GROUNDWATER QUALITY
ASSESSMENT AT OLUSOSUN LANDFILL, LAGOS, NIGERIA

By

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We accept this thesis as conforming
to the required standard

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Abstract

An assessment of the groundwater quality at the Olusosun landfill in Lagos, Nigeria was conducted to determine interactions between the landfill wastes and the groundwater and the potential migration of pollutants into the neighbouring communities. Groundwater samples were collected from four locations within the landfill bi-weekly for three months (March 19, 2013 to May 28, 2013), and analysed for water quality parameters and metals. The results indicated that the concentrations of some metals (Cr, Fe, Cd, Mn, and Co) and other water quality parameters in some sampling locations were slightly above the World Health Organization (WHO) and the Nigerian Standard for Drinking Water Quality (NSDWQ) standard limits. Lead was also detected in the groundwater samples, though at concentrations within the standard limits. Conclusively, the Olusosun landfill has impaired groundwater quality, thereby, posing environmental and human health concerns to the neighbouring communities of Oregun, Ketu and Ojota.
# Table of Contents

Abstract......................................................................................................................................................... 2

Introduction ..................................................................................................................................................... 7
  Background .................................................................................................................................................. 7
  Objectives .................................................................................................................................................... 8

Research Question.......................................................................................................................................... 9
  Approach .................................................................................................................................................... 9

Literature Review ............................................................................................................................................ 10
  Potential Impacts of Landfills .................................................................................................................. 10
  Groundwater Contamination by Landfills ............................................................................................... 12

Metals and Water Quality Parameters ........................................................................................................ 14
  Chromium (Cr). ........................................................................................................................................... 14
  Iron (Fe). ...................................................................................................................................................... 14
  Cadmium (Cd). ............................................................................................................................................ 15
  Manganese (Mn). ....................................................................................................................................... 15
  Lead (Pb). ...................................................................................................................................................... 16
  Zinc (Zn). ..................................................................................................................................................... 16
  Cobalt (Co). ................................................................................................................................................ 16
  Copper (Cu). ............................................................................................................................................... 16
  Calcium (Ca). .............................................................................................................................................. 17
  Magnesium (Mg). ..................................................................................................................................... 17
  Nitrates. ......................................................................................................................................................... 17

Water Quality Parameters............................................................................................................................ 17

Study Area ..................................................................................................................................................... 18

Methodology .................................................................................................................................................. 20
  Field Sampling ......................................................................................................................................... 20
  Laboratory Analysis .................................................................................................................................. 24
  Data Evaluation ....................................................................................................................................... 24

Results and Discussion................................................................................................................................. 25
Metals .................................................................................................................................................... 25
Chromium (Cr). ......................................................................................................................................... 26
Iron (Fe). .................................................................................................................................................. 27
Cadmium (Cd). .......................................................................................................................................... 27
Manganese (Mn). .................................................................................................................................... 28
Lead (Pb). ................................................................................................................................................ 28
Zinc (Zn) and Copper (Cu). ..................................................................................................................... 29
Cobalt (Co). ............................................................................................................................................ 29
Calcium (Ca) and Magnesium (Mg). ........................................................................................................ 29
Water Quality Parameters ...................................................................................................................... 30
pH........................................................................................................................................................... 31
Dissolved Oxygen (DO). .......................................................................................................................... 31
Nitrates .................................................................................................................................................... 32
Total Dissolved Solids (TDS).................................................................................................................. 32
Comparison of Current Results with that of Oyeku and Eludoyin (2010) ............................................. 33
Conclusions and Recommendations ....................................................................................................... 34
Groundwater Quality and Potential Effects ............................................................................................ 34
Landfill Waste Management .................................................................................................................. 33
Recommendations .................................................................................................................................. 37
References ............................................................................................................................................... 39
Appendix A: Complete Data of Laboratory Result ............................................................................... 47
List of Figures

Figure 1: Map Showing the Site Location in Lagos, Nigeria.........................................................19

Figure 2: Map Showing Approximate Sample Locations and the Communities of Oregun, Ojota and Ketu..............................................................23

List of Tables

Table 1: Sampling Timeline.................................................................20

Table 2: Metals Concentration in Groundwater Samples...........................................24

Table 3: Descriptive Statistics of Metal Concentration in Groundwater Samples.............24

Table 4: Water Quality Parameters in Groundwater Samples........................................29

Table 5: Descriptive Statistics of Water Quality Parameters in Groundwater Samples.......29

Table 6: Descriptive Statistics of Metals and Other Water Quality Parameters in Oyeku and Eludoyin (2010).................................................................32
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Introduction

Background

Groundwater is the water located beneath the ground surface in soil pore spaces and in the fractures of rock formation (United States Geological Survey (USGS), 2009). Groundwater is the largest available source of fresh water as two thirds of global fresh water is found underground (Annenberg Learner, 2012). About two billion, people worldwide use groundwater and up to 80% of drinking water in Europe and Russia is groundwater (Earth Sciences for Society Foundation, 2005). Further, more than 50% of the United States population use groundwater for drinking (USGS, 2009). In Africa including Nigeria, a majority of the population rely on groundwater supplies for drinking and other household uses. Therefore, groundwater must be protected from contamination resulting from anthropogenic activities.

The intensity of human activities has led to increasing environmental pollution, which impacts negatively on environmental and human health. The pathways through which humans and other ecological entities are exposed to environmental pollutants include water, air, soil and plants. The mode of exposure is either by ingestion, inhalation, through the skin (dermal exposure) or a combination of two or all. Human activities which contaminate groundwater include landfill, mining, accidental spills of chemicals or waste materials, placement of septic and other tanks in hydrological and geological unstable locations, underground pipeline leakage, improper application of fertilizers and pesticides, among others (Lehr, 2002). Because groundwater is part of the hydrologic cycle, contaminants in other parts of the cycle, such as surface water, can be transferred into groundwater supplies (Groundwater Foundation, 2012). In the same vein, groundwater might contain some impurities even, if it is unaffected by human activities; the composition depends on the prevailing geology including the mineralogy of the
rock materials through which the groundwater migrates (Lenntech, 2011). Further, groundwater being part of the hydrologic cycle also plays a significant role in maintaining the surface water systems through flows into lakes and base flow into rivers; thereby, supporting the inflow needs of the surface water. These flows are often crucial for maintaining the biodiversity and habitats of sensitive ecosystems (Tharme, 2003).

Contaminated groundwater is unsafe for human consumption. The effects on any exposed populations can include sub-chronic toxicity, chronic toxicity and carcinogenicity, depending on the type of contaminants, leading to higher public expenditure on health care. In addition, surface water quality and the health of the aquatic organisms can be negatively affected when groundwater transfers contaminants to surface water through the hydrologic cycle.

Objectives

This study aims at assessing groundwater contamination at the Olusosun Landfill located in Lagos, Nigeria. The majority of the inhabitants of the communities of Oregun, Ojota and Ketu that surround the landfill rely on private boreholes as sources of portable water. Thus groundwater contamination originating from the landfill can potentially have negative environmental and human health impacts in the communities.

A study by Oyeku and Eludoyin (2010) indicated that the groundwater supplies of Oregun, Ojota and Ketu communities were contaminated with heavy metals including Cu, Fe, Cd, Pb, Mn, Zn and Co. They hypothesized that the landfill is the point source of the contamination, however, there could be other anthropogenic and non-anthropogenic sources. This study was therefore conducted to assess groundwater quality at the Olusosun Landfill, Lagos-Nigeria, with the following objectives.
• Determine if there are any interactions between the landfill waste and the groundwater; and

• Accept or reject the hypothesis that the landfill is a point source of groundwater pollution to the neighbouring communities.

Research Question

• What impact does the Olusosun Landfill has on groundwater quality in the nearby communities of Oregun, Ojota, and Ketu in Lagos State, Nigeria?

• Are there other potential sources of contamination?

• Are there any control measures that can be proposed to address any groundwater contamination problem identified in the study?

