

Characterization of Ambient Air Quality in Selected Urban Areas in Uganda

A Low-Cost Approach

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WORLD BANK GROUP

Urban, Disaster Risk Management, Resilience and Land Global Practice

January 2021

Abstract

Many cities and urban centers around the world experience high air pollution episodes attributable to increased anthropogenic alterations of natural environmental systems. World Health Organization estimates indicate strong exceedances of prescribed limits in developing countries. However, the evidence on local pollution measures is limited for such cities and Uganda is no exception. Informed by the practical realities of air quality monitoring, this paper employs a low-cost approach using passive and active monitors to obtain characterization of pollution levels based on particulate matter 2.5, nitrogen dioxide, and ozone over a six-month period (starting in December 2018) for selected urban centers in three of the four macro-regions in Uganda. This is the first attempt to comprehensively assess pollution

levels at a near-national level in Uganda. A combination of distributed stationary monitors and mobile monitors installed on motorcycle taxis (*boda-boda*) was employed in selected parishes to obtain spatiotemporal variations in the pollutant concentrations. The results suggest that seasonal particulate levels heavily depend on precipitation patterns with a strong inverse relation, which further corroborates the need for longer monitoring periods to reflect actual seasonal variations. Informed by the observed level of data completeness and quality in all the monitoring scenarios, the paper highlights the practicability and potential of a low-cost approach to air quality monitoring and the potential to use this information to inform citizens.

This paper is a product of the Urban, Disaster Risk Management, Resilience and Land Global Practice. It is part of a larger effort by the World Bank to provide open access to its research and make a contribution to development policy discussions around the world. Policy Research Working Papers are also posted on the Web at <http://www.worldbank.org/prwp>. The authors may be contacted at nlozano@worldbank.org.

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Characterization of Ambient Air Quality in Selected Urban Areas in Uganda: A Low-Cost Approach¹

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Key Words: Urban Air Pollution Uganda, Low-cost Air Quality Monitoring in Uganda, mobile air pollution monitoring, Spatiotemporal Variations.

JEL: Q01, Q53, R00,

¹ This work is part of the Pollution Management and Environmental Health program (PMEH) supported under TF0A3415. The PMEH program focuses on providing technical assistance to these countries, facilitating pollution management, promoting public awareness, and helping them reduce the negative effects of pollution on health. The findings, interpretations, and conclusions expressed in this paper are entirely those of the authors. They do not necessarily represent the views of the International Bank for Reconstruction and Development/World Bank and its affiliated organizations, or those of the Executive Directors of the World Bank or the governments they represent.

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1. Introduction

1.1 Background

Air pollution episodes are prevalent in cities and urban centers usually resulting from the cumulative anthropogenic alterations of the natural environmental systems, due to the inevitable and increasing demand for limited resources that often exceed the carrying capacity of cities (Gramsch et al., 2006; Martínez, 2015). According to WHO (2018), more than 80% of inhabitants in monitored urban centers are exposed to pollution levels that exceed WHO prescribed limits (Annex 1).

Consequently, populations in fast-growing urban centers are exposed to air pollution–linked health threats (WHO, 2018) with significant dependence on exposure periods. Broadly speaking, a 2018 WHO report indicates that 7 million people die every year from exposure to air pollution with the majority of deaths occurring in developing countries. WHO further ranks air pollution (i.e. both outdoor from industries, construction & automobiles, and indoor from solid fuel combustion) among the 24 leading risk factors for global mortality (WHO, 2009). A recent OECD (Economic Co-operation and Development Centre) study quantifying human and financial costs of Africa's outdoor air pollution found air pollution to be more deadly in Africa than malnutrition or dirty water; specifically, it estimates that air pollution in Africa kills 712,000 people a year prematurely, compared with approximately 542,000 from unsafe water, 275,000 from malnutrition and 391,000 from unsafe sanitation (OECD, 2016).

Findings from empirical epidemiological studies consistently show association of pollutant exposure and exacerbation of illnesses and increased mortality for cardiovascular and respiratory cases among vulnerable groups, e.g., older people, children, pregnant women, lower socio-economic groupings in low-income countries, etc. (Seaton et al., 1995; Brunekreef & Holgate, 2002; Bellinger, 2005; Kampa & Castanas, 2008). Respectively, morbidity and mortality cases are largely linked to lung cancer, ischemic heart disease and stroke, Chronic Obstructive Pulmonary Disease (COPD), and respiratory infection. For example, a 9-year study (1990s) covering 38 million people in 8 European cities found a significant increase in hospital admissions for asthma and COPD, and Cardiovascular Disease (CVD) for people older than 65 years per $10\mu\text{g}\text{m}^{-3}$ exposure to PM_{10} . More recently (2015), exposure to $\text{PM}_{2.5}$ caused 4.2 million deaths accounting for 7.6% recorded total global deaths thus making it the most important pollutant, and also ranked the 5th global risk factor in 2015. Additionally, O_3 accounted for over 0.25 million deaths (Atkinson et al., 2001; Cohen et al., 2017; WHO, 2018).

A snapshot of historical pollution trends and projections in developed countries and the world's megacities indicate higher per-capita emission levels than cities in low-income economies. However, this outlook is projected to be altered as air pollution has been increasingly severe in fast-expanding cities from non-industrialized countries often exceeding WHO limits (Mayer, 1999). Without any additional action to limit or control air pollution, challenges are only expected to increase as firms and people concentrate further in cities as economic growth rises (Bose, 2010; Kilroy et al., 2015; Martínez, 2015).

Whereas strong regulatory regimes (e.g. restriction of lead and sulfur bearing fuels, strict emission limits, etc.) and technological advances have generally resulted in improved air quality in industrialized economies over time, e.g., China from 2013-2015 (Zheng et al., 2017), a broad plethora of literature and seminal studies still denote distributed pollution levels across a wide

spectrum of urban settings (i.e. from small urban centers to megacities) sufficient enough to be linked to adverse health effects.

In fact, one of the first major efforts to contextualize urban air pollution from a global perspective commissioned by the WHO and UNEP found pollution levels that could be associated with serious health effects in 20 megacities (i.e. cities with a population of more than 10 million) across the world. Generally, exceedances of WHO limits were much higher in megacities in developing countries (largely situated in Asia) with Suspended Particulate Matter (SPM) being the most severe, whereas gaseous pollution levels were somewhat spread throughout the sampled megacities. While air pollution seemed particularly more severe in megacities in developing countries, each megacity had at least one pollutant level exceeding WHO health protection guidelines with vehicle traffic being the single most important ambient pollution source accounting for CO, NO_x, HC and Pb. This was largely based on data from some of the 270 established monitoring sites under the Global Environment Monitoring System/Air Programme covering 45 countries by 1992 (WHO & UNEP, 1993; Mage et al., 1996).

Likewise, subsequent studies investigating urban air quality on a global scale which also focused primarily on megacities and major urban centers found considerable levels of poor air quality. A snapshot of further insights from the global perspective studies (non-encyclopedic list) have been presented as follows: An assessment of air quality from the years 1990-2000 in the 'principal cities' of the world selected from Europe, Africa, North America, Latin America, Asia and Oceania by Baldasano et al (2003) which identified O₃, PM₁₀ and NO₂ as pollutants of concern. Particularly, nearly half of the cities had maximum daily hourly O₃ levels above 200µgm⁻³ with North America (Mexico City), and Latin America (São Paulo, Santiago) recording the highest levels i.e. 491µgm⁻³, 403µgm⁻³, 351µgm⁻³ respectively, whereas most cities in Asia had high PM levels with a number of cities exceeding 300µgm⁻³. These pollutant concentrations were several times higher than the WHO threshold values at the time (i.e. 120 µgm⁻³ and 60-90µgm⁻³ for daily 8-hour O₃ and suspended particulate matter respectively).⁶ A similar study by Gurjar et al. (2008) classified air quality in 18 megacities based on a Multi-Pollutant Index (MPI) and found poor air quality in 13 of the megacities studied. Work on air pollution trends for Kolkata, Mumbai and Delhi (3 megacities in India) by Gurjar et al (2016) based on historical monitoring data (1991-2012) highlighted the severity of NO_x and Particulate Matter ambient concentrations largely coming from transportation and industry. The geographic span of these sampled megacities during various timescales i.e. North America, Europe, Africa, Central and South America and Asia, highlights the historical significance of urban air pollution as a major health and environmental issue for both developed and developing countries, although there has been significant decline in SO₂ and Pb levels attributable to regulatory enforcement.

Rapid population increase coupled with air pollution precursors and economic drivers e.g. motorization, combustion energy, industrialization, and other infrastructural developments may lead to inferring that air quality may be deteriorating in fast-growing urban centers in Africa. However, actual evidence is limited given the lack of adequate real-time monitoring data sets. Countries in Sub-Saharan Africa particularly have had minimal or oftentimes unsuccessful attempts to implement effective air quality control programs (Mage et al., 1996; Mayer, 1999; Baldasano et al., 2003; Petkova et al., 2013), and for a number of cases, data are nonexistent e.g. the WHO (2016) compilation of urban ambient air pollution in global cities had only 9 Sub-Saharan African countries with active monitoring in place, a possible reduction from what was reported in Schwela (2012).

⁶ This study referred to WHO guidelines of 1979, but the standards have since been updated and revised. the current standards are the WHO Air Quality Guidelines 2005.

Nonetheless, a consolidated review of urban air quality based on Particulate Matter by Petkova et al. (2013) for cities in Africa found exceedances of WHO annual and 24-hour limits with levels higher than what is ordinarily observed in already industrialized countries in Europe and America. This is typical in Uganda where available and collective empirical evidence from published and grey literature dating back to the year 1987⁷ points towards a gradual deterioration of air quality in Kampala (Uganda's largest city).

This paper summarizes the key findings and insights from an empirical air quality data collection exercise using low-cost tools. The study advances previous efforts using a low-cost approach and attempts to comprehensively characterize ambient air pollution for selected urban areas in 25 districts in Uganda. This is the first attempt to comprehensively characterize air pollution on a near-national scale, as all previous initiatives focused on Kampala with a single exception i.e. Kirenga et al. (2015) that evaluated Kampala and Jinja. A review of individual published studies indicates a broad measure of limitations and shortfalls that could have rendered air quality characterization (based on specific study findings) inconclusive e.g. limited averaging periods-impeding assessment of temporal variations, pollutants profile, and spatial coverage.⁸ This work provides an important step toward filling this data and knowledge gap.

In what follows, this paper starts by providing a description of the materials and methods used for the low cost and innovative data collection effort used in this study. Section 3 presents the main characterization of pollution measures throughout sampled parishes in Uganda, a first effort of this kind. We conclude with some insights for policy making and suggestions for future research contributing to improving the understanding of air pollution patterns in the developing world.

2. Materials and Methods

2.1 The Case for Low-Cost Air Quality Monitoring

The first step towards managing and reducing air pollution is monitoring. One needs to quantify its scale, magnitude and spatial distribution to really understand where the challenges lie. However, air quality data inadequacy is often linked to the lack of institutional capacity mainly attributed to the associated resource burdens of air quality monitoring e.g. distinctive traditional certified reference instruments are expensive to set up and maintain (Castell et al., 2017 and Hugh et. al 2019). This often leads to sparse distribution of monitoring networks in developing countries; moreover, the unique practical realities of urban centers in resource-strained countries make traditional reference monitoring unaffordable. Consequently, various international environmental agencies and regulatory bodies including US-EPA, European Environment Agency and the United Nations Environment Programme (UNEP) recognize the dire need for supplementary monitoring techniques to provide indicative air quality data.

⁷ These studies include Nyangababo (1987), Nyangababo & Salmeen (1987), Matagi (2002), ICF International (2009), Schwander et al (2014), Kirenga et al (2015), KCCA (unpublished) (2019).

⁸ For example, Nyangababo (1987), and Nyangababo and Salmeen (1987) use lichens and moss for assessment of heavy metal traces in ambient air from industries and traffic; whereas the study is a good reference baseline for ambient heavy metal concentrations in Kampala, it cannot be a representative indication of the current air quality situation given the drastic changes in the physical environment within the last 30 years. Matagi (2002) provides a qualitative profile of emission sources but lacked quantitative measurement data. Schwander et al. (2014) whose findings were based on two 24-hour measurements in a single location can only be used to characterise levels within the monitoring location and restricted to 24-hour averaging periods. Kirenga et al., (2015) was the first study to focus on 2 major urban areas in Uganda (Kampala and Jinja), however, this was restricted to one-month monitoring and therefore findings are restricted to concentrations experienced within one meteorological month, disregarding the pronounced seasonal fluctuations in pollution levels.

Low-cost monitors (both passive and active) that can cost a fraction of the reference monitors⁹ have increasingly been adopted to supplement reference monitors. However, the monetary boundaries of ‘low-cost’ are still colloquial and very subjective e.g., US-EPA defines ‘low-cost’ as <US \$2,500, and Morawska et al. (2018) review of low-cost sensing technologies preferred a US \$1,000 threshold (Castell et al., 2017; Morawska et al., 2018). To date, several initiatives (see **Table 1** for a non-exhaustive list of initiatives) from academia and regulatory bodies have taken interest in low-cost active sensor platforms. The paradigm shift from traditional monitoring restricted to reference instruments towards a mixed network of sensors can be attributed to its immense and demonstrable potential for substantive reduction in monitoring costs and improvement in spatial coverage-a strong case for low-cost approaches to revolutionize urban air quality management.

This study leverages on these advances and employs low-cost monitors (primarily AirQo from Makerere University) uniquely designed to withstand the environmental and physical conditions such as dust, extreme weather conditions, unreliable power and intermittent internet connectivity. These devices are portable air quality monitors that can be deployed statically or mounted on mobile devices (**figure 2**) to provide pollution snapshots. AirQo monitors were supplemented by diffusive passive samplers also proven to be cost-effective for characterizing spatial variability over varying landscapes e.g. urban and rural as well as seasonal and annual trends (Van Reeuwijk et al., 1998; Chao and Law, 2000; Vardoulakis et al., 2009).

