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Assessment and Mapping of Black Carbon and $PM_{2.5}$ Variability: A Case Study in Nairobi city

By

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Declaration

This thesis is my original work and has not been presented for a degree in any other university.

Signature ……. Date……

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Supervisor's Approval

This thesis has been submitted for examination with our knowledge as university supervisors.

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Dedication

This work is dedicated to my supportive family especially my beloved husband Kennedy Munene and son Ryan Muugi.

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May the Almighty God bless you all.

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List of Abbreviations

ADD	Aerodynamic Diameter
AADT	Annual Average Daily Traffic
AXIL	Analysis of X-ray spectrometry by Iterative Least square
BC	Black Carbon
CCN	Cloud Condensation Nuclei
DL	Detection Limit
EDXRF	Energy Dispersive X-ray Fluorescence
EMCA	Environmental Management and Coordination Act
GIS	Geographic Information Systems
GPS	Global Positioning System
GWR	Geographically Weighted Regression
IAEA	International Atomic Energy Agency
KENHA	Kenya National Highways Authority
KNBS	Kenya National Bureau of Statistics
KURA	Kenya Urban Roads Authority
NCC	Nairobi City County
NEMA	National Environment Management Authority
OLS	Ordinary Least Squares
PM	Particulate Matter
$PM_{2.5}$	Particulate Matter with ADD <2.5 μm
QXAS	Quantitative X-ray Analysis System
RH	Relative Humidity
SA	Spatial Autocorrelation

SDGs	Sustainable Development Goals
SPM	Suspended Particulate Matter
SRM	Standard Reference Material
TSP	Total Suspended Particles
TXRF	Total Reflection X-ray Fluorescence
UNEP	United Nations Environment Program
VIF	Variance Inflation Factor
WHO	World Health Organization
XRF	X-Ray Fluorescence

Abstract

Airborne particulate matter is of great concern in the global environment due to associated negative effects on human health and environment, and its contribution to climate change. Reported here is carried out evaluation and mapping of $PM_{2.5}$ mass concentration and Black Carbon (BC) in Nairobi city. Air sampling was conducted at nine selected sites within Nairobi city between 17/05/2016 to 22/06/2016. Sampling was done for 8 hours and samples analyzed at the Institute of Nuclear Science laboratory for Particulate Matter ($PM_{2.5}$) and trace elements (Pb, Mn, Zn, Zr, Fe and Cu). BC was analyzed at Gothenburg University, Sweden.

The mean 8-h $PM_{2.5}$ concentrations in the nine sampling sites selected for the study ranged between 147 ± 89 μg m^{-3} and 52 ± 4 μg m^{-3}. Mean BC concentration for the nine sampling sites ranged from 8.6 ± 3.3 μg m^{-3} to 2.1 ± 1.2 μg m^{-3}. OLS dispersive models were further used to map out the pollution levels across the city. Elemental content of the sampled fine particulates included Cu, Mn, Zn, Fe, Pb, and Zr which were found to be above 50, 1210, 470, 200, 30 and 480 ng m^{-3} which was their respective detection limits. The detected trace elements accounted for 15 % of the species in $PM_{2.5}$, while BC accounted for 8 %. The highest mean concentration was recorded for Fe, followed by Mn and Cu at 2800 ± 3800 ng m^{-3}, 2600 ± 42 ng m^{-3}, and 2200 ± 38 ng m^{-3}, respectively.

The WHO health guideline for 24-h mean $PM_{2.5}$ concentrations is 25 μg m^{-3}. This study represents an eight hour mean hence it was not possible to directly compare the concentrations with the WHO guidelines. However, it is evident that the values are very high if we consider the low activity hours of the night. This means that the population like those driving in jam, traffic police, pedestrians, or individuals living in apartments near the roadways, are all constantly being exposed to high pollution levels. Long-term exposure to these pollutants can have negative effects on public health such as respiratory and cardiovascular ailments, hence there is need for intervention measures.

Chapter 1:

Introduction

1.1 Background

Air pollution is described as a scenario where substances resulting from various natural and human activities exist at concentration levels significantly higher than the background ambient concentrations, and to cause undesirable consequences on human beings , animals or even the environment (Ramanathan and Carmichael, 2008). $PM_{2.5}$ is defined as of particles with effective aerodynamic diameter ≤ 2.5 μm. These particles have potential to penetrate deep into the lungs. With regard to their origins, $PM_{2.5}$ could originate from either anthropogenic or natural sources (Artíñano et al., 2003).

The Naturally occurring $PM_{2.5}$ results from certain inevitable, yet transient, atmospheric conditions (Godish et al., 2004). The $PM_{2.5}$ concentration levels in the atmosphere are influenced mainly by emissions, land cover and topography. Although hardly anything can be done to abate the natural causes of $PM_{2.5}$, a lot more could be accomplished in reducing the anthropogenic sources. The anthropogenic $PM_{2.5}$ is considered as an important public health and environmental challenge (Bernstein and Abelson, 2005). This is largely due to the fact that enhanced pollutant concentrations are released into the atmosphere, posing a considerable hazard to people's wellbeing (Pope et al., 1995).

Black Carbon (BC) is results from partial combustion of substances composed of amorphous carbon such as fossil fuels, biofuel and biomass. It constitutes the fine PM, that is, it has aerodynamic diameter <1 μm, and composed of clumps or chains of 50 - 100 nm particles. These little particles have the ability to change climate and affect human and environmental health. Although the impact of BC concentration in the atmosphere on climate change is yet to be properly understood, recent scientific studies have established that it could be one of the key contributor to global warming (Ramanathan and Carmichael, 2008).

Automobile traffic is often a significant cause of Particulate Matter (PM) in developing cities, which are characterized by a rapid growing economy, coupled with an inefficient transport and land-use systems that could consequently lead to increased levels of $PM_{2.5}$ in the atmosphere

(Kinney et al., 2011). For instance, heavy traffic could possibly create pollution hotspots, such that health risks at those particular sites exceed those encountered in other parts of the city (Kinney and O'Neill, 2006).

Nairobi city is characterized by high population growth mainly resulting from rural-urban migration. This exerts pressure on the available infrastructure for transport and solid waste management. Incidences of heavy traffic and open garbage/ refuse burning are common thus contributing to air pollution. However, limited scientific data is currently available on pollution levels and dispersion in the city, which in turn affects creation and implementation of relevant pollution mitigation measures. This study therefore seeks to assess the $PM_{2.5}$ and BC concentrations in different areas across the city and apply dispersion models to evaluate the spatial variation in pollution levels.

1.2 Problem statement

Environmental monitoring and assessment are important in regulatory and advisory policy making process, for the safety of the public. Urbanization with associated industrial development and growth in mobility has led to increased air pollution levels, especially in densely populated areas like Nairobi city. Gaita (2017), found air quality status within Nairobi city to be deteriorating. Ambient air pollution exposes an eminent danger towards human health, ecosystem and the well-being of residents. Air degradation impacts are manifested through adverse health effects, reduced visibility and damage to materials and ecosystem. WHO (2016) associates 3.7 million premature deaths with ambient particulate matter exposure annually. Information on pollutants concentration and their spatial variation is crucial in making informed decisions on the necessary steps to reduce these pollutants, hence to control and mitigate their effects. Several short scientific studies have already been conducted in Nairobi on ambient air pollution, but none of these studies have shown the spatial variations of these pollutants. Nairobi has a large market for second-hand vehicles and most roads and roundabouts with traffic jams create possible air pollution hotspots which need to be assessed.

1.3 Study Objectives

1.3.1 Main Objective

The overall objective of this research was to evaluate near road $PM_{2.5}$ and map the status.

1.3.2 Specific Objectives

The specific objectives were:

i. To evaluate $PM_{2.5}$ and BC concentrations at selected sites within Nairobi city.

ii. Determine trace elements content in the $PM_{2.5}$ using EDXRF spectroscopy.

iii. Map the spatial variations of BC and $PM_{2.5}$ concentrations within Nairobi city

iv. Present the findings to stakeholders through seminars and final report.

1.4 Research Justification and Significance

The findings of this work will provide the necessary data on the concentrations of $PM_{2.5}$ and BC in Nairobi City County (NCC), as well as their spatial variations. The mapped information on the two evaluated species will provide easier appreciation of air quality situation and it is therefore expected to promote policy initiatives that will address air pollution. This study will also promote the need to have efficient and effective air quality management strategies geared towards improving the air quality in NCC. Environmental and human health organizations such as National Environment Management Authority (NEMA), WHO and Nairobi City County can use the obtained data in environmental assessment and management programs. The maps will also guide city people on pollution risk areas.

1.5 Scope

This research entailed fieldwork sampling where people had to set up samplers and guard them from any interference. This required funds which were limited hence only nine sites could be sampled. Consequently, limited data gave almost similar results as most of the variables affecting pollution concentrations like topography and population data was the same for these sites. Getting secondary data from government organizations was a long and tedious process which took more time than expected. Annual Average Daily Traffic (AADT) was obtained from KENHA and KURA while weather parameters were obtained from the Kenya meteorological department. GIS modelling was done to show the variation of air pollutants (primary data) in relation to the secondary data (vehicle volume and weather parameters).

1.6 Report organization

This report is organized into five chapters. Chapter one is the introduction which sets the research background, problem statement, justification, objectives, limitations of the research and explains the thesis organization. Literature review on environment and airborne particulate matter as well as related effects on climate and human health are highlighted in chapter two. Chapter three gives a description of the study area, conceptual framework, data, tools and GIS modelling used in execution of the research. Results are presented and discussed in chapter four. The conclusion of the report is presented in the last chapter and suggestions on further research offered.

CHAPTER 2:

Literature Review

2.1. Environment (Global policies and SDGs, National policies and strategies)

Outdoor air pollution kills approximately 3 million individuals annually WHO (2018). Air pollution can be used like a marker for sustainable development. Policies to deal with air pollution thus can bring in many different benefits to human health, not just through air quality improvements but also many other benefits like enabling physical activity. The WHO Air Quality Guidelines (WHO, 2006), gives an evaluation of health effects associated with air pollution, and thresholds with regards to levels that could be detrimental on health.

Outdoor air pollution is an indicator for SDGs: in health (Goal 3) and in cities (Goal 11). Issues related to outdoor air pollution are reflected in the Sustainable Development Goals (SDGs). Air pollution concentration within cities is cited as an indicator pertaining to urban sustainable development (SDG 11) while mortality due to air pollution is used as an indicator to the health SDG goal (SDG 3). Efficient estimations for exposure and effects as a result of air pollution is thus crucial to better inform policy makers.

According to GOK (2010), there are different laws linked to air quality and air pollution in Kenya that include but not limited to Environmental Management and Coordination Act (EMCA, 2018), National Environmental policy 2013 (NEP, 2013), Public Health Act (PHA, 2012), cap 242, National Transport and Safety Act 2012 (NTSA, 2012), and the Kenya Standard Act (KSA2013), cap 496. The EMCA (2018) is the principal law regulating pollution prevention. The National Environment Management Authority (NEMA), established under EMCA, 2018, is the government body which regulates, and provides general oversight and co-ordination over all issues related to the environment. Kenya National Ambient Air Quality regulations, Air Quality Regulations 2014 (AQR, 2014), provides for general prohibitions and permissible levels of both stationery and mobile sources. The initial Air Quality Regulations 2008 (AQR, 2008), didn't set any specific air quality guidelines but rather recommended their formulation. The regulations were updated in 2014 by adding limit values. However, there is no national monitoring program for ambient air quality in Kenya.

2.2. Airborne Particulate Matter

An aerosol is a collection of solid or liquid particles suspended in a gas (Hinds, 1999). Airborne particles are all examples of aerosols and may include smoke, dust, smog, mist, fume, haze, fog, and clouds. Aerosol particles of aerodynamic diameter $\leq$ 2.5 μm are usually called "fine" particles, while those of aerodynamic diameter > 2.5 μm and < 10 μm are referred to as "coarse" fraction. The characteristics of course and fine particles are quite different in terms of their sources, removal mechanisms, chemical composition, optical properties; and deposition in the respiratory system. For example, the $PM_{2.5}$ fraction can penetrate deeper into the lungs, thus posing a significant health risk particularly to human beings (Miller and Xu, 2018).

Coarse particles are usually generated through mechanical processes. They are primarily comprised of soil dust, tire wear particles, fly ash, among others (Gunawardana et al. 2011). The fine and accumulation mode particles consist mainly of particles originating from combustion sources, in addition to secondary aerosol compounds such as nitrates, ammonium, sulphates, and secondary organics, resulting from chemical reactions leading to gas- particle conversion (Hinds, 1999). There are two mechanisms through which the particles may be taken out of the atmosphere: First is the dry deposition, whereby the particles settle on the earth's surface, and secondly through wet deposition where they are incorporated into cloud droplets during the development of precipitation (Bond et al., 2013).

Black carbon stems from biomass and fossil fuel combustion. It consists of a wide variety of carbonaceous substances ranging from char black carbon i.e. the partly combusted plant tissue residues, to extremely graphitized soot black carbon i.e. the volatile compounds produced within flames (Bond et al., 2013). Right from their formation, the aerosol black carbon develop like hydrophobic prime spherule particles of intermittent geometry that provides an active site for depositing other chemical species. As the particle size decreases (especially sizes less than 2 mm), their potential to remain airborne within the atmosphere is enhanced, thus promoting long range transportation (Zidek, 1997).

2.3. Particulate Matter and Environment

Air in its natural condition is life supporting. It however becomes harmful when its composition is altered through the introduction of hazardous elements into it. Air pollutants may be solid (dust and particulates), liquid or gases. Air pollution in urban centres is caused by automobile emissions, dusts from unpaved roadways, poorly planned land use patterns, fuel combustion, atmospheric conditions as well as industrialization (Kinney et al., 2011; Marlier et al., 2016). Urban aerosols contain mixtures form both primary sources like transport sector, industries, natural sources, and power generation, and secondary aerosols formed through gas-to-particle conversion processes. High $PM_{2.5}$ concentration levels have been reported in different cities (Kinney et al., 2011; Marlier et al., 2016).

Airborne particulate matter results either via direct emissions of particulates or through discharge of various gases such as SO_2 and NO_X that either condense directly into particles or undergoes a series of chemical transformations into species which later condense to form particles. Therefore a full description of atmospheric aerosol necessitates specification of not only their contribution but also their sizing, chemical make-up, state (i.e. liquid or solid) and morphology (Jimoda, 2012).

