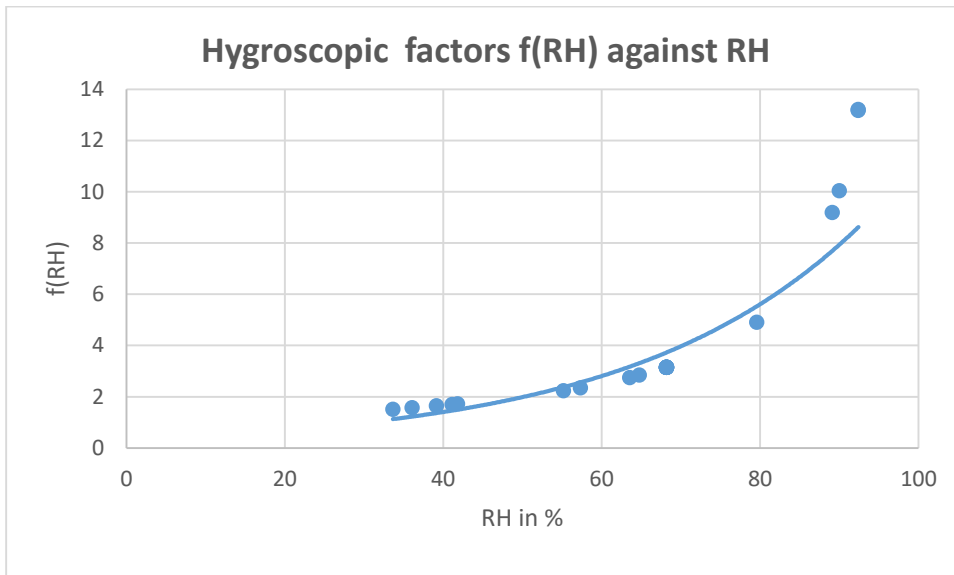


Figure 3: Figure showing a relationship between the hygroscopic factor $f(RH)=\log(1+RH)$ and RH in %.

Other studies have utilized fitting curves based on experimental measurements to analyze aerosol scattering and its relationship with relative humidity (Koelemeijer, 2006). The hygroscopic factor, which is derived as a function of relative humidity, demonstrates that aerosol scattering does not follow a simple linear relationship with relative humidity.

Instead, the relationship appears to be non-linear, as shown by the parabolic figures observed in previous studies. These figures suggest that the scattering of aerosols varies in proportion to changes in relative humidity. Specifically, the variation in aerosol scattering is influenced by the dynamic shift between absorption and extinction in the aerosol optical depth (AOD). The interaction between these two factors leads to the complex behavior of aerosol scattering as a function of environmental humidity conditions.

CHAPTER4: RESULTS AND DISCUSSION

4.1: TEMPORAL VARIATION OF PM2.5 CONCENTRATION IN KIGALI WITH SEASONS.

The study of particulate matter (PM2.5) concentrations in Kigali city was conducted at five different monitoring stations: Gacuriro, Rusororo, Kimironko, Gikomero, and Jali, over a period from January 2018 to January 2022. The data collected at these stations were used to analyze the temporal variations in PM2.5 levels across different seasons.

The hourly variations in PM2.5 concentrations were examined for three distinct seasons: the rainy season, the dry season, and the transition period between them. These variations are crucial for understanding how local meteorological conditions influence air quality and how PM2.5 levels fluctuate over time.

The following figures represent the hourly variations of PM2.5 concentrations during each of these seasons, providing insights into the trends and patterns observed at the five stations. By comparing the seasonal variations, we can assess the impact of seasonal factors, such as rainfall and temperature, on particulate pollution in Kigali.