Table 1: Examples of low-cost sensor platform initiatives

Initiative	Focus area(s)
EuNetAir http://www.eunetair.it/	Developing new sensing technologies for air pollution control and environmental sustainability
CamMobSense	Focusing on small scale sensor deployment
EveryAware http://www.everyaware.eu/	Aiming to enhance environmental awareness using portable gas sensors
Citi-Sense and Citi-Sense-MOB http://www.citi-sense.eu/	Technological platforms for distribution monitoring
PiMi Airbox	Indoor air quality monitoring
Smartsantander http://www.smartsantander.eu/	Developed networks of internet-based devices (including air quality) for smart cities
CAIRSENSE	US-EPA project for testing low-cost sensors

⁹ Measurement instruments certified by regulatory bodies, e.g., US-EPA operating under a rigorous set of regulatory protocols, are usually referred to as the ‘gold standard’ of air quality monitoring.

Village Green https://www.epa.gov/air-research/village-green-project	US-EPA community-based project aimed at raising awareness on local air quality
AirVisual https://www.airvisual.com/	Aimed at creating a crowd sourced global network for static air quality monitors
PurpleAir https://www2.purpleair.com/	a US-based low-cost air quality monitoring network

Data collection focused on anticipated emissions from anthropogenic processes within the predefined study areas with a primary focus on Particulate Matter (PM_{2.5} and PM₁₀), supplemented by NO₂ and O₃ passive data sets. These pollutants are not only indicative of the ambient air pollution profile in Uganda but are also within the context of WHO-classical and US-EPA-criteria pollutants i.e. pollutants considered to have adverse effects on human health upon inhalation and ingestion (through contaminated food & water), and to a small extent, dermal contact (cited in Kampa & Castanas, 2008) as informed by empirical clinical and epidemiological studies (see table 2).

Table 2: Classical and Criteria Pollutants (WHO, 2005; EPA, 2018)

Classical Pollutants	Criteria Pollutants	Major Sources
PM	PM	Automobile-generated particulates, combustion emissions, industrial sources, dispersion and ambient suspension of loose surface particulates by wind, etc.
NO ₂	NO ₂	Direct combustion of fossil fuel from thermal fixation of atmospheric nitrogen in the combustion environment
O ₃	O ₃	Series of reactions between NO ₂ and VOCs, CO, CH ₄ , etc. initiated by sunlight
SO ₂	SO ₂	largely combustion of Sulphur bearing fuels
	CO ¹⁰	Incomplete combustion of fuels and inadequate ventilation due to limited oxygen supply e.g. tobacco smoke, engine exhaust, etc.

2.2 Geographic Scope (Study Area)

This study was restricted to predefined geographical project boundaries in selected sub-counties¹¹ within three of the four macro-regions of Uganda (i.e. Central, Southern and Eastern) defined to

¹⁰ Only available from US-EPA criteria pollutants.

¹¹ Sub-counties are the official administrative units which collectively make up a district, which then are aggregated to form macro-regions (presently four in total).

be representative of the spatial distribution of manufacturing firms in Uganda, and consistent with the official administrative boundaries of Uganda. Because the air pollution assessment was designed to accompany a firm survey designed to be representative of the firm distribution across the country, exclusion of the Northern region was informed by low population density and low firm density of the targeted firm categories. The study set out to collect 6-month pollution data with primary focus around the major emission sources in urban centers¹² and targeted firms within the sampled locations.

As mentioned above, the decisions for deployment of monitors started from the pre-selected sub-counties and was supplemented by collation of grey literature to help establish parish level boundaries for the monitoring exercise (i.e. re-aligning with the pre-selected boundaries from the firm-level survey) and map out tentative locations for stationary monitors including boundaries for mobile monitoring-partly informed by the authors' knowledge of the local environment.

The field validation exercise to all the selected sub-counties followed, with the objective to confirm static deployment locations and identify boundaries/routes for supplementary mobile monitoring for areas where static would not have adequate spatial coverage. Spatial boundaries and buffer zones of key pollution generating activities with the potential to affect local air quality were also identified during the field validation exercise. As anticipated, major pollution generating activities including target firm categories were largely situated in urban areas. For stationary deployment, a maximum of 1-2km impact zones (region within the physical environment and activities that can affect local air quality) were considered as most major emission sources within the study areas are closer to the ground (<3m above the ground) having largely localized effects. This was partly informed by study objectives and the fact that there is no official air quality monitoring in Uganda (i.e. there are no Air Quality Management Areas).¹³ Lists of all the sampled sub-counties with respective parishes were uploaded onto a portable mapping tool (ArcGIS collector) for precision during the field visits and corresponding GPS coordinates for all potential locations in visited sub-counties were obtained (**figure 1**).

¹² Since there is no universal threshold/definition for urban centers (Chomitz et al., 2005; UN, 2017), we adopted the official classification of urban areas in Uganda, i.e., gazetted administrative centers including District Headquarters, Cities, Municipalities, Towns, Town Boards and all Trading Centers with a population of more than 1,000 persons (UBOS, 2001) and all sampled locations met this criterion. This threshold is also comparable to other jurisdictions, e.g., Chomitz et al. (2005) and UN (2017), and adopting a different threshold would not have significantly altered the sampling, in fact even the US census threshold of 288 persons per square kilometer adopted for the parish level firm survey was way below the average parish level population density.

¹³ It is typical for regulatory practice, e.g., UK-EA, to define impact zones for air quality risk assessments prior to establishing monitoring sites.

using AirQo monitors (<https://www.airqo.net/>) for real-time particulate matter sampling and 2-month passive sampling using Palmes-type diffusion tubes supplied by Gradko International for supplementary gaseous monitoring (NO₂ and O₃). Monitoring devices were installed between 2.5 to 4m high (i.e. within breathing zone) to ensure pollution levels captured is reflective of population exposure. For O₃ and NO₂, monitoring tubes were removed at the end of every 4 weeks and shipped to a UK based ISO 17025 accredited laboratory for pollutant analyses and results relayed over emails. Volunteers were opportunistically identified and recruited to host the monitoring devices.

Mobile sampling was conducted along predefined routes converging at a stationary monitoring location. These were largely ‘popular’ *boda-boda* routes within the respective geographic boundaries. It is standard practice for *boda-boda* riders to operate from within specific geographic boundaries, and rider recruitment (from the predefined areas of interest) was largely informed by this fact. All devices deployed on *boda-boda* had inbuilt GPS modules to track and attribute monitoring data to specific locations (see figures 2a and 12). Data was then streamed in near-real-time to an online platform over a local cell-phone network.

Under mobile monitoring, riders were presented with 2 scenarios:

Scenario 1 (Opportunistic Monitoring): Mobile data routes were identified and highlighted to the riders but *boda* movements were not restricted i.e. riders were free to collect data alongside their regular schedules.

Scenario 2 (Restrictive Monitoring): Riders were asked to spend about 30 minutes in selected spots during specific times of the day i.e. morning before 08:30, afternoon between 14:00 and 16:30, and evening between 17:00 to 21:00 (riders usually stop working after 21:00). In addition, they were asked to specifically ride through the defined routes on their way to/from the selected spots. In both cases, monitoring was done during active hours of the day to correspond with riders’ typical working hours i.e. (from around 06:00 to 21:00) and the stoppage times were chosen to correspond to the highs and lows of expected typical diurnal profile (figure 4).

Real-time PM data from active monitors (AirQo and PurpleAir tools) were automatically uploaded to the cloud platform at a frequency ranging 30-80 seconds, with variations depending on mode i.e. whether static or mobile and available power options. The resulting data sets informed the average pollutant concentrations within specific static deployment neighborhood along with spatiotemporal variations from mobile sampling.¹⁴

2.3.1 Meteorological Data

Supplementary meteorological data (humidity, temperature and precipitation) were obtained from weather stations situated within the national climatic zones in line with sampled locations. These compilations included both historical data sets and measurements obtained during the pollution assessment period. Sampled precipitation compilations were superimposed on pollution plots to indicatively assess the meteorological influence on seasonal variations.

¹⁴ All active monitors were collocated (in a controlled environment) with a high-end factory calibrated instrument Turnkey Osiris (<https://turnkey-instruments.com/product/osiris/>) prior to deployment to establish any correction factors, whereas analysis for the passive monitors was handled by an ISO 17025 accredited laboratory.

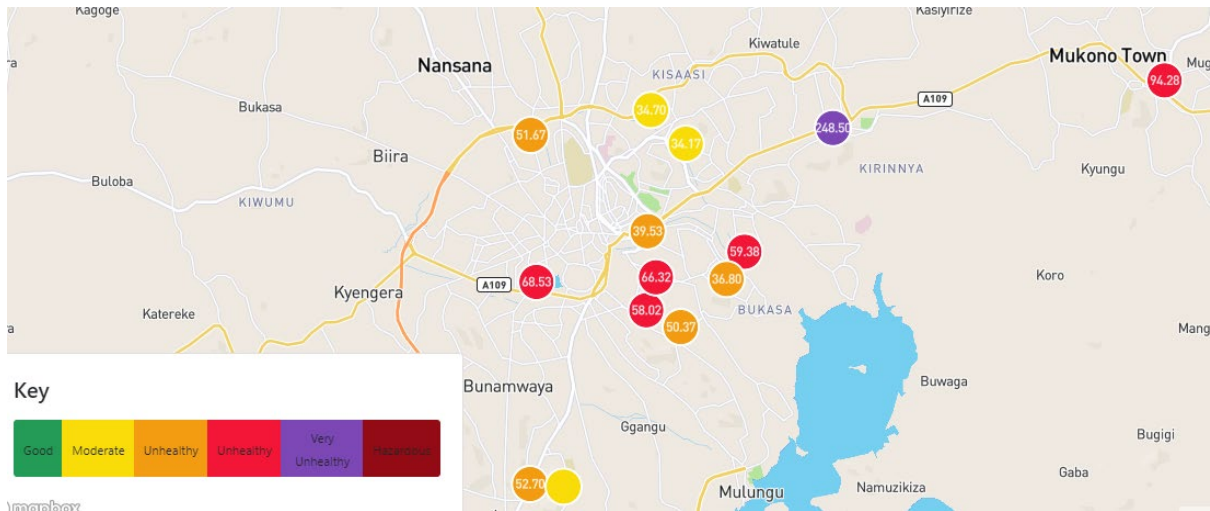


Figure 3b: Distribution of static Installations in Kampala and Wakiso Districts (Central Uganda: 25-Aug-2019)

3. Results and Discussion/Key Insights

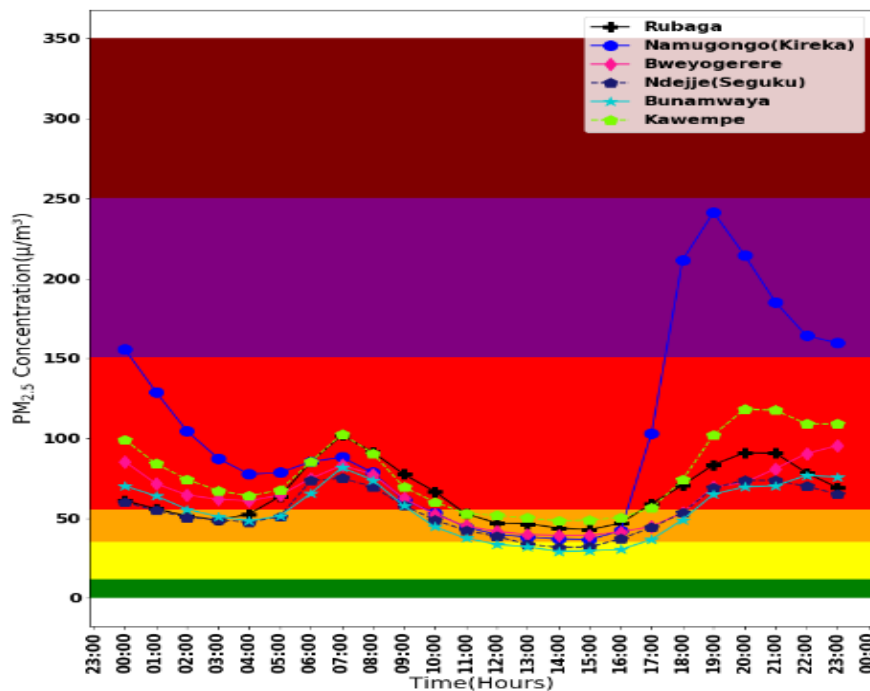
Air quality levels across all monitoring locations exhibit distinctive diurnal, weekly and seasonal/monthly variations. Insights on pollution variations generated from the 6-month monitoring data sets obtained from selected monitoring locations (in all sampled regions) have been presented as spatiotemporal profiles. These profiles have been further disaggregated as diurnal, weekly, and monthly variations for PM_{2.5} and gaseous pollutants (NO₂ and O₃). Results are clustered to correspond to geographical macro-regions considered for the study i.e. locations within Kampala and Wakiso (central business districts of Uganda), Rest of Central, and locations in Eastern and Western Uganda. Kampala and Wakiso are clustered separately due to their unique status as central business districts of Uganda with the highest population density relative to the rest of the country, in addition to having the highest concentration of pollution generating activities (UBOS, 2011, 2016).

