# PHOTOGRAMMETRY BASED ANALYSIS FOR THE RISKS ASSOCIATED WITH LANDFILLING IN DEVELOPING COUNTRIES: CASE STUDY, CHUNGA LANDFILL, LUSAKA, ZAMBIA.

**by**

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# DEDICATION

To my parents who have always prayed for me and watched God work miracles in my life.

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**Statement of Originality**

'I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person nor material which to a substantial extent has been accepted for the qualification of any other degree or diploma of a university or other institution of higher learning, except where due acknowledgement is made in the acknowledgements'.

**Date:** **28/02/2020**

**Signature:** 

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## ABSTRACT

Solid waste is recognized globally as being a present and growing threat to a sustainable environment. Urban (and rural) growth correlates strongly with increasing waste production in all cities, presenting a particularly challenging problem to cities in Developing Counties that can often lack the resources and management strategies to effectively dispose of waste. The poor management of a landfill creates immediate environmental risks to the surrounding communities from disasters such as waste tip collapse, ground water pollution, and smoke plume production from landfill fires. Landfill topography can be assessed using Structure from Motion (SfM) photogrammetry. This research has used photogrammetry and geospatial analysis to map and assess risks posed by the only engineered Landfill (Chunga Landfill) in Lusaka, Zambia.

Waste volume at the landfill was estimated at 761, 815 cubic metres, which accounts for 6.5 percent of the total landfill capacity. This is considerably a low waste volume, as the Lusaka population is currently estimated at 2,647,000, and some estimates suggest that the city creates around 1 million tonnes of waste annually. The low amount of waste at the landfill has been mainly attributed to low levels of city-wide municipal collection. Most waste is processed locally by individuals within the city and disposal of the total waste which is estimated at 40%.

The geomorphology of Chunga landfill, based on my 3-D model derived from systematic UAV photogrammetric data shows a range of features including: a maximum waste tip height of 18. 85 m above ground; steep waste tip slopes of up to 53 degrees; a drainage system that is significantly uncontrolled and leaking pollutants into the wider environment; and abundant landfill fires with resulting pollutant plumes. The risk associated with these aspects includes: over-steepened and potentially unstable waste-tip slopes; respiratory and other human health impacts linked to fire-plumes and water pollution; risks to workers within the site near steep slopes and landfill fires. Landfill fires are first observed in 2013 and continue to burn until the present day, resulting in smoke plumes that blow west, south west and north west. There is significant exposure from these plumes to hundreds of thousands of residents who live within the plume trails, exposed to fine particulate matter and gases.

The drainage system at Chunga landfill is observed to result in the pollution of Chunga river that flows from the north western region of the city to the south east. This situation occurs because Chunga landfill water and sludge streams do not all flow into the designated drainage pond, and thus impacts the surface and ground water quality, making it unfit for human consumption. The current drainage system threatens the stability of the waste heaps due to the presence of rivulets that cut away at the steep slopes of the waste heaps which may result in waste collapse.

Recommendations for improving the environmental performance of the Chunga landfill facility include; waste slope maintenance by reducing steep slopes to at least 11 to 14 degrees, drainage maintenance by engineering drainage canals that drain in the designated drainage reservoir, extinguishing of landfill fires to reduce plume exposure and continued landfill monitoring by photogrammetry to track waste volume, height and waste tip slopes.

The use of photogrammetry for landfill monitoring is a cost-effective method for analysing the change in geomorphology overtime and further research that has the potential to improve waste management practices in Lusaka and other developing cities. The use of drones in Lusaka is currently a growing field and faces challenges which stem from the access to Unmanned Aerial Vehicles (UAV's) and the regulations allowing access to airspace.

# 1. CHAPTER ONE

## 1.0 INTRODUCTION

The challenge for waste management authorities in Lusaka, the capital city of Zambia and other Developing World cities is the collection, transport and disposal of massive and increasing amounts of waste. Of the total waste produced in Lusaka, it is estimated that only 40% is collected and deposited at Lusaka's largest landfill(Luke, 2017). A report by the Word Bank estimates that 90% of waste in developing cities ends up in undesignated dumps or openly burnt (WorldBank, 2019a). The indiscriminate dumping of waste leads to a host of health and safety issues as well as environmental problems that Developing Nations struggle to cope with. The waste that does end up in designated landfills requires management that neutralises its impact on the environment and public health. Developing Nations face the challenge of landfill management due to the expensive nature of landfill construction a maintenance (Rodić & Wilson, 2017).

Chunga Landfill, since its construction in 2007, until the present day has been the only engineered landfill in Lusaka designated by the Lusaka City Council (LCC) for waste disposal (Chishiba, 2002). This, therefore, means that waste from all over Lusaka should be deposited at Chunga landfill site to satisfy the growing Lusaka population (Fox, 2012) The population of Lusaka is estimated at 2, 647, 000 in 2019, growing to 5,143,000 by 2034 (PopulationStats, 2020a). Urbanisation caused by migration from rural areas to Lusaka has been the main driver 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 increased to 1,807,000 (Edema, Sichamba, & Ntengwe, 2012). Some estimates suggest that Lusaka currently produces 1 million tonnes of waste per year (Nawa, 2017). The challenge of waste management in African cities like Lusaka is therefore projected to worsen with the growing populations, unless corrective management strategies are put in place.

The need for this research is starkly highlighted by past disasters, that have resulted in loss of life, such as the land slide that killed over 60 people in Ethiopia in March of 2017. The majority of victims of landfill disasters are residents closest to that landfill and those that earn a living through scavenging  landfill (Phiri & Morgenroth, 2017). Another landslide killed 16 people in Maputo, Mozambique at the Hulene landfill in march, 2018 (Yoshida, 2018). This collapse was triggered by intense rainfall patterns, and therefore this research will utilize data sets such as rainfall and wind direction to factor into risk modelling. Similar examples outside Africa include The Meethotamulla Landfill Disaster in Sri Lanka in 2017 that resulted in the death of 36 people, including 4 children (Siriwardana, Jayasiri, & Hettiarachchi, 2018). The Aberfan and Love Canal Disasters that collectively caused over 150 deaths from  landslides (Johnes, 2000) and chemical pollution (Phillips, Hung, & Bosela, 2007) respectively. Landfill induced fires such as the Riverton landfill fire in Jamaica, that burned for two weeks, and  caused over 800 respiratory related cases reported to local hospitals (Duncan, 2018) are a significant threat at many landfill sites. Lusaka's Chunga landfill has deteriorated since its construction in 2006, and has been a source of concern, as a wide range of waste types from all over the city is dumped there and is now a clear hazard to the numerous waste pickers who scavenge the site for a living, and the general public  living in close proximity  and associates with the landfill (Benard Chileshe, 2017).

*Table 1:  Examples of landfill collapse incidences in Developing Countries since 2000. High numbers of casualties are seen from Addis Ababa and Indonesia disasters with at least three occurring in 2017 (Yoshida, 2018)*

| Year | Month | Location | Dumpsite | Casualties |
|---|---|---|---|---|
| 2000 | July | Philippines, Manila | Payatas dumpsite | 200< |
| 2005 | February | Indonesia, Bandung | Leuwigajah dumpsite | 143 |
| 2015 | December | China, Shenzhen | Hongao Dumpsite | 77 |
| 2016 | April | Guatemala, Guatemala City | Guatemala Dumpsite | 24 |
| 2017 | March | Ethiopia, Addis Ababa | Koshen Dumpsite | 113 |

| | | | | |
|---|---|---|---|---|
| 2017 | April | Siri Lanka, Colombo | Meethotamulla dumpsite | 34 |
| 2017 | September | India, Delhi | Ghazipur Landfill | 2 |
| 2018 | March | Mozambique, Maputo | Hulene dumpsite | 16 |

Developing nations like Zambia, with a Lower Middle Income status according to the World Bank, (WorldBank, 2019b), struggle with science- based evidence to improve Solid Waste Management (SWM) practices. My research, therefore, identifies the need to study Solid Waste Management in a developing city like Lusaka, by assessing the risk of Landfills to the environment and public health by asking the research question:

“Can UAV imagery processed with Structure from Motion (SfM) photogrammetry be used to model a landfill for environmental risk assessment on surrounding communities?”

The World Health Organization (WHO) has identified waste management and the risks associated with it, as an area that is lacking modern research and analysis. Tools that highlight the risk associated with waste allow for better risk communication to the waste industry and allows governments to develop science and evidence based  (W. H. O. WHO, 2000). Several studies have focused on the effects of gaseous emissions and pollution resulting from landfills with little focus on the physical risks attributed to them, as well as their potential to cause harm through landslides, fires or spread of particulate matter. For sustainable development to occur, a compromise has to be drawn between economic and environmental costs, risk assessment makes this compromise possible (Butt, Lockley, & Oduyemi, 2008).

Photogrammetry using ‘structure from motion’ (SfM) is a modern, cost effective technique that allows for the processing of high resolution image datasets for creating 3D Digital Elevation Models (DEMs) (Westoby, Brasington, Glasser, Hambrey, & Reynolds, 2012). SfM utilizes photographic images to match and track unique features (Javernick, Brasington, & Caruso, 2014) and create a point cloud, that can be georeferenced to ground control points collected in the field (Fonstad, Dietrich, Courville, Jensen, & Carbonneau, 2013). Through SfM, the same surface is analysed from multiple perspectives and this allows for the creation of a true 3D point cloud (Micheletti, Chandler, & Lane, 2015).

Remote sensing technology has been successfully utilized in a number of landfill related studies, such as (Stohr, Su, DuMontelle, & Griffin, 1987) , (Kwarteng & Al-Enezi, 2004) and (Esposito, Matano, & Sacchi, 2018). Previous research has focused on the use of satellite images because it provided an opportunity to analyse changes in large surrounding areas, with little research specifically targeting landfill morphology, (Silvestri & Omri, 2008). The use of SfM techniques has been applied to natural landslides for the calculation of volumes of added and removed materials, as well as the prediction of areas of potential movement, that could result in a future landslides, (Lucieer, Jong, & Turner, 2014). This type of research will add to landfill management and policy development, supporting reduction and effective disposal of waste.

This research used an Unmanned Aerial Vehicle (UAV) to capture images of a landfill in Lusaka Zambia (Chunga Landfill) to analyse using 'Structure for Motion' (SfM) photogrammetry, and use the resultant data and models to analyse a range of potential risks and environmental management practice at the Chunga Landfill Site. The stages of this research are outlined as:

1. *Field work*.

I. Image acquisition and key point extraction.

This required taking pictures of the Landfill from multiple positions to identify features in each image to be used for the 3D location of matching features in the various photographs. This allows for the identification of keys points of interest over the landscape in each image (Westoby et al., 2012).

II. 3D scene construction

Key points in the multiple images are matched using the nearest neighbour and Random sample Consensus algorithms to create 'tracks' that link key points in the various images (Arya, Mount, Netanyahu, Silverman, & Wu, 1998) . Point – cloud reconstruction is then developed from tracks with minimum two key points and three images, all others being discarded if they do not meet this criteria. (Snavely, Seitz, & Szeliski, 2006)

III. Post processing and digital elevation model generation

This implies transforming from a relative to an absolute co-ordinate system by manual identification of ground control points in the point cloud and computing an appropriate transformation. At this stage, any mismatches that are obvious outliers and any unnecessarily constructed surroundings are manually removed.

2. *Accuracy Assessment.*

The accuracy of the model was determined either by setting ground control points or repeating the modelling process several times to determine consistency.

3. *Risk assessment.*

To determine environmental risk to surrounding communities, risk maps were constructed from geospatial analysis that highlight communities vulnerable to risks identified from the Structure for motion model analysis.

4. *Plan of Study Overview.*

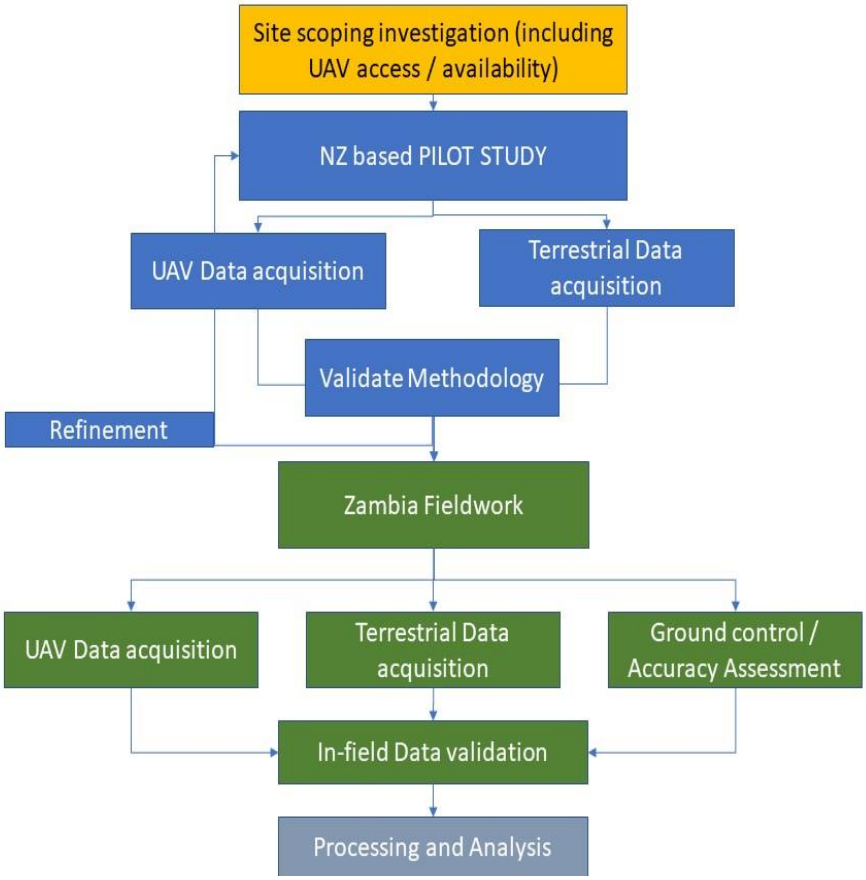


*Figure 1:1: Project Research overview for Chunga Landfill in Lusaka Zambia.*

5. *Data Outputs.*

- Digital Surface Models
- Risk analysis maps
- Accuracy Assessment

The scope of this research focuses on: defining waste and waste streams; waste management practices in developing and developed countries; landfill design and its impact on solid waste management; examining examples of landfill disasters; creating a high resolution 3-D geospatial model of the Chunga Landfill Site; analysing the 3-D model and identifying implications for multivariate risk and environmental impacts; designing practical recommendations for the future working of the Chunga Landfill. . Understanding each of these research elements was vital in understanding and appreciating the role photogrammetry plays as a research tool to analyse and improve Solid waste management in Zambia and other Developing Countries.

# 2. CHAPTER TWO

## 2.0 LITERATURE REVIEW

### *2.1 Definition of Waste*

Waste has yet to have a fixed definition that experts and common people will agree on. (Drackner, 2005) and (White, Dranke, & Hindle, 2012) however agree that waste can be defined as any by-product of human activity that is no longer considered useful or valuable. Waste products will physically contain the same kind of materials as useful products, the only difference being that these products won't be of value anymore. With that in mind, waste can also be categorised into various schemes as shown in (Fig 2.1.1)

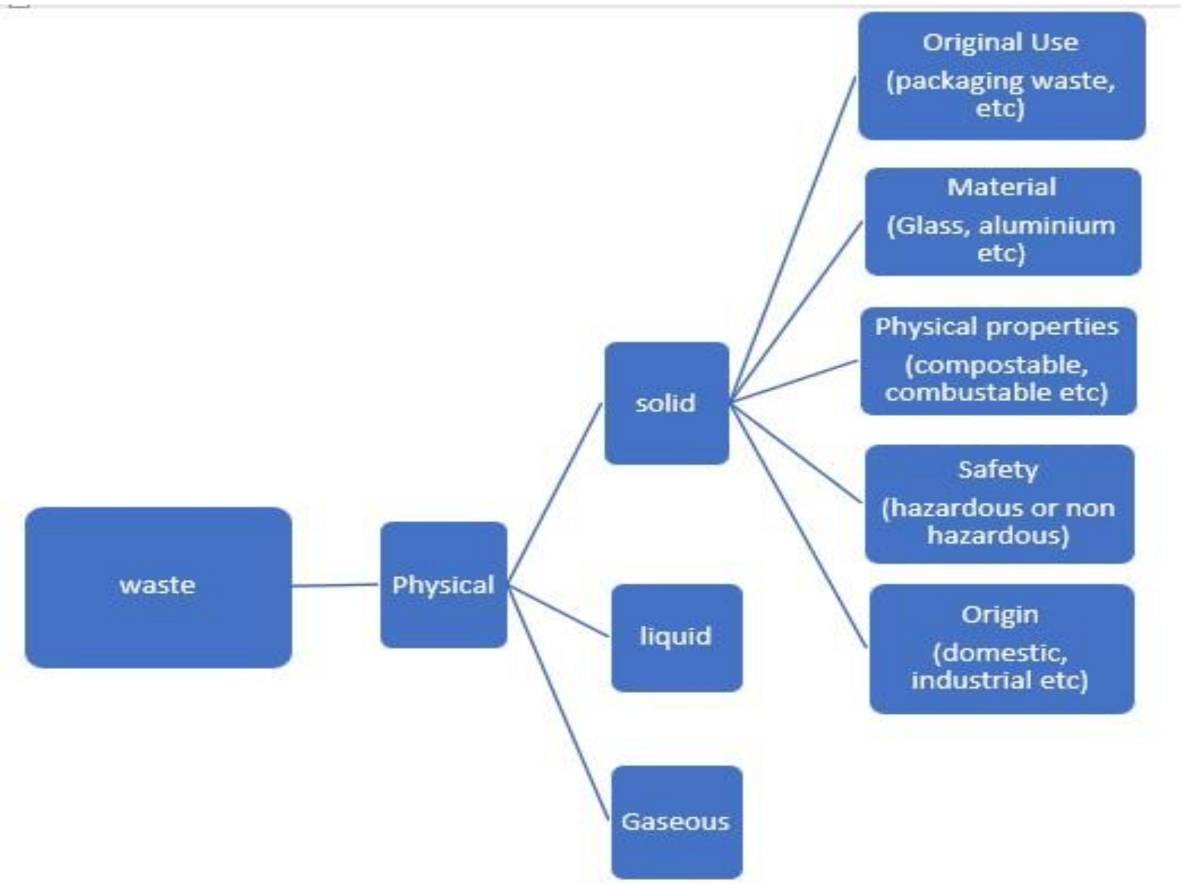


*Figure 2:1.1: The Categories of waste, subdivided to three physical states, solid, liquid and gaseous. Solid waste if further subdivided based on factors such as origin, safety, physical properties, material and original use (White et al., 2012)*

As shown in (Figure2.1.1), Waste is categorised by its physical state, either solid, liquid or gaseous. Under solid waste are further sub-categories that are determined by the original use of the waste, waste-origin, physical properties, and levels of safety posed by the waste. The categorisation used in (Figure 2.1.1) is one way of defining waste while (Pichtel, 2005) takes an approach of categorising waste based only on source, some of the major ones being: Municipal, Hazardous, Industrial, Medical, Universal, Construction and demolition (C&D), Radioactive, Mining , Agricultural.

Given the broad variation in defining waste, this research will focus on Municipal Solid Waste (MSW) which will have the following suggested definition of: "The waste generated at residences and commercial establishments (e.g., Offices, restaurants, retail shops) and institutions (e.g. Prisons, hospitals, schools,), but not including Construction and Demolition (C&D) materials, automobile scrap metals or medical/pathological waste" (Chandler et al., 1997).

or

As defined by the Environmental Protection Agency (EPA) in the United States which includes waste from residential, multifamily, commercial and institutional sources, but also specifies in its definition to exclude materials such as water, waste water treatment residue and (C&D) waste (USEPA, 2007)

## *2.2 The evolution of waste*

For as long as human beings have inhabited the earth, waste has been produced and disposed in various forms with solid waste being one of the most abundant and potentially most harmful (Melosi, 2004). Ancient civilisations did not however have a problem with waste, at least not to the extent that modern societies are required to cope with. The problem of waste for human society is put into perspective by tracing it from ancient time to the industrial revolution in Europe. The historical connection between refuse and urbanization becomes quite apparent in this context. The first urban sites were the result of a shift from nomadic lifestyle of the hunter-gatherers to food production that required permanent sites around 10,000B.C. Over time a form of waste management was necessary as it was clear that, on-site dumping and natural decomposition would not do (Melosi, 2004).

With the necessity to dispose of waste, three main forms of waste disposal have been used since ancient times until present. (Cossu, 2012), states that these three forms of waste disposal have been landfilling, recycling, and combustion, with the method used mainly based on factors such as politics, and social and cultural practices that govern each group of individuals. Factors such as poor waste management, lack of awareness of environmental risks caused by poor waste management, and urbanization have affected waste management practice through time (Achankeng, 2003; Hoornweg & Bhada-Tata, 2012; Vij, 2012). Developing Nations are positioned to see the highest net percentage increase of urban dwellers over the next 50 years. Currently the global world population stand at over 50% urbanized, as compared to the 1900's when c. 10% of the world's population lived in cities (Grimm et al., 2008).

Africa is a continent with numerous developing and highly urbanised cities. Activities such as the slave trade, colonialism, and pre-colonial nation governance and administration (e.g. Zimbabwe, Ethiopia) among others, helped to concentrate populations and create early cities. These sites blossomed, and others developed in post-colonial times to become the urbanized cities we see today.

Currently African cities use 20 – 50% of their budget on solid waste management, yet only 20 – 80% of waste, is collected with a portion of it being illegally dumped (Achankeng, 2003). Achankeng also states that uncollected, unprocessed, and badly managed waste is a disaster in the waiting, as it affects human health and causes environmental degradation (Achankeng, 2003). Africa has been identified as a key region for improvement in solid waste management practices and consumption of products given the rapid rate of population growth and urbanization (Hoornweg, Bhada-Tata, & Kennedy, 2013).

## *2.3 The waste Management Hierarchy*

Landfilling which is also a know as Sanitary landfilling , is a systematic process of burying garbage in layers of earth. This process involves an engineered method of disposing solid waste within an engineered cavity in the ground. This can, reduce environmental impacts by spreading the waste into thin layers, compacting it to smaller volumes, and covering it with earth each day (Sumathi, Natesan, & Sarkar, 2008). Engineered in-ground landfill disposal is the most preferred option in the Developed World. As environmental consciousness grows, the concept of reducing re-using and recycling waste streams will hopefully mean that the use of landfills will be reduced.

Increasing environmental consciousness, including the whole debate around Climate change is the greatest driving force to the changing of waste management practices. (Finnveden, Johansson, Lind, & Moberg, 2005). The authors further state that the *hierarchy* of waste disposal, i.e., the relative importance of approaches to waste management, varies depending on waste policy. One popular waste hierarchy model is given below (Fig.2.2).

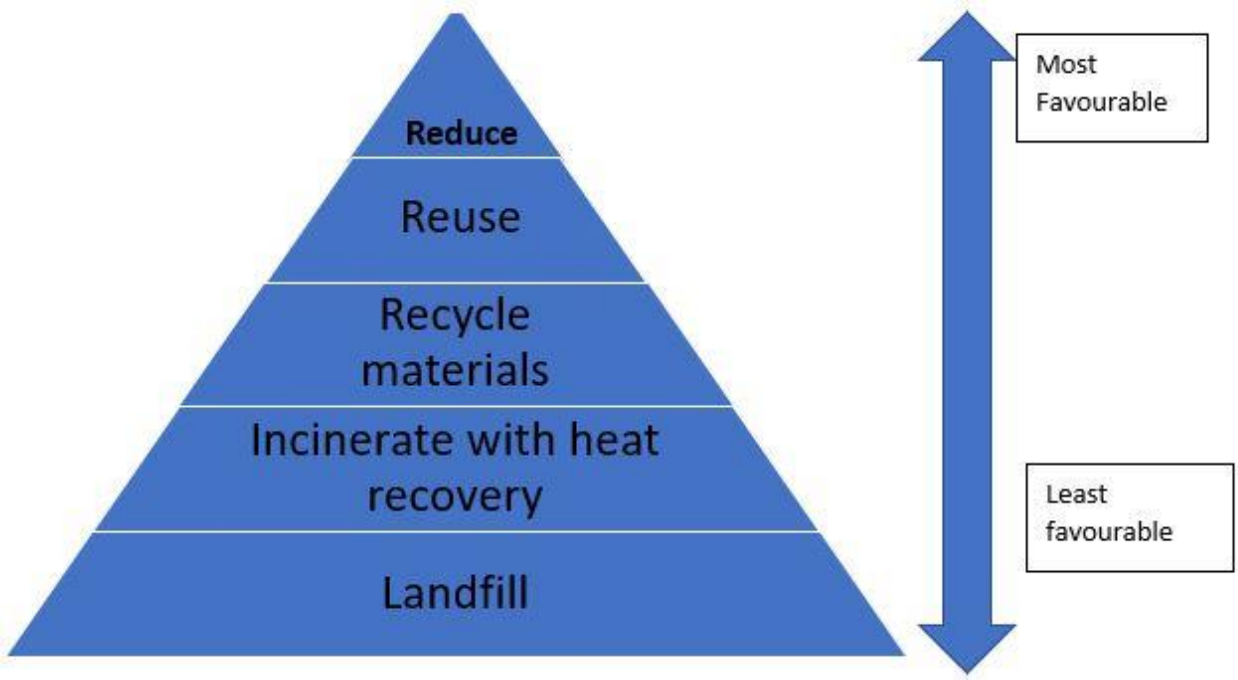


*Figure 2.2 :A suggested pyramid for globally recognized and recommended waste management hierarchy for sustainable waste management (Finnveden et al., 2005).*

The Waste Management Hierarchy began to formulate in the early 70s, when environmentalists analysed and critiqued waste disposal, as the sole solution to managing waste. This hierarchy acts as a guide to Integrated Solid Waste Management practices (ISWM). (Bagchi, 2004) states that this hierarchy is, however, not set in stone, and not based on scientific principles. It will depend on each community to decide how best to combine disposal practices based on available resources, and environmental policies. From a public health standpoint, waste management was equated to having a "prevention is better than cure" approach, as it was more viable and cost effective to reduce the amount of waste being produced than to spend resources on disposing of it (Gertsakis & Lewis, 2003). It is generally agreed that reducing waste is essential for solid waste management. Re-use of product saves energy by avoiding the manufacture of the same product, while recycling requires energy. Despite recycling having had a positive influence on public perceptions towards waste generation, and impacting the amount of waste that ends up in landfills by a fraction, its impact on waste management has, overall, been limited (Sakai et al., 1996). The author also states that sustainability of these recycling programs is unsatisfactory due to a fluctuating market for waste. Recycling can be further encouraged by adjusting recycling targets and addressing these limits

Incineration, the management of municipal and hazardous wastes by burning, as part of an integrated waste management system is designed to reduce waste volumes, and sterilise waste, before final disposal. More modern incinerators are designed for energy efficiency and recovery (Sakai et al., 1996). Incineration, when compared with recycling, is at times a more economically viable waste management option. Incineration produces heat which can be used for a range of purposes such as heating of houses and offices. Countries such as Sweden use Incinerators for heating buildings, and the production of electricity (Finnveden, Björklund, Reich, Eriksson, & Sörbom, 2007). The environmental impacts of incineration have however been criticised, as they can produce dioxins and furans, which are highly toxic. Chlorine Dioxin, a highly toxic substance, has been described as a high risk to public health(McKay, 2002).

The (ISWM) hierarchy omits a waste management practice that has gained ground in parts of the world: this omitted practice is termed Zero Waste. Zero waste is a holistic system that aims to eliminate waste going to landfills (Zaman, 2015). First initiated by the Zero Waste New Zealand Trust in 1997, with organisations in Canada, United states of America, Korea, and Ireland following suit. The zero waste movement grew with the aim of redesigning the way resources and materials flowed through society, as well as redesigning the industrial system, to ensure that materials are made to be reused, recycled, or replaced into nature or the market place (Tennant-Wood, 2003).

## *2.4 Proposed Mechanisms for Effective Solid Waste Management (SWM).*

It is important to have an integrated system of managing waste if a nation is to have a sustainable economy and environment. Nations that seek industrial acceleration at the expense of solid waste management ultimately lose resources to rectify the impact on the environment, public health and safety (UNEP, 2005). The United Nations Environmental Program (UNEP) highlights the standard solid waste management mechanisms that are being utilised by industrialised countries. (Figure 2.3)

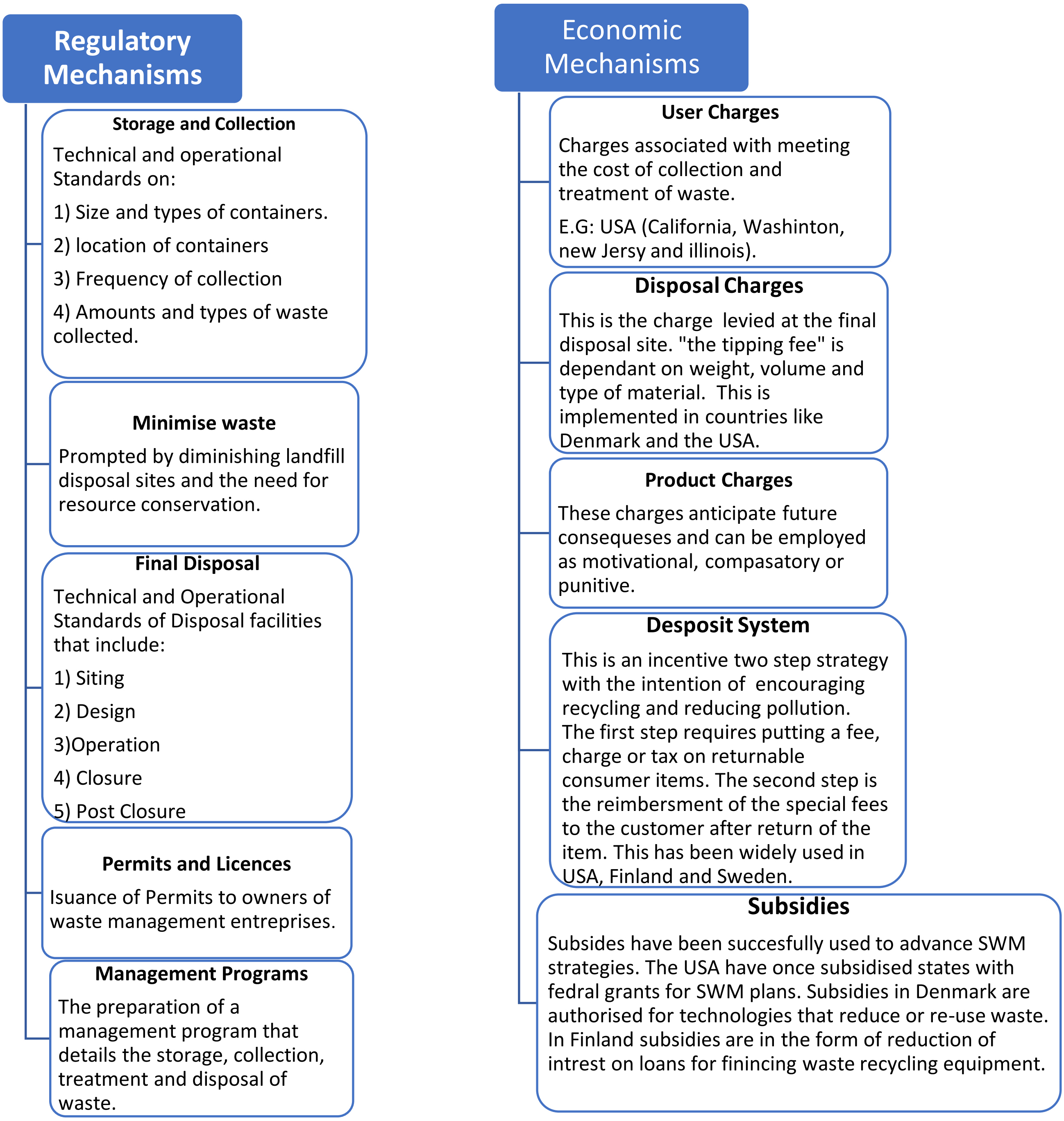


*Figure 2.3: Mechanisms Used by Industrialised countries for effective SWM. (UNEP, 2005)*

The regulations that govern these mechanisms are made by acts and rules, with the acts being products of a national constitution. In an instance that a national constitution is unavailable, these acts are generated through, national policy, international law, and procedures specific to each country (Chandrappa & Das, 2012). It has however been observed by (Wilson, McDougall, & Willmore, 2001) that several of these legislations have professionalised Solid waste management, while some have caused system dysfunction.

