MSc Program
Environmental Technology & International Affairs

Nutrient Balance in Waste Treatment and Disposal in Nairobi, Kenya: Case of the Dandora Dumpsite

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"Master of Science"

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Affidavit

I, **PAUL MWANGI MUCHUKI**, hereby declare

1. that I am the sole author of the present Master's Thesis, "NUTRIENT BALANCE IN WASTE TREATMENT AND DISPOSAL IN NAIROBI, KENYA: CASE OF DANDORA DUMPSITE", 73 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
2. that I have not prior to this date submitted this Master's Thesis as an examination paper in any form in Austria or abroad.

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Abstract

Nutrient loss to MSW streams is a major concern for food security and environmental protection. As such, the need to avoid waste and recover the useful fractions for future purposes is quickly becoming a necessity. Since more than 50% of organic materials are found in the waste streams of commingled garbage, this study focuses on the organic fraction of MSW mostly generated by households, markets and restaurants terminating at the landfill. The research reveals that in Nairobi a two-pronged waste management system of collection and disposal is operated. This is unsustainable as 2,000 t/d of MSW are generated, 420 t/d are illegally dumped after collection while 750 t/d are not collected and a total 200 t/d are recycled informally. Only 830 t/d MSW are landfilled and the impact on waste management from the population and its consumption yields that the HHs, restaurants and markets are the major contributors to the voluminous organic waste. The theoretical NB model relies on N, P and K as indicators to seek a sustainable solution through closing the nutrient cycle. These indicators show positive results of a net stock of nutrients in the landfill and in the dumped portions scattered around the city. This shows a correlation to nitrification and possibly high levels of heavy metals in the Nairobi River. As 51% of all waste flows are organic matter, the individual contribution to MSW volumes at 1.57 kg per day reveals that 0.8 kg per capita per day is exclusively OFMSW and thus the impact on nutrient flows to waste streams in Nairobi is quantified as between 1 kg to 3 kg/capita/yr NPK or 119 kg/capita/yr of generated OFMSW containing essential nutrients for animal and plant development. Of this input into the WMS, between 0.3 to 0.7 kg/capita/yr NPK is lost to leaching at the landfill as observed in this study. The NB presents a method to achieve sustainable nutrient balance through MFA and closing of the nutrient cycle. The study explores urban mining, composting and biogas/ cogeneration as ideal solutions to managing OFMSW in Nairobi. There was however, a gross lack of sufficient data to build the models thus extrapolations and estimations were made to remediate the theoretical modeling. Through modeling, a positive indication of 30% N, 70% P and an increment of 52% K was revealed to be present in the landfill in just a year while 70% N and 25% P is lost through leaching. The potential to recover these nutrients is proposed through the intermediate and optimized models of MFAs in the study.

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List of Abbreviations/Acronyms

BAU	Business as usual
CBD	Central Business District
CBK	Central Bank of Kenya
CBO	Community Based Organization
CBS	Central Bureau of Statistics
CCN	County Council of Nairobi
HHs	Households
ISWM	Integrated Solid Waste Management
KENAO	Kenya National Audit Office
KNBS	Kenya National Bureau of Statistics
MFA	Material Flow Analysis
MSW	Municipal Solid Waste
NCC	Nairobi City County/Nairobi City Council
NMR	Nairobi Metropolitan Region
NB	Nutrient Balance
OECD	Organization for Economic Co-operation and Development
OFMSW	Organic Fraction of Municipal Solid Waste
PT	Pamoja Trust
SNB	Sustainable Nutrient Balance
STAN	SubSTance flow Analysis
SWM	Solid Waste Management
UFMSW	Useful Fraction of Municipal Solid Waste

Exchange rate:[1]

€ 1 (EURO) = KSh 119.2428; KSh 1 (SHILLING) = € 0.0084

US$ 1 (DOLLAR) = KSh 87.9861; KSh 1 (SHILLING) = US$ 0.0114

Number separators: Decimal . (period) and thousands , (comma) (e.g. 1,000.00)

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[1] Referent: https://www.centralbank.go.ke/index.php/rate-and-statistics, (16 June, 2014).

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It has been a challenge and gratitude must be given to who deserves -
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I am grateful for the work and supervision by Prof. Brunner even at the most stressful of times and with the swiftest feedback, admirable to say the least! His work on this thesis was instrumental to enable its composition. The wealth of knowledge and experience was the expertise necessary to achieve much in this often overlooked but invaluable field.

I would also like to thank my friends for the support and the memories; the experiences that last a lifetime and the bonds that never break.

As we move from resource waste to resource recovery, waste can no longer be treated as such, it is a valuable resource for our anthropogenic future…

“As long as the earth endures, seedtime and harvest, cold and heat, summer and winter, day and night will never cease.” Genesis 8:22

"What is the use of living, if it be not to strive for noble causes and to make this muddled world a better place for those who will live in it after we are gone? How else can we put ourselves in harmonious relation with the great verities and consolations of the infinite and the eternal? And I avow my faith that we are marching towards better days. Humanity will not be cast down. We are going on swinging bravely forward along the grand high road and already behind the distant mountains is the promise of the sun."

Winston Churchill, Dundee, Scotland, 10 October 1908

1 Introduction

This section introduces the subject of the study and brings an overview of the scenario around the topic of municipal solid waste (MSW). The problem of MSW generated from the population of Nairobi is shortly visited as to elucidate the objective of the study, which is to theoretically establish a model for nutrient balance of a landfill from MSW. The methods on how to solve the problem are then highlighted followed by a breakdown of the data sources in the study.

1.1 The General Topic

Municipal Solid Waste (MSW) is a gargantuan topic in developing countries, more so in disposal aspects. It is vital since up to a half of the budget of municipalities in low-income countries are expended on MSW management (Le Courtois, 2012). As such, it has numerous opportunities for private sector investment and revenue. The roots of the disposal problem however are a lack of conscience by the population enhanced through their growth and the rate of consumption, laced with meagerly funded MSW management. Furthermore, the MSW management systems are two-pronged: collection and disposal. These factors effectively outstrip the capacity of the waste handlers to manage MSW in a modus to attain the goals of waste management.

MSW fractions in the developing countries contain rich fractions of nutrients that can be recovered for the propagation of organic subsistence but end up in waste streams. These countries are eager for solutions that accommodate their needs on, food production and security, economic growth, development and sanitation. As low income to medium income countries are developing at a fast rate to cope with population expansion, waste management and food security are a major concern. The focus area is thus on the City of Nairobi, Kenya and the Dandora dumpsite in particular, on the recovery of organic fractions from waste streams of MSW.

1.2 The Problem

As great demand and focus is on Nairobi on matters from demographics and migration to trade and commerce, of far less prominence is the proper management of MSW. According to the World Bank (2011), the overall goal of MSW management is to collect, treat and dispose all generated MSW in an environmentally and socially satisfactory manner while employing the most economical means available once the wastes are outside households and other premises.

In this regard, uncollected or unmanaged waste is the most visible environmental problem augmented by unimplemented MSW management policies, inadequate treatment and disposal, derisory landfill disposal and a debilitated MSW operations strategy. The County Council of Nairobi's capacity to collect and dispose MSW is at present inept to cope with the prevailing situation hence the eyesores of large amounts of uncollected MSW mostly predominant in slums, back streets and street corners around Nairobi. The contribution by the population through illegal dumping and littering is essentially undeniable in view of the societal responsibilities to keep the environment clean. From a KENAO audit (2007), it was revealed that the NCC does not maintain any complete and reliable data of waste generated in the city. However, according to the Nairobi Governor, generated MSW is estimated at 2,000 tonnes daily and the County Council of Nairobi (CCN) collects approximately 1,400 tonnes of it while private firms supposedly collect the remainder (NCC, 2014a). The proportion of MSW generated to that collected is dismal with disparity in collection services offered by the CCN and private firms in suburbs (Magutu et al., 2007) as opposed to other areas.

Nairobi's only official dumping site that was established in the 1970s is situated in Dandora which is owned and operated by the CCN and has been operational for over 40 years. Previously a quarry, the 30 acre open dumping site is reportedly beyond capacity thus contributing to inadequate collection and disposal, uncontrolled and illegal dumping and littering occurring citywide; waste pickers and scavengers also indiscriminately litter with unusable waste materials while other residents and slum dwellers use rivers and any open space as dumping grounds. The population's participation in dumping is central to the problem.

The mammoth fraction that does not make it to the salvage pile in this facility directly adjacent to Nairobi River is often burned openly and uncontrollably. The dumping site acts as a sink and it has no other uses save for storage of disposed MSW. As a result, landfill gas from aerobic decomposition and toxic fumes from open burning plague the facility and its environs while the NCC machinery on site carries out rudimental and insufficient compacting of waste.

Thus, the County Government came up with a strategy to close the facility in Dandora and move to another location (Kamau, 2013; NCC, 2014b). However, the new site in Ruai is in contention due to aviation safety and furthermore, in view of current demographic and development trends, lacks of proper and established MSW and other waste management policies, this problem at the dumpsite will persist. There lies the gap in the knowledge on how to best deal with Dandora dumpsite in the wake of a new move to landfill only inert waste at Ruai and convert the current Dandora dumpsite to a collection, segregation and recycling center while establishing a 50 MW Waste to Energy (WtE) plant (Guguyu, 2014) on site.

The methods as to how to achieve this are elusive and with insufficient research, literature or data on how to handle the mammoth fraction is a particular problem. This study proposes a method that can salvage the dumpsite through resource recovery in order to ensure the release of only inert waste and significantly reduce nutrient losses from waste streams and closing the nutrient cycle.

1.3 Objective of the Study

The notion that the Dandora dumpsite is beyond capacity can be well contested due to the nature of how waste is managed on site. With the mammoth fraction of MSW in developing countries coming from organic residue, the potential to decrease volume at the dumpsite is favorable. Whereas anthropogenic metabolism is as continuous as time, the objective is to study the organic fraction that can be recovered from the existing untreated and unmanaged waste at the open dumpsite and to build a theoretical system derived from a nutrient balance (NB) model. Through the NPK indicators, the NB model will be used to evaluate resource recovery from waste streams mostly from households, restaurants and markets for reuse with the aid of Material Flow Analysis (MFA) quantification to explicate the flows from MSW collection.

1.4 Significance of the Study

Anthropogenic metabolism is embedded in human development and can only be managed and improved. The demand for resources is steadily outgrowing the capacity to supply them and waste streams are a major bleeding artery to anthropogenic metabolism. This study encourages scientific research on nutrient recovery from urban mines such as landfills. This knowledge can be used to enhance sanitation, development and food security goals primarily in developing countries. The study can also be used to make better policy decisions in the handling of MSW, dumpsites and landfills.

1.5 Research Questions

The research question is whether nutrients can be recovered from MSW streams to sustain anthropogenic metabolism by capping on their losses from waste disposal. This study aims to answer this question in three parts; the first being an overview of the literature and research on MSW in Nairobi and theoretical concepts on MFA to evaluate the point of investigation for nutrients in MSW that end up in the dumpsite. Secondly, a breakdown of MSW streams potential of nutrient recovery to explain how sustainable NB can be implemented to cap on nutrient losses. This study uses the indicators Nitrogen (N), Phosphorus (P) and Potassium (K) that form part of the organic fraction of MSW (OFMSW) to create a nutrient balance for this purpose. In the third part, the study discusses this theoretical model and elucidates on the approach taken with MFA to show the flows from the NB model, to simulate a sustainable nutrient balance.

1.6 Hypothesis

The main hypothesis for this research is that resource scarcity and food security are interdependent. Consumption by the population impacts this interdependence through waste streams. The resultant waste generated as MSW has an immense organic fraction that can be recovered for the propagation of the nutrient cycle but are lost in waste streams to landfills especially in developing countries. Using the case of the Dandora dumpsite in Nairobi, a theoretical model based on NB will yield a determinant of nutrient losses to MSW streams and the potential for resource recovery.

1.7 Methodology

A theoretical model of nutrient balance will be the basis of analysis of nutrient loss to MSW at the Dandora landfill. The nutrient balance will use nitrogen, phosphorus and potassium (NPK) as the indicators for nutrient concentration to test the hypothesis. This will then be supported by MFA of the waste management in Nairobi County. The study will be based on thorough literature and research review from both published and unpublished research, scientific papers and statistical data from national and international organizations pertaining to MSW streams, and organic fractions of municipal solid waste for the modeling of the system. The base year for this study is 2009.

1.8 Data Collection

The data used in this research is extracted from statistics, scientific research papers, articles, national and international sources and publications from governmental, non-governmental and international organizations. Most recent updates from news reports and articles published online are factored in and the MFA uses the data and analyses in the literature review and subsequent chapters.

Data on MSW is calculated using estimates from the NCC and the analysis from the statistical reports on population and housing mostly from 2008 to 2009, a poverty threshold and GDP statistics. The inherent gaps from use of such data will be discussed and included in the respective subsequent sections of this study.