PM_{2.5} Diurnal Profiles

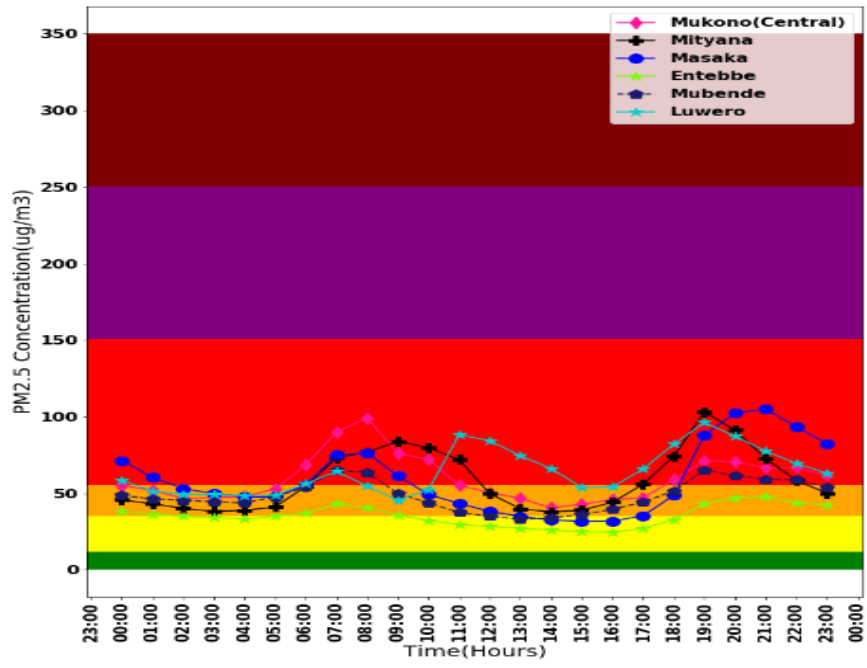
Diurnal variations indicate a consistent pattern with what would be expected for a typical day i.e. higher pollution levels were observed in the evening hours (starting around 5 pm) up to early morning (around 8 am). Consistent with this pattern, in Kampala and Wakiso, highest pollution levels are seen between 06:00 and 09:00, and 18:00 and 00:00, whereas 09:00 to 16:00, and 00:00 to 05:00 are the least polluted hours. While similar patterns are observed in other sampled locations, in Eastern Uganda, peak levels are considerably lower in these areas (e.g. Mbale Industrial division). These diurnal patterns are akin to findings in other studies across the world (Chow et al., 1999; Watson and Chow, 2002; DeGaetano and Doherty, 2004; Zhao et al., 2009; Chen et al., 2015, etc.). The variations indicate strong dependence on activity patterns within the monitoring locations e.g. high automobile transit time during rush hours (early morning and late evenings) which have been proven to increase emission levels (Sjodin et al., 1998; Zhang and Batterman, 2013), outdoor cooking in the evenings, and other commercial activities, etc. This is also enhanced by the influence of day to day meteorological/weather and atmospheric conditions on pollution dispersion i.e. daytime conditions (e.g. hot sunny days) being characterized by turbulent ambient conditions that increase pollution dispersion as opposed to calm weather situations typical of night time and early morning conditions i.e. lower temperatures with usually lower wind speeds (DeGaetano and Doherty, 2004; Zhu et al., 2006).

Since dispersion is proportional to the pollution decay gradient (Zhu et al., 2006; Karner et al., 2010), ambient concentrations/pollution levels relayed by the monitoring device are usually dependent on the rate of pollution decay towards background concentrations. Pollution decay is usually slower at night due to reduced dilution effect as dispersion is inversely related to wind speeds. In essence, main road monitoring locations and large commercial centers exhibit sharp temporal variations that could be linked to the influence of daily activities patterns and prevailing atmospheric conditions experienced in a typical day. Typical were monitoring locations in clusters within the central business districts of Uganda (**figure 1 and 3**) e.g. Kireka and Kawempe (UBOS, 2011, 2016) (about 8 and 5m from the main roads respectively) which exhibited sustained sharp/much higher temporal peaks between 05:00 to 09:00 and 18:00 to 23:30 for the entire monitoring duration, a strong contrast with other geographic clusters outside the central business districts.

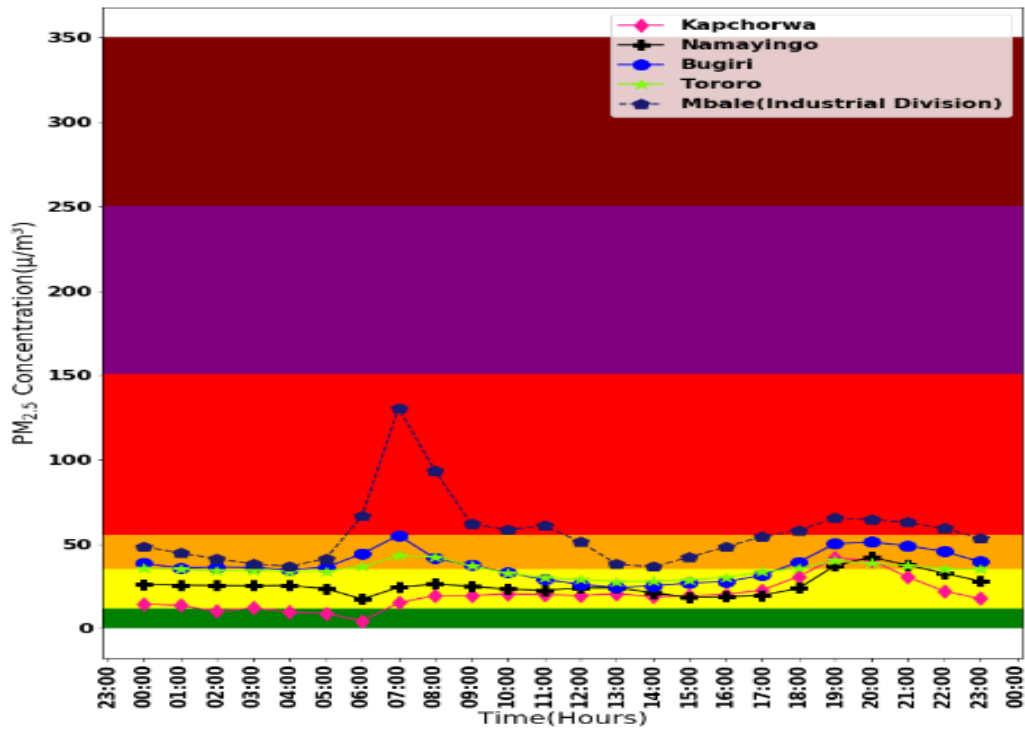
However, two adjacent locations (<2km apart) within Kampala and Wakiso cluster (i.e. Bweyogerere and Kireka), and Eastern geographical clusters (Mbale-**figure 4c**) showed interesting outlier characteristics, i.e. sustained disparity in temporal peaks, and visible pollution sources (i.e. human activities) not seeming to correlate with observed temporal peak levels, respectively. While these deviations and disparities could be attributed to site-specific contexts (e.g. site locations, (sustained) localized temporal alterations in the physical environment, e.g. **figure 13**), further research for example focusing on transboundary pollution effects and pollution source apportionment, could provide useful insights into these sharp contrasts such as sustained high temporal spikes outside the central business districts. On the other hand, the disparities could also be pointing towards the spatial inadequacy of fixed ambient monitors towards estimating pollution levels over a wide area with diverse physical characteristics i.e. not being able to capture instantaneous and even sustained localized pollution within the vicinity of monitoring location e.g. Kireka and Bweyogerere (<2km apart). This provides a strong rationale for the use of multiple-sensor deployment strategies within a given urban setting.



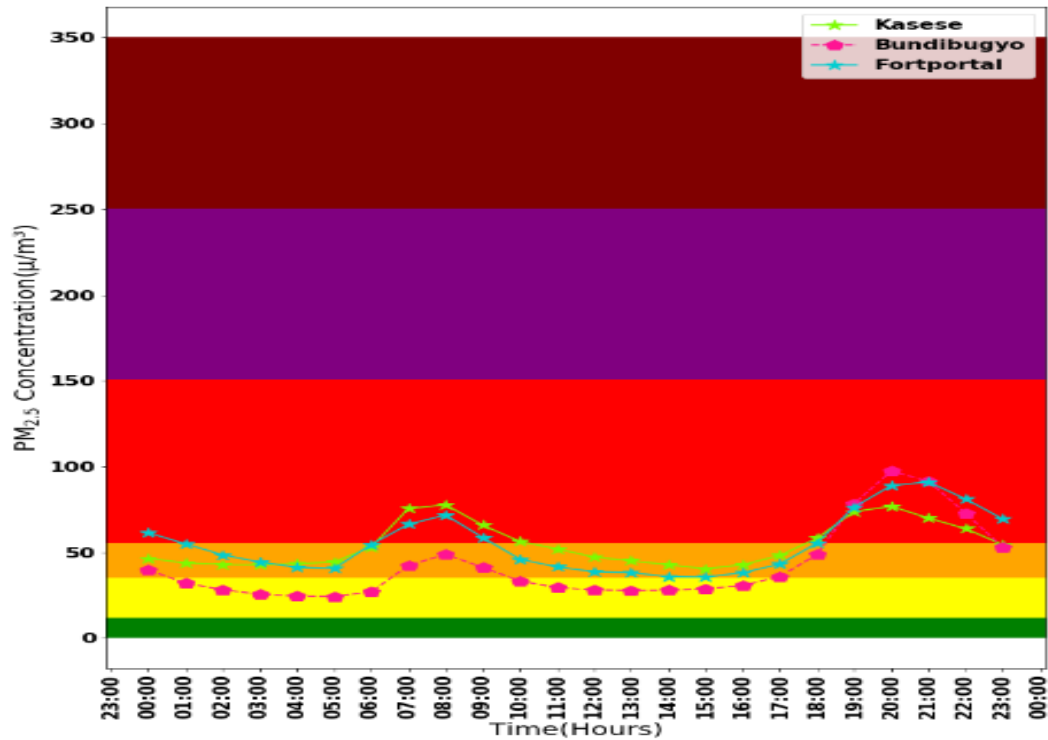
(a) Kampala and Wakiso



(b) Rest of Central Uganda



(c) Eastern Uganda



(d) Western Uganda

Figure 4: $PM_{2.5}$ Diurnal profiles for selected monitoring locations

Legend: Based on the US-EPA Air Quality Index (AQI)

AQI Category	Corresponding $PM_{2.5}$ Conc./ $\mu g m^{-3}$
Good	0-12.0
Moderate	12.1-35.4
Unhealthy for sensitive groups	35.5-55.4
Unhealthy	55.5-150.4
Very unhealthy	150.5-250.4
Hazardous	Above 250.5

Weekly Variations (7-day period)

Daily $PM_{2.5}$ mass concentration over a 7-day period (**figure 5**) ranges from ~ 30 to $107 \mu g/m^3$. However, pollution levels in all monitoring locations and geographical clusters show no apparent correlation across all areas i.e. do not conform to particular patterns with different locations having different days of peak pollution. Kireka, Kawempe and Bunamwaya are exceptions (**figure 5a**) with peak pollution levels observed in all cases on Wednesday, Thursday, Friday and Saturday throughout the 6-month period. Temporal peaks for Kireka and Kawempe were over $105 \mu g/m^3$ and $80 \mu g/m^3$ on Wednesday and Thursday, while Bunamwaya followed suit with a similar pattern from Tuesday to Sunday with highest pollution levels recorded on Wednesday ($\sim 55 \mu g/m^3$). However, all geographical clusters showed haphazard trends in the weekly pollution levels but clusters outside Central maintained lower temporal profiles (highest level being Sunday about $63 \mu g/m^3$ experienced on Sunday in Jinja (Buwenge). On the contrary, Entebbe 4b and Busia 4c experienced the lowest pollution levels (below $35 \mu g/m^3$) on Sunday, Monday (Entebbe) and Saturday (Busia) (**figure 5b and 5c**).

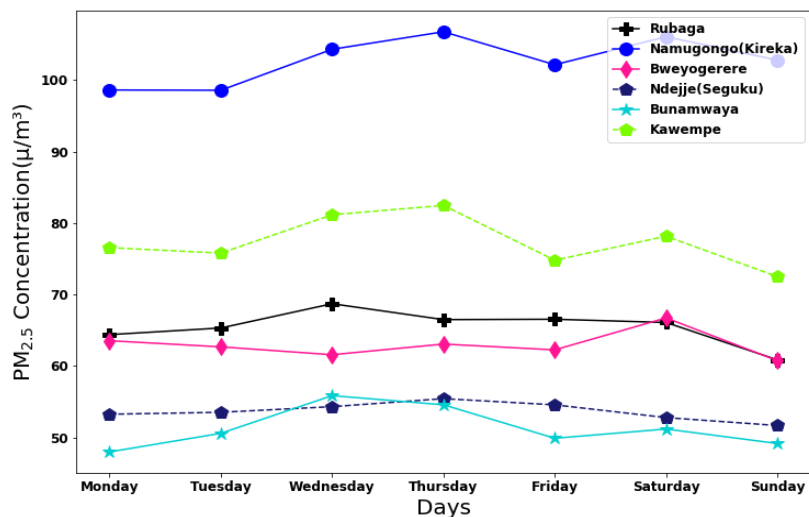
Haphazard pollution patterns could be a result of the nature of localized pollution sources/drivers within the respective monitoring locations which could be affecting other pollutant levels e.g. low $PM_{2.5}$ levels on

Mondays within central business districts (**figure 5a**) despite the usually observed traffic congestion during rush hours brings to light the significance of other pollutant levels and sources-akin to the findings in Watson and Chow (2002). Influence of other pollutants can be further supported by ‘weekend effect’ cycle often associated with photochemical and other gaseous pollutants which result from the strong dependence of surface pollution levels on anthropogenic sources (Cleveland et al., 1974; Beirle et al., 2003).