The EU has recognised climate change as another reason to incorporate legislation to solid waste management that reduce greenhouse gas emissions. This can be achieved through the diversion of biowaste from landfills, improving energy efficiency at waste disposal and treatment facilities, promoting compost as a form of fertilizer as opposed to mineral fertilisers, value addition to waste products such as recycled materials, to reduce consumption of resources and increasing materials utilities(Pires, Martinho, & Chang, 2011).

# 3. CHAPTER THREE.

## 3.0 SITE SELECTION AND LANDFILL DESIGN.

This chapter describes the process of landfill site selection and design. Both are important aspects of landfill management and are directly related to the environmental and social impact of waste disposal utilising landfills. Badly sited and/or designed landfills could pose a risk to the environment and surrounding communities, as outlined in this chapter, despite management practices that attempt to follow stipulated guidelines. The location and design of Chunga landfill is central to appreciating the landfill risks identified using photogrammetry in this research.

### *3.1 Landfill Site Selection*

The siting of a Landfill is a key component of municipal solid waste management. Several factors need to be considered when making this decision and the process requires an interdisciplinary effort and the input of various stakeholders. Landfill siting is becoming increasingly difficult due to growing environmental awareness, reduced municipal and governmental funding , and social and political opposition to certain aspects of waste management (Şener, Süzen, & Doyuran, 2006). The site selection of a landfill has been described as a difficult, tedious, complex, and protracted process, requiring evaluation of several different criteria (Chang, Parvathinathan, & Breeden, 2008). One major obstacle to decision makers is the *"Not In My Back Yard (NIMBY)"* phenomenon, where communities are against the siting of a landfill in a particular area because they believe it will adversely affect the surrounding environment, and economic and other socio-cultural aspects, such as the reduction of house prices located close to the landfill facility(Bagchi, 2004; Baxter, Eyles, & Elliott, 1999; Chang et al., 2008; Rushbrook & Pugh, 1999).

The cost of developing landfill sites may be high from an economic and social aspect but (Rushbrook & Pugh, 1999) argue that the cost of a poorly chosen site will require higher expenditure on waste transport, site development and operation, or environmental protection.

The authors further state that from a social perspective, the site may face long term opposition from the public. It is therefore imperative that strict guidelines and criteria for site selection are adhered to for the long term, successful operation of the disposal facility.

Methods of locating a landfill site have been placed in three categories by (Baban & Flannagan, 1998), as show in (Figure 3.1.1).

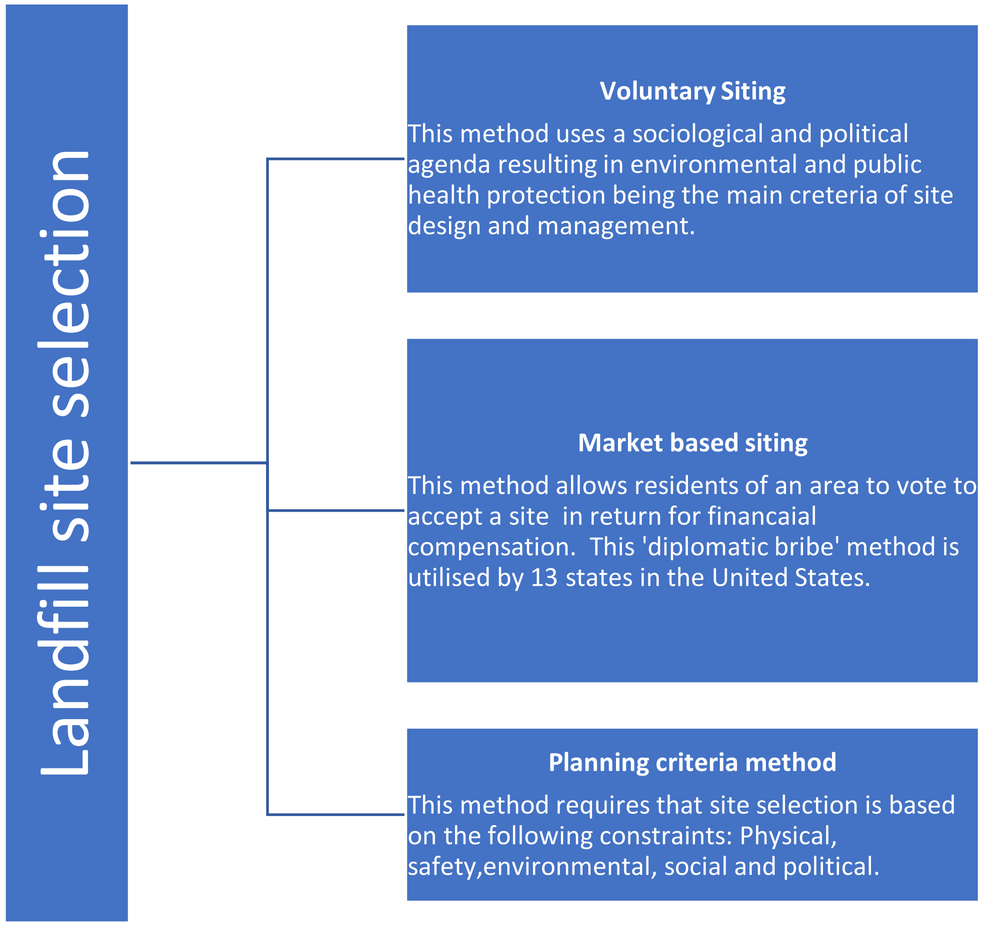


*Figure 3:1.1: Landfill site selection Methods. (Baban & Flannagan, 1998)*

Among the three methods mentioned in Figure (3.1.1), (Baban & Flannagan, 1998) state that voluntary siting and market based siting are ill-considered, as they represent a one-dimensional attempt at solving a problem which aims at satisfying the public, while not being environmentally-optimal, nor accounting for technical and economic considerations. Planning criteria methods can be comprehensive in addressing environmental, geological and safety factors, the economic practicality of the project, and political acceptance. On the other hand, (Baxter et al., 1999), have categorised the three key principles/practices of site selection as being trust, equity, and community participation, categorically looking at the social principles that lead to the successful siting of a landfill.

Public participation, equity and trust as observed by (Baxter et al., 1999) are a major part of getting the site selection correct.  Trust is essential for creating a cohesive relationship between key stakeholders such as government, the siting agents and the community hosts. Equity in this instance has been used to refer to environmental equity/ Justice and more specific forms of social, spatial and procedural equity. It is important that words used to describe ideas or concepts convey the intended message, (Ikeme, 2003) however warns that in literature on sustainability, it is difficult to find  concepts that are as misused and misunderstood as much as those such as  equity, and environmental justice, and admits that in most literature, the notion of equity, disruptive justice, procedural justice and environmental justice, are used inconsistently.

Another three important issues to consider when selecting a landfill site are: data collection, location criteria, and preliminary assessment of public reactions (Bagchi, 2004). This research pays specific interest in location criteria as it directly relates to the risk posed to the natural environment, and surrounding communities, by a poorly regulated landfill. Usually landfills cannot be sited within certain distances of certain natural and manmade areas. Furthermore, they cannot be built within or above known strategic mineral resources including sand, gravel, clay, and construction mineral deposits as well as metallic minerals. Examples of prohibitive distances to key environmental/cultural features include the following: (Table 2).

*Table 2:. Location Criteria of Landfill site selection with regards to the restrictive radius of regions such as lakes, rivers, airports etc..  (Bagchi, 2004)*

| Region | Restrictive Radius | Notes |
|---|---|---|
| Lake or Pond | 300m (1000ft) | Includes any navigable lake pond or flowage. If the landfill is sited less than 300 m, a surface water monitoring program should be established. |

| | | |
|---|---|---|
| River | 90m (300ft) | Includes navigable rivers and streams. Distance may be reduced for non-meandering rivers. |
| Flood Plain | 100-year flood plain | Regulations may require a more restrictive floodplain (e.g., 500-year floodplain) siting criteria. Landfills must not be built within the floodplains of major rivers. |
| Highway | 300m (1000ft) | This is mainly for aesthetic reasons. |
| Public Parks | 300m (1000ft) | An exception to this restriction is when a screen is used. Measures must be taken to keep unauthorized personnel out of the landfill. |
| Critical Habitat Area | Within | Critical areas being ecological areas with endangered species. |
| Wetlands | Within | Defining a wetland is not always easy. If any doubt exists, regulatory bodies should be contacted. Disturbing these ecosystems should be avoided. |
| Unstable Areas | On unstable areas | An area may be declared unstable due to natural or human activities such as expansive soils or areas where high quantities of gas |

| | | |
|---|---|---|
| | | have been extracted, respectively. |
| Airports | 3048 m (10,000ft) | Birds are attracted to landfills as they can be a food source. Large number of birds close to an airport can be a hazard to aircrafts. |
| Water Supply Well | 365 m (1200 ft) | This is especially recommended for down gradient-wells. |
| Active Fault Areas | 60 m (200 ft) | Active fault areas are subject to earthquakes which may cause landslides or soil liquification. |
| Seismic Impact Zone | An area with a 10% or greater probability that the maximum horizontal acceleration caused by an earthquake at a site will exceed 0.1g in 250 years. | In addition to liquefication, earthquake induced ground vibration can also compact loose granular soils resulting in uniform or differential settlement of the landfill base. |

A practical example of the landfill criteria for site selection is highlighted by (Şener et al., 2006) as a decision tree that reinforces the complexity of landfill site selection (Figure 3.2). The study used GIS for site selection of a landfill at potential sites near Ankara city in Turkey.

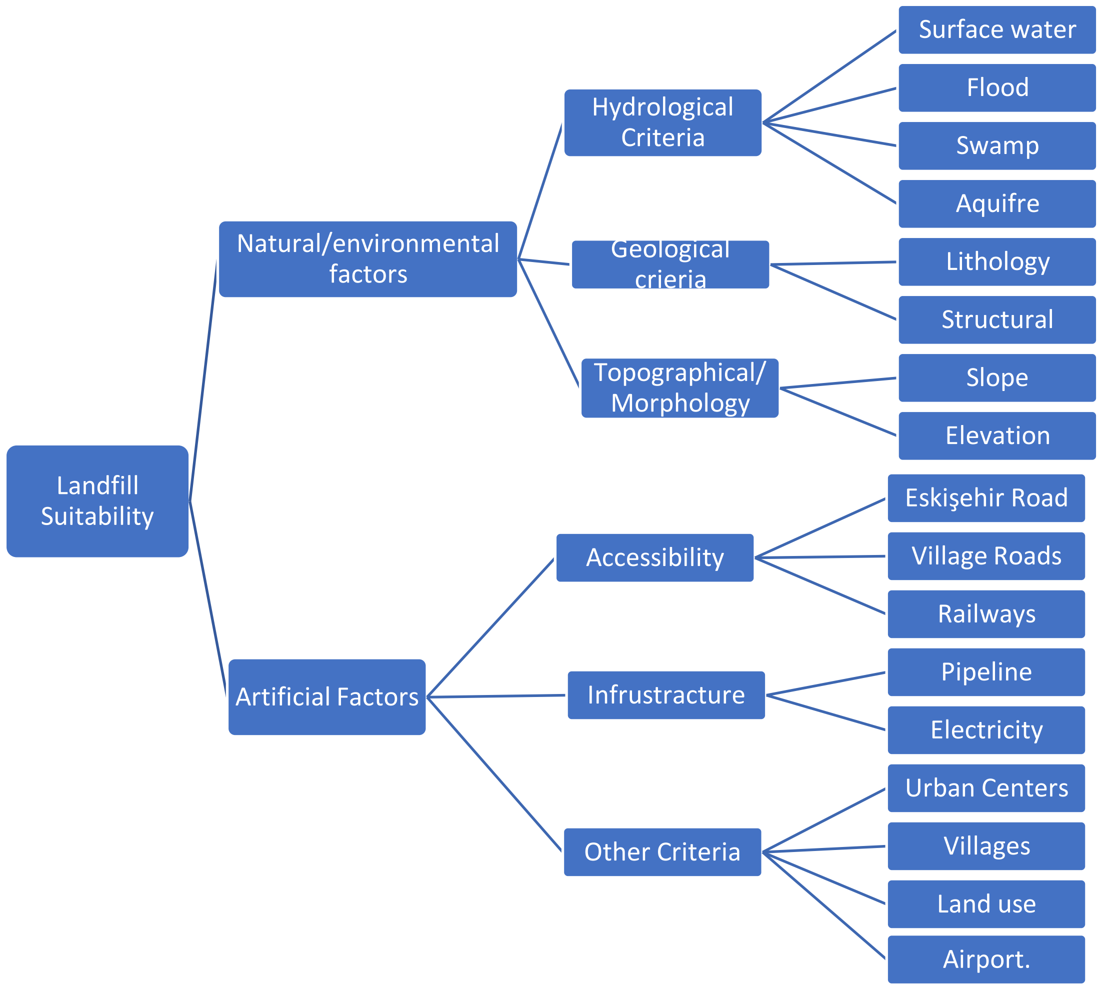


*Figure 3:2: Decision tree for Landfill site selection at potential sites near Ankara city in Turkey (Şener et al., 2006)*

Using the above site selection criteria, a range of potential landfill sites can be identified for any area. Additional hydrogeological and geotechnical analyses will be needed for the selection of the final site, alongside municipal planning permission processes and societal acceptance.

## *3.2 Landfill Design*

Like site selection, the design of a landfill is a complex process that requires the integrated efforts of professionals from engineering, environment, hydrology and geology fields. Landfills are categorised into three groups i.e., Sanitary landfills, Industrial waste Landfills, and Hazardous waste landfills (USEPA, 2007). Over the last two decades, to control the negative effects of landfill sites, experimental testing and field pilot studies have been tested with the aim of controlling the negative effects of landfills on the environment (Warith, 2003). As part of the design process several considerations need to be reviewed and are briefly discussed in (Table 3) below.

*Table 3: Design considerations for the construction of a landfill expected to meet environmental and socially acceptable standards (EPA, 2000)*

| Design consideration | Notes |
|---|---|
| Nature and Quantities of waste | This dictates the control measures required at the site, varying between hazardous and non-hazardous facilities. |
| Water control | The quantity of water entering the landfill may need to be minimised to reduce leachate generation. |
| Protection of soil water | This requires a liner that meets prescribed permeability and thickness requirements which may be natural in nature or artificial. |
| Leachate management | To avoid leachate accumulation, a system to direct it to a treatment or storage facility may be required. |
| Gas control | All landfill gas must be monitored and collected for treatment, utilisation or safe disposal. |
| Environmental nuisances | This involves the control of nuisances such as noise, odour, dust, dust litter, vermin and fires. |
| Stability | This considers the stability of the subgrade, the basal liner system, the waste mass and capping system. |

| | |
|---|---|
| Visual appearance and landscape | From an aesthetics perspective, the visual appearance during and after landfilling should be considered. |
| Estimated cost of the facility | This includes the total cost of construction, operation, closure and after care. |
| Monitoring requirements | This should be also considered at design stage |
| After use | The designer should consider the intended after use of the facility. |
| Construction | This is directly related to the environmental effects of construction. |
| Risk Assessment | A comprehensive assessment of the risk to the environment and public health is required. |

According to (Rao, Sultana, Kota, Shah, & Davergave, 2016), when estimating the area to be used for a landfill, an extra 15% allowance should be factored in to allow for the housing of equipment, infrastructure, and the creation of a green belt around the landfill. (Rao et al., 2016) state that, “there is no standard method for classifying landfills based on their capacity” and suggest the following classification: Small size landfill will have an area less than 5 hectares or between 5 to 25 hectares, while a large sized landfill will have an area greater than 25 hectares. The designer will need to take the size of the landfill into account as shown by a (Seok Lim & Missios, 2007) study that concluded that landfill size does have an impact on property value. The study concluded that large landfills or large volumes of waste reduced the property value of houses compared to smaller landfills. This highlights one reason the “Not In My Back Yard” (NIMBY) syndrome is a major obstacle to site selection and design. An example of a large landfill is “The Keele Landfill in the Greater Toronto Area” that is approximated to be 376 hectares in area, opened in 1983, and received up to 28 trillion tonnes of waste, before eventually being closed in 2003. A small landfill example would be the Simcoe Landfill, that was 20 hectares in size, located in Ontario Canada

### *3.3 Landfill Liners.*

Sanitary landfills, as earlier defined, require continuous cover and compacting to avoid environmental exposure to litter, vermin attraction, and erosion. The liner is recognised as being of prime importance, as it is the only material separating the waste from the environment. If the landfill is not designed and constructed properly, especially in relation to the liner, the future cost could be considerable (Ashford, Visvanathan, Husain, & Chomsurin, 2000). The primary purpose of the liner system is therefore to protect the soil and ground water from pollution emerging from the landfill, with the greatest threat to ground water being leachates (Hughes, Christy, & Heimlich, 2008). Leachate has been defined as any contaminant liquid that is generated from water seeping through a solid waste disposal site (Cheremisinoff, 1998). Leachate, a toxic sludge, is generated from various sources which include rain water and the physical, chemical and biological breakdown of waste in landfills (Youcai, 2018).

Liners are categorised as single, composite, or double liner systems (Fig 2.3), with the type of liner used being determined by the threat posed by the waste in each kind of landfill (Hughes et al., 2008). Several criteria maybe used to evaluate the effectiveness of landfill liners with regards to chemical liners, (Katsumi, Benson, Foose, & Kamon, 2001) suggest that leakage rate and solute flux are two possible criteria. (Foose, 1996) cited in (Katsumi et al., 2001) contributes to this line of thought by indicating that the effectiveness of the liner is dependent upon the performance criterion selected, which may also include chemical concentration.

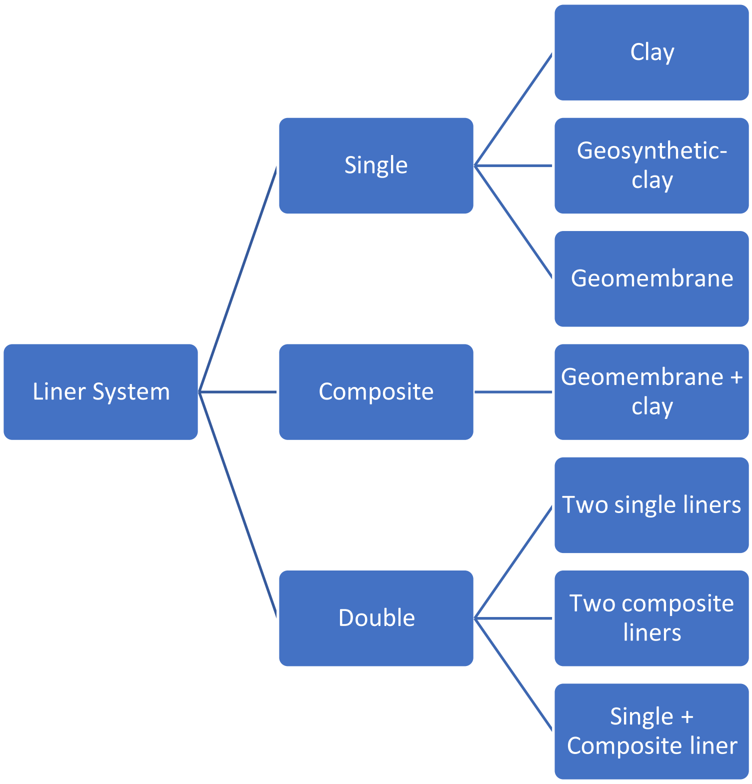


*Figure 3:3: Landfill Liner Systems showing the different types of liners used for landfill design. (Hughes et al., 2008)*

Figure (3.4) below shows a cross section of the different liner systems represented in (Figure 3.3).

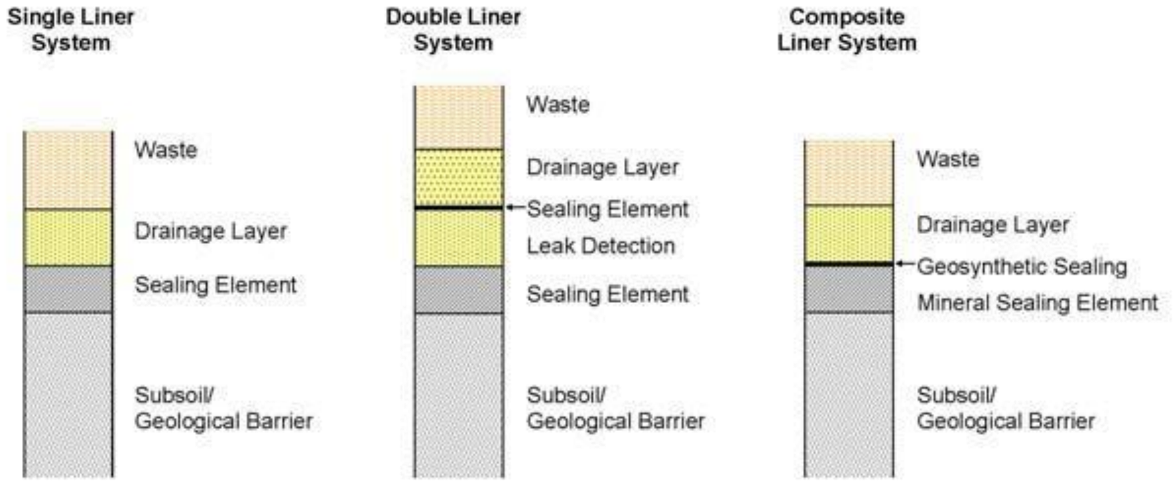


*Figure 3:4:Liner systems for landfill design, showing Single, Double and Composite liner Systems used in landfill design (Ramke, 2012)*

A study by (Seymour, 1992) concluded that there is no ideal liner material and suggested that the "optimum security against leakage is provided by using composite mineral/geomembrane liners, where the geomembrane liner is in direct contact with mineral layer (clay or bentonite)".

The term Geomembrane refers to textiles used in geotechnical engineering and they are designed to have a permeability as low as possible, in other words restrict fluid flow (Giroud, 1984). The Geosynthetic Clay Liners used in Composite liners comprise of a thin layer of Sodium or Calcium Bentonite bonded to a geomembrane (Bouazza, 2002). The Clay liners act as the last line of defence against leachate filtration. Clay Liners are supposed to have a low hydraulic conductivity of up to 1 x $10^{-6}$ to 1 X $10^{-7}$ cm/s to be used as landfill clay liners. (Daniel, 1993)

A cross section of a landfill, as shown in (Figure 3.5), gives a visual representation of the layers that build the operation criteria of a landfill up until it is completely covered.

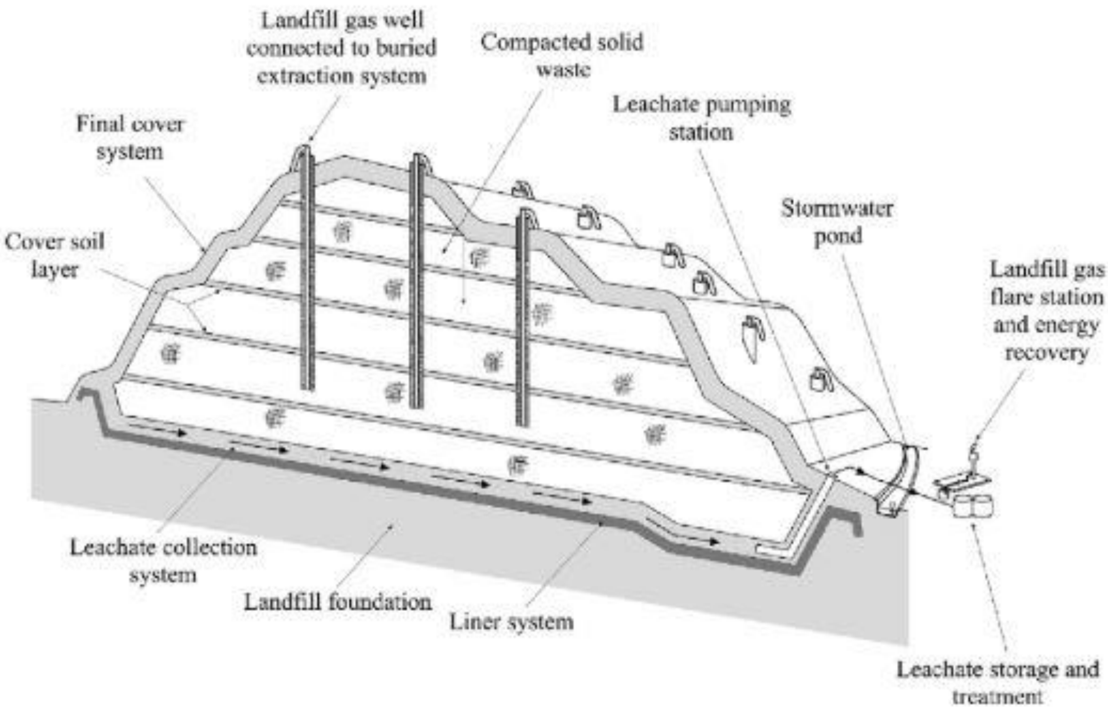


*Figure 3:5:A Landfill Cross section showing the operational sections including a leachate collection system, liner system, gas collection wells, storm water pond, compacted waste, final cover etc. (Townsend et al., 2015)*

### *3.4 Landfill cover design.*

A landfill cover is designed to reduce the infiltration of water into the landfill (Bagchi, 2004). Bagchi further states that a cover consists of a multilayer configuration (Image 2.3), with each layer designated a specific function.

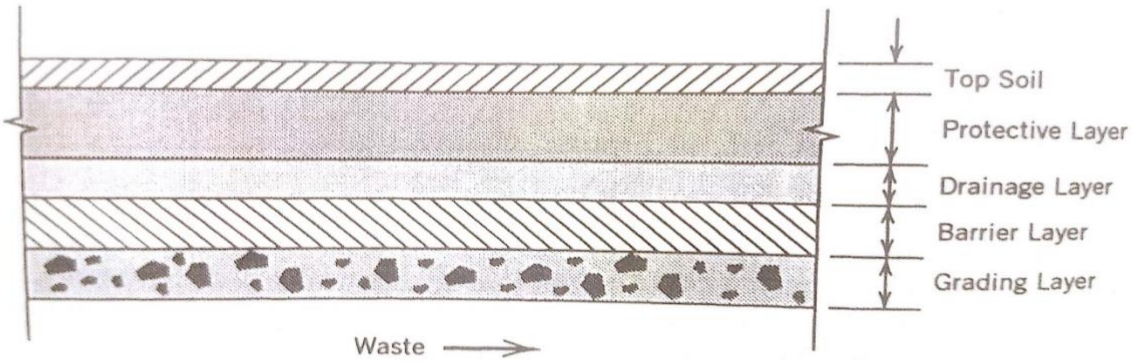


*Figure 3:6: A Multilayer configuration of landfill cover (Bagchi, 2004)*

The grading layer is usually 15 – 16 cm thick and should consist of course-grained material while the barrier layer consists of either, clay, synthetic clay liner, or synthetic membrane with the intention of stopping water infiltration. The drainage layer is important as it provides better drainage of the protective layer. The protective layer is designed to protect the barrier layer from freeze-thaw and desiccation cracks with a recommended thickness of 30 to 105 cm. However, a 1998 report by the EPA, showed that 544 landfills studied in California subjected to various climates had 72% to 82% of their covers failing due to barrier layers being made of compacted clay (Dwyer, 1998). The EPA also stated that landfill covers with compacted clay barriers and geomembranes are "not very efficient" for arid regions. The cracks in the barrier have been attributed to clay being compacted with moisture and then cracking due to reduced volume as the clay dries. From a Zambian context, this is important, due to seasonal climatic condition changes and the current situation of regular droughts and floods, that have become more frequent. It is therefore important to consider and research how effective multilayer landfill covers/liners would be in various climatic conditions.

### *3.5 Landfill gas wells*

In 1962, the New York state department of health introduced regulations that required that refuse disposal centres take a “sanitary landfill” operation approach and municipal incinerators operate to meet air pollutions standards (Nosenchuck, 1996). Carbon dioxide and methane are the major gaseous products of landfills. Methane is highly flammable and gets trapped in pockets that can result in explosions or fire if ignited (Stenborg & Williams, 1994). The United States of America estimates that $9.0 \times 10^{5}$ Mg/year of methane are released annually from USA landfill sites (Eklund, Anderson, Walker, & Burrows, 1998). The authors studied the Fresh Kills landfill in New York, which was, until 2001 the world’s largest landfill. In 1998 it covered an area of 1200 hectares. The area covered by the Municipal Solid Waste (MSW) waste was 426.5 hectares, with a waste mould exceeding 45m. An intricate system of passive and active gas collection wells were produced, with the landfill producing 400, 000 $m^{3}$/day of gas. This example highlights the potential that large landfills have for gaseous pollution through emission if not monitored and treated or used as an energy resource.

The effective collection of gas produced by landfills can be utilised to produce energy. In the USA, in 2004, there was an estimated 2300 active landfills and, of these, 382 had operational “landfill-gas-to-energy” projects (Jaramillo & Matthews, 2005). The authors state that at the time of publication, the total capacity for landfill-gas to energy projects was 1089MW with 4MW being generated by the average landfill. The potential a landfill has for gas generation over its life cycle is illustrated in (Figure 3.7) below and shows how much is collected in relation to what is utilised for energy.