The data on waste generation, segregation and composition analyses, and collection and disposal quantities was analyzed from studies and research carried out by non-governmental organizations, publications, news items, and the NCC from 2001 to 2014. Data for the NB model and segregation analyses are estimated through use of the available data in publications and as expounded in the corresponding chapters.

In brief, the study focuses on the organic fraction of Municipal Solid Waste. The problem identified is the loss of nutrients to MSW streams that terminate at the landfills. The particular landfill for this study is situated in Kenya's capital, Nairobi in Dandora area. The waste collection is handled by the NCC and other private firms. However, their collection capacity is inadequate while the population actively exacerbates the dumping problem. The facility pollutes the adjacent Nairobi River and environment through open burning, anaerobic decomposition and leaching. As there is little recycling, a huge fraction is left over for compacting. Thus, the objective of this study is to focus on the organic fraction by establishing whether nutrients can be recovered from waste streams using a nutrient balance model utilizing N, P and K as the indicators. The methods to achieve this are through a theoretical nutrient balance model centered on MFA and data from secondary published and unpublished papers, articles and research as well as calculations and analyses.

> **"It's the little things that citizens do. That's what will make the difference. My little thing is planting trees."**
>
> **Wangari Maathai**

2 Nairobi County and MSW

This section introduces the study area and a thorough review on secondary literature on MSW generation and management for Nairobi. The study boundary is the MSW management system of Nairobi County. The future extension of the county into a metropolitan region is discussed to enhance the importance of MSW management. Consequently, an overview of MSW management is examined. This is elaborated by combining population dynamics, GDP and a poverty level indicator to calculate per capita generation and the capacity gap in collection. It culminates with concept models of MSW flows from generation to landfilling through which the link of consumption, waste generation and collection contributes to nutrient losses.

2.1 Nairobi Demographics and MSW

Nairobi County is the largest city as well as the capital city of Kenya, which bears the title of logistics, business and commercial hub of East Africa. This former rail construction depot developed into the capital of British East Africa in 1905 (Onyancha et al., 2011; NCC, 2013). The city boundaries have since been revised no less than five times as it gradually expanded in an arbitrary and unexpected modus (CBS, 1981) subsequent to location at an apt altitude of between 866m and 2,607m above sea level. In the period 1969 to 1979, emergence of market towns as "growth centres" saw the decline of migration fluxes that terminated at Nairobi and Mombasa (CBS, 1981).

Onwards to 2014, the city has grown to an estimated 4.5 million residents due to migration and natural development. Notably, Nairobi is strategically located in relation to accessing other parts of Africa and it acts as the continent's gateway since the Great North Road corridor passes through the city. It is also the access route to various economies in Africa as well as the Indian Ocean and South Asia while Jomo Kenyatta international airport (JKIA) is at a mean flight time of 5.5 hours from major African cities (Omwenga, 2010).

Presently, Nairobi County consists of eight constituencies; seventeen sub counties and eighty-five wards. Some areas have increased density of human-created structures as compared to the surrounding areas since the city has a huge population living in slums. In 2009, the census conveyed 3.1 million people in total as the Nairobi population, factoring migration and natural development (KNBS, 2010). This population resided in 985,016 households (HHs) within Nairobi's 695.1 km^2 at a density of 4,515.6 people per Km^2 (Opendata, 2011) with incessant slums subsisting close to affluent neigbourhoods, swelling probably in line with colonial layouts.

On the other hand, in 2008 an estimated 1.3 million people out of the total Nairobi population lived in 254,000 households in informal settlements and as squatters (Pamoja Trust, 2008). According to Karanja and Makau (2008), these slums occupy only 5% of the residential land with 50% of the city's population being the slum dwellers on 1% of the total area of Nairobi as exemplified in statistics from 2008 and 2009 in *Table 1*.

Table 1: 2008 slum population estimates with the 2009 Census population of Nairobi County (Pamoja Trust, 2008; Opendata, 2011)

Constituency	Wards	Slums	Nairobi Census	Density	Area (km^2)	Slums Pop.	Slum (Acres)
1. Makadara	4	18	218,641	9,485	23.1	202,502	86.95
2. Kamukunji	11	11	261,855	21,605	12.1	92,792	102.20
3. Starehe	6	22	274,607	25,640	10.7	131,614	165.10
4. Lang'ata	10	17	355,188	1,592	223.2	506,530	279.50
5. Dagoreti	10	28	329,577	8,534	38.6	86,189	209.17
6. Westlands	5	10	247,102	2,537	97.4	42,288	54.25
7. Kasarani	15	31	525,624	6,082	86.4	98,270	1,167.55
8. Embakasi	24	13	925,775	4,546	203.6	130,000	99.00
Total	**85**	**150**	**3,138,369**	**4,515**	**695.1**	**1,290,185**	**2,163.72**[2]

The constituency units in this study are as gazetted for the 2009 census. The provisional data on the slums population is from Pamoja Trust[3] research (2008). The use of this provisional data is due to the decennial census, which does not extricate informal settlements or slums as a category in the censual statistics. Thus, it is deductible from the above analysis that approximately 1.9 Million people in 2009 did

[2] This is an equivalent of 8.76 km^2.

[3] PT is a Non Profit organization that works with urban poor communities across Kenya to promote their access to land, shelter and basic services. The information is summarized and tabulated in *Appendix I*.

not reside in slums and nearly half of the population of Nairobi subsists in slums. Anomalies from encroachment on riparian, road, rail, power, other utility reserves such as oil and water pipelines and private property are intrinsic. These are partially due to lack of land tenure, inadequate infrastructure access, overridden planning and lack of disposal space and facilities (Pamoja Trust, 2008). The slums of Nairobi further handicap logistics and MSW management.

2.2 The Nairobi Metropolitan Region (NMR)

Moreover, Nairobi is rapidly expanding into a 32,000 km^2 metropolitan region as seen in
Figure 1.

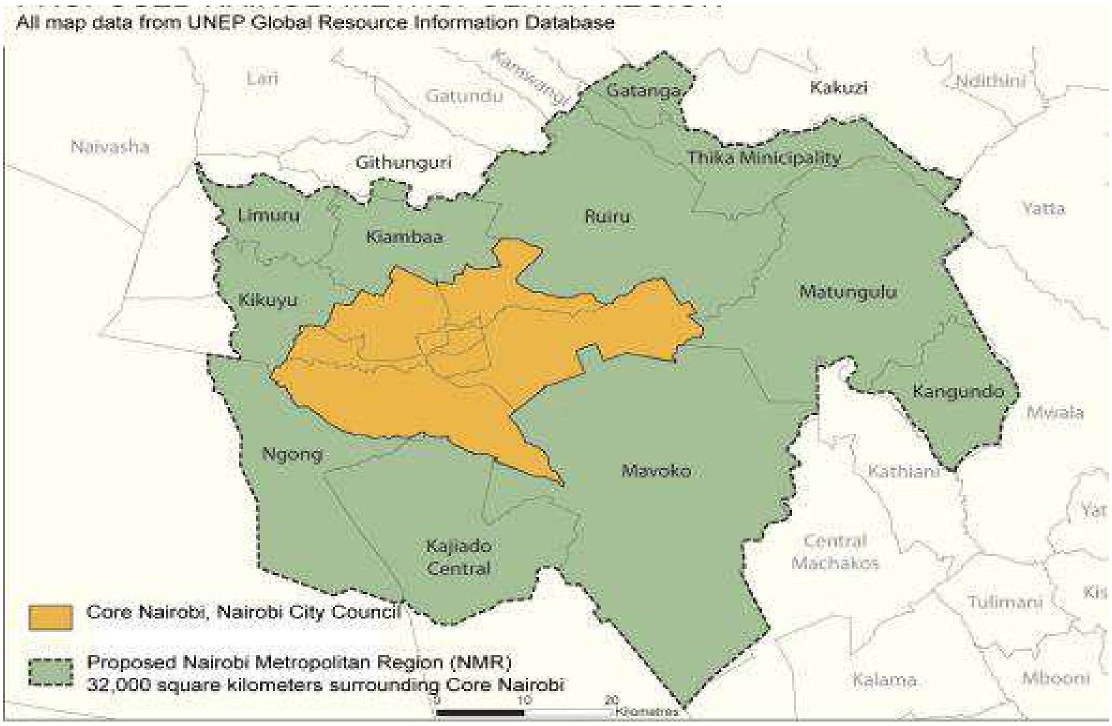

Figure 1: Map of NMR showing the Nairobi County boundary (World Bank, 2014)

This region includes four County Councils, six Municipal Councils and four Town Councils, which are in fifteen different administrative jurisdictions expounded in *Figure 2.*

	Local Authority	Projected Population (2007)
1.	City Council of Nairobi	2,647,951
2.	Municipal County of Kiambu	76,004
3.	Municipal County of Limuru	112,324
4.	Municipal County of Machakos	192,377
5.	Municipal County of Mavoko	54,640
6.	Municipal County of Ruiru	127,074
7.	Municipal County of Thika	101,320
8.	Town Council of Kajiado	15,408
9.	Town Council of Karuri	105,607
10.	Town Council of Kangundo	15,408
11.	Town Council of Kikuyu	191,769
12.	County Council of Kiambu	375,558
13.	County Council of Masaku	607,599
14.	County Council of Olkejuado	495,943
15.	County Council of Thika	521,291
	Total	5,640,273

Source: Adopted, Ministry of Nairobi Metropolitan Development, 2008, p.19.

Figure 2: NMR projected population for 2007 (World Bank, 2014)

NMR was estimated to have a population of 6.3 million in 2007 which is double that of Nairobi County as compared to the 2009 census. The NMR[4] is projected to comprise 14.3 million at a density of around 450 people per km^2 in 2030 as projected in

Figure 3. This is a population 4.6 times the 2009 population figure of Nairobi as exemplified in *Figure 4* comparing the two regions by a projected population growth. The population of Nairobi County is plotted through a 4.3% per annum growth rate on base year 1999 against the given Metropolitan population. The population is in millions while the period is from 1999 to 2030.

Year	1999	2007	2012	2017	2022	2027	2030
Total National Population	28.7	36.3	41.5	47.2	52.9	58.7	62.1
Total Urban Population	5.4	9.0	12.3	16.9	23.1	31.7	38.2
Metropolitan Population	4.8	6.3	7.6	9.0	10.8	12.8	14.3
Urban % of National Population	18.8	24.8	29.6	35.8	43.7	54.0	61.5
NMR % of National Population	16.7	17.4	18.3	19.1	20.2	21.7	22.8
NMR % of Urban Population	88.5	70.3	61.7	53.3	46.3	40.2	37.0

Source: Adopted, Ministry of Nairobi Metropolitan Development, 2008, p.21.

[4] The NMR connects the North-South and East-West Trans African Highway (TAH). The North-South TAH that originates from Cairo through to Gaborone and to Cape Town is 8,860 km long while the East-West TAH from Lagos to Mombasa is 6,260 km long.

Figure 3: NMR population projections (World Bank, 2014)

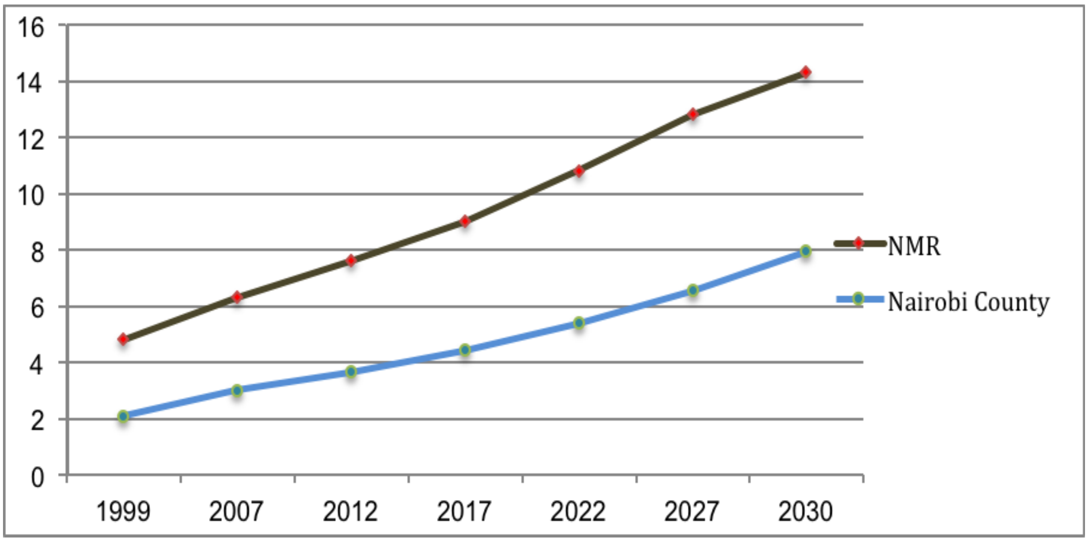

Figure 4: Comparative population of Nairobi County and NMR

Subsequently, a US$ 330 million[5] Nairobi Metropolitan services improvement project for urban services and infrastructure commenced May 10, 2012 and is expected to culminate on June 30, 2017 (World Bank, 2014).