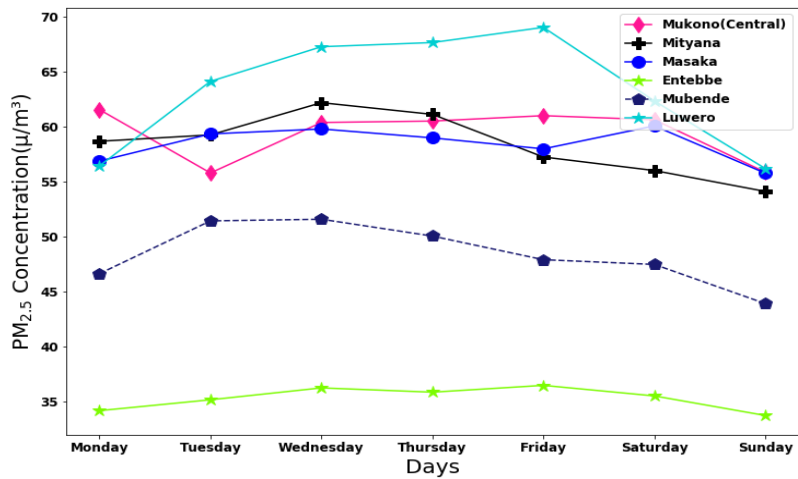
Likewise, persistent replication of disparities in the weekly profile between adjacent sampled locations i.e. Kireka and Bweyogerere (<2km apart) is yet another notable observation. These inconsistent variations make it difficult to derive conclusive weekly trends over a given geographic cluster using sparse monitoring data sets and a single pollutant which in essence re-emphasizes the need for a multi-pollutant approach and multiple sensor placements for accurate pollution estimates over a given geographic landscape.

In spite of the wide variation in daily patterns, diurnal PM_{2.5} concentrations far exceeded the daily air quality limits considered for this assessment i.e. 25µg/m³ and 35µg/m³ for WHO and EU, and US-EPA respectively. The exceedances of pollution standards are also consistent with the findings from published air quality studies in Uganda i.e. Schwander et al. (2014) and Kirenga et al. (2015) which ranged from ~50µg/m³ to over 240µg/m³ 24-hour averages with lower concentrations for sampling sites outside Kampala (Jinja).

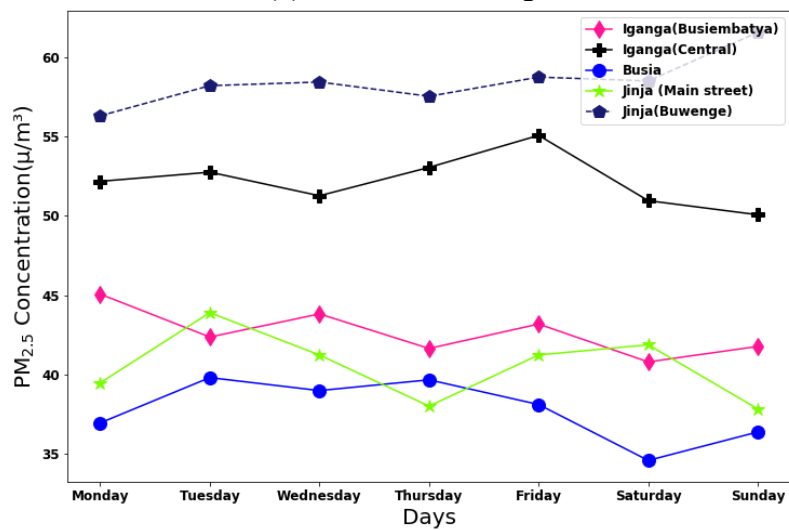
Furthermore, our analysis confirms (as expected) a strong positive correlation between pollution levels and degree of urbanization across all sampled regions which is also consistent with seminal work in the field e.g. Mage et al. (1996). With the administrative-based annual urbanization growth rate in Uganda averaging between 2.5 and 5% per year over the last 10 years (Jie et al., 2010; UBOS, 2014; CIA, 2018; UN, 2018), such correlation provides a warning sign and a call to think about measures that can minimize pollution as urbanization advances.



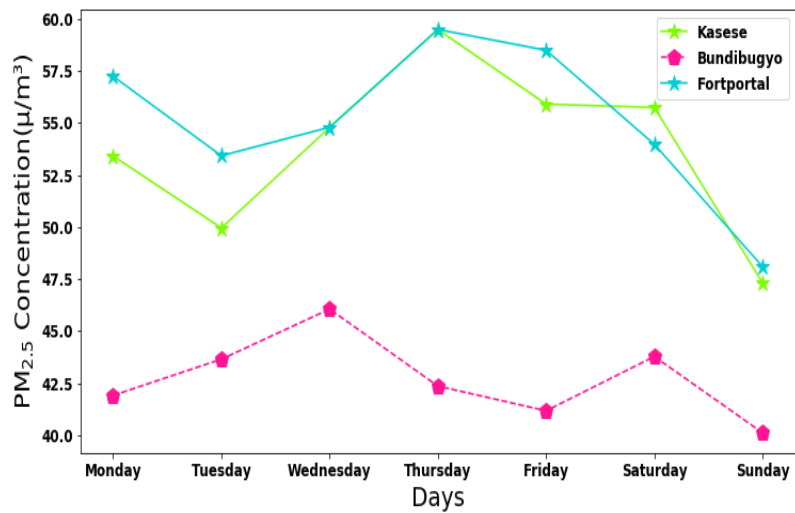
(a) Kampala and Wakiso



(b) Rest of Central Uganda



(c) Eastern Uganda



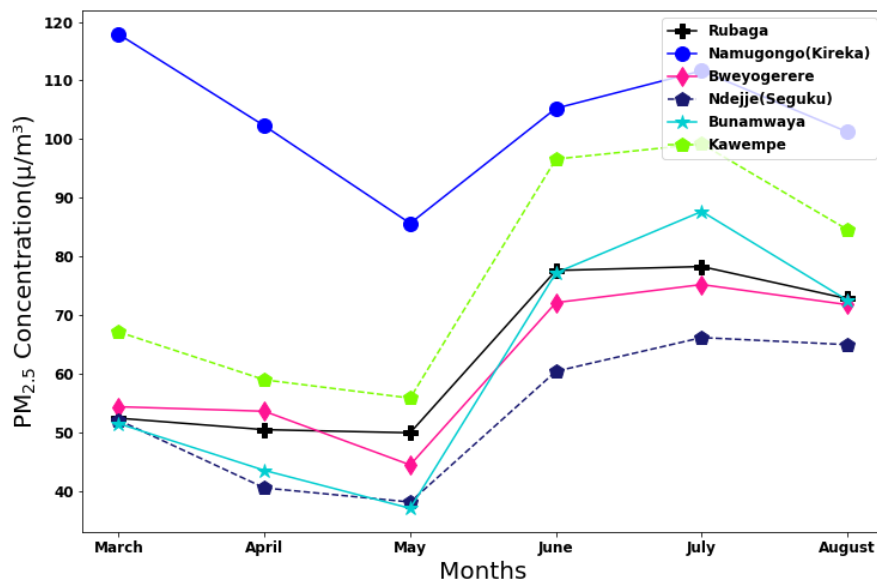
(d) Western Uganda

Figure 5: 7-day daily PM_{2.5} averages for all sampled geographic clusters

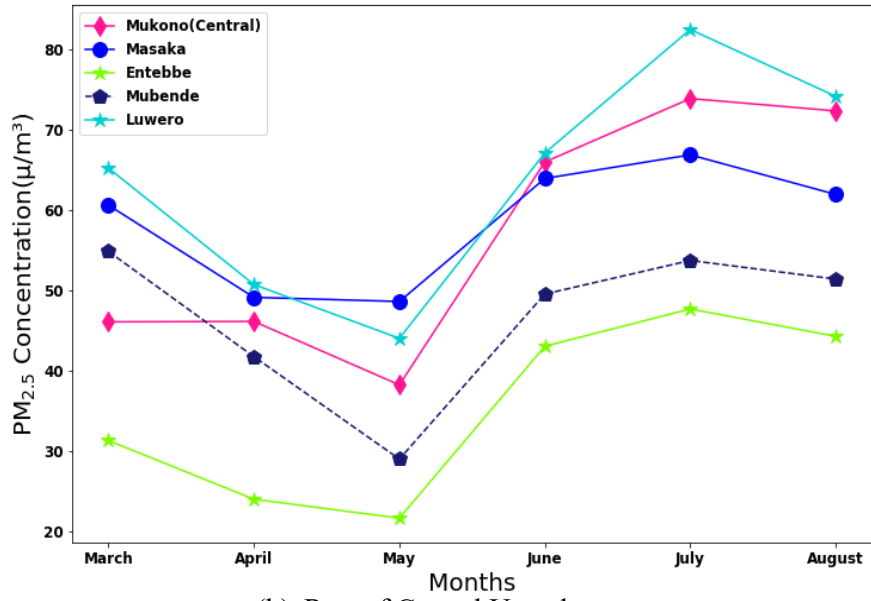
Monthly/Seasonal Variations

PM_{2.5} and Meteorological Influence

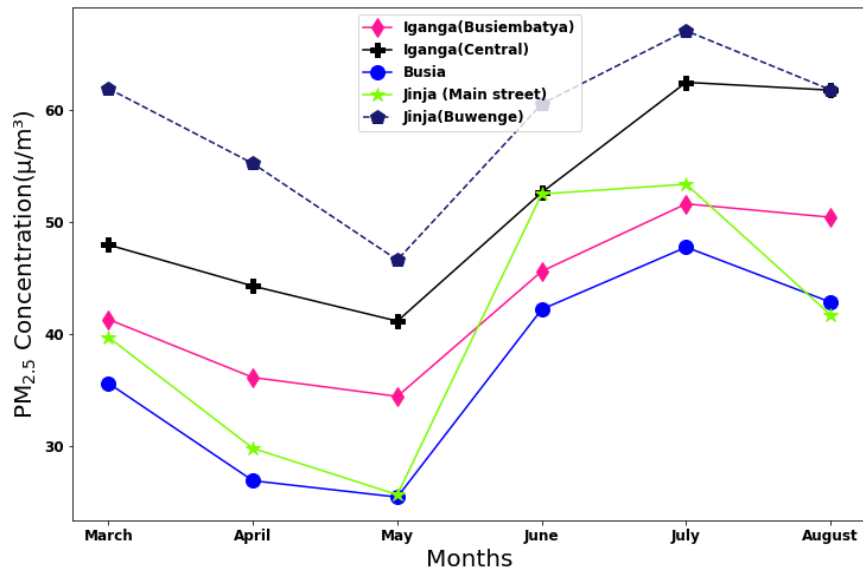
Monthly pollution levels follow a consistent pattern across all geographical clusters as if to replicate a sinusoidal curve. Peak pollution levels are reported in March, the highest being over 115 $\mu\text{g}/\text{m}^3$ for Kireka (Kampala and Wakiso cluster-6a) while Entebbe (6b) registered the lowest (just over 30 $\mu\text{g}/\text{m}^3$ for the same month). Pollution levels decreased sharply reaching the lowest levels in the months of April and May. This was consistent for all sampled locations with Busia, Jinja and Entebbe registering the lowest levels just above 20 $\mu\text{g}/\text{m}^3$. Thereafter, pollution levels increase gradually until July (most polluted month) where another peak is registered before it starts to decline. This ‘sinusoidal’ pattern can be linked to the effect of precipitation levels/meteorological conditions experienced within a given meteorological month in the sampled locations. In particular, the inverse relations between Particulate Matter and precipitation and unstable stormy periods that influence pollution dispersion and decay, dilution, and suppression (Chow et al., 1999; Zhu et al., 2006; Karner et al., 2010; Yan et al., 2016), other meteorological factors notwithstanding. The inverse correlation of precipitation levels and PM_{2.5} is further demonstrated by the superimposed graphical plots of total monthly rainfall/precipitation experienced within selected geographical clusters and pollution levels (figure 7). While pollution source attribution is beyond the scope of this paper, the strong suppression effect caused by precipitation/rainfall patterns on pollution levels could point towards easily ‘washable’/dissolved chemical elements.