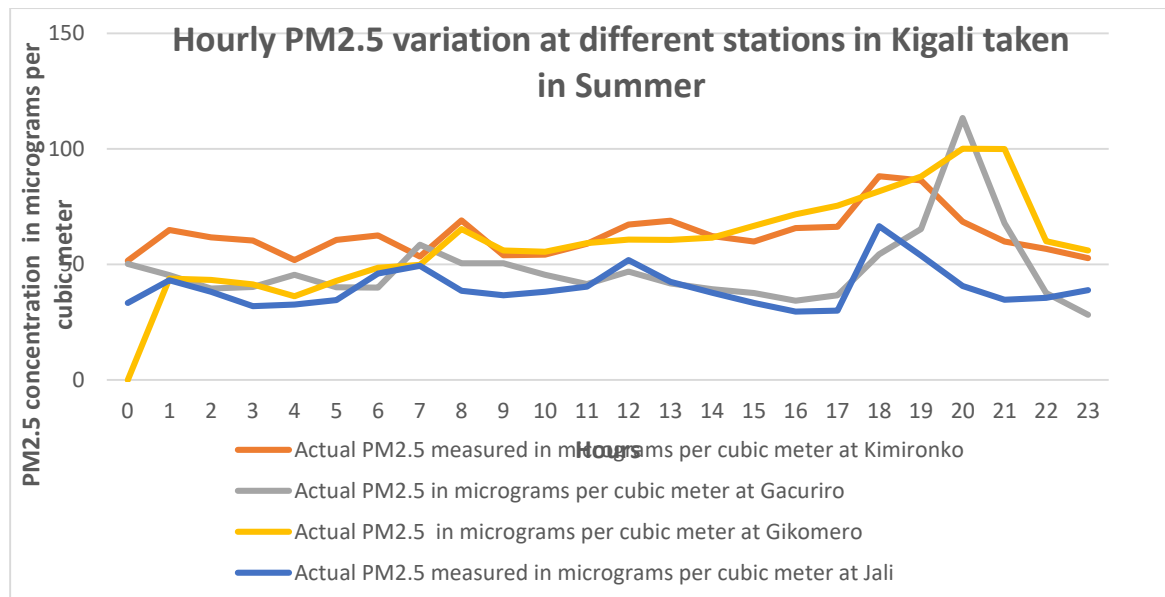


Figure 4: Figure showing hourly variation of PM2.5 at different stations in Kigali taken in summer.

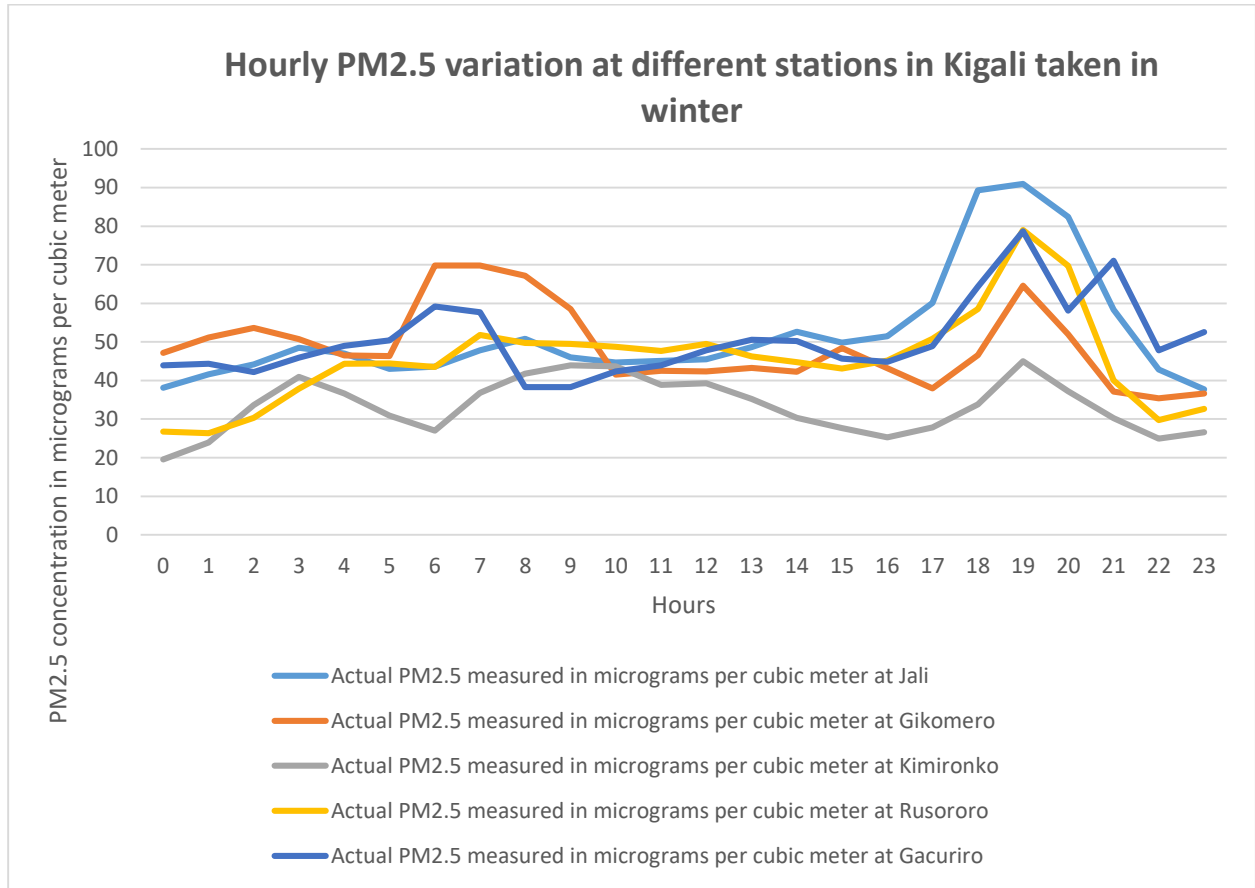


Figure 5: Table showing hourly variation of PM2.5 at different stations in Kigali taken in Winter