This Nairobi Metropolitan Spatial plan was prioritized to facilitate balanced and coordinated metropolitan and national growth and take special consideration to protect agricultural and water catchment areas while developing strong growth centres outside the city, maybe easing the population flux experienced in the city's past. However, in the spatial plan is a deficit in adequate planning and earmarking waste management services whilst the higher the population, the higher the consumption and that is correlated to the generation of waste, expounded in section *2.3.2*.

Some of the NMR challenges expected include rapid population increase, encroachment into agricultural and water catchment areas, haphazard, uncoordinated and incompatible urban and rural development, inadequate infrastructure and utility services, environmental degradation and poor sanitation

[5] € 243 Million or KSh 29 Billion.

(Omwenga, 2010). For this reason, this study also incorporates a model on the NMR potential in terms of MSW generation against status quo collection in section *2.3.3*.

2.3 MSW Management in Nairobi County

Municipal Solid Waste is defined as the waste produced from activities of waste generators in domestic, commercial, and institutional areas, street sweepings, and nonhazardous wastes consisting mainly of food waste and rubbish (KENAO, 2007).

Waste is defined as “an item or a substance that is either damaged, beyond repair or can no longer be put to its intended use and is therefore to be discarded or parted with” (KENAO, 2007). This waste is generated, collected, transported and disposed of within a municipal authority’s jurisdiction, in this case, the Nairobi City County. The anthropogenic metabolism of the Nairobi system, given the statistics in section *2.3.1* to *2.3.3*, presents an overview of the demographical complex and stress on waste disposal and collectively, the waste management services of MSW.

The NCC thus introduced a zoning concept from October 2014 and an inauguration commencing with zone 7 comprising of Kangemi, Kilimani and Kileleshwa areas. The scheme divides the city into 9 zones[6] in total thus concentrating more on service delivery and efficiency in public-private[7] working relations between the NCC and registered private waste collection companies (NCC, 2012; 2014a). Worth noting is that this scheme is in the pilot phase of a bilateral project between the Kenya and Japan governments for a collection and transportation franchise system and it does not include the NMR[8].

Efforts to enhance segregation of garbage are being implemented wherefore organic waste is placed in green liner bags, recyclables in blue liner bags, and normal waste in brown liner bags (NCC, 2014b). The Governor kicked off a US$

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[6] Divided according to the population, area size, income level and its ratio planned at the constituency level except for the subdivision of Starehe constituency in which the CBD is demarcated as a zone.

[7] Termed as, cooperation with Public Service Providers (PSP).

[8] For more information on the project, see http://www.nairobi-swm-project.or.ke/.

2.27 million[9] project for placing colour-coded bins in sets of 3 to enhance sorting of garbage between recyclables and non-recyclables at the source of MSW generation (Njoroge, 2014). This is an effort targeting community participation as well as the other stakeholders in waste management. A monthly cleanup initiative was also launched and targeted to improve collection of waste (NCC, 2014b) and participation by involving Community based Organizations (CBOs) and especially women and youth groups who also operate in challenging zones such as slums and rivers to improve sanitation (Pamoja Trust, 2008).

2.3.1 Waste Generation and Collection

To enable waste collection[10], the system relies on the waste generators who are charged with collecting, segregating and disposing their waste in designated waste receptacles and ensuring that the waste is transferred to a licensed collector who shall transport and dispose the waste in a designated waste disposal facility such as a landfill[11]. Waste generators[12] are also required to minimize their waste by following cleaner production principles. These generators include households, schools and other learning institutions, hospitals and some commercial enterprises.

From the 1970s up to mid-1980s, garbage collection was rigorously carried out around the city by the local authorities (Kasozi and von Blottnitz, 2010). Due to deterioration of their vehicles and lack of maintenance coupled with institutional failures (KENAO, 2007), the services dwindled away to an almost halt. In this regard, the NCC presently does not collect waste from waste generators but rather at collection points or other areas where it is dumped.

Subsequently, the NCC does not charge residents for waste management services but generates revenue from license fees levied on private waste collectors as per KENAO (2007). Some private companies base their rates on the volume collected,

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[9] €1.67 million or KSh 200 million.

[10] Regarded as an import flow of MSW in this study.

[11] Regarded as a sink.

[12] Regarded as sources or generators.

the type of waste, and frequency of collection and location of the client and may offer services such as incineration and supply of bins (Garbage Dot Com Ltd, 2009).

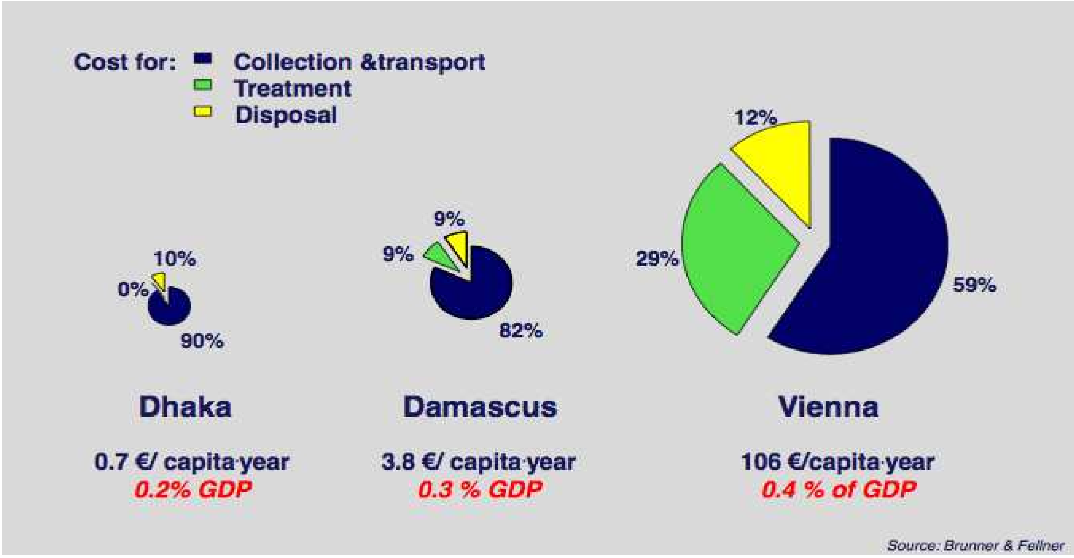

Figure 5: Costs of MSW management compared by GDP (Brunner and Fellner, 2007)

Brunner and Fellner (2007), report that low-income countries spend most of their solid waste management (SWM) budget on collection and transportation alone, which costs about 0.2% of their GDP on MSW management at US$ 0.8 per capita. However, in July 2014, the Governor re-introduced MSW collection services in Nairobi levied at US$ 1.14 [13] per HH per month and US$ 3.41 [14] monthly for institutions and commercial premises (Guguyu, 2014). Thus, HH per capita costs for MSW management for Nairobi at US$ 1.6 and the per capita GDP of US$ 2,917[15] indicate that MSW management as a fraction of GDP of the city is around 0.05%. Collection and transport alone account for 99% of the costs while disposal takes the remainder, with nothing done about treatment of the waste.

Comparing Nairobi to the three cities summary in *Figure 5*, the amount spent on disposal is negligible while collection and transport costs can be credited to private firms since the NCC does not currently offer direct services other than disposal at

[13] € 0.84 or KSh 100.

[14] € 2.52 or KSh 300.

[15] Calculated from the 2009 GDP of US$ 37 Billion and disposal charges of US$12 per tonne (€ 8.6 or KSh 1,020).

Dandora. It is understandable that a major portion of the population cannot afford to spend considerably on waste management due to low income and poverty however; while citizens are irresponsible about the environment and handling their waste in a responsible way, confidence in services delivery is important. The average citizen will employ the services that are cost effective and meet the individual need for disposal from a household level and thus the importance of effective and inexpensive combinations in waste management.

The reintroduction of collection services could translate to NCC collection management under the zoning concept, briefed in section *2.3*. This also controls unsolicited, unregulated and unprofessional participants from operating as waste collectors and limiting the impacts of improper collection, transportation and disposal of waste.

As a follow-up, 46 private garbage collectors out of 56 were barred from carrying out their operations in the City as a move to enforce operation standards (Njoroge, 2014; Guguyu, 2014). The NCC began standardizing by having a base minimum of 100 clientele and the types of vehicles private waste collectors should use to edge out the ones with too few clientele and the others with either dilapidated or undersized equipment (Njoroge, 2014). These standards specify a minimum 10 tonne vehicle capacity and it should be closed, branded with its respective company's logo, provide name and logo branded liner bags to ease identification and curb illegal dumping (Njoroge, 2014; Guguyu, 2014) hence reinforcing the 2006 Waste Management Regulations.

To bolster this, the NCC tasked the sub-county supervisors of environment to facilitate the creation of a database of clients willing to subscribe to the NCC collection systems reintroduced by the Governor of Nairobi. This strategy not only enhances competition between the waste collectors in the estates, suburbs and their environs but also improves collection and sanitation.

Part of the waste management strategy is the installation of 700, 3-tier litterbins across the CBD and its environs (NCC, 2014b) and by depending on the individual effort for keeping the city clean by not littering and binning of the waste at the designated points with segregation. The Dandora dumpsite will also have a perimeter wall constructed to divide it from a soon-to-be upgraded Dandora market and the establishment of a waste-to-energy (WtE) project to generate up to 50

Megawatts of electricity (Guguyu, 2014) in accordance with an integrated solid waste management plan (ISWM).

2.3.2 GDP and Poverty Level Indicator link to MSW

To figure out the quantity of waste generated and collected on aggregate, the link to consumption has to be scrutinized. In economics, the consumption function shows that consumption is correlated to income and logically it follows that waste generation is a shadow of consumption patterns. It is supported that MSW generation increase is due to high urbanization rates and economic development originating from increase in the chain reaction of revenue, consumption and waste production (Hoornweg and Bhada-Tata, 2012; Le Courtois, 2012).

Further, to understand how the spending trends of the population in Nairobi affects the generation and collection of MSW, the use of socio-economic tools aids in quantifying these factors. Hence, 2009 GDP and a poverty level indicator data are essential to reveal the overall consumption and the reason for a big margin between the slums, the general Nairobi region and thus, MSW generation, *ceteris paribus*[16].

Only a fraction of the SWM budget is allocated to disposal (Hoornweg and Bhada-Tata, 2012). From their budget, the NCC procured and commissioned 44 trucks in April 2013 together with 6 tractor shovels to load the tipper trucks, 19 side-loaders and 6 skip trucks to transport waste containers to be placed in markets (NCC, 2014a; Njoroge, 2014; Guguyu, 2014). They stated that 70% of MSW would be the capacity by the end of April 2013 at a rate of 1,400 t/d while Creative Consolidated carrying out CBD sanitation from March 1, 2013[17] handles a capacity of 250 t/d (Njoroge, 2014; Guguyu, 2014). Consequently, 30% remains uncollected daily alluding to the perennial problem of capacity for both the NCC and private sector to manage collection and disposal of MSW.

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[16] For instance, a rise in disposable income also increases consumption. Consumption for small income earners may exceed disposable income.

[17] The published date of contract commencement period between the NCC and Creative Consolidated.

As reported by the Nairobi Governor, the city generates an approximate 2,000 t/d[18] of MSW (NCC, 2014a), which calculates to 1.57 kg per capita per day using the 2009 Nairobi census and slums population figures as expounded in *Table 1*. Approximately 1,250 t/d total is the city collection limit while 750 t/d remains uncollected since the collection reported (Njoroge; Guguyu, 2014) is: NCC collection of 800 t/d, Creative Consolidated capacity of 250 t/d and other private firms that collectively manage 200 t/d. In 1998, JICA reported that the Dandora dumpsite was beyond its capacity having received 1.8 million m^3 of MSW while its estimated capacity was 500,000 m^3 and that the approximately 30 acre[19] dumpsite legally receives an average 830 t/d of MSW from records reading from 2006 to 2009 (ITC, 2001; von Blottnitz and Ngau, 2010).