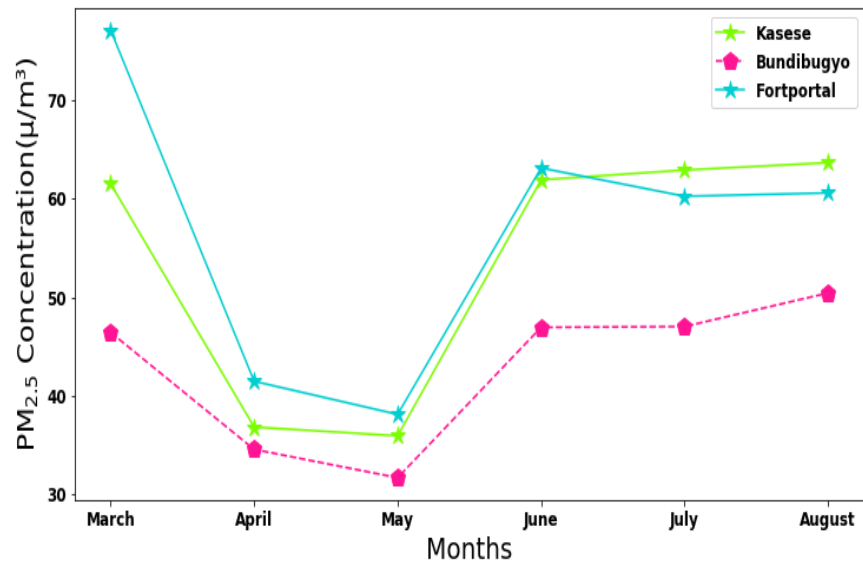
(a) Kampala and Wakiso



(b) Rest of Central Uganda

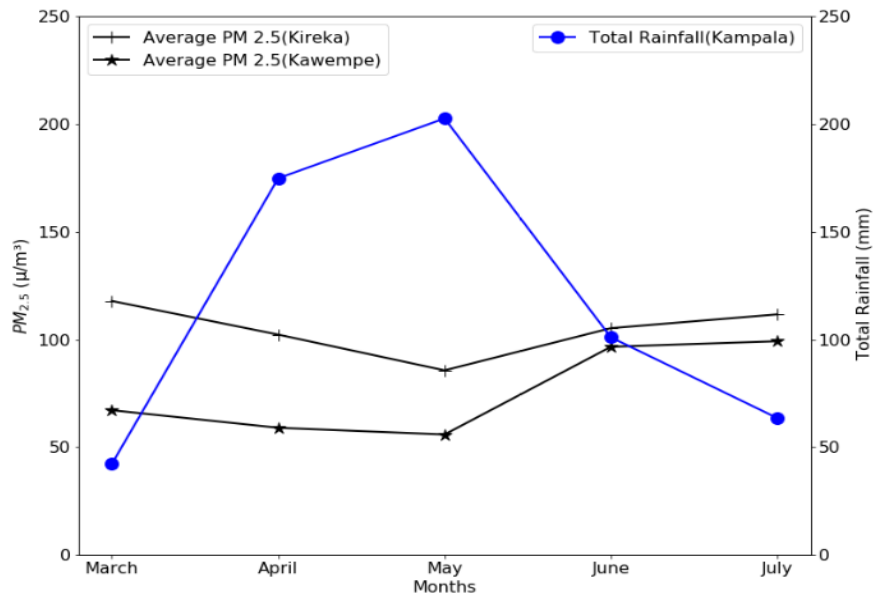


(c) Eastern Uganda

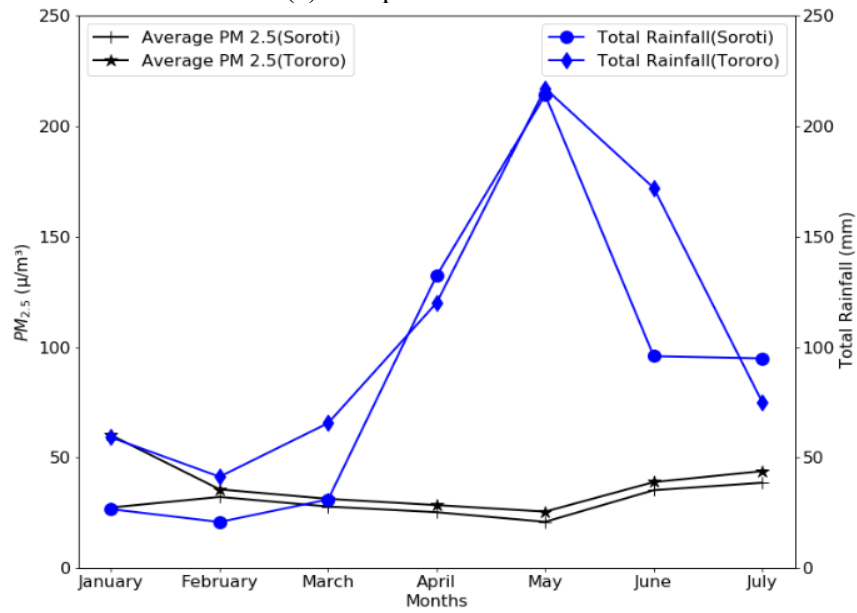


(d) Western Uganda

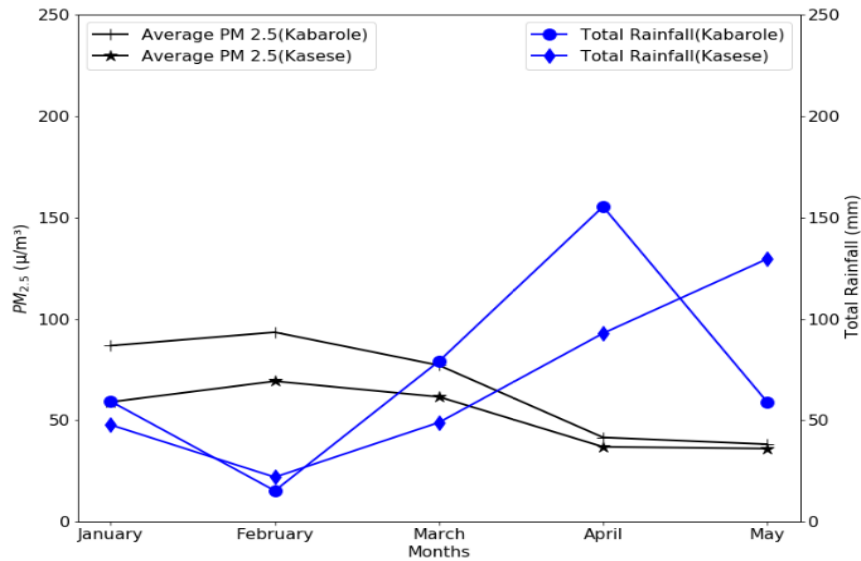
Figure 6: Monthly/seasonal variation



(a) Kampala and Wakiso



(b) Eastern Uganda



(c) Western Uganda

Figure 7: Influence of meteorology (precipitation) on seasonal profiles

NO₂ and O₃ Variations

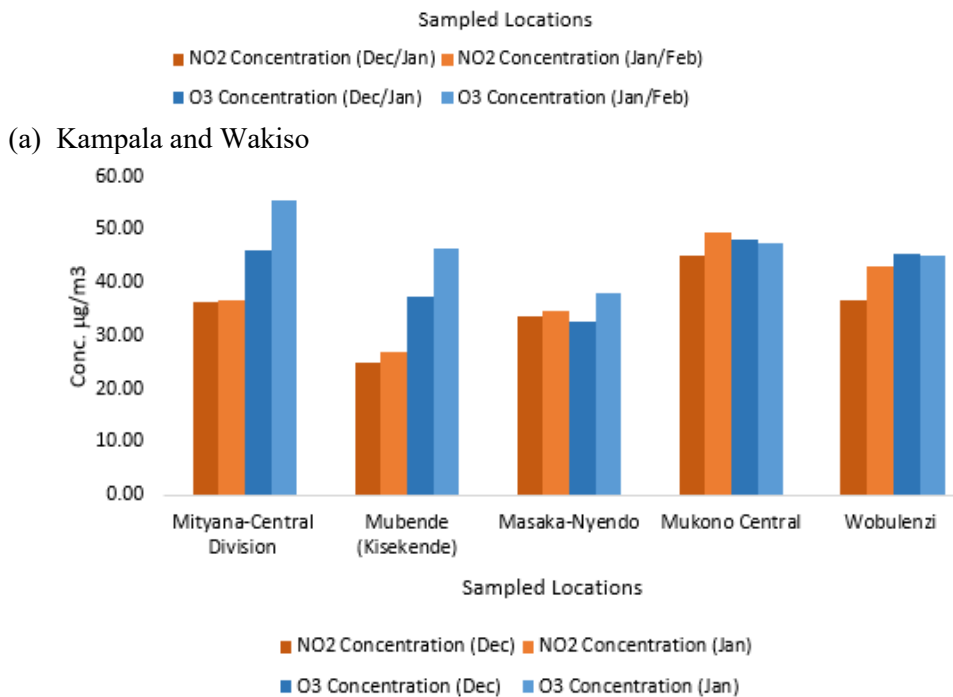
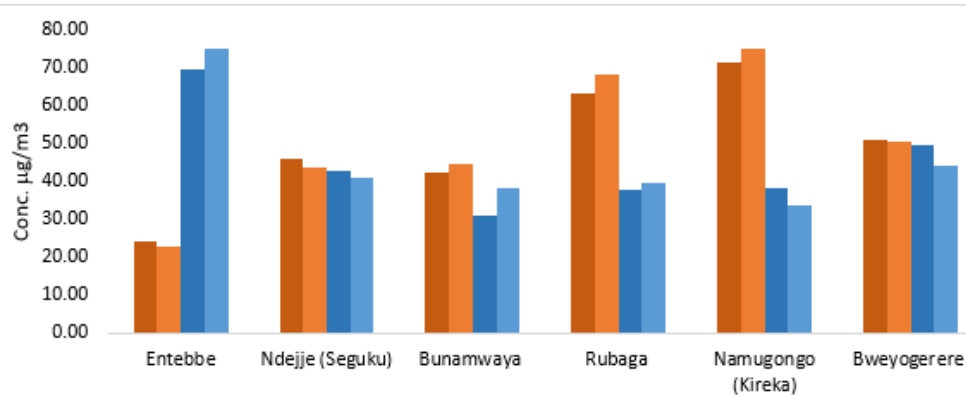
NO₂ levels exhibited distinctive variations throughout all geographic clusters ranging from <math><5\mu\text{g}/\text{m}^3</math> to over $70\mu\text{g}/\text{m}^3$ with locations within the Central clusters (with more pollution generating activities) largely experiencing much higher levels than Eastern and Western clusters (**figures 8(a-d)**). This is consistent with the notion that urbanization levels and traffic density have strong positive correlations with NO₂ attributed pollution (Mage et al., 1996; Studnicka et al., 1997; Krämer et al., 2000; Rijnders et al., 2001). Most notably, ambient NO₂ is widely considered an appropriate marker and a major indicator of traffic pollution as a primary combustion emission (Studnicka et al., 1997; Van Reeuwijk et al., 1998; Krämer, et al., 2000; Rijnders, et al., 2001; Nerriere et al., 2005) which is further validated by the enhanced correlation of measured NO₂ levels with automobile population (observed traffic) and observed street topology (that influence pollution dilution) in all monitored locations. Furthermore, the fact that household combustion energy profile in Uganda is predominantly biomass (about 95%) leaves very little room for the influence of domestic NO₂ sources on ambient levels e.g. Chao and Law (2000) on personal exposure.

Likewise, O₃ levels ranged between $\sim 30\mu\text{g}/\text{m}^3$ to over $90\mu\text{g}/\text{m}^3$ but exhibiting strong inverse relations with NO₂ pattern i.e. Eastern and Western clusters registering higher O₃ levels than Central cluster, with the highest levels being $\sim 90\mu\text{g}/\text{m}^3$ in Namayingo also with the lowest NO₂ levels i.e. $<5\mu\text{g}/\text{m}^3$ (**figure 8c**). Smaller urban centers and rural locations experiencing higher O₃ concentrations could be strongly attributed to the chemical nature of O₃ as a secondary pollutant i.e. higher atmospheric retention time because of limited fossil/petroleum combustion activities in rural settings or smaller urban areas, compared to major urban centers where O₃ retention is hindered by atmospheric chemical decomposition i.e. reactions with other combustion emissions.

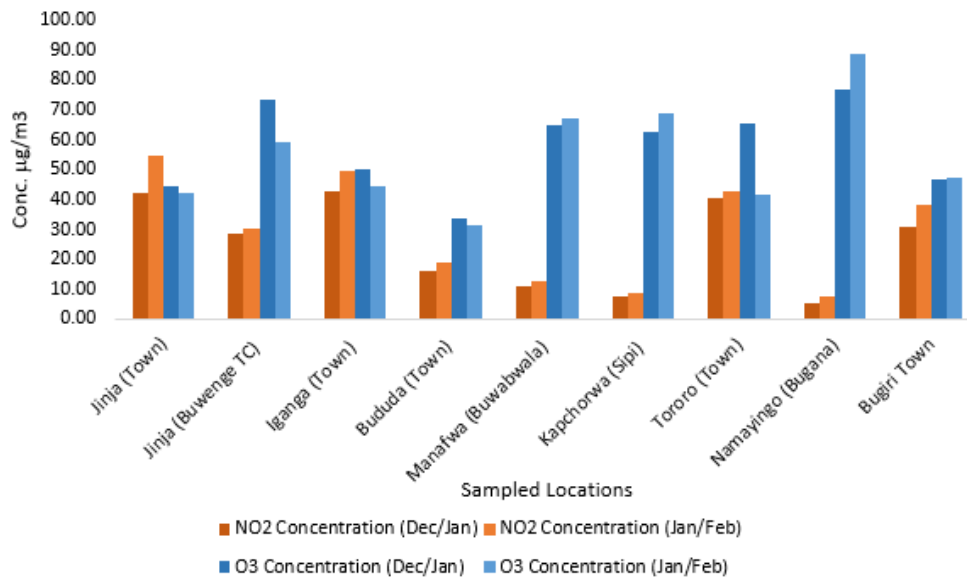
While O₃ formation partly depends on prevailing weather conditions-particularly sunlight intensity that influences photochemical reactions from precursor pollutants e.g. VOC, CH₄, NO_x, CO, etc. (Ganguly and Tzani, 2011; Zhang et al., 2015; Yan et al., 2016), it is not possible to derive any conclusions on meteorological influence based on 2-month monthly estimations, in addition to making direct comparisons to recommended long-term limits (e.g. WHO annual for the case of NO₂). Another major limitation of the passive diffusive approach to quantifying gaseous pollutants

is the inability to estimate short-term temporal variations making it impossible to obtain temporal insights e.g. diurnal pollution distribution.