2.4 Air pollution and Human Health

Ambient air pollution emanates from both anthropogenic and natural sources. In urban settings, the contribution of anthropogenic pollutant sources far exceeds natural sources. These sources include residential heating, cooking, and lighting, vehicular emissions, power plants, and industrial facilities. These sources emit both gaseous and particulates that could lead to adverse effects on health due to short-term or long-term exposure. PM2.5, ozone, SO2 and NOx are some of the pollutants strongly linked to health effects (WHO, 2018).

Ambient air pollution is a leading cause of mortality and ailments especially in developing countries. The associated health effects and risks range from frequent hospitalization, emergency room visits, and premature deaths. According to WHO (2016) report on the burden of disease

due to ambient pollution, 4.2 million premature deaths globally occur, for example from acute lower respiratory infections, ischemic heart disease, chronic obstructive pulmonary disease, lung cancer, and stroke. For instance, the $PM_{2.5}$ fraction of the pollutants, which contains known carcinogens such as BC and polycyclic aromatic hydrocarbons (PAHs), can penetrate deep into the lung pathways and bloodstreams resulting in cerebrovascular, cardiovascular, and respiratory effects (Khreis et al., 2017, Zanoli et al., 2017; Orellano et al., 2017).

In children, long and short-term exposure to ambient air pollution can result in aggravated asthma, respiratory infections and reduced lung function. A study by Orellano et al. (2017), through systematic reviews and multilevel meta-analysis linked ambient pollutants, $PM_{2.5}$, NO_2 and SO_2, to aggravated asthma in children. Therefore, presence of these pollutants in the atmosphere at elevated levels could be associated with higher incidence, prevalence, hospitalizations, or worsening of symptoms of asthma. The asthma exacerbations due to air pollution were associated with airways inflammation and remodeling, oxidation stress,

There is evidence linking $PM_{2.5}$ with adverse health effects (WHO, 2018; Khreis et al., 2017, Zanoli et al., 2017; Orellano et al., 2017). Unfortunately, there is no threshold $PM_{2.5}$ concentrations below which no health effects are observed. Therefore, the WHO air quality guidelines are aimed at achieving the lowest PM concentrations possible. The WHO guideline values are 10 and 25 ug m^{-3} for the annual and daily mean $PM_{2.5}$ concentration respectively. Studies carried out in Nairobi, show pollution levels surpass this guideline value (Gaita et al., 2014, Kinney et al., 2011). This observation has been linked to rapid urbanization, poor solid waste disposal, increased motorized transport, industrial emissions and indoor energy sources. Therefore, the city residents are at significant risk of adverse health effects linked to air pollution, hence need for monitory and pollution mitigation measures.

2.5 Air pollution and climate effects

There is increased awareness on measurable effects of BC on earth surface and atmospheric warming, mainly via radiative scattering and absorption in the atmosphere, as well as via changes to system albedo on the earth surface (Shrestha et al., 2010). These two effects make

BC an effective driver of climate change both at local and global scale. After carbon dioxide which exerts a net positive radiative forcing of about 1.6 Wm^{-2}, BC has been considered as the secondly greatest contributor to global warming, having a net positive radiative forcing of between 1 to 1.2 Wm^{-2} (Shrestha et al., 2010). Putting this into consideration, plus BC's short lifetime in the atmosphere, makes the control of BC emissions especially those emanating from fossil fuel among the fastest and most efficient means of managing global warming.

BC particles can bring about warming effect as well as dimming and cooling effect. This is through absorption of radiations reflected to the atmosphere from the earth's surface, and by scattering shortwave solar radiations before they reach the earth's surface respectively (Bond et al., 2013). The dimming effect resulting from BC is not directly comparable to that of GHGs radiative forcing since it does not necessarily result in a cooling effect. Generally, it results from increased atmospheric solar absorption, that could be a factor of 3 or more in comparison with dimming caused by reflection of solar radiation (cooling effect) by greenhouse gases (Shrestha et al., 2010). The magnitude of these effects is linked to various atmospheric components, besides the concentration and location of the aerosols in the atmosphere. At locations with highly absorbing aerosols, the radiative effect of these particles at the top of the atmosphere can transform from cooling to warming effect, especially over highly reflective surfaces like clouds.

Aerosols can interact either directly with the solar radiation and infrared radiation from earth's surface, or indirectly affect the planetary albedo through alteration of the cloud properties. The single scattering albedo, W_O is among the most important factors in determining the magnitude and sign of the forcing. It is described as the ratio of the aerosol scattering effect relative to the total sum of aerosol absorption and scattering effect. According to Horvath (1998), aerosol in the accumulation mode is the most crucial with regards to radiative forcing, since they are very efficient in absorbing and scattering solar radiation, in addition to their long lifetime in the atmosphere.

Scattering of light can be described as the redistribution or dispersion of the incident radiation in different directions, while maintaining its energy / wavelength. The two types of scattering are: Mie scattering and Rayleigh scattering (Bond et al., 2013). Mie scattering is the predominant mode when incident beam encounters the accumulation mode particles i.e. the diameters of the

particles are in the order of the wavelength of the incident beam. Although Mie scattering is far more common in onward direction, a significant portion of light is scattered backwards into the space, hence cooling effect/ negative forcing.

Light absorption by particulate matter entails conversion of the incident light into heat (thermal energy), resulting in positive forcing (warming effect) of the aerosol, as well as the surrounding air. As a result, there is a decline in the light that reaches the surface, hence a cooling effect. However, there is a higher concentration of aerosols from the anthropogenic sources in the lower troposphere that tend to absorb more light, hence producing a net positive or warming effect (Andreae and Rosenfeld, 2008).

Absorbing aerosols have been found to lower heat convection as well as play a role in cloud re-evaporation (Andreae and Rosenfeld, 2008; Ackerman et al., 2000). In addition, a thick layer of absorbing particles over the ocean can lead to reduced evaporation rate as well as disrupt the entire hydrological cycle (Ramanathan et al., 2001). Among the aerosol particles, the elemental carbon constituent has been identified as the key light absorption component. According to a study by Mayol-Bracero et al. (2002), aerosol particles emitted from biomass burning consist of a substantial degree of polymeric organic substances.

Any change in aerosol number concentrations and chemical composition will ultimately affect the radiative properties, microphysics, as well as lifetime of clouds, since aerosols act as cloud condensation nuclei (CCN). The indirect effects can be categorized as the first and second indirect effect. The first indirect effect is induced by a rise in number concentrations of cloud condensation nuclei. The increased number of CCN has been attributed to combustion and pollution. This increase will consequently lead to elevated number of smaller droplets because the available water content in the atmosphere will be distributed among all the nuclei (Bond et al., 2013). These smaller aerosols tend to reflect more light back to the space than their larger counterparts, resulting in a cloud albedo effect, which consequently leads to a net cooling effect. The second indirect effect is caused by enhanced rainfall reductions and an increase in cloud lifetime due to higher CCN number that hinders the droplets from attaining the 14 μm threshold radius (Shrestha et al., 2010).

2.6 Particulate Matter Mapping and Studies

Mulaku and Kariuki (2001) carried out a study on analysis and mapping of air pollution status in Nairobi City. A basic spatial distribution map in respect of total suspended particles (TSP) that included pollen, smoke, dust and other solid particles employing geographic information system (GIS) techniques was produced. Eleven sampling stations representative of residential, industrial and commercial areas were selected. A hand held global positioning system (GPS) was used to locate the sampling locations and the data was the integrated with a digitized base map data for Nairobi. The GPS data was combined with measurement data to gives a map showing distribution of TSP in Nairobi. Regions were then categorized into Low (below WHO annual guidelines), Medium (exceeded WHO annual guideline by a factor less than 2), and High levels (exceeded WHO guidelines more than a factor of 2) of total suspended particulate matter (TSP), thus producing class boundaries. The end map depicted that TSP levels in most parts of the City fell in the medium and high categories, and high TSP levels noted in the City Centre and residential areas east of the city probably due to their closeness to the City's industrial area. The study recommended use of advanced dispersion model that would give a clear distribution pattern by considering specific pollutant sources, meteorological conditions, census data, topography and also the distance from source(s); of which most of these information wasn't readily available for the study. This study has taken into consideration the sources of pollution (Annual Average Daily Traffic (AADT) / vehicle volume) and meteorological conditions as suggested by Mulaku and Kariuki (2001).

Karue et al. (1992) conducted a research with the aim of determining the level of TSP in Nairobi. The TSP samples were assessed for elemental content using Energy Dispersive X-Ray Fluorescence (EDXRF) spectroscopy. The study showed that several activities within the city like industrial processes, construction work, use of road unworthy vehicles and dust from unpaved streets contributed greatly to SPM levels in the air.

A study by Gatari et al. (2005a) on elemental make up of tropospheric aerosols in Nairobi and Hanoi in Vietnam , observed that Si, Cl, K and Fe exceeded atmospheric concentrations of 100 ng m^{-3}. According to the study, the key contributors to air pollution in Nairobi city were emissions of traffic, and biomass and waste burning. The study further warned that there could be high levels of air pollution as a result of high population growth rate.

van Vliet and Kinney (2007) studied on effects of roadway emissions on the quality of air, with emphasis on PM concentrations in Nairobi City. The roadway $PM_{2.5}$ concentration were found to be about 20 times more, in comparison to an urban background site, whilst black carbon was ten times higher. In a similar research by Gatari et al. (2009), on depiction of aerosol particles in an industrial zone in Nairobi, it was noted that industrial activities, soil dust and emissions from automobiles were the leading pollutants in the area. The author recommended more studies on aerosol particles in the region to be carried out, to provide realistic long-term patterns of elemental concentrations in order to facilitate evaluation of source strengths.

Jieqiong-Luo et al. (2017) adopted the geographically weighted regression (GWR) to examine the area spatial heterogeneity of the relationships between $PM_{2.5}$ levels and geographic aspects. Regression approach is highly effective during the evaluation of geographically non-stationary and varying relationships between dependent variable Y versus a set of explanatory/ independent variables Xj (j = 1, 2… m) at local scale. By introducing the geographical position details to the traditional regression method, the GWR quest to exhibit the way the association between the dependent and independent variables differs within the whole location (space) described by the equation 2.1.

$$Y_i = 0(U_i, V_i) + 1(U_i, V_i)X1_i + 2(U_i, V_i)X2_i + L + m(U_i, V_i)Xm_i + E_i \quad \text{……equation 2.1}$$

Where (U_i, V_i) and E_i are respectively area coordinate and regression residual of the i^{th} position.

In GWR model, the regression coefficients show the local spatial variation, as well as the standard errors of the coefficients. General regression formula is given by equation 2.2.

$$Y = \beta_0 + (\beta_1 X_1) + (\beta_2 X_2) + ... + (\beta_n X_n) + E \quad \text{……..equation 2.2}$$

Where:

- Dependent variable (Y): The parameter being predicted
- Independent variable (X): Parameter(s) explaining (Explanatory variable) the dependent variable.
- β- coefficient: Weights exhibiting the connection relating to the independent and dependent variable.

- E: The value not defined by the model

In this research GWR could not apply because it requires datasets of several hundred features whereas there were 54 observations from the sampling data. In this case, ordinary least squares (OLS) was adopted based on multiple regression.

2.7 EDXRF Spectroscopy

X-ray fluorescence (XRF) spectrometer is a common and widely used method, with a wide range of application such as analyses of filter samples, biological samples and geological samples (Gatari et al., 2005a; Gaita et al., 2014; Tolosana-Delgado & McKinley, 2016; Ling et al., 2017).Using this technique, both major and trace elements ranging from Na to uranium can be investigated. Other advantages associated with the technique are; it is fast where analyses takes seconds or few minutes, non-destructive, relatively independent of the chemical state of the sample and has low detection limits (Ling et al., 2017).

In XRF spectrometer, x-rays generated from either an x-ray tube or a radioactive source are used to excite the atoms contained in the sample. Here, the incoming radiation knocks off an electron from the inner shell leaving the atom in an excited/ high energy state. A transition of an electron from the outer orbitals follows resulting in emission of photo whose energy is characteristic of the elements contained in the sample. Finally, detection and integration of the characteristic energy lines helps in qualitative and quantitative determination of elemental concentrations (Young et al., 2016).

The XRF technique can play a crucial role in air pollution studies for determination of elemental content. A study by Gaita et al. (2016), used energy dispersive x-ray spectrometer (EDXRF) to determine trace element content in filter samples. The obtained data was then used to determine the source strengths of $PM_{2.5}$ in Nairobi, using positive matrix factorization (PMF) model. The PMF model helps in calculating the source fingerprints, contributions and uncertainties. A similar study was carried out by Gatari et al. (2005a), to determine the elemental composition of aerosols in different cities (Nairobi and Hanoi in Vietnam). The authors noted that the multi-

elemental analyzing capability of EDXRF technique and statistical treatment of the data are indispensable tools in aerosol source identification.

2.8 Conclusion

From the literature review, we find scanty data on levels of air pollutants experienced by city dweller and spatial dispersion in African cities and Nairobi in particular. Most studies appeared limited in scope, capturing one or a few sites to represent the whole city. By combining a larger number of sampling sites across Nairobi city and mapping tools, the current study will be able to give a clear picture of the city's pollution status. This will provide the data to quantify associated health impacts and thus useful for policy formulation.

CHAPTER 3:

Methodology

3.1. Study area

This research work was conducted in Nairobi City. The City is in south-central Kenya approximately 150 kilometers south of the equator (Figure 3.1). It is Located within latitudes 1° 10’ S and 1° 25’ S and longitudes 36° 40’ E and 37° 05’ E at an elevation of approximately 1680 metres above sea level.