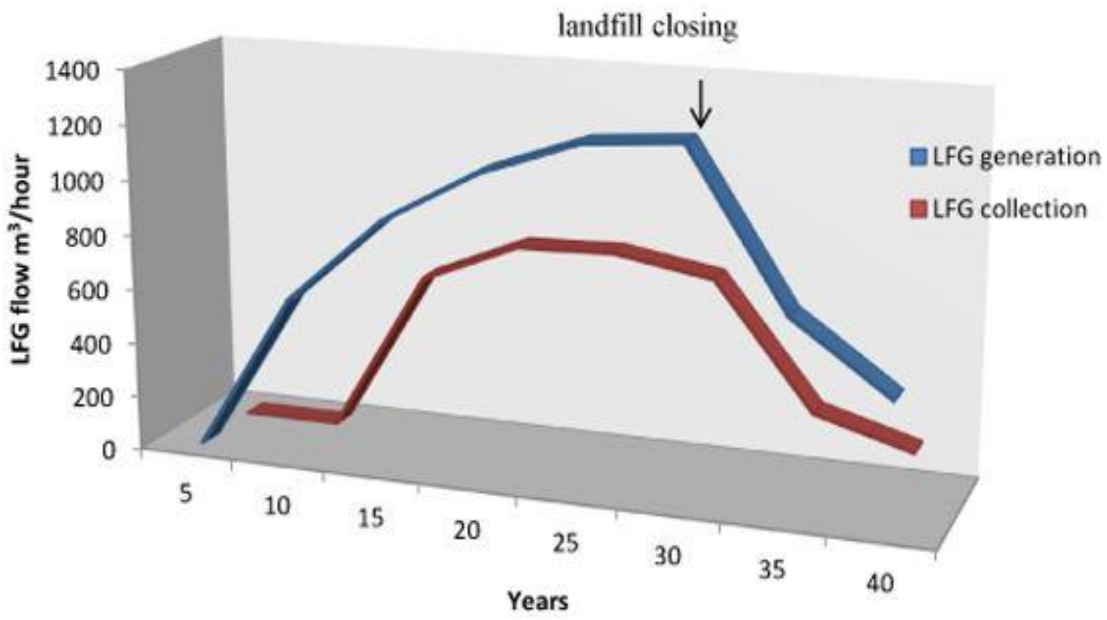


*Figure 3:7: Potential for landfill gas generation and collection over time (Njoku, Odiyo, Durowoju, & Edokpayi, 2018)*

(Willumsen, 2001) reports that approximately 950 landfill gas plants exist worldwide with the highest number,325, located in the United States, followed by Germany (Table 2.3)

*Table 4: distribution of Landfill gas plants in the world (Willumsen, 2001)*

| Country | Approximate number of Plants |
|---|---|
| USA | 325 |
| Canada | 25 |
| Germany | 150 |
| France | 10 |
| Holland | 60 |
| UK | 135 |
| Spain | 10 |
| Italy | 40 |
| Austria | 15 |
| Switzerland | 10 |
| Norway | 20 |
| Denmark | 21 |
| Sweden | 70 |
| Finland | 10 |
| Poland | 10 |
| Czech Republic | 5 |
| Hungary | 5 |
| China | 3 |
| Australia | 25 |
| Brazil | 6 |
| | **955 (Total)** |

Based on the table above, is quite clear that Africa and other developing countries are not utilising waste as a renewable source of energy. (Njoku et al., 2018) attributes this slow shift, by African countries, to exploiting the potential of landfill-gas to energy plants to, "ranging from lack of skilled expertise, inadequate knowledge of the technology involved, lack of political will, inadequate funding for LFG utilization projects, and monopoly situations of the power sector, among others."

However, since the power grids of many African countries cover the urban cities, the presence of landfill sites in these urban areas presents an opportunity to create electricity at relatively low cost for grid connection (Scarlat, Motola, Dallemand, Monforti-Ferrario, & Mofor, 2015).

### *3.6 Landfill Operation and Closure.*

When planning for the operation of a landfill, "phasing should allow for the progressive use of the landfill so that construction, operation (filling), and restoration can occur simultaneously in different parts of the site" (EPA, 2000). These phases as shown in (Image 2.5) layout, take into consideration waste volume to determine the lifespan and size of the phase.

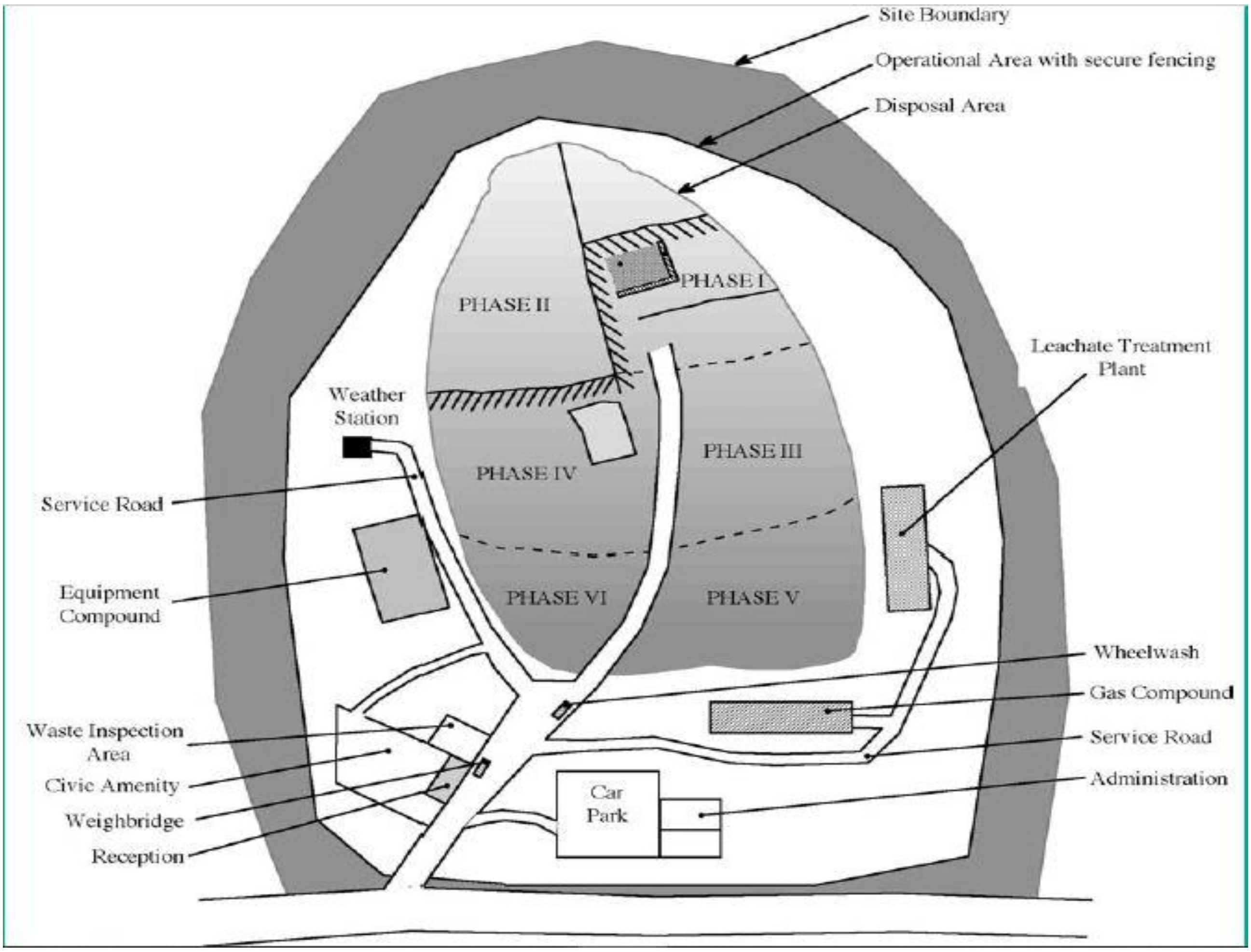


*Figure 3:8: Landfill phase Layout (EPA, 2000) sourced from: www.epa.ie*

In terms of operating the landfill, phase planning is important and a phase plan in which each phase has a final cover in the shortest possible time would be most ideal, (Bagchi, 2004). One major aspect of landfill operations is covering the waste, and the author also states that there are three types of cover that may be used in a landfill, daily cover, intermediate cover, and final cover. Daily cover, commonly using sandy soils, performs many functions that are designed to improve aesthetics and reduce environmental interaction with waste through pollution or disease vectors such as birds and rats. Bagchi, also states that "intermediate cover is used when portions of a landfill remain open for a long time" and this method reduces leachate production.

Post Landfill care strives to reduce the long-term effect of leachate on ground water and surface water and this is done by continuous monitoring and treatment of leachate

In Europe, post landfill care is guided by the recommendations of the European Union Landfill directive that is particularly concerned with the prevention of pollution of surface and ground water, and the pollution of soil and air (Burnley, 2001). The main aim of this directive has been to reduce the amount of biodegradable waste ending up at landfills and thus reducing leachate produce. The main regulations that govern leachate management and landfilling include, Landfill Directive, the Waste Framework Directive 2008/98/EC , the Urban Wastewater Treatment Regulations Council Directive 99/31/EC and the Water Framework Directive 2000/60/EC (Brennan et al., 2016). Once a landfill has been capped, closed and declared inactive, it can then be used as a park, golf course or for agricultural purposes. Final use of the closed landfill should be arrived at during initial design planning of the landfill. The Fresh kills landfill in New York has attempted forest restoration of a 1.5ha portion of the landfill by planting 18 species of plants and trees, all native to north eastern north America(Robinson & Handel, 1993). The study suggested that even though the site did not produce any seedlings, it did attract dispersers that introduced 20 new species to the forest community.

# 4. CHAPTER FOUR.

## 4.0 LANDFILL DISASTERS.

### 4.1 Ghazipur landfill (India)

Landfill slope failure is a key cause of landfill related disasters. These types of disasters not only have an adverse effect on the environment but also threaten human safety. (Karunasena, Amaratunga, Haigh, & Lill, 2009) define a disaster as, “a situation or event, which overwhelms local capacity, necessitating a request to national or international level for external assistance; an unforeseen and often sudden event that causes great damage, destruction and human suffering.” In 2016, the government of India put in place solid waste management guidelines that were intended to reduce the risk of a landfill collapse. One such guideline was to limit the height of each landfill to 20 metres for environmental and safety reasons. However, one of the largest landfill in the country, the Ghazipur landfill, located in one of the most populated cities of India, Delhi, exceeded this limit by 30 metres and on 1st September, 2017, collapsed, with the movement of over 50 tonnes of waste, leading to the death of two people (Yadav, Singh, & Manthapuri). This disaster lead to the government shutting down the landfill. However, due to the lack of an alternative source, the landfill continues to be unlawfully used, presenting a new risk to the population and the environment. According to (Singh, Kumar, & Roy, 2017), the collapse of the landfill was not only the result of excessive use, but traced the problem back to land fill site selection. The authors further recognise a risk to the environment, humans, and ground water, as well as to adjacent water bodies.

### 4.2 Koshe landfill (Ethiopia) and Hulene (Mozambique) landfill disasters

Two major landfill disasters have recorded a high death toll due to the collapse of MSW in two African cities. The first being the collapse of the Koshe landfill in March of 2017 that resulted in the death of 115 people in Addis Ababa (Figure 4.1) and the second collapse that killed 15 people at Hulene landfill in the capital of Mozambique, Maputo. The communities directly affected by these disasters are the poor communities that reside around these dumpsites, and derive their source of income scavenging the local waste sites Women and children are involved in informal recycling, as was the case in Ethiopia, with some losing their lives to garbage landslides (Ahmed, Louty, Osman, & Godfrey, 2018).

**Death toll from rubbish dump landslide in Ethiopia rises to 65**

**Rescue workers search 74-acre site for survivors, with residents blaming construction of biogas plant for disaster**

▲ The Koshe landfill site outside Addis Ababa had been home to hundreds of people. Photograph: Zacharias Abubeker/AFP/Getty Images

At least 65 people were killed in a giant landslide at Ethiopia's largest rubbish dump this weekend, officials said on Monday, with entire families including children buried alive in the tragedy.

*Figure 4:1: Newspaper Article on Koshe Landfill Disaster. Source: (thegaurdian, 2017)*

## *4.3 Aberfan and Love Canal Disasters.*

The highest death toll of children from a waste heap currently documented occurred on 21$^{st}$ October of 1966 and became known as the Aberfan Disaster. The collapse of a waste coal heap from the mining village of Aberfan caused a landslide that killed 116 children and 28 adults as the slide of coal mining waste travelled from the waste site to the village and Primary School below (Johnes, 2000). Landfill disasters are not only restricted to the collapse of piles of waste but also contamination of surrounding water and ground water, as was the case with the Love Canal landfill, that contained over 21 000 tonnes of chemical waste, accumulated between 1942 and 1953. The Love Canal facility had no liner to prevent leakages to the local environment (Phillips et al., 2007). The pollution from this landfill led to several public health concerns such as miscarriages in pregnant mothers and birth defects and low birth weight in children among the exposed communities (Rushton, 2003).

## *4.4 The Meethotamulla Landfill Disaster (Sri Lanka)*

On the 14th of April 2017, the Meethotamulla garbage dump in Colombo, Sri Lanka collapsed (Figure 4.2), a disaster that affected 36 families with 32 people killed, including 4 children (Siriwardana et al., 2018). A recent study by (Dissanayake, Hettiarachchi, & Siriwardana, 2018) attributed the collapse of the garbage dump to poor monitoring and environmental management.

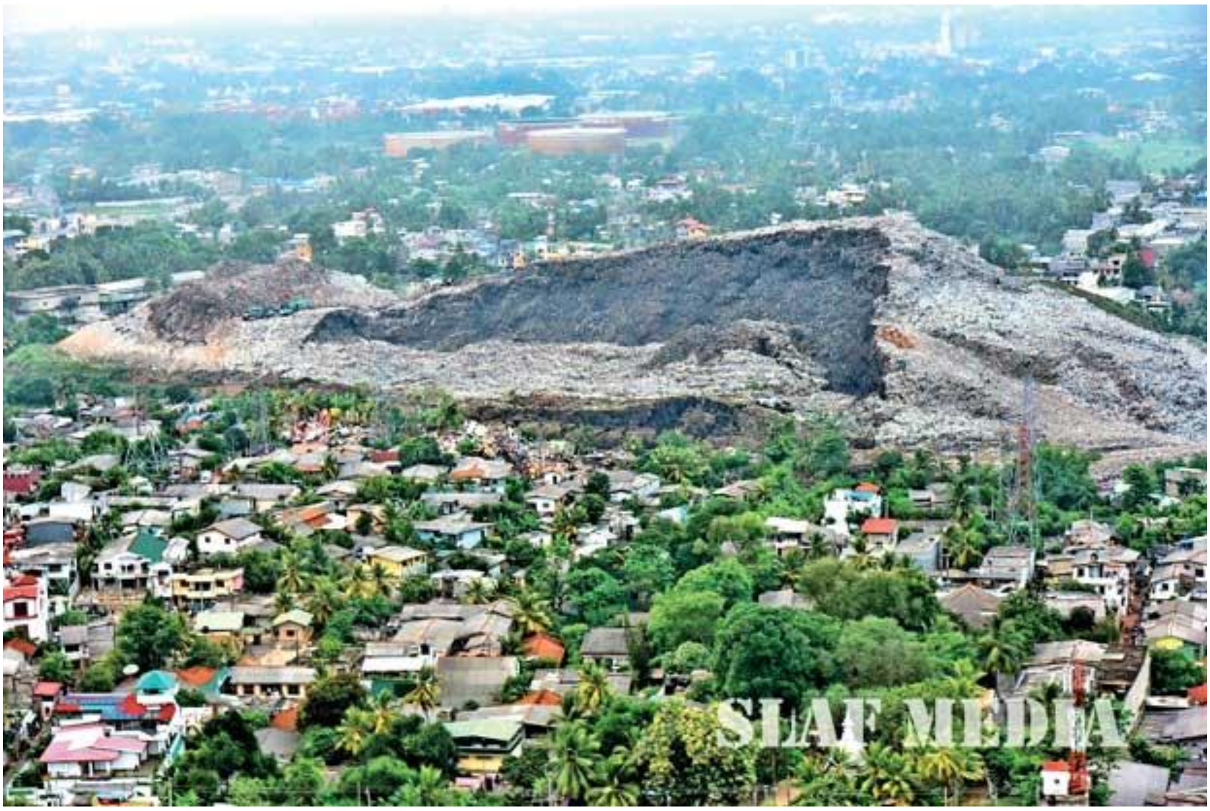


*Figure 4:2: Aerial views of the disaster site reported on the web through Sri Lanka Air Force Media footage. Available at http://www.dailymirror.lk/article/Meethotamulla-tragedy--127303.html*

A study by (Basha & Raviteja, 2018) concluded that the "mean value of shear strength parameters of Municipal Solid Waste (MSW) and its associated variability responsible for the collapse of Meethotamulla garbage dump are friction angle, $\varphi=20^\circ$ and stability number, $c/\gamma H=0.05$" while analysis proved that the most likely reason for the dump failure was the reduction in shear strength parameters of the MSW due to intense rainfall. In less technical terms, the disaster was caused by a combination of building the waste heaps too high, making the slopes of the waste heaps too steep, uncontrolled dumping of a wide variety of waste-types, lack of management of water, drainage, and gas, with the final landslide-trigger being heavy rainfall that reduced internal friction within the waste material, encouraging waste-slurry flow and sliding through gravity.

### *4.5 Leuwigajah dumpsite (Indonesia) collapse*

This disaster claimed the lives of 147 people on February 21$^{st}$, 2005. Three days of heavy rains resulted in the landslide of 2.7 million cubic meters of waste, sliding down the valley, like an avalanche (Koelsch, Fricke, Mahler, & Damanhuri, 2005). The authors of this study concluded that the, failure was most likely the result of severe damage to reinforcement particles due to a smouldering fire and water pressure in the soft subsoil. (Lavigne et al., 2014), attributes the main cause of the collapse to explosions caused by sudden biogas release inside that landfill.

Major landfill disasters such as waste-heap landslide resulting in casualties is representative of the significant risk that many poor people in Developing Nations face, especially the scavengers that earn a living from picking, recycling, and selling materials from dump sites. The waste from the Leuwigajah dumpsite buried 71 houses. It is not uncommon to have poor and vulnerable families settle around a landfill which is both a hazard and a resource. The most vulnerable in these communities, as observed by (Lavigne et al., 2014), are the children.

### *4.6 Landfill slope failure*

Due to its heterogenous nature, it is impossible to fully characterise the engineering properties of waste, but it is important that its basic behaviour is understood with the range of key engineering properties (Dixon & Jones, 2005). (Dixon & Jones, 2005) also demonstrated the possible modes of landfill failure in which the waste body played a role (Figure 3.3). Lessons have been learnt from these disasters and provided the industry with data on the operation, expansion and stability of landfill slopes. (Eid, Stark, Evans, & Sherry, 2000) studied the slope failure of a landfill in Ohio and concluded that “the mobilized shear strength of MSW can be represented by an effective stress friction angle of $35^0$ and cohesion ranging from 0 to 50 kPa, with an average of 25 kPa, depending on the waste constituents. A combination of effective stress cohesion and friction angle of 40 kPa and $35^0$, respectively, was estimated for the waste involved in this slope failure." Results of this study can therefore be applied to landfill design while considering physical properties of MSW that are of interest for geotechnical purposes such total weight, in situ moisture content, etc , while also considering mechanical properties such as stiffness, compressibility and shear strength(Castelli & Maugeri, 2014). The results of research such as quoted above inform policy and waste facility design operations suggesting, that waste heap slopes no greater than 35 - degrees, and waste being accumulated within sites should be regulated in terms of waste type and annual storage of waste. Other policy addresses the management of water and drainage and gas.

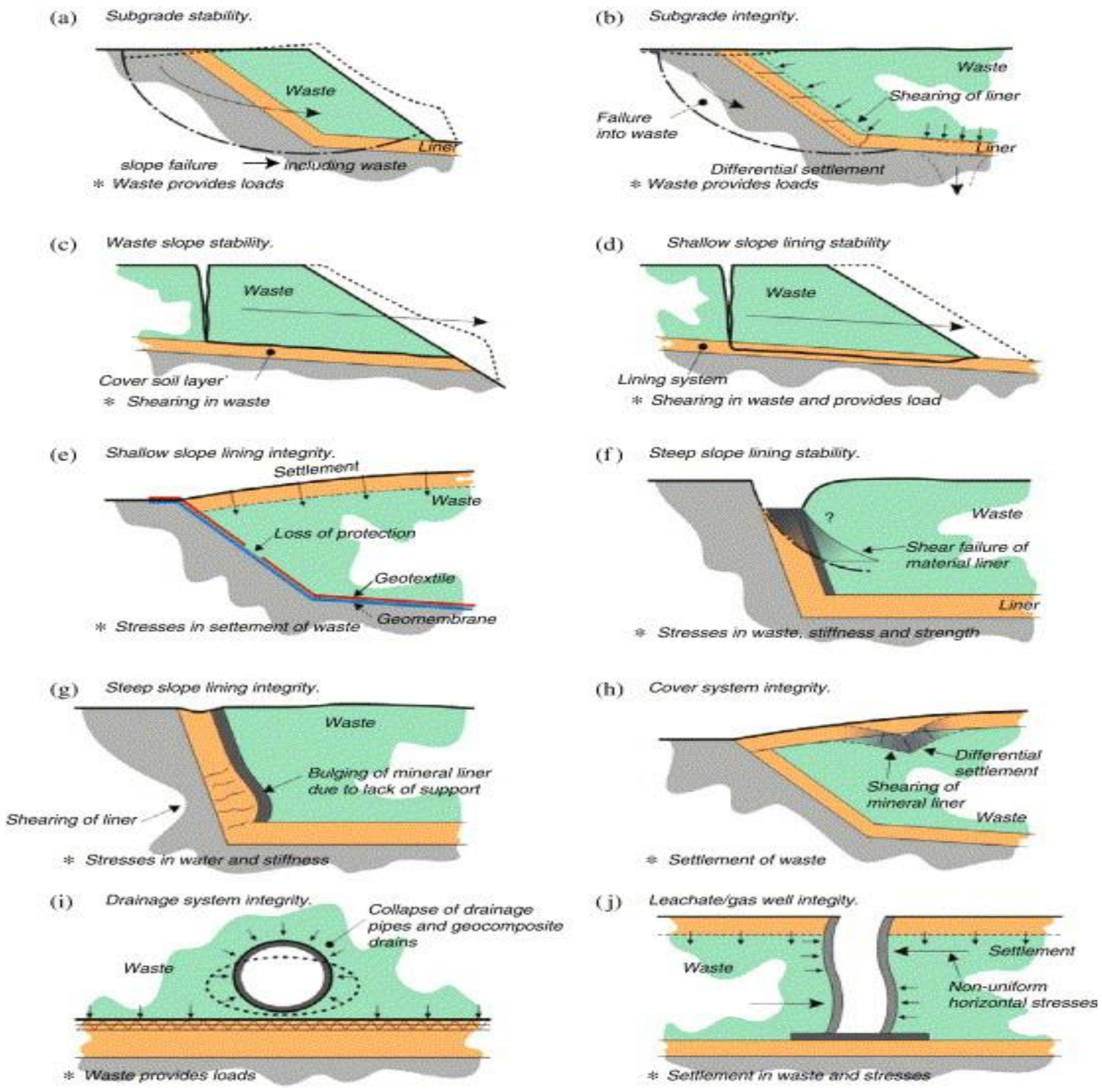


*Figure 4:3: Potential landfill failures: Stability and Integrity (Dixon & Jones, 2005)*

## *4.7 Landfill Fires*

On March 11th 2015 the Riverton landfill in Jamaica started to burn (Figure 4.4) and continued to burn for two weeks resulting in over 800 people reporting respiratory problems  (Duncan, 2018). Smoke from this landfill is a common occurrence and has been a source of air pollution resulting in a dense fog observed during the night and early morning, (Thomas-Hope, 1998). A Study by (Weichenthal et al., 2015) on the impact of a landfill fire on ambient air quality found that there is an increase of harmful substances such as benzene and dioxins/furans. These toxic substances produced are a health risk to personnel that work at the landfill and the public. According to (Lohmann & Jones, 1998), "Polychlorinated dibenzo-*p*-dioxins and -furans (PCDD/Fs) are two groups of persistent, semi-volatile and toxicologically significant trace organic contaminants"

*Figure 4:4: Riverton landfill fire resulting in a dense fog. Source: (Petchary, 2014) available at [https://petchary.wordpress.com/2014/03/16/the-burning/](https://petchary.wordpress.com/2014/03/16/the-burning/)*

Sub-surface fire are harder to extinguish than surface fires usually because they are harder to detect(Øygard, Måge, Gjengedal, & Svane, 2005). The author also expresses that sub-surface fires cause crevices which affect the structural integrity of the landfill and may lead to collapse of the waste heap. Landfill fires are placed in four categorises based on how easily they can be extinguished. Level one is small easily extinguished garbage fires while level two is for fires that occur on the face of the landfill on the side where garbage is being dumped. Level three fires are more serious and may take up to a week to put out. Level four fires cover an area of at least one hectare and take more than a week to extinguish (Jurbin, 2003).

The generation of heat inside a well-insulated waste heap has been traced as the source of landfill fires. The biological decomposition of waste through aerobic (with oxygen) or anaerobic (without oxygen) processes, produce heat at an average temperature of 60 to 71$^{0}$C (Stearns & Petoyan, 1984). Through a process called pyrolysis, these reactions change from biological to chemical and produce excess heat through this exothermic process and this extreme heat is transferred through conduction and/or convection (Stearns & Petoyan, 1984) & (Jurbin, 2003). Landfills in developing nations that are poorly designed and managed without effective capping mechanisms allow the flow of oxygen into the subsurface and thus are continuously at risk of landfill fires. In the developed world, landfill fires have also been recorded in countries such as Finland, Sweden and the U.K (Ettala, Rahkonen, Rossi, Mangs, & Keski-Rahkonen, 1996). The Authors research showed that in Finland fires were generally on the edge of the landfills with only four fires being deeper than 8 m. However, they also state that fires where ignited and prolonged by air flow through drainage pipes resulting in the need to take this into consideration during landfill design.

# 5. CHAPTER FIVE

**5.0 METHODS AND RESULTS**

This Chapter discusses the different methodologies adopted for this research project. The methods are presented as a three-step process:

1. site selection
2. Image acquisition
   I. Equipment
   II. Site Access
   III. Flight Plan
3. Photogrammetry.
   I. Photogrammetry workflow
   II. 3D point cloud output

## *5.1 Research Site*

### *5.1.1 Site location*

The study was carried out in the capital city of Zambia, Lusaka, at Chunga Landfill (Figure 5.1) located approximately 7 km and North West of the central business district and 800 m from the great north road (Chishiba, 2002). The site is geographically located at 15$^o$20'57.55" S, 28$^o$16'04.92" E at an elevation of 1215m (GoogleEarthPro, 2019). The site is accessed via a road network that primarily converges into the Great North Road, the main route to the north of Zambia. High volumes of waste are transported to the site by a variety of vehicles including, light and heavy-duty trucks, tractors and waste maintenance vehicles. (Chishiba, 2002) estimates that 62% of the traffic to the site is due to open flat vans/trucks while 19% is from specialised waste collection vehicles and another 19% from enclosed vehicles. Due to the heavy traffic at the site, officers are present to direct vehicles to tipping stations.

The site covers an area of 24.53 hectares and has a fenced perimeter of 2.15km, based on land composed of clay, sandy and gravel soils.

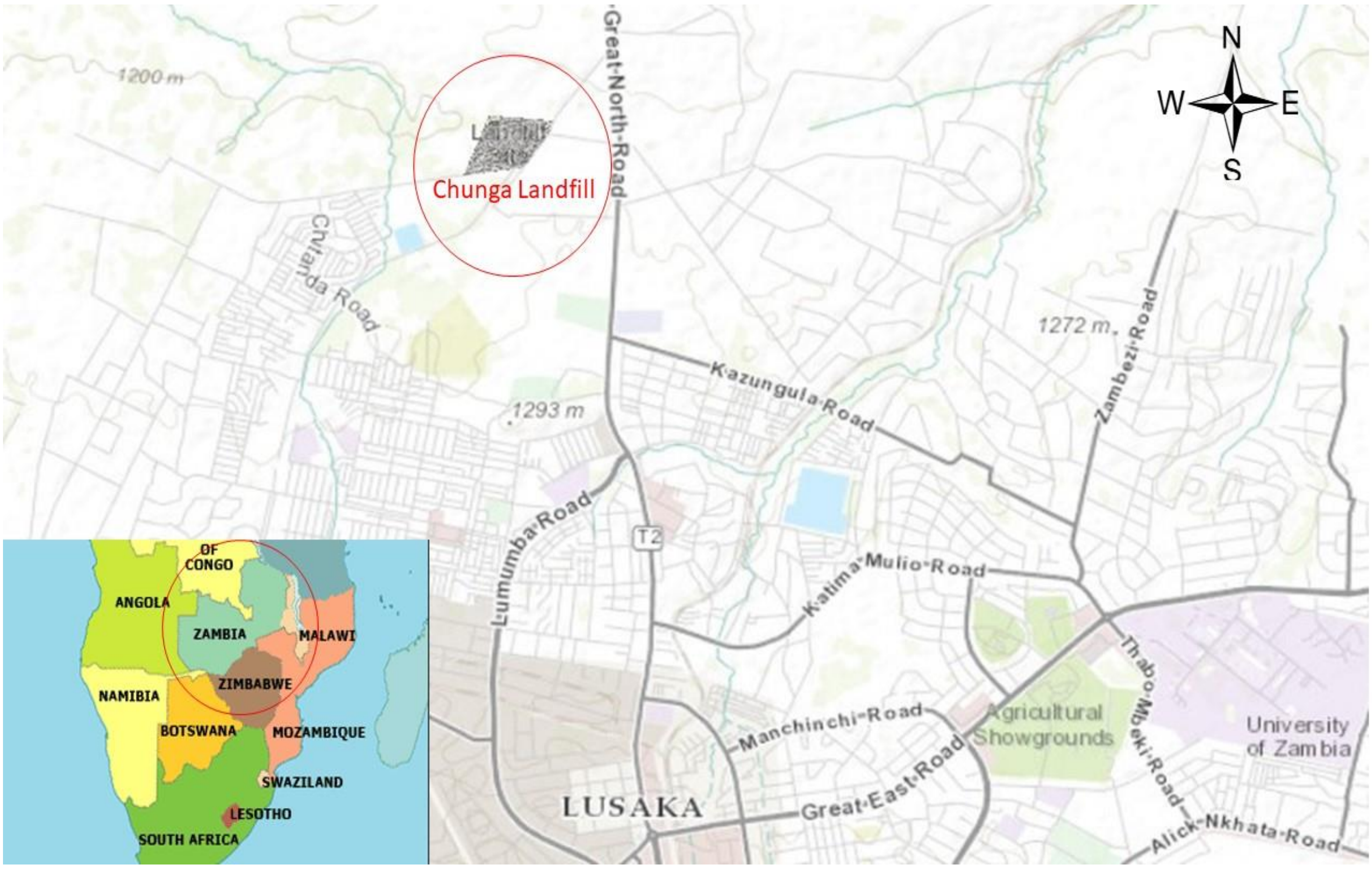


*Figure 5:1: Geographical location of research site, Chunga Landfill, in Lusaka Zambia located north west of the Lusaka City is the only engineered Landfill in the city.*

### *5.1.2 Results*

The Site was selected as it is central to Lusaka's MSW management system run by the Lusaka city council as the official dump site. Various forms of waste are deposited at the site, as specified by (Chishiba, 2002) and reported in Table 5. (Chishiba, 2002) also provides the amount and type of waste varies per year, estimating approximately 1800tons/month from industrial and commercial waste, 6.46 tons/month organic waste, and 10.01 tons/month wastepaper.