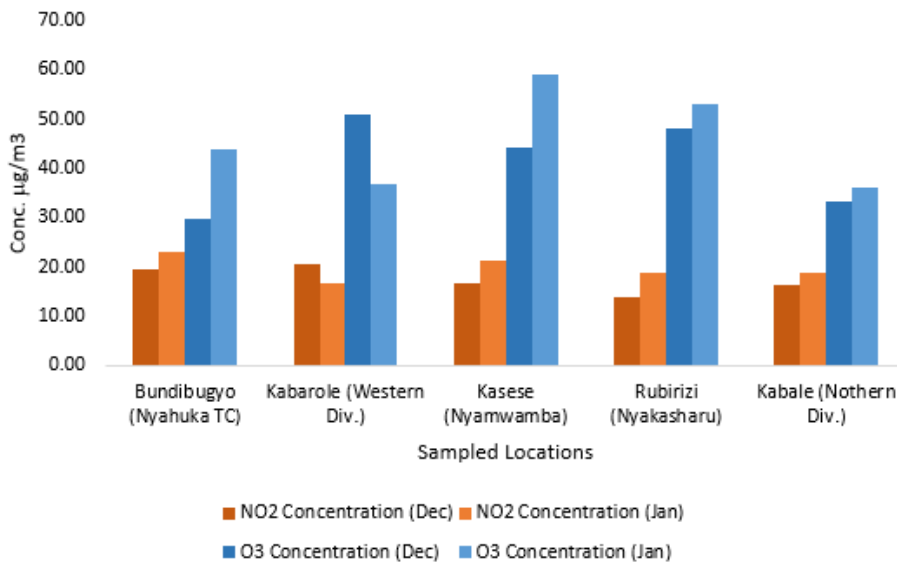
While longer monitoring campaigns would be an important consideration for future studies, these findings remain vitally important to indicatively highlight the contrast between urban and rural pollution levels with respect to combustion gaseous emissions, in addition to providing the only pollution baseline on a near-national scale.



(b) Rest of Central



(c) Eastern Uganda



(d) Western Uganda

Figure 8: 2-month concentrations for NO₂ and O₃

Mobile Data Sets

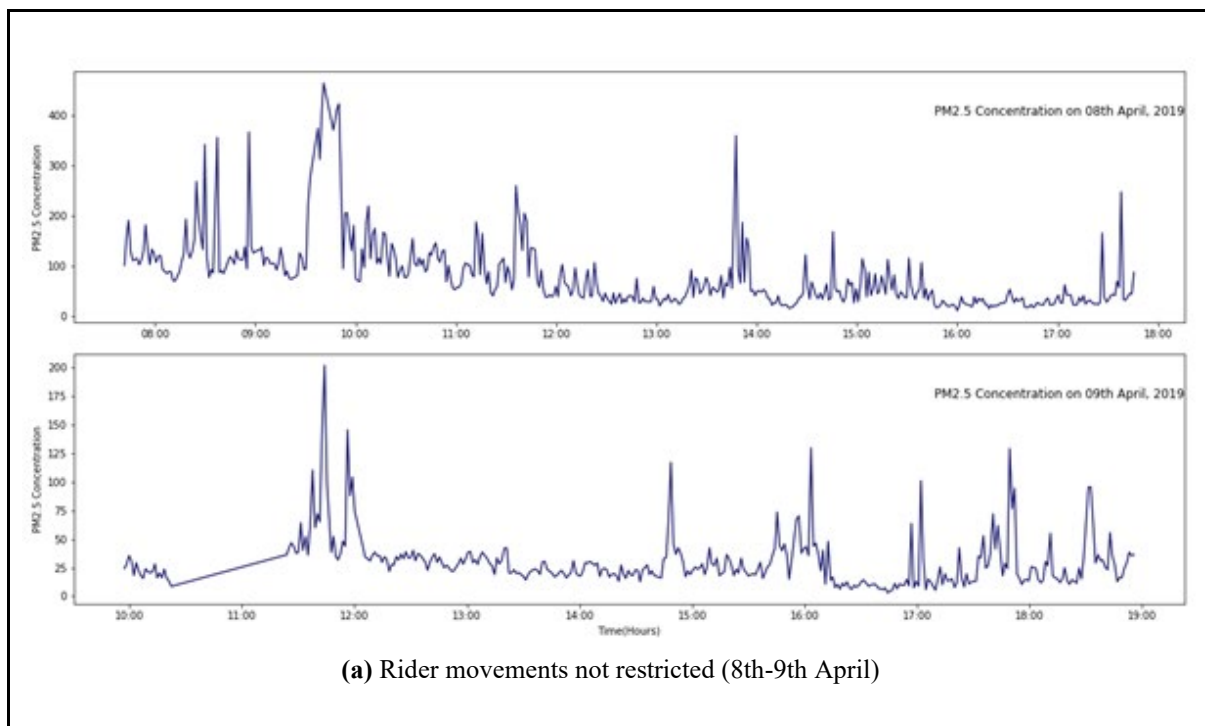
Scenario 1 (Opportunistic Monitoring) versus Scenario 2 (Restrictive Monitoring)

Further insights into supplementary mobile data sets have been presented (figures 9 and 10). The mobile data sets obtained reflect real-time and distinctive micro-level characterization largely linked to the street physical databases and indicative of the high temporal resolution of the data collection approach and varying spatial settings. The first monitoring Scenario (**Opportunistic Monitoring**) (figure 9a) provided ‘running data’, a key assumption being no prolonged stoppages unless prompted by extreme traffic situations (it is typical for *boda boda* to be minimally affected by traffic situations). Monitoring Scenario 2 (**Restrictive Monitoring**) (figure 9b) provided ‘controlled and consistent’ running data with some static data sets for selected spots out of the regular main route situations. To explore the reproducibility of the temporal variations in the PM_{2.5} concentration levels, monitoring data sets for 2 consecutive days (independent samples) are

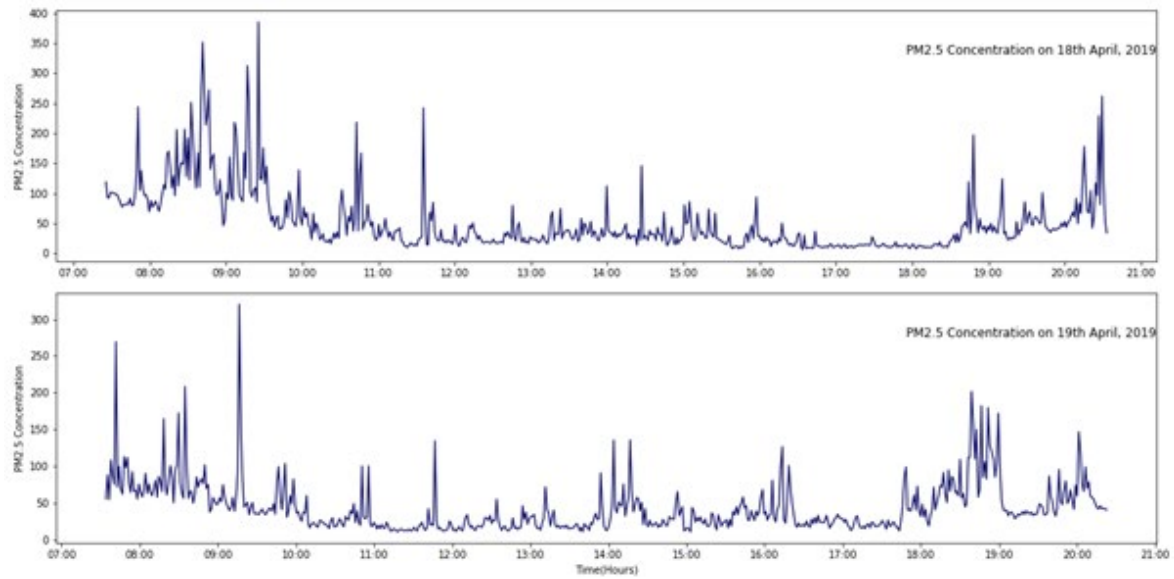
presented for both scenarios. Because there were more sampling days for **Scenario 1** (primarily due to the cost implications of **Scenario 2**), 2-day data sets were randomly chosen within two weeks from the sampling days of **Scenario 2** to ensure consistent meteorological conditions during the monitoring period. For comparative purposes, we evaluated data sets from two monitoring locations i.e. one from Kampala and Wakiso and another from the Eastern cluster (Tororo).

Monitoring data sets for the two scenarios exhibit consistency in the measurement trend for **Scenario 2** and the longer time lag in **Scenario 1** (i.e. fewer measurement entries). This is largely because riders were more conscious of their routes and speed under **Scenario 2** which produced some consistency and replicability in the measurement data sets. Variations appear to be stronger for Tororo (Eastern Cluster and located over 200km from Kampala) which could be explained by the clustered nature of pollution sources as you move away from the urban centers coupled with the fact that *boda boda* riders tend to travel much longer distances in rural-urban centers-typical of urban centers outside Kampala-Wakiso areas.

Distributed spikes stretching throughout the monitoring duration (in both scenarios) result from exposure to instantaneous emission episodes typical of microenvironments which can be systematic or accidental e.g. domestic burning (**figure 13**), exposure to vehicle exhaust, instantaneous particulate suspension from unpaved roads, etc. However, the trends for both scenarios tended to conform to the diurnal pollution profile obtained from static monitors as influenced by street topology, atmospheric and meteorological conditions, pollution generating activities. While **Scenario 2** would be more ideal for a mobile assessment study, these results indicate that both scenarios can potentially be used to provide a snapshot (Spatio-temporal) of the air quality situation in the monitored areas, somewhat similar to stationary data sets. These insights further advance the case for mobile monitoring to supplement conventional static monitoring due to ability to capture micro-level pollution drivers i.e. high spatial and temporal resolution (e.g. **figure 13**) that result in large pollution level disparities within a given monitoring locality (Weijers et al., 2004; Zwack et al., 2011; Elen et al., 2013; Van den Bossche et al., 2015), and potential to aid personal exposure epidemiological studies e.g. Berghmans et al. (2009).



(a) Rider movements not restricted (8th-9th April)



(b) Rider asked to make strategic stops at the point of interest (18-19th April). Stoppage times between: 7:30-8:30, 13:30 to 14:30 and 18:00 to 19:00

Fig. 9. $PM_{2.5}$ profile from the two monitoring scenarios for Namugongo-Bweyogerere-Nakawa mobile routes (Kampala-Wakiso Cluster)

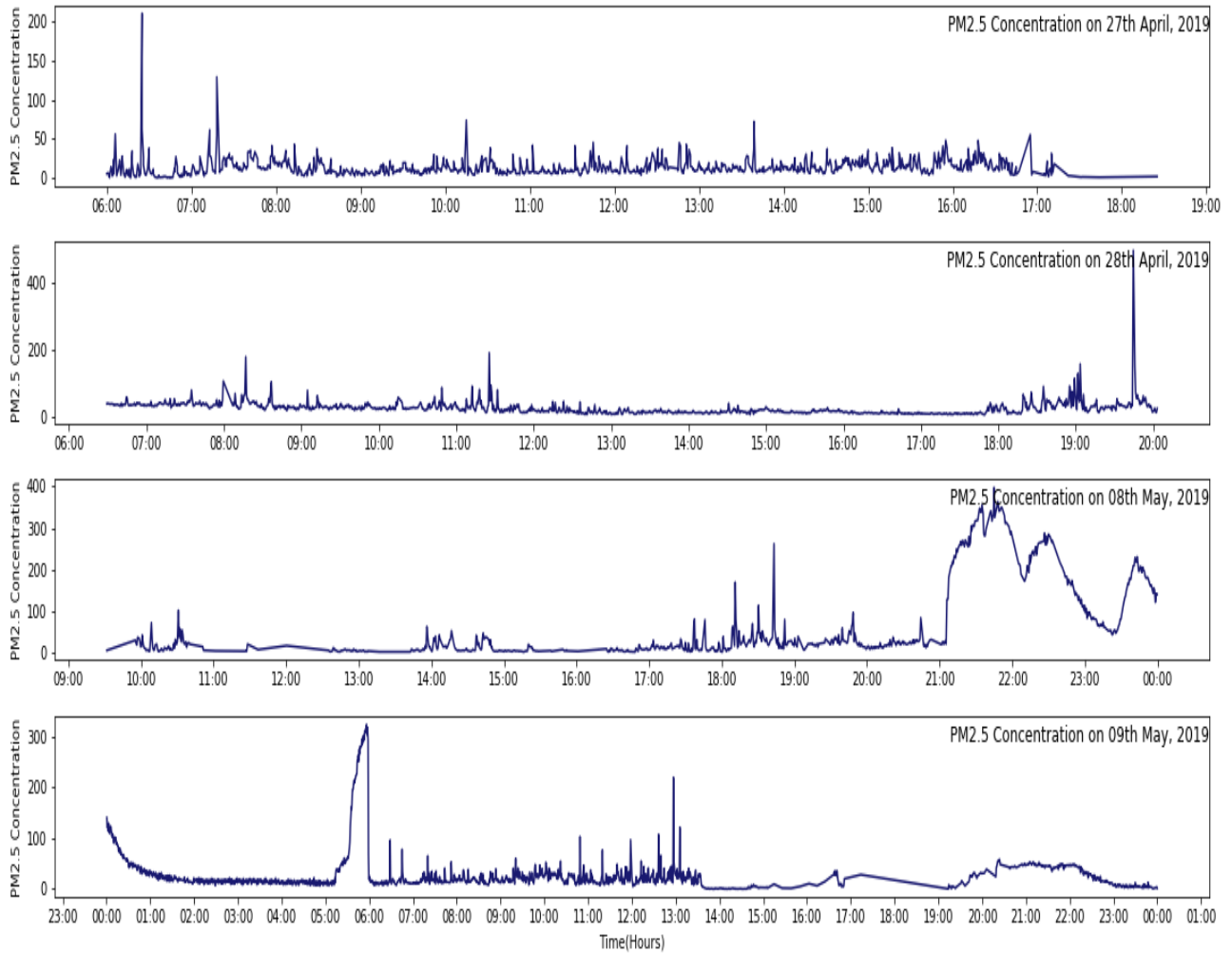


Fig. 10. Non-restrictive rider movements (8-9th-May), and 27-28th April-riders asked to make strategic stops (7:30-8:30, 13:30 to 14:30 and 18:00 to 19:00) at points of interest for Tororo-Malaba mobile routes (outside Kampala-Wakiso areas-more than 200km)

Mobile versus Static Data Sets

In order to further establish the relationship between mobile and static monitoring data sets, static and mobile data sets are compared for one of the *boda* routes under Restrictive Sampling Scenario and one static location (**figure 11**) within Kampala-Wakiso cluster. The choice of the mobile routes and sampling days are informed by the proximity (about 400m apart) of the point of interest (i.e. pre-determined stoppage point for *boda* rider) to the static location (**figure 12**). This was the closest attempt to simulate a collocation situation. However, the strength of the comparison is limited as mobile measurements are taken from various locations and relies on the assumption that the static monitoring data relatively represents the neighborhood. Nonetheless, valuable insights into the spatial variabilities and representativeness can still be obtained from comparing the two data sets (Van den Bossche et al., 2015).