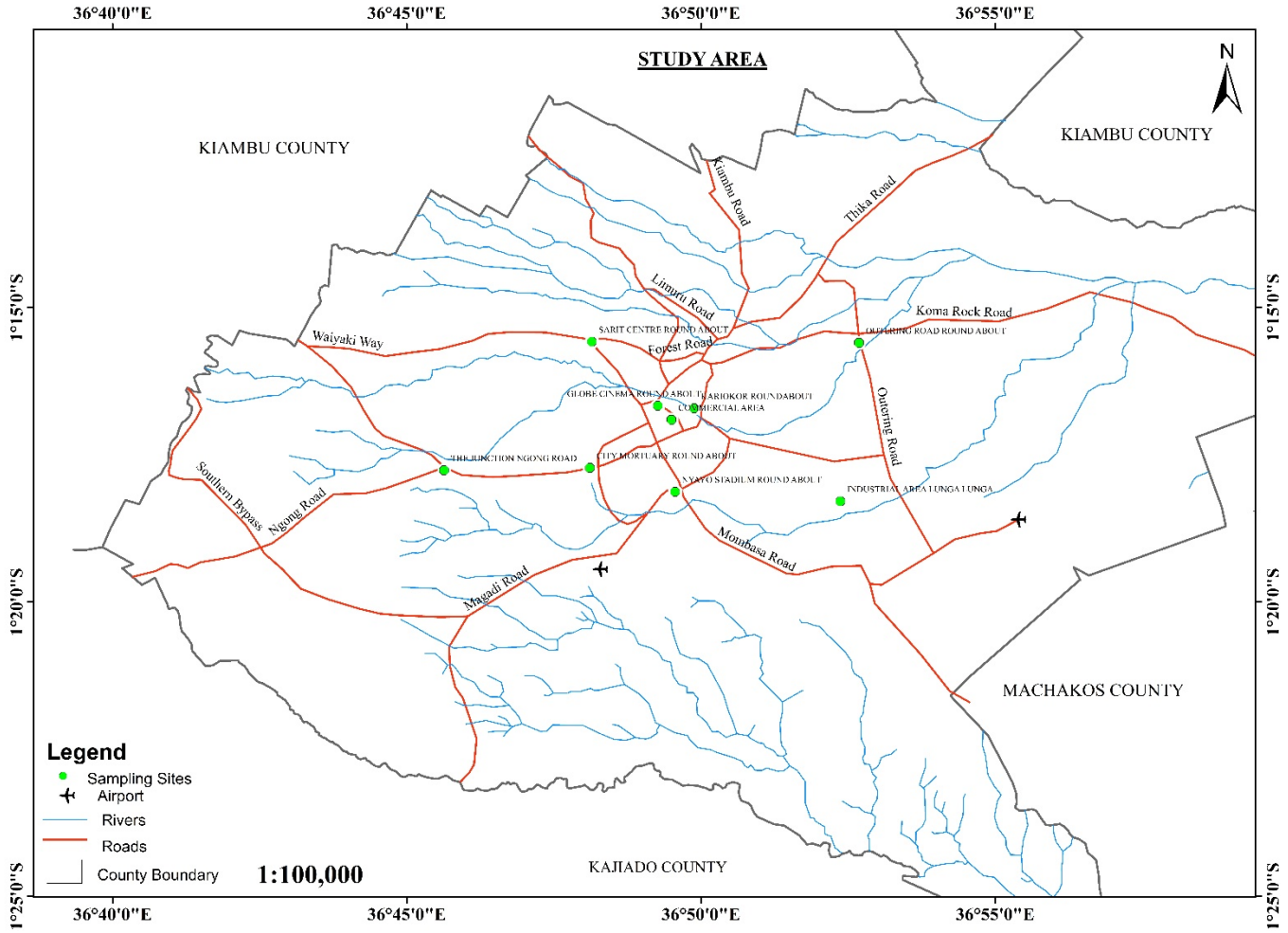


Figure 3. 1: The map of the study area.

3.2. Conceptual framework

This informs on the procedures undertaken to achieve the objectives of the study as presented on Figure 3.2. The first step was the definition of the problem through literature review. An intensive research was done to determine the actual problem in Nairobi city. The required data and variables were also determined. The second step was the collection of this data through fieldwork and secondary data acquisition. The secondary data used included vehicle volume (herein referred as AADT) and weather parameters all obtained from government agencies.

The datasets obtained were in different formats and mostly as text files and tabular data. This data was cleaned and parameters of interest obtained. All the relevant parameters were combined in an attribute table. The field observations ($PM_{2.5}$ and BC) constituted the dependent variables while all the other parameters were treated as independent variables. This formed the basis of the multivariate regression modelling which was the next step.

Pollution modeling was undertaken as the fourth step. In this OLS computation was done in a GIS environment. Explanatory variables coefficients were determined to show the strength and type of relationship between the explanatory variable and the dependent variable. Explanatory variable redundancy checks were determined by testing the model through determination of variance inflation factor (VIF). In this case the VIF of elevation, wind direction and distance from the road were > 7.5 hence redundant and were dropped from the model and the pollution model was rerun.

The final model was produced when all the factors influencing pollution were found to have VIF < 7.5 meaning they are significant in this study and included AADT, wind speed, air pressure, temperature and humidity. The relationship between the dependent variable and each explanatory variable is presented in chapter four.

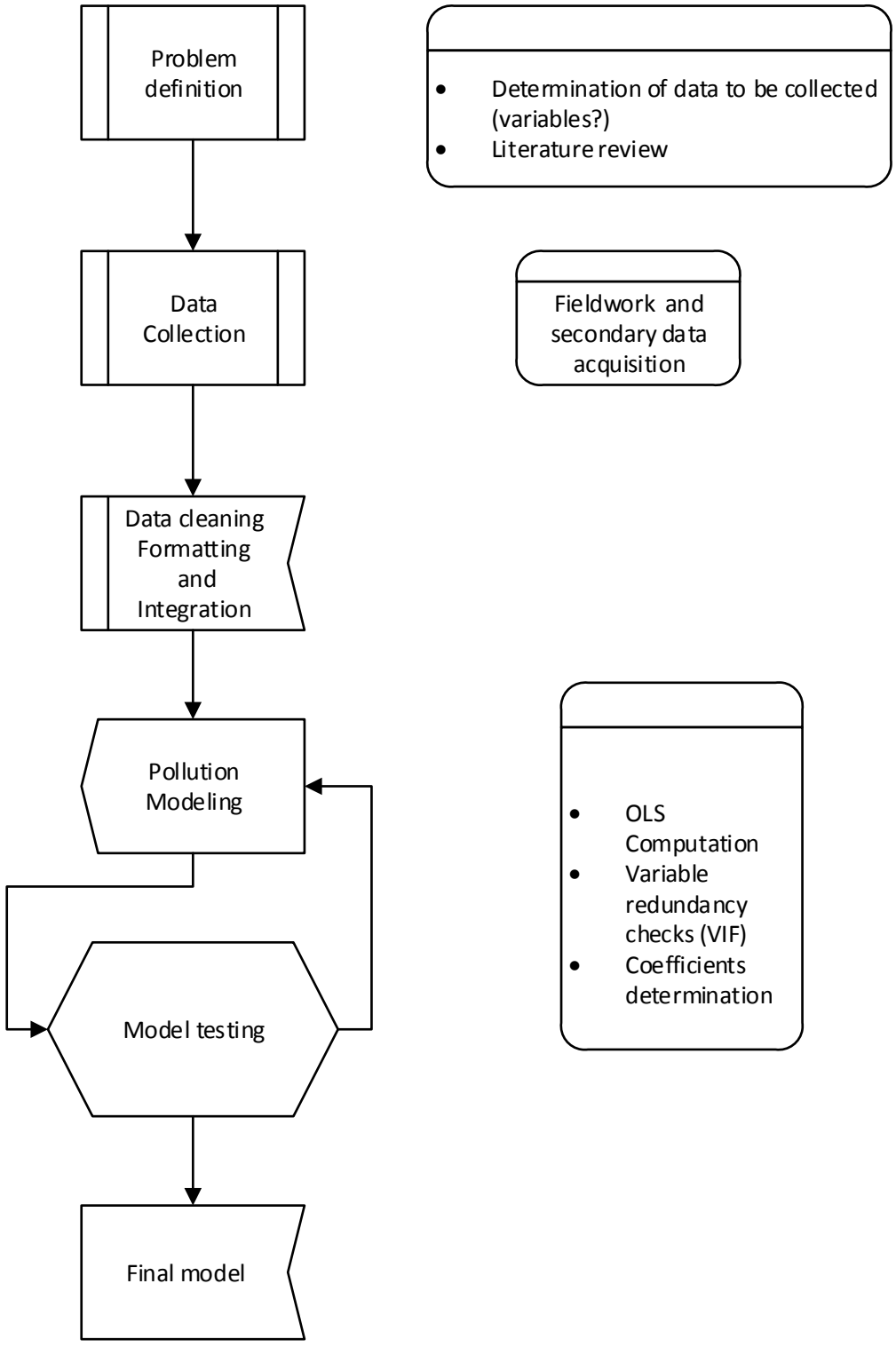


Figure 3. 2: Conceptual framework

3.3 Sampling

Primary data was obtained from field measurements (see appendix) where sampling was carried out in all the nine identified sites within Nairobi city. BGI 400S personal air samplers (Figure 3.3) were used to collect the fine particles on pre-weighed Teflon filters. For each sampling site, three different spots were selected on different roads. The samples were collected for a period of eight hours simultaneously in the three selected sampling spots, reflecting both the morning session (0730 – 1530 hours) and afternoon session (1130 - 1930 hours). It was not possible to undertake a 24 h sampling since the samplers were set in public places where the security of the personnel and equipment could not be guaranteed, especially at night. The sampling period in this study reflects the activity hours when city residents are undertaking their daily routines. The results will be significant in the scope of air pollution measurement since this is the period that will need to be addressed by any control measures regulating air pollution in Nairobi city.

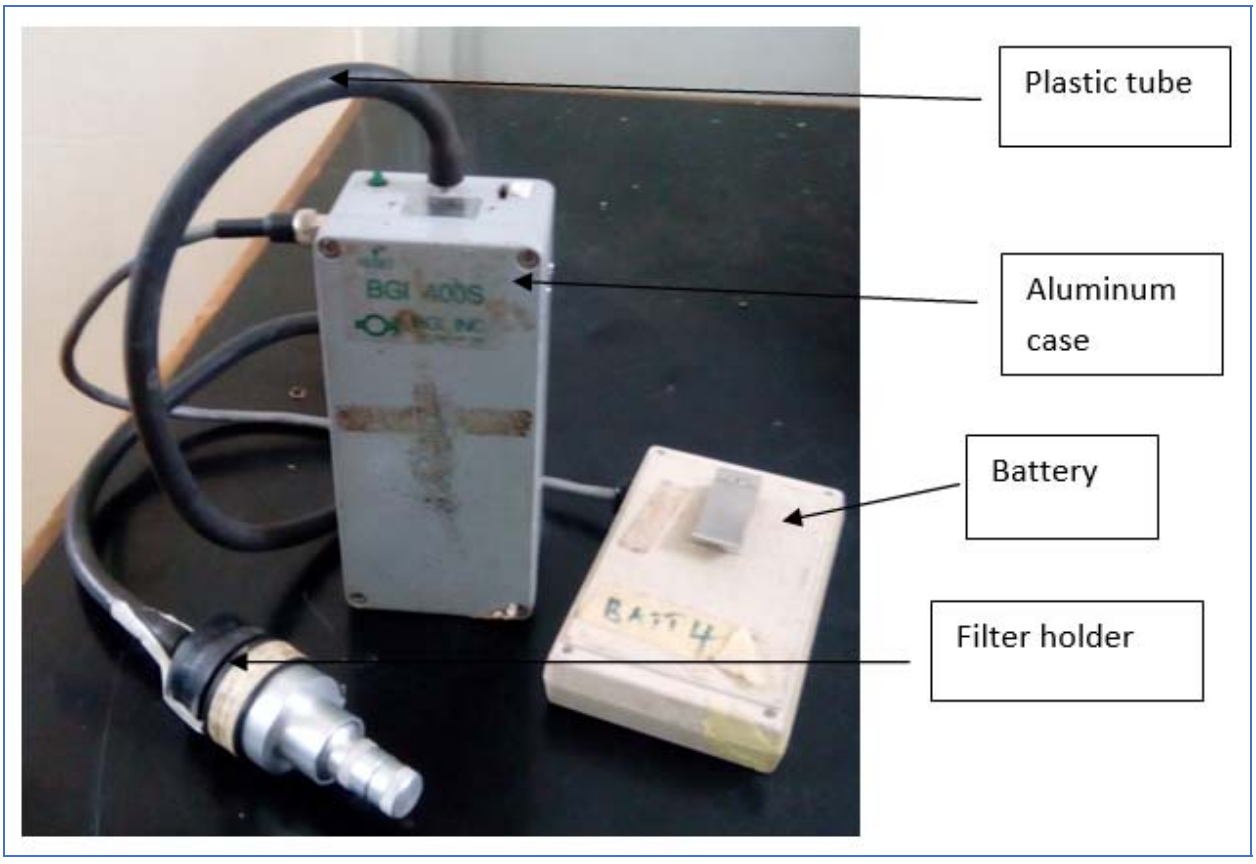


Figure 3. 3: BGI 400S personal sampler

The BGI-400 is designed for usage using the BGI cyclone that runs at 4 LPM and measure $PM_{2.5}$ fraction. An aluminum case houses the double diaphragm pump, electronic control board, double pulsation dampers and an elapsed time indicator having a Lithium battery backup. External controls consist of an on/off switch, flow rate setting potentiometer which is accessed through a hole for resetting the elapsed time indicator. The whole interior of the case is covered with sound deadening material that leads to basically quiet operations. An appropriate filter is usually placed into the filter holder which is connected by a length of plastic tube to the inlet of the sampler.

The sampling campaign was carried out in nine locations across the city. Below is a brief description of the sampling sites as shown in figure 3.4.

i. **Globe cinema roundabout:** The roundabout is an entry point to Nairobi CBD. It receives traffic from Thika superhighway, the busiest highway in Eastern Africa, Westlands via museum hill, and Uhuru highway. Majority of the vehicles using the road were private cars and public service vehicles. Heavy commercial vehicles were rare.

ii. **Outer-Ring road roundabout:** The roundabout is locally known as "Rounda". The roundabout forms an intersection between outering road, Juja road and Komarock road. The sampling location had a high density of heavy commercial vehicles and public service vehicles. In addition, there were road construction activities taking place nearby. Biomass burning was also evident.

iii. **Nyayo Stadium roundabout:** The roundabout forms a junction between Mombasa road and Langata road. The roundabout receives traffic to and from Nairobi CBD and Industrial area. Most vehicles that passed through the junction were private cars and public service vehicles, since heavy commercial vehicles are denied transit through the CBD. The personal samplers were set at the entry to the roundabout along Uhuru highway, Langata road, and Lusaka road.

iv. **City Mortuary roundabout:** This site is located next to Kenyatta National hospital and the city mortuary. It forms the intersection between Ngong road, Valley road and Mbagathi road.

v. **Nairobi CBD:** The sampling site is located within Nairobi central business district. Three locations were selected i.e. at the junction of Accra and River Road, Junction of Accra road and Tom Mboya Street, and near Kenya National Archives, Moi Avenue. The site has numerous retail shops, supermarkets, among other businesses, with a high pedestrian and vehicle traffic. Additionally, the sampling site hosts a mini bus stops, serving as an important transfer point for PSVs linking various destinations in rural Kenya as well as urban and peri-urban estates.

vi. **Industrial area:** The sampling area has a dense concentration of industries. Pedestrian and vehicle traffic was generally low.

vii. **Kariokor (Ngara) Roundabout:** The roundabout serves as an access point to downtown Nairobi CBD and estates east of the city (Eastlands). It receives traffic to and from Juja road, Thika road and Jogoo road. Biomass burning was taking place in the area, mostly as a source of warmth for the street families living in the location.

viii. **Sarit centre (Westlands) Roundabout:** Serves traffic to and from urban and peri-urban estates west of the city.

ix. **The junction (Dagoretti corner) Roundabout:** The roundabout is located next to the Junction shopping mall. It forms the intersection between Naivasha road, Ngong road and King'ara road, linking the city of Nairobi to Langata, Dagoretti, Karen and Ngong estates in the outskirts of the city. Majority of the vehicles using these roads are private cars and low number of heavy commercial vehicles.