*Table 5: 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, 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. |

The Chunga landfill is the only engineered landfill in the city (Luke, 2017) and due to the high urban population of approximately 2.5 million residents, has high volumes of waste deposited daily. This site was of interest for research as it has deteriorated due to lack of funding to manage the facility and has been a cause for concern with regards to public health (Benard Chileshe, 2017).

## *5.2 Image Acquisition*

*5.2.1 Accesses to the Site*

The site is managed by the Lusaka City Council (LCC) under the Public health department and run by the Solid waste Management section. To access the site for research I was required to formally apply to the LCC and be given permission to carry out my research. Due to the laws governing the fight of drones in the country, I was required to apply to the Zambia Civil Aviation Authority (ZCAA), to fly over the landfill with a licenced drone pilot. Overall, the process of acquiring clearance and access to the site from both the LCC and ZCAA took three weeks between 4$^{th}$ June 2019 to 26$^{th}$ June 2019.

## *5.3 Equipment*

***5.3.1 Field Hardware***

*5.3.1.1 Unmanned Aerial Vehicle (UAV)*

A DJI Phantom 4 (Figure 5.2), Unmanned Aerial Vehicle (UAV) or Drone was used to acquire 966 images on the 27$^{th}$ of June 2019, flown at a height of 70m. This UAV is ideal for photogrammetry as it has a 12.4 mega pixel (MP) camera and 60 mega bit per second (mbps) for video acquisition and covers a range of 6000 meters which adequately covered the research area. The Phantom 4 has a flight time of 25 – 30 minutes on a fully charge battery, therefore two extra 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.

*Figure 5:2: Phantom 4 (UAV) used for image acquisition at Chunga landfill.*

5.3.1.2 GNSS receivers (EMLID Base and Rover)

As a back up to GPS information recorded by the UAV, I used two GNSS receivers to record Ground Control Points (GCP) that would improve the absolute position of the landfill if needed. One receiver act as a Base station (Figure 5.3) and the second as a rover. The base station remains in one place and sends corrections to the moving rover. The two GNSS receivers utilise a technique known as Real Time Kinematic (RTK) to achieve centimetre accuracy (Volodina, 2020).

*Figure 5:3: An EMLID Rover is held in place to collect GCP at Chunga Landfill.*

5.3.1.3 Site Safety

To ensure safety on the busy site and not interfere with site operations, I notified the site manager of the date and time I would be on the site, 27th June 2019 at 2pm. I was escorted by site officers and wore overalls and safety boots. The same safety gear was required for the drone pilot and his assistants.

### 5.3.2 Field software

The drone was flown using two missions planned using the Pix4D survey application for Android.

The first flight was a single grid pattern capturing the entire area of the landfill Vertically as shown in (Figure 5.4).

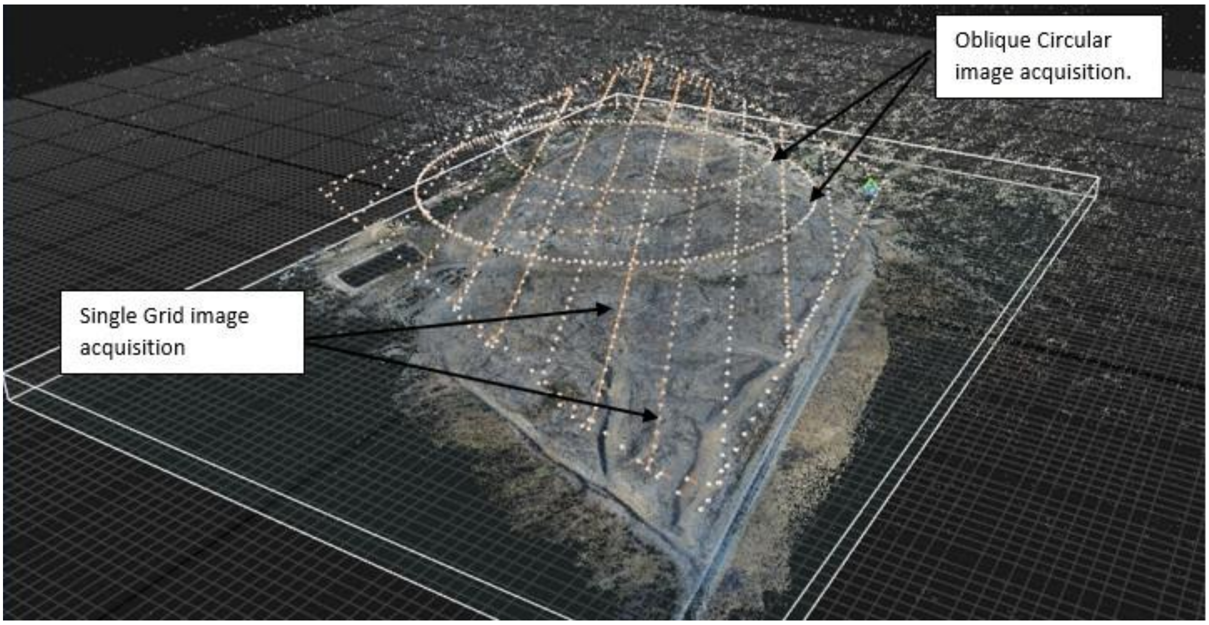


*Figure 5:4:Flight Missions and camera position for image acquisition at Chunga Landfill (s.r.o, 2019)*

The second mission was a circular flight that captured the landfill at an oblique angle in a circular path at different heights as seen in (Figure 5.4) above. The images were acquired between 2:00pm and

3:30pm during winter with minimal cloud cover allowing for clear images with significant light to capture clear images. The UAV was set to capture images every two seconds allowing for an image overlap of approximately 80%. (Figure 5.5) below illustrates image acquisition and how image overlap is attained over an area of interest for the purpose of photogrammetry.

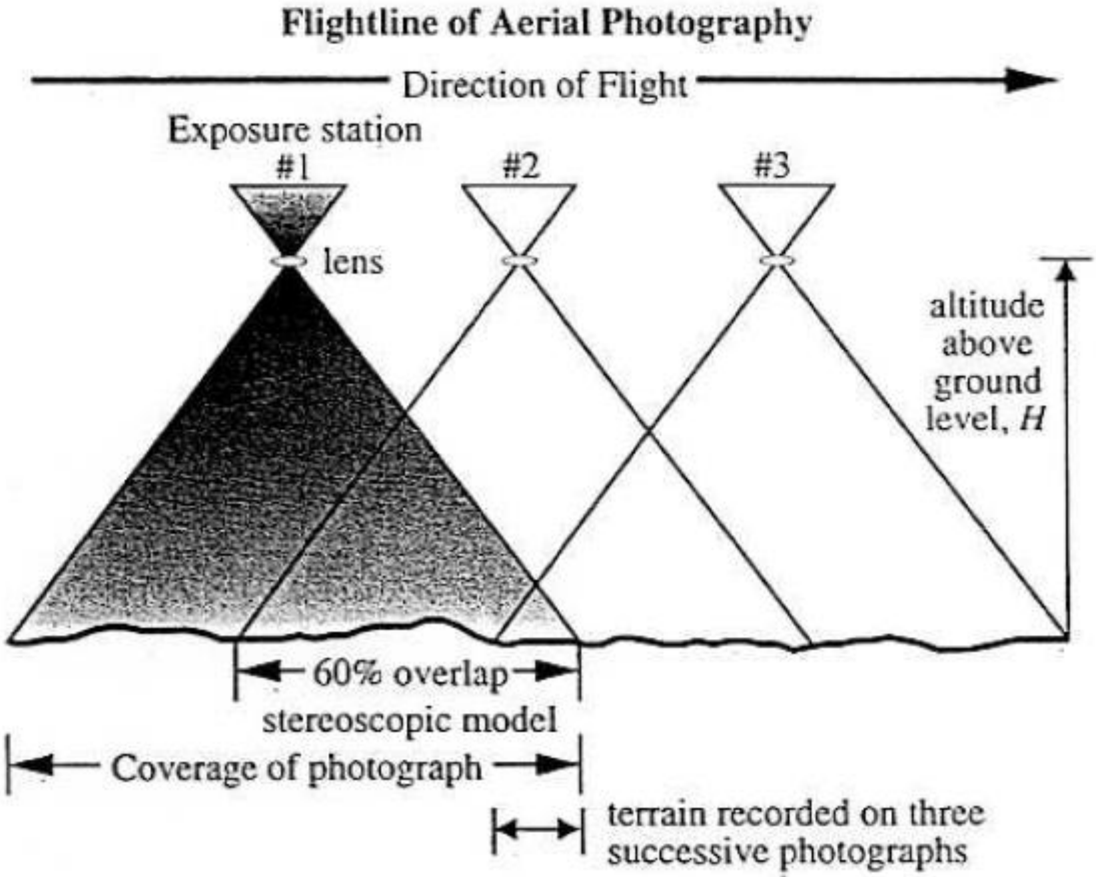


*Figure 5:5: Example of image acquisition to ensure image overlap. In this figure, 60% image overlap is achieved during aerial photography (Kuche, 2019)*

## 5.4 PHOTOGRAMMETRY METHOD

### *5.4.1 Processing Software*

*Table 6: Software used for Photogrammetry processing and analysis.*

| Software | Process | Source |
|---|---|---|
| Reality Capture (s.r.o, 2019) | For Image processing using photogrammetry to create a 3D point cloud. | https://www.capturingreality.com/ |
| Cloud Compare (Girardeau-Montaut, 2016) | 3D point cloud and Triangular mesh processing tool. | https://www.danielgm.net/cc/ |
| Potree (Schütz, 2016) | An open source point cloud rendering and editing software also useful for 3D point cloud analysis. | http://potree.org/ |
| ArcMap 10.5.1 (esri$^{TM}$, 2019) | To create maps, perform spatial analysis and manage geographic data. | https://desktop.arcgis.com/en/arcmap/ |

### *5.4.2. 3D point cloud processing*

The georeferenced drone images were processed using the photogrammetry software Capture Reality (s.r.o, 2019) to create a 3D point cloud with a workflow shown in (Figure 5.6). (Micheletti et al., 2015) States that by measuring the same image from multiple perspective results in a truly 3D point cloud as opposed to a 2.5D model.

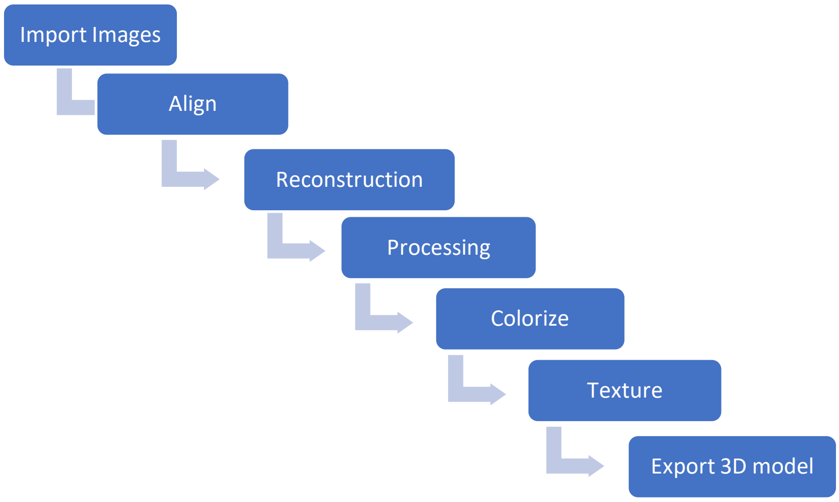


*Figure 5:6: Reality Capture Workflow for Point cloud 3D model processing (s.r.o, 2019)*

*Table 7: Reality Capture workflow and processing of the 3D reconstruction of*

| Process | Notes |
|---|---|
| Project creation and image import. | I imported raw images into reality capture with 80% overlap for alignment and reconstruction. The software groups all images into one component when there are enough images.<br>If there not enough images for the grouping of one component, then there is need for the creation of control points that represent the same point in the 3D model.<br>I did not import any images that I considered poor quality, for example those having large amounts of smoke or motion blur. |
| Align | I selected the component for reconstruction by first defining a region in the software. This removes any surrounding areas not required |

| | |
|---|---|
| | by the objective and increases processing time. |
| Reconstruction | I selected the component for reconstruction and reconstructed by first selecting the reconstruction region in the software. |
| Colorize | This method is recommended when the point cloud is dense and homogenous as was with my |
| Export 3D | A 3D Mesh can then exported after using the simplify tool in Reality Capture with the mesh used in the creation of maps. |

The 3D point cloud (Figure 5.7) shows the general geomorphology of the landfill with the main road that provides accesses to the landfill and surrounding areas. The model can be rotated at an axis to analyse the gullies created resulting from waste heaps, the internal paths used by trucks to get to tipping points and drainage routes. Measurements of the height of waste heaps, area and topographic analysis are carried out using the 3D model.

## 5.5 PHOTOGRAMMETRY RESULTS

Figure 5:7: Chunga Landfill Point Cloud

https://geospatialweb.aut.ac.nz/Lusaka_Dump/Lusaka_Dump_v1.html

### *5.5.1 Landfill Site Subdivisions*

Based on geomorphological features such as height, location and type of waste, the landfill was divided into zones whose characteristics were analysed individually.

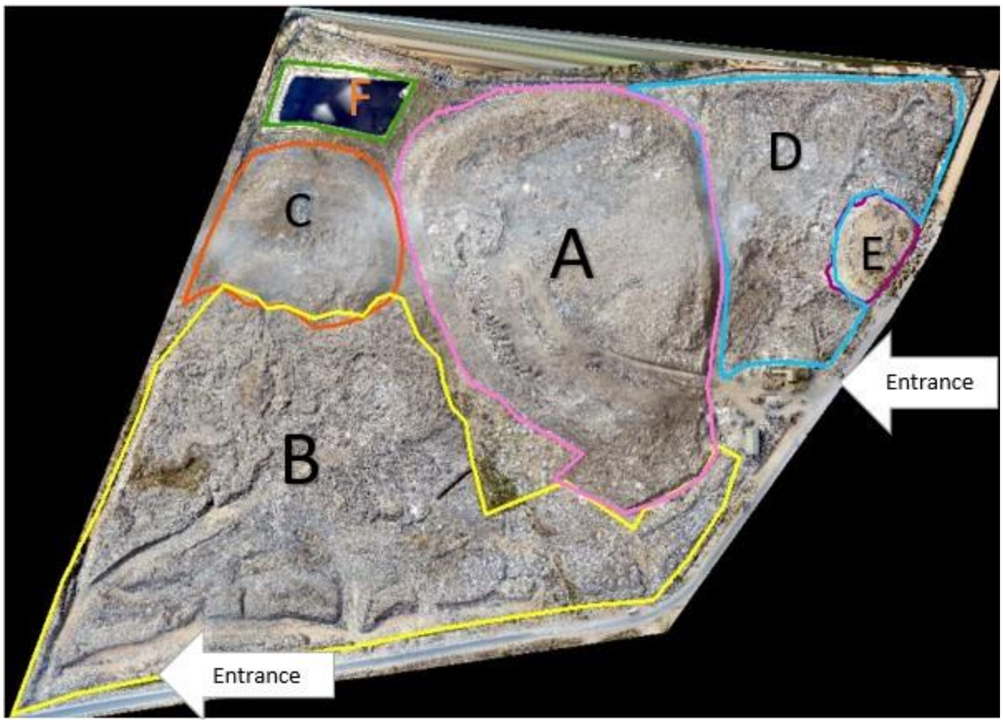


*Figure 5:8:Delineated landfill zones based on physical properties, separated into five zones that are studied individually. (esri™, 2019)*

The five zones that represent different sections of the landfill or cells, were created and labelled as *A to F* (Figure 5.8). The Zones were delineated by creating polygon shape files that could be analysed individually as they varied in physical features such as area, volume, height and slope. The analysis of waste types in each zone was not utilised in zone selection as despite the high resolution of images, the homogenous nature of the waste heaps made waste type identification difficult. However, Zone E, was selected specifically because the type of waste differed from the rest of the dump site as it was construction-based materials.

The site only has two entrances for vehicles, the main entrance where the weigh bridge is located and records are taken such as the waste type, vehicle registration or company and amount of waste. The first entrance leads directly to zones A, D and E while the second entrance, to Zone B and C, is used either when works are being carried out on the other zones or during the rainy season as this area is considered less steep and more stable. Zone F is a pond that is designed to be the drainage area for the dump site. Corresponding with the DSM, the pond is at the North-west, the area with the lowest surface elevation.

It was important to study the landfill in subdivided zones as this would allow for a comprehensive risk assessment of the entire site based on the characteristics of each section of the landfill.

### *5.5.2 Landfill Topography Analysis*

In this section I detail the topography of the landfill based on topographic features.

The topography as a measurement from the lowest point on the landfill indicates that the lowest point of the site is in the North while the highest point is in the north-west. *Zones B, D and E* are therefore topographically at higher points of the Landfill compared to Zone C and the northern portion of *Zone A* (Figure 5.9).


*Figure 5:9: Terrain elevation at Chunga landfill based on the lowest point at the landfill (Zone F) and NOT measured in relation to sea level.*

Given that the site is lowest in zone F, it is an indication that the site was engineered to drain in this zone and is primarily a leachate storage unit designed to drain all landfill liquid and seepage.

### *5.5.3 Waste Heap Heights Analysis*

#### *5.5 3.1 Method*

Determination of height of the waste heaps in each zone, required the analysis of the 3D model using the point cloud rendering software Potree (Schütz, 2016) by using the height tool to measure from the base of the waste mould to the highest point of each waste heap (Figure 5.10).

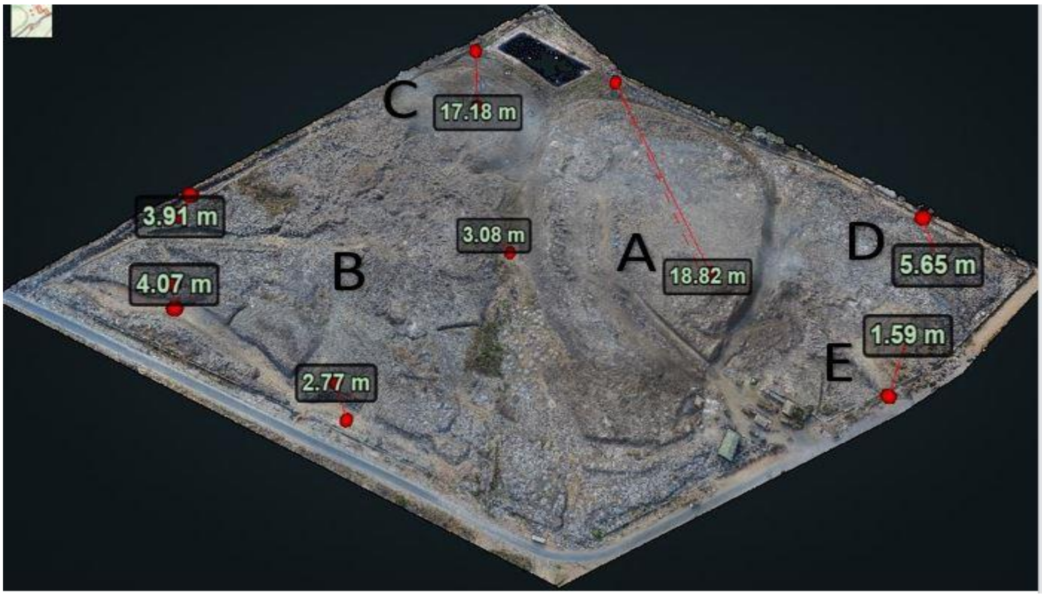


*Figure 5:10: Heights Of waste heaps shown measured from the lowest point of each waste heap showing waste Heap A having the highest height of 18.82 meters above ground. (Muleya. M, 2019)*

### *5.5.3.2 Results*

*Zone A* waste heap measuring at 18.82 meters is the highest waste heap on the site while *zone E* has the least height at 1.59. Waste in *Zone B* averages a height of 3.4 m high while *zone C* is measured to be at 17.18m. (figure 5.10).

Interpretation.

## 5.6 Evolution of Chunga landfill.

### *5.6.1 Method*

Using Google Earth pro, historical satellite images were analysed to document the evolution of Chunga landfill from 2006 to 2019.

Google Earth Pro is a virtual globe under the Google Limited Liability Company (LCC) that is freely accessible online. It is one of the most popular virtual globes in use by researchers today. A virtual globe provides a 3D representation of the earth and terrain with assess to satellite images, GIS and remotely sensed data(Yu & Gong, 2012)

### *5.6.2 Results of Landfill Evolution Analysis*

Google Earth pro allows for access to historical satellite images of different dates based on acquisition time and the first satellite image of the dumpsite is traced to 9/24/2000 when bare land is observed. The lack of satellite images between 9/24/2000 and 6/16/2004 however do not give an exact time period for when the site became active as a dumpsite before construction begun. The presence of waste in the satellite image acquired in 6/16/2004 however signifies that waste dumping at the site begun sometime between 2000 and 2004. Signs of construction to engineer the site into cells is observed in the image acquired on 9/25/2006, showing engineering activity particularly north-east of the site. Satellite images between 2006 and 2012 show increase waste volume based on the area of waste covering the site. There is also an observed increase in housing structures around the landfill through the latter six-year period. Due to the nature of the 2D satellite images, the geomorphology of the site appears to maintain it area and its height however, apparent changes in 2012 to 2018 images indicate the presence of smoke from underground fires as flames cannot be observed (Figure 5.11)

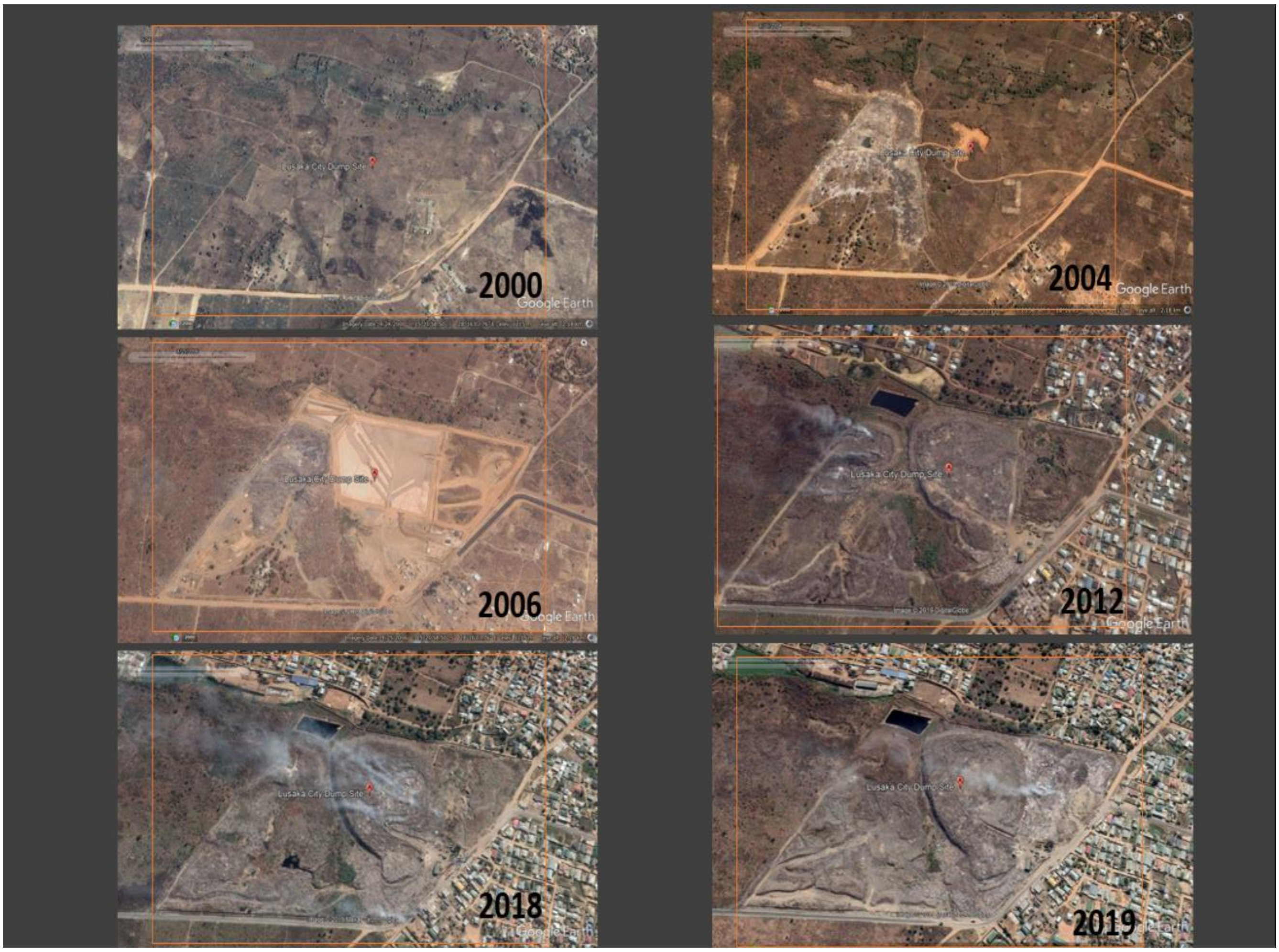


*Figure 5:11: Chunga Landfill Evolution showing its construction in 2006 and the increased volume of waste over six years. The follow up years show increased residential housing around the landfill as well as more constant plume (GoogleEarthPro, 2019)*

A total of satellite images currently exists for the Lusaka city dump site all analysed to document the evolution of the dump site.

## 5.7 Digital Surface Model (DSM) Creation

### *5.7.1 Method*

Reality Capture was also used to create a Digital Surface model (DSM) from the dense point cloud. 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$^{TM}$, 2019) ArcMap 10.5.1, for further analysis as it cannot be  processed in programs such as Google Earth(Wampler, Rediske, & Molla, 2013).

### *5.7.2 Results and Interpretation of DSM Analysis.*

The Chunga Landfill is higher in the southwest and eastern region and gradually reduces in elevation towards the northwest. This is represented by the DSM map shown in (Figure 5.12) that uses a colour gradient that shows regions with the highest elevations in brick red with gradual reduction in colour intensity and corresponding elevation until the colour blue represents the lowest region.

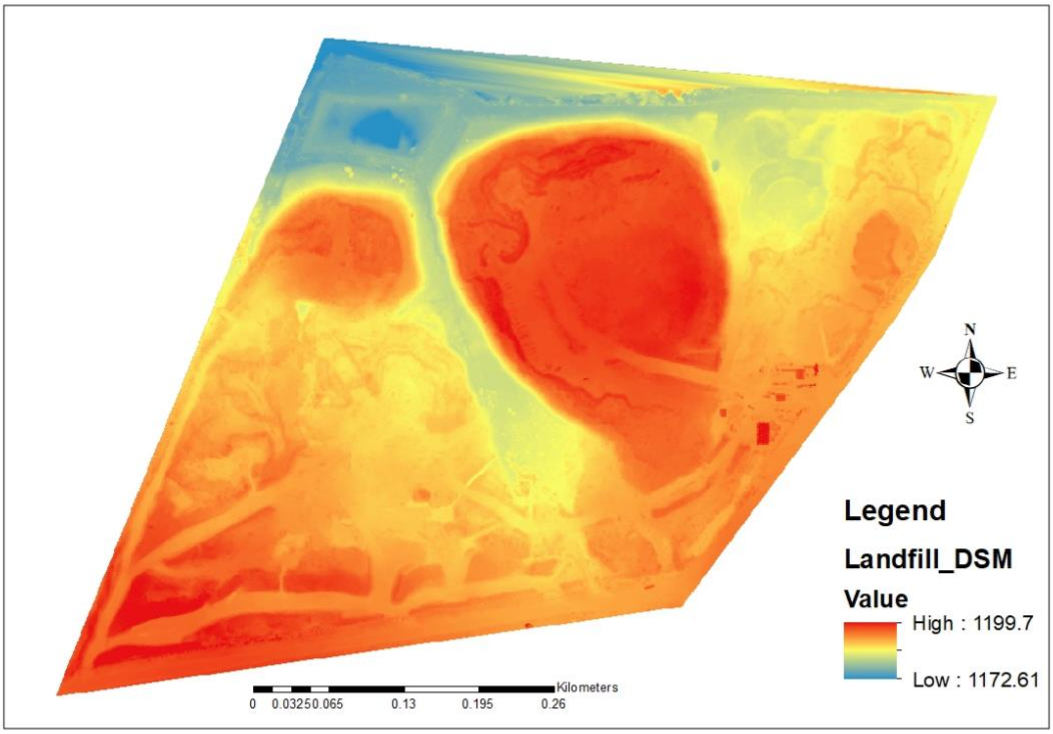


*Figure 5:12: Chunga Landfill Digital Surface Model (DSM) showing the changes in elevation based on waste heap elevations and landfill topology*

## 5.8 Drainage mapping

### *Results*

The drainage map of Chunga landfill was generated using the Hydrological tool in ArcMap and is shown below, (Figure 5.13), laid over the DSM of the site.

