

*Full Length Research Paper*

# The environmental impact of landfill fires and their contaminant plumes at the Chunga landfill site, Lusaka, Zambia

Muleya Milimo<sup>1\*</sup>, Hinchliffe Graham<sup>2</sup> and Petterson Michael<sup>2</sup>

<sup>1</sup>Department of Environmental Science, Faculty of Health and Environmental Sciences, Auckland University of Technology (AUT), Zambia.

<sup>2</sup>Department of Environmental Science, Faculty of Health and Environmental Sciences, School of Science, Auckland University of Technology (AUT), New Zealand.

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The management of solid waste is recognised as a challenging activity with respect to the environment, particularly within rapidly growing urban centres in Lower Income Countries. This paper examines the issue of landfill-waste-generated fires and resultant pollution plumes sourced within the Chunga Landfill Site, Lusaka, Zambia. The authors present the results of a geospatial analysis research programme to map and assess risks posed by landfill combustion. The project identified fires and their plumes in the period 2013 to 2019. Pollution plumes are predominantly oriented East to West but also form plumes blowing towards the South West and North West. The area impacted by landfill plumes increased from 34 ha in 2013 to 133 ha in 2019. There is significant existential and potential human-exposure to these plumes. An estimated 5000 residents live within the areas affected by landfill-combustion-plumes. The authors suggest the following framework for landfill management to be adopted: (1) for waste to be increasingly sorted and segregated with different disposal options developed for different types of waste; (2) for methane and gas evacuation pipes to be inserted into the Chunga Site in a systematic rectilinear manner which allows for its safe dispersal: alternately collect the gases as usable biogas; (3) rapid extinguishing of any fires; (4) weekly monitoring of the landfill site by UAV and on-the-ground inspections; (5) active weekly monitoring of air quality; (6) develop a communication strategy that aims to engage local residents and other stakeholders concerning Chunga Landfill waste management; (7) the further drafting of medium-long term waste management policy in Lusaka that takes account of the rapid population growth and increasing landfill requirements.

**Key words:** Landfill fires, smoke plume, photogrammetry, geospatial mapping, disaster, risk management.

## INTRODUCTION

This paper documents and analyzes photogrammetric, environmental management, and waste management research, focused on Chunga Landfill Site, Lusaka,

Zambia. Whilst this paper reports on a case study, the research has international relevance, particularly for Lower to Middle Income countries. Here the authors focus

\*Corresponding author. E-mail: milimomuleya@gmail.com.

on the issue of landfill combustion with resultant fires and pollutant plumes containing potentially harmful substances (PHS). This work has revealed the existence of burning waste at Chunga from at least 2013 to the present day. Remote sensing analysis demonstrates that the Chunga Landfill Site experiences multi-centred landfill fires that persist for significant time periods.

Landfill-generated plumes are transported via the predominant winds present within the Chunga locality, with a real and potential impact on a significant population as the plumes travel down-wind. This research has not focused on the human population, in terms of health studies, but rather the objective is to study landfill fires by mapping the plumes created by these fires, highlight the areas impacted by fire-plumes and assess the environmental impact of the plumes.

This paper describes the purpose, methodologies and results from the Chunga Landfill Fires research and sets the issue in context with the challenge of generic waste management within Lusaka, and the wider world.

Waste management is a global challenge. The world production of solid waste has grown from 1 million to 7 million tonnes per day from 1950 to 2020, with an estimated peak of 12 million tonnes per day by 2100 (Hoorweg, 2013). Africa has been identified as a key region for improvement in solid waste management practices given the rapid rate of population growth and urbanization (Hoorweg et al., 2013).

Lusaka is an example of a rapidly growing African city with a population change of 934, 000 in 1996 to 2, 647, 000 in 2019 (PopulationStats, 2020). Management of higher volumes of solid waste associated with rising populations and increasingly urbanised populations is one of the higher magnitude environmental challenges of the 21<sup>st</sup> century.

Low income countries are positioned to see the highest net percentage increase of urban dwellers over the next 50 years. The population of Lusaka was estimated at 2,647,000 in 2019, growing to 5,143,000 by 2034 (PopulationStats, 2020). Increased urbanisation is mainly caused by inward-migration from rural areas, and consequent increasing levels of consumption, have been the main drivers of increased waste production in the city over the last two decades. In 1996, when Lusaka's urban population was at 934, 000, waste production was estimated at 220,000 tonnes per year. This figure increased to 530, 000 tonnes per year in 2011, when the urban population was c. 1.8 million (Edema et al., 2012).