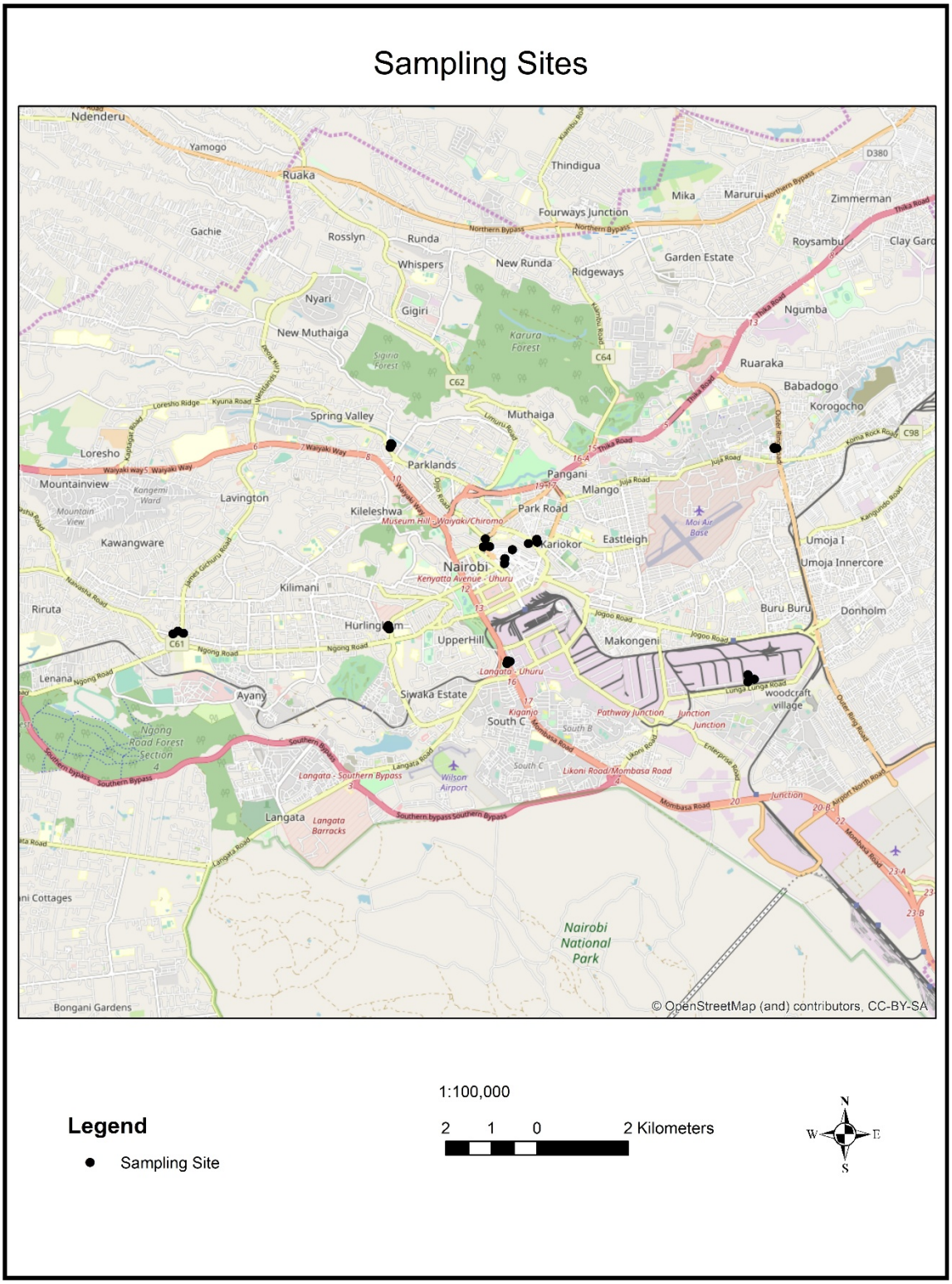


Figure 3. 4: Sampling sites

The samplers were mounted on a stand at a height of 1.5 meters, to approximate the breathing zone. A total of six samplers were deployed per sampling site, whereby, three samplers were

running simultaneously for the morning session and the other three for the afternoon session. The flow rate of these samplers was set at four liters per minute (LPM), through an anodized aluminum cyclone to remove particles with aerodynamic diameter greater than 2.5 μm prior to deposition of fine particulates on the Teflon filters. Air was drawn in by the sampler's vacuum pump that was powered by a rechargeable battery. Prior and after every sampling event, flow rates were measured and recorded using a pre-calibrated rotameter. In addition, the sampling periods were recorded by a digital timer on the sampler. After sampling, the loaded filters were sealed in Petri dishes to avoid contamination and were transported to the laboratory for gravimetric and elemental analyses.

3.4 Sample Analyses

A total of 54 samples were collected during the sampling campaign. The samples were analyzed for $PM_{2.5}$, elemental content and BC concentration. $PM_{2.5}$ mass concentration was determined gravimetrically using a microbalance. This is achieved by getting the difference in filter weights before and after sampling, and factoring in the volume of air, expressed in μg m^{-3}. The volume of sampled air was calculated by multiplying the flowrate by the filter sampling period.

EDXRF spectrometer at the Institute of Nuclear Science and Technology was used in this study to analyze $PM_{2.5}$. The spectrometer has a tungsten anode X-ray tube and a silver secondary target. The general XRF principles apply, where electron beam emitted from the anode are accelerated towards the secondary target. The primary beam excites the secondary Ag target, which in turn emits characteristic X-rays that excite the elements in the sample. A Si(Li) detector was used to detect the characteristic lines emitted from the sample, indicative of the elemental content. Each sample spectra was acquired for a period of 1000 s at a tube voltage and current of 30 KV and 80 μA, respectively.

Spectra deconvolution was carried out using AXIL, a component of Quantitative X-ray Analysis Software (QXAS) from the International Atomic Energy Agency (Bernasconi et al., 2000). The software was used to identify and quantify different elements using the K_α and L_α lines in the spectra. Here, elemental concentrations were obtained in μg m^{-2}, which were then converted into ambient concentrations in μg m^{-3}, by factoring in the sampled air volume and the sample

deposition area. For quality assurance purposes, thin standard reference sample filters; SRM 2783_1462 and SRM 2783_Blank, from National Institute of Standards and Technology, were analyzed in a similar manner as the sampled filters. The thin standard spectra were used to calculate the detection limits (DL) of the analytical method using equation 3.1 (van Grieken and Markowicz, 1993).

$$DL = 3C\frac{\sqrt{N_b}}{N_P} \quad \text{.....equation 3.1}$$

Where; C is the certified concentration, N_b is the background area, and N_p is the element peak area.

Black carbon analyses were carried out at the Gothenburg University using black carbon reflectometer (ESM Emberline, model FH62 1-N). The reflectometer measures the reflected light intensity from the loaded filters. The reflected light intensity at 650 nm is observed to nonlinearly reduce as BC concentrations rise on the filter (Gaita et al., 2014).

3.5 Pollution Dispersion Model

A pollution dispersion model based on regression was developed to assess the relationship between the dependent and the explanatory variables. It involved the use of the field measurement ($PM_{2.5}$, and BC) data and secondary data. Secondary data was obtained from government organizations. This included vehicle volume termed as Annual Average Daily Traffic (AADT) obtained from Road agencies (KURA and KENHA) for the roads where sampling was done. Meteorological data (wind speed, air pressure, temperature and wind direction) was obtained from the meteorological Department of Kenya. The approximate number of vehicles per site obtained from KENHA and KURA traffic flow data is shown in table 3.1.

Table 3. 1: Traffic flow for access roads to the sampling sites

S/No.	Road	AADT	S/No.	Road	AADT
1	Kirinyaga	21767	15	River Road	9503
2	University Way	16150	16	Outering Road	38657
3	Kipande Road	21767	17	Juja Road	21917
4	Lusaka	44666	18	Koma Rock Road	2692
5	Uhuru Highway	79981	19	Naivasha Road Junction	9692
6	Lang'ata	44666	20	Ngong Road Junction	21052
7	Ngong	15443	21	Kingara Road Junction	4780
8	Mbagathi	61059	22	Synresin Industrial Area	2148
9	Valley Road	26562	23	Darling Industrial Area	2148
10	Ring Road	22277	24	Lunga Lunga Road	3148
11	Ngara Road	22277	25	Lower Kabete Road	17812
12	Racecourse Road	17978	26	Parklands Road	18393
13	Moi Avenue	10978	27	Ring Road Parklands	18393
14	Tom Mboya	16779			

A Regression model was adopted for the study where Ordinary Least Squares (OLS) was adopted based on multiple regression equation 3.2.

$Y = a + b_1 X_1 + b_2 X_2 + b_3 X_3 + ... + b_n X_n + u$ …….equation 3.2

Where Y= Dependent variable

X= independent/explanatory variables

a = intercept

b = slope

u = regression residue

When running the OLS model, elevation, distance from the roads and wind direction proved statistically redundant due to the nature of the sampling and were dropped from the model.

CHAPTER 4:

Results and Discussions

4.1 $PM_{2.5}$ Mass Concentration

The results of fine particulate matter concentrations in samples collected in major roundabouts across Nairobi City are presented in Figure 4.1. The highest mean concentration values were recorded at Kariokor at 147 ± 89 μg m^{-3}, while the lowest was recorded at the industrial site at 52 ± 4 μg m^{-3}.

The high $PM_{2.5}$ concentrations reported at Kariokor and Outer-Ring roundabouts could be attributed to anthropogenic activities taking place in the area, as well as vehicle type and density. For instance, at Kariokor roundabout which is intersection between Racecourse road, Ngara road and ring road, burning of refuse was observed right in the middle of roundabout during morning hours. In addition, the area also hosts light (Jua Kali) industries where activities such as burning of tyres and plastics, as well as smelting of metals take place. Majority of the vehicles plying through the area were heavy commercial vehicles and public service vehicles (buses and minibuses), which are run on diesel fuel. On the other hand, Outer-Ring roundabout located east of the city, forms an intersection between Outer-Ring road, Juja road and Komarock road. The area was characterized by road construction activities, high density of diesel vehicles such as buses and heavy commercial vehicles, as well as roadside food kiosks where biofuels were used. These activities in addition to heavy traffic experienced could have contributed to the high $PM_{2.5}$ concentrations recorded.

The lowest mean $PM_{2.5}$ concentration was recorded in an industrial site at 52 μg m^{-3}. The low PM concentrations could be attributed to minimal activities taking place in the location. In addition, low traffic volumes were observed. This is contrary to expectations where industrial areas are associated with high pollution levels. It is worth noting that sampling during this particular study was done at a shoulder level, whereas most industries release emissions through chimneys, hence their impact could be experienced more at higher heights and far off areas due to wind dispersion.

Three sampling locations were selected per sampling site for sample collection. The sites were located on different access roads to the roundabouts or on different streets in the case of CBD and the industrial site. Although variations in $PM_{2.5}$ concentrations amongst these sites were noted, these variations were not statistically different. The differences could be contributed by difference in pollution dynamics such as vehicle density on a particular road/ street, proximity to pollutant sources and anthropogenic activities taking place.

The study was designed to capture both morning (0730 – 1530 hours) and afternoon (1130 – 1930 hours) sessions. In some sampling sites, differences in $PM_{2.5}$ concentrations between the two periods were reported. For instance, at Sarit Center round about, the mean $PM_{2.5}$ concentration for the morning session was 104 $\mu g\ m^{-3}$, as compared to the afternoon session at 52 $\mu g\ m^{-3}$. The huge difference could have been brought about by change in weather where heavy downpour was experienced in the afternoon. This contributed washout of the particulates hence the measured lower concentrations. A similar observation was reported by Gaita et al. (2014), in a two-year $PM_{2.5}$ monitoring study in an urban background site in Nairobi City. The lowest concentrations were recorded during the rainy seasons while the highest was during the dry periods. The author further linked a higher annual mean in the year 2009 relative to the subsequent year to a drought spell, during which the WHO air quality standard for 24 h was frequently exceeded. Other probable reasons for these differences could be heightened human related activities during certain hours and changes in traffic density.

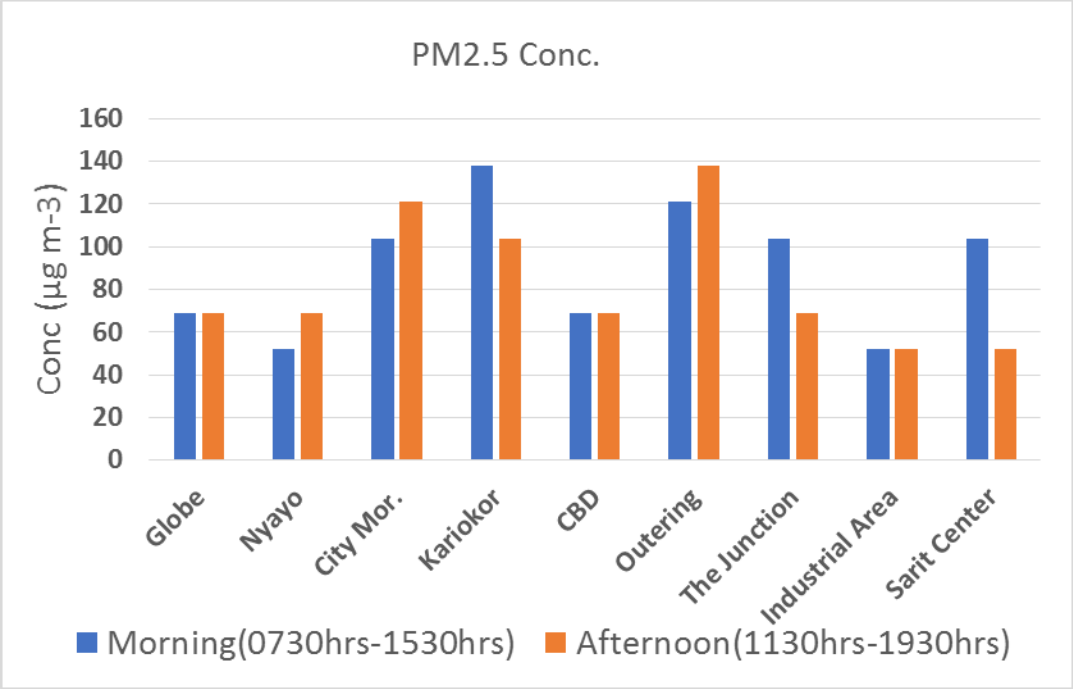


Figure 4.1: Mean $PM_{2.5}$ concentrations in major roundabouts across Nairobi City

This data was collected for eight hours, representing the daytime/ peak averages, for two months. Therefore, the captured data can neither be compared directly with the world health organization's 24 h mean nor the annual health related guidelines for $PM_{2.5}$ concentrations set at 25 µg m^{-3} and 10 µg m^{-3} respectively (WHO, 2006). However, this research data represents the peak activity hours and was expected to be higher than the 24 h mean that represents both the peak and low activity hours, at night.