Approach

Groundwater samples were collected from existing boreholes at four locations within the landfill bi-weekly over a 3-month period (March 19, 2013 to May 28, 2013), and analysed for metals and other water quality parameters. The results obtained were compared to the Guidelines for Drinking Water Quality of the World Health Organization (WHO) (2011) and the Nigerian Standard for Drinking Water Quality (NSDWQ) (2007). Additionally, the data was compared to the groundwater chemistry in Oyeku and Eludoyin (2010).
Literature Review

Potential Impacts of Landfills

The International Waste Association defines Landfill as “the engineered deposit of waste onto or into land in such a way that pollution or harm to the environment is prevented, and through restoration of land provided which may be used for other purpose” (Bagchi, 1994). Landfills have the potential to create risks to the environment, including negative impacts on air, water and soil quality. Landfill sites are potential anthropogenic sources of groundwater and surface water pollution. Contaminants in wastes, which are not properly contained can leached and pollute water, (especially groundwater), during recharge when storm water infiltrates the landfill and percolates down through the wastes. Groundwater can also be polluted when it migrates horizontally through wastes in landfills. According to Al Sabhai, Abdul Rahim, Wan Zuhairi and Alshaebi (2009), the main problem associated with landfills is the formation of leachate and eventual contamination of groundwater and soil due to contaminant migration. Leachate outflow and infiltration is the most critical source of groundwater contamination from the existing landfills in Lagos State, Nigeria (Longe & Enekwechi, 2007).

Contaminated groundwater can impact surface water quality through interactions within the hydrologic cycle. Groundwater and surface water are connected by their transitional zone in a hydrologic continuum and contamination of one usually affects the other (United States Environmental Protection Agency (USEPA), 2000). Understanding contaminant fate and transport in this zone is important to risk assessments and water quality monitoring (USEPA, 2000). The soil through which contaminated water flows can be polluted when the soil adsorbs contaminants from the groundwater. In their study, Gharaibeh, Awad and Riad (1989), indicated the possibility of groundwater, surface water, and soil pollution by landfill leachate plume in the
El-Akader region of North Jordan. Plants that are grown in contaminated soils can absorb contaminants from the soils by root uptake, whilst contaminants in the soil can be transferred to soil organisms through ingestion, inhalation, or dermal. Humans can be exposed to contaminants through the ingestion of plants, which grow on contaminated soils, and or through the ingestion of animals such as cattle or other ungulates, which feed on contaminated plants, as well as through the inhalation of particulates from the contaminated soil. Contaminants can also be transferred between species in the food chain through the process of bio-magnification.

The impact of any landfill on groundwater quality depends on various factors, including the composition of the waste, degree of compaction, amount of leachate, and climate, which dictates the pattern of rainfall that prevails in the landfill region. The impact is also dependent on the hydraulic gradient or the flow system, the geology of the underneath material (Akoteyon, 2012) and soil composition. For instance, the soil stratigraphy at the Solus landfill in the Alimoso Local government area of Lagos State-Nigeria, consisting of clay and silty clay appears to have significantly influenced contaminants leachability resulting in low contaminant concentrations in groundwater (Longe & Balogun, 2010). Other important factors that affect the fate and transport of groundwater contaminants include solubility of the contaminants and the chemistry of the groundwater including the pH.

Groundwater monitoring is an important aspect of sustainable landfill management. It provides water quality data that can be used to either meet leachate discharge guidelines or develop remediation goals. Groundwater pollution can be detected early and the potential human and environmental risks can be managed when groundwater monitoring and an iterative risk assessment is incorporated into the environmental management plans (EMPs) of landfills. Once groundwater is contaminated it is difficult to remediate due to accessibility (Eshiet &
Agunwamba, 2012). According to Yenigul et al. (2005), ideal site selection and engineering designs of landfills are not the solutions for stopping the leakages of leachate plumes into groundwater. Therefore, iterative groundwater monitoring is necessary, irrespective of the ideal site selection and the engineering design of a landfill. More so, continuous groundwater monitoring enables the management of a landfill to be aware of any pollution from its outset and thus provides the opportunity to remediate the pollution before it becomes pandemic. Especially, if that groundwater is known to be the major source of water supply in Lagos State, Nigeria including the study area and its contamination would pose environmental and human health risks.

According to Akoteyon (2012), the global increase in the demand for fresh water due to rapid growth in the population and accelerated pace of industrialization has made groundwater risk assessment imperative at Landfills. Moreover, groundwater monitoring or risk assessment conforms to the normative principles of sustainability, which includes the precautionary principle and equity (Bosselmann, Engel, & Taylor, 2008). Groundwater monitoring should be done by collecting and analysing groundwater samples from the wells that are within the immediate vicinity of the landfill. However, if there are no wells, which are within the immediate vicinity of the landfill, monitoring wells should be installed at strategic locations within the landfill. A network of wells is of vital importance in detecting leakage plumes of landfill leachate (Yenigul et al., 2005).

Groundwater Contamination by Landfills

The contamination of groundwater by landfill leachate has been documented (Longe & Enekwechi, 2007; Longe & Balogun, 2010; Akoteyon, 2012; Akinbile & Yusoff, 2011; Eshiet &
Agunwamba, 2012; Chian & Dewalle, 1976). Groundwater near the Anoliosia Landfill in the Attics Region, Greece was found to be not portable and unsuitable for irrigation water (Fatta, Papadopoulos & Loizidou, 1999). Private wells located 300m downstream from the Liangollu Landfill in New Castle County in Delaware were heavily polluted and subsequently abandoned (Chian & DeWalle, 1976).

Studies in Nigeria have also shown impairment in groundwater quality through leachates outflow and infiltration from landfills (Longe & Enekwechi, 2007). Analytical results from groundwater samples taken from wells near the Solus Landfill site in Alimosho Local Government Area of Lagos State, Nigeria indicated that the groundwater had been moderately impacted with a mean pH value of 6.13 (Longe & Balogun, 2010). Akoteyon (2012) conducted studies at Landfills in Igando, Lagos-Nigeria and concluded that groundwater quality had been greatly impacted; heavy metal concentrations in the groundwater samples collected from three landfills were high. Cadmium accounted for about 23.3% of the groundwater contamination, while lead and copper accounted for 19.3 and 8.8% respectively. Groundwater near a municipal landfill in Akure, Ondo State, Nigeria, was also found to be contaminated with iron, lead, zinc and chromium (Akinbile & Yusoff, 2011). Also in Owerri, Imo State, Nigeria, the Avu dumpsite at the Owerri-Port Harcourt expressway was found to have a significant adverse effect on the surrounding soil and water environment (Eshiet & Agunwamba, 2012). Finally, according to Longe and Balogun (2010), there are no properly designed solid waste facilities in Lagos State, Nigeria and inadequate solid waste management is a major environmental problem. The contributing factors include lack of technical skills, and financial and institutional constraints.
Metals and Water Quality Parameters

Metals including Cr, Fe, Cd, Mn, Zn, Co, Cu, Ca, Mg and other parameters such as pH, Dissolved Oxygen (DO), Total Dissolved Solids (TDS) and Nitrate were analysed in this study in order to assess groundwater quality at the Olusosun Landfill. The metals and parameters were selected based on their potential harmful effects on environmental and human health and because Landfills are potential anthropogenic sources of their introduction into the environment. In order to protect public health, jurisdictions such as WHO (2011), USEPA (2011), have published contaminant limits above which concentrations in water, air and soil have the potential to impact human and environmental health.

Chromium (Cr).

Chromium was discovered in 1797, in France by Louis Nicholas Vauquelin. It has a specific gravity (SG) of 7.19 (WebElement, 2012). Chromium is not found naturally as a free metal. Its most common ore is chromite ore (FeCr$_2$O$_4$), which is found in countries including Turkey, United States of America, and South Africa. Chromium metal is produced by the reduction of the ore. Chromium is used to harden steel, to manufacture stainless steel and to form alloys. It is also used to give glass an emerald green colour and in the textile and aeronautic industries (WebElement, 2012). Chromium compounds are regarded as highly toxic.

Iron (Fe).

Iron is a metal with a SG of 7.874. Iron is the fourth most abundant element in the Earth’s crust and its common natural source is hematite Fe$_2$O$_3$ and magnetite (Fe$_3$O$_4$); the ore from which iron metal is extracted. Iron has a lot of applications in industries and plays important roles in biology.
Cadmium (Cd).

Cadmium and its compound are extremely toxic. It has an SG of 8.7. Exposure to cadmium is known to cause cancer and targets the body’s cardiovascular, renal, gastrointestinal, neurological, reproductive, and respiratory systems (United States Department of Labor, 2013). Cadmium is soluble in acids but not in alkali. Cadmium industrial waste streams including those emanating from Landfill leachates mainly end up in soils. Sources of cadmium into waste streams include zinc production, battery production, phosphate ore extraction and industrial manure (Lentech, 2013). Cadmium may also enter the air through waste combustion and burning of fossil fuels. Human exposure to cadmium is mainly through food. People who smoke and those who live close to hazardous landfills have higher exposure to cadmium.