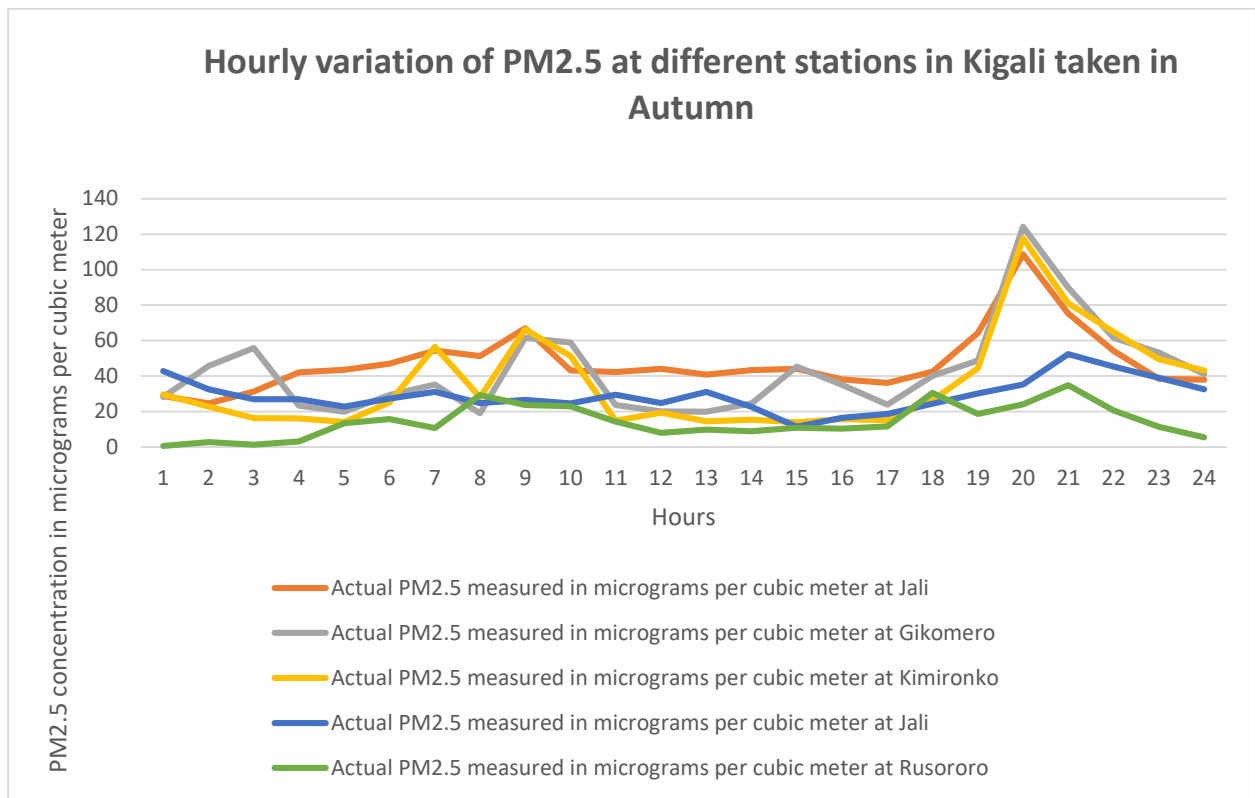


Figure 6: Figure showing hourly variation of PM2.5 at different stations in Kigali taken in Autumn

The peak concentrations of particulate matter (PM2.5) are generally observed during the morning hours, specifically between 7:00 AM to 9:00 AM, and in the evening, from 5:00 PM to 9:00 PM. During these periods, the concentrations of PM2.5 are significantly higher, with the lowest values typically recorded during the remaining hours of the day.

The overall highest PM2.5 concentrations were recorded during the dry season (summer). At monitoring stations like Gikomero and Gacuriro, concentrations frequently exceeded 100 micrograms per cubic meter ($\mu\text{g}/\text{m}^3$) during these months. In contrast, the lowest values were generally observed during the wet seasons (winter and autumn), when rainfall helps to reduce the presence of particulate matter in the atmosphere.

Upon analyzing these observations, several key factors contributing to these high concentrations can be identified. One of the primary reasons for elevated PM2.5 levels during peak hours is the increased presence of pollutant agents in the atmosphere. These pollutants include not only PM2.5

but also PM₁₀, carbon monoxide (CO), sulfur dioxide (SO₂), ammonia (NH₃), ozone (O₃), and nitrogen oxides (NO_x), all of which contribute to deteriorating air quality.