4.2 BC Concentration

The results obtained from black carbon analyses of the Teflon filters using thermal optical method are presented in Figure 4.2. Compared to previous studies carried out in the area, the BC concentration values obtained in this study were considerably lower. The mean concentration for the nine sampling sites ranged from 8.6 ± 3.3 µg m^{-3} to 2.1 ± 1.2 µg m^{-3}.

Higher concentrations were reported in areas that had high density of diesel vans (locally known as 'Matatus'). For instance, the highest concentrations were recorded at Sarit Centre, Globe

Cinema and Kariokor roundabouts. Globe Cinema and Kariokor form an entry point to Nairobi central business district (CBD) and heavy public transport (matatus) were observed for the better part of the sampling durations. The two sites serve the traffic from Thika road, one of the busiest highways in Eastern Africa, as well as the highly populated estates east of the city. In addition, incidences of biomass burning witnessed in the area could have contributed to the higher concentration levels. Sarit Centre also recorded high number of vehicles especially during morning hours. On the other hand, the lowest BC concentrations were reported in an industrial site. This site reported the lowest vehicle traffic and human activities.

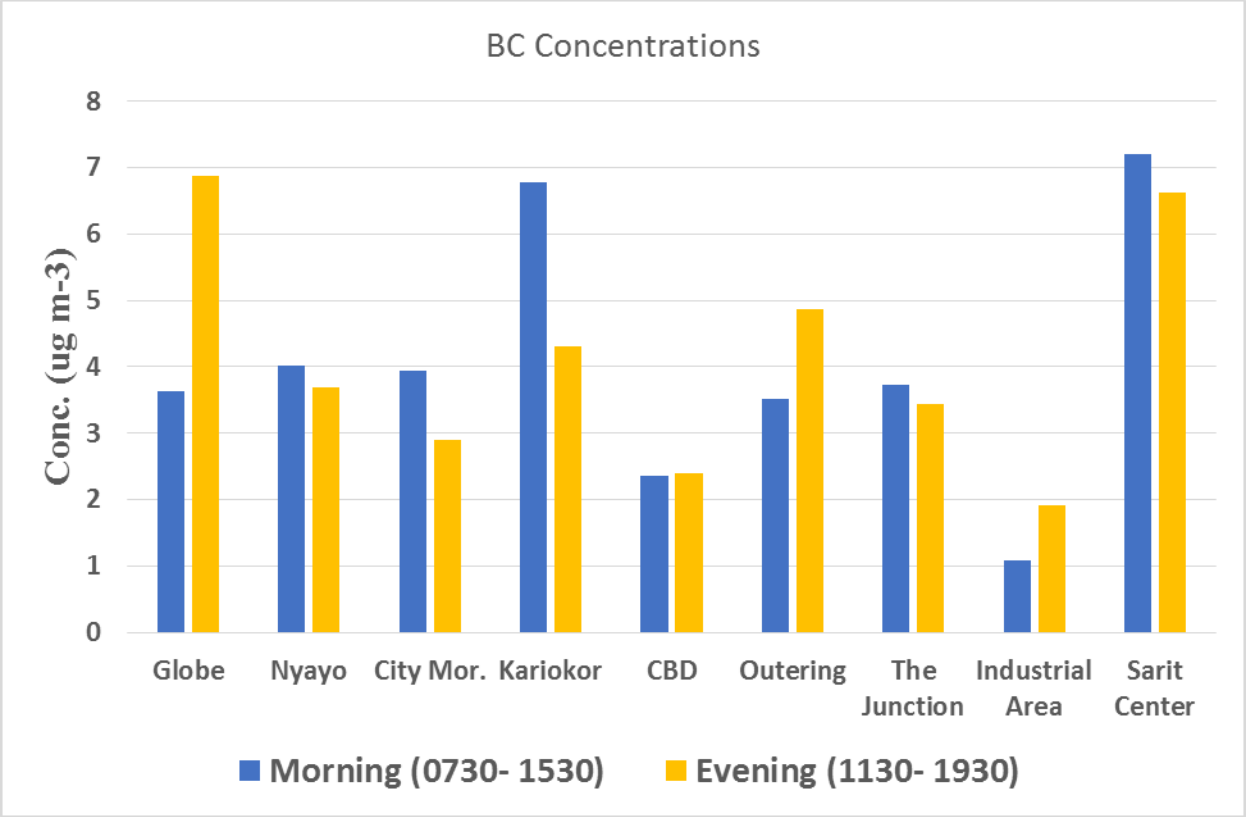


Figure 4. 2: Mean BC concentrations

A positive correlation between $PM_{2.5}$ and BC concentrations was observed (Figure 4.3, r^2 = 0.56). This is an indicator of the significance of BC component to $PM_{2.5}$ composition in the city. The most significant sources of BC in urban environment are incomplete combustion of fuels,

traffic emissions, biomass and waste burning, generators, thermal electric power plants and diesel burning boilers (Gatari et al., 2009).

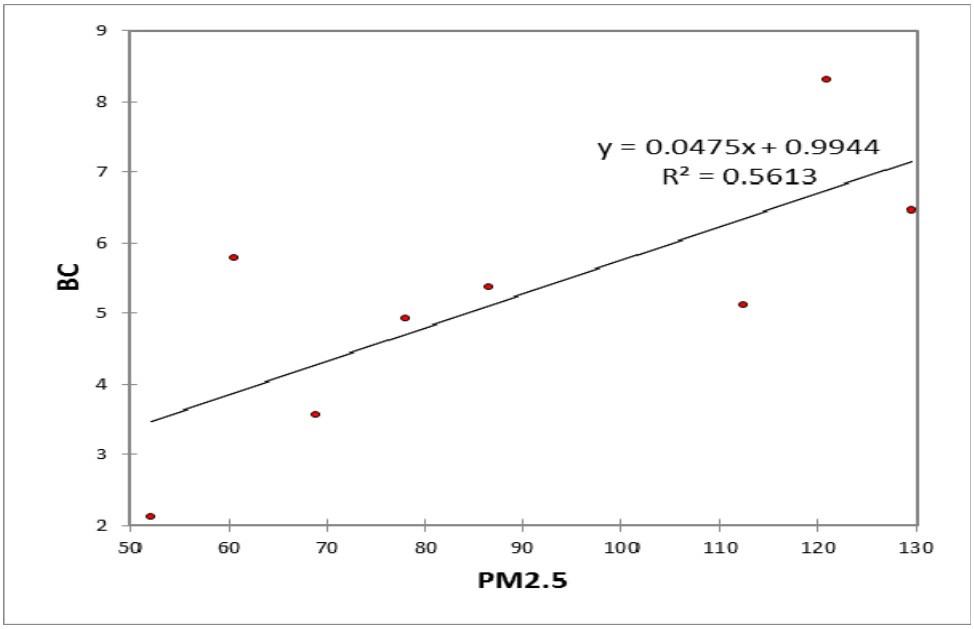


Figure 4. 3: Correlation between BC and PM2.5 concentrations

The BC fraction of the $PM_{2.5}$ was found to vary and is a good indicator of completeness or incompleteness of combustion of fuels (Gatari et al., 2019). In this study, the BC fraction ranged between 4 – 10 % (Table 4.1). A previous study by Gatari et al. (2019) at a street canyon and subsequent assessment of BC on Nairobi archived samples of 2009, reported a higher BC fraction that ranged between 34% - 56 % which was attributed to biomass burning and fossil fuels combustion. The lower BC fraction observed in this study may be due to reduced traffic emissions, pollutant dispersion and dilution of the BC component by the mineral dust and volatile organic carbon component. A related study by van Vliet & Kinney (2007), reported a BC fraction of 24 %, while Gaita et al. (2014), in an urban background in Nairobi reported a BC fraction of 11 %.

Table 4. 1: Percentage of BC fraction in $PM_{2.5}$

Site	BC	PM2.5	% BC fraction
Globe Cinema Roundabout	8.58	98	9%
Nyayo stadium Roundabout	5.78	60.5	10%
City Mortuary Roundabout	5.13	112.5	5%
Kariokor roundabout	8.31	121	7%
Central business district	3.57	69	5%
Outering roundabout	6.46	129.5	5%
The Junction roundabout	5.37	86.5	6%
Industrial Area(Lunga Lunga road)	2.12	52	4%
Sarit Center roundabout	4.92	78	6%

BC is one of the health detrimental components of $PM_{2.5}$. Although comparatively lower concentration levels have been reported in this study, the study was conducted for a short period hence cannot be conclusive in terms of seasonal variations and trends. Higher concentrations have been reported in previous short-term studies (Gatari et al., 2019; van Vliet & Kinney, 2007). This means that the city residents such as the shopkeepers, drivers and pedestrians, could still be exposed to high pollution levels with detrimental effects on their heath. A report by WHO (2004), identified urban air pollution as a risk factor to lung cancer and cardiovascular diseases. Similar findings were made by the Clean Air Task Force report (CATF, 2014), where black carbon and diesel combustion emissions were identified as a significant cancer risk factor.

4.4 Elemental Concentrations

The Teflon filters used to collect data for $PM_{2.5}$ were analyzed for elemental content using EDXRF spectrometer. First, method validation was done using certified reference material, ICP multi-element from International Atomic Energy Agency (IAEA). Table 4.2 gives the results of the analyses of the thin sample, where the experimental and certified values were statistically similar. This meant that EDXRF spectrometer could be confidently used in the analyses of the collected samples. The data from the certified reference material was further used to calculate the detection limits.

Table 4. 2: Experimental Vs. certified values of trace elements

	Experimental	Certified
Ca	14 ± 2.1	13 ± 1.4
Cu	<0.15	-
Mn	0.31 ± 0.07	0.32 ± 0.04
Fe	27 ± 3.1	26 ± 1.9
Zn	1.8 ± 0.2	1.8 ± 0.2

The elemental content of the fine particulates sampled across major roundabouts in Nairobi city are presented in Table 4.3. Fe, Mn, Cu, Zr, Zn, and Pb were determined above detection limits. The detected trace elements accounted for 15 % of the species in $PM_{2.5}$, while BC accounted for approximately 8 %. The highest mean concentration was recorded for Fe, followed by Mn and Cu at 2800 ± 3700 ng m^{-3}, 2600 ± 40 ng m^{-3}, and 2200 ± 370 ng m^{-3} respectively. The higher Fe content could be associated with iron oxide that is contained in Kenyan soils giving them the reddish colour (Gaita et al., 2016). The lead content in $PM_{2.5}$ was less than WHO annual

guideline of 500 ng m^{-3} (WHO, 2000). This observation could be linked to the phasing out of leaded gasoline that was previously added in vehicle engines as anti-knock agent.

Table 4. 3: Detection limits and elemental concentrations (ng m^{-3})

	Mn	Fe	Cu	Zn	Zr	Pb
Detection limits	1210	200	50	470	480	30
City mortuary roundabout.	2370	2260	2580	1080	850	< 30
Central business district	2430	670	1560	950	860	210
Industrial area	2360	1060	2850	1110	750	100
Kariokor roundabout.	3500	11540	2220	800	930	70
Nyayo roundabout.	2610	570	2220	1010	850	60
Globe roundabout.	2030	1350	2240	810	1020	170
sarit center roundabout.	2410	340	1910	810	880	90
The Junction roundabout.	2930	1020	1970	1120	890	30
Outering rd. roundabout	2570	6520	2300	1140	870	30
Average	**2600 ± 40**	**2800 ± 3800**	**2200 ± 380**	**1000 ± 100**	**900 ± 70**	**90 ± 60**

Table 4.4 shows the correlation matrix between various elements determined in this study. It was observed that there was no significant correlation between these elements. This could be due to contribution of these elements from different sources. For instance, Gaita et al., (2014), used PMF which is a multivariant factor analysis method for source apportionment of $PM_{2.5}$ content. Elements were associated with several source factors. For example, Fe was associated with exhaust and non-exhaust emissions, mineral dust, combustion processes, as well as industrial emissions. Similar observations were made for other elements.

Table 4. 4: Elemental correlation matrix

Variables	Fe	Cu	Zn	Zr	Pb
Fe	**1**	0.14	-0.19	0.24	-0.29
Cu		**1**	0.38	-0.37	-0.43
Zn			**1**	-0.64	-0.51
Zr				**1**	0.25
Pb					**1**

The elemental concentrations obtained in this study are higher than those obtained by Gaita et al. (2016) at a height of 17 m above ground level. Iron, Mn, Zn, and Cu were determined in samples at 69 ± 99 ng m^{-3}, 4.7 ± 6.2 ng m^{-3}, 22 ± 38 ng m^{-3}, 22 ± 38 ng m^{-3}, and 0.7 ± 2.3 ng m^{-3}, respectively. Other elements determined above detection limits included Si, S, K, Ca and titanium.

Gatari et al. (2005b) carried out research on trace element categorization of pollution origins within the equator town of Nanyuki, Kenya. In fine PM, the highest concentrations were reported for S, Cl, and K and 390 ± 30 ng m^{-3}, 390 ± 40 ng m-3 and 545 ± 65 ng m^{-3}. Values for most elements were below those reported in this study. For instance, Fe and Mn concentrations were determined at 60 ± 10 ng m^{-3} and 5 ± 1 ng m^{-3}. This could be attributed to heightened activities in Nairobi city as compared to Nanyuki town. The lead levels were however comparable to those reported in this study at 13 ± 2 ng m^{-3}.