As already intimated, unlike static data sets, mobile monitoring captured micro-level pollution drivers reflected in the temporal spikes and variabilities throughout the monitoring period as demonstrated in **figures 9 & 10**. These expansive concentration disparities re-emphasize the spatial boundary limitations of static monitors and their inability to explicitly capture micro-level pollution drivers e.g. from instantaneous exposures. The temporal disparities further reaffirm the

substantive influence of micro-level extreme pollution episodes on measured concentrations, and subsequently the spatial distribution. However, a relatively comparable replica of the diurnal temporal profiles for the static and mobile monitoring scenarios denotes the potential for the two approaches to be deployed concurrently. While static monitoring may not capture micro-level pollution episodes, mobile monitoring might equally not be ideal for monitoring during certain weather conditions e.g. rainy days, and also due to rider-behavior induced bias.

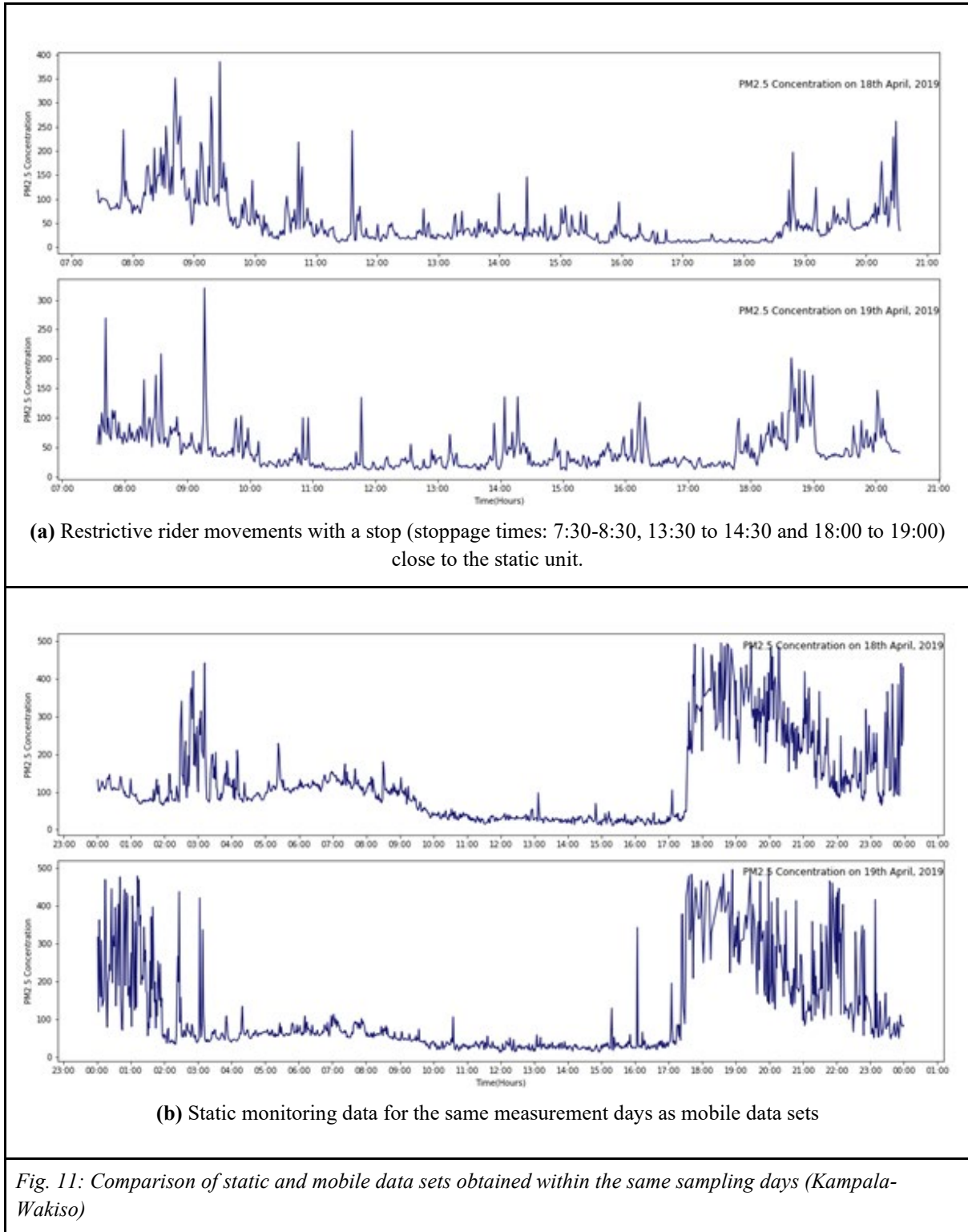


Fig. 11: Comparison of static and mobile data sets obtained within the same sampling days (Kampala-Wakiso)

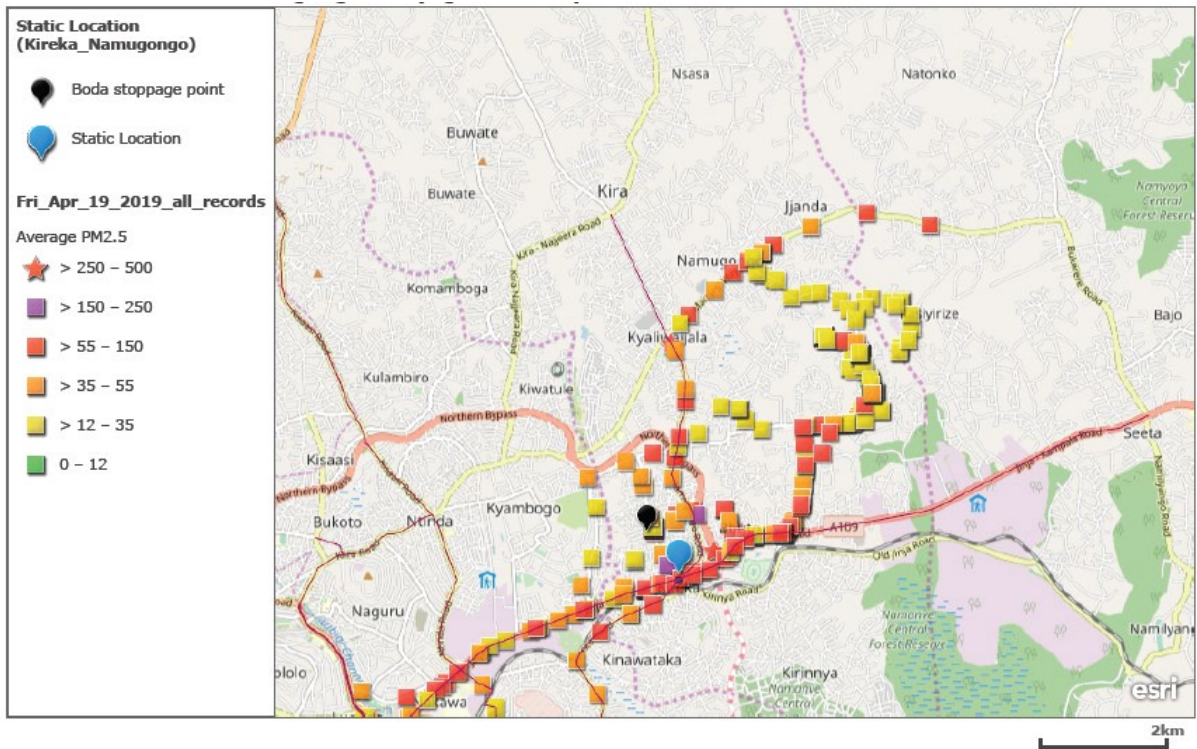


Fig. 12: Location of mobile stoppage point relative to static monitoring location

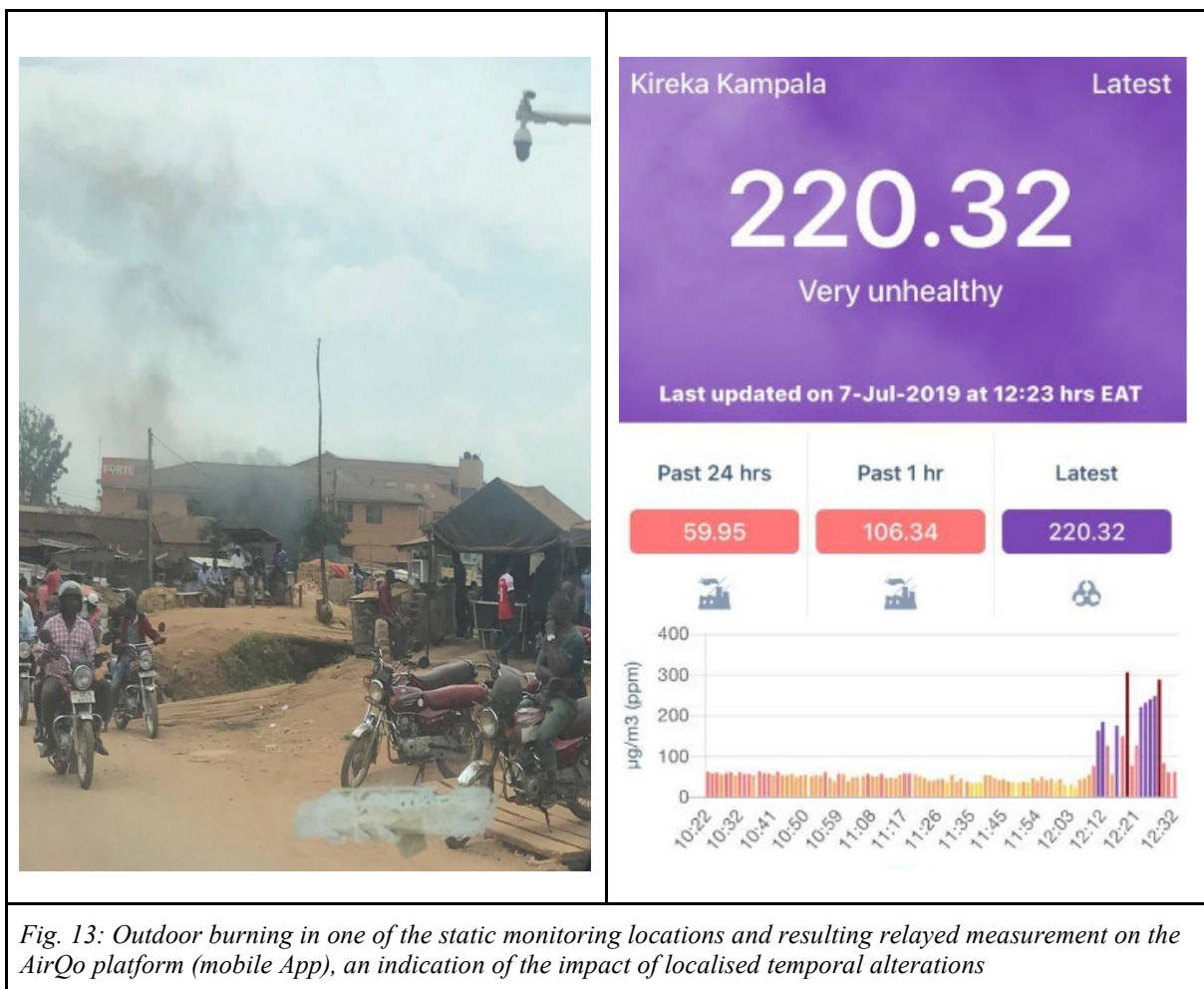


Fig. 13: Outdoor burning in one of the static monitoring locations and resulting related measurement on the AirQo platform (mobile App), an indication of the impact of localised temporal alterations

4. Conclusion

Air pollution concentrations in urban areas are determined by a balance of factors between pollutant generation (and subsequent accumulation) and pollution dispersion. Generally, indicative findings point towards the gradual deterioration of ambient air quality within the study areas. But more specifically, PM_{2.5} pollution data sets show significant spatiotemporal variations in pollution profiles across all the sampled locations. Spatiotemporal patterns generally indicate strong disproportionate correlations between pollution levels (for PM_{2.5}, NO₂ and O₃) in central business districts and outside central business districts. Notably, concentrations for Kampala and Wakiso were systematically higher than upcountry locations (i.e. Eastern and Western clusters) with some PM_{2.5} diurnal temporal exceptions. The influences of traffic levels and urban topology (presented in seminal literature) were also confirmed in the case study areas. Despite varying pollution levels, PM_{2.5} and NO₂ results indicate a wide measure of substantial exceedances of WHO, EU and US-EPA temporal (24-hour) and annual limits.

We further conclude that inconsistent and haphazard weekly profiles and the probable absence of the ‘weekend effect’ highlights the need for multiple pollutant assessments and also reiterates the inadequacy of sparse monitoring data sets. This further corroborates the need for multiple sensor deployment with a plausible mixture of both static and complementary mobile monitors to estimate pollution levels and inform the development of high-resolution pollution maps while identifying micro-level/localized drivers. In addition, the strong influence of rainfall patterns on seasonal particulate levels justifies the need for long-term monitoring to reflect actual seasonal variations.