The emission of these harmful gases is primarily driven by anthropogenic activities, especially transportation, the combustion of fuels (such as liquefied petroleum gas, coal, and wood), and emissions from power plants. The increased use of fossil fuels during the dry season, coupled with the higher demand for energy for heating or transportation, leads to a greater release of pollutants into the atmosphere. As these emissions accumulate, they contribute to the higher concentrations of particulate matter observed during the morning and evening hours, when traffic congestion and fuel combustion activities are at their peak.

In summary, the temporal variation of PM_{2.5} concentrations in Kigali can largely be explained by the combined effects of seasonal changes, meteorological factors, and anthropogenic activities. The dry season, with its higher levels of pollution due to increased fossil fuel combustion, results in the highest concentrations of particulate matter, whereas the wet season, which benefits from rain's cleansing effect, typically experiences lower PM_{2.5} levels

4.2. TIME-BASED VARIATIONS OF MODIS AOD AND PM_{2.5} OVER RWANDA.

The map below illustrates the temporal variations of MODIS Aerosol Optical Depth (AOD) and PM_{2.5} concentrations over Rwanda from the year 2000 to 2020. The map provides a time-sequenced representation of the variations in aerosol levels, showing how particulate matter (PM_{2.5}) and aerosol concentrations have fluctuated across the years. These variations are the result of numerous factors that influence air quality on a daily basis, including changes in aerosol concentrations, weather patterns, and other environmental conditions.

The MODIS AOD data provides a satellite-based measurement of aerosols in the atmosphere, which is particularly useful for monitoring large-scale air quality changes. Aerosol optical depth is a key indicator of aerosol load in the atmosphere and is sensitive to changes in pollution, dust, and smoke. By analyzing AOD data over time, we can assess seasonal and long-term trends in air quality across Rwanda.

On the other hand, PM_{2.5} concentrations, which refer to fine particulate matter with a diameter of 2.5 micrometers or smaller, are measured locally through ground stations and offer insights into

the health impacts of airborne particulate matter. The concentration of PM_{2.5} can be influenced by several factors, including emissions from vehicle traffic, agricultural activities, combustion of solid fuels, and natural sources like dust storms and forest fires.

One of the key reasons for the observed variations in PM_{2.5} concentrations over time is the dynamic interplay between aerosol levels, meteorological conditions, and Planetary Boundary Layer Height (PBLH). The PBLH refers to the height of the atmospheric layer in which most weather and pollution occur.

During certain weather conditions, such as high pressure systems, aerosols and pollutants are trapped near the surface, leading to higher PM_{2.5} concentrations. Conversely, rainy weather or strong winds can lead to a reduction in aerosol levels, as precipitation helps wash out particles from the atmosphere, and winds disperse them.

The year-to-year fluctuations seen in the map are also influenced by anthropogenic factors, including population growth, urbanization, and industrial activity. For instance, the dry season typically leads to higher particulate concentrations due to reduced rainfall and increased burning of agricultural waste, while the wet season generally sees lower concentrations due to the cleansing effect of rain.

By examining these variations in MODIS AOD and PM_{2.5} concentrations over a 20-year period, we gain valuable insights into the changing air quality trends across Rwanda. These time-based variations are critical for understanding how local and regional factors, including both human activity and climate, contribute to the long-term trends in air pollution.

Time Series, Area-Averaged of Aerosol Optical Depth 550 nm (Deep Blue, Land-only) daily 1 deg. [MODIS-Terra MOD08_D3 v6.1] over 2000-02-24 - 2019-07-06, Shape Rwanda, Region 40.7812W, 33.75S, 66.0938E, 42.8906N