Manganese (Mn).

Manganese is a metal that resembles iron. It is hard and very brittle, thereby, essential in metallurgical production. The iron and steel industry accounts for 85% to 90% of its total demand (USGS, 2013). End uses of manganese include construction products, machinery, transportation, aluminium alloys and dry cell batteries. Non-metallurgical uses include plant fertilizers, animal feed, and colorants for brick (USGS, 2013). Manganese compounds are less toxic when compared with other popular metals, such as copper and nickel (Hasan, 2008).

Lead (Pb).

Lead is regarded as an heavy metal, which can be poisonous to animals including humans at very small concentrations. Lead is usually found in ore together with other metals including silver, copper, zinc and gold. The main lead mineral is galena (PbS), which accounts for 86.6%
lead by weight. Much of human exposure to lead comes from anthropogenic activities including mining, use of fossil fuels, leaded gasoline and paint, and landfills.

**Zinc (Zn).**

Zinc is a metallic element and the 24th most abundant element in the Earth’s crust. The most common zinc ore is Sphalerite (ZnS). Its major applications include galvanising and alloys. Zinc is an essential mineral with exceptional biologic and public health importance. However, concentrations in humans above the optimum level can be toxic and can result to adverse biological effects.

**Cobalt (Co).**

Cobalt is a ferromagnetic metal with an S.G of 9, (WebElement, 2012). Corbett, erythrite, glaucodot and skutterudite are the main ores of cobalt, but most cobalt is obtained not by active mining of cobalt ores, but rather by reducing cobalt compounds that occur as by-products of nickel and copper mining activities (Shedd, 2008). Cobalt is a strategic mineral used in diverse commercial, industrial, and military applications (Shedd, 2008). Cobalt has beneficial biological effects, but excess concentrations can damage the human health. Human exposure to cobalt is through the air, water, and food.

**Copper (Cu).**

Copper is a reddish metal with an S.G of 8.9. It is a good conductor of heat and electricity. The electrical industry uses 60% of the world copper production, while the construction industry, industrial machinery, and alloys account for 20%, 15% and 5% respectively (Lenntech, 2013). Copper has beneficial biological effects in human.
body system can handle large concentrations of copper, but the ingestion of more than 15mg of copper has been reported to be toxic to humans (Health Canada, 2006).

**Calcium (Ca).**

Calcium is an alkaline metal with an SG of 1.55. It is the fifth most abundant element by mass in the Earth’s crust. Calcium is not found naturally as an element. It is usually in mineral compounds such as Calcium carbonate (CaCO₃), Calcium chloride (CaCl₂), and Calcium carbide (CaC₂). Calcium is used for the production of cement and as a reducing agent in the extraction of other metals. It is also an important element in human physiology.

**Magnesium (Mg).**

Magnesium is also an alkaline metal with an SG of 1.74. It is the eight most abundant element in the Earth’s crust. Magnesium cannot be found naturally in its elemental state, but in mineral compounds such as magnesite (MgCO₃) and dolomite CaMg(CO₃)₂. Magnesium plays vital roles in all living organisms and its deficiency in humans can result into adverse health effects.

**Nitrates.**

Nitrates are nitrogen-oxygen chemical units, which combine with various organic and inorganic compounds and its greatest use is for the production of fertilizer (USEPA, 2012). The major route of exposure of nitrates to humans is water.

**Water Quality Parameters.**

pH, DO, and TDS of the landfill’ groundwater were analysed in this study because of the vital roles they play in contaminant characteristics and behaviour. pH is a measure of the
groundwater acidity and it influences the fate and transport including the leachability of contaminants. DO is a measure of the dissolved oxygen in groundwater, while TDS is a measure of the solids such as metals, which are dissolved in the groundwater. The TDS in a water solution has a linear relationship with its conductivity.

**Study Area**

The Olusosun landfill, which began operation in 1992, is located at Oregun in Lagos State, Nigeria. The landfill size is 42.7 hectares (Lagos Waste Management Authority (LAWMA), 2011), and it is situated about 10km South East of Ikeja Local Government Area, and between 6°23’N; 2°42’E and 6°41’N; 3°42’E (Oyeku & Eludoyin, 2010). The estimated lifespan of the landfill is 20 years. The communities of Oregun, Ojota and Ketu bound the landfill.
Figure 1: Map showing the site location in Lagos, Nigeria
The majority of the inhabitants of the communities that bound the landfill rely on private boreholes as sources of potable water, owing to lack of or inadequate supplies of public water. Lagos State is the commercial capital of Nigeria with a population of more than 17 million and annual growth rate of 3.2% (Lagos State Government, Nigeria, 2011). Because of the high human population, the state generates large volume of waste daily. The Olusosun Landfill site receives approximately 40% of the total waste deposits (LAWMA, 2011). The Lagos Waste Management Authority (LAWMA) manages the landfill, which receives unprocessed wastes of all types, ranging from organic to inorganic and hazardous to non-hazardous wastes. The wastes include batteries, unserviceable electronics and computers, household cleaners, industrial wastes, pharmaceuticals and personal care products (PPCPs), among others. The landfill does not have any protective bottom layer constructed to protect leachate plumes from migrating into groundwater and its average depth is about 9 m.

The hydrology of Olusosun Landfill is part of the hydrology of the Lagos metropolis. The subsurface lithology comprises of an alternating sequence of sand and clay deposits (Longe et al., 1987). Further, according to Longe et al. (1987), three aquifer horizons are the sources of groundwater in the Lagos Metropolis; the first is a water-table with an average thickness of 8 m, which is mostly harvestable through dug wells. The other two are confined aquifers with thickness of 10-25 m and 10-35 m respectively and are harvested through boreholes.

**Methodology**

**Field Sampling**

In an effort to determine if there is any groundwater contamination from the Olusosun landfill and following approval to conduct this study by the Lagos Waste Management Authority
(LAWMA), groundwater samples were collected from boreholes at four locations within the landfill at regular intervals (bi-weekly) for a period of three months (March 19, 2013 to May 28, 2013). The sampling timeline is shown in Table 1.

**Table 1: Sampling timeline**

<table>
<thead>
<tr>
<th>Samples</th>
<th>Date</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>First batch</td>
<td>19&lt;sup&gt;th&lt;/sup&gt; March, 2013</td>
<td>1.15 pm</td>
</tr>
<tr>
<td>Second batch</td>
<td>2&lt;sup&gt;nd&lt;/sup&gt; April, 2013</td>
<td>1.55 pm</td>
</tr>
<tr>
<td>Third batch</td>
<td>16&lt;sup&gt;th&lt;/sup&gt; April, 2013</td>
<td>2.10 pm</td>
</tr>
<tr>
<td>Fourth batch</td>
<td>30&lt;sup&gt;th&lt;/sup&gt; April, 2013</td>
<td>1.30 pm</td>
</tr>
<tr>
<td>Fifth batch</td>
<td>14&lt;sup&gt;th&lt;/sup&gt; May, 2013</td>
<td>12.45 pm</td>
</tr>
<tr>
<td>Sixth batch</td>
<td>28&lt;sup&gt;th&lt;/sup&gt; May, 2013</td>
<td>1.25 pm</td>
</tr>
</tbody>
</table>

The sampling points were existing boreholes that were designated as Bh1, Bh2, Bh3, and Bh4, and were located close to each of the four perimeters or the boundaries of the landfill (Figure 2). The boreholes were of small diameter and they were installed with the aid of mechanical drilling rigs. According to Longe et al. (1987), the second aquifer horizon is the major source of portable and industrial water in the Ikeja area of Lagos State, Nigeria, including the study area and exists within the depth of 20 m and 70 m. The aquifer has been reported to have average values of transmissivity and storage coefficient of 1120 m<sup>2</sup>/day and 3.77 x 10<sup>4</sup> respectively (Longe, 2011). The coordinates and the surface elevations of the sampling boreholes, which were taken with a Garmin GPS 76 are as follows:

Bh1: N 06° 35.788' E 003° 22.739'. Elevation: 49.5 meter.
Bh2: N 06° 35.458'E 003° 22.504'. Elevation: 25.4 meter.

Bh3: N 06° 35.690'E 003° 22.482'. Elevation: 23.9 meter.

Bh4: N06° 35.384'E 003° 22.934'. Elevation: 30.5 meter.