Table 2: Calculated MSW by portions generated, collected and uncollected (NCC 2014a; Njoroge; Guguyu, 2014)

MSW	Portion	Kg/d	t/d	t/yr
Generated	City total	2,000,000	2,000	730,000
	Per Capita	1.57	0.002	0.6
- general	General total	1,449,956	1,450	529,234
	Per Capita	3.97	0.004	1.5
- in slums	Slums total	347,130	347	126,702
	Per Capita	0.95	0.001	0.4
Collected				
- share	NCC	800,000	800	292,000
	Creative Consolidated	250,000	250	91,250
	Other private firms	200,000	200	73,000
	City total	1,250,000	1,250	456,250
Capacity	Reported	1,400,000	1,400	511,000
	Initial Gap	650,000	650	237,250
Uncollected	City total	750,000	750	273,750

The GDP was calculated on a per capita average in slums using a poverty threshold of US$ 1.2 to approximate the amount of MSW generation in relation to

[18] This figure is corroborated in a JICA presentation by Higashinakagawa (2013).

[19] Other studies report it as: 26.5 hectares, 43.5 ha and even 53 ha.

consumption in the slums. These two economic indicators are used as scales to consumption stimulation from income of generators. In *Table 2*, the calculations are based on the 2009 GDP of US$ 37 billion[20] for a population of 3.1 million inhabitants of Nairobi for the same year of whom 1.3 million people live in the slums while 1.9 million people are the “general population” living outside the slums as exhibited in *Table 1*. The calculated Nairobi County per capita GDP is US$ 2,917, slum per capita GDP is US$ 438 while the general population per capita GDP is US$ 1,271.

The calculated amount of MSW generated per capita in the slums and the general population of Nairobi County is given in kg/day and ton/year. From the generated 2,000 t/d of MSW, 1,250 tonnes is collected. The reported capacity of 1,400 t/d (Njoroge, 2014) is not actualized thus revealing an initial capacity gap of 650 t/d from the total generated MSW estimation.

The data illustrates that the per capita general population generates three times as much MSW than the per capita slum population. Consequently, a stock of generated MSW is 730,000 t/yr from 0.6 t/capita/yr, the stock uncollected is 273,750 t/yr or 0.9 t/capita/yr in Nairobi County.

Since *Table 2* does not take into consideration the legal dumping limit of 830 t/d at the Dandora dumpsite, it simplifies the collection problem. It also does not consider the recovery of 200 t/d that end up in valorization. However, the adjusted collection based on legally accepted dumping is thus 1,250 t/d is collected, 750 t/d uncollected from generators, 420 t/d illegally dumped and 830 t/d dumped in Dandora dumpsite. Illegal dumping can thus be assumed to take place around the dumpsite and at unofficial locations within the city by the private firms as well. This analysis is modeled in *Figure 8*.

2.3.3 Models of Nairobi County MSW flows

From the analysis afore, a concept of material flows of the general MSW generated in Nairobi County is exhibited. The models follow the existing two-pronged MSW management system of collection and disposal and the flows in tonnes per day

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[20] GDP in current US$ (World Bank, 2014).

using the per capita generation statistics and collection aggregate figures presented in the previous section.

The model presented in *Figure 6* shows the input into the MSW management system boundary of Nairobi County as total generated MSW subject to disposal, while the three groups of collectors (NCC, Creative Consolidated and other private firms) are represented in the process *MSW Collection*. The capacity is represented as the flows *Collected* and *Uncollected* that end up in the processes, *Landfill* and *Dumped MSW* respectively.

At the process *Landfill*, which represents the Dandora dumpsite, a stock of 1,050 t/d is accumulated while 200 t/d is extracted from the landfill by scavengers, thus represented by the export flow *to recyclers and manufacturing*. At the process *Dumped MSW,* there is a probable stock of 750 t/d however, the export flow *F6* to the environment is unquantifiable due to unknown flows.

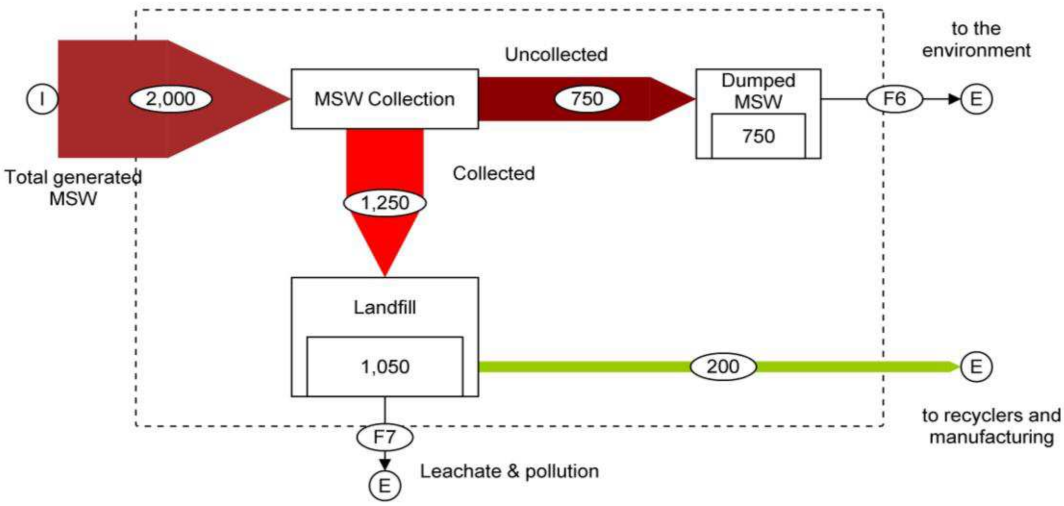

Figure 6: Status quo model of MSW flows (t/d) in Nairobi County

The export flow *F6* represents environmental pollution from dumping which can also be affected both negatively and positively. When it is positive, scavenging can recover recyclables or portions can be used as animal feed from the MSW generated by urban farms and even biogas generation that is privately pursued mainly by HHs. When negative, the uncollected waste ends up in trenches, drainage pipes, productive land and even the hydrologic cycle. The other export flow *F7*, *Leachate & pollution*, represents those negative environmental externalities that affect Nairobi River, which is adjacent to the dumping site, by leachate, open burning and scattering waste strewing into it. The flow is unquantifiable due to lack of data.

However, the status quo model can be expounded into a greater one by extending the MSW management system boundary and factoring in population, MSW generation, etc. For instance, if the NMR was to be included, we can estimate the amount of MSW using some of the statistics. This assumption uses the 2009 GDP and the 2007 projected population of 5.64 Million in *Figure 2* at a 1.57 kg/capita/day rate of MSW generation as in *Table 2*. The calculation estimates a total 8,855 t/d of MSW would be generated, which is over four times the city's 2,000 t/d in status quo. Consequently, 7,605 t/d would be uncollected at the current 1,250 t/d collection capacity.

Plausible reasons for the margin in per capita rates are the differences in waste generation rates that can occur even within a city while periurban areas may consume less due to lifestyle differences and their potential to reuse and recycle (Hoornweg and Bhada-Tata, 2012). Issues to consider in the NMR due to lifestyle differences is the potential for the periurban areas to carry subsistence farming, produce biogas for private use, composting and availability of fresh organic foods and produce from proximate kiosks or markets.

There still looms a capacity gap, as lack of resources and points for central storage as well as collection in the various areas is not entirely addressed. The example above assumes that there is no change in MSW collection capacity as shown in *Figure 7*. The model reveals a significant increase in dumping flows outstripping collection to Dandora dumpsite, hence the need for another dumpsite and collection facilities as indicated by the flow *Uncollected*.

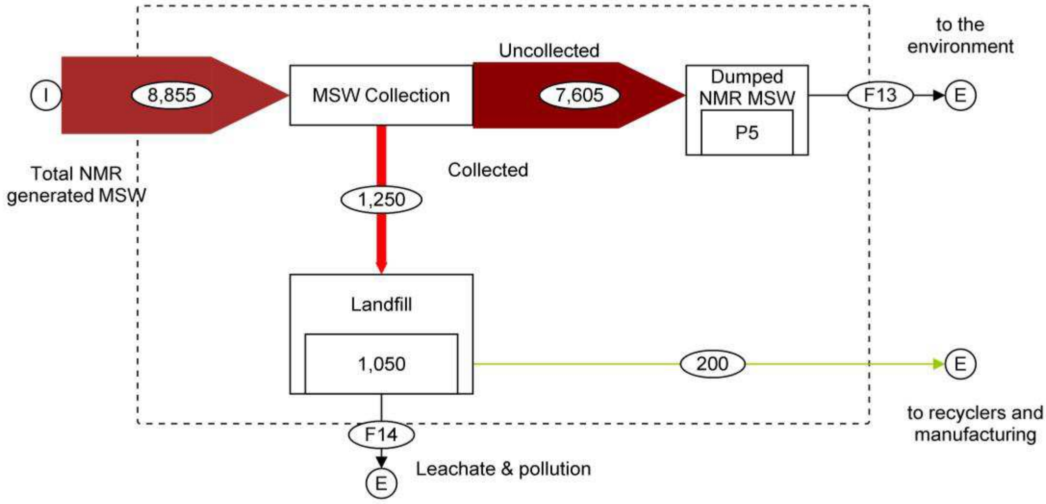

Figure 7: Example of MSW flows (t/d) in NMR based on the status quo model

The flow to *Dumped MSW* in all the above cases is thus more concerning than to the landfill. For this reason, it is important for the purpose of this study to determine the amount of MSW for nutrient recovery that is available and this is done in section *3*. In addition, two negative export flows in the models cause pollution while there is a positive export towards recycling and manufacturing. These exports shall be discussed further in the next chapter.

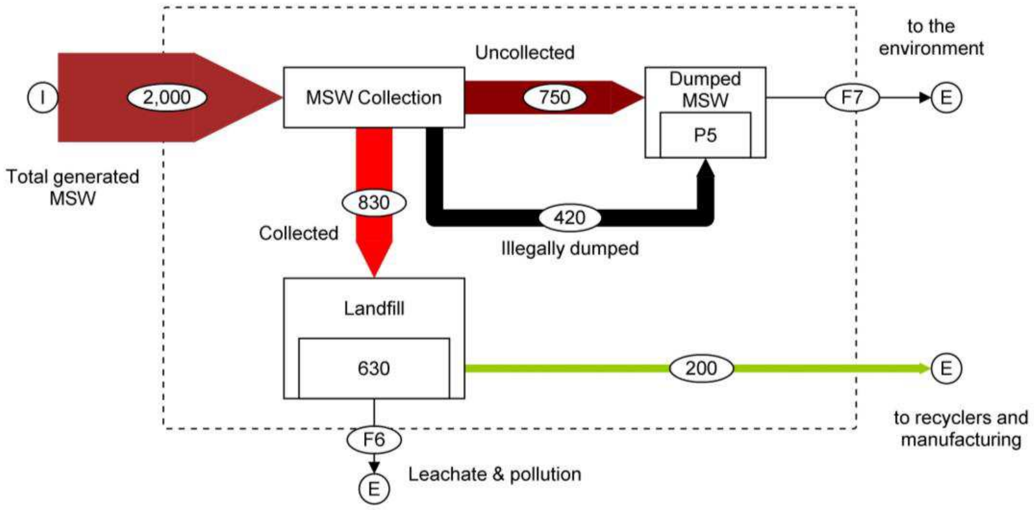

Figure 8: Illegal dumping factored in to the status quo model

In the model above, 2,000 t/d is generated, 1,250 t/d is collected while 750 t/d remains uncollected. The dumpsite limit of 830 t/d however increases dumping of a further 420 t/d from collection by private firms, giving a total flow to Dumped MSW as 1,170 t/d in status quo. However, the MSW stock *P5* is affected by various factors such as recovery for recycling and manufacturing, animal feed and composting because it can occur anywhere along all the flows except from the collected stock at the landfill in Dandora, thus exports are not all quantifiable from lack of such data.

The models above are assisting tools used to direct research into missing data and flows. The lack of data can thus be filled in through either hypothetical or substantive estimations from quantitative data. It is likely that some factors such as reuse in the periurban areas cannot be certainly quantified without direct survey due to materials recirculating in subsistence lifestyles, which can be treated as stocks in this case. Some, if not all periurban areas practice open burning in dumps created in private land since collection services of MSW are either inaccessible or inconveniently costly for the sub-county level. Consequently, more research in terms of periurban generation and disposal would be required to support the NMR expansion in terms of distance, population and waste management especially for the organic fraction.

In summary, the MSW generation is 1.57 kg/capita/day while it is higher for the general population (3.97 kg/capita/d) than in the slums (0.95 kg/capita/d). The slum population has a significantly lower per capita GDP of US$ 438 as opposed to US$ 1,271. Dumping can be primarily attributed to slums due to the lack of proper disposal as well as insufficient, if any, collection; and private firms not allowed to dump in the dumpsite once the 830 t/d limit is reached. If the Nairobi County expands into NMR at status quo, the City would need more capacity for collection and disposal. The models indicate negative outputs to the environment for instance, Nairobi River, from leachates, open burning pollution and illegal dumping but a positive output from recovery to recycling and manufacturing processes. Despite the negative externalities and connotations, the models present a big potential for resource recovery for nutrients in MSW.

"In nature there is no waste; everything is connected to everything else; everything must go somewhere; and there is no such thing as a free lunch."