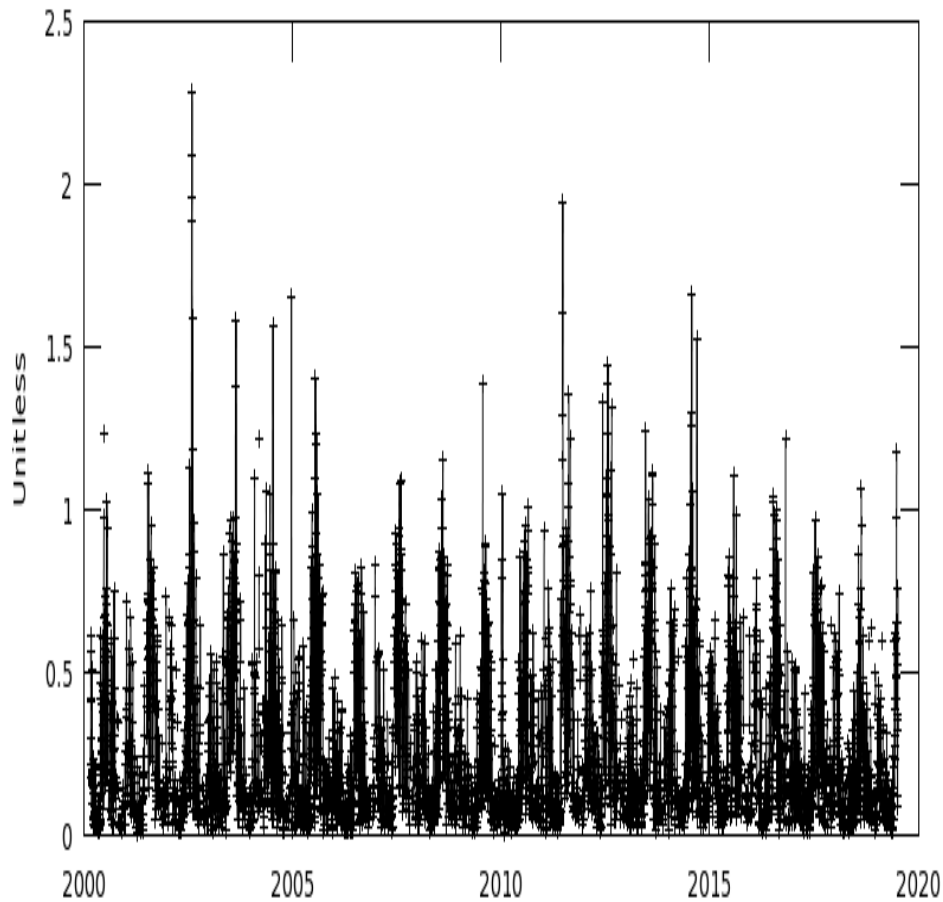


Figure 7: Figure showing annual variation of aerosols from 2000 to 2019

The map below illustrates the variations in PM_{2.5} and MODIS AOD concentrations over time. MODIS data is collected in two parts of the day: the morning and the afternoon. Specifically, the Terra satellite, which collects AOD data in the morning, passes over Rwanda around 10:30 AM local time (LST), while the Aqua satellite, which collects AOD data in the afternoon, passes over at approximately 1:30 PM LST. As a result, the AOD data can be categorized into two distinct classes each day: AOD AM (morning) and AOD PM (afternoon).

The PM_{2.5} data, representing the concentration of fine particulate matter, varies over time based on daily meteorological conditions and human activities. These fluctuations are largely influenced

by anthropogenic factors such as traffic, industrial emissions, and the burning of biomass, as well as by natural processes like wind patterns and weather conditions.

Furthermore, the map highlights the peak values of aerosol optical thickness (AOD) observed during different times and shows how AOD concentrations have changed over the years. By visualizing these variations, we can better understand how aerosol concentrations fluctuate seasonally and annually, and how these changes correlate with local air quality, particularly PM_{2.5} levels.