Comparable elemental contents have been recorded in other African cites. Ezeh et al., 2015, assessed elemental content of $PM_{2.5}$ across Nigerian Cities. The Fe, Mn, Zn and Pb concentrations were determined at 1500 – 12800 ng m^{-3}, 115 – 175 ng m^{-3}, 95 – 170 ng m^{-3} and 22 – 65 ng m^{-3} respectively.

4.5 Particulate Matter based on multivariate regression modeling

A pollution dispersion model based on regression was developed to assess the relationship between the dependent and the explanatory variables. The histograms present the way each variable is distributed. OLS doesn't need variables to be normally distributed. Every scatter plot represents the relationship between dependent and the explanatory variable. Strong relationships appear as diagonals while the direction of the slant signifies if the relationship is negative or positive. Coefficients represent the strength and type of relationship between the dependent and explanatory variable. The Variance Inflation Factor (VIF) indicate the redundancy of the explanatory variable if it is >7.5.

Table 4. 5: Model of morning $PM_{2.5}$ variables

Variable	Coefficient	VIF
AADT	-0.05	1.40
WINSPEED	-0.50	1.73
AIRPRES	116.60	1.56
TEMP	1.37	2.29
HUMIDITY	-1.91	2.24

Table 4.5 shows that temperature and Air pressure have positive relationship with morning $PM_{2.5}$ while humidity, vehicle volume and wind speed have negative relationship. VIF values shows that the model variables are not redundant as the values are <7.5. This is illustrated by the scatter plots in Figure 4.4.

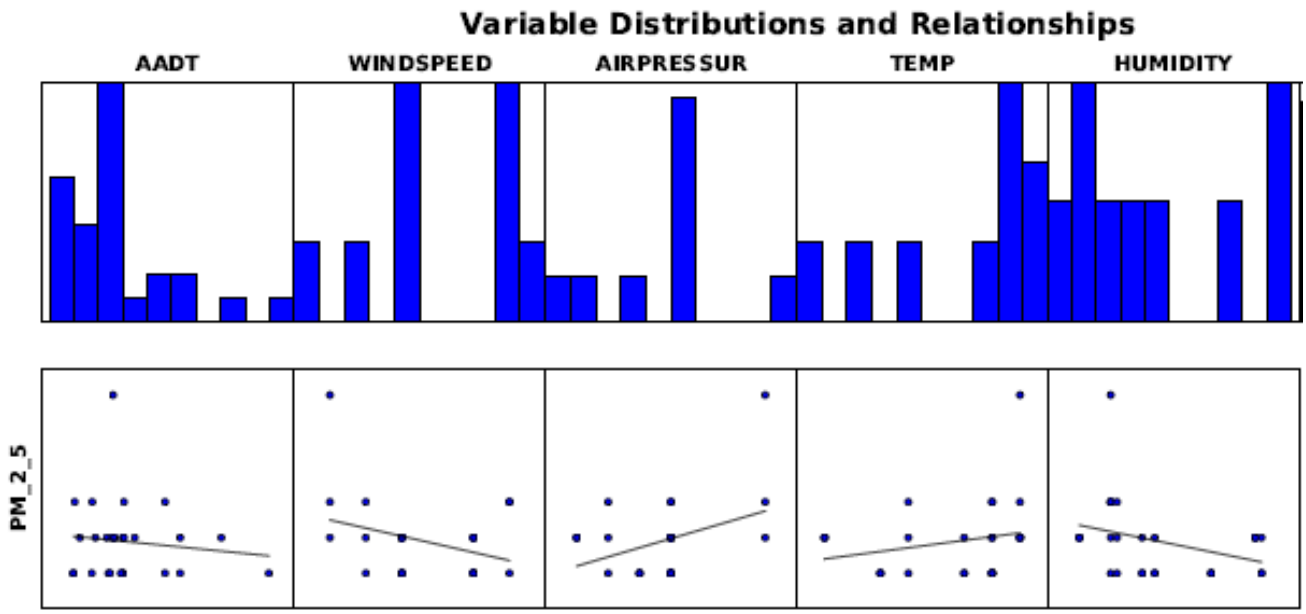


Figure 4. 4: Top) Histogram indicating distribution of each independent variable and, bottom) scatter plot representing the relationship between morning $PM_{2.5}$ and the independent variables

Table 4.6 shows that AADT, wind speed, air pressure and temperature have a positive relationship with afternoon $PM_{2.5}$ while humidity has a negative relationship with afternoon $PM_{2.5}$. The scatter plots in Figure 4.5 illustrates this variation.

Table 4. 6: Model of afternoon $PM_{2.5}$ variables

Variable	Coefficient	VIF
AADT	0.03	1.69
WINSP	0.56	1.68
AIRPRES	0.69	1.67
TEMP	1.19	2.36
HUMIDITY	-1.47	2.04

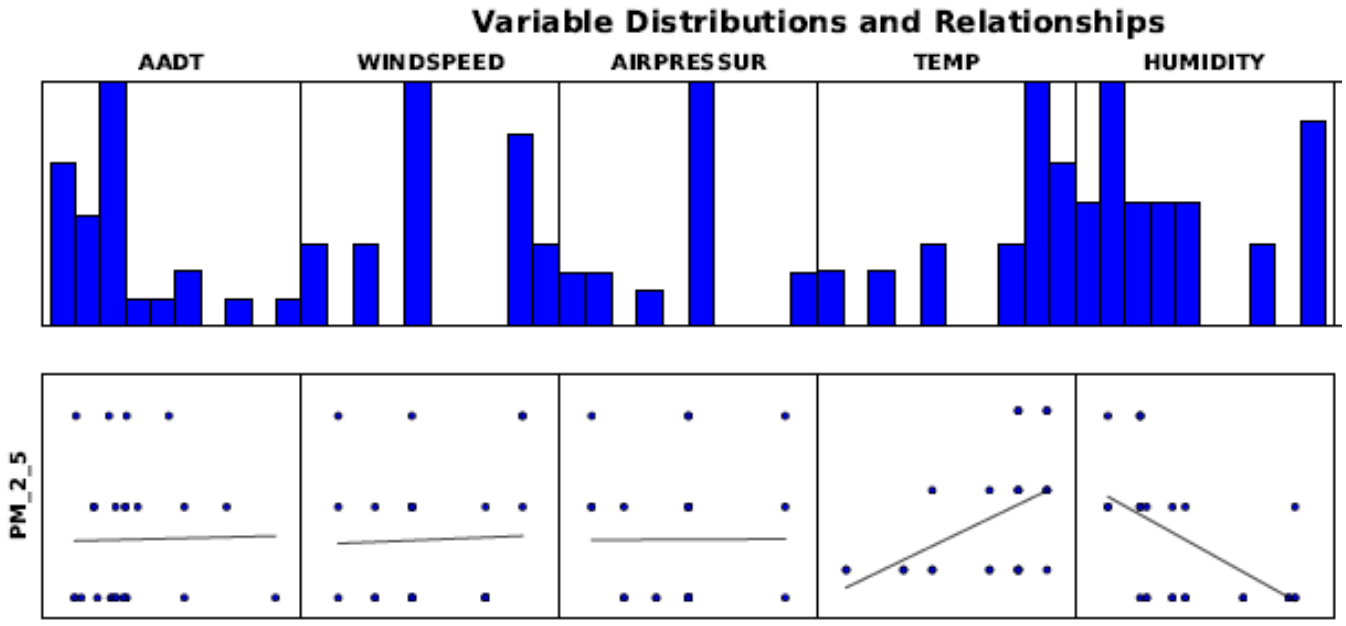


Figure 4. 5: Histogram indicating distribution of each independent variable (top), and scatter plot representing the relationship between afternoon $PM_{2.5}$ and the independent variables (bottom).

The variation of BC in $PM_{2.5}$ is shown in the model variables in Table 4.7 and 4.8, and scatter plots in Figures 4.6 and 4.7.

Table 4. 7: Model of morning BC variables

Variable	Coefficient	VIF
AADT	0.29	1.86
WINSPEED	-0.41	1.68
AIRPRES	124.60	1.53
TEMP	0.06	2.58
HUMIDITY	-0.92	2.28

AADT, air pressure and temperature have positive relationship with morning BC while wind speed and humidity have negative relationship with morning BC. This is illustrated by the scatter plots in figure 4.6.

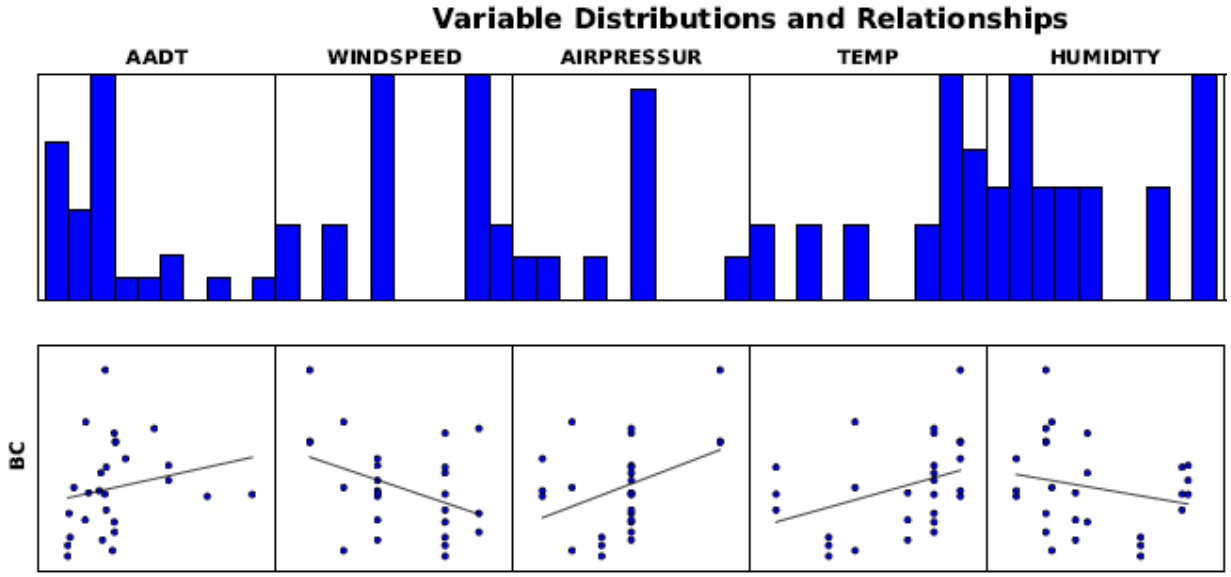


Figure 4. 6: Histogram indicating distribution of each independent variable (Top), and scatter plot representing the relationship between Morning BC and the independent variables (bottom)

Table 4. 8: Model of afternoon BC variables

Variable	Coefficient	VIF
AADT	0.16	1.73
WINSPEED	0.83	1.65
AIRPRES	87.01	1.63
TEMP	0.55	2.36
HUMIDITY	-0.87	2.08

From table 4.8, Vehicle volume, wind speed, air pressure and temperature have positive relationship with evening BC while humidity has negative relationship with afternoon BC. The scatter plots in figure 4.7 illustrates this variation.

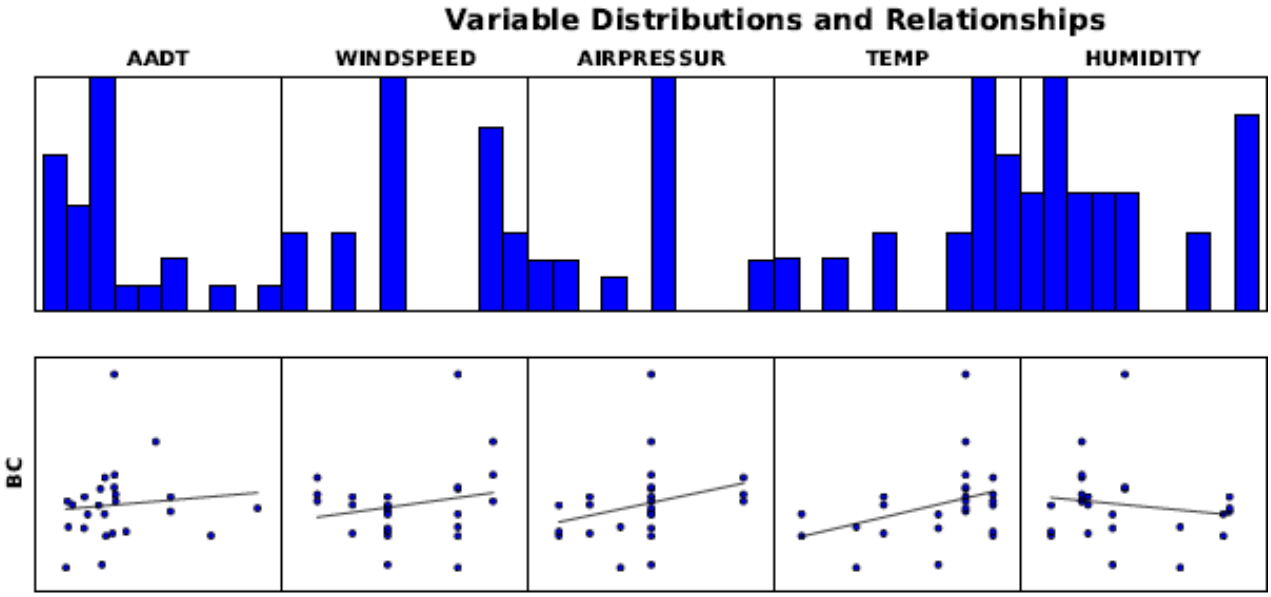


Figure 4. 7: Histogram indicating distribution of each independent variable (top) and, scatter plot representing the relationship between Afternoon BC and the independent variables (bottom)

4.6 Particulate Matter Variability

The variability of the BC and $PM_{2.5}$ concentration was mapped onto a base map of Nairobi and output maps produced showing this variation spatially. The size of the circle is proportional to the concentration per location as shown on each map legend.