Water samples were pumped out of the bore holes with electrical pump. Fresh water samples were collected in plastic bottles, which were properly labelled. Prior to the collection of the groundwater samples, the containers were washed and rinsed with clean water, in order to maintain the integrity of the water samples.
Figure 2: Map showing approximate sample locations and the communities of Oregun, Ojota, and Ketu
Laboratory Analysis

Groundwater samples were taken on the same day of collection to the University of Lagos (UNILAG) chemistry laboratory where they were analysed for metals with Atomic Absorption Spectrometer (AAS) (Perkin Elmer A Analyst 200). Samples were preserved at 4°C and analysis was carried out within seven days of sample collection.

Metal analysis was carried out by taking 50 ml of the water sample into a 250 ml conical flask, 10 ml of aqua regia was added and the mixture was evaporated on a hot plate in the fume cupboard to dryness. The sample was reconstituted with 25 ml of deionised water and filtered with a filter paper and funnel for AAS metal analysis. The metals that were analysed include Iron (Fe), Cadmium (Cd), Manganese (Mn), Lead (Pb), Zinc (Zn), Chromium (Cr), Copper (Cu), Cobalt (Co), Calcium (Ca), and Magnesium (Mg).

Other water quality parameters analysed include total dissolved solids (TDS), pH, Nitrate (N), and Dissolved oxygen (DO). pH was analysed with a standard pH meter (Jenway 3520). DO was analysed with a Jenway 3420 Electrochemistry Analyzer and TDS was done with a model DDS -307 Conductivity Meter. Nitrate was analysed with Hatch 2000 Spectrometer.

Data Evaluation

The results obtained were compared to the groundwater chemistry of the neighbouring communities of Oregun, Ketu and Ojota, which were reported by Oyeku and Eludoyin (2010) and the water quality guidelines of the World Health Organization (WHO) (2011), and the Nigerian Standard for Drinking Water Quality (NSDWQ) (2007). Descriptive statistical analysis was conducted using Microsoft Excel 2010.
Results and Discussion

Metals

The mean concentrations of metals in the groundwater samples, over the three months are shown in Table 2 while Table 3 shows the descriptive statistics. Additionally, the WHO water quality guideline and the maximum permitted levels of the NSDWQ are included in Table 2 for comparison. The complete data set is provided in Appendix A.

Table 2: Mean Metals Concentration (mg/l) in Groundwater Samples

<table>
<thead>
<tr>
<th>Sample</th>
<th>Cr</th>
<th>Fe</th>
<th>Cd</th>
<th>Mn</th>
<th>Pb</th>
<th>Zn</th>
<th>Co</th>
<th>Cu</th>
<th>Ca</th>
<th>Mg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bh1</td>
<td>0.021</td>
<td>0.461</td>
<td>ND</td>
<td>0.217</td>
<td>ND</td>
<td>0.146</td>
<td>0.057</td>
<td>0.041</td>
<td>5.669</td>
<td>25.498</td>
</tr>
<tr>
<td>Bh2</td>
<td>0.039</td>
<td>0.440</td>
<td>0.005</td>
<td>0.408</td>
<td>0.006</td>
<td>0.204</td>
<td>0.077</td>
<td>0.051</td>
<td>7.045</td>
<td>41.735</td>
</tr>
<tr>
<td>Bh3</td>
<td>0.058</td>
<td>0.916</td>
<td>ND</td>
<td>0.259</td>
<td>0.01</td>
<td>0.156</td>
<td>0.051</td>
<td>0.047</td>
<td>12.774</td>
<td>74.348</td>
</tr>
<tr>
<td>Bh4</td>
<td>0.013</td>
<td>0.404</td>
<td>ND</td>
<td>0.177</td>
<td>ND</td>
<td>0.086</td>
<td>0.063</td>
<td>0.043</td>
<td>11.295</td>
<td>91.270</td>
</tr>
<tr>
<td>NSDWQ</td>
<td>0.05</td>
<td>0.3</td>
<td>0.003</td>
<td>0.2</td>
<td>0.01</td>
<td>3.0</td>
<td>NS</td>
<td>NS</td>
<td>1.0</td>
<td>75</td>
</tr>
<tr>
<td>WHO</td>
<td>0.05</td>
<td>0.3</td>
<td>0.003</td>
<td>0.05</td>
<td>0.01</td>
<td>NS</td>
<td>NS</td>
<td>2.0</td>
<td>75</td>
<td>50</td>
</tr>
</tbody>
</table>

*Note.* NSDWQ Values are the maximum permitted levels in the Nigerian Standards for Drinking Water Quality, ND- Not detected, NS- Not supplied. WHO values are the maximum permitted levels in the WHO Drinking Water Quality Guideline.
Table 3: Descriptive Statistics of Metal Concentrations in Groundwater Samples

<table>
<thead>
<tr>
<th>Parameters (Mg/l)</th>
<th>Range</th>
<th>Mean</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chromium (Cr)</td>
<td>0.009 – 0.0175</td>
<td>0.0327</td>
<td>0.039</td>
</tr>
<tr>
<td>Iron (Fe)</td>
<td>0.124 – 2.46</td>
<td>0.5547</td>
<td>0.499</td>
</tr>
<tr>
<td>Cadmium (Cd)</td>
<td>0.004 – 0.007</td>
<td>0.0053</td>
<td>0.001</td>
</tr>
<tr>
<td>Manganese (Mn)</td>
<td>0.12 – 0.419</td>
<td>0.2651</td>
<td>0.110</td>
</tr>
<tr>
<td>Lead (Pb)</td>
<td>0.003 – 0.02</td>
<td>0.0080</td>
<td>0.0063</td>
</tr>
<tr>
<td>Zinc (Zn)</td>
<td>0.049 – 0.266</td>
<td>0.1478</td>
<td>0.0659</td>
</tr>
<tr>
<td>Cobalt (Co)</td>
<td>0.025 – 0.084</td>
<td>0.0620</td>
<td>0.0148</td>
</tr>
<tr>
<td>Copper (Cu)</td>
<td>0.036 – 0.058</td>
<td>0.0455</td>
<td>0.0061</td>
</tr>
<tr>
<td>Calcium (Ca)</td>
<td>4.008 – 16.833</td>
<td>9.195</td>
<td>3.356</td>
</tr>
<tr>
<td>Magnesium (Mg)</td>
<td>22.5 – 97.92</td>
<td>58.212</td>
<td>27.835</td>
</tr>
</tbody>
</table>

Chromium (Cr).

The results (Table 2) show that chromium (Cr) concentrations in all the sampling locations except BH3 were within the limit of the WHO guidelines and the NSDWQ. The mean Cr concentration in Bh3 which was 0.058 mg/l, was slightly above the 0.05 mg/l guideline/standard. The toxicity of chromium compounds depends on the oxidation state of the metal. Exposure to chromium (VI) compounds have been associated with lung cancer while chromium (III) is an essential element, which can be toxic at high doses (Agency for Toxic Substances and Disease Registry (ATSDR), 2008). Chromium plays a role in how insulin helps the body regulate blood sugar levels (University of Maryland Medical Centre, 2011). Its
deficiency in the human body has been associated with diabetes, infertility and cardiovascular disease (ATSDR, 2008).

**Iron (Fe).**

Iron (Fe) concentrations in all the sampling points were higher than both WHO guideline and the NSDWQ maximum acceptable concentration of 0.3mg/l indicating that the groundwater in the landfill is contaminated with iron. The average Fe concentration of 0.9 mg/l in sampling point Bh3 was exceptionally high. This elevated concentration may be due to the proximity of the sampling point to the active portion of the landfill where waste deposition is ongoing and the waste is yet to be covered with topsoil. This portion is more prone to water percolation and contaminant leaching during precipitation owing to the exposure of the landfill wastes. However, the average Fe concentration of 0.9 mg/l does not pose potential health risk since the recommended dietary allowance for iron is between 7mg and 18mg per day, depending on age and gender and as such several litres of water would need to be consumed per day before toxicity could occur (Livestrong.com, 2013). Though, iron in water does not pose a potential risk to human health, concentrations above the standard limit of 0.03mg/l can cause food and water to become discoloured. In the same vein, water with high iron concentrations is not ideal for washing because it would stain whatever it has contact with (Livestrong.com, 2013).