Lusaka developed its first purpose-built waste management landfill disposal site at Chunga, North West of Lusaka city in 2007 as part of its solid waste management strategy (Table 1). Of the total waste produced in Lusaka, it is estimated that c. 40% is collected and deposited at Lusaka's largest landfill site (Luke, 2017). A report by the Zambia Environmental management Agency (ZEMA) has estimated that between 2016 and 2018, an average of 29% of waste was

collected and deposited at the landfill with an estimated 1000 tons of waste produced a day (ZEMA, 2019).

Landfill fires are a consequence of the spontaneous combustion of methanogenic landfill deposit material (e.g., rotting organic waste) and occur both within the surface regions and within the main body of landfill deposits. Landfill fires may produce a wide range of potentially harmful substances (PHS) through the burning of chemicals, plastics, and other waste materials. A study by (Weichenthal et al., 2015), on the impact of landfill fires on ambient air quality, discovered that there was a concomitant increase in PHS such as benzene and dioxins/furans. These toxic substances are a health risk to a range of vulnerable populations including Landfill Site workers, and residents living close to Landfill sites, as well as contaminating the surrounding environment and biosphere. According to (Lohmann and Jones, 1998), "*Polychlorinated dibenzo-p-dioxins and -furans (PCDD/Fs) are two groups of persistent, semi-volatile and toxicologically significant trace organic contaminants present in Landfill fire products.*" Whilst no studies to date have definitively identified these PHS species at Chunga, their presence is suspected, as there are parallels between fires at Chunga and other, better-studied landfill fire zones, with respect to the character of stored waste and the fires themselves. The uncontrolled combustion of waste containing PHS results in widespread environmental pollution including depositing materials within the soil and deeper geological environments, surface and ground waters, and ingestion by humans, animals and plants (Zhang et al., 2015).

Landfill fires can be classified from a number of analytical viewpoints, according to cause, source, magnitude, and so on. This paper uses a classification system based on how easily fires can be extinguished (Jurbin, 2003):

- 1) Level one -small easily extinguished garbage fires.
- 2) Level two -fires that occur on the face of the landfill, on the side where garbage is being actively dumped.
- 3) Level three - fires are more serious and may take up to a week to extinguish.
- 4) Level four - fires cover an area of at least one hectare and take more than a week to extinguish (Jurbin, 2003).

The biological decomposition of waste through aerobic or anaerobic processes, produce exothermic reactions yielding extraneous heat for the surrounding environment. Landfills can produce average internal temperatures of 60 to 71 °C (Stearns and Petoyan, 1984).

Through the process of pyrolysis, these exothermic reactions change from biological to chemical transferring heat to the surrounding areas through conduction and/or convection of entrenched fluids within the landfill deposit, and radiation within the immediate vicinity (Jurbin, 2003; Stearns and Petoyan, 1984). Poorly designed and managed Landfill Sites that lack an effective surface cap or seal allow the flow of oxygen into the Landfill deposit

**Table 1.** Types of waste dumped at The Lusaka city dump site (Chunga Landfill) showing the various types of waste that is dumped at the site, excluding hazardous industrial waste (Chishiba, 2002).

Type of waste	Composition
Industrial waste	This comprises waste from construction and demolition processes while also including light industrial waste such as, clothes, ash, and polythene. This type of waste does NOT include hazardous wastes.
Green waste	Waste from road maintenance, mainly vegetation and wood.
Packaging waste	This includes plastics, cardboard, and aluminium foil.
Commercial/ Trade waste	This includes waste from trading institutions such as, shops, offices, hotels, restaurants, and garages. The waste comes in the form of packaging material, paper, and automotive parts.
Household and Institutional waste	Waste from households and institutions such as hospitals, schools, prisons etc.

subsurface, and are consequently placed at higher risk levels with respect to landfill combustion. Sub-surface fires are more difficult to extinguish than surface fires, usually because they are harder to detect, and get to directly, (Øygaard et al., 2005), also suggest that sub-surface fires cause fractures and crevices to form within the landfill structure, which affects the structural integrity of the landfill deposit and can become a factor in landfill collapse.

## MATERIALS AND METHODS

### Research site location

The Chunga Landfill Site is located at Latitude 15°20'57.55" South, Longitude 28°16'04.92" East, at an elevation of 1215m (GoogleEarthPro, 2019). The site covers an area of 24.53 ha and has a fenced perimeter of 2.15km. The Chunga Landfill Site is built upon bedrock geology of metamorphic schists and carbonates with overlying clay-sand-gravel rich loam soils. The presence of large areas of karstic substrate under Lusaka is noted which could allow for the ingress of pollutant fluids from Landfill Sites such as Chunga (Figure 1).