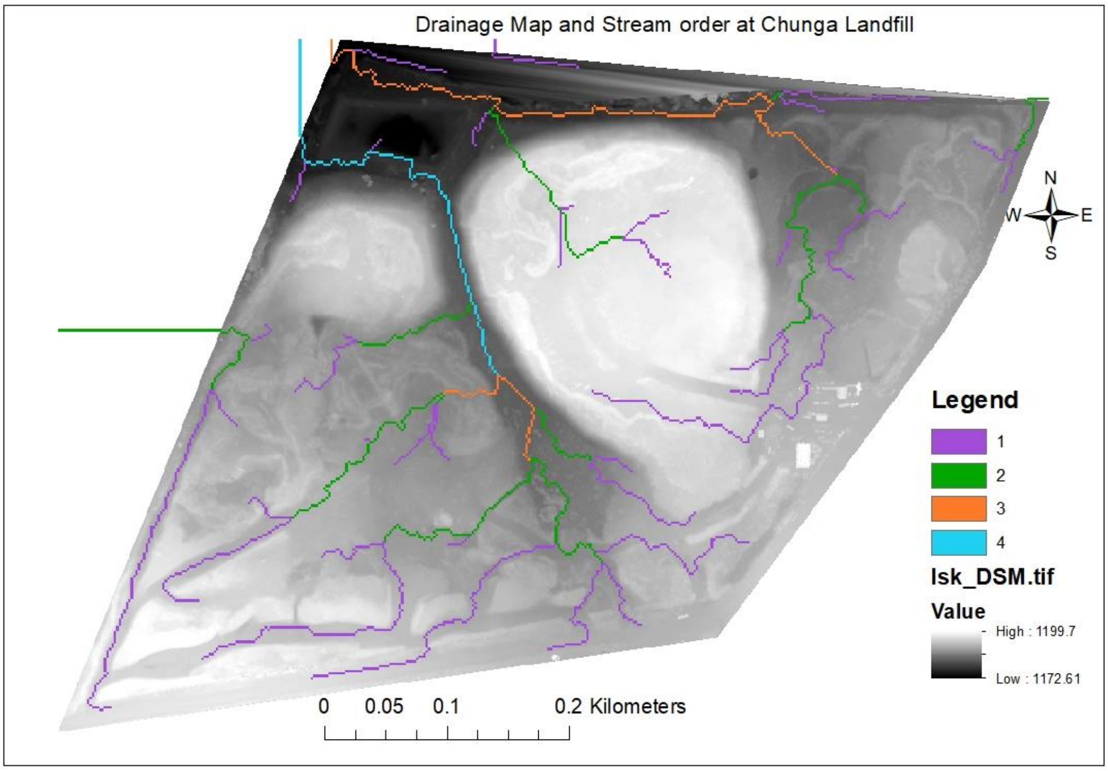


*Figure 5:13: Drainage map of Chunga Landfill, showing stream order, over the DSM.*

### *5.8.1 Drainage Map Interpretation*

The drainage map shows the streams that are created in the event of rains or flash floods that happen during the rainy season. 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 drainage pattern can be described as dendritic to trellis in form which in hydrology refers to drainage resembling the branch or root architecture of a tree (dendritic) or river sections that meet one another at right angles (trellis) (Rosgen, 1994). The drainage map is presented as a colour coded Stream Order, a representation of the stream network of the site. The Stream Ordering tool in ArcMap assigns a numeric order to links in a stream network (esri$^{TM}$, 2019).

Based on the map in (Figure 5.13), the stream order is from (1 to 4). Stream classification is based on the combination of lower of lower digit orders to form the next order up. From my results, streams of the order 1 (Purple), combine and form streams of the order 2 (Green), while streams of the order 2 combine to form streams of the order 3 (orange) and finally streams of the order 3 combine to create streams of the order 4 (Blue).

Most streams of order 1, are observed in zone B of the landfill, flowing from the south and south west of the site, ultimately flowing N-NW, following the general gradient to lowest ground. These Streams flow predominantly along the deeper and better-defined gullies, that have been created as paths for vehicles disposing waste. In Zone B we see six streams of the order 2 and fourteen streams of the order 1. Zone B is therefore a catchment area of interest due to the high number of streams forming in this region. Only one stream of the order 4 is observed and is the result of streams flowing from the Zone B catchment area. This high value stream flows in a valley between Zone A and B to the drainage pond but does not appear to drain into the pond. Another high value pond, order 2, is seen North of Zone A flowing in the north western direction towards the drainage pond but is also observed to flow around the pond. It is interesting to note that some streams are cutting their own valleys through hydrologic erosion: these are independent of the engineering of the site and suggest that natural processes are occurring independently of the planned engineered drainage. Examples of this process are the river channels forming within the highest part of the site (Zone A).

### *5.8.2 Rivulet Creation and Interpretation*

The presence of rivulets is evident through observation in images and the 3D model, yet they are not detected by ArcMap during the creation of the drainage map, as they are rather subtle features. These rivulets were identified and presented by manual digitisation from visual observation (Figure 5.14). The Rivulets highlighted in pink are important as they are integral to the drainage system of the site. They form on the slopes of the waste heaps, and could, in theory, destabilise elements of the waste heap morphology through slope undercutting processes, particularly during times of high and prolonged rainfall.

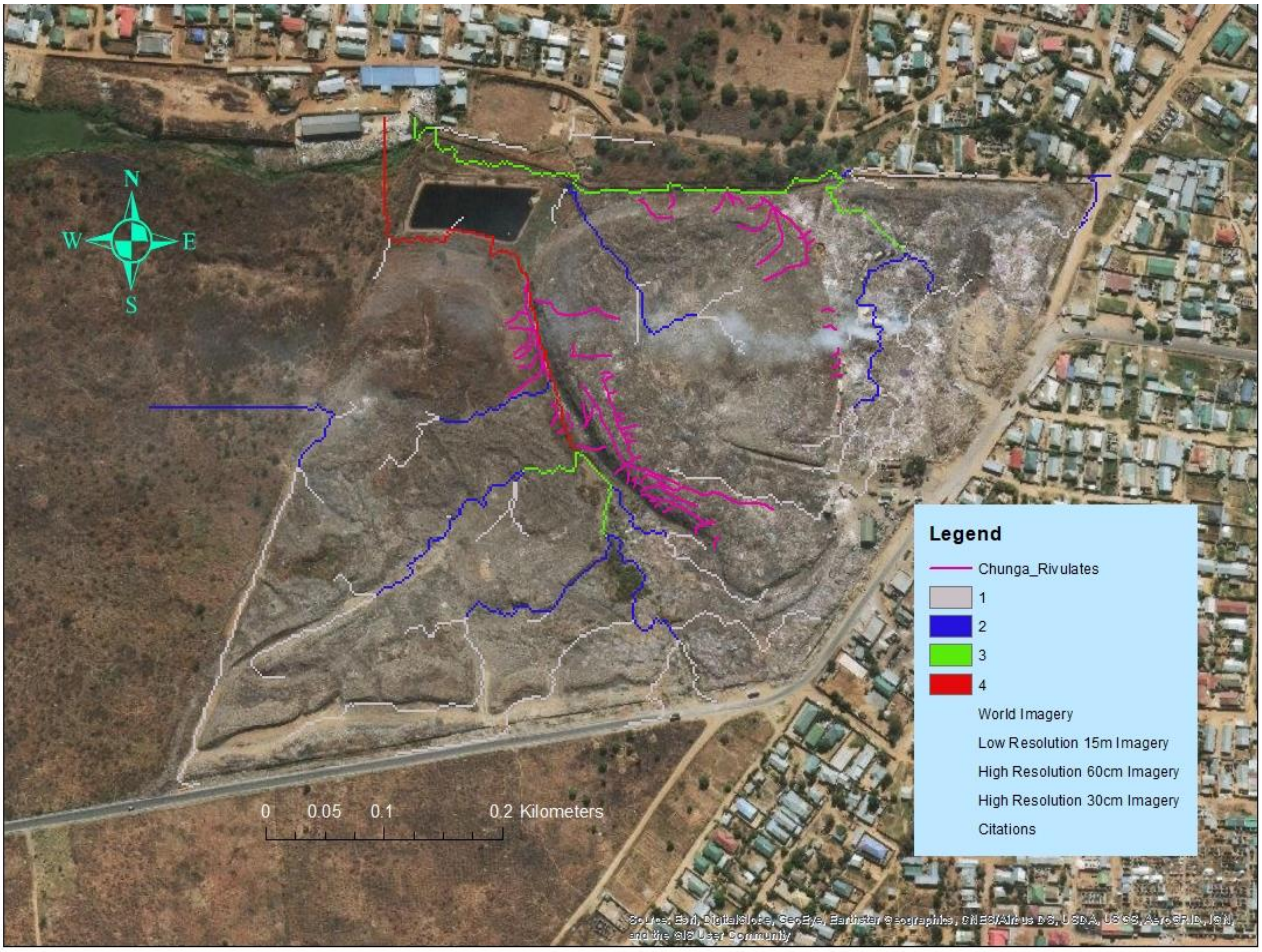


*Figure 5:14:Rivulets on waste heaps and Streams that have been created and flow due to rainwater. They drain beyond the drainage pond into Chunga river and pollute this fresh water body.*

The rivulets appear mainly on the south-western and western and north eastern faces of the *Zone A* waste heap, and along the western side of the central gully between Zones A and C. The Northern face of the tip is observed to have formed rivulets that were omitted in the drainage map created in ArcMap. The rivulets drain mainly into the streams of orders 4 and 3 at the base of the *Zone A* waste heap. According to the Environmental monitoring and operations manual for Chunga by (Chishiba, 2002), the hydrological engineering properties of the site were designed so that all waters would drain into the pond situated to the NW of the site and then flowing into the Chunga stream beyond the site boundaries. This study shows that not all water drains as planned, and some streams flow independently of the planned engineered drainage. There are potential pollution impacts to deeper groundwaters and surface waters as the streams will contain dissolved and suspended substances sources from waste materials.

## 5.9 Flow Accumulation and Direction

### *Results*

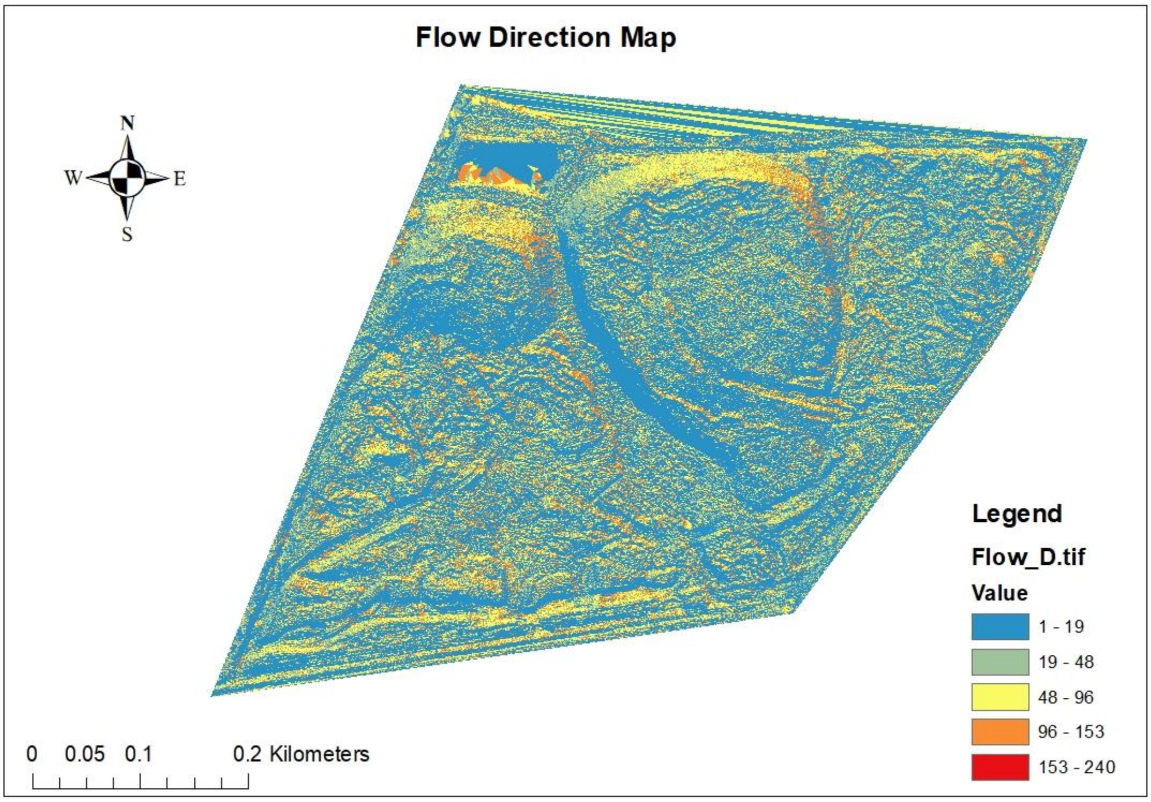


*Figure 5:15: Flow Direction Map at Chunga landfill showing the direction of flow of water based on with assignment of a range of values with directions as seen in the map legend*

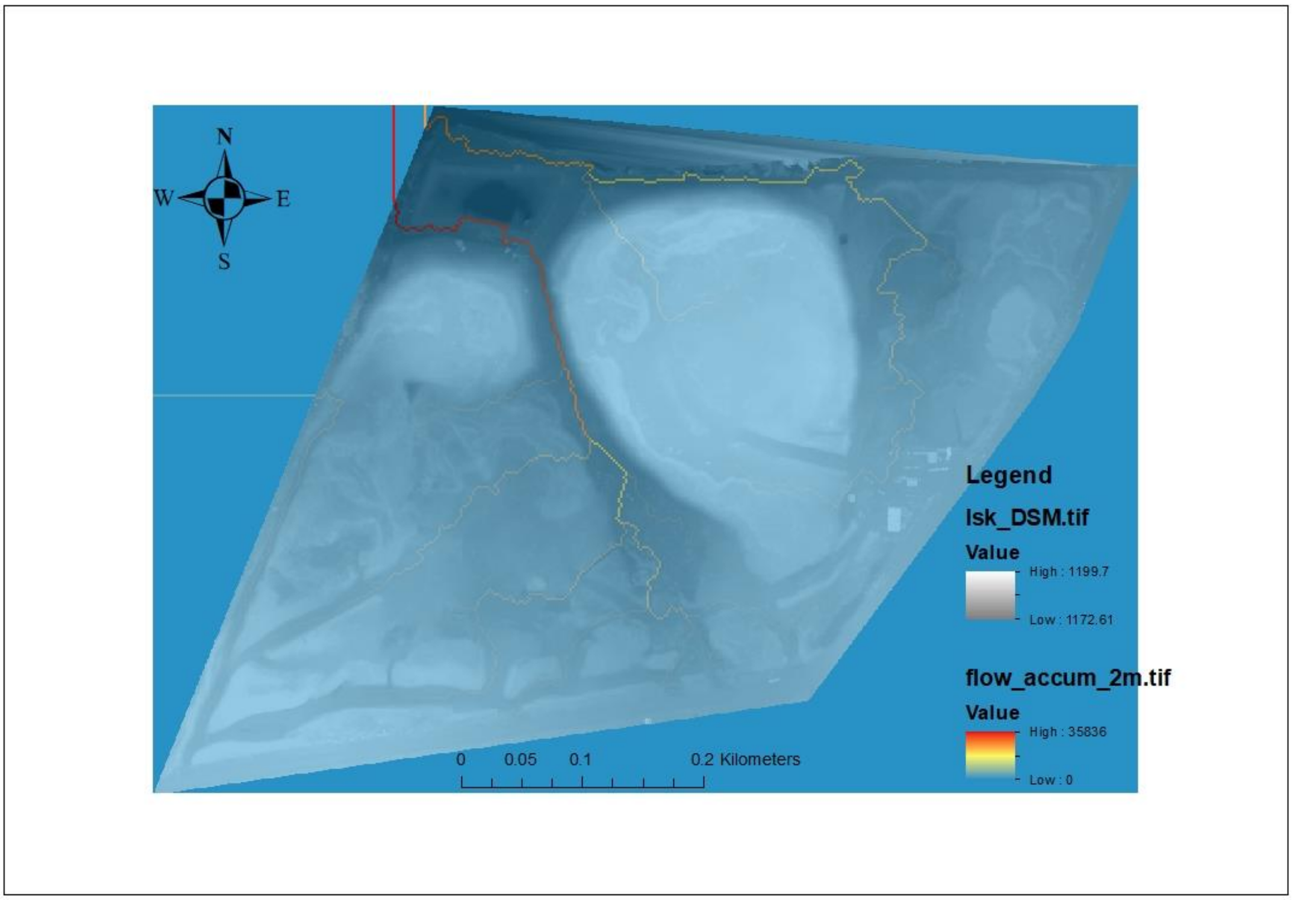


*Figure 5:16: The Flow Accumulation Map at Chunga Landfill is indicative of the flow of water based on volume at the landfill and is dependents on the slope of the terrain.*

### *5.9.1. Flow Direction and Accumulation Interpretation*

According to (Venkatramanan, Ramkumar, Anithamary, & Ganesh, 2013), any catchment system will generate a particular architecture of drainage channels depending on ground topography and erosive forces. The authors further state that in GIS, flow direction (figure 5.15) can be obtained using a DEM to determine direction of flow from every cell in the raster while flow accumulation (Figure 5.16) which equates to the sum of the number of upslope cells that flow into each cell. Flow direction and flow accumulation are important tools that have been used in studying river morphology.

Flow direction maps show the direction water will flow based on slope of the terrain and that is why the DEM is important in the creation of the map. According to (GISgeography, 2018), a value is assigned to the direction of flow of water as seen in (figure 5.15), flow directions to the East, south and west are given a value between 1 and 19, while a North to north western direction of flow is given a value between 19 and 48, while a range of 48 to 96 signifies a North west to North east and finally the range of 96 to 240 is assigned to north west flow direction.

The flow accumulation map in (figure 5.16) on the other hand is best explained as being quantitative as it indicates how much water would flow through a region. Therefore, the flow accumulation map below indicates that there would be higher amounts of water flowing the orange to red regions as compared to the yellow regions. This data compliments Stream order map created in figure (5.13) showing the stream with the highest flow accumulation as also having the highest order of 4.

## 5.10. Waste Volume calculation.

### *Method.*

The volume within each zone was calculated as a sum of the volume of each pixel within the polygon to represent the total volume of waste. To eliminate error, the surface raster was interpolated using the Kriging interpolation tool, from the original DSM. Kriging interpolation method is a popular method used in statistics as it uses the original data of regionalised variables and creates a linear unbiased estimation of the values of the regionalized variables at the interpolation points (Yang et al., 2019). It was important to interpolate the terrain using original points not covered by waste such as the road network, as this allowed for the calculation of waste volume only and eliminating the sloping terrain. The geoprocessing model for waste volume is represented in (Figure 5.17).

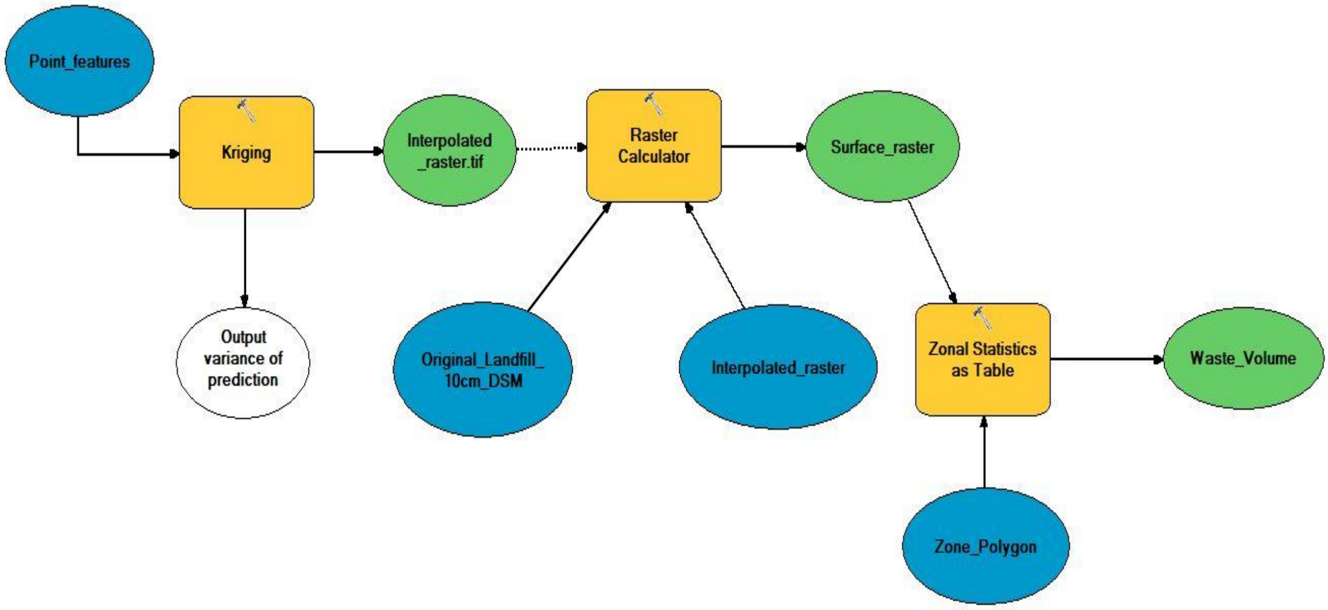


*Figure 5:17 :Geoprocessing model showing the steps in ArcMap used to calculate waste volume including interpolation by using the Kriging method (esri$^{TM}$, 2019)*

| Waste Zone | Zone A | Zone B | Zone C | Zone D | Zone E | Total |
|---|---|---|---|---|---|---|
| Volume ($m^3$) | 558,993 | 34, 683 | 108, 308 | 37, 487 | 12, 344 | 751,815 |
| Height (m) | 18.82 | 3.4 | 17.18 | 5.65 | 1.59 | N/A |
| Area (Hectares) | 6.54 | 9.80 | 1.82 | 3.80 | 0.39 | 22.35 |

*Table 8: Physical dimensions of waste at Chunga Landfill based on Volume, Height and Area, with zone A having the highest volume and height.*

### *5.10.1. Interpretation of physical dimensions of Chunga Landfill*

*Zone A* has the most volume of waste at 558, 993m$^3$ and highest waste heap at 18.82m high. Zone B covers the greatest area and a volume of 34, 683m$^3$ of waste despite the low average height of 3.4m. *Zone C* has the second largest waste volume at 108, 308m$^3$ despite the having a small area of 1.82ha. Zone D compared to Zone C has a larger area at 3.80ha yet a lower volume of waste, 37,487m$^3$ due to having a lower average height of 5.65m. Zone E has the lowest waste volume of 12,344m$^3$, least height at 1.59m and the smallest area of 0.39ha

The total area covered by waste is estimated to be 22.35ha of the total 25ha of the site while the total volume of waste is estimated to be 751,815 m$^3$.

My research therefore shows that Chunga landfill could be considered a small landfill based on its area that is estimated at 22 hectares.

## 5.11. Smoke Plume mapping and wind Data

### *5.11.1. Method*

Google satellite images from 2007 to 2019 were analysed by creating KML polygons around plume that could be observed. Polygons created from the aforementioned period were converted to raster polygons in ArcMap and stacked using the cell statistics tool to create a density map (Figure 5.18).

### *5.11.2. Results*

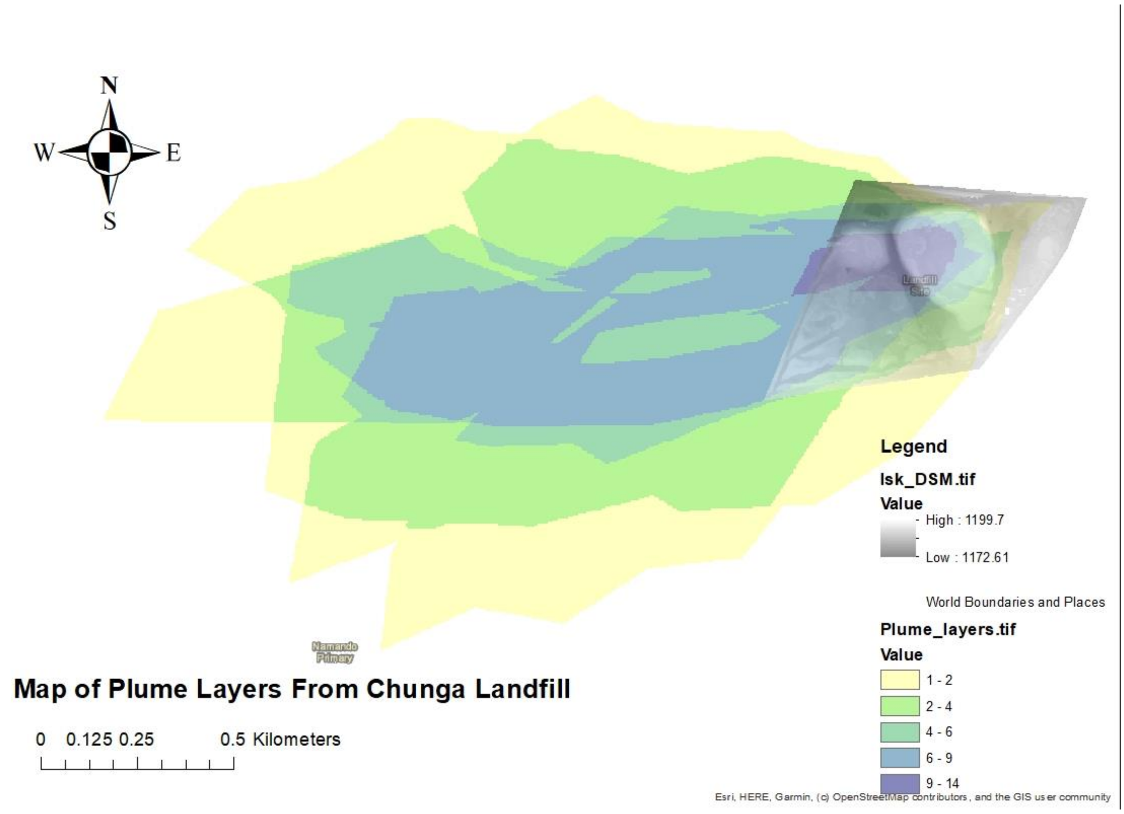


*Figure 5:18: Map of Plume Layers and plume density from Chunga Landfill*

### *5.11.3. Plume Data Interpretation*

(Pokorný & Malerová, 2017) described Smoke plume as the vertical smoke column above a fire focal point and states that the general characteristics of a smoke plume are based on the geometry, temperature, gas flow speed and smoke quantity. This section shows the data obtained from mapping plumes resulting from Chunga Landfill fires as well as presenting wind data for Zambia which includes wind direction and speed for Zambia and southern Africa, respectively. This data is important as it highlights the impacts of fires and resultant plumes from the landfill and how they impact the environment and public health.

The region over the landfill (Figure 5.18), has the most overlap with 9 – 14 plume raster layers covering that region and represented by the dark blue colour. The light blue region has a wider range yet fewer overlapping layers with between 6 – 9. An overlap of 4 – 6 layers of plume is represented by the green area with the lighter shade of green representing 2 – 4 overlapping layers. The regions that are only exposed between a single or double layer of plume throughout the period analysed appear at the edge of the map as a single raster layer. Plume directions are identified from this image analysis

It is evident from (Figure 5.18) that the dominant plume direction is just south of west (c. 260° using the metric scale of geographical compass orientation) but varies between SW and just north of west (21°5 to 280°). These directions result from predominantly easterly winds. The Lusaka/Zambian Meteorological Office produce data of wind directions for Lusaka and these indicate predominant Easterly winds with weaker southerly and northerly winds blowing during January-March in addition to the easterly winds (Meteoblue, 2019).

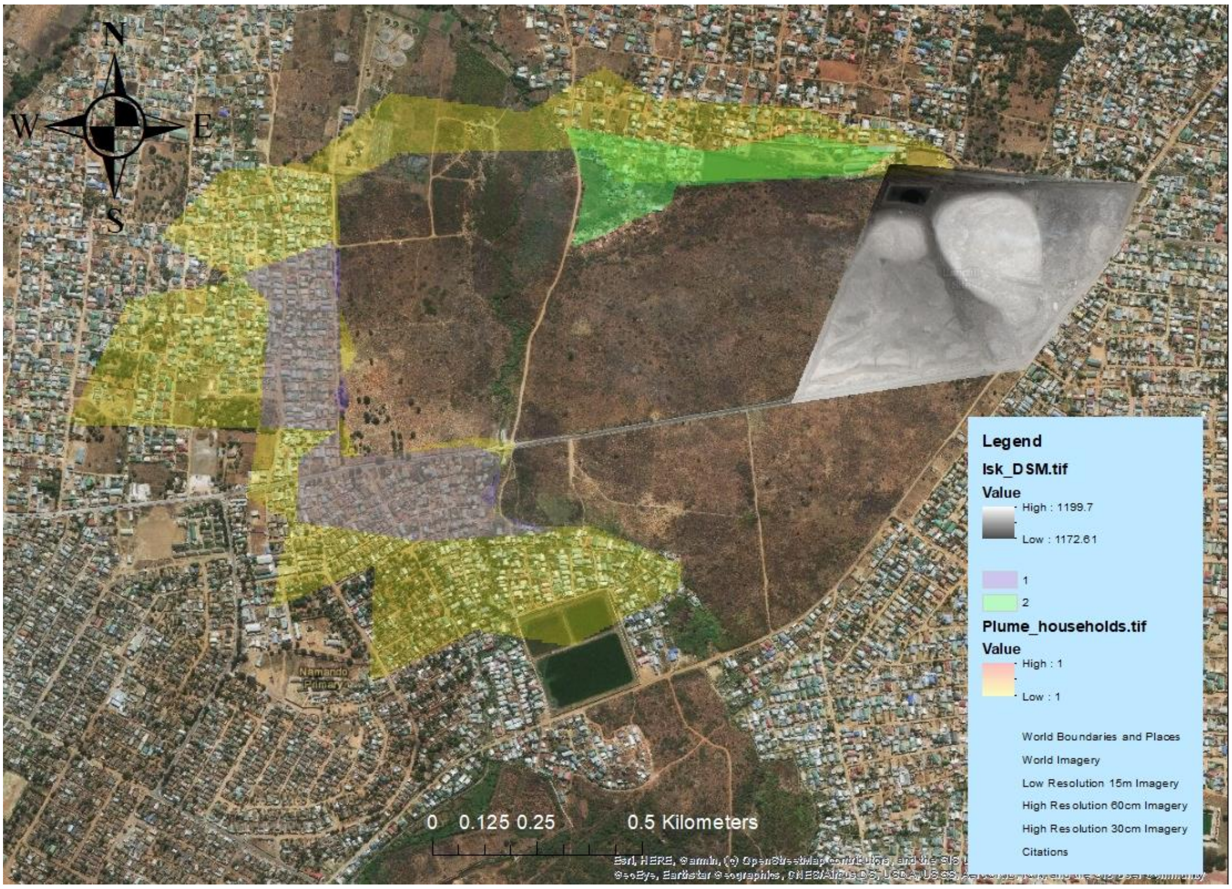


*Figure 5:19: A Map of Households Under risk of plume from Chunga Landfill as evidenced by communities under plume layers to the west and south west of the landfill. This map is based on visual observation of plume.*

The Map in (Figure 5.19), shows the households that are observed under the plume layers created by the landfill fires. 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 a 1 - 2 layers (Yellow) of plume as well as those exposed to 2 – 4 layers of plume (green and purple).

*Figure 5:20: 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.*

### *5.11.4. Wind Data Interpretation*

Wind direction which is reported based on the where it originates, shows that for July 2019, according to (Meteoblue, 2019), was predominately Easterly winds, implyig that wind was blowing from east to West. (Figure 5.21) shows wind direction as recorded on 23rd July, 2019.