**Cadmium (Cd).**

Cadmium (Cd) was detected at only one of the sampling points (Bh2) where the average concentration was 0.005 mg/l. This was slightly above the NSDWQ limit of 0.003 mg/l, but within the maximum contaminant level (MCL) of 0.005 mg/l in other jurisdictions, such as United States Environmental Protection Agency (USEPA), (USEPA, 2013) and Canadian...
Drinking Water Quality Guideline (2012). According to the Nova Scotia Environment (2008), exposure to high levels of cadmium can cause gastrointestinal discomfort and kidney damage. Water with cadmium concentrations above 0.005 mg/l should not be used for drinking, cooking and tooth brushing. The presence of cadmium in water samples from Bh2 may be attributed to the proximity of the sampling point to the active portion of the landfill where deposition of wastes is on-going.

**Manganese (Mn).**

Manganese (Mn) concentrations in all the sampling points were within the NSDWQ maximum permissible value of 0.2 mg/L, except in sampling point Bh2 where the average concentration was 0.4mg/L. There is currently no WHO guideline for manganese. The World Health Organization, discontinued the drinking water quality guideline for manganese in 2011 (WHO, 2011) since the previous guideline (0.4mg/L) was well above manganese normally found in drinking water (NCBI, 2012).

**Lead (Pb).**

Lead was not detected in samples from Bh1 and Bh4 while the average concentrations in Bh2 and Bh3 were 0.006 mg/L and 0.01 mg/L respectively. These concentrations were within the WHO guideline and the NSDWQ permissible concentration of 0.01 mg/L. The lead detected in groundwater samples originated from used batteries and other lead bearing wastes in the landfill.
**Zinc (Zn) and Copper (Cu).**

Zinc (Zn) concentrations in groundwater samples were all below the NSDWQ maximum permissible limit of 3 mg/L. WHO does not have any standard limit for Zn. Copper (Cu) concentrations detected in groundwater samples were also negligible and below the WHO and the NSDWQ standard limits of 2.0 mg/L and 1.0 mg/L respectively. Therefore, zinc and copper concentrations in groundwater did not present any drinking water concerns. Zinc is beneficial to human and other ecological entities. However, at higher concentrations zinc can be toxic to the biological system of humans. Additionally, excessive zinc concentrations in soil results in phyto-toxicity, which reduce plant survival and biodiversity. Sources of Zn and Cu include wastes such as batteries, electronics, alloys, electroplating and automotive parts. Zinc and copper have limited mobility in soil, and anthropogenic impacts to groundwater are small (MPCA, 1999).

**Cobalt (Co).**

The mean cobalt concentrations in groundwater, which was observed in all the sampling points ranged from 0.050- 0.077 mg/L. Cobalt is an essential element for the growth of marine algal species including chrysophytes, and Dino flagellates (Bruland, Donat, & Hutchins, 1991). Cobalt has also been shown to enhance growth of some plants at low concentrations but at higher concentrations, cobalt is toxic to humans and to other ecological entities including plants (Nagpal, 2004).

**Calcium (Ca) and Magnesium (Mg).**

Calcium and magnesium concentrations in groundwater samples from all the sampling points were very low. Calcium and magnesium do not pose potential adverse health effects in drinking water. Therefore, no health based guideline values were proposed for calcium and magnesium in the WHO water quality guidelines (WHO, 2011). The presence of both ions in
water increases its hardness, which results in the use of more soaps than what is necessary for bathing and washing. Both Calcium and magnesium are beneficial to human health, past epidemiological studies have supported the hypothesis that extra magnesium and or calcium in drinking water can contribute to reduced cardiovascular disease and other health benefits in populations (WHO, 2009).

**Water Quality Parameters**

The average pH and the other average concentrations of water quality parameters including DO, TDS, are given in Table 4 while descriptive statistics are shown in Table 5. The complete data set is provided in Appendix A.

**Table 4: Water Quality Parameters in Groundwater Samples**

<table>
<thead>
<tr>
<th>Sample</th>
<th>pH</th>
<th>Dissolved Oxygen (DO) (mg/L)</th>
<th>Total Dissolved Solids (TDS) (mg/L)</th>
<th>Nitrates (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bh1</td>
<td>5.665</td>
<td>0.527</td>
<td>89</td>
<td>9.25</td>
</tr>
<tr>
<td>Bh2</td>
<td>5.855</td>
<td>0.655</td>
<td>508.5</td>
<td>14.75</td>
</tr>
<tr>
<td>Bh3</td>
<td>5.480</td>
<td>0.698</td>
<td>207.125</td>
<td>14</td>
</tr>
<tr>
<td>Bh4</td>
<td>5.502</td>
<td>0.493</td>
<td>220</td>
<td>66</td>
</tr>
<tr>
<td>NSDWQ</td>
<td>6.5-8.5</td>
<td>NS</td>
<td>500</td>
<td>50</td>
</tr>
<tr>
<td>WHO</td>
<td>6.5-8.5</td>
<td>NS</td>
<td>500</td>
<td>50</td>
</tr>
</tbody>
</table>

Notes:
NSDWQ Values are the maximum permitted levels in the Nigerian Standards for Drinking Water Quality
NS - Not supplied.
WHO values are the maximum permitted levels in the WHO Drinking Water Quality Guideline.
Table 5: Descriptive Statistics of Water Quality Parameters in Groundwater Samples

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Range</th>
<th>Mean</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>5.480 - 5.855</td>
<td>5.626</td>
<td>0.296</td>
</tr>
<tr>
<td>Dissolved Oxygen (DO) (mg/L)</td>
<td>0.493 - 0.698</td>
<td>0.5935</td>
<td>0.135</td>
</tr>
<tr>
<td>Total Dissolved Solids (TDS) (mg/L)</td>
<td>89 - 508.5</td>
<td>256.0</td>
<td>167.406</td>
</tr>
<tr>
<td>Nitrates (mg/L)</td>
<td>9.25 - 66</td>
<td>26.0</td>
<td>28.381</td>
</tr>
</tbody>
</table>

The pH of groundwater indicated acidic conditions and this could be attributed to metal contaminants albeit at low concentrations. pH is one of the factors which influence the fate and the transport of contaminants in the environment. Increasing acidity (low pH) can cause some metals and nutrients to dissolve in water thereby releasing toxic elements that may pollute groundwater. Conversely, decreasing acidity (high pH) can cause certain nutrients to become insoluble and thereby unavailable for plant growth. When the soil pH is greater than 7.5 calcium can tie up phosphorus, making it less available to plants (Lake, 2000). Depending on other factors such as solubility, contaminants leaching and groundwater contamination is enhanced in the low-pH wastes in the Olusosun landfill. Most jurisdictions including USEPA (2013), and NSDWQ (2007) allow the pH of water to fall between 6.5 and 8.5.

**Dissolved Oxygen (DO).**

Dissolved oxygen (DO) is an important factor used for water quality control. The DO in the groundwater samples from all the sampling points was below 1.0 mg/L, indicative of low
oxygen levels in the groundwater that is emanating from the landfill. There is no drinking water quality guideline for DO. However, a good level of dissolved oxygen is essential for aquatic life since they are put under stress when the DO in water drops below 5mg/L (Lenntech, 2012). Oxygen levels, which remains below 1-2 mg/L for a few hours can result in fish kills (Lenntech, 2012). Oxygen enters streams and surface water from the atmosphere and from groundwater discharge. Therefore, the contribution of oxygen from groundwater discharge is significant in areas where groundwater supplies the inflow needs of surface water (USGS, 2013).

**Nitrates.**

Nitrate concentrations in the groundwater samples except in sampling point Bh4, were within the WHO guidelines and NSDWQ maximum permissible limits. Sample Bh4 had an average nitrate concentration of 66 mg/L, which was above the permissible limit of 50 mg/L. The elevated nitrate concentration in Bh4 was not consistent with the detected concentrations in other sampling points, which ranged from 9.25 - 14.75 mg/L. Groundwater from landfills can transfer its excessive nitrate contents to surface water, which can result in eutrophication. Further, high nitrate levels in water can interfere with the ability of the red blood cells in humans to transport oxygen (Wheatley River Improvement Group (WRIG),(2013) and can also cause methemoglobinemia or blue baby syndrome, a condition found especially in infants under six months (Self & Waskom, 2013).

**Total Dissolved Solids (TDS).**

The total dissolved solids (TDS) in the groundwater samples, except Bh2 were lower than the WHO guideline and NSDWQ maximum permissible limit of 500 mg/L (Table 4). All the
values indicated pollution of groundwater by dissolved chemical constituents including toxic metals.