Dr. Barry Commoner, Laws of Ecology

3 OFMSW

The focus now turns to the organic fraction of municipal solid waste (OFMSW) since it contains the nutrients N, P and K mentioned as indicators in previous sections of this study. OFMSW is effectively the largest and bulkiest proportion of MSW. To build the theoretical model of Nutrient Balance based on a Sustainable Nutrient Balance, the recovery of OFMSW nutrients from waste streams terminating at the landfill is paramount. This study chapter therefore builds theoretical methodology by systematically analyzing OFMSW, its flows and chemical composition.

3.1 Why concentrate on the OFMSW?

The mammoth fraction in MSW is OFMSW. The local inputs of nutrients to this source include the hinterland and urban farms. MSW is generated by sources through flows comprising household, restaurant and market waste, among other organic wastes that end up in landfills like Dandora or pollute the urban and periurban environment[21] (Cofie et al., 2010). As the generators of waste, the urban population is the major source of the OFMSW streams terminating at landfills. MSW streams are consequently the key source of nutrient loss in the urban environment.

OFMSW consists of organic waste: putrescibles - food wastes such as peelings and leftovers; garden or farm wastes such as cut grass, leaves, tree trimmings, plant based materials; paper, and wood (Pichtel, 2014) with high moisture content and density, depending on the weather. This fraction is composed of nutrient rich materials normally found in waste streams in African countries at about 51% of the entire composition of municipal solid waste (CCN, 2010) while 38% recyclables and 11% residual waste constitutes the rest (von Blottnitz and Ngau, 2010). By valorizing this fraction, capacity of the dumpsite can be greatly improved through diverting this waste stream from generators travelling directly to landfills.

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[21]The urban or periurban environment is referred to as an urban nutrient sink in Cofie et al. (2010).

In lower income and middle-income countries such as Kenya, the problem of MSW management stems from lack of resources to ensure sanitation and proper waste management since the municipal budgets attaches 1% to disposal and over half the budget on collection and transportation. According to Brunner and Fellner (2007) as explained in section *2.3.1*, collection and transportation uses 90% and disposal takes up the 10% remainder of the waste management budget of these countries. In Nairobi, collection and transport is primary, taking up 99% of the total cost while disposal takes up a mere 1%.

3.1.1 What is Sustainable Nutrient Management?

For the above reasons, a sustainable nutrient balance (SNB) can be defined as the recovery of nutrients from waste streams of the OFMSW in (urban) sources and sinks and dispatching them back to the anthroposphere for reuse in a way that closes the nutrient cycle. Recovery of these resources or nutrients can be achieved through urban resource recovery or rather, urban mining in landfills[22] (Recology, 2015). This definition is further discussed in section *4.1.1*.

Consequently, increase in source separation and collection of MSW in the zones stated in section *2.3* realizes better and cleaner fractions with reduction in waste volumes supported by the blossoming of viable valorization markets. Presently, over 2,000 people[23] are engaged informally in the resource recovery sector in MSW handling at the Dandora dumpsite. They recycle about 200 t/d of the usable fraction of MSW (UFMSW), which is just 7% of the entire inorganic fraction (CCN, 2010). Nairobi's OFMSW hurdles lie in the awareness and market of composting, which are both currently miniaturized (Hoornweg and Bhada-Tata, 2012) and the termination of OFMSW streams at the Dandora dumpsite.

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[22] To read more on urban mining, see: www.ids-environment.com/common/paper/paper_54/read_aerobic_landfilling.pdf.

[23] To read more from the Mukuru Recycling Centre, see: www.ucl.ac.uk/dpu-projects/drivers_urb_change/urb_society/pdf_gender/HABITAT_BestPractice_Senner_Mukuru%20_Recycling.pdf.

3.2 Resource Recovery

The ISWM project (2010) states that 51% of MSW is organic which is a viable source of energy production as well as nutrient recovery. This study focuses on nutrient recovery as a resource from MSW management. The importance of diverting the OFMSW from waste streams is for valorization through: composting, diversion to ease downstream recovery, improving material quality at minimal cost especially from source separation, avoiding commingled waste mechanical separation systems that are expensive (Kasozi and von Blottnitz, 2010), and enhancing a NB of the system as described in section *4.1.1*.

To save on transportation and disposal costs, Material Recovery and Transfer Facilities (MRF) are used to salvage recyclables and the organic fraction not sent to the composters (CCN, 2010). This resource recovery from waste treatment and disposal can significantly contribute to closing the nutrient cycle and develop a sustainable nutrient balance. The nutrient cycle is considered open since nutrients in waste streams do not return to the natural cycle but rather are lost to landfills that hold them as stocks; this is further poised in section *4.3*.

From the positive export flow outputs modeled in section *2.3.3*, MRFs have a high potential to recover both organic and inorganic materials for valorization. This can be essential for recycling and manufacturing however, in this study, the focus is on the organic fraction; the MRFs are essential to this study as they offer a way to recover high quality organic fractions from segregation while recovering the landfill.

Table 3: Status quo estimated and forecasted OF quantities (von Blottnitz and Ngau, pg.3, 2010)

	Quantities in tonnes/day					
Year	**2009**		**2015**		**2020**	
	Best	**Worst**	**ISWM**	**BAU**	**ISWM**	**BAU**
Total generated	3000	3200	3500	4400	4000	5400
OF valorized at source	2%	1%	10%	2%	25%	2%
OF otherwise valorized	1%	1%	4%	2%	5%	2%
OF rotting/scavenged/illegal	35%	39%	21%	36%	5%	36%
OF to official dump	13%	10%	15%	10%	15%	10%

Table 3 is adopted in part from von Blottnitz and Ngau (2010), concentrating on the OFMSW. The generated MSW for 2009 is a 50% higher estimate against this study's value from *Table 2* in its base year. The former table is made on the approach of an ISWM plan that postulates the pathways of the 51% OFMSW collected per day.

In this regard, the predictions at status quo analysis show that, the best scenario would recover 3% OFMSW at the source through valorization: this can be by biogas production, composting or animal feeds. The remaining 35% can be considered to be the OF uncollected and/ or dumped while the fraction that is actually collected and makes it to the dumpsite is only 13% at best.

This explanation can be integrated into the earlier conceptual model in *Figure 8* to further enhance a MFA scenario from calculation using the model: 42% of MSW is legally dumped at the dumpsite in Dandora while 58% consists of illegal dumping and valorization at the source or otherwise.

However, by the estimates of percentage content of OFMSW, we can derive that for 2,000 t/d generated in Nairobi, 51% is OF, giving us 1,020 t/d. The estimates do not differ by a big margin and therefore, in evaluation, the general and calculated assumptions are upheld.

The important observation from von Blottnitz and Ngau (2010) is that waste composition from different generators varies greatly with up to 60% OF content in HH waste and a decrease to 37% at collection points as tabulated in *Table* 4.

Table 4: Analysis of OFMSW (% composition) (Kasozi and Blottnitz, pp. 9-10, 2010)

	Compositions (%)	
Organic/ Biodegradable	**At Immediate Source**	**At Communal Collection Waste Points**
Waste source	**Directly from Households**	**Located in Residential areas**
Residential areas (HHs)	58.6	46.1
	Direct from premises	**In general business & commerce area**
Retail & shops	43.6	
Offices & workplaces	25.9	
Institutions, including Education, Religious & non-hazardous healthcare	48.9	
Catering - restaurants, hotels & eating places	69.2	
Business, commercial & institutional generators	36.4	51.3
City-wide	50.9	43

Table 4 is constructed from surveys carried out by Kasozi and von Blottnitz (2010), also found in von Blottnitz and Ngau (2010) and CCN (2010). From this analysis, the deduction is that HHs and restaurants are the major contributors to the OF and rightly so as the population spends a big proportion of their time in these two areas of the anthroposphere. This is also an indicator of the impact that population and consumption based on GDP affect MSW management, especially on where to concentrate collection to recover OFMSW.

However, the inclusion of markets in the analysis, since they deal mainly in high quantities of organic produce, in the same manner above would enhance information on OFMSW generation. Furthermore, the variation of between 60% and 37% at collection points can be explained by the valorized or reused 3% at each source with comparison to more HHs than restaurants. Moreover, wastes from HHs differ greatly from waste from institutions since more processed foods are consumed outside the HHs and more organic food wastes are consumed in the luxury of HHs and restaurants.

3.2.1 Waste Analysis

In Nairobi, the waste from the generators is not source separated[24] and the collectors are only transporters and scavengers. The only separation done is at the landfill site where scavengers sift for reusable, recyclable and valuable elements for trade. Source separation is ideal to enhance material recovery from the waste streams and reducing MSW management costs.

For purposes of this study, the UFMSW is the amount of MSW that can be recovered from the waste streams for reuse, recycling and as feedstock for the WtE plant. The OFMSW is the fraction of MSW that can be recovered for composting, biogas production, etc.

From the models of Nairobi County in section *2.3.3*, uncollected and commingled daily MSW fractions tend to accumulate around the city fast while the Dandora dumpsite is not an optimum solution, yet. There is an alternative however for mixed waste treatment because of the current non-segregation of waste. This presents a positive implication for resource recovery at the landfill since the current volume at the Dandora dumpsite can theoretically be rechanneled for production of energy and other applications while retrieving inert waste for sanitary landfilling. This is a method to recycle the landfill that can enhance land use management, environmental cleanup and mitigation of negative externalities for sustainability.

Considering that only 7% of UFMSW is recycled by scavengers at a rate of 200 t/d, the potential for material recovery can be enhanced by segregation while the current commingled waste at the dumpsite can be simultaneously and progressively reprocessed. One advantage with this option would be to retrieve more fractions for appropriate processes while increasing capacity of storage (De Baere and Mattheeuws, 2013) thus eliminating a need for more space or alternative land for landfilling.

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[24] Except for the pilot project in zone 7: refer to footer [8] and/ or section *2.3.*

3.2.2 Waste Composition

The OFMSW is composed of various kinds of organic materials. For this, we can also study the composition of the OFMSW further by quantifying the materials. This study presents the breakdown by ITC (2001) since it is the only one available at the time. As mentioned in section *3*, this study on OFMSW is only concerned with the highlighted materials in *Table 5*.

It is thus interesting to note that even in 2001 there seemed to be a higher production of food wastes in low income than in the high income HHs. This is probably due to land occupied, income inequality, lifestyle differences and population density and size thus considering, the high-income food waste generation trend of OFMSW is actually higher. The grass and wood difference is also a sign that the implication of nearly half of the population living in slums that occupy 1% of Nairobi's land can also be reflected in waste generation.

Table 5: MSW study carried out in Nairobi (ITC pg. 3, 2001)

Material	Average	High income	Low income
Food	51.5%	50%	57%
Paper	17.3%	17%	16%
Textiles	2.7%	3%	2%
Plastics	11.8%	14%	12%
Grass/Wood	6.7%	8%	2%
Leather	0.9%	1%	1%
Rubber	1.5%	1%	2%
Glass	2.3%	2%	2%
Cans	1.7%	2%	1%
Other metal	0.9%	1%	0%
Other	2.7%	7%	4%

The ITC reported the proportion of dust and fines in their analysis was great and their calculations are presented in *Table 6*. Presence of dust fines can also be a pointer of nutrient transfer from soil into the waste streams terminating at dumpsites, which can accumulate in time and affect lithophylic substances such as Phosphorus.

Table 6: Chemical analysis of MSW (ITC pg. 3, 2001)

Moisture	64.2%
Ash	8.9%
Combustible	26.8%
C	49.33%
H	5.45%
N	1.22%
S	0.14%
Cl	0.21%
O	43.75%

3.2.3 Sampling

The waste analysis data is retrieved from secondary statistics on studies done at the Dandora dumpsite and around Nairobi by JICA (Japan International Cooperation Agency), members of The Environmental & Process Systems Engineering Group from the University of Cape Town in conjunction with the UNEP and ITC (Intermediate Technology Consultants).

Notably, in an analysis report by the latter, it was stated “[t]here are no statistics for total production of wastes in Kenya (…)” (ITC, 2001) and thus, the data is mostly aggregated and projected with some information on collection trends and the generation statistics for instance, in section *2.3.2*. Whereas the substance composition values for N, P and K in section *4.1.1* will be based on studies by Murell (2008) and Manyuchi et al. (2013).

3.3 Variability in the Study

There is variability in the statistics and literature majorly between this study and the ISWM plan. In reference to section *2.3.2*, this study is based on the published MSW generation estimations for 2014 of 2,000 t/d in Guguyu (2014) and NCC (2014a; 2014b). The ISWM project data is based on the year 2009 however, with estimations at least 50% higher at 3,000 to 3,200 t/d while ITDG estimated 2,400 t/d in 2004 (von Blottnitz and Ngau, 2010). The generation at micro level was 0.59, 0.61 and 0.65 kg/capita/day from JICA, ITDG (Intermediate Technology Development Group) and the ISWM project respectively. In comparison, this study calculated the waste generation as 1.57 kg/capita/day, over twice the amount of the ISWM plan. This is principally due to the variance in population, GDP and total estimates of MSW generated as illustrated in *Table 7*.