Informed by the observed level of completeness for static monitoring data sets and comparison of data sets for the two mobile scenarios, we further conclude that engaging volunteers for opportunistic monitoring has huge potential, not only for high-resolution air quality monitoring but also as an avenue for increasing awareness of air pollution. In other words, the practicability and the potential of a low-cost monitoring network to succeed in the setting of Uganda and perhaps Sub-Saharan African are highly demonstrated. Determining the actual costs of setting up and maintaining a large network of low-cost monitors would be an interesting line of inquiry for subsequent studies.

Although this paper is limited to providing an overview of air pollution levels within the study areas, there is a strong basis for the key findings to inform future lines of research, which could include pollution source attribution and composition, transboundary effects on local pollution, pollution trapping and street topology effects (i.e. street canyon effect), personal exposure assessment, quantifying the economic impacts of pollution, hindcasting and forecasting studies, and most importantly, exploring effective models for citizen science engagement and mitigation actions. Further still, it would also be important to continue the measurement of air pollution over a long-term period to assess annual trends as well as expanding the geographic scope of the work.

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Annex

Annex 1: WHO, EU and US-EPA air quality standards (WHO, 2005; EEA, 2008; US-EPA, 2016)

Pollutant Category	Pollutant Parameter	Standards				Exceedances (maximum allowable exceedances)
		Averaging Periods	WHO/ μgm^{-3}	EU/ μgm^{-3}	EPA[1]	
Gaseous pollutants	NO ₂	1 hour	200	200	188.14 (100ppb)	18 times; 98 th percentile of 1-hour daily maximum concentrations, averaged over 3 years (EU; US-EPA)
		8 hours	-	120	-	
		Annual	40	40	99.71 (53ppb)	
	Ozone (O ₃)	8-hour	100	120	137.4 (0.07ppm)	Annual fourth-highest daily maximum 8-hour concentration averaged over 3 years (US-EPA)
Particulates	PM _{2.5}	24 hours	25	25	35	98th percentile, averaged over 3 years (US-EPA)
		Annual	10	10	12, 15[2]	Annual mean averaged over 3 years (US-EPA)
	PM ₁₀	24 hours	50	50	150	35 times a calendar year; not to be exceeded more than once per year on average over 3 years (US-EPA)
		Annual	20	40	-	-

[1] Conversion factor: $\text{ppb} = \mu\text{g}/\text{m}^3 \times 24.45/\text{MW}$ Where: $\text{MW} = \text{Pollutant Molar Weight}$

[2] Primary and secondary standards respectively

Annex 2: Installation locations for passive monitors

Region	District	Location Name and ID	Date and Time				Dist. from road with regular traffic (approx.)	Site description and visible emission sources
			Start		Stop			
Western	Bundibugyo	Nyahuka TC: WN_BGYO_AQ1	08/12/2018	10:20	19-02-19	10:08	10	Major commercial centre of the selected sub-county. Monitoring location in the middle of the business centre. Visible sources included, automobiles, outdoor cooking, fuel station operations.
	Kabarole	Western Div.: WN_KRLE_AQ1	08/12/2018	14:20	19-02-19	12:55	250	Location away from the major commercial establishments of Fort Portal Municipality; predominantly residential with minimal commercial establishments; surrounded by unpaved roads and some furniture businesses. Gaseous emission sources likely to be from automobiles
	Kasese	Nyamwamba: WN_KSSE_AQ1	08/12/2018	17:15	22-02-19	18:30	200	Mixed residential and commercial area but outside the major town centre within minimal vehicle/automobile movements.
	Rubirizi	Rubirizi: WS_RBZI_AQ1	09/12/2018	10:33	18-02-19	16:41	3	Major commercial centre of the selected sub-county. Location in the middle of the business centre along the highway.
	Kabale	Northern Div.: WS_KBLE_AQ1	09/12/2018	18:30	19-02-19	19:15	500	Predominantly residential with minimal commercial activities. Site surrounded by unpaved roads
Central	Mityana	Central Div: CW_MTNA_AQ1	07/12/2018	15:10	19-02-19	18:15	2	Middle of the commercial centre of Mityana municipality. Primary emission sources likely to include direct automobile emissions
	Mubende	Kisekende: CW_MBDE_AQ1	07/12/2018	18:00	19-02-19	16:50	5	Located within the commercial centre of the selected parish; major businesses include fabrication, grain milling and general merchandise. Emission sources include automobile emissions, fabrication gases
	Masaka	Nyendo: CW_MSKA_AQ1	10/12/2018	9:25	17-02-19	14:21	5	Heavily commercial with mixed settlements and visibly high population density. Primary sources to include automobile emissions
	Wakiso	Entebbe: CE_WKSO_AQ1	20/12/2018	12:22	01-03-19	11:08	15	The back end of Kitoro market within mixed settlement and commercial area. Likely emissions to result from occasional automobile traffic and

							outdoor cooking	
	Ndejje Div: CE_WKSO_AQ2	20/12/ 2018	13:38	01-03- 19	10:32	2.5	Along Entebbe highway within major commercial establishments and mixed settlements. Emissions likely to result from vehicular movements along the highway and localised particulates from nearby grain milling firm	
	Bunamwaya Div: CE_WKSO_AQ3	20/12/ 2018	14:05	01-03- 19	10:20	3	Mixed residential, some industrial and commercial activities.	
	Namugongo- Kireka: CE_WKSO_AQ4	21/12/ 2018	8:30	01-03- 19	15:56	2	Heavily commercial with adjacent commercial car park. Emission sources include vehicles and other automobiles (trucks, commercial and private vehicles, and motorcycles) along the highway, outdoor cooking, and industrial facilities	
	Bweyogerere Div: CE_WKSO_AQ5	21/12/ 2018	9:15	01-03- 19	15:30	10	Industrial area with mixed settlements and commercial establishments. Emission sources likely to include heavy trucks along the highway and industrial emissions	
Kampala	Rubaga Div: CE_KPLA_AQ1	20/12/ 2018	14:40	01-03- 19	10:06	3	At the junction of major roads; area characterised by mixed residential and commercial activities	
Mukono	Central Div.: CE_MKNO_AQ1	21/12/ 2018	10:00	01-03- 19	14:40	2	Predominantly commercial with frequent automobile traffic in the area.	
Luwero	Wobulenzi: CE_LWRO_AQ1	21/12/ 2018	12:45	01-03- 19	13:05	4	Along the highway with major commercial activities within the sub-county. Primary emissions to include outdoor cooking and automobile sources	
Eastern	Jinja	Central Division ES_JNJA_AQ1	26/12/ 2018	12:45	03-03- 19	10:55	5	Commercial area, outdoor cooking, industrial and automobile emissions
		Buwenge TC ES_JNJA_AQ2	26/12/ 2018	14:08	03-03- 19	13:22	10	Centre of Buwenge TC, emissions likely to result from automobile sources within the area
	Iganga	Central Div: ES_IGGA_AQ1	26/12/ 2018	15:38	03-03- 19	16:25	3	Predominantly commercial. Sources to include outdoor cooking and automobile generated emissions

	Busiembatya ES_IGGA_AQ2	28/12/ 2018	17:20	03-03- 19	16:56	250	Residential side of the major commercial centre surrounded by grain/rice, furniture businesses and general merchandise. Minimal traffic except along the highway about 400m from the location. Emissions from occasional traffic within the area and outdoor cooking
Mbale	Industrial Div: EN_MBLE_AQ1	26/12/ 2018	17:30	03-03- 19	19:06	2.5	Predominantly surrounded by furniture and grain businesses. About 2km from the major commercial centre of Mbale town. Occasional traffic, wood and grain dust suspension.
	Lwasso EN_MBLE_AQ2	27/12/ 2018	17:52	04-03- 19	19:12	2	At the foot of mt. Elgon located over 1400m above sea level. Predominantly residential (although sparse) with minimal commercial activities. Sources to come from occasional automobile movements in the area
Bududa	Bududa TC EN_BUDA_AQ1	27/12/ 2018	10:29	04-03- 19	17:15	2.5	Centre of Bududa town and major commercial establishments. Unpaved roads with frequent vehicular movements.
Manafwa	Bumurwa EN_MFWA_AQ1	27/12/ 2018	11:45	04-03- 19	16:20	2	Adjacent to Buwabwala Health Centre III. Trading centre with commercial activities typical of a rural setting in Uganda. Also, surrounded by unpaved roads
Kapchorwa	Sipi EN_KPWA_AQ1	27/12/ 2018	14:10	04-03- 19	13:12	3	Predominantly residential with minimal commercial activities
Soroti	Eastern Div. EN_SRTI_AQ1	28/12/ 2018	8:30	04-03- 19	9:40	1	Centre of Soroti town (major commercial centre of the district). Localised automobile generated sources likely to be predominant.
Tororo	Eastern Div. EN_TRRO_AQ1	28/12/ 2018	11:00	05-03- 19	8:40	1	Centre of Tororo town (major commercial centre). Emission sources primarily from industrial from the 3 cement factories and automobiles
Busia	Eastern Div. ES_BSIA_AQ1	28/12/ 2018	12:12	05-03- 19	10:05	2.5	Location sited and the centre of Busia town. Anticipated sources from heavy traffic entering and exiting Uganda-Kenya border

Namayingo	Bugana EN_NYGO_AQ1	28/12/ 2018	14:40	05-03- 19	12:25	500	Located about 20km from Namayingo town (major commercial centre in the district). Characterised by unpaved roads predominant rural settlements and minimal commercial activities. Occasional traffic likely to be the source of gaseous emissions but very low concentrations to near background levels.
Bugiri	Eastern Div. EN_BGRI_AQ1	28/12/ 2018	16:18	05-03- 19	14:35	3	Major commercial centre of Bugiri town. Trucks and other commercial vehicles likely to be the emission sources

Annex 3: Installation locations for static monitors

Region	District	Static Location Name and ID	Date and Time		Distance from the road (approx.)/m	Monitoring Mode (Static/Mobile)
			Start	Stop		
Western	Bundibugyo	Nyahuka TC: WN_BGYO_AQ1	2019-01-14	2019-05-30	10	Static
	Kabarole	Western Div: WN_KRLE_AQ1	2019-01-14	2019-05-30	250	Static
	Kasese	Nyamwamba: WN_KSSE_AQ1	2019-01-14	2019-05-30	200	Static
	Rubirizi	Rubirizi TC: WS_RBZI_AQ1	2019-01-14	2019-05-30	3	Static
	Kisoro	Southern Div. WS_KSRO_AQ1	2019-01-06	2019-05-30	5.0	Static
	Kabale	Northern Div.: WS_KBLE_AQ1	2019-01-19	2019-05-30	500	Static
Central	Mityana	Central Div: CW_MTNA_AQ1	2019-03-15	2019-05-30	2	Static
	Mubende	Kisekende: CW_MBDE_AQ1	2019-01-13	2019-05-30	5	Static
	Masaka	Nyendo: CW_MSKA_AQ1	2019-01-19	2019-05-30	5	Static
	Wakiso	Entebbe: CE_WKSO_AQ1	2019-03-16	2019-05-30	2.5	Static
		Ndejje Div: CE_WKSO_AQ2	2019-03-16	2019-05-30	2.5	Static and mobile

		Bunamwaya: CE_WKSO_AQ3	2019-03-17	2019-05-30	3	Static and mobile
		Namugongo (Kireka): CE_WKSO_AQ4	2019-01-07	2019-05-30	8	Static and mobile
		Bweyogerere: CE_WKSO_AQ5	2019-01-07	2019-05-30	10	Static and mobile
	Kampala	Rubaga: CE_KPLA_AQ1	2019-01-04	2019-05-30	3	Static and mobile
		Kawempe CE_KPLA_AQ2	2018-12-06	2019-05-30	3	Static and mobile
	Mukono	Central Div.: CE_MKNO_AQ1	2019-01-07	2019-05-30	2	Static and mobile
	Luwero	Wobulenzi TC: CE_LWRO_AQ1	2019-03-17	2019-05-30	4	Static
Eastern	Jinja	Central Division ES_JNJA_AQ1	2019-03-23	2019-05-30	5	Static and mobile
		Buwenge TC ES_JNJA_AQ2	2019-03-23	2019-05-30	10	Static
	Iganga	Central Div: ES_IGGA_AQ1	2019-06-01	2019-05-30	3	Static and mobile
		Busiembatya ES_IGGA_AQ2	2019-05-04	2019-05-30	250	Static
	Mbale	Masaba Ward EN_MBLE_AQ1	2019-01-31	2019-05-30	5.0	Static and mobile
		Lwasso EN_MBLE_AQ2	2019-01-31	2019-05-30	2	Static and mobile
	Bududa	Bududa TC EN_BUDA_AQ1	2019-02-01	2019-05-30	2.5	Static
	Manafwa	Bumurwa EN_MFWA_AQ1	2019-02-01	2019-05-30	4	Static
	Kapchorwa	Kachorwa-Sipi EN_KPWA_AQ1	2019-01-31	2019-05-30	3	Static
	Soroti	Eastern Div. EN_SRTI_AQ1	2019-01-31	2019-05-30	1	Static
	Tororo	Eastern Div. EN_TRRO_AQ1	2019-02-02	2019-05-30	2	Static and mobile
	Busia	Eastern Div. ES_BSIA_AQ1	2019-02-02	2019-05-30	2.5	Static and mobile
	Namayingo	Bugana EN_NYGO_AQ1	2019-02-02	2019-05-30	500	Static

	Bugiri	Eastern Div. EN_BGRI_AQ1	2019-05-03	2019-05-30	3	Static
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