**Comparison of Current Results with that of Oyeku and Eludoyin (2010)**

Table 6 is the statistical analysis of the chemistry of the groundwater in the nearby communities of Ojota, Ketu and Oregun, which was evaluated by Oyeku and Eludoyin (2010). Table 6 was compared with Table 3 which is the descriptive statistics of metal contaminants found in groundwater samples, which were analysed, in this study. The purpose of the comparison was to confirm the hypothesis of Oyeku and Eludoyin (2010), that the landfill is the point source of the groundwater pollution in the listed communities.

**Table 6: Descriptive Statistics of Metals and Other Water Quality Parameters in Oyeku and Eludoyin (2010).**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Mean ± Standard Deviation</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>PH</td>
<td>8.30 ± 2.77</td>
<td>3.2 – 12.4</td>
</tr>
<tr>
<td>Copper(Cu) (mg/L)</td>
<td>0.02 ± 0.04</td>
<td>≤ 1 – 3.3</td>
</tr>
<tr>
<td>Iron(Fe) (mg/L)</td>
<td>4.23 ± 6.40</td>
<td>≤ 1 – 21.4</td>
</tr>
<tr>
<td>Lead(Pb) (mg/L)</td>
<td>2.40 ± 3.30</td>
<td>≤ 1 – 14.8</td>
</tr>
<tr>
<td>Zinc(Zn) (mg/L)</td>
<td>0.04 ± 0.06</td>
<td>≤ 1 – 0.23</td>
</tr>
<tr>
<td>Cobalt(Co) (mg/L)</td>
<td>1.03 ± 1.10</td>
<td>≤ 1 – 3.3</td>
</tr>
</tbody>
</table>

As shown in Tables 3 and 6, the metal contaminants detected in the surrounding communities’ groundwater samples by Oyeku and Eludoyin (2010) were also found in this study. However, Oyeku and Eludoyin (2010), recorded higher concentrations of Fe, Pb and Co in their study. According to Oyeku and Eludoyin (2010) the mean concentrations of these metal
contaminants were 4.23, 2.4 and 1.03 mg/L respectively, compared to the values recorded in this study, which were 0.555, 0.008 and 0.060 mg/L, respectively. As a result, this study presumes that the Olusosun landfill may not be the only source of groundwater pollution in the Ojota, Ketu and Oregun communities. The elevated metal concentrations in groundwater outside the landfill, which was recorded by Oyeku and Eludoyin (2010), suggested the possibility of co-polluting sources such as the paint and the plastic industries in Oregun, as the groundwater migrates downstream.

**Conclusions and Recommendations**

**Groundwater Quality and Potential Effects**

This study assessed the groundwater quality at the Olusosun landfill in Lagos, Nigeria. Groundwater samples were collected bi-weekly over three months (March 19, 2013 to May 28, 2013), from four locations close to the perimeters of the landfill. Results of laboratory analysis of the water samples indicated that metals and other contaminants from the landfill leachate have impaired the groundwater quality at the landfill. The concentrations of metals (Cr, Fe, Cd, Mn, and Co) and other water quality parameters in some of the sampling locations slightly exceeded the WHO (2011) water quality guideline and the NSDWQ (2007) maximum acceptable limits. Lead was also detected in the groundwater samples, however, the concentrations were within the standard limits.

Long-time exposure of humans to Pb and other heavy metals in the groundwater could potentially result in adverse biological effects including impaired nervous system and gastrointestinal disorder and mental retardation, impaired growth and death in children. Thus the
landfill makes the groundwater unsafe for drinking and other household uses due to the potential environmental and health threats associated with the metal contaminants.

Furthermore, the higher concentrations of metals discovered by Oyeku and Eludoyin (2010), in the groundwater of Ojota, Oregun and Ketu communities, downgradient of the landfill suggest the possibility of other sources, which co-pollutes the groundwater as it migrates away from the landfill.

**Landfill Waste Management**

This study observed that the bottom layer of the Olusosun Landfill was not lined to prevent the escape of the leachate plume into groundwater. International best practice requires that new and laterally expanding landfills should have among other things bottom protective layers, leachate collection system, groundwater monitoring wells, and drainage ponds to which all surface runoff are channelled, in order to protect groundwater and surface water from contamination. Additionally, at the Olusosun landfill, waste was left exposed to the atmosphere for a long time period before being covered with soil; in some instances the waste was not covered. This enables storm water percolation and leaching of contaminants present in the waste into groundwater. Uncovered sanitary waste breeds insects, rats and other rodents while the aesthetics of the environment are improved and atmospheric odour is eliminated when landfill wastes are properly covered.

The Olusosun Landfill currently does not have an environmental management plan (EMP) and an environmental management system (EMS) in place to assess and address the potential environmental and human health risks associated with the Landfill. Landfill monitoring is key to sustainable landfill management and therefore, it is included within the best
practices in landfill management e.g., standard for landfills in Alberta (Standard for Landfills in Alberta, 2010), requires that all landfill conduct groundwater sampling and analysis at least once per year. Periodic groundwater monitoring at the Olusosun Landfill would ensure contaminant characterization and provide vital scientific data for risk management. Data gathered including the environmental transport, fate, biological uptake and effects of the contaminants could assist in the management of the environment and any required remediation. Moreover, the landfill management owes the surrounding communities to a duty of care by ensuring that the communities are not affected by any externalities of the landfill.

Lack of government control including appropriate regulations and risk based guidelines, knowledge gap, lack of data, and inadequate funds are paramount among the reasons why developing nations including Nigeria cannot imbibe sustainable landfill management. For instance, there are no regulations, which classify landfills and the type of wastes that can be received by the landfills. Consequently, hazardous and non-hazardous wastes are placed in the same landfills. Furthermore, landfills in developing countries including the Olusosun Landfill do not have any waste processing mechanism in place. As a result, all types of wastes such as industrial, chemical, sanitary and hospital wastes including used batteries, computers and electronics are placed together in landfills, which account for the presence of toxic contaminants in groundwater.

Another situation that calls for concern is the location of the landfill. Residential land use expansion has made further dumping of wastes at the landfill a matter of environmental and human health concern. The Olusosun Landfill is currently surrounded by residential neighbourhoods (see Figure 2), which increases its potential impact on environmental and human health. Appropriate placement of a landfill is key to ensuring its sustainability. According to the
American National Solid Waste Management Association (NSWMA) (2008), modern landfills are built in locations that protect human health and the environment as well as the structural integrity of the landfill.

**Recommendations**

This study recommends that the management of Olusosun landfill should adopt international best practice (NSWMA, 2008), which requires that landfills be engineered, to protect human health and the environment by containing leachate. Although, placing a liner at the bottom of the landfill to prevent leachate migration is no longer possible, the infiltration of precipitation which increases the volume of leachate generated can be prevented by covering the wastes in all areas of the landfill with low permeability natural material such as compacted clay. Following this, the original top soil should be placed as the final layer to support re-vegetation. In addition, covering the waste would improve the aesthetics of the environment, prevent the breeding of insects, rats and other rodents, and eliminate offensive odour. This study also recommends the installation of drainage pipes to collect surface runoff from the landfill into a lined artificial pond. The water from the pond must be analysed periodically and the data should be evaluated to ensure it meets the NSDWQ (2007) standard prior to discharge to any receiving water body.

Furthermore, the Olusosu Landfill management should immediately put in place a sustainable environmental management plan (EMP) which would serve as the policy blueprint for the environmental and the sustainability goals of the landfill. The EMP would also include an environmental management system (EMS) to achieve the goals. The landfill management should use the International Standard Organization (ISO 14001) standard document for guidance. More
importantly, the EMS should have as a key component of the system, iterative risk assessment programme, which would continually assess the potential risks of the landfill to the environment including water, soil and air.

One of the setbacks for sustainability in the developing countries of Africa is the lack of regulations and the institutions to enforce regulations. In the cases, where the regulations and institutions are in place, lack of funds, lack of the rule of law, government impunity, corruption and knowledge gaps make it impossible to enforce such regulations. To address government and market failure, this study recommends that environmental jurisdictions in Nigeria such as the National Environmental Standards and Regulations Enforcement Authority (NESREA) and the Lagos State Environmental Protection Agency (LASEPA) should establish risk based environmental guidelines and standards for new and laterally expanding landfills in Nigeria. The risk-based guidelines must cover through pre-operation to the closure of landfills. It must include site selection, baseline studies to establish background information on environmental quality parameters, engineering designs, operational protocol, environmental monitoring and reporting standards, landfill closure, and post-closure land use. Examples of such guidelines and standard documents are: Standards for Landfills in Alberta (2010) and the Government of Newfoundland and Labrador’ Environmental Standards for Municipal Solid Waste (2010). Additionally, appropriate authorities must enact regulations classifying landfills and the type of wastes, which they can receive. Situations where hazardous and non-hazardous wastes are dumped together in the same landfill are dangerous to the environment and to public health. Besides, such regulations would incentivise societies to sort their wastes before depositing them in landfills.