### Types of waste present at Chunga Landfill

#### *Climatic characteristics of study site*

The climatic conditions at Chunga landfill are characteristic of regions located in central Africa. The periods of rain in Zambia occur between November and March annually: however, changes in climate conditions have resulted in extreme weather conditions such as droughts and floods. The highest temperatures are reported in October, averaging 24.7°C. In July, when the study was conducted, average temperatures were recorded at 16°C. July to September is dry and windy with Easterly winds being predominant.

### Data acquisition

#### *Equipment*

One of the core activities of the Chunga Landfill Research project was the surveying and subsequent production of a 3-dimensional

photogrammetric model of the Chunga Landfill Site itself. The following equipment was used for this survey: a DJI Phantom 4 (Figure 2), Unmanned Aerial Vehicle (UAV) or Drone was used to acquire 966 images on the 27<sup>th</sup> of June 2019, flown at a height of 70m. This UAV has a 12.4 mega pixel (MP) camera and 60 mega bit per second (mbps) facility for video acquisition and covers a range of 6000 m which adequately covered the research area, that has a perimeter of 2, 142 m. The Phantom 4 has a flight time of 25 to 30 min on a fully charged battery. Two additional batteries were used to extend the flight time and ensure full data coverage was collected in one session. The phantom 4 is equipped with a global positioning system (GPS) and Global Navigation Satellite System (GLONASS), providing real time position of images acquired.

### GNSS receivers (EMLID Base and Rover)

As a back up to GPS information recorded by the UAV, two Global Navigation Satellite System (GNSS) receivers were used to record Ground Control Points (GCP) that would improve the absolute position of the landfill if needed. One receiver acted as a Base station (Figure 3) and the second as a rover station. The base station remained in one place and sent corrections to the moving rover. The two GNSS receivers utilized a technique known as Real Time Kinematic (RTK) to achieve centimetre accuracy (Volodina, 2020).

### Data processing

#### *Digital surface model (DSM) processing*

The georeferenced drone images were processed using the photogrammetry software Capture Reality (S.R.O, 2019) to create a Digital Surface Model (DSM). A digital surface model represents the surface elevation of the terrain and includes structures such as buildings and trees, implying that each pixel in the DSM has an elevation "Z" value that is representative of the elevation above bare earth. The analysis of this data type was done by importing the DSM into the GIS program, (Esri<sup>TM</sup>, 2019) ArcMap 10.5.1, for further analysis as it cannot be processed in programs such as Google Earth (Wampler et al., 2013).

### Fire-plume mapping

Google satellite images were obtained between 2007 to 2019. These sequential series of time images allowed the study of plume



**Figure 1.** Geographical location of research site, Chunga Landfill, in Southern Africa, Lusaka Zambia, located north west of the Lusaka City is the only engineered Landfill in the city (Esri. OpenStreetMap Basemap data © OpenStreetMap contributors, 2021).



**Figure 2.** Phantom 4 (UAV) used for image acquisition at Chunga landfill.



**Figure 3.** An EMLID Rover is held in place to collect GCP at Chunga Landfill.

locations over time to be undertaken. The plumes were mapped and georeferenced. Maps were produced by creating KML polygons around identified fire-plumes. KML is a file format that is used in an Earth Browser such as Google Earth to display geographic data. Polygon shapes were converted to raster polygons, in *ArcMap*, and stacked using the cell statistics tool, that added each raster layer on top of the other, to create a fire-plume density map (Figure 6).

#### Fire-Plume area calculations

A plot of the average area covered by fire-plumes for the years, 2007 to 2019, was created (although fires have only been observed in images from 2013 and later), based on the methods described above. The area affected by fire-plumes was determined by visual observation and measurement, using the measurement tools in Google Earth Pro. The plot shown in (Figure 8) is the result of the examination of 39 images over the 12-year period. Nineteen images did not contain fire-plumes.