4.3. CORRELATION BETWEEN RELATIVE HUMIDITY AND PM_{2.5}.

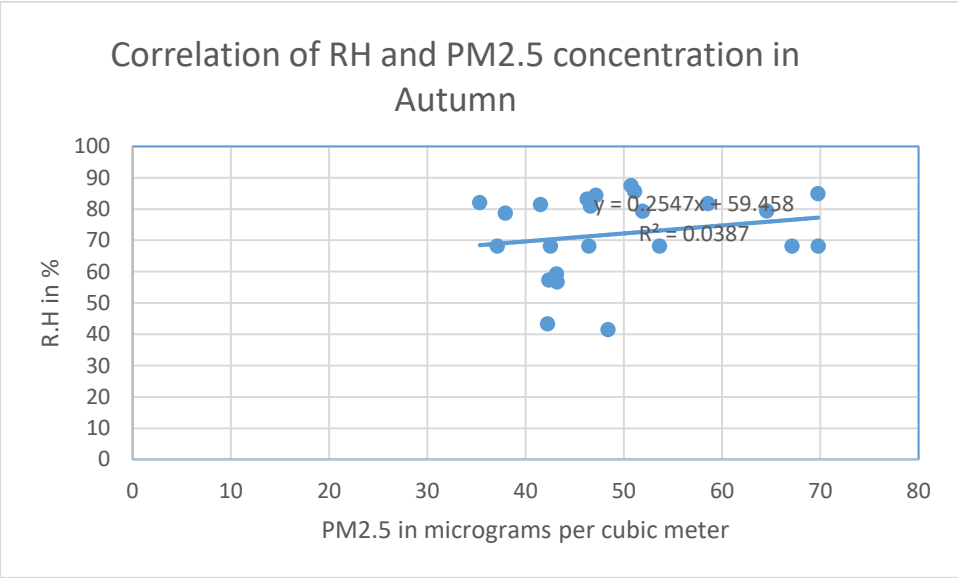
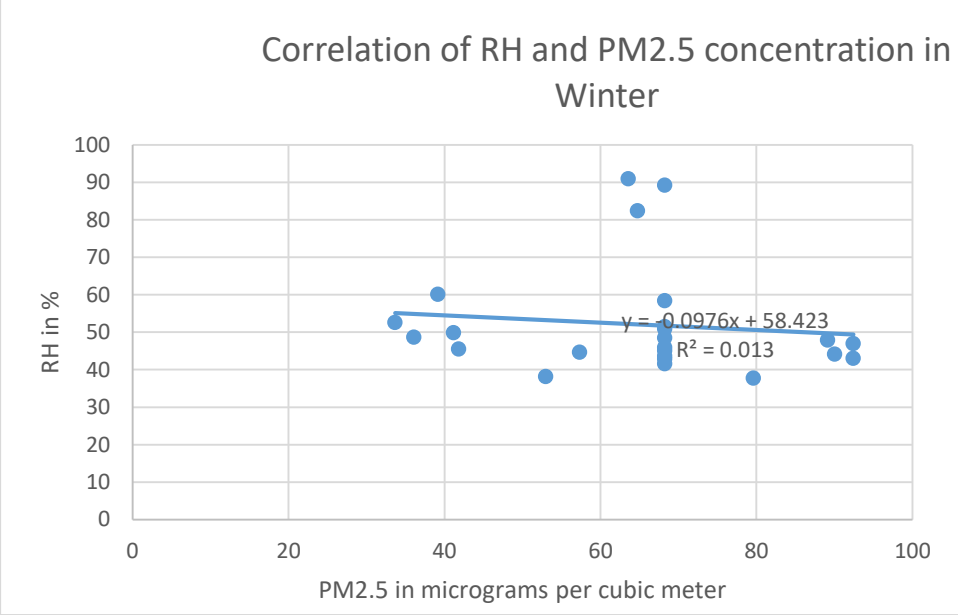
To start with defining a term correlation, Correlation in statistics means a measure or value that indicates the extent to which two or more variables fluctuate in relation to each other. Its correlation coefficient explains a statistical measure of the strength of a linear relationship between two variables.

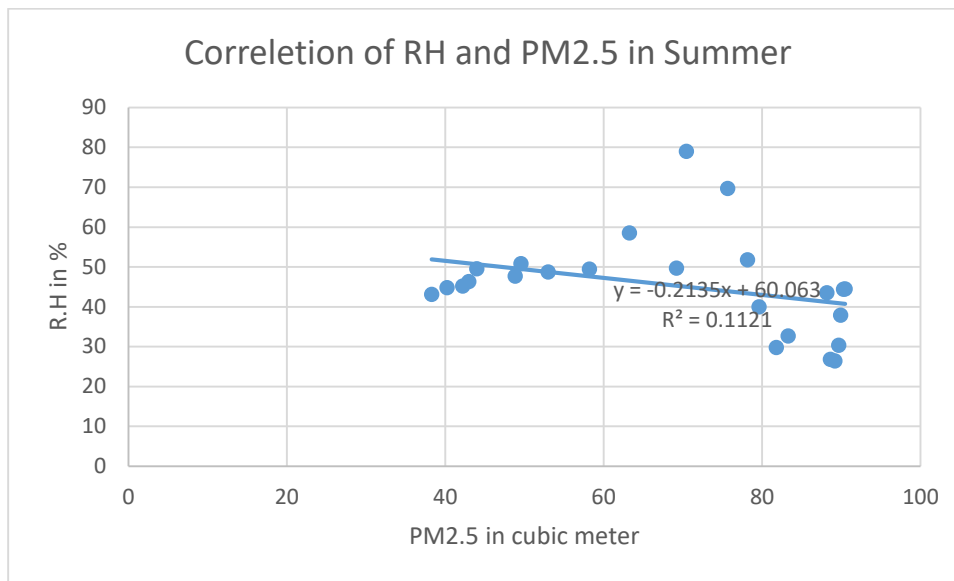
For instance, a Correlation coefficients whose magnitude are between 0.9 and 1.0 indicate variables which can be considered very highly correlated. Correlation coefficients whose magnitude are between 0.7 and 0.9 indicate variables which can be considered highly correlated.

Correlation coefficients whose magnitude are between 0.5 and 0.7 indicate variables which can be considered moderately correlated. Correlation coefficients whose magnitude are between 0.3 and 0.5 indicate variables which have a low correlation. Correlation coefficients whose magnitude are less than 0.3 have little correlation.