Finally, the location of the Olusosun Landfill is no longer ideal because of its proximity to residential neighbourhoods and the potential contamination of the groundwater, which is used
as portable water. In addition, the landfill has currently exhausted its lateral land space and has exceeded its lifespan. Therefore, this study recommends that the management of the landfill should consider closing the landfill and establish a new one. The new landfill should preferably be located far from residential neighbourhoods and outside environmentally sensitive areas; such as flood plains, and wetlands.
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Appendix A: Complete Data of Laboratory Results

Sample Batch No.: 1

Date of Collection: 19th March, 2013

Time: 1.15pm

Table A1: Metals Concentration in Groundwater Samples (Batch 1)

<table>
<thead>
<tr>
<th>Sample</th>
<th>Cr (mg/L)</th>
<th>Fe (mg/L)</th>
<th>Cd (mg/L)</th>
<th>Mn (mg/L)</th>
<th>Pb (mg/L)</th>
<th>Zn (mg/L)</th>
<th>Ca (mg/L)</th>
<th>Mg (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bh1</td>
<td>0.016</td>
<td>0.361</td>
<td>ND</td>
<td>0.129</td>
<td>ND</td>
<td>0.086</td>
<td>4.008</td>
<td>23.33</td>
</tr>
<tr>
<td>Bh2</td>
<td>0.019</td>
<td>0.381</td>
<td>0.005</td>
<td>0.332</td>
<td>0.01</td>
<td>0.126</td>
<td>7.2144</td>
<td>41.99</td>
</tr>
<tr>
<td>Bh3</td>
<td>0.175</td>
<td>0.896</td>
<td>ND</td>
<td>0.419</td>
<td>0.02</td>
<td>0.249</td>
<td>16.8336</td>
<td>97.97</td>
</tr>
<tr>
<td>Bh4</td>
<td>0.011</td>
<td>0.403</td>
<td>ND</td>
<td>0.176</td>
<td>ND</td>
<td>0.085</td>
<td>11.296</td>
<td>91.26</td>
</tr>
</tbody>
</table>

Note: All units are in mg/L
ND-Not detected
Bh-Borehole (Sampling Location)

Table A2: Water Quality Parameters Concentration in Groundwater Samples (Batch 1)

<table>
<thead>
<tr>
<th>Sample</th>
<th>pH</th>
<th>Dissolved Oxygen (DO) (mg/L)</th>
<th>Total Dissolved Solids (TDS) (mg/L)</th>
<th>Nitrates (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bh1</td>
<td>5.44</td>
<td>0.87</td>
<td>57.5</td>
<td>10.0</td>
</tr>
<tr>
<td>Bh2</td>
<td>6.52</td>
<td>0.79</td>
<td>678.0</td>
<td>16.0</td>
</tr>
<tr>
<td>Bh3</td>
<td>5.35</td>
<td>0.77</td>
<td>200.5</td>
<td>29.0</td>
</tr>
<tr>
<td>Bh4</td>
<td>5.50</td>
<td>0.49</td>
<td>221.0</td>
<td>65.0</td>
</tr>
</tbody>
</table>
Sample Batch No. 2

Date of Collection: 2\textsuperscript{nd} April, 2013

Time: 1.55pm

Table A3: Metals Concentration in Groundwater Samples (Batch 2)

<table>
<thead>
<tr>
<th>Sample</th>
<th>Cr (mg/L)</th>
<th>Fe (mg/L)</th>
<th>Cd (mg/L)</th>
<th>Mn (mg/L)</th>
<th>Pb (mg/L)</th>
<th>Zn (mg/L)</th>
<th>Co (mg/L)</th>
<th>Cu (mg/L)</th>
<th>Ca (mg/L)</th>
<th>Mg (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bh1</td>
<td>0.020</td>
<td>0.124</td>
<td>ND</td>
<td>0.129</td>
<td>ND</td>
<td>0.061</td>
<td>0.065</td>
<td>0.042</td>
<td>5.108</td>
<td>25.23</td>
</tr>
<tr>
<td>Bh2</td>
<td>0.050</td>
<td>0.248</td>
<td>0.005</td>
<td>0.491</td>
<td>ND</td>
<td>0.186</td>
<td>0.071</td>
<td>0.039</td>
<td>6.914</td>
<td>39.6</td>
</tr>
<tr>
<td>Bh3</td>
<td>ND</td>
<td>0.194</td>
<td>ND</td>
<td>0.120</td>
<td>ND</td>
<td>0.054</td>
<td>0.056</td>
<td>0.041</td>
<td>12.833</td>
<td>88.64</td>
</tr>
<tr>
<td>Bh4</td>
<td>0.010</td>
<td>0.164</td>
<td>ND</td>
<td>0.121</td>
<td>ND</td>
<td>0.049</td>
<td>0.066</td>
<td>0.036</td>
<td>14.643</td>
<td>87.47</td>
</tr>
</tbody>
</table>

Note. All units are in mg/L
ND-Not detected
Bh-Borehole (Sampling Location)

Table A4: Water Quality Parameters Concentration in Groundwater Samples (Batch 2)

<table>
<thead>
<tr>
<th>Sample</th>
<th>Ph</th>
<th>DO (mg/L)</th>
<th>TDS (mg/L)</th>
<th>Nitrates (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bh1</td>
<td>5.67</td>
<td>0.46</td>
<td>76.5</td>
<td>8.0</td>
</tr>
<tr>
<td>Bh2</td>
<td>5.96</td>
<td>0.70</td>
<td>526</td>
<td>24.0</td>
</tr>
<tr>
<td>Bh3</td>
<td>5.65</td>
<td>0.68</td>
<td>210</td>
<td>8.0</td>
</tr>
<tr>
<td>Bh4</td>
<td>5.43</td>
<td>0.43</td>
<td>213</td>
<td>8.0</td>
</tr>
</tbody>
</table>
Sample Batch No.3

**Date of Collection:** 16\textsuperscript{th} April, 2013

**Time:** 2.10pm

**Table A5: Metals Concentration in Groundwater Samples (Batch 3)**

<table>
<thead>
<tr>
<th>Sample</th>
<th>Cr</th>
<th>Fe</th>
<th>Cd</th>
<th>Mn</th>
<th>Pb</th>
<th>Zn</th>
<th>Co</th>
<th>Cu</th>
<th>Ca</th>
<th>Mg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bh1</td>
<td>0.023</td>
<td>0.214</td>
<td>ND</td>
<td>0.324</td>
<td>ND</td>
<td>0.143</td>
<td>0.055</td>
<td>0.041</td>
<td>6.312</td>
<td>27.00</td>
</tr>
<tr>
<td>Bh2</td>
<td>0.049</td>
<td>0.256</td>
<td>0.004</td>
<td>0.411</td>
<td>ND</td>
<td>0.266</td>
<td>0.084</td>
<td>0.057</td>
<td>6.468</td>
<td>40.23</td>
</tr>
<tr>
<td>Bh3</td>
<td>0.009</td>
<td>0.156</td>
<td>ND</td>
<td>0.234</td>
<td>ND</td>
<td>0.121</td>
<td>0.074</td>
<td>0.049</td>
<td>11.211</td>
<td>56.34</td>
</tr>
<tr>
<td>Bh4</td>
<td>0.012</td>
<td>0.136</td>
<td>ND</td>
<td>0.224</td>
<td>ND</td>
<td>0.066</td>
<td>0.062</td>
<td>0.050</td>
<td>9.123</td>
<td>96.12</td>
</tr>
</tbody>
</table>

*Note.* All units are in mg/L
ND-Not detected
Bh-Borehole (Sampling Location)

**Table A6: Water Quality Parameters Concentration in Groundwater Samples (Batch 3)**

<table>
<thead>
<tr>
<th>Sample</th>
<th>pH</th>
<th>DO (mg/L)</th>
<th>TDS (mg/L)</th>
<th>Nitrates (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bh1</td>
<td>5.67</td>
<td>0.34</td>
<td>106.00</td>
<td>10.00</td>
</tr>
<tr>
<td>Bh2</td>
<td>5.96</td>
<td>0.54</td>
<td>404.00</td>
<td>9.00</td>
</tr>
<tr>
<td>Bh3</td>
<td>5.65</td>
<td>0.68</td>
<td>198.00</td>
<td>11.00</td>
</tr>
<tr>
<td>Bh4</td>
<td>5.43</td>
<td>0.56</td>
<td>211.00</td>
<td>98.00</td>
</tr>
</tbody>
</table>
Sample Batch No.4

Date of Collection: 30th April, 2013

Time: 1.30pm

Table A7: Metals Concentration in Groundwater Samples (Batch 4).