## RESULTS

### Digital Surface Model (DSM)

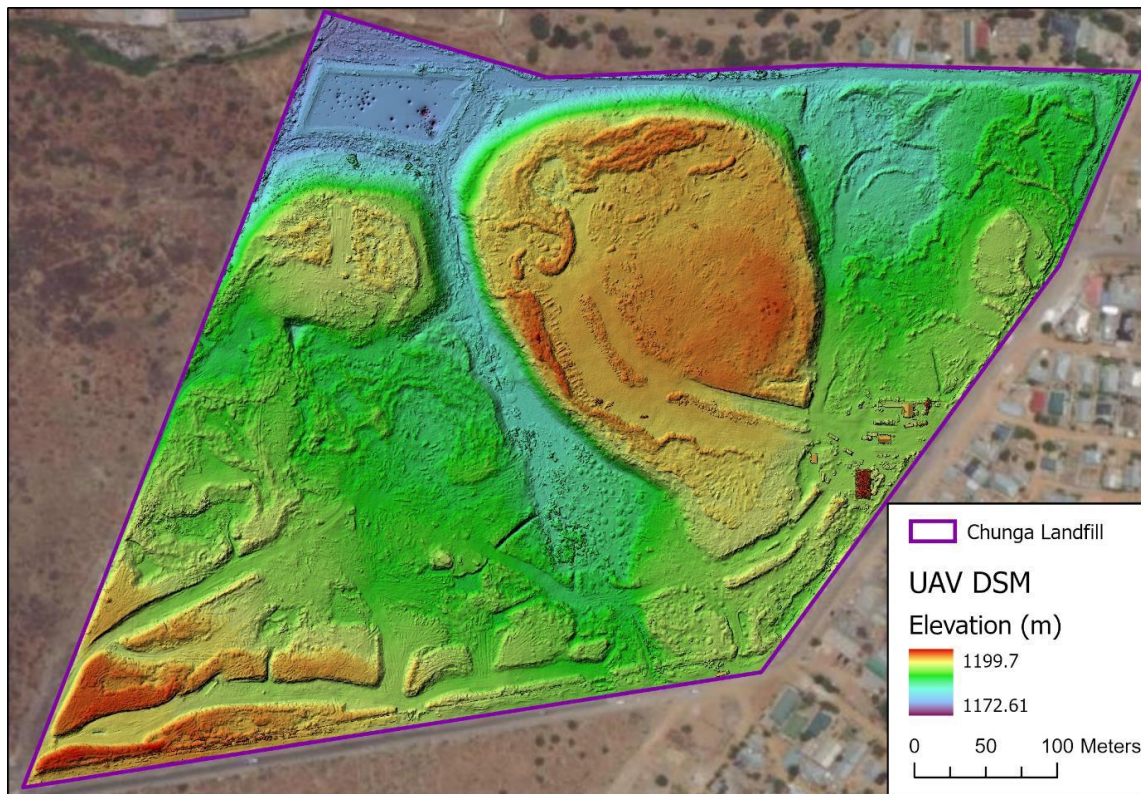
The Chunga Landfill site is shown as a digital surface model (DSM) in Figure 4. The general geomorphology can be expressed as two main ridges with a valley between them. The eastern lobate ridge is the largest and most extensive with a maximum height of c. 1200m, and measures some 320m NNW-SSE by 200m east-west. The western 'ridge' is more nebulous in form with higher areas to the north and southwest. A valley-oriented NNW-SSE separates and drains the two key ridges. In the NW

there is a drainage lake, which our research shows does not retain all draining waters from the Landfill site. Overall, the site is higher in the southwest and eastern region and gradually reduces in elevation towards the northwest. This has been designed for drainage of waters towards the drainage lake in the NW of the site. The digital surface model is displayed in Figure 4, with a colour gradient as the topography key. Highest elevations are shown in a brick red colour, with a gradual reduction in colour intensity corresponding to lower elevations. The colour blue represents the lowest topographic regions. The DSM not only allows for analysis of structural elevation but also presents accurate geographical location of the landfill site.

### Fire sources

The research shows that fires at the landfill are mainly visible on the waste heaps to the North (A), North East (B) and North West (C) of the landfill (Figure 5). The Map shows the fires as red borders and the landfill Digital Surface Model (DSM) with the higher elevations appearing as red while lower elevations appear blue to violet. These regions have been mapped to show the main sources that is, combustion of waste mainly at the surface and shallow depth levels. From the DSM we observe that the fires are mainly located on the waste heaps North (A) and North east (B), with a high and lower elevation respectively.

Waste to the North West (C) is also seen as a source of fires yet not the main source of plumes. Imagery from



**Figure 4.** Chunga Landfill Digital Surface Model (DSM) showing the general shape and form of the site and changes in elevation based on waste heap elevations and landfill topology. Note the prominent balloon-shaped brick-red coloured ridge on the eastern side and more nebulous ridges on the western side. A broad NNW-SSE trending valley drains much of the landfill. The lowest elevation is in the NW of the site and contains a lake appearing as a deeper blue colour in NW corner (Esri, 2021).

satellite images using Google Earth (GoogleEarthPro, 2019), from 2013 to 2019, were used to record the location and temporal variation in landfill combustion. The fires are interpreted to be level two and level three fires, based on their relative longevity, difficulty to extinguish, and location within the landfill structure. The research also shows that waste heap (A) is the oldest of the fire groupings, followed by waste heap (B) and (C). Figure 5 show that waste heaps (A) and (B) are the major fire sources resulting in plume smoke.