Table 7: Variance based on population, GDP and generated MSW between four studies

Item	JICA	ITDG	ISWMP	Study
Base year	1999	2004	2009	2009
Population	2,143,254	2,656,997	3,265,000	3,138,369
GDP	$12.9 B	$16.1 B	$37 B	$37 B
Generated t/d	1,530	2,400	3,200	2,000
kg/capita/day	0.59	0.61	0.65	1.57

This however does not affect the aggregate share of OFMSW which ITC (2001), Hoornweg and Bhada-Tata (2012), Cofie et al., (2010) and World Bank (2011) have estimated as around 51% for African, middle-income and low-income areas and countries. From the primary and secondary analysis, it emerges that more than 51% of the waste generated in Nairobi is organic waste. The ISWM project report estimates that half of this fraction, i.e. 25% is about 1,000 t/d while this study calculates that 51% is 1,020 t/d.

In 1999, estimates of MSW generation by JICA were 1,530 t/d (von Blottnitz and Ngau, 2010) and this breakdown is briefly illustrated in *Table 8* showing the MSW generated in tonnes/day from HHs, markets, shops and restaurants and including road sweepings. The assessed MSW collection rate of von Blottnitz and Ngau (2010) is at 50% while the collection rate of this study is calculated as 62.5%.

Table 8: JICA estimations of 1999 MSW generation (ITC pg.3, 2001)

Generator	tonnes/day
Shops and restaurants	94
Houses	1,285
Markets	82
Road sweepings	69
Total	**1,530**

To recapitulate on *Table 4*, it is shown above that HHs, restaurants and markets contribute the largest portions to waste streams. With the calculations of this study and supporting evidence from other studies carried out both in and around the Dandora dumpsite, Nairobi and other parts of the world, it is clear that more than 50% of MSW contains organic matter. This organic matter is thus easily segregated at source when proper measures are put in place. The quantity or quality may vary due to natural conditions, collection schedules, types of MSW generators or sources, capacity of collection and actions of generators.

In retrospect, existing publications also have conflicting data as to the size of land on which Dandora dumpsite occupies or operates. Majority studies such as this one use a 30 acre average while other studies use 25.7 hectares[25]. According to von Blottnitz and Ngau (2010), there are records for 2009 collection levels from the CCN that peg 830 t/d as the allowed dumping maximum at Dandora dumpsite. Previously, KENAO (2007) had carried out an audit that revealed the lack of record keeping and this is markedly an improvement but that is the only reported figure.

Subsequently, this study relies on the associated calculations and estimations in section *2.3* as the similarities in trends correspond to the other study projections from official statistics and estimations. A question of what happens to the waste transported to the dumpsite when the daily quota is reached raises further concern, however, for resource recovery it presents an opportunity which will be elucidated in chapter *4*. An assumption for the 420 t/d is explained using *Figure 8* and *Table 3*.

Furthermore, this study presents the potential through which the dumpsite can be recovered by resource recovery. Urban mining of a landfill is a way of volume reduction and through combustion of UFMSW; the WtE plant can convert the waste into energy. The evidence does not support the closure of the dumpsite but rather indicates that reclamation can be done and the need for an alternative land for landfilling is not substantially discussed by the studies. By closing Dandora dumpsite, the problem cannot be solved by simply covering the top with soil. The reasons will be further elaborated in the next chapter.

3.3.1 Projecting waste quantities

Nairobi is growing in terms of demographics as well as in urban sprawl. The most probable method of estimating the generation of solid waste aggregates is to factor in population growth as well as GDP growth for forecasting MSW generation trends. For this study, extrapolation of population and GDP data was done using growth rates and historical patterns. MSW generation can therefore be calculated using the factors of the respective fractional composition of MSW for aggregates.

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[25] Discussed on page*16* and footnote [19].

In summary, the OFMSW is the largest fraction that is not valorized in Nairobi County. It is founded in this study through calculation that the OFMSW is more than 50% of MSW collected. The potential for resource recovery is highlighted by the informal sector recycling capacity of 200 t/d in an activity carried out by over 2,000 scavengers. This is a 100 kg per capita or 36.5 t/capita/yr informal niche responsible for 7% of UFMSW recovery. This also highlights the importance of waste segregation to enhance recovery of fractions for valorization and the need for MRFs. This will as well increase value to recovered materials and enhance recycling. Despite numerical and statistical differences and use of a combination of aged and new information in the studies done on MSW in Nairobi, the results converge towards the same trends but there is a need to harmonize the data available and improve research. The research however shows that the need to close Dandora and move to another location is unfounded in the various studies due to lack of substantial analysis in the literature as well as lack of scientific proof. This issue is revisited in the next chapter.

> **“Don’t only practice your art, but force your way into its secrets, for it and knowledge can raise men to the divine.”**
>
> **Ludwig van Beethoven**

4 Nutrient Balance

Based on the data analyzed in this study, this section will focus on building the theoretical model that tests the NB hypothesis “whether nutrients can be recovered from MSW streams to sustain anthropogenic metabolism by capping on their losses from waste disposal.” This modeling is hypothetically defined as a method for estimating the nutrient loadings of N, P and K in waste streams of OFMSW terminating at the Dandora dumpsite that can be recovered back to the nutrient cycle. The model uses findings of the nutrient loadings, which will act as indicators of nutrient loss from the anthroposphere to the landfill through OFMSW. This section borrows liberally from the studies by Phong et al. (2010), de Molina et al. (2010), Murell (2008) and the report by DEFRA (2013) as guidelines to structure the model.

4.1 Nutrient Balance in OFMSW

The nutrient balance methodology was developed by OECD and adopted by statistical databases such as EUROSTAT for agricultural purposes and for country comparisons (DEFRA, 2013). In the DEFRA report (2013), nutrient balance is an accounting system for nutrients that identify where they are coming from to control the amount of nutrients doing damage. According to Bindraban et al. (2000), land quality includes the purposes of environmental management as a fundamental element of sustainability. A nutrient balance is therefore a nutrients indicator examining inputs and outputs to reveal positive or negative interactions in organic material streams that cause environmental problems and affect land quality.

Accordingly, using sampling data, a nutrient balance can simulate a method to achieve a sustainable nutrient balance. The NB provides a simple technique for estimating the annual nutrient loading (Phong et al., 2010) by giving an indication of the potential risk associated with loss of nutrients. These losses can impact on air quality (ammonia emissions), water quality (nitrate and phosphate levels in rivers) and climate change (nitrous oxide emissions) (DEFRA, 2013). The nutrient balance detects leaching, eutrophication, chemical deterioration of soil and loss of potential production capacity or scarcity of nutrients caused by insufficient fertilization and so on that is important for soil productivity and nutrient replenishment (de Molina et al., 2010).

Hence, the proposed NB model in this study is a tool for presenting the assumption of existence of nutrient stocks in the Dandora landfill owing to the OFMSW portions accumulating there. To achieve balance, the inputs and outputs should be complementary (Σ in = Σ out). If a balance is not achieved, the deficit is considered as either a stock or loss within the system being evaluated, which in this study is the Dandora dumpsite.

The input sources considered by Phong et al. (2010) and DEFRA (2013), are atmospheric deposition and biological fixation, inorganic and organic fertilizers, manures from livestock, atmospheric deposition, seeds and planting materials, harvested crops, forage, harvested fodder crops, pasture and crop residue.

This theoretical study however, does not incorporate use of the soil nutrient balance data as such but deviates by using the inputs as derived from MSW generation statistics presented in section *2.3*. The inputs are an estimated calculation based on OFMSW analysis of waste composition and theoretical assumptions based on models for observing particular flows to investigate. The inputs for this theoretical model as discussed in section *3* are consequently limited to the 51% of MSW generated at a rate of 2,000 t/d by the city, which is assumed to originate mostly from HHs, restaurants and markets. The outputs are thus derived through estimated calculations.

This nutrient balance model is structured from the studies by Murell (2008), Phong et al. (2010), de Molina et al. (2010), and the report by DEFRA (2013). As stated in the second chapter of this study, the system boundary is the Nairobi MSW management system in the base year, 2009. The sources of OFMSW are the waste generators and the flows are driven by waste collection, non-collection, dumping and extraction of nutrients from the system. The sink is the Dandora dumpsite occupying a 30 acre piece of land that should hold the nutrients as a stock to prove the hypothesis true.

In order to build this model, rudimentary representations such as in section *2.3.3* can be useful bases to help indicate missing information, data needed and processes for expansion, further investigation or exclusion.

4.1.1 Nutrient Balance for the Study

This tool is used to measure the change in stocks of nutrients in the OFMSW streams to the dumpsite. The NB monitors the equilibrium between inputs and outputs containing nitrogen, phosphorus and potassium (NPK) existent in the organic waste streams. The nutrient balance is required to determine through calculations, the amount of N, P and K gained or lost for the quantification of these nutrients that end up in the Dandora landfill since direct analysis was not performed for this study. The method used is supported through calculations and estimations by research on composting and anaerobic digestion of organic materials.

In argumentation to support the study's hypothesis, DEFRA (2013) reports that urban nutrient flows might reveal the potentials for nutrient recycling in agriculture observing that the problems occur from expanding megacities and inadvertently mismanaged organic waste, which this study postulates to end up in landfills. To enhance sustainability, plant nutrients should be recovered and reused to close the ecological nutrient cycle, which in return yields a sustainable nutrient balance. "Concomitantly, recycling can reverse nutrient mining as well as remediate health and environmental problems caused by the organic waste, (…) but a lack of information must be addressed" (DEFRA, 2013).

Incidentally, a dearth of nutrients indicates diversion of OFMSW from the landfill while a surplus poses a serious environmental risk since positive nutrient balances lead to pollution of ground and surface waters (Bindraban et al., 2000; DEFRA, 2013).

4.2 Development and use of a Nutrient Balance Model

According to conceptual evolution:

- At initial stage, the model can show low external loading, low or no internal loading.
- Early development can show high external loading, low or no internal loading.
- Over time, it can show high or low external loading, continued internal loading. Can be measured in quality e.g. nutrients concentration and quantity e.g. nutrients per acre.

These observations by Phong et al. (2010) can be used to analyze nutrient balances taken periodically to estimate the gain or loss of nutrients.

4.2.1 Advantages of Nutrient Balance

The advantages of using a NB are:

- It is the only means to capture all wastes from generators (Beigl et al., 2008).
- It aids in quantification of changes in nutrient stocks as a crucial identifier to problematic systems.
- It sets current conditions to measure changes for future work by identifying areas of concern.
- The difference between gross inputs and outputs of nutrients to the system is used as a measure of these changes.
- The indicators in the NB combine the rate of nutrient change and the nutrient stock.
- The model is flexible and can be customizable.
- It can estimate a full range of nutrient inputs and removals from all sources.
- It can assist in the development of waste management strategies.[26]
- It can assist in the planning of waste collection services.[27]
- The nutrient input or removal from each source is either estimated directly (atmospheric deposition) or calculated by applying a coefficient (e.g. for the amount of nitrogen that a dairy cow produces each year) to the corresponding physical data characteristic (e.g. number of dairy cows).
- The relevant coefficients are derived from research and the physical data is taken from a wide range of data sources, many of which are already published as official statistics.

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[26] Referenced: Daskalopoulos et. al., 1998 (Beigl et al., 2008).

[27] Referenced: Grossman et. al., 1974 (Beigl et al., 2008).

4.2.2 Disadvantages of Nutrient Balance

The report by DEFRA (2013) critiques the system as:

- Although based on internationally recognized methodology, the NB estimates are subject to a level of uncertainty/ error margins.
- The physical data on which the estimates represent are subject to uncertainty because it is generally collected using a sample survey with associated sampling error margins.
- Similarly, the coefficients are derived from sound research but are subject to uncertainty and are based on average rates, out of necessity (e.g. average amount of nitrogen taken up by growth of a tonne of wheat).
- There can be a considerable amount of variation within averages with no cost-effective method of considering this variation.
- Bindraban et al. (2000) state that different NBs follow different inputs and outputs thus if used for the same study, the result may lead to different forms of imbalances and cause problems of completely different character.
- This nutrient budget is partial because it abstracts only the nutrients that are estimated and it does not include factors such as erosion, runoff, exact input and output quantities and measured data or atmospheric deposition (Murell, 2008).
- Reconstruction of historic nutrient balance requires historical indepth knowledge of the site features e.g. soil and geomorphology features (de Molina et al., 2010).
- While historical data that exists might be contradicting and inaccurate, it may be biased to conceal facts in cases such as impacts on the area (de Molina et al., 2010).