According to (Szewczuk & Prinsloo, 2010), strong “westerlies” affect the weather of the southern and sub central parts of Southern Africa. These winds can be strong curving from Limpopo Province in South Africa and move further North towards Zimbabwe and Zambia.

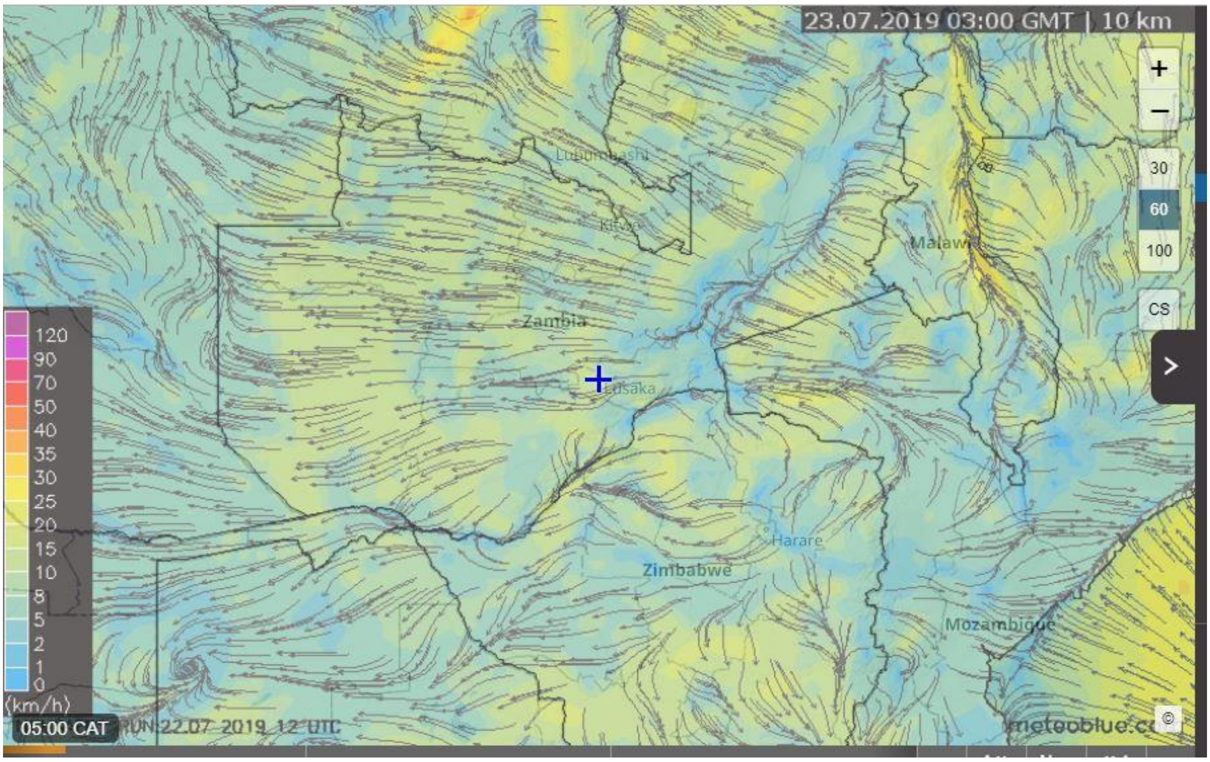


*Figure 5:21: Wind direction for Zambia in July 2019. (Meteoblue, 2019)*

Research by (Fant, Gunturu, & Schlosser, 2016), shows the wind speed of southern Africa being high at the southern and eastern regions, between 5 and 7(m/s). Zambia lies in central Africa and according to the data generated by the authors, wind speeds would be between 4 and 6(m/s) and approximately between 4 and 5(m/s) at Lusaka.

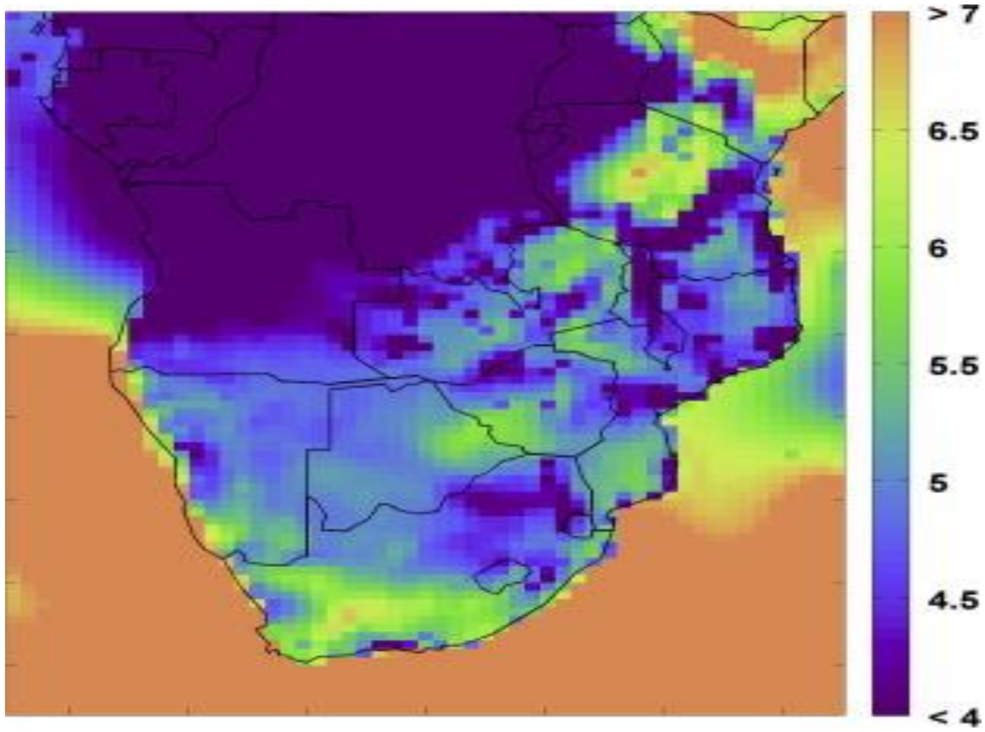


*Figure 5:22:Mean Wind speed of the southern African region measured in meters per second (m/s) (Fant et al., 2016)*

## 5.12. Plume Average Area

### *5.12.1. Method*

A plot of the average area covered by plume for years, 2007 to 2019, was created based on google map images for each year. The area was determined by visual observation of plume and measuring the area with the measurement tools in Google Earth Pro. The plot shown in (Figure 5.23) is the result of the examination of 39 images over the 12-year period with 19 of the images examined not showing any area of plume while 20 of the images had clearly visible layers of smoke plume. The plot below therefore is a representation of the area observed to be covered by smoke plume with the available satellite images (Table 4).

### *5.12.2. Results*

*Table 9: Number of images analysed for plume presence or absence to determine the average area covered by smoke plume at Chunga landfill. Data also shows the direction the smoke plume is carried by the wind to be primarily West, South west and North west.*

| year | Images with visible plume | Images with No plume | Average Plume Area in Hectares (Ha) | Plume Direction |
|---|---|---|---|---|
| 2007 | 0 | 1 | 0 | N/A |
| 2008 | 0 | 0 | 0 | N/A |
| 2009 | 0 | 0 | 0 | N/A |
| 2010 | 0 | 0 | 0 | N/A |
| 2011 | 0 | 0 | 0 | N/A |
| 2012 | 0 | 0 | 0 | N/A |
| 2013 | 2 | 0 | 34 | South West |
| 2014 | 6 | 1 | 46 | South west, West and North west. |
| 2015 | 0 | 6 | 43 | N/A |
| 2016 | 5 | 2 | 34 | West and South West |
| 2017 | 2 | 7 | 14 | West and North West |
| 2018 | 3 | 0 | 110 | South and North West |

| | | | | |
|---|---|---|---|---|
| 2019 | 2 | 1 | 143 | North West |

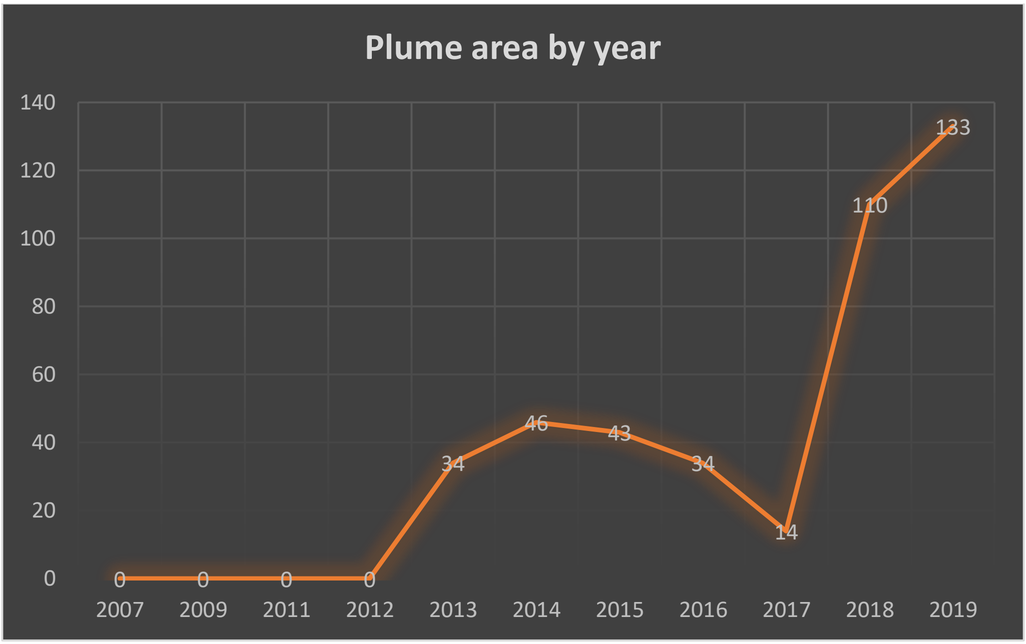


*Figure 5:23 The plot of the average smoke plume area resulting from Chunga landfill between 2007 and 2019, showing the first satellite images of plume in 2013 with an average area of 13 (Ha).*

### *5.12.3. Interpretation of Plume area analysis*

Between 2012 and 2015 there was an increase in plume and with the average area cover being between 34 – 46 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 plume increased to 110Ha in 2018 and increased further in 2019 to the highest observed plume cover of 133Ha. Results show that 2013 was the first year 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.

## 5.13. Waste Heap Slope Analysis.

### *5.13.1 Results*

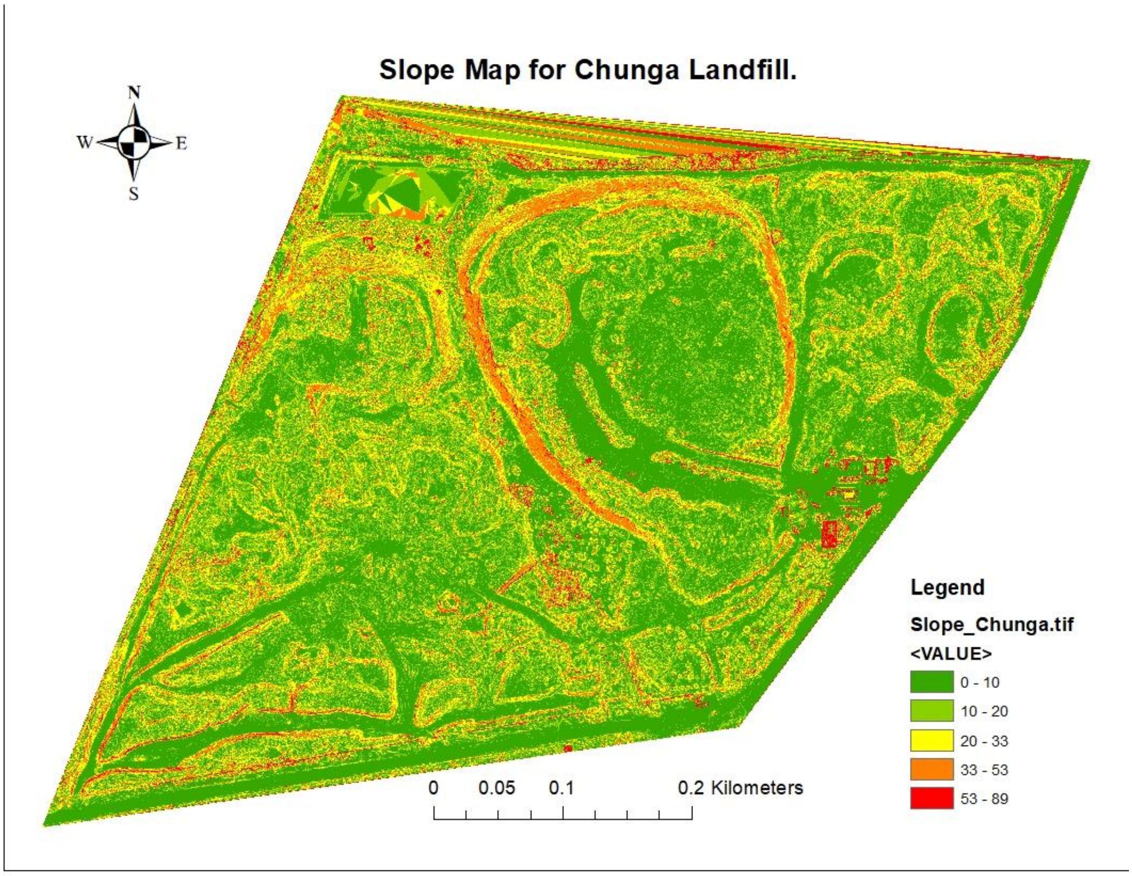


*Figure 5:24: Slope Map for Chunga Landfill*

### *5.13.2. Slope Analysis Interpretation*

ArcMap was utilised in creating slope raster data from the digital surface model of the Landfill. This included slope angle and slope direction (aspect) as shown in figures (5.24 & 5.25) respectively. The slope angle as shown in (Figure 5.24), indicates that the steepest slopes are around the Eastern, Northern and Western faces of *Zone A* waste heap. The western face of *Zone A* is estimated to have a slope angle of between 33 – 53 degrees which is similar to the eastern and northern faces. Based on Table 4 data, this would put the "Y/X" values of slope around this waste heap as being less than 1:1.5. Slope angles of *zone C* are estimates at between 20 and 33 degrees, that is having “Y/X” values between 1: 2.7 and 1:5, around the eastern and northern regions of the waste mound.

*Zones B and D* are relatively flat and with low slopes except in regions where waste has been piled to create gullies and pathways and these regions generally have slopes below 13.2 degrees.

Waste heaps at Zone A have the steepest slopes of the entire site followed by the waste heap at Zone C. Regions in the map legend labelled having a slope angle of 53 – 89 are in fact buildings and other infrastructure such as a water tower that the software identifies as almost having a 90-degree angle.

### *5.13.3 Slope Angle*

Slope measures steepness and direction of a line and can be expressed in as an angle, grade or gradient. This research expresses slope as an angle in degrees.

Mathematically, this angle is expressed as;

<u>Slope expressed as Angle</u>

S angle = $\tan^{-1}(y / x)$

where

S angle = angle (degrees)

x = horizontal run (m)

y = vertical rise (m) (ToolBox, (2009))

Example - Slope as Angle

Slope as angle for an elevation of 1 m over a distance of 2 m can be calculated as

S angle = $\tan^{-1}((1 \text{ m})/ (2 \text{ m}))$

= 26.6 degrees

According to (Chishiba, 2002), the Chunga landfill is engineered to have a ‘safe’ waste gradient of 1:5 which translates to 11 degrees.  11 degrees was decided upon in the original design of the waste facility as this angle produces highly stable slopes. The slopes can be expressed as angles in degrees or as a ratio of Y:X coordinates as shown in (Table 4). The slope angles shown in (Table 4) show 1 to 45-degree angles and their equivalent Y:X coordinates.

*Table 10: Slope Angles represented as Degrees and their equivalent X and Y coordinates.*

| **Angle (Degrees)** | Y | X |
|---|---|---|
| 1 | 1 | 57.29 |
| 2 | 1 | 28.64 |
| 3 | 1 | 19.08 |
| 4 | 1 | 14.30 |
| 5 | 1 | 11.43 |
| 5.74 | 1 | 10 |
| 6 | 1 | 9.514 |
| 7 | 1 | 8.144 |
| 8 | 1 | 7.115 |
| 9 | 1 | 6.314 |
| 10 | 1 | 5.671 |
| 11 | 1 | 5.145 |
| 12 | 1 | 4.705 |
| 13 | 1 | 4.331 |
| 14 | 1 | 4.011 |
| 15 | 1 | 3.732 |
| 16 | 1 | 3.487 |
| 17 | 1 | 3.271 |
| 18 | 1 | 3.078 |
| 19 | 1 | 2.904 |
| 20 | 1 | 2.747 |

| | | |
|---|---|---|
| 21 | 1 | 2.605 |
| 22 | 1 | 2.475 |
| 23 | 1 | 2.356 |
| 24 | 1 | 2.246 |
| 25 | 1 | 2.145 |
| 26 | 1 | 2.050 |
| 27 | 1 | 1.963 |
| 28 | 1 | 1.881 |
| 29 | 1 | 1.804 |
| 30 | 1 | 1.732 |
| 31 | 1 | 1.664 |
| 32 | 1 | 1.600 |
| 33 | 1 | 1.540 |
| 34 | 1 | 1.483 |
| 35 | 1 | 1.428 |
| 36 | 1 | 1.376 |
| 37 | 1 | 1.327 |
| 38 | 1 | 1.280 |
| 39 | 1 | 1.235 |
| 40 | 1 | 1.192 |
| 41 | 1 | 1.150 |
| 42 | 1 | 1.111 |
| 43 | 1 | 1.072 |
| 44 | 1 | 1.036 |
| 45 | 1 | 1 |

*Table 11: Slope Angle in degrees (ToolBox, (2009))*

## 5.14. Slope Direction Analysis

### *5.14.1. Results*

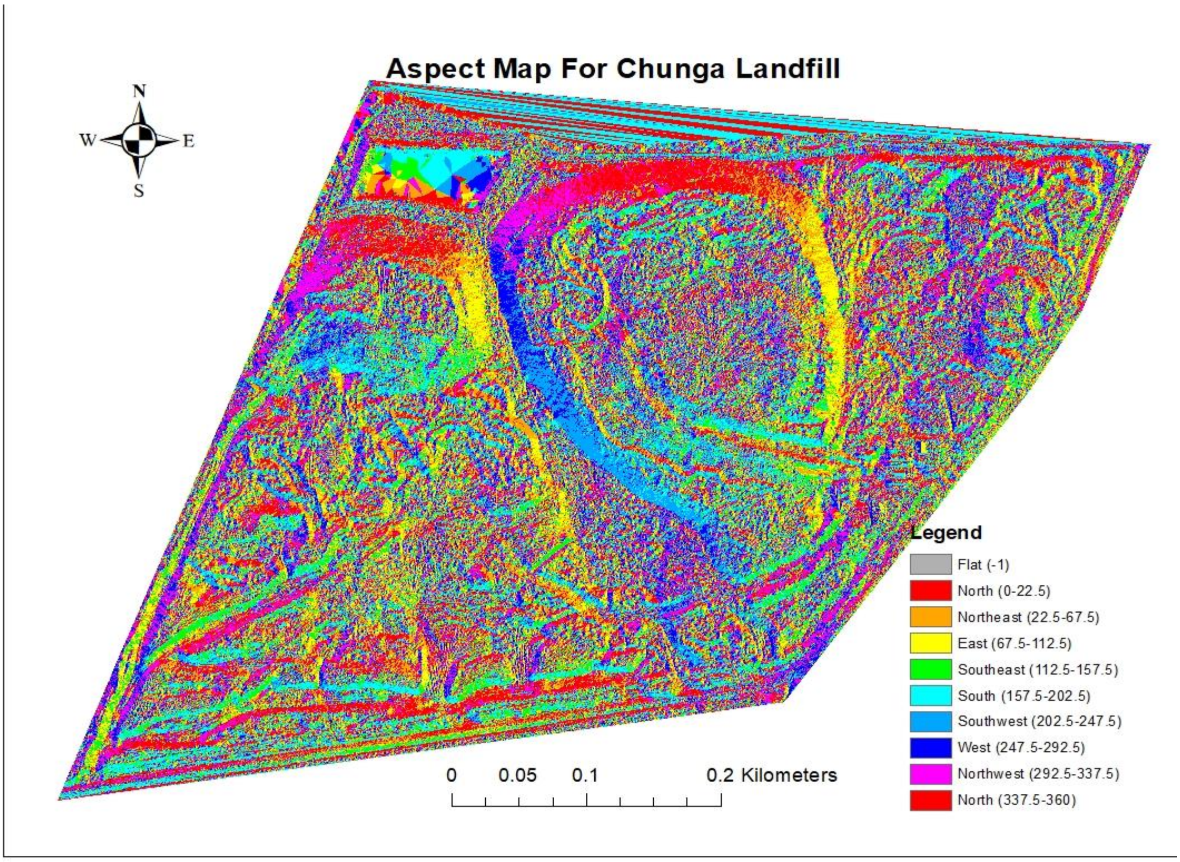


*Figure 5:25:: Map showing the direction of flow based on slope (Aspect) at Chunga Landfill*

### *5.14.2. Slope Direction interpretation*

The slope aspect raster (figure 5.25) using a colour code represents the direction of slope for each Zone. *Zone A* has the most definitive directions of slope as shows in (Figure 5.24). The eastern slope represented by yellow covers most of the eastern face of the Waste tip. Western and south-western slopes are represented by a deep blue and lighter shades of blue further south. The western end of *Zone A* has a region of western slope while most of the surface slopes to the south west and south. *Zone C* shows similar slope direction to *Zone A* due to similarity in shape. *Zones B, D and E* lack definitive slope patterns as seen from the heterogenous colour coordination.

## 5.15. <u>Cross Section Profiles of waste heaps</u>

### *5.15.1 Method*

To create the cross section profile of each waste heap, (Figure 5.26), ArcMap by (esri™, 2019) creates shape flies that have X and Y values. These values represent distance and elevation and are created using DEM raster data.

### *5.15.2 Results*

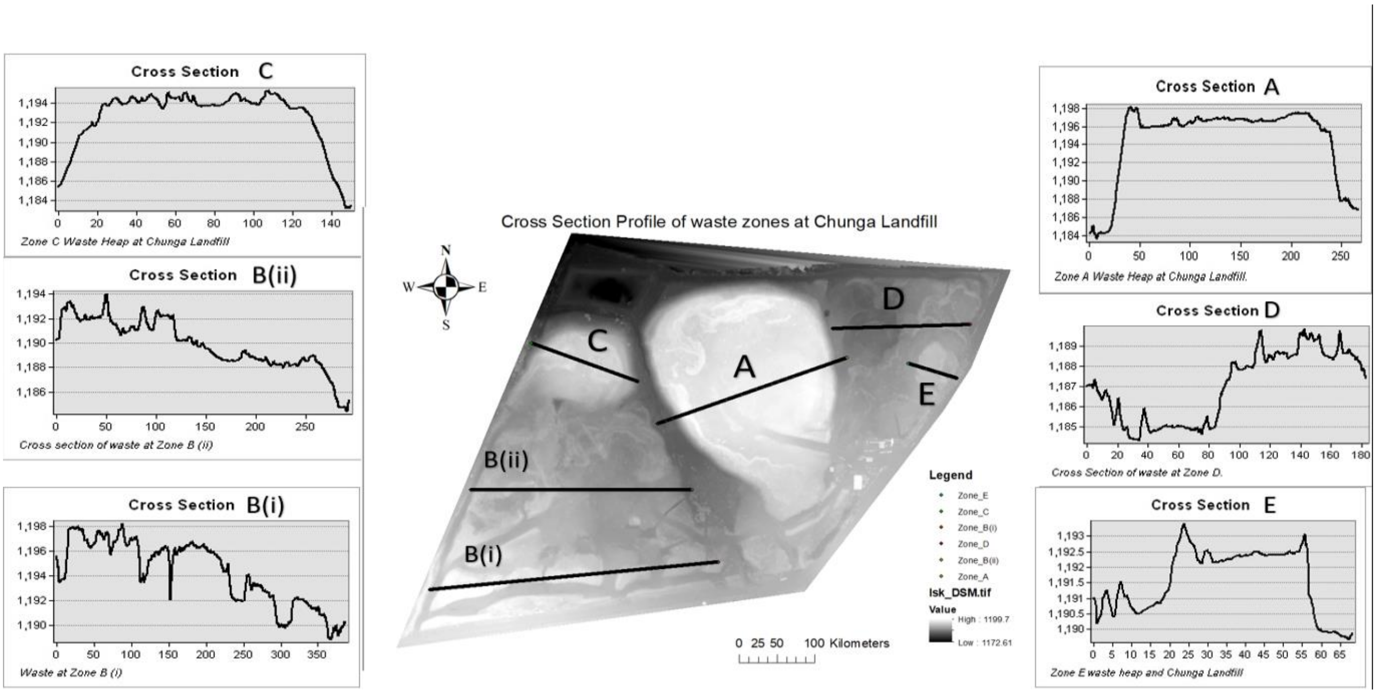


*Figure 5:26: Cross section Profiles of Waste heap Zones at Chunga Landfill.*

### *5.15.3. Cross Section Analysis Interpretation*

As depicted in (Figure 5.26), variations in elevation, slope and topology can be seen by analysing the cross-section graph of each Zone. The highest landfill at Zone A has a steep slope that flattens out at an elevation of 1, 196m and remains flat for approximately 200M. This profile is similar to the waste heap at section C and differs mainly in horizontal distance that only covers 100m.

Zone B narrows and reduces in elevation going north. Two cross section profiles have been extracted for zone B, i.e. B(i) and B(ii) and the trend is to have higher waste in the west and it reduces in elevation towards the east going to 1,100m. The waste profile at zone D shows increase elevation towards the east and ragged edges that have not been flattened out as seen in Zone A and C. The cross-section graph of waste at Zone E appears flat at an elevation of 1,190m covering 65m, the least of all the waste zones.  These profiles are important for analysing the topography of the waste heaps and how they relate to characteristics such as, slope, drainage patterns, topography etc.

## 5.16. Waste Sorting (Recycling) Stations

### *5.16.1 Results*

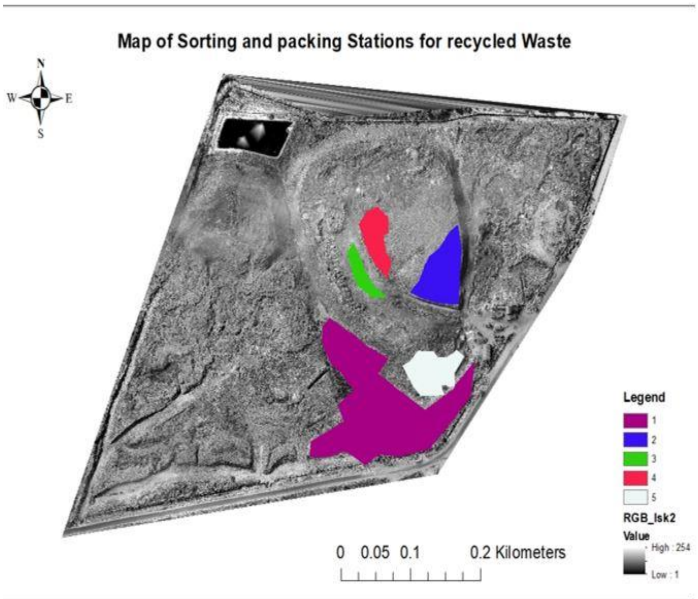


*Figure 5:27: Map of sorting Piles and aerial image of Sorting piles and Chunga Landfill.*

### *5.16.2 Waste Sorting Interpretation*

Recycling of plastic and glass containers at the site has resulted in the circular piles of sorting piles that are located south of waste heaps A and B close to the main road. The map in (Figure 5.27), highlights the location of these recycling piles around the landfill. The recycling of this waste is carried out by Waste pickers who earn a living from this practice and yet the practice is discouraged by the Lusaka city council for various reasons with safety being the most important.

The area between Zone A and B has the largest area of recycling piles located to the south close to the landfill entrances. This area is cardinal as a drainage canal and yet it clogged by the presence of plastic bottle that waste pickers have sorted.

# 6. CHAPTER SIX

## 6.0. DISCUSSION

### *6.1. Construction of Chunga Landfill*

To understand the current state of Chunga landfill, it is important to understand its origin and evolution. (Benard Chileshe, 2017) state that the Landfill was constructed in 2006 funded by the Danish Government, which is consistent with Satellite imagery, from 2006 acquired using Google Earth Pro (GoogleEarthPro, 2019). However, images from 2004 show waste have been deposited on the western end of the landfill before engineering commenced. The engineered end of the entire dump site therefore lies on the east and North eastern end of the site which was completed and became the primary dumping area between 2007 and 2008. The waste dumped at the site is from all over the city, mostly unsorted and consists of plastic, bottles, domestic, clinical, industrial and commercial waste (Benard Chileshe, 2017; Chishiba, 2002).

The engineering of Chunga Landfill was the result of the National Solid waste Management Strategy for Zambia (NSWMS), developed in 2004 by the Environmental Council of Zambia. The NSWMS proposes integrated strategies for tackling the problem of solid waste management. To improve National Solid waste management, the government of the Republic of Zambia introduced legislation such as the Environmental Protection and Pollution Control Act (EPPCA), amended in 1999, CAP 204 which established the Environmental Council of Zambia (ECZ). The NSWMS document recognises several factors that need to be put in place for the improvement of Solid waste management which include:

i) The reduction of waste generation
ii) Improve waste collection and transportation
iii) Reduce the volume of waste requiring disposal
iv) Develop and adopt environmentally sound treatment and disposal facilities.(ECZ, 2004)

The fourth point above relates to the development of infrastructure for safe waste disposal such as transfer stations and landfills and an effective environmentally conscious waste management operational strategy. s well as equipment and personnel to effectively run these facilities. Zambia is one of 193 countries seeking to achieve the Sustainable Development Goals (SDG) generates funding from domestic and international sources to fund SGD projects which also include Solid Waste Management

(SWM) goals. (Rodić & Wilson, 2017), state that 12 of the 17 SDGs of the 2030 Agenda for Sustainable Development adopted by the United Nations members states in September 2015, can be directly linked to SWM. The authors recognise that some Developed and Developing Nations shun away from landfill construction due to the high cost that go into creating a state-of-the-art Landfill. Donor funding facilitated the construction of Chunga landfill and the upgrading of an existing landfill in Dakar, Bangladesh, and this highlights the financial struggle that Developing Countries have in constructing and operating modern landfills without external resources. (Rodić & Wilson, 2017) have further stated that some nations have been provided with funds for operating and construction of landfills through the Clean Development Mechanism (CDM) developed under the Kyoto Protocol. The CDM allows Annex I parties to initiate projects that reduce greenhouse gas emissions in non-Annex I parties and in return Annex I parties obtain Certified Emission Reductions (CER) for their investment (de Chazournes, 1998). Research by (Plöchl, Wetzer, & Ragoßnig, 2008) Catalogued the number of CDM projects according to region as shown in Table 5 below.