### Plume mapping

Figure 6 displays the geographical extent of the mapped fire-plumes. The bright colours show the highest density of overlapping fire-plume trajectories (between 9 and 14 individual plumes are present within brighter yellow to red regions).

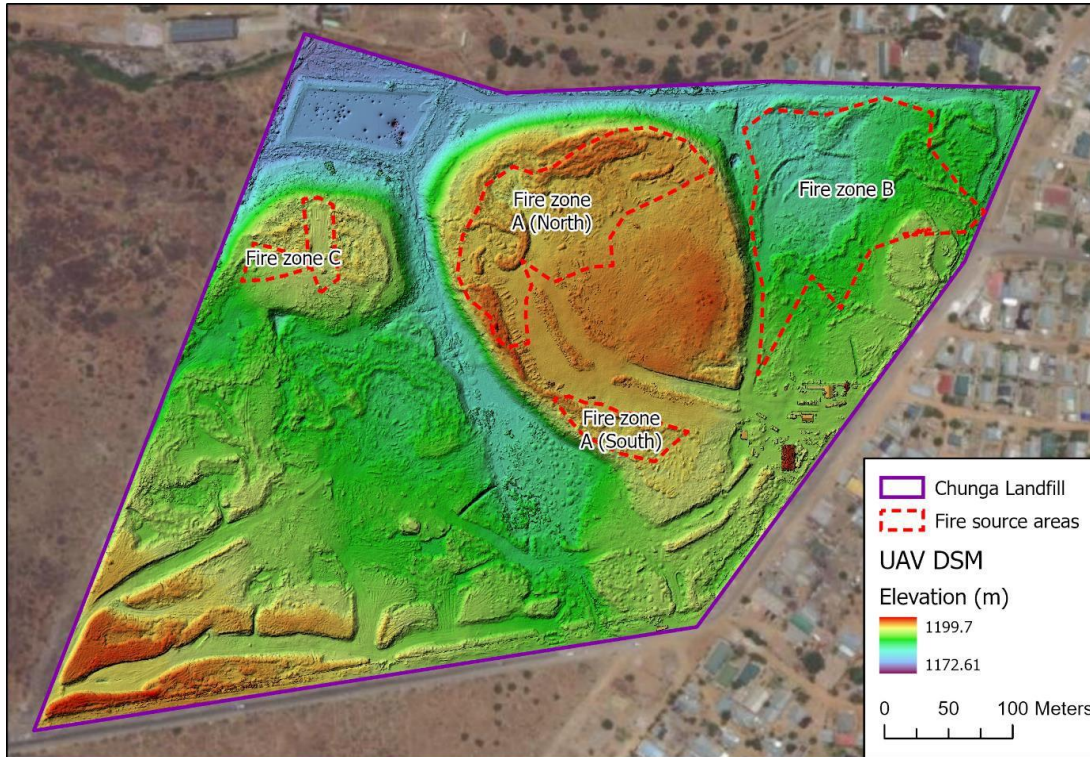
Light green to yellow regions corresponds to 6-9 fire-plume trajectories and green regions 2-4 trajectories. Dark green colour indicates the lowest density of fire-plumes and map and the maximum-peripheral extent of Chunga fire-plumes.

Figure 6 also show that the Chunga fire-plumes can cover three main areas: 1) the Chunga Land Fill site itself; 2) the open ground to the west of the Chunga Landfill Site and 3) a large area of residential properties located around the edges of the open ground area. At least 800 to 1000 individual houses have been estimated to be affected by plumes using the software.