Some of the inherent drawbacks expected of this theoretical methodology are:

(a) Lack of precise data on inputs by the generators of OFMSW,
(b) No measured outputs in leachate and pollutants,
(c) No measured nutrient concentrations or published nutrient removal rates,
(d) The materials are only calculated in wet weight,
(e) The model is completely dependent on estimations,
(f) A difference when P and K are used in either oxide or elemental form.
(g) No in-depth historical records on the landfill.
(h) No direct sample analysis was done.

Assumptions:

(1) The NB is incremental in inputs into the dumpsite than output,
(2) The nutrient content calculated from OFMSW does not increase or decrease annually therefore, it is constant,
(3) The only output from the dumpsite is through decomposition and leachate,
(4) The nutrients are stable and the use of coefficients based on decomposing and leaching estimations,
(5) Atmospheric deposition is factored in leachate due to water presence in the leachate,
(6) The dumpsite contains soil from gradual deposition.

4.3 Rationale for a Static Model

In section *3.1.1*, SNB is defined as the recovery of nutrients from waste streams of the OFMSW in sources and sinks in a way that closes the nutrient cycle. However, Brunner (2013) observes that over a short time, nutrient cycles are not closed but are spirals because "…the natural system does not come back to exactly the same point." The models in *2.3.3* are based on static hypothesis and they reflect upon the asertion by Brunner (2013) that static situations form cycles while volatile systems are like spirals oriented to a certain direction. de Molina et al. (2010) also find that a model reconstructing a historic nutrient balance must inevitably be static.

To support this further and to explain the unquantifiable flows, Sheldrick et al. (2002) summarize that nutrient losses occur as follows: the substances N and K are affected by leaching. N is lost through leaching as nitrate, volatilization as ammonia and gaseous loss through denitrification. P is lost through soil fixation and topsoil erosion; it is recoverable from sources such as agricultural land at 20-30% for the first year, and then continually decreases annually. K is lost through leaching but it accumulates in soil when input increases.

Therefore, the missing data can be quantifiable from the chemical pathways by which the substances change in composition. For N, volatilization into ammonia (NH_4) presents a landfill problem in itself as it accumulates in leachate. Calculations of the nutrient concentrations are essential for this model in that they present quantifiable data for the nutrient balance.

Calculation of Input of N, P, K in OFMSW

From Murell (2008) and Manyuchi et al. (2013) this study assimilates the conversion factors for calculations of P and K as 2.29 and 1.20 respectively. This converts elemental P to P_2O_5 and K to K_2O. We can then calculate for the Dandora dumpsite, the Nutrient input in kg/ha using equation 1:

Equation 1:

$$\text{Nutrient Input} = \text{OFMSW (kg hectare}^{-1}\text{)} \times \text{nutrient concentration (\%)} / 100\%$$

To derive the nutrient input into Dandora dumpsite, the OFMSW kg/ha has to be calculated first. For the calculations below, the *Figure 8* numbers are used for the OFMSW (51% of MSW generated). The reason for use of this status quo model is that the model has all the factors and flows considered within it, for this study.

Therefore: 51% of 2,000 t/d = 1,020 t/d OFMSW generated.

Thus, 638 t/d is collected, 383 t/d is uncollected, 214 t/d illegally dumped, 423 t/d landfilled, and 597 t/d is the uncollected + illegal dumping total.

In the 12.14 ha (30 acre) dumpsite, the OFMSW kg/ha input concentration rate can be calculated:

As: 1,020,000 / 12.14 ha = 84,020 kg/ha generated

Therefore, 52,553 kg/ha is collected, 31,507 kg/ha uncollected, 17,644 kg/ha illegally dumped, 26,466 kg/ha is landfilled, and 49,152 uncollected + illegal dumping.

The calculations above reveal the nutrient concentrations and are further converted to nutrient concentration per hectare. From the calculations using equation 1, the N, P, K flows are calculated using per day figures as:

For N: this study uses the figures of Vermicompost[28]. The study was carried out in Harare, Zimbabwe where the weather conditions are similar to Nairobi's.

Nutrient composition (%)	Vermicompost	Vermiwash
Ammonical-N	1.05	0.20
Nitrate-N	0.0	0.09
Nitrogen	1.05	0.29
P_2O_5	0.29	0.0
K_2O	0.19	0.47

Figure 9: Chemical composition of Vermi-products (Manyuchi et al., 2013)

Therefore, 84,020 x 1.05 / 100 = 882 kg/ha generated; 552 kg/ha collected; 331 kg/ha uncollected; 185 kg/ha illegally dumped; 366 kg/ha landfilled; and 516 kg/ha uncollected + illegally dumped.

For P_2O_5: 84,020 kg/ha x 2.29 / 100 = 1,924 kg/ha in generated OFMSW;

1,203 kg/ha collected; 722 kg/ha uncollected; 404 kg/ha illegally dumped; 799 kg/ha landfilled; 1,126 uncollected + illegally dumped.

For K_2O: 84,020 kg/ha x 1.20 / 100 = 1,008 kg/ha in generated OFMSW;

631 kg/ha collected; 378 kg/ha uncollected; 212 kg/ha dumped; 418 kg/ha landfilled; 590 kg/ha is uncollected + illegally dumped.

The input calculations above are tabularized in *Table 9.*

[28] Vermicomposting is optimally carried out at feedstock temperature range of 25-45◦C; pH 5-9 and moisture content 45-75%. Nairobi has an average temperature of 25◦C.

Table 9: Summarized OFMSW and N, P, K Inputs for NB Model

*Per Day figures	OFMSW t	OFMSW kg/ha	N kg/ha	P_2O_5 kg/ha	K_2O kg/ha
Total generated	1,020	84,020	882	1,924	1,008
Collected	638	52,553	552	203	631
Uncollected	383	31,507	331	722	378
Illegally dumped	214	17,644	185	404	212
Landfilled	**423**	**34,868**	**366**	**799**	**418**
Uncollected + illegal dumping	597	49,152	516	1,126	590

From the calculations in this section, the row *Landfilled* conveys the salient figures indicative of the amount of nutrients/day getting into the landfill in comparison to each stage of the WMS of Nairobi County.

Consequently, output flows of the nutrients are calculated. However, the case of this model is atypical. When organic substances are depleted, it occurs due to their solubility, considering the Dandora dumpsite is an old, open landfill subject to direct precipitation and moisture. It is further assumed that the nutrient output is only through leachate, which is explained below. For this, the substances are calculated by estimation.

Leachate

Assuming that the landfill being a former quarry, was not prepared for the initial dumping by use of protective liners or membranes raises the issue of how permeable the landfill is and how diffusion of leachate occurs in exchange to groundwater sources and the Nairobi River. Principally, inquiry on this naturally and anaerobically decomposing landfill exposed to weather and geological elements all year round, is required but it currently lacks.

The theory of mass transfer and Fick's law of diffusion can be used in the scientific analysis of this matter. Additionally calculating nitrogen using the Total Kjeldahl Nitrogen (TKN) as it is the sum of organic nitrogen, ammonia (NH_3) and ammonium (NH_4^+) can account for nitrogen and some potassium for purposes of estimating the amount of these essential nutrients available from the landfill.

However, these methods are beyond reach for this study thus a projection by calculation of the values is used to build the theoretical approach for nutrient balance.

Calculation of outputs of N, P and K

Nutrients change form through chemical transformation and are lost through leachate in aqueous conditions. Therefore, the assumption is that a concentration average of 70% of N and an average of 25% of P from total input is lost. K is assumed to accumulate by 10% in this static model since it accrues in concentration in the long run. This assumption enables the quantification of NPK in the form calculated for inputs in the previous subsection. The estimation is tabularized below:

Table 10: Estimation of N, P and K losses

*Per Day figures	N kg/ha	P_2O_5 kg/ha	K_2O kg/ha
Generated	617	481	1109
Collected	197	154	354
Uncollected	162	181	416
Illegally dumped	130	101	233
Landfilled	**256**	**200**	**460**
Uncollected + Illegally dumped	361	282	649

The hypothetical nutrient balance therefore yields the following net change:

Table 11: Nutrient Balance for the Dandora dumpsite as per calculations

*Per Day figures	N	P_2O_5	K_2O
	kg/ha	**kg/ha**	**kg/ha**
INPUT	366	799	418
OUTPUT	256	200	- 460
INPUT-OUTPUT	**110**	**599**	**878**

Accordingly, the result is a general positive which proves a stock of nutrients in the landfill. This stock is however, partly in soluble and mineralized form due to the leachate occurring from precipitation affecting the landfill under uncontrolled and anaerobic decomposition conditions. For long periods in time (100-1000 years), it can be assumed that most of N leaves the landfill. However, for this study, it is assumed the nutrients are not converted into soluble or mineralized form to simplify the model. The NB figures in tonnes/year are therefore: 487 N t/yr, 2,654 P_2O_5 t/yr and 3,890 K_2O t/yr. All values however need to be converted for purposes of the MFA. Thus, which contains all the data necessary for the MFA, is converted to t/yr figures below.

Table 12: Converted figures for OFMSW, N, P and K (t/yr)

*Per Year figures	OFMSW t/yr	N t/yr	P_2O_5 t/yr	K_2O t/yr
Total generated	372,300	3,908	8,525	4,467
Collected	232,688	1,245	2,721	1,427
Uncollected	139,611	1,467	3,199	1,675
Illegally dumped	78,182	820	1,790	939
Landfilled	**154,504**	**1,622**	**3,540**	**1,852**
Uncollected + illegal dumping	217,797	2,286	4,989	2,614

All data calculated afore was presented in tonnes/day and kilograms/hectare. The table above is the conversion into tonnes/year figures, *ceteris paribus*.

Revision of tables 9, 10 and 11

The tables *Table 9*, *Table 10* and *Table 11* are further revised to kg per capita and year figures for the evaluation of nutrient loss each citizen in Nairobi contributes. These are tabulated in tables *Table 13*,

Table 14 and *Table 15* as follows.

Table 13: Summarized OFMSW and N, P, K Inputs for NB Model in kg/capita/yr

*Per Year figures	OFMSW t/yr	OFMSW kg/cap	N kg/cap	P_2O_5 kg/cap	K_2O kg/cap
Total generated	372,300	118.63	1.25	2.72	1.42
Collected	282,870	90.13	0.40	0.87	0.45
Uncollected	139,611	44.49	0.47	1.02	0.53
Illegally dumped	78,182	24.91	0.26	0.57	0.30
Landfilled	**154,504**	**49.23**	**0.52**	**1.13**	**0.59**
Uncollected + illegal dumping	217,797	69.40	0.73	1.59	0.83

Table 14: Estimation of N, P and K losses in kg/capita/yr

*Per Year figures	N kg/cap	P_2O_5 kg/cap	K_2O kg/cap
Generated	0.87	0.68	1.57
Collected	0.42	0.22	0.45
Uncollected	0.23	0.26	0.59
Illegally dumped	0.18	0.14	0.33
Landfilled	**0.36**	**0.28**	**0.65**
Uncollected + Illegally dumped	0.51	0.40	0.92

Table 15: Nutrient Balance for the Dandora dumpsite in kg/capita/yr

*Per Year figures	N	P_2O_5	K_2O
	kg/cap	kg/cap	kg/cap
INPUT	0.52	1.13	0.59
OUTPUT	0.36	0.28	- 0.65
INPUT-OUTPUT	**0.16**	**0.85**	**1.24**

These tables use the study's base year, 2009 population for Nairobi County as shown in *Table 1.* Each row can be used to calculate the NB at each level of OFMSW in the WMS. In scrutinizing *Table 13*, if the uncollected potion does not end up as feeds, biogas or compost, approximately half of the total nutrient concentration is lost and the other half flows to the landfill in a year. The nutrient cycle loses most nutrients to the landfill and in this case, there is lower nutrient loss in the uncollected and dumped potions than in the landfill. The difference is the potential of the nutrients in the dumped portion to circulate back into the nutrient cycles than in the landfill.

Roughly, a 1:2:1 ratio in Kg/capita and year of NPK is found in waste. As K is cumulative in nature in the system, it collectively becomes a stock with a lower probability of loss from leaching as N and P and is comparatively of least importance. However, in regards to nutrient conversion, N and P are the most unstable since they are easily lost from the nutrient cycle and rather hard to retrieve once they leave the cycle. This leads to dependence on mining of the rare phosphorus ore and on the Haber-Bosch process to retrieve nitrogen from the atmosphere into usable form; all by methods that consume a lot of energy and time.

From *Table 14*, the estimated amount of losses of N and P show how the impact of OFMSW in waste can affect the anthroposphere in terms of pollution per capita at each stage. The definite loss is however represented in the *Landfilled* row. Each loss per capita contributes to an overall increase at the landfill. The inputs and outputs generate a NB at the landfill of 0.16 N and 0.85 P kg/capita/year which is 30% and 75% of total stream to the landfill of N and P respectively whereas K increases by 52% at 1.24 kg/cap/yr as *Table 15* shows. This represents what the landfill retains. What is lost is 70% of N, 25% of P.