4.6.1 $PM_{2.5}$ Variability

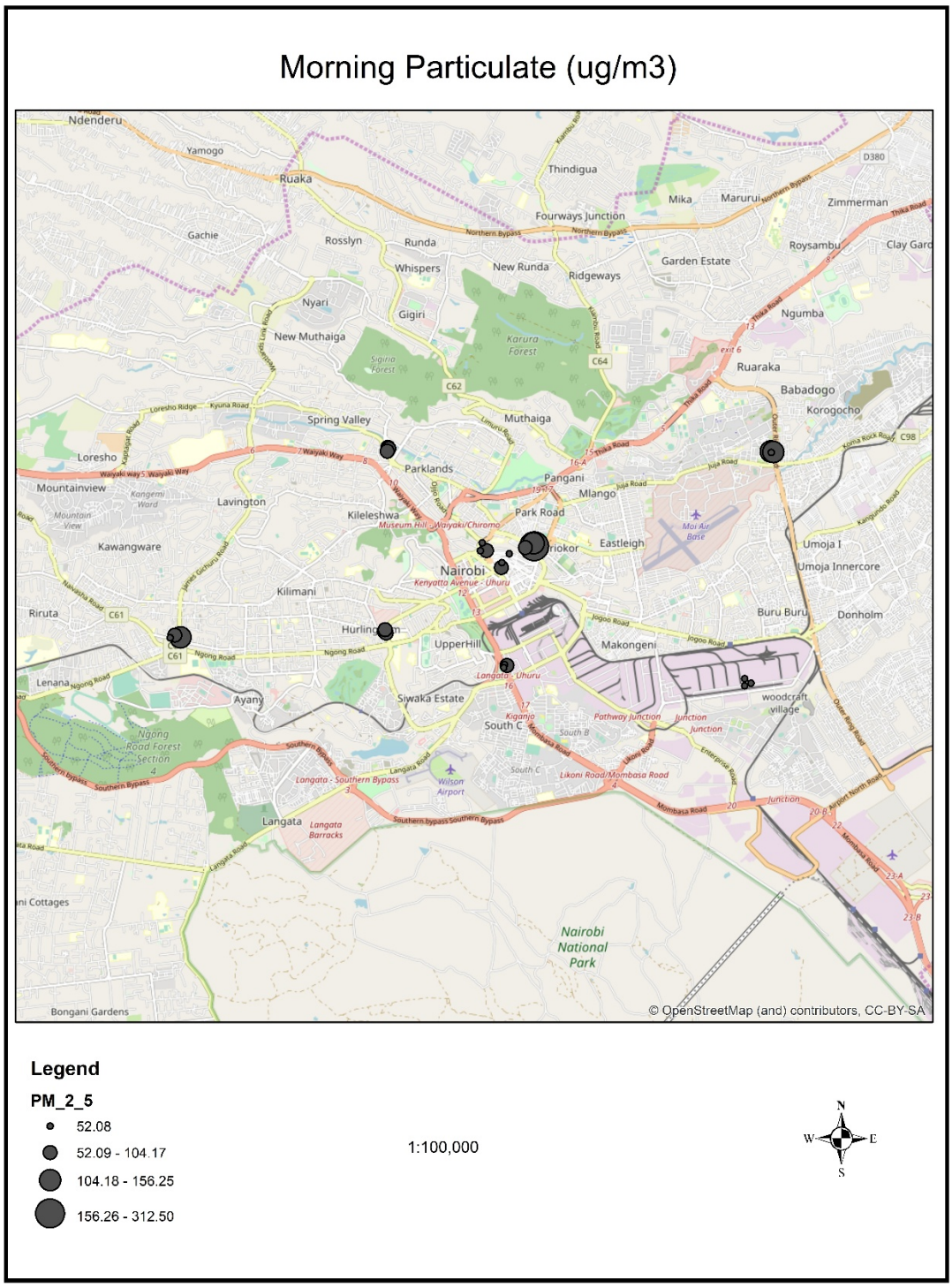


Figure 4. 8: Morning $PM_{2.5}$ spatial distribution

The map clearly shows that the highest concentration was mapped at Kariokor roundabout while the lowest concentration was mapped at industrial area.

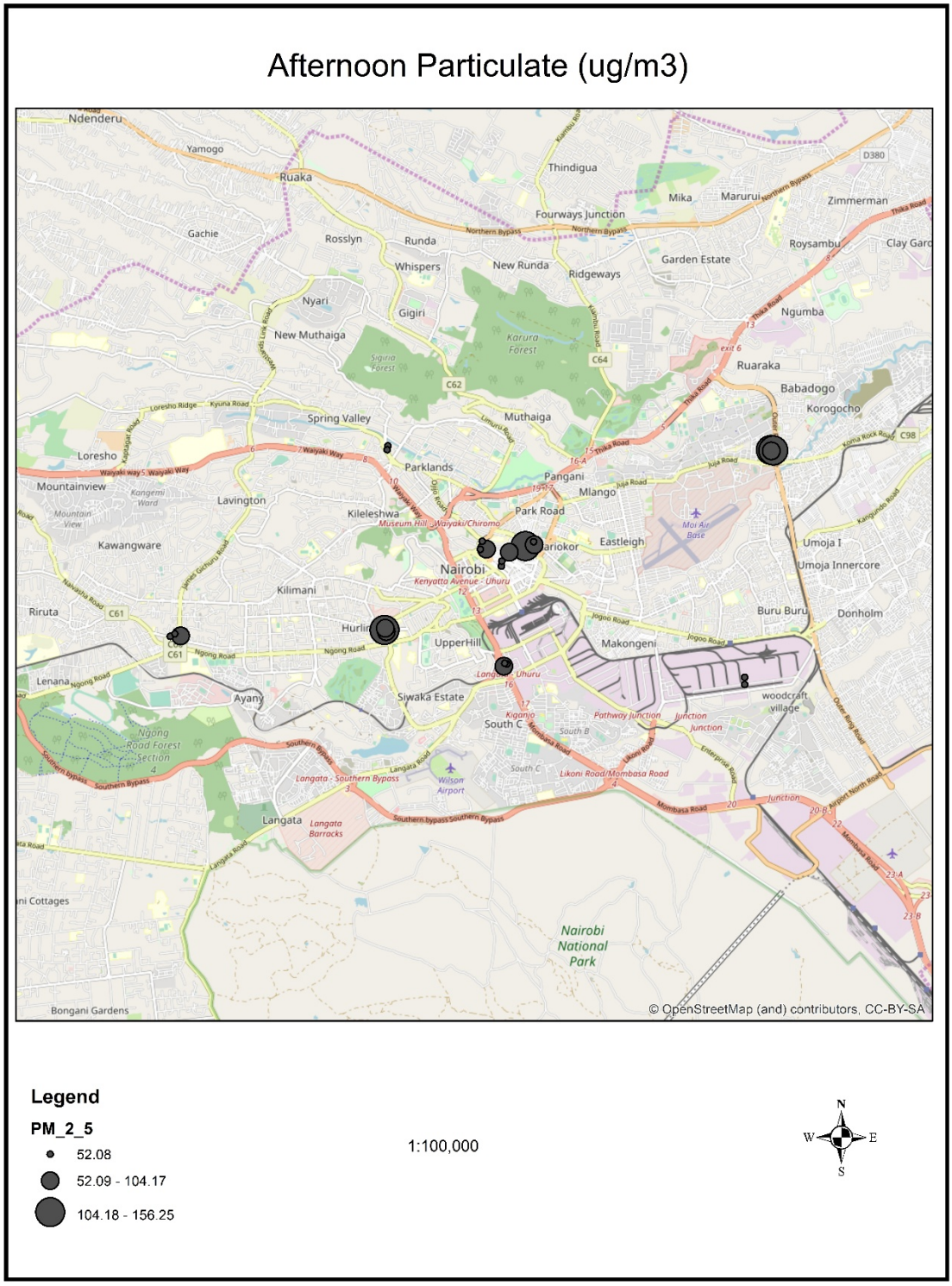


Figure 4. 9: Afternoon $PM_{2.5}$ spatial distribution

The highest concentrations were mapped at Kariokor round about and Outer-Ring road round about while the lowest concentration was mapped at industrial area and sarit centre.

4.6.2 BC Variability

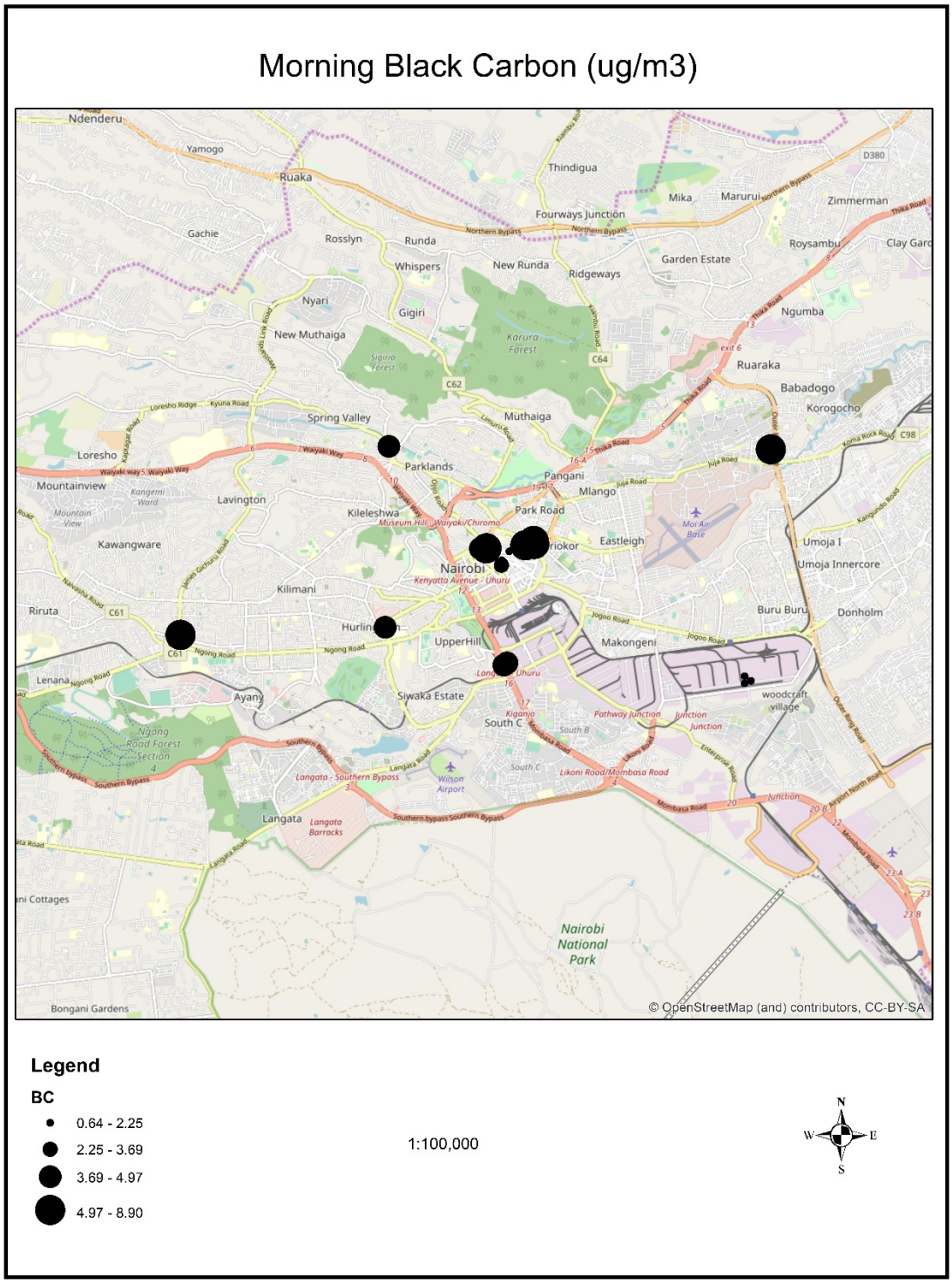


Figure 4. 10: Morning BC spatial distribution

The lowest concentration was mapped at industrial area while kariokor had the highest concentration.