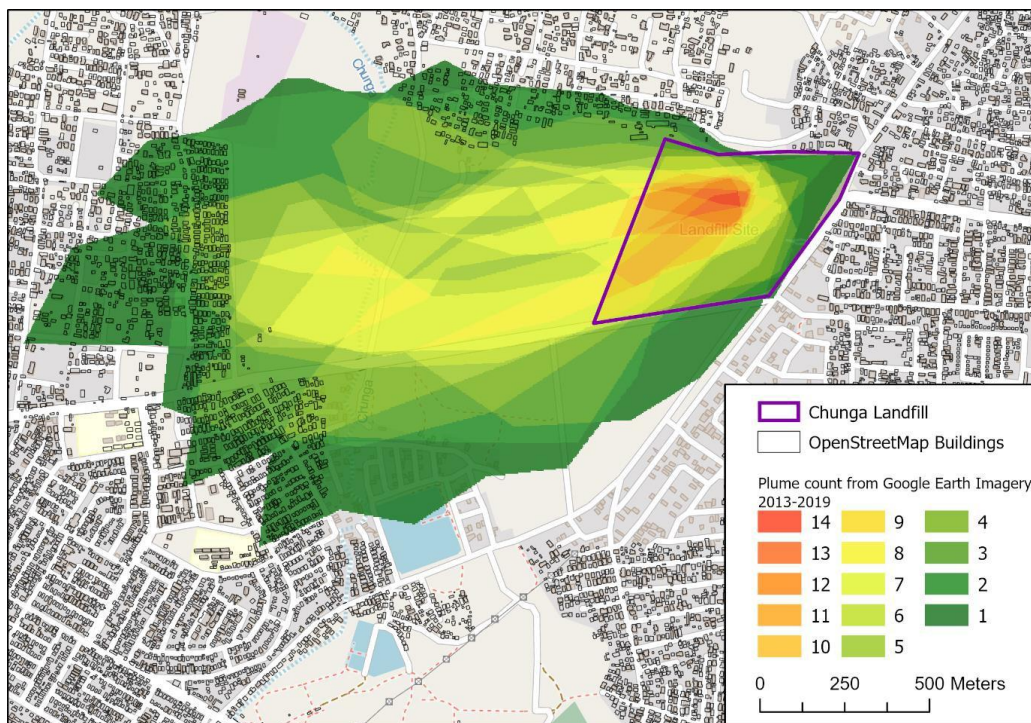
The households are primarily to the North West, west and southwest of the landfill site. Those households immediately west of the plumes are the most exposed to most plumes with those south and north of the plume trail suffering a lesser but significant level of exposure to plume pollution. The map shows households that are exposed to different densities of plume activity (1 - 2 plume events (dark green), and 2 - 4 plume events (green to light green)). An aerial image of plumes from the landfill as captured by the Unmanned Aerial Vehicle (UAV) shows thick plumes from multiple focal points being carried by Easterly winds (Figure 7).

### Average plume area

Between 2013 and 2015 there was an increase in plume



**Figure 5.** A map of Chunga Landfill showing regions where fires have been identified to burn resulting in plume smoke from 2013 to 2019.



**Figure 6.** A Map of Households Under risk of plume from Chunga Landfill as evidenced by communities under plume layers to the west and south west of the landfill. This map is based on visual observation of plume and also maps plume density. The Map Legend shows plume cover from 2013 to 2019 (Esri. OpenStreetMap Basemap data © OpenStreetMap contributors, 2021).



**Figure 7.** Smoke Plumes from subsurface fires at Chunga landfill resulting from multiple fire focal points across the landfill. The Plume blows primarily west to south west affecting residents of surrounding communities (Aerial Image taken at the landfill site).

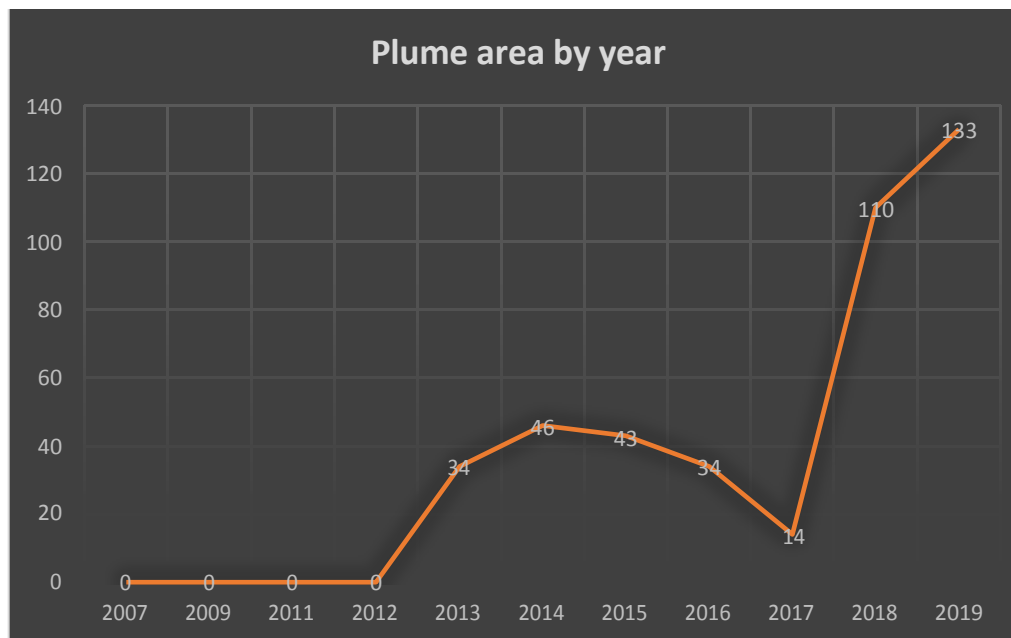
activity with an average area cover of 41 ha. There was a noticeable drop in plume coverage between 2015 and 2017, with a drastic increase in plume area between 2017 and 2019. The area covered by plumes increased to 110 ha in 2018, and increased further in 2019 to the highest observed plume cover of 133 ha. Results show that 2013 was the first year we can detect in which smoke plume at the landfill became visible on satellite images and the area covered progressively increased until 2015 when it decreased but as still present. The increased extent of plume coverage in 2018 and 2019 is observed to reach residential properties within the surrounding communities. Figure 8 show that fire plumes were not observed from the data prior to 2013 and have recently increased since 2017.