*Table 12: Shows Clean Development Mechanism (CDM) projects by region showing how many are in each region and their respective Certified Emission Reduction (CER) between 2007 and 2012 (Plöchl et al., 2008)*

| Region | Number of projects | Percentage (%) | CER (2007 to 2012) |
|---|---|---|---|
| Latin America | 556 | 27.5% | 16.5% |
| Asia and Pacific | 1391 | 68.8% | 77.5% |
| Europe and Central Asia | 17 | 0.8% | 0.3% |
| Sub-Saharan Africa | 27 | 1.3% | 3.8% |
| North Africa and Middle east | 31 | 1.5% | 1.9% |
| Less Developed World | 2 022 | 100% | 100% |

According to their research, between 2007 and 2017, sub-Saharan Africa had 27 of 2, 022 CDM projects which was 1.3% of the total CDM projects in the Less developed world. With the African population expected to continue to grow over the next decade, it is questionable why sub-Saharan Africa and North African have less than 3 percent of the CDM projects aimed at waste management. (D. Who, 2013) observes that East Asia is now the world's fastest growing region for waste, followed by Southern Asia (India) in 2025, with this distinction shifting to Africa in 2050. The construction of Chunga landfill in 2007 is therefore one of 27 CDM projects aimed at the reduction of greenhouse gas emissions. The Chunga landfill thus was constructed with the intention of improving Solid Waste Management (SWM) and function as a unit to reduce greenhouse gas emissions via Danish funding. However due to operational costs, the landfill has not maintained its full functions as a tool for reduction of greenhouse gasses as evidenced by constant fires resulting from methane release in to the atmosphere(Luke, 2017).

## *6.2. Structure and Geomorphology of Chunga Landfill*

### *6.2.1 Landfill Height and Slope Analysis.*

The waste dumped at the landfill accumulates, piles up and should ideally be managed to have the least impact on the environment. However, with Chunga landfill, this is not the case. The landfill waste is visible from up to a 600 meters radius around the landfill and has become an eyesore to the community and the general public. The Landfill measures up to a maximum height of 18 meters (Figure 5.7) above ground which when compared to other landfills such as the Meethotamulla dump site in Siri Lanka that measured at 48 meters (Wijeyeratne, 2017), shows a difference of 30 meters. Meethotamulla dumpsite has been operational for over two decades from the early 90s while Chunga Landfill was designed to have a life span of 25 years (Luke, 2017) if properly managed. This therefore implies that in its 14 years of existence, the landfill has attained a height of 18 meters above ground with 11 more years of waste accumulation before being closed in 2031. (Table 3) compares Chunga landfill to some of the largest landfills in the world based on size, waste deposited per day and the city's population. As observed the difference in landfill size and the amount of waste deposited at these landfills huge. South Koreans, Sudokwon landfill in Incheon is almost ten times the size of Chunga landfill with a population that is equally ten times larger. Despite having a population similar to Zambia, Rome's Malagrotta Landfill is 10 times larger than Lusaka's Chunga landfill and has almost 5000 tonnes of waste deposited daily. This lack of similarity also shows the differences in waste management approaches to the final disposal of waste at landfills between large developed cities and developing cities like Lusaka.

*Table 13: Comparison of Chunga landfill to three of the world's largest landfill based on size, waste deposited per day and city population (Karuga, 2019)*

| Landfill | Location | Size of Landfill (Acres) | Waste deposited per day (tonnes) | Population |
|---|---|---|---|---|
| Chunga Landfill | Lusaka, Zambia | 54 Acres | 53 tonnes | 2. 2 million |
| Sudokwon landfill | Incheon, South Korea | 570 Acres | 19000 tonnes | 22 million |
| Malagrotta Landfill | Rome, Italy | 680 acres | 5000 tonnes | 2.8 million |
| Laogang Landfill | Shanghai, China | 830 acres | 10000 tonnes | 24.2 million |

Several factors will determine what the final height of Chunga landfill will be when it is eventually closed but given the current rate of accumulation, it can be estimated that by 2031, the landfill will be between 30 and 35 m above ground. However, given the current economic circumstances, it is unlikely that Lusaka will have another dumpsite constructed within the next 11 years and more likely Chunga Landfill will take on higher volumes of waste as is anticipated with increasing populations (PopulationStats, 2020a). The potential for the landfill to grow even larger lies with improved waste collection practices that the city now lacks. Lusaka's annual waste production in the year 2000 was estimated at 220,000 metric tonnes and estimated to have increased to 530, 000 metric tonnes in 2011(Siachiyako, 2016). The impact of increased volumes of waste will be the production of higher mountains of waste that increase the environmental and public health risk when poorly managed. An example of such risk is observed with Koshe Landfill in Addis Ababa in Ethiopia that collapsed in 2017 after reaching heights of up to 40m after 50 years of receiving huge volumes of waste up to an average of 550 tonnes of waste a day (Raviteja & MunwarBasha, 2017) which is equivalent to 200,750 tonnes a year. Chunga landfill receives ten times less waste annually at 19 200 tonnes a year compared to Addis Ababa, however population comparisons show Addis Ababa being double that of Lusaka.

*Figure 6:1: The mountain of waste at Koshe Landfill in Addis Ababa that collapsed due to excessive dumping and slope failure (Raviteja & MunwarBasha, 2017)*

Koshe landfill is double the height of Chunga Landfill and has operated for 50years, receiving high volumes of waste from a population that is twice that of Lusaka, at 4,794,000. The disaster resulting from the poor management of the Koshe landfill should be a learning point for the Landfill managers across the world, including Chunga i.e. LCC, as the waste has not yet reached the status of Koshe or Meethotamulla landfills.

The oldest landfill in the city of Delhi in India, Ghazipur landfill (Figure 6.2), is another example of what the consequences of dumping high volumes of waste passed the landfills capacity to store it can be.

Towering at a height of 65m above ground, the landfill still receives almost 2000 tonnes of waste a day, has become a hazard to aircraft, and surrounding residents,  has been operating since 1984 (Yadav et al.). A 2017 collapse killed two people, who were buried in tonnes of collapsed waste: this is a reoccurring risk observed for landfills that are building upwards, attaining great heights, with unregulated volumes of waste.

*Figure 6:2: Ghazipur Landfill in Delhi India, towering above 50m height still receives 2000 tonnes of waste a day (CASSELLA, 2019).*

Analysis of landfill height for this research was critical to the understanding of the stability of the landfill. Factors comprising the geometry of a landfill include boundaries, height, and slope.  (Omari, 2012), states that increasing, particularly heights & slopes, increases hazard potential, and risk, thus reducing safety.

Results of the slope analysis at Chunga Landfill show steep slopes on the Western, Northern and Eastern faces of the waste heap at Zone A, with slopes measuring as steep as 53-degree angles on all three faces. Being the largest waste heap on the site, this is cause for concern as these steep slopes are similar to the Koshe Landfill in Addis Ababa Ethiopia that suffered slope failure at 48 degrees causing a “waste slide” from a 20m height covering a distance of 100m and destroying at least fifty houses (Raviteja & MunwarBasha, 2017). (Raviteja & MunwarBasha, 2017) states that “Slope failure may occur for various reason which include filling the landfill beyond its capacity, improper operation, construction around the landfill or the absence of leachate and methane disposal”.

Research by (Omari, 2012) studied how the slope of a landfill affects its stability by analysing three slopes, 1:3, 1:4 and 1:5 which are equivalent to 18, 14 and 11 degree angles respectively. The study used the software program, SLOPE/W, to compute the factor of safety (FOS) for each slope and compared it to the FOS value of 1.5, which is considered the geotechnical standard for slope stability. The results showed that any slope with a Safety factor below the geotechnical standard for slope stability, 1.5, was considered unstable while slopes with a safety factor of 1.5 or greater were considered stable (Table 6 ). (Omari, 2012) showed that by increasing the slope of a landfill beyond 14-degrees, reduced the level of stability and increased the possibility of slope failure. Based on this understanding of the relationship between slope angle and landfill stability, my results show that Chunga landfill waste heaps have high levels of instability with slopes as steep as 53 degrees. This implies the Factor of Safety for Chunga is below the geotechnical standard for slope stability of 1.5 and thus unstable. The waste heap at Zone A which contains the most volume of waste and height above ground measure of 18.2m, has slopes that range between 33 and 53 degrees while the waste heap at Zone C, the second largest waste heap has slopes ranging between 22 and 33 degrees. These two sites contain the most waste and are currently the regions of most activity from the movement of heavy loaded waste management trucks dumping more waste to waste pickers and Landfill stuffs everyday activities. Safety at the site based on slope stability for the Lusaka City Council (LCC) must be a priority as this presents the most present risk. Slope failure would result in loss of life, damage to infrastructure and equipment. The cost of landfill maintenance through slope reduction as a mitigation measure is more economical that dealing with the fallout of a landfill tragedy due to collapse of waste. Results of this study therefore show that Chunga landfill falls below international standards and is a current environmental and public health risk after assessing and analysing waste slopes.

*Table 14: Slope Stability analysis for three different Landfill slopes to determine a Factor of Safety (Omari, 2012)*

| Slope | SLOPE/W (safety factor) | Slope Stability |
|---|---|---|
| 18 degrees | 1.25 | Unstable |
| 14 degrees | 1.62 | Stable |
| 11 degrees | 1.96 | Stable |

The risks identified from slope stability analysis at Chunga show that potentially, the drainage pond at Zone F lies in the path of potential waste collapse which would result in this system getting blocked. The closest waste heaps to the drainage pond at Zone F are waste heaps A and C. These waste heaps also have the steepest slopes and currently the most unstable. A waste slide at the Northern face of these waste heaps would barricade and choke the drainage pond to the north west. This implies that rainwater would not have an exit during the rainy season. The three waste heaps at Zones A, C and E in (Figure 5.26) are seen to have cross section profiles that highlight steep slopes and plateau tops. This shows lapses in waste management that are tasked with ensuring stable slopes. The three waste heaps appear to have similar cross sections and may imply a design flaw by managers. It is important that managers correct the slope angles of these waste heaps as projections show that over the next decade waste volume is staged to increase in response to increased populations. Engineering landfill slopes for slope stability requires specialised machinery, which includes bulldozers, Loaders and Landfill Compactors (SPREP, 2010). The unavailability or broken down status of this machinery is a challenge the Lusaka City Council faces when dealing with waste and slope maintenance and the lack of funds to replace this expensive equipment does affect operations. (SPREP, 2010) does observe that the spreading and compaction of waste does affect the capacity and stability of the landfill. This in turn also affect the life span of the landfill as low compaction decreases landfill life span while high compaction prolongs it.


*Figure 6:3: Models of Landfill equipment used for slope maintenance at Landfills. Unavailability of this equipment at Chunga landfill highlights challenges in slope maintenance by managers (SPREP, 2010).*

## *6.3 Waste Volume Analysis.*

The maps generated to show flow and slope direction also incidentally show the direction of waste heaps in the event of a collapse due to slope failure. The region's most at risk therefore would be the south-west to western slope of zone A and B as well as the northern and eastern slopes of Zone A and B. The extent of damage that would be expected to impact the surrounding communities and environment would be dependent on the volume of waste at the time of the collapse. Currently the total volume of waste at Chunga landfill is estimated to be 751,815($m^3$) with 558,993 ($m^3$) of the total waste being located at Zone A waste heap (Table 3). These results obtained using photogrammetry are similar to recorded data by (Chishiba, 2002) who estimates that the total amount of waste deposited into the landfill stands at 1600 tonnes per month. In 14 years of the landfill being operational, this would be equivalent to 268, 800 tonnes (761, 156$m^3$).

The underwhelming percentage of waste collected and deposited at Chunga landfill is of concern when compared to the amount of waste produced in Lusaka. Projections by (Jica, 2020) estimated that by 2020, the volume of waste at the landfill would have reached 11,613,341.936 $m^3$ which is the estimated full capacity of Chunga landfill. This forecast for waste volume by (Jica, 2020), assumed an annual 4% increase of waste production and 60% to 85% waste collection rate between 2007 and 2020 (Table 15).

*Table 15: Waste production and collection forecast by JICA and LCC projecting waste volume of 4,101,213 tonnes at Chunga Landfill by 2020 (Jica, 2020)*

| Year | Amount of Waste (t/year) | Assumed Collection Rate (%) | Assumed collection Waste (t/year) |
|---|---|---|---|
| 2007 | 272, 910 | 65 | 177,391 |
| 2008 | 283,826 | 70 | 198,678 |
| 2009 | 295,179 | 75 | 221,385 |
| 2010 | 306,987 | 80 | 245,589 |
| 2011 | 319,266 | 85 | 271,376 |
| 2012 | 332,037 | 85 | 282,231 |

| | | | |
|---|---|---|---|
| 2013 | 345,318 | 85 | 293,520 |
| 2014 | 351,131 | 85 | 305,261 |
| 2015 | 373,496 | 85 | 317,472 |
| 2016 | 388,436 | 85 | 330,170 |
| 2017 | 403,973 | 85 | 343,377 |
| 2018 | 420,132 | 85 | 357,112 |
| 2019 | 436,936 | 85 | 371,397 |
| 2020 | 454,415 | 85 | 386,253 |
| TOTAL | 4,992,043 | 85 | 4,101,213 |

My results therefore show that Chunga landfill with a current total waste volume of 761,156 $m^3$, is only at 6.5% capacity, which falls below its operational design efficiency and lifespan. Due to the low rate of landfill collection and disposal, the lifespan on the landfill may be extended beyond 2034 to accommodate waste deposits. By the time the site is finally closed, material such as liner, may be degraded beyond its effective working capacity. Given that the production of waste will, most probably, continue to increase over the years, particularly when Lusaka is predicted to become one of the larger cities in Africa, with a potential population of 5,183,000 by 2034 (PopulationStats, 2020a) waste collection has to increase to at least 85%, as originally projected by (Jica, 2020) to effectively manage waste in Lusaka. The Zambian Government, through the Lusaka City Council (LCC) therefore needs to develop mechanisms that increase waste collection and disposal by at least an order of magnitude that brings the percentage of waste to 80 to 90% from the 40% deposited at the Landfill site. As shown above, a woefully small amount of waste is stored at Chunga and it can therefore be said that currently the key gap affecting waste management in Lusaka is the collection and depositing of waste. Policy makers and managers need to bridge this gap by investing in mechanisms that encourage the adequate collection of waste around the city and disposed in the designated landfills. Waste collection in Accra Ghana saw an in improvement between 1985 and 2000, increasing from 51% to 91% respectively due to the involvement of private Partner participation (Fobil, Armah, Hogarh, & Carboo, 2008). The involvement of Private sector participation in waste collection saw improved quality of services, an increase in number and capacity of private waste collection enterprises and improved coverage of waste collection within the city. The authors also observed that however, the waste collection scheme that encouraged Private sector participation Ghana, showed promise within the first 15 years, yet factors such as, lack of transparency when awarding contracts to private companies, lack of community participation, lack of monitoring of private contractors contributed to its erosion. The government of Zambia through the Ministry of Local Government could learn from the successes and failures of cities that have implemented frameworks aimed at improved waste collection.

Recycling reduces the amount of waste that is disposed in the landfills and contributes to environmental sustainability and yet the huge sums of plastic at the landfills shows that these materials aren't being recycled or separated at the source. The reliance of waste pickers to sort plastic from dumped only eliminates a fraction of the waste from the landfill. Policies that encourage the separation of waste at the source make the final disposal of waste significantly more efficient.

Cross section profiles of the waste heaps in each zone show how the current volumes of waste are piled up and how they form the topography of the landfill. It is observed that Waste at Zone C and A piles up with steep slopes to form a plateau, while Zones B, D and E are quite irregular and form several gulley's that are now part of the drainage system. It is anticipated that increased volumes of waste over time will change these profiles significantly, with higher waste hills, and potentially unsafe slope gradients. The volume of waste, if Chunga is used effectively as a disposal site, will increase dramatically, perhaps reaching its original design capacity of 11,613,341 $m^3$over the next 10 years with increased population and urbanisation. Theses parameters may affect the overall geomorphology of the landfill and managers will need to plan how to deal with this added waste by focusing on waste content i.e., encourage waste separation at the source, ensure slope maintenance as waste is deposited, maintain gas wells and improve methane collection, extinguish landfill fires and maintain and engineer drainage canals. The cross-section profiles generated during my research allow managers to plan and visualised the best place to deposit waste over time. However, for this to be effective, follow up studies will need to be carried out to determine changes in the, volume and shape of the landfill and photogrammetry is a cost-effective tool that can be used.

## *6.4. Chunga Landfill Drainage Analysis.*

The collapse at Meethotamulla, was also the result of several days of floods that destabilised the structural integrity of the landfill coupled with steep and badly engineered slopes, lack of drainage of the slopes, tipping of all kinds of waste and poor waste management. Zambia, like many other African countries, experiences changes in climate related extreme weather anomalies from droughts to flash floods whose impact on landfill stability could be catastrophic. In the years when Lusaka receives normal and above normal rainfall, serious flooding has been known to occur in regions particularly north of the city (W. S. Nchito, 2007). The rain season lasts approximately 5 months, from late November, and produces an average of 820mm of rainfall, with 70% of the total rainfall in Lusaka falling as flash storms, that last less than 30 minutes. (W. S. Nchito, 2007). Chunga landfill is susceptible to flooding, due to its poor drainage infrastructure, and, according to the Lusaka City Council, dumping of waste during the rainy season is restricted to the less steep section of the landfill (Zone B).

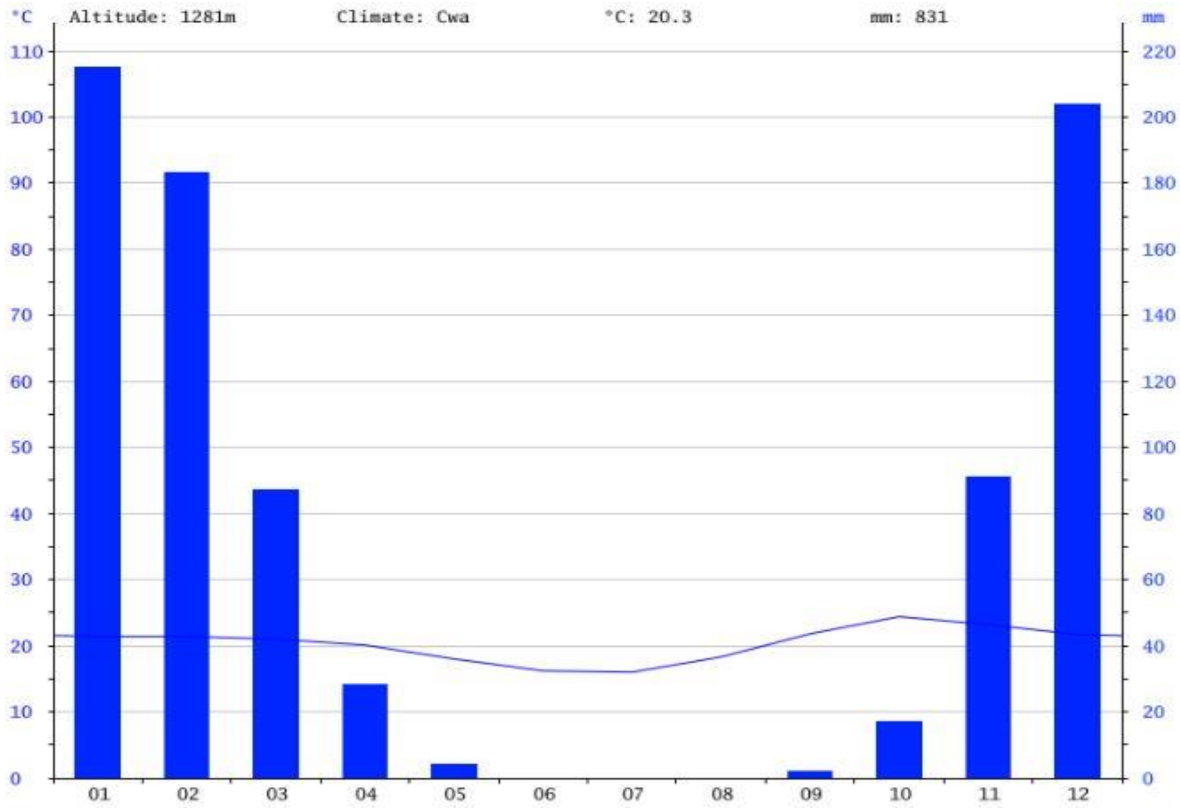


*Figure 6:4: Graph of Rainfall Data for Lusaka by Month showing average rainfall of 831mm with Dec/Jan/Feb are particularly hazardous months for flash storms that could impact on the Chunga Landfill Site. (Climatedata.org, 2020).*

Lusaka's rainfall pattern according to (Climatedata.org, 2020) shows high amounts of rainfall during 5 months of the year, November, December, January, February and March, particularly December to February. Therefore, between November and March, Chunga landfill is vulnerable to heavy rainfall and flash floods which affect landfill waste heap stability.

The flow direction and slope direction data respectively, show how the geometry of the waste heaps at the landfill affect the directional flow of water due to rain. Study of this map sets the tone for understanding the drainage pattern of Chunga landfill as the map demonstrates in which direction water would flow and form streams. The waste heap at Zone A has a South to western slope and northern to north eastern slope which according to the flow accumulation raster result in two of the main streams that form the drainage pattern of the landfill. Based on the flow accumulation data, it can be deduced that the stream that forms at the base of the southern to western slope of Waste heap A, has the most quantity of water flowing through that region. This assumption is reinforced by mapping the stream order of the drainage system which shows the western streams having an order of 3 and 4 which is the highest of the landfill. This knowledge presents an opportunity of managers of the site, the Lusaka City Council (LCC), to improve the drainage system and know which regions to focus on especially with limited resources. It has been observed that water does not flow into the drainage pond and this would be an area of focus for the LCC by channelling water from these streams into the pond. It is important to engineer the drainage system and not rely on naturally created drainage streams as their location my weaken the structure of the landfill. Landfill managers should ensure water drains where it is supposed to and not form streams in the form of rivulets as seen on waste heaps A and C.

The impact of flooding and improper drainage systems at some landfill sites has resulted in ground water contamination from leachate percolation, as was the case with the largest landfill in Nigeria, the Olososun Landfill (Aboyeji & Eigbokhan, 2016). Here, 60% of water collected around the landfill was declared unsafe for human consumption without further treatment (Majolagbe, Adeyi, & Osibanjo, 2016). In this study, "Forty (40) water samples were collected from twenty different hand dug wells around Olososun dumpsite bimonthly, for two consecutive years and analysed for various physicochemical parameters." The researchers observed that samples from wells downstream of the landfill wear significantly polluted with highs Nitrate and Chloride levels. Chloride was observed to be 142 mg/L, while nitrate levels increased from 33.1 mg/L in 2009 to 35.6mg/L in 2010 above the standard set by the World Health Organisation (WHO), at 10 mg/L for safe drinking water.

Landfill flooding also leads to erosion of Landfill materials and the release of pollutants such as, lead paint, insecticides, solvents and construction material (Young, Balluz, & Malilay, 2004). Chunga landfill was designed with a leachate collection system and storage reservoir which based on my research is failing to contain waste liquids that arise from water flow resulting from improper drainage canals to the storage reservoir (Figure 6.5).

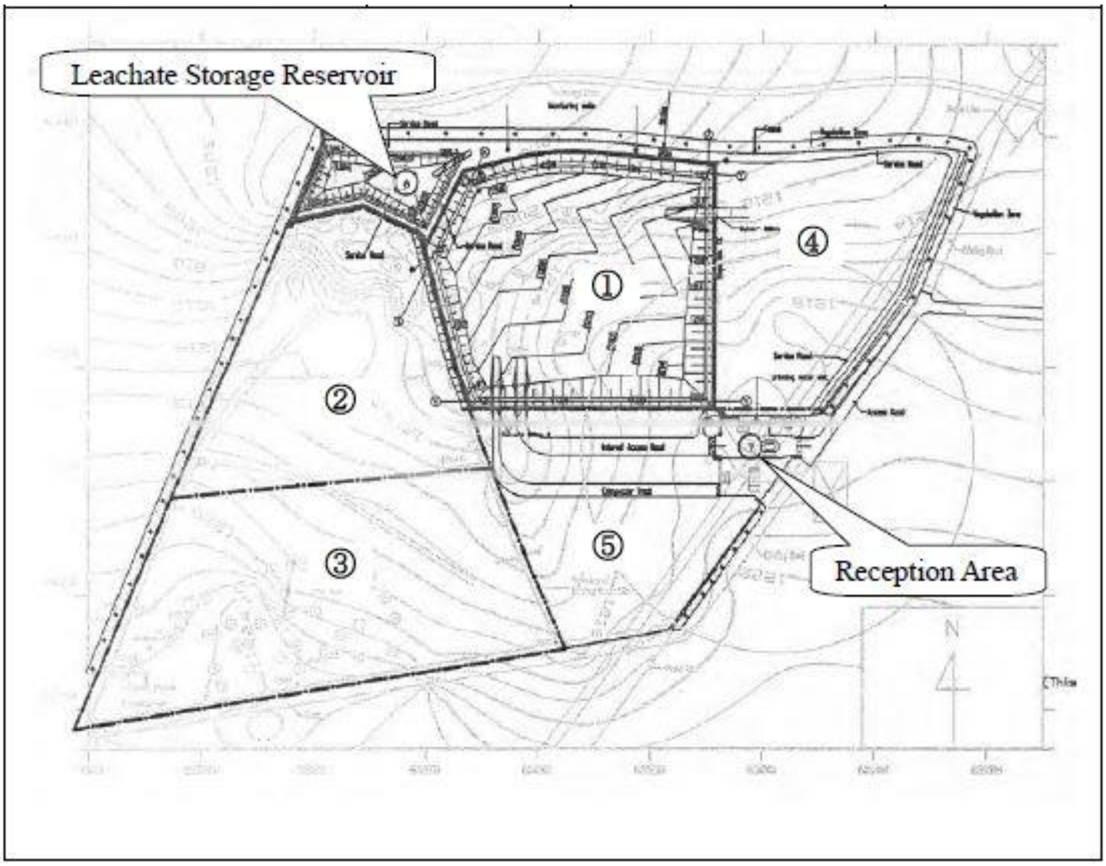


*Figure 6:5: Chunga landfill design with Leachate Storage reservoir to store leachate and the drainage of rainwater (Jica, 2020).*

The impact of the ineffective containment and drainage system of the Chunga landfill stems from poor funding for landfill maintenance in areas such as drainage repair, monitoring and engineering which has resulted in the pollution of ground water, as the landfill exists south of the Chunga River sub-catchment Area (Figure 6.6). As at now, pollutants from Chunga river may flow into Mwembeshi River, located downstream of the Chunga landfill.

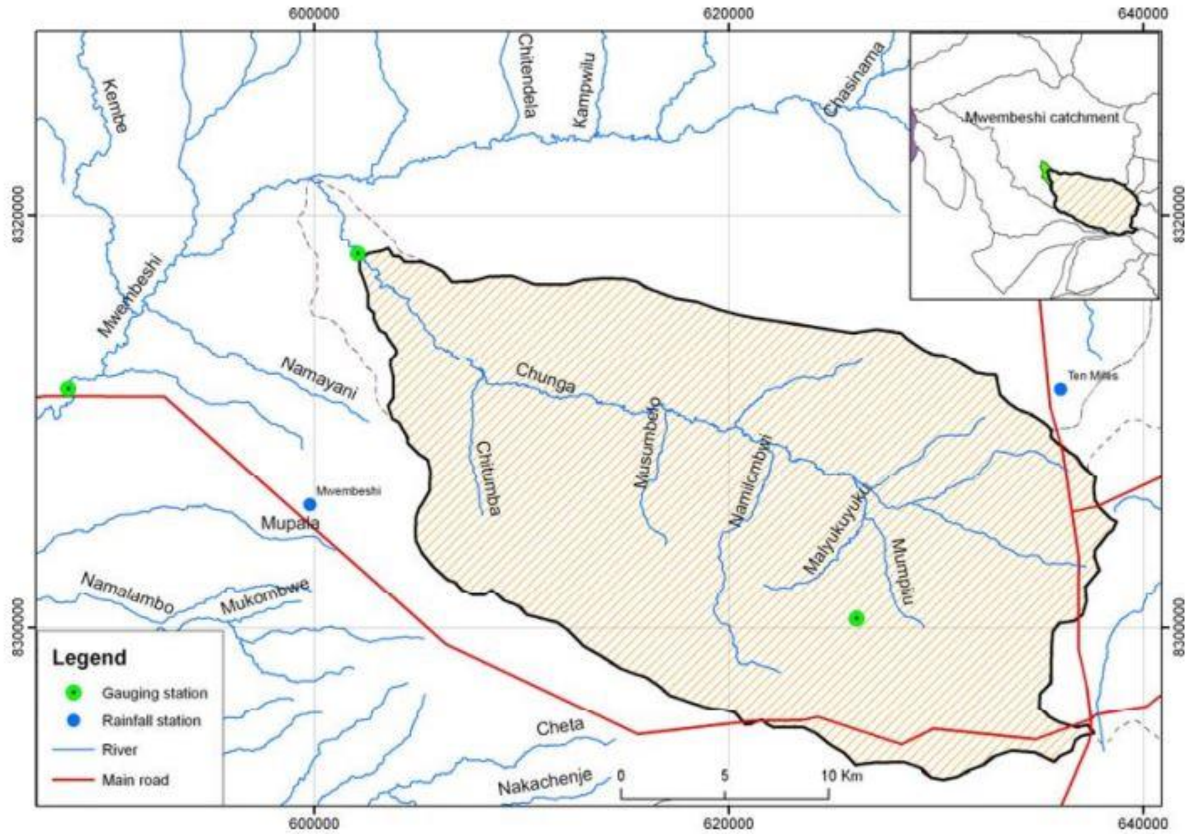


*Figure 6:6: Chunga River and sub-catchment area which is the major source of ground water for Lusaka city (Bäumle, 2011).*

A report by states that Chunga River is one of two Rivers that carry toxic water that is not fit for human consumption without treatment. The Lusaka Water and Sewerage Company (LWSC) has therefore set up a ground water monitoring stations around Chunga river that have recorded up to 25 to 200 (mg/l) of Nitrate at boreholes while the Nitrate concentration threshold for ground water is stated to be 20 (mg/l) as observed by (Hu et al., 2005). This shows high levels of nitrate levels that may result from landfill pollution. The effects of drinking water with excessive nitrate levels results in health risks such as Anaemia, enlargement of the thyroid gland, birth defects, hypertension and increased incidence of 15 types of cancer (Gao, Yu, Luo, & Zhou, 2012). The pollution of this water source therefore may affect the high-density communities by reducing the access to drinking water that's safe for human consumption.