Therefore depending on correlation coefficient obtained in different seasons, we can state if relative humidity and PM_{2.5} is moderate, strong or low correlated. In the figure of winter season the correlation coefficient is found to be $R=0.11$ to mean those variables very low correlated, for Autumn season it is somehow similar because its value also is 0.19; both values belong in the same group of very low(0.1-0.3).

A significant change is observed for the summer season because its coefficient of correlation (R) is 0.33 even though is low but it does belong to same group as the ones given by other seasons. See the following figures.





4.4. ASSESSMENT OF HEALTH RISK LEVEL BASED ON AIR QUALITY INDEX GIVEN BY CONCENTRATION OF PM2.5.

A health risk is the chance or likelihood that something will harm or otherwise affect your health ((A.H. Abdul-Tharim, 2011).

In this case it is clear to say that a chance of something to happen is referred as Risk, which means risk is taken as probability of occurrence of any situation that tends a person to go in danger. Health risk level may affect negatively the residents unless they do take care themselves depending on the level of concern they in.

Most crucial thing in this proposal, is to say that the quantity the health risk level depends on duration of air pollution exposure and a significant value of air quality index. Several health effects attributed to short-term and long-term exposures can be classified as follows:

With regarding to the value of AQI due to PM2.5 which is 105.7, this value was calculated by applying this equation of Air Quality Index (AQI) for PM_{2.5} = $\frac{(C_{obs} - C_{min})(I_{max} - I_{min})}{(C_{max} - C_{min})} + I_{min}$ and it belongs in level of concern of unhealthy to certain sensitive group of people. See the following table.

Table 5: Table showing AQI Color, Levels of Concern and Air Quality Index

AQI Color	Level of concern	Air Quality Index
Green	Good	0 to 50
Yellow	Moderate	51 to 100
Orange	Unhealthy for Sensitive Groups	101 to 150
Red	Unhealthy	151 to 200

This result explains that Air Pollution Level of Kigali city is Unhealthy for Sensitive Groups in other words it poor., this value warns a sensitive group like Active children, adults, and people with respiratory diseases to care themselves though to find air quality index of air in areas of Kigali requires us to consider air all pollutants.

CHAPTER 5. CONCLUSION AND RECOMMENDATIONS

5.1. CONCLUSION

This thesis, titled "Assessment of Health Risk Level Associated with Exposure to Particulate Matter Less than 2.5 Microns in Kigali, Rwanda," focuses on analyzing the concentration of PM_{2.5} as measured by ground observation and its predicted values over a five-year study period from 2018 to 2022. The primary objective of this analysis was to assess the health risk levels associated with varying concentrations of PM_{2.5} in Kigali. This report not only evaluates the current air quality but also aims to provide insights into potential health impacts due to poor air quality in urban settings.

As detailed in the Methodology section of the thesis, the analysis revealed that the air quality index (AQI), based on PM_{2.5} concentrations, indicated that air quality in Kigali is often classified as unhealthy for sensitive groups. This suggests that those with pre-existing respiratory conditions, children, the elderly, and other vulnerable populations may be at an increased risk due to prolonged exposure to elevated levels of PM_{2.5}.

However, it is important to emphasize that, while the AQI values obtained from this study provide a reasonable indication of air quality, the estimates should not be taken as 100% accurate. The study encountered several challenges that could have introduced errors into the data analysis. These errors arise from a variety of sources, which include inconsistencies in data collection, changes in observational sites, and issues with equipment calibration.

Several factors contributed to potential errors in the data and analysis. One major issue was the missing hourly data for certain days, which can lead to gaps in the time series and reduced accuracy in the calculated averages. Additionally, instrument calibration errors or improper use of instruments could have impacted the reliability of the measurements. Changes in the instruments used throughout the study period also contributed to discrepancies between data sets. Furthermore, human error—such as mistakes in data recording, computation of daily averages, and inconsistent handling of the datasets—also played a role in the observed uncertainties. Despite these challenges, the overall objectives of the study have been achieved, and the results provide valuable insights into air quality in Kigali.

The study found that PM_{2.5} concentrations were particularly high during the morning and evening hours, specifically around the times when people commute to and from work. The highest concentrations were recorded during the morning rush hours, between 7:00 AM and 9:00 AM, and in the late afternoon and evening, between 5:00 PM and 7:00 PM. These elevated concentrations are likely due to increased human activities during these times, such as the use of vehicles, industrial emissions, and household activities like cooking. The emissions from vehicles and domestic heating significantly contribute to the buildup of particulate matter in the atmosphere. Additionally, the evening period, particularly after people return home and prepare dinner, tends to see an increase in localized air pollution due to biomass burning and other household energy usage.