## DISCUSSION

Fires at the Chunga landfill have been a cause for concern due to their continuous presence over a significant time period the contents of the waste plumes, and the distribution of plumes resulting from these flames. The

cause of these fires is mainly attributed to production of methane and other flammable gases from organic waste (Luke, 2017), resulting in plumes that are observed to travel primarily Westwards and South-Westwards from the Chunga site, driven by predominant Easterly winds throughout the year. The analysis of plume data generated from primary research and Google Earth image analysis from 2007 to 2019, and resulting data were used to construct a plume density and direction map (Figure 6). Each plume polygon was examined to interpret which areas produced the highest-lowest density and most frequent plume trajectories over the 13 years of analysis. The region directly west of the landfill has the highest impact with 9 to 14 cumulative polygon segments. It is evident from Figure 6 that the dominant plume direction is just south of west (c.  $260^{\circ}$  using the metric scale of geographical compass orientation) but varies between SW and just north of west ( $215^{\circ}$  to  $280^{\circ}$ ). These directions result from predominantly easterly winds, measured to move at an average speed of 4.5m/s (Fant et al., 2016). The Lusaka/Zambian Meteorological Office produce data of wind directions for Lusaka and these indicate predominant Easterly winds, with weaker





**Figure 8.** The plot of the average smoke plume area resulting from Chunga landfill between 2007 and 2019, showing the first satellite images of plume in 2013 with an average area of 13 (Ha).

southerly and northerly winds blowing during January-March, in addition to the easterly winds (Meteoblue, 2019). This suggests that the footprint of plumes could be more extensive with plumes extending north-south during certain seasons. Our research, however, did not capture north-south plume directions. The contaminant plumes directly affect people at the landfill site, including staff, visitors, and waste pickers. Many other plumes may not have been recorded via the Google photographs, and it has also been theorized that with distal distance from the fire source the plumes will decrease in density, and become less visible to satellite images. Estimates from visible plumes are at the lower end of the likely number of residents impacted by the plumes. However, even if only 800 to 1000 households are directly impacted by fire-plumes, this indicates that a population of c. 4000 -5000 Lusaka residents is at risk to PHS derived from Chunga Land Fill Site Fire- Plumes, using the figure of c. 5 people per household in Lusaka (Zamstats, 2015). This represents a significant public health exposure hazard for the households that are observed under the plume layers created by the landfill fires. Plumes are most dense at proximal locations, and least dense at distal locations.

Residential structures, as far away as 3 km west of the waste site are affected by a single distal plume layer, including a primary school to the south west, Namando Primary school (Figure 6). Houses within 1-2 km west of Chunga are particularly impacted by denser plumes. The plume primarily affects the residents of the low cost, high density Chunga and Lilanda settlements. The effect on public health could be significant, although no studies of

impacts have been undertaken. Due to the non-segregation of waste at the Chunga Landfill site, materials that will burn probably include: plastic; cloth; wood; rubber; organic materials; domestic waste; industrial waste; and possibly even chemicals. A wide range of potentially harmful substances that can have an impact on human respiratory systems are present, in addition to potential longer-term medical impacts resulting from the ingestion of heavy metals, organic compounds, and a range of gases. Pollutants could include: benzene; furans/ dioxins; and a range of solid particulate matter in suspension (PM2.5) (Weichenthal et al., 2015). Research by (Weichenthal et al., 2015), found increased concentrations of dioxins/furans and benzene in the atmosphere caused by landfill fires produced at a landfill in Iqaluit Canada. The presence of NO<sub>2</sub>, (Nitrogen dioxide) O<sub>3</sub>, (Ozone) and PM2.5.