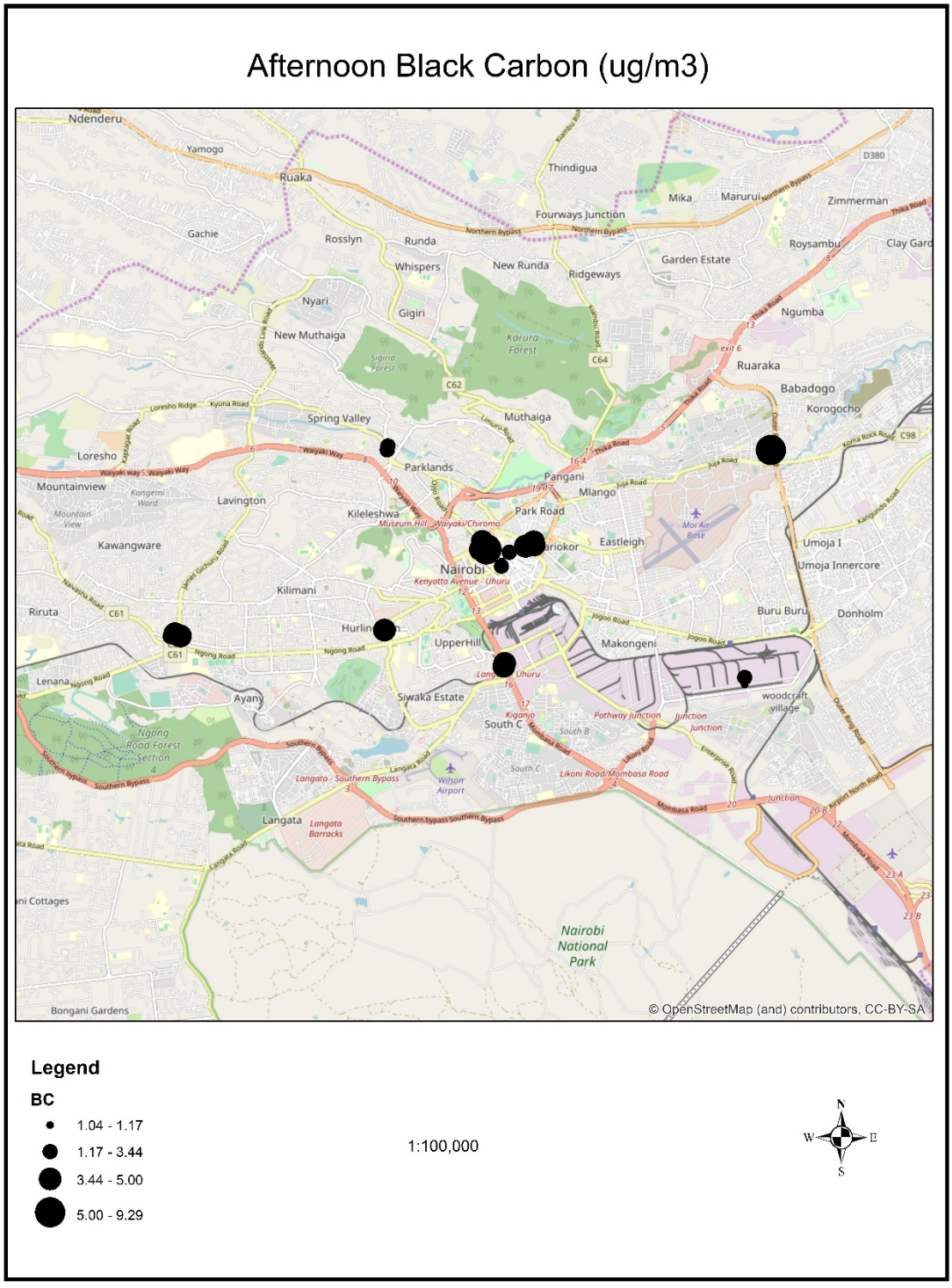
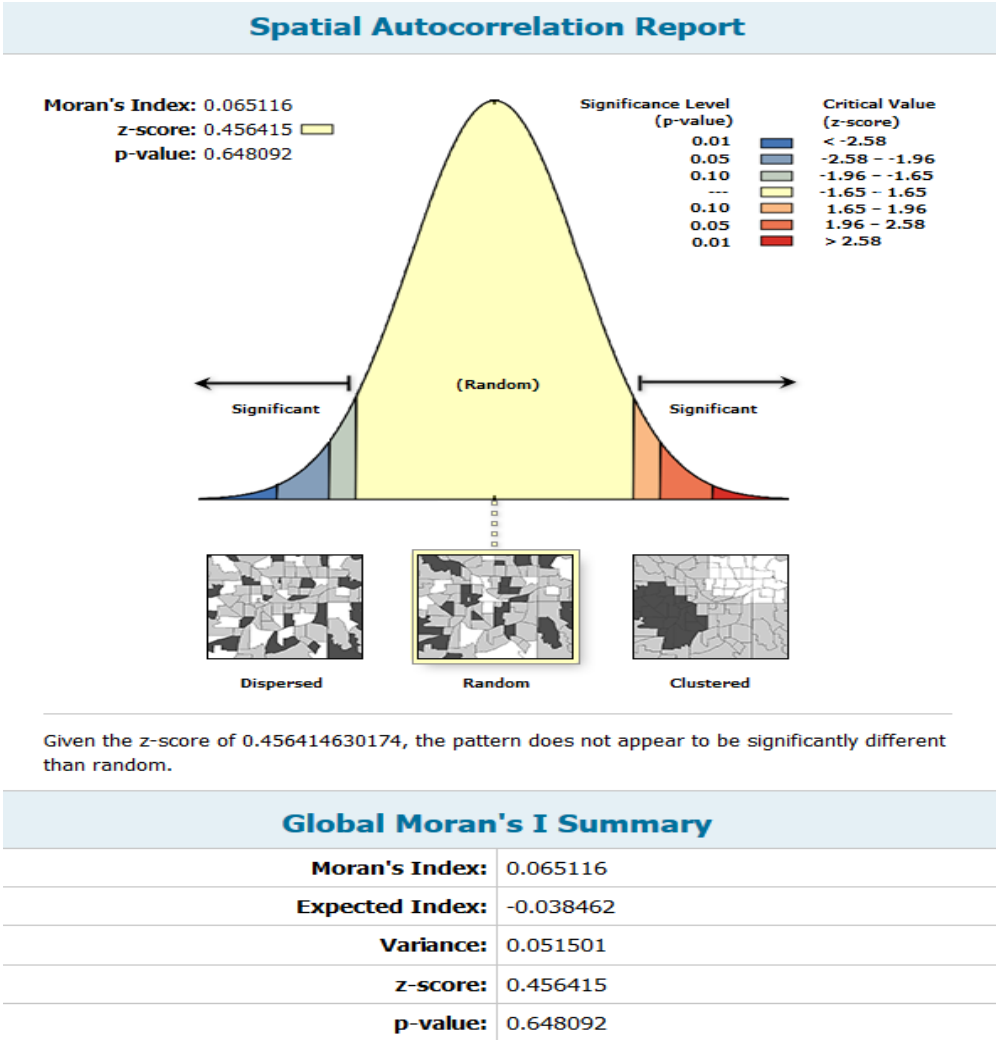


Figure 4. 11: Afternoon BC spatial distribution

The lowest concentration was mapped at industrial area while globe and outer-ring road had the highest concentration.

4.7 Spatial Autocorrelation for Particulate Matter

Spatial Autocorrelation (Morans I) is a spatial statistics tool for analyzing patterns. In this research both $PM_{2.5}$ and BC produced a random distribution pattern as shown in the output result presented in figure 4.12.



Global Moran's I Summary

Moran's Index:	0.065116
Expected Index:	-0.038462
Variance:	0.051501
z-score:	0.456415
p-value:	0.648092

Figure 4. 12: Spatial Autocorrelation (SA) results of $PM_{2.5}$ and BC

The SA results mean that the pollution concentration is randomly distributed among the different locations within Nairobi city. This means that the spatial processes promoting pollution concentration is random chance.

CHAPTER 5:

Conclusions and Recommendations

5.1 Conclusions

The overall objective of this study was to evaluate near road $PM_{2.5}$ in Nairobi city and map the status. According to the first specific objective, sampling points were mainly selected on major roundabouts within the city using a BGI 400S personal samplers. $PM_{2.5}$ mass concentration was evaluated gravimetrically. The highest mean concentration value was recorded at Kariokor at 147 ± 89 μg m^{-3}, while the lowest was recorded at the industrial site at 52 ± 4 μg m^{-3}. The reported concentration differences could be linked to vehicle density, weather and proximity to pollutant sources. The BC concentration values obtained in this study were considerably lower compared to previous studies possibly because the sampling was done during rainy season. The mean BC concentration for the nine sampling sites ranged from 8.6 ± 3.3 to 2.1 ± 1.2 μg m^{-3}. There was a significant correlation between $PM_{2.5}$ and BC concentrations.

The second objective was to determine trace elements in the $PM_{2.5}$ using EDXRF spectroscopy. The elemental contents of Zn, Mn, Cu, Fe, Pb, and Zr were determined above detection limits. The highest mean concentration was recorded for Fe, followed by Mn and Cu at 2800 ± 3800 ng m^{-3}, 2600 ± 40 ng m^{-3}, and 2200 ± 380 ng m^{-3} respectively. The detected trace elements accounted for 15 % of the species in $PM_{2.5}$, while BC accounted for 8 % of the total mass.

The third objective was to map the spatial variations of $PM_{2.5}$ and BC concentrations within Nairobi County. Using GIS the concentrations of BC and $PM_{2.5}$ were mapped and spatial variation maps presented in chapter four. GIS modelling was further undertaken to determine the factors influencing this spatial variation. Temperature, Air pressure and vehicle volume were found to have positive influence on the pollution dispersion in terms of dispersion of the pollutants from the source. Humidity and Wind speed have a negative influence on the pollutant's concentrations. Through multivariate regression, the amount of pollution at a point can be predicted. A compiled report of this research will be given to the environment department of the Nairobi metropolitan services as per the fourth specific objective.

5.2 Recommendations

Environmental pollution monitoring and assessment is important in regulatory and advisory policy making, for the safety and wellbeing of population. With improving economic situations in Kenya, more vehicles are being purchased, mostly second-hand vehicles. A large fleet of second-hand vehicles, in addition to low maintenance capacity in terms of affordability and competence, could result in increasing BC and $PM_{2.5}$ concentrations. Therefore, it is important to undertake regular monitoring of air pollution status. Regular sampling and analysis of air pollution data can better inform policy makers as well as development partners. More research can be carried out especially sampling for long periods and during different seasons of which this study could not achieve due to limitation of time and resources especially human and financial.

GIS is important when space science need to be integrated with policy. For more accurate results, more data is required for calibration of the GIS model. Dense regular sampling would yield a better pollution model hence a clearer picture of the air pollution status. Future study on air pollution should consider 24hr measurements which would be comparable to WHO guidelines.

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Appendices

Appendix 1: $PM_{2.5}$ Mass concentration and BC concentration

Location	Sampling Duration	Filter Code	Mass Conc. (ug m-3)	BC Conc (ug/m3)
Globe Roundabout	Morning	KE-130	52	2.16
		KE-133	52	4.4
		KE-136	52	4.33
	Afternoon	KE-137	52	4.47
		KE-139	104	6.1
		KE-141	104	9.29
Nyayo Rounaabout	Morning	KE-129	52	3.38
		KE-134	104	4.66
		KE-140	52	4
	Afternoon	KE-131	52	3.44
		KE-132	104	4.06
		KE-138	52	3.58
KNH Roundabout	Morning	KE-144	104	3.3
		KE-146	104	3.54
		KE-149	104	4 4.97
	Afternoon	KE-143	156	3.7
		KE-145	104	2.41
		KE-147	104	2.58
Kariokor Roundabout	Morning	KE-148	104	5.73
		KE-152	312	8.9
		KE-153	156	5.69
	Afternoon	KE-150	104	4.88
		KE-151	156	3.88
		KE-154	52	4.16

Appendix 1: PM2.5 Mass concentration and BC concentration (Cont'd)

Location	Sampling Duration	Filter Code	Mass Conc. (ug m-3)	BC Conc (ug/m3)
CBD	Morning	KE-135	52	1.36
		KE-172	52	2.25
		KE-175	104	3.45
	Afternoon	KE-155	52	3.31
		KE-156	52	1.17
		KE-173	104	2.72
Outering rd roundabout	Morning	KE-102	156	2.54
		KE-103	52	1.71
		KE-104	156	6.3
	Afternoon	KE-101	156	3.88
		KE-106	104	5.0
		KE-107	156	6.42
The Junction-Ngong Rd	Morming	KE-105	104	3.69
		KE-109	52	0.89
		KE-167	156	6.59
	Afternoon	KE-164	52	3.72
		KE-165	52	2.5
		KE-166	104	4.06
Industrial Area	Morming	KE-108	52	1.12
		KE-159	52	0.64
		KE-160	52	1.48
	Afternoon	KE-158	52	1.04
		KE-161	52	2.78
Sarit Centre Roundabout	Morming	KE-075	104	2.69
		KE-076	104	4.59
		KE-078	104	3.4
	Afternoon	KE-073	52	3.33
		KE-079	52	2.39

Appendix 2: Elemental concentration in filter samples

Location	Sampling Duration	Filter Code	Mn	Fe	Cu	Zn	Zr	Pb
Globe Roundabout	Morming	KE-130	1,31	<0.02	3,41	1,19	0,57	<0.03
		KE-133	3,43	2,95	2,32	0,94	1,01	0,81
		KE-136	2,16	1,26	1,41	0,84	1,24	<0.03
	Afternoon	KE-137	1,40	0,69	2,85	0,36	1,11	<0.03
		KE-139	1,85	0,51	1,22	0,74	1,20	<0.03
		KE-141	2,14	1,20	1,97	0,80	0,82	<0.03
Nyayo Rounaabout	Morming	KE-129	2,38	1,08	1,74	0,74	0,97	<0.03
		KE-134	0,65	0,14	1,96	1,30	0,42	<0.03
		KE-140	4,62	<0.02	2,65	1,35	0,65	0,13
	Afternoon	KE-131	2,63	<0.02	2,13	0,83	0,50	0,19
		KE-132	1,87	2,19	2,37	0,60	1,43	<0.03
		KE-138	3,53	<0.02	2,47	1,27	1,16	<0.03
KNH Roundabout	Morming	KE-144	3,20	3,92	3,16	1,18	1,38	<0.03
		KE-146	1,40	0,69	2,85	0,36	1,11	<0.03
		KE-149	1,85	0,51	1,22	0,74	1,20	<0.03
	Afternoon	KE-143	1,77	1,68	2,61	1,27	0,36	<0.03
		KE-145	4,13	8,43	1,48	0,76	0,88	0,22
		KE-147	2,29	2,64	2,37	0,88	0,88	<0.03
Kariokor Roundabout	Morming	KE-148	2,50	2,36	2,11	0,50	0,74	<0.03
		KE-152	7,60	48,30	3,04	1,47	1,90	0,14
		KE-153	1,72	4,26	1,41	0,36	0,86	<0.03
	Afternoon	KE-150	2,79	3,30	2,94	0,85	0,38	<0.03
		KE-151	4,13	8,43	1,48	0,76	0,88	0,22
		KE-154	2,29	2,64	2,37	0,88	0,88	<0.03

Appendix 2: Elemental concentration in filter samples (Cont'd)

Location	Sampling Duration	Filter Code	Mn	Fe	Cu	Zn	Zr	Pb
CBD	Morming	KE-135	3,31	0,36	1,13	1,08	1,09	0,13
		KE-172	2,63	<0.02	2,13	0,83	0,50	0,19
		KE-175	2,07	0,52	2,12	1,04	0,72	0,34
	Afternoon	KE-155	2,70	1,22	1,67	0,92	1,01	0,18
		KE-156	3,87	1,90	3,10	1,03	0,63	<0.03
		KE-173	1,66	0,58	1,33	0,80	0,64	<0.03
Outering rd roundabout	Morming	KE-102	1,65	5,30	2,35	0,96	0,76	<0.03
		KE-103	2,01	<0.02	2,20	1,58	1,06	<0.03
		KE-104	2,12	3,44	2,45	0,98	0,87	<0.03
	Afternoon	KE-101	3,57	11,70	2,66	1,29	1,52	<0.03
		KE-106	2,29	2,64	2,37	0,88	0,88	<0.03
		KE-107	2,94	5,67	1,77	1,36	0,35	<0.03
The Junction-Ngong Rd	Morming	KE-105	2,64	1,59	1,40	1,23	0,83	0,05
		KE-109	2,72	<0.02	1,81	0,84	1,18	<0.03
		KE-167	4,01	1,05	2,31	1,73	1,13	0,04
	Afternoon	KE-164	1,85	0,12	1,77	0,99	1,15	0,05
		KE-165	3,87	1,90	3,10	1,03	0,63	<0.03
		KE-166	2,53	1,49	1,44	0,95	0,46	<0.03
Industrial Area	Morming	KE-108	2,25	<0.02	2,76	0,89	0,72	0,20
		KE-159	2,01	<0.02	2,20	1,58	1,06	<0.03
		KE-160	2,36	2,06	3,24	0,60	0,62	<0.03
	Afternoon	KE-158	2,07	<0.02	2,95	1,16	0,75	<0.03
		KE-161	3,11	3,26	3,13	1,37	0,64	0,27
Sarit Centre Roundabout	Morming	KE-075	2,04	1,52	1,12	0,91	0,59	<0.03
		KE-076	2,24	2,76	2,52	0,83	0,57	<0.03
		KE-078	3,12	<0.02	2,71	0,91	1,37	0,14
	Afternoon	KE-073	2,85	0,71	0,87	0,81	0,79	<0.03
		KE-079	1,82	<0.02	2,35	0,63	1,13	0,27