In terms of the correlation between various environmental parameters and PM_{2.5} concentrations, the study observed a moderate, albeit weak, relationship between relative humidity (RH) and ground-level PM_{2.5}. The correlation coefficient (r) fluctuated between 0.19 and 0.33 across the three seasons (rainy, dry, and transition seasons). This suggests that while relative humidity may play a role in modulating particulate levels, it is not the dominant factor influencing PM_{2.5} concentrations in Kigali.

Further analysis indicated that MODIS AOD data showed a relatively stronger correlation with ground-level PM_{2.5} in the summer season, with the correlation increasing by approximately 17%. This is likely due to higher aerosol concentrations and more stable weather conditions during the dry season. Conversely, in the wet seasons (autumn and winter), the correlation between MODIS AOD and PM_{2.5} was less consistent, and relative humidity and Planetary Boundary Layer Height (PBLH) did not provide reliable correlations. During these seasons, rain and increased atmospheric mixing can dilute or remove particulate matter from the air, making it harder to establish a consistent correlation.

Satellite data, particularly from MODIS, proved to be an effective tool for estimating surface-level PM_{2.5} concentrations, although several factors must be taken into account when interpreting these results. The combination of meteorological and aerosol parameters, such as PBLH and relative humidity, can introduce variability and errors into the satellite-based estimates. The complex nature of these atmospheric factors means that while satellite data can offer a good approximation of surface concentrations, it cannot fully replace on-the-ground measurements.

In summary, the analysis of PM_{2.5} concentrations in Kigali has provided valuable insights into air quality trends, seasonal variations, and potential health risks associated with particulate pollution. While the results of this study are valuable, it is important to acknowledge the challenges and uncertainties introduced by data gaps, calibration issues, and the complexity of atmospheric parameters. The combination of meteorological conditions and aerosol concentrations creates a challenging environment for accurate predictions, and the errors associated with these factors must be addressed in future studies.

To minimize uncertainty and improve the accuracy of air quality predictions, further research is needed. More consistent and continuous air pollution monitoring, improved calibration techniques, and the integration of more advanced predictive models could significantly enhance our understanding of air pollution dynamics in Kigali and other urban centers in Rwanda. Future studies should also focus on refining the correlation between satellite-based data and ground-level observations, particularly in the context of different weather conditions and seasons.

This research serves as a stepping stone towards more accurate and reliable air quality monitoring, and with continued efforts, it will be possible to better predict and mitigate the health risks posed by particulate pollution in Kigali and similar urban areas.

5.2. RECOMMENDATIONS

To address the growing air pollution concerns in Kigali and mitigate the associated health risks, the following recommendations are made:

- ❖ **Comprehensive Air Quality Monitoring:** A city-wide, complete air pollution monitoring system should be established across Kigali. This should be a priority for the government and environmental agencies. Such monitoring would provide detailed data on pollutant concentrations, allowing for more informed decision-making and better public health interventions.
- ❖ **Development and Enforcement of Regulations:** The government should develop and enforce stricter regulations and policies aimed at reducing air pollution in urban areas, with a specific focus on Kigali. This could include limiting emissions from industries,

improving waste management practices, and regulating vehicle emissions. Effective enforcement of these regulations is key to ensuring their success.

- ❖ **Dust Control Measures:** There is an urgent need to implement effective dust control measures to minimize the release of particulate matter, particularly from industries such as wooden manufacturing. These industries are significant contributors to air pollution. Proper dust management technologies, such as air filtration systems, should be introduced to reduce PM emissions at the source.
- ❖ **Promotion of Personal Protective Equipment (PPE):** To protect vulnerable workers, especially in industries where particulate matter exposure is high, the use of personal protective equipment (PPE) such as face masks should be encouraged. This is particularly important for outdoor workers, construction laborers, and those involved in manufacturing and industrial processes that emit pollutants.
- ❖ **Air Quality Awareness and Education:** Introducing training programs on air quality management and mitigation strategies can help raise awareness among the public and industries. These programs should emphasize the importance of planting more trees, which can act as natural air filters, and highlight the need to avoid unnecessary deforestation. Promoting a culture of environmental stewardship is essential for long-term improvements in air quality.
- ❖ **Promotion of Clean Mobility:** The government should explore and implement strategies for clean mobility by promoting the use of electric vehicles (EVs), including hybrid cars. This would significantly reduce vehicular emissions, which are a major contributor to urban air pollution. The introduction of national electric mobility strategies and providing incentives for EV adoption will contribute to cleaner air and more sustainable transport in Kigali.

By implementing these recommendations, Kigali can move towards significantly improving its air quality, thereby reducing the public health risks associated with PM_{2.5} and other pollutants. These efforts will also create a model for other urban centers in Rwanda and Africa to follow in addressing air pollution and promoting environmental sustainability.

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