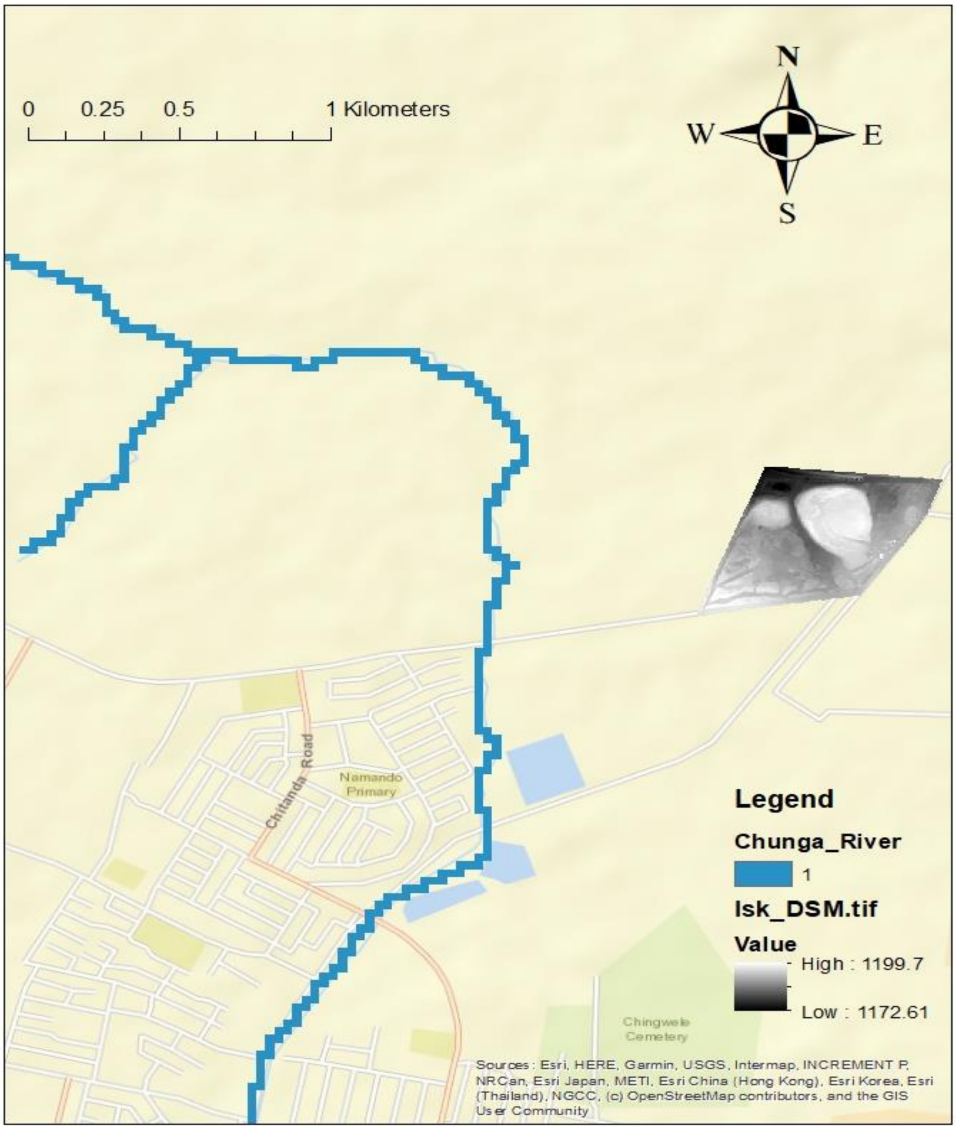


*Figure 6:7: Chunga River flowing from the North west with high concentration of Nitrates and polluted water*

## 6.5. Fires and Plume Analysis

Fires at the Chunga landfill have been a cause for concern due to their perpetual nature, 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 5.18). 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. The contaminant plumes directly affect the people at the landfill, including staff, visitors, and waste pickers. Plumes are most dense at proximal locations, and least dense at distal locations. Residential structures, as far away as 3km 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 5.19). Houses within 1-2km 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-separation of waste at the Chunga Landfill site, materials that will burn probably include: plastic; cloth; wood; medical waste; rubber; organic materials; domestic waste; industrial waste; and possibly even chemicals. A wide range of potentially harmful substances that can impact on human respiratory systems, in addition to potential longer-term medical impacts resulting from the ingestion of heavy metals, organic compounds, a range of gases and so forth. Pollutants could include: benzene; furans/ dioxins; and a range of solid particulate matter in suspension ($PM_{2.5}$) (Weichenthal et al., 2015). Research by (Weichenthal et al., 2015) found increased concentrations of dioxins/furans and benzene in ambient air due to landfill fires produced at a landfill in Iqaluit Canada . The presence of $NO_2$ (Nitrogen dioxide), $O_3$ (Ozone) and $PM_{2.5}$ (Particulate matter of diameter < 2.5 micrometre) was detected .Similar research by (Toro & Morales, 2018) observed an increased $PM_{2.5}$ concentration of 200µg $m^{-3}$ 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 & Cohen, 2008). For developing countries like Zambia, many of individuals from the aforementioned vulnerable populations earn a living from the landfill as waste pickers.

*Figure 6:8: A drone image of plume from Chunga Landfill fires blowing west towards high-density, low-cost settlements.*

Air pollution from fires have also been observed in landfills such as the Riverton Landfill in Jamaica. The landfill has been a cause for public concern as it has recorded 415 fires between 1995 and 2015 (Table 15).

*Table 16: Fires recorded at Riverton Landfill between 1996 and 2015 by the fire department in Jamaica (Duncan, 2018)*

| | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC | TOTAL |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1996 | 3 | 1 | 4 | 1 | 3 | 1 | 0 | 0 | 1 | 1 | 0 | 0 | 15 |
| 1997 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1998 | 2 | 0 | 4 | 0 | 0 | 1 | 1 | 2 | 1 | 0 | 0 | 2 | 13 |
| 1999 | 3 | 1 | 5 | 2 | 2 | 2 | 2 | 8 | 0 | 0 | 0 | 1 | 26 |
| 2000 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 1 | 0 | 0 | 3 |
| 2001 | 0 | 0 | 2 | 0 | 0 | 5 | 6 | 0 | 3 | 0 | 0 | 0 | 16 |
| 2002 | 2 | 1 | 4 | 4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 11 |
| 2003 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 6 | 1 | 1 | 0 | 0 | 10 |
| 2004 | 0 | 1 | 0 | 1 | 1 | 3 | 0 | 4 | 0 | 0 | 1 | 1 | 12 |
| 2005 | 1 | 2 | 0 | 3 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 8 |
| 2006 | 4 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 6 |
| 2007 | 7 | 0 | 6 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 15 |
| 2008 | 0 | 1 | 4 | 4 | 6 | 5 | 9 | 0 | 0 | 0 | 0 | 1 | 30 |
| 2009 | 0 | 3 | 1 | 3 | 0 | 0 | 1 | 2 | 1 | 0 | 1 | 2 | 14 |
| 2010 | 3 | 2 | 0 | 0 | 1 | 0 | 0 | 0 | 4 | 1 | 0 | 0 | 11 |
| 2011 | 1 | 0 | 0 | 0 | 2 | 4 | 5 | 4 | 0 | 3 | 2 | 4 | 25 |
| 2012 | 4 | 19 | 3 | 1 | 2 | 1 | 4 | 2 | 0 | 0 | 3 | 2 | 41 |
| 2013 | 2 | 0 | 0 | 0 | 7 | 7 | 13 | 9 | 4 | 0 | 5 | 10 | 57 |
| 2014 | 12 | 0 | 0 | 16 | 2 | 5 | 7 | 0 | 3 | 7 | 3 | 2 | 56 |
| 2015 | 4 | 0 | 5 | 15 | 5 | 6 | 3 | 3 | 4 | 1 | 0 | 0 | 46 |
| TOTAL | 48 | 32 | 39 | 50 | 32 | 41 | 52 | 40 | 24 | 16 | 14 | 27 | 415 |

The Riverton landfill receives 60% of the of the national waste collected, amounting to an estimated 2406 tonnes of unmonitored waste dumped daily which is almost 900,000 tonnes annually for a country with a population of 2.9 million people (Duncan, 2018). The author states that over 800 respiratory related cases were reported to hospitals in the city during a 2-week period of waste-tip burning. Landfill fires also affect developed countries such as the USA that recorded almost 8,300 landfill fires in 2001 with a number of these landfill fires being spontaneous sub-surface fires (Moqbel, 2009). Several of the fires at Chunga landfill are of a sub-surface nature and thus difficult to extinguish and are therefore a hazard to the environment and public.

## *6.6. Waste Pickers at Chunga Landfill*

The waste pickers at Chunga Landfill have become a permanent fixture at the landfill and scavenge the waste heaps for materials they consider of value, such as plastic, cardboard, bottles, and other (Benard Chileshe, 2017). The practice of waste picking, which is technically illegal, yet extensively practiced, contributes to the recycling of inorganic materials at the landfill, and the economic livelihood of hundreds of people in Chunga. Sorting piles of bottle and plastic are observed throughout the landfill, and, with the development of recycling companies looking for materials, a demand has been created. (Madekivi, 2017) states that Lusaka has almost 25 recycling companies, whose main interest is purchase of plastic. The author observed that waste pickers from Chunga landfill recover plastic bottles (32%), plastic bags and sacks (27%), scrap metal (16 %), paper and boxes (18 %), and wood (8 %). The waste pickers are aware of the risks associated with this line of work and yet despite this, poverty drives them into this way of life (Benard Chileshe, 2017). The health risks to waste pickers are a public health matter, and Chileshe's research shows that coughing and respiratory problems are the most commonly reported health complaints by the waste pickers. Chileshe lists several health risks which include, respiratory diseases like asthma, bronchitis, and tuberculosis, communicable diseases due to close proximity and contact with carcasses and medical waste, physical injury, and choking/suffocation from smoke.

*Figure 6:9: Waste pickers at Chunga Landfill sorting materials for sell or personal use. In this image seen collecting waste from truck as they arrive to dump waste.*

The presence of the waste pickers at the landfill poses a risk that could result in injury or even death, given the hazards identified from fires and slope instabilities during this study. My research shows that waste pickers are piling up recycling materials collected from all over the site at the base of the landfill to sort them out (Figure 6.10). These piles are vulnerable to land/waste slides resulting from slope failure. These recycling piles are also observed to be placed along the drainage route of one of the main drainage streams flowing from south west to north west to the drainage pond with a high volume of water. This not only poses a risk for the waste pickers but also affects the drainage efficiency of the landfill by obstructing the natural flow of water. This region for piling recycling material seems to be favourable as it avoids direct exposure to smoke from the landfill fires.

*Figure 6:10: A pile of plastic bottles collected and sorted by a waste picker for sell to recycling companies.*

## *6.7. Population and Waste Production Trends for Lusaka and Zambia*

Urbanisation has been a major factor attributed to the challenges of solid waste management around the world over several decades (Hoornweg & Bhada-Tata, 2012; Melosi, 2004; Vij, 2012). Despite Africa's population being 15% of the global population, it contributes only 6% of the global Green House Gases, with sub-Saharan Africa emissions being less than a quarter of the global average(Couth & Trois, 2011). When compared to the United States of America, the percentage of Green House Gases from waste in Africa, is three time greater in Africa, with the primary cause being methane emissions from landfills (Couth & Trois, 2009). The relationship between Green House Gas emissions and urbanization therefore shows correlation especially with regards to waste production as it is anticipated that as African cities, including Lusaka, become more urbanized, there will be more waste produced leading and deposited into landfills.

Lusaka has been no exception to the increased populations over that last 3 decades, with people from all over the country leaving their hometowns for the capital city in search for jobs, education, better health services and generally a better quality of life. According to (Fox, 2012), Zambia's urbanization trends begin to show growth in the late 1950s and early 1960s with 45% percent urbanization of major cities especially Lusaka the Capital. This urbanisation was correlated to a surplus of food from local productivity and aid between 1970 and 1975. The mortality rate between 1970 and 1990 has significantly reduced and recent urbanisation reached its peaked from 1980 to 1990. (Fox, 2012) states that Zambia was one of a few other sub-Saharan African countries that experienced the phenomenon of de-urbanisation in the 1990s, resulting from reduced food production, well as increased mortality rate. The rising mortality rate were not only attributed to Zambia's economic failures but also the resurgence of deadly diseases such as Malaria and HIV/AIDS.

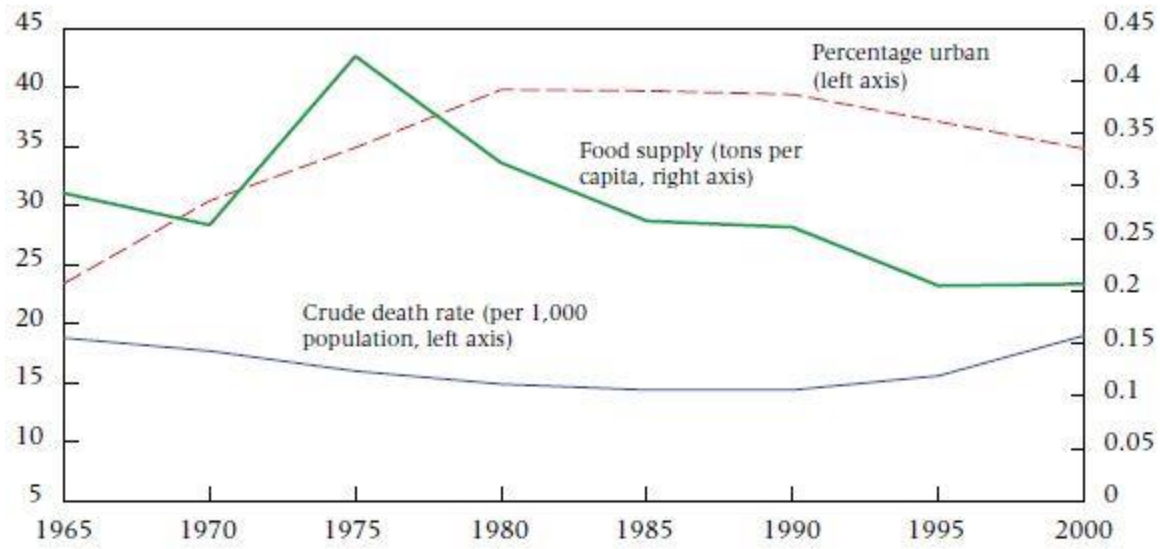


*Figure 6:11: Graph showing Urbanization in Zambia and its relationship to Food supply and mortality rates between 1965 and 2000. (Fox, 2012)*

Satellite images from 2006 to 2019 show an increase of housing structures around the Northern, Eastern and Southern ends of the Landfill but no housing developments on the Western end. During the fifties, the Lusaka City Council built a huge housing area known as Matero with houses that were rented out to Council employees and private companies (Schlyter, 2003). The growth of this original settlement has now engulfed the landfill, with low-cost, high-density housing first observed in satellite images in 2006 (figure 5.11). Research by (Silavwe, 1994) shows that in 1963, the urban population in Zambia constituted only 20 percent of the total population and yet in thirteen years had doubled to 40 percent. This rapid population growth is cause for concern as it highlights the need for putting in place mechanisms to deal with the larger amounts of waste produced in these urban cities such as Lusaka, Kitwe, Chingola, Mufulira, Luanshya and Ndola that experienced an annual population growth rate of 8 percent. Table 6 shows data collected by the central statistical office in Zambia (GRZ, 2010), showing the changes in population in Lusaka for both the Urban and Rural communities. Between 1990 and 2000, there is an is a 54.5% increase in the peri-urban populations of Lusaka compared to a 37.5% increase in central urban population. This difference in population increase (Fox, 2012), is representative of the period of de-urbanisation, also shown in (Figure 6.13). The next decade however, between 2000 and 2010, showed a 63.7% increase in Urban populations compared to a 30.2% increase in Rural populations. This indicates that urban growth again re-established itself following the ending of high morbidity due to AIDS and improved food supplies. This urban growth coincided with the construction of the Chunga landfill in 2006. Urban Lusaka in 2010, four years after the Chunga Landfill was constructed, had a population of 1,854,907 and the landfill had been gazetted as the only engineered and main dumping site for the city. The average amount of annual waste generated in Lusaka in 1996 was estimated at 220, 000 tonnes, and increasing by 141%to 530, 000 tonnes in 2011 (Edema et al., 2012). Recent reports however place the current annual production of waste in Lusaka at 1 million tonnes with only half of it ending up at the landfill (Nawa, 2017) and this correlates to increased populations during this period. There is a proportional increase of waste when weighed against urbanization and it can be simply put that the more people living in a city like Lusaka, the more waste will be produced and require the proper disposal.

*Table 17: Lusaka Urban and Rural Population Statistics from 1990 to 2010 showing percentage increase in population for each decade.*

| | 1990 - 2000 | | | 2000 - 2010 | | |
|---|---|---|---|---|---|---|
| Rural/Urban | 1990 Population | 2000 Population | percent change | 2000 Population | 2010 Population | Percent Change |
| Lusaka Province | 991,226 | 1,391,329 | 40.4 | 1,391,329 | 2,191,225 | 57.5 |
| Rural | 167,213 | 258,327 | 54.5 | 258,327 | 336,318 | 30.2 |
| Urban | 824,013 | 1,133,002 | 37.5 | 1,133,002 | 1,854,907 | 63.7 |

In June of 2019, when this research was carried out, the urban population of Lusaka was estimated to be at 2,647,000 (Figure 6.14) which accounts for 14.8% of the total Zambia population estimated at 17, 681,000 (Figure 6.15). Of the total urban population of Lusaka, it is estimated that 1, 267,440 reside in and around the city area accounting for approximately 48% of the total Lusaka population. This population in and around the city area produces most of the waste that ends up in the landfill as a result of the efforts of the LCC and private companies that collect and dump the waste. From this population, the LCC estimates that only 40 percent of the waste generated is dumped in the landfill while 60 percent of waste is not collected and is either illegally dumped or burnt in back yards (Luke, 2017).

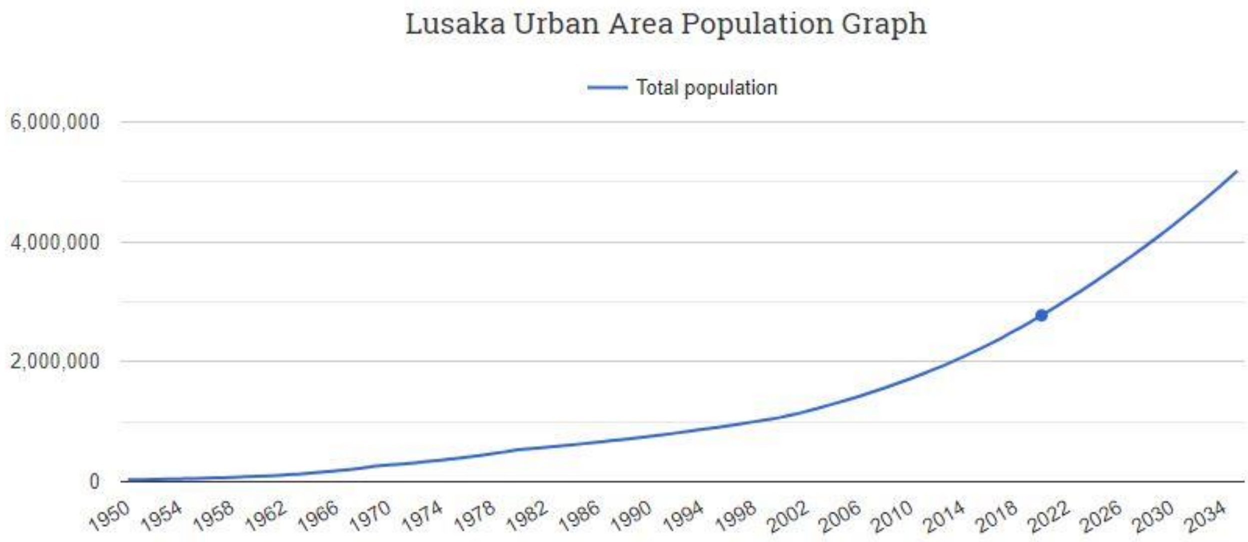


*Figure 6:12: Lusaka's Population growth from 1950 until present estimated at 2,647,000 (PopulationStats, 2020a).*

More than 75% of Lusaka's residents live in high density, unplanned peri-urban settlements commonly referred to a Compounds which as far back as the mid-90s did not have any form of waste collection systems and consequently, it is estimated that nearly 97% of solid waste produced in these compounds remains there and is disposed in uncontrolled dumpsites(W. Nchito & Myers, 2004). As of the year 2000, this situation had not changed significantly despite the increased populations owing to only 40% of waste ending up in the Chunga Landfill as observed by (Luke, 2017).

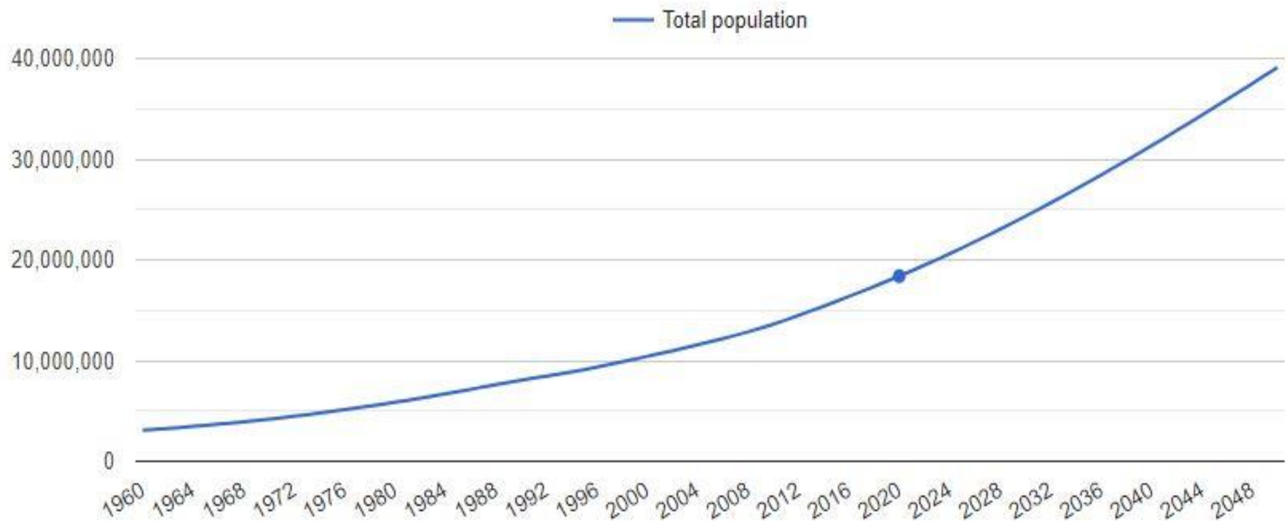


*Figure 6:13:Zambian populations population projections with a current estimation of 17,681,000 (PopulationStats, 2020b)*

The population projections for Lusaka in 2034, after 30 years the Chunga landfill being in operation, is estimated to be 5,183,000 which doubles the current population and certainly also increases the amount of waste production due to increased urbanization, industrialisation and economic development. The implications for solid waste disposal at landfills such as Chunga are increased volumes of waste within the next 14 years and the ability to deal with these huge sums of waste will depend on solid waste management strategies put in place. History however suggests that standards of solid waste management will not see any drastic improvement and that includes standards of landfill maintenance which has deteriorated in the last 13 years. In 1990, the population of the town of Lagos in Nigeria was estimated to be 5,067,000 and this city produced and estimated 786,079 tonnes of waste per year (Olorunfemi, 2011). With this benchmark for waste production compared to the population of an African city, it can be estimated that Lusaka will have the potential to produce equivalent volumes of waste with the projected population increase.

### *6.8. Challenges*

This research a has shown the potential for photogrammetry in SWM in both developed and developing countries. Chunga landfill is a site, researchers have carried out different studies on and yet this is the first-time photogrammetry was used to study the landfill. The major challenges to this study were getting approval from the Zambia Civil Aviation Authority (ZCAA) and finding a licensed drone pilot to capture Aerial images. Drone pilots are required to be licensed by the ZCAA and obtain a Remote Pilot Licence (RPL) which currently few drone pilots have, as this is a growing and expensive field. An application must be written to the ZCAA to obtain permission to fly drones in Lusaka and to gain access to the landfill I was required to applying to the LCC to obtain permission from the authorities. This process took approximately three weeks to get the ZCAA and LCC clearance and find a pilot licensed by ZCAA.

Access to recent documentation on waste volumes from the Lusaka City Council proved challenging. This is also attributed to the breakdown of the weigh bridge at the landfill making it difficult to obtain accurate data.

The photogrammetry process was not challenging as the software used was user friendly without any complications and however, calculating of Waste volume required interpolation to accommodate changes in topography. The Digital Surface Model did not provide a significant region that would be representative of the original landscape during the interpolation process. Interpolation was however important as without it, waste volumes would appear higher than reality and would result in inflated volumes.

# 7. CHAPTER SEVEN

## *7.1. Recommendations*

### 7.1.1 Landfill Maintenance

Based on my research, to reduce the risk to the community and the environment, management of Chunga Landfill need to consider improving slope maintenance to reduce it from current slope angles that range between 33- and 53-degree angles to the recommended angle for landfill slope stability of 11 to 14 degrees. This would increase slope stability and reduce the risk of waste collapse from slope failure. My research shows that waste slopes greater than 14 – degrees have a low Factor of Safety (FOS). The recommended FOS for landfills is 1.5 and Chunga landfill with waste slopes as steep as 53 – degrees interprets to a FOS considerably below the recommended standard.

Drainage maintenance at Chunga Landfill would be beneficial in reducing leachate production and reduce pollution of Chunga River and surrounding ground water. My research identified the presence of drainage streams that did not drain into the designated leachate storage reservoir. Several of these streams have been created naturally and are not engineered to optimize the landfill drainage system. These streams and rivulets have also weakened the structural integrity of the waste heap by creating cracks on the surface of the waste heaps. My research highlights the need for an effective drainage system by stating landfill disasters that have been the result of floods. Due to steep slopes, high waste volume and heavy rains, the Meethotamulla Landfill Disaster in Sri Lanka in 2017 resulted in the death of 36 people, including 4 children. Based on Zambia's climatic patterns, the clearing of the drainage system in preparations for rains are recommended between June and September, which are the dry seasons.

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. Management requires to put in a framework to deal with landfill fires that have burned continuously since 2013 causing up to 133 (Ha) smoke plumes according to my research. These fires may result from spontaneous combustion due to methane pocket in the waste heaps. 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.

Biannual monitoring is recommended at Chunga landfill using photogrammetry. This would allow for 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

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.

### *7.1.2. Solid waste Management*

My research shows that currently Lusaka only deposits 40 percent of waste into the Chunga landfill despite the over two million people population present in the urban city. This shows a gap in the waste management framework of the Lusaka City Council. Results show that this gap could be bridged by considering the following:

I) Investing in waste collection equipment and labour as a City Council to increase the percentage of waste collected within the city. The collection of a greater percentage of waste reduces the amount of waste that gets dumped and burn at undesignated locations.

II) Encouraging Small and Medium Enterprises to invest in the waste collection and disposal business. This increases the regions covered by waste collection enterprises allowing for the increased waste collection in Lusaka City. This also increases the capacity for waste collection by taking the pressure of the Lusaka City Council, the institution mandated with waste collection.

III) Encouraging public participation in waste management disposal at designated dump sites by providing incentives for waste separation and recycling to communities, institutions and business houses. This would improve waste sorting, recycling, reusing and reduce the amount of waste that ends up at landfills. The recyclable waste such as plastic, cardboard and glass at Chunga landfill is currently sorted by waste pickers. These individuals from vulnerable communities are at risk of being victims of landfill disasters such as, waste collapse, fire, smoke plume, and diseases. My research shows that waste picking despite being a way to earn a living have public health implications that could lead to injury, sickness or death.

## 7.2. CONCLUSIONS

This research has shown that Photogrammetry can be used as a tool for landfill risk assessment by creating a 3D model of Chunga landfill in Lusaka and analysing its geomorphology. The landfill that was constructed in 2007 currently contains a total volume of 751,815 cubic meters of waste with the highest waste heap standing at 18.82 meters above ground. For this research, the landfill was subdivided into Zones from A – E and was determined that waste heap at Zone A contained 74 percent of the waste at the dumpsite and was the highest. Slope angles were observed to have potential for slope failure and cause waste to collapse due to steep slope angles measured as steep as 53 degrees at Zones A and C. These slopes considerably exceed structural design recommendations for landfill slope stability at 11 – 14 degrees and thus prove to be a potential risk. Below the South western face of the Zone A waste heap, is an unofficial waste picking sorting station that lays in the path of a potential waste collapse.

Another potential cause for waste collapse has been identified as heavy rainfall or floods, which occur between November and March in Lusaka. Chunga landfill is designed with a leachate and rainwater drainage reservoir, yet drainage maps show drainage inefficiency as streams flowing from the South-east and East do not drain into this structure. The drainage pattern of the landfill shows that drainage occurs into the Chunga river, a freshwater body that is a part of Lusaka's ground water system flowing from the North – west of Lusaka, therefore polluting this river. Drainage challenges are mostly experience during the rainy season between November and March when Lusaka experiences up to 800mm of rainfall. Zone B of the landfill has several streams that are of the stream order 1 that flow North-East to combine and form Streams of order 2. This sequence of stream combinations continues until the main stream of order 4 is formed that flows at the western base of the largest waste heap on the landfill. Another major stream flows at the northern base of the waste heap flowing east also of the Order 4. The presence of these streams that constantly wash away the base of the landfill over time, creates cracks and rivulets that contribute to the weakening of the waste heap.

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 hectares to 143 hectares 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 and October and therefore, this time of the year results in a greater wind distribution of particulate matter.

Lusaka's Population is currently estimated at 2,647,000 and of the total waste produced, estimated at 1 million tonnes a year, only 40 percent is estimated to be collected and disposed at Chunga Landfill. This accounts for the low volume of waste determined to be disposed at the landfill over the 14 years it has been operational. Currently the landfill has a capacity of 11,613,341 $m^3$ which puts the amount of waste deposited at only 6.5%. The volume of waste produced by the Lusaka population is projected to double by 2034 as is the population and consequently the challenge of waste management is expected to be greater.

Waste pickers play a huge role in recycling inorganic waste and are estimated to account for nearly 980 tonnes per year of waste that is removed from the Landfill. Waste pickers at the landfill earn a living from picking recycling materials such as plastic, glass and cardboard that they sell to recycling companies. This occupation is considerably risky due to exposure to unstable waste slopes, landfill fires, smoke plume, leachate, water pollution and disease.

My research shows the potential for using cost effective technological solutions in Developing Countries. This method of Landfill analysis can be effective for landfill research and monitoring allowing for the adoption of practices to improve waste management. This research can be replicated in any country and can be improved by adopting a long-term monitoring approach of landfills using photogrammetry. This would provide insight into the geomorphological evolution of a Landfill and considerably reduce risk associated with landfilling and improve Solid Waste Management.

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