(Particulate matter of diameter < 2.5 micrometre) was detected. Similar research by (Toro and Morales, 2018), observed an increased PM2.5 concentration of 200µg m<sup>-3</sup> after 3 days of monitoring a landfill fire at the Santa Mata landfill in Chile. These toxins pose a health risk to vulnerable populations particularly children, pregnant women, the elderly, and/or individuals with pre-existing chronic respiratory conditions (Krzyzanowski and Cohen, 2008).

For Low Income Countries like Zambia, many individuals from the aforementioned vulnerable populations earn a living from the landfill as waste pickers. Waste pickers earn a living by picking “valuable” and unrecycled waste such as plastic and metals, which they resell to recycling

companies. However, for recyclable materials to effectively reach recycling stations, stake holders such as the Lusaka City Council should upscale efforts to encourage the separation of waste before it reaches the landfill.

This research has implications for policy and management related to landfill sites not only at Chunga, but by extrapolation to other landfill sites in Lusaka and elsewhere. The authors suggest the following framework for landfill management be adopted: 1) for waste to be increasingly sorted and segregated with different disposal options developed for different types of waste. At the very least the more combustible, and organic waste elements should be separated and perhaps composted rather than disposed amongst other waste types. 2) For methane and gas evacuation pipes to be inserted into the Chunga Site in a systematic rectilinear manner to be disposed of in a different manner to other waste types. Alternately these biogases can be collected and used for energy purposes, whilst at the same time reducing contributions to atmospheric greenhouse gases; 3) rapid extinguishing of any fires be that remain following better waste sorting to be undertaken; 4) weekly monitoring of the landfill site by UAV and on-the-ground inspections to be undertaken; 5) active weekly monitoring of air quality and specific analysis of pollutant species to be undertaken by the Lusaka City Council; 6) the design of a communication strategy that aims to engage in more proactive communication and consultations with local residents and other stakeholders in waste management at Chunga; 7) the further drafting of medium-long term waste management policy in Lusaka that takes account of the rapid growth in urbanisation and resultant waste production.

Extinguishing of landfill fires that cause massive plume smoke reduces the risk of respiratory complications in the communities particularly west, south west and North West of the landfill. The authors encourage Landfill Operators put into practice an action framework that effectively deals with landfill fires. It is therefore recommended to improve Landfill Gas Collection to prevent methane release. Methane collected could be used for energy production as demonstrated by Sweden and other Developed and Developing Nations (Finnveden et al, 2007). This has the added advantage of limiting additional greenhouse gas contributions to the atmosphere.

Weekly monitoring is recommended at Chunga landfill using photogrammetry. This would allow the assessment of waste heap slopes, volume, Landfill Fires, smoke plume resulting from fires, and the drainage status. Photogrammetry is cost effective and presents an opportunity for managers to continuously monitor the status, public and environmental impact of Chunga Landfill. They acknowledge that any temporal trends are based on a limited amount of data. The authors' results demonstrate that there is a significant fire-plume issue relating to the Chunga Landfill site, that this hazard varies in intensity, and there is a suggestion that it will become

an increasingly important issue as more material is deposited within the Landfill Site.

Future research is needed to understand the impact so far that Chunga landfill has had on soil, air and ground water quality as these aspects are directly related to public health.

Zambia's population is pegged to double over the next decade and hence the need to focus on research into reduced pollution from Landfill waste to improved soil quality for agriculture, clean drinking water and improved air quality for susceptible communities.

## Conclusion

The immediate and most visible risk to the environment and surrounding communities comes from constant smoke plume resulting from landfill fires first recorded in 2013. Results show that between 2013 and 2019, the area covered by smoke plume has increased from an average of 34 ha to 143 ha, respectively. Smoke plume is observed to be carried south west, west and North West of the landfill by primarily easterly winds throughout the year. The landfill is surrounded by high densities communities. The western direction in which plume is carried, at an average speed of 4.5 (m/s), puts these communities in the west, north west and south west are most at risk. The dry season in Lusaka lasts between May to October and therefore, this time of the year results in a greater wind distribution of particulate matter.

## CONFLICT OF INTERESTS

The authors have not declared any conflicts of interests.

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