<table>
<thead>
<tr>
<th>Sample</th>
<th>Cr</th>
<th>Fe</th>
<th>Cd</th>
<th>Mn</th>
<th>Pb</th>
<th>Zn</th>
<th>Co</th>
<th>Cu</th>
<th>Ca</th>
<th>Mg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bh1</td>
<td>0.025</td>
<td>1.145</td>
<td>ND</td>
<td>0.284</td>
<td>ND</td>
<td>0.205</td>
<td>0.051</td>
<td>0.039</td>
<td>7.246</td>
<td>26.43</td>
</tr>
<tr>
<td>Bh2</td>
<td>0.038</td>
<td>0.874</td>
<td>0.006</td>
<td>0.399</td>
<td>ND</td>
<td>0.236</td>
<td>0.077</td>
<td>0.058</td>
<td>7.584</td>
<td>45.11</td>
</tr>
<tr>
<td>Bh3</td>
<td>0.014</td>
<td>2.416</td>
<td>ND</td>
<td>0.264</td>
<td>ND</td>
<td>0.198</td>
<td>0.069</td>
<td>0.052</td>
<td>10.218</td>
<td>54.44</td>
</tr>
<tr>
<td>Bh4</td>
<td>0.018</td>
<td>0.911</td>
<td>ND</td>
<td>0.186</td>
<td>ND</td>
<td>0.143</td>
<td>0.060</td>
<td>0.043</td>
<td>10.118</td>
<td>90.22</td>
</tr>
</tbody>
</table>

Note. All units are in mg/L
ND-Not detected
Bh-Borehole (Sampling Location)

Table A8: Water Quality Parameters Concentration in Groundwater Samples (Batch 4).

<table>
<thead>
<tr>
<th>Sample</th>
<th>pH</th>
<th>DO (mg/L)</th>
<th>TDS (mg/L)</th>
<th>Nitrates (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bh1</td>
<td>5.88</td>
<td>0.44</td>
<td>116.0</td>
<td>9.0</td>
</tr>
<tr>
<td>Bh2</td>
<td>4.98</td>
<td>0.59</td>
<td>426.0</td>
<td>10.0</td>
</tr>
<tr>
<td>Bh3</td>
<td>5.27</td>
<td>0.66</td>
<td>220.0</td>
<td>8.0</td>
</tr>
<tr>
<td>Bh4</td>
<td>5.65</td>
<td>0.49</td>
<td>236.0</td>
<td>92.0</td>
</tr>
</tbody>
</table>
Sample Batch No.5

Date of Collection: 14th May, 2013

Time: 12.45pm

Table A9: Metals Concentration in Groundwater Samples (Batch 5).

<table>
<thead>
<tr>
<th>Sample</th>
<th>Cr (mg/L)</th>
<th>Fe (mg/L)</th>
<th>Cd (mg/L)</th>
<th>Mn (mg/L)</th>
<th>Pb (mg/L)</th>
<th>Zn (mg/L)</th>
<th>Co (mg/L)</th>
<th>Cu (mg/L)</th>
<th>Ca (mg/L)</th>
<th>Mg (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bh1</td>
<td>0.021</td>
<td>0.47</td>
<td>ND</td>
<td>0.211</td>
<td>ND</td>
<td>0.179</td>
<td>0.058</td>
<td>0.042</td>
<td>5.668</td>
<td>22.50</td>
</tr>
<tr>
<td>Bh2</td>
<td>0.035</td>
<td>0.42</td>
<td>0.007</td>
<td>0.405</td>
<td>0.003</td>
<td>0.207</td>
<td>0.079</td>
<td>0.051</td>
<td>7.049</td>
<td>43.94</td>
</tr>
<tr>
<td>Bh3</td>
<td>0.014</td>
<td>1.017</td>
<td>ND</td>
<td>0.254</td>
<td>0.005</td>
<td>0.177</td>
<td>0.025</td>
<td>0.045</td>
<td>11.770</td>
<td>68.60</td>
</tr>
<tr>
<td>Bh4</td>
<td>0.016</td>
<td>0.401</td>
<td>ND</td>
<td>0.178</td>
<td>ND</td>
<td>0.084</td>
<td>0.060</td>
<td>0.044</td>
<td>12.300</td>
<td>89.19</td>
</tr>
</tbody>
</table>

Note. All units are in mg/L
ND—Not detected
Bh—Borehole (Sampling Location)

Table A10: Water Quality Parameters Concentration in Groundwater Samples (Batch 5).

<table>
<thead>
<tr>
<th>Sample</th>
<th>pH</th>
<th>DO (mg/L)</th>
<th>TDS (mg/L)</th>
<th>Nitrates (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bh1</td>
<td>5.66</td>
<td>0.421</td>
<td>110.0</td>
<td>8.50</td>
</tr>
<tr>
<td>Bh2</td>
<td>5.86</td>
<td>0.690</td>
<td>408.0</td>
<td>11.0</td>
</tr>
<tr>
<td>Bh3</td>
<td>5.50</td>
<td>0.690</td>
<td>177.13</td>
<td>10.0</td>
</tr>
<tr>
<td>Bh4</td>
<td>5.50</td>
<td>0.510</td>
<td>229</td>
<td>62.0</td>
</tr>
</tbody>
</table>
Sample Batch No.6

Date of Collection: 28th May, 2013

Time: 1.25pm

Table A11: Metals Concentration in Groundwater Samples (Batch 6).

<table>
<thead>
<tr>
<th>Sample</th>
<th>Cr</th>
<th>Fe</th>
<th>Cd</th>
<th>Mn</th>
<th>Pb</th>
<th>Zn</th>
<th>Co</th>
<th>Cu</th>
<th>Ca</th>
<th>Mg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bh1</td>
<td>0.022</td>
<td>0.45</td>
<td>ND</td>
<td>0.225</td>
<td>ND</td>
<td>0.199</td>
<td>0.056</td>
<td>0.041</td>
<td>5.670</td>
<td>28.50</td>
</tr>
<tr>
<td>Bh2</td>
<td>0.040</td>
<td>0.45</td>
<td>0.005</td>
<td>0.409</td>
<td>0.005</td>
<td>0.203</td>
<td>0.075</td>
<td>0.050</td>
<td>7.041</td>
<td>39.53</td>
</tr>
<tr>
<td>Bh3</td>
<td>0.009</td>
<td>0.817</td>
<td>ND</td>
<td>0.262</td>
<td>0.005</td>
<td>0.137</td>
<td>0.030</td>
<td>0.047</td>
<td>13.778</td>
<td>80.10</td>
</tr>
<tr>
<td>Bh4</td>
<td>0.011</td>
<td>0.408</td>
<td>ND</td>
<td>0.176</td>
<td>ND</td>
<td>0.088</td>
<td>0.068</td>
<td>0.042</td>
<td>10.290</td>
<td>93.35</td>
</tr>
</tbody>
</table>

Note. All units are in mg/L
ND-Not detected
Bh-Borehole (Sampling Location)

Table A12: Water Quality Parameters Concentration in Groundwater Samples (Batch 6).

<table>
<thead>
<tr>
<th>Sample</th>
<th>pH</th>
<th>DO (mg/L)</th>
<th>TDS (mg/L)</th>
<th>Nitrates (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bh1</td>
<td>5.67</td>
<td>0.63</td>
<td>68.0</td>
<td>10.0</td>
</tr>
<tr>
<td>Bh2</td>
<td>5.85</td>
<td>0.62</td>
<td>609.0</td>
<td>18.5</td>
</tr>
<tr>
<td>Bh3</td>
<td>5.48</td>
<td>0.71</td>
<td>237.13</td>
<td>18.0</td>
</tr>
<tr>
<td>Bh4</td>
<td>5.503</td>
<td>0.475</td>
<td>211.0</td>
<td>71.0</td>
</tr>
</tbody>
</table>