In terms of food security, the total amount of nutrients that are in the waste flow from generators indicates an immense loss of readily available nutrients from generators since more than 1.2 to 3 kilograms per capita and year of each nutrient is lost to waste and only 0.5 to 1 kilogram can be traced to the dumpsite.

With a continued loss of nutrients from the nutrient cycle into the landfill, more imports of inorganic fertilizer have to be injected into the regional cycle of nutrients while the existing ones are wasted. The nutrient balance reveals that the potential to divert nutrients from waste streams is important since approximately 0.3 kg/cap/yr or 942 t/capita/yr of usable N and P nutrients terminate as leachate. If the *Uncollected* and *illegally dumped* are collected and valorized, a bigger share of nutrients can be available for various uses. The single largest loss however remains with the *Landfilled* portion as this is a definite flow. The latter loss is represented as a stock in the landfill while the former loss is represented as a stock of the total dumped.

The essence of retrieving the nutrients from waste streams is to sustain the process of nutrient cycling while reducing the amount of energy needed to convert the nutrients to plant usable form. The latter is achieved by composting which is a cost effective method to recycle NPK and of reducing organic waste volumes while valorizing what is neglected after use and nourishment.

The question remains whether the positive concentration of these nutrients as shown in the NB in *Table 11* and *Table 15* is good for the anthropogenic metabolism. The chemical composition of the nutrients in the old landfill changes due to anaerobic decomposition and precipitation thus requiring a thorough study and analysis of the leachate.

Subsequently, a NB model is important as an indicator for the amounts of concentrated substances ending up in waste streams and thus in the landfill. As such, the inherent problems with the method are lack of data and the overreliance on estimations. This can be overcome by scientific inquiry into the research and laboratory testing of samples. Though some of the data is retrieved from studies done on similar aspects, the accuracy of the outcome as to how much concentration exists of the various substances in this particular landfill needs a comprehensive study.

This landfill therefore presents a unique opportunity for research into long-term anaerobic digestion in a dumpsite that is likely to be in direct contact with groundwater due to the lack of a membrane between the waste and the geology. It also presents both a resource recovery mine and a great potential to negatively impact the environment if no steps in mitigation are actualized.

4.4 Modeling Parameters for the MFA

To illustrate the integration of the NB with the MFA, the study assumes that the residual waste, 49% is UFMSW which is separated at the MRF and transported to the landfill. At the landfill, the UFMSW can be diverted further to the WtE plant to be built on site at a later stage of the ISWM plan. Therefore in this study, it is assumed that this potential resource is transported to the dumpsite for storage, thus UFMSW is a stock at the Dandora dumpsite but this is not modeled in this study.

The OFMSW on the other hand can then be recovered from the waste streams for processing as compost or for biogas production and so on. In these recovery options of OFMSW the focus is on the nutrients and establishing a sustainability process in treatment and disposal. The following subsection describes scenarios that can be used to realize the goals of waste management and develop sustainability. The current stock in the landfill is not included in order to clearly analyze the current rate of nutrient flows from this study's analysis. The scenarios are based on the existing WMS to simulate conditions from status quo to an intermediate and finally an optimized model. More justification for the latter will be made in the results section.

4.5 Scenarios

In order to propose a shift from status quo towards a sustainable nutrient balance, and optimization for sustainability, section *4.2* is a guide on which to evaluate the scenarios.

The data generated in this study is integrated into MFA data through the flows that were analyzed in the previous chapters. The study also intends to show the potential for sustainable nutrient balance in waste treatment and disposal achieved through analysis, nutrient balance and MFA modeling. As discussed earlier, the three options proposed for sustainability are diversion from waste streams, composting and urban mining. The current two-pronged waste management system is the core of these models.

4.5.1 Scenario 1: Status quo, 2009 (t/yr)

In this scenario, it is assumed there is no segregation, the OFMSW flows straight to the dumpsite and there is illegal dumping and an uncollected fraction as presented in *Figure 8*. This earlier model is populated with figures from the calculations in this study. The total amounts in t/yr of OFMSW with an output of total leachate are the only flows in and out respectively. This two-pronged system only contains three processes and a total of five flows.

4.5.2 Scenario 2: An intermediate model towards sustainability

This scenario in t/yr is based on enhancing collection and diversion of OFMSW to the MRF processes. This scenario simulates a medium term plan, skewed tendency towards sustainability by employing all the available resources and including treatment options. The input is scaled up from status quo total collection of OFMSW generated in Nairobi while the uncollected fraction and leachate remains the same as status quo. The model is improved to a three step system which has three stocks and a total of ten flows to introduce treatment into the system and some segregation.

4.5.3 Scenario 3: An optimized model towards sustainability

This is a best-case model for Nairobi derived from increasing efficiencies in the intermediate model with mitigation measures, full scale segregation and recovery.

This scenario encompasses parts of the ISWM plan and is further developed for sustainability. The collection capacity is highly improved and stocks are moved from the generators environment by capitalizing on franchising and efficiencies within collection and transportation.

In summary, a nutrient balance is a tool used in this study to evaluate the loss of nutrients by consumption and into the dumpsite. The calculations reveal a more alarming trend in the dumping aspect of waste handling. This study however establishes the dumpsite as singularly the largest capacity with nutrient stock and through the evaluation of the nutrient balance, the hypothesis is confirmed. The dumpsite is injected with at least half of the per capita amount of nutrients in waste and about 30% of nitrogen and 75% of phosphorus and 52% increment in potassium levels is retained by the dumpsite while 70% N and 25% P is lost through leaching. There are inherent challenges in modeling from estimates and assumptions which produce a varying degree of uncertainty. The shortfalls however were identified through static modeling of this study and through careful analysis of existing models to tailor a solution for this particular study. Through static models, cycles can be illustrated and thus the approach of this study was based on static modeling, *ceteris paribus*. The scenarios are therefore further development tools to examine the preliminary results herein and illustrate the use of the methodology to improve the WMS as will be discussed in the next chapter.

“The ultimate wisdom which deals with beginnings, remains locked in a seed. There it lies, the simplest fact of the universe and at the same time the one which calls faith rather than reason.

Hal Borland

5 Results and Discussion

In this section, MFA is described and each process, stock and flow used in the MFA is explained. The study model is presented in terms of MFAs based on the three scenarios from the previous chapter and are discussed in detail. The processes and flows used in the models are highlighted to describe the models. The analysis from this section will culminate in a results section from the data of this study.

5.1 MFA of Nutrient Balance Model

According to Brunner and Fellner (2007), a material flow analysis (MFA) is a valuable tool to follow the path of among other materials, organic chemicals, from source to sink. It is a robust data system that utilizes balancing where what comes in must go out. In finding the inputs of the waste management system, the hypothesis to outputs can be made and tested. In this section, the modeling and data that was presented and discussed in the previous chapters is used to produce an MFA that will analyze flows of nutrients in the OFMSW and to show the potential of nutrient recapture. The processes are based on the two-pronged system of collection and disposal and are improved for treatment to demonstrate the potential of OFMSW diversion and recovery.

5.2 Description of MFA models

This study presents its findings using this well established tool that is widely used in the scientific community, its applications in calculation of resource efficiencies, for optimizing waste management, regional planning and for environmental and resource management. The MFA is a tool promoted by renowned scientific organizations such as the International Society for Industrial Ecology (ISIE) for instance, for resource conservation and environmental protection (Baccini and Brunner, 2012). This study uses the software STAN 2.5 to trace the pathways of the indicators NPK in OFMSW. According to Baccini and Brunner (2012), this system evaluates the current modus for early recognition of developments to show beneficial and harmful practices of waste management in preparation for the future.

In this study, this will be achieved by the results and discussions of the MFA presented in this section. The subsequent MFAs are biased towards sustainability and closing the nutrient cycle. The system is not comprehensively evaluated as pointed out in previous chapters however, stocks of the total dumped and landfill account for some of the status quo shortfalls.

The MFA model in this study consists of flows of MSW from generation and up to the landfill in Dandora and exports outside the system. As expounded in chapter *1*, the system boundary is the MSW management of Nairobi County and based on the two-pronged system of collection and disposal that currently is operational. The flows and processes are described in the next subsection.

5.2.1 The Processes

The model has four processes in total. These processes in alphabetical order are:

Dandora dumpsite (P3)

This process represents the 30 acre landfill at Dandora and bears a stock of nutrients. The recovery through mining is represented by an export flow F9 *MSW fertilizer*. The flow F5 represents *Leachate* which exports from the landfill as a pollutant to the Nairobi River and loss of nutrient stock while the flow F10 introduces new stock into the landfill in terms of *Dry OF* in the intermediate model. In the optimized model, the process receives flow F11, *Proximal collection* and flow F12, *Wet OF* extracts to the process *MRF*. An additional output F13 to *Cogeneration* exports out of the boundary of this system.

Dumping / Franchising (P2)

This process is initially a collective of two flows and bears a stock. It represents the uncollected waste from generators mainly in slums and hard to reach areas such as Nairobi River. It also represents the waste flow that is illegally dumped across the county. The Input flow F2, *Uncollected OFMSW* and the flow F3 *Illegally Dumped* feed into this process. It is then improved by the flow F8, *Recovered* in the intermediate model. This process is finally optimized and transformed into *Franchising* and an additional efficiency flow F11 *Proximal collection* extracts from this process.

MRF (P4)

This process is introduced in the intermediate and optimized models and represents the Material Recovery Facilities which bear a stock. The process receives inputs from *Waste collectors* in P1 and recovery of fractions from *Dumping* in process P2 which is later transformed into *Franchising* in the optimized model. It produces three flows; *Composting, Biogas and Cogeneration* and *Dry OF* in the flows F6, F7 and F10 respectively. In the optimized model, it receives an input *wet OF* from flow F12.

Waste Collectors (P1)

This process represents the services offered by the waste collectors. The process thus includes for the status quo: Creative Consolidated, NCC and other private firms which form the capacity of collection in the system. They are grouped since the optimized model caters to systematic changes by the franchise system highlighted in section *2.3.1*.

5.2.2 The Flows

There are input and output flows as well as trans-process flows that represent the flow of OFMSW from generation to further utility outside the system. The flows are presented in order of numerical sequence.

Collected OFMSW (F1)

This is the first of two input flows into the system of waste management in Nairobi. It is 51% of the total generated MSW as indicated in the study. This major import flows into the system to the process P1, *Waste collectors*.

Uncollected OFMSW (F2)

This is the second input flow into the system boundary. It represents the uncollected fraction of OFMSW. It is the major contributor to stock in the process P2, *Dumping* which is later transformed into the process, *Franchising* with no stock in the optimized model.

Illegally Dumped (F3)

This flow represents the OFMSW that is available for collection but is either unlawfully dumped in undesignated areas, into the river, drainage, open fields and anywhere in the city. It also represents the collection rejected from the landfill when over quota.

Legally landfilled / Segregated at Source (F4)

This flow represents the waste collected and transported to the process *Dandora dumpsite* in status quo model and is later converted to *Segregated at source* and diverted from flowing to the landfill but rather to the process P4 *MRF* for valorization.

Leachate (F5)

This flow represents the amount of loss of nutrients from the landfill. It also indicates a negative externality of pollution that mends up in the hydrological cycle mostly through the Nairobi River.

Compost (F6)

This flow emanating from the process P4 *MRF* represents the export from the waste handling system after valorization as compost. This is a flow of a recycling product.

Biogas and Cogeneration (F7)

This flow is an export from the process P4 *MRF* for the purpose of energy distribution. This process is a valorized flow.

Recovered (F8)

A pollution control flow diverts OFMSW from undesired areas such as rivers and into a valorization process through the process *MRF*. This represents the flow of OFMSW from the process P2 *Dumping/Franchising* and into the process P4 *MRF*.

MSW Fertilizer (F9)

This represents a flow of recovered and/or recycling products from P3 *Dandora dumpsite* for reuse as fertilizer.

Dry OF (F10)

This flow represents the flow of dried organic fractions from the process P4 *MRF* into the process P3 *Dandora dumpsite* for manufacturing MSW fertilizer.

Proximal collection (F11)

This is a flow that introduces the collection of OFMSW from areas close to the *Dandora dumpsite*. It is only found in the optimized model.

Wet OF (F12)

This flow represents the flow of wet organic substances and materials from the process P3 *Dandora dumpsite* to P4 *MRF* into the process of *Biogas and Cogeneration* and *Composting*.

5.2.3 Stocks

These are the reservoirs of substances and materials in the system as contained within certain processes. These stocks form as a result of not being transferred out of the process or system boundary. In this study, the stocks can either accumulate or reduce depending on the function of the process and the flows feeding or extracting from it.

5.3 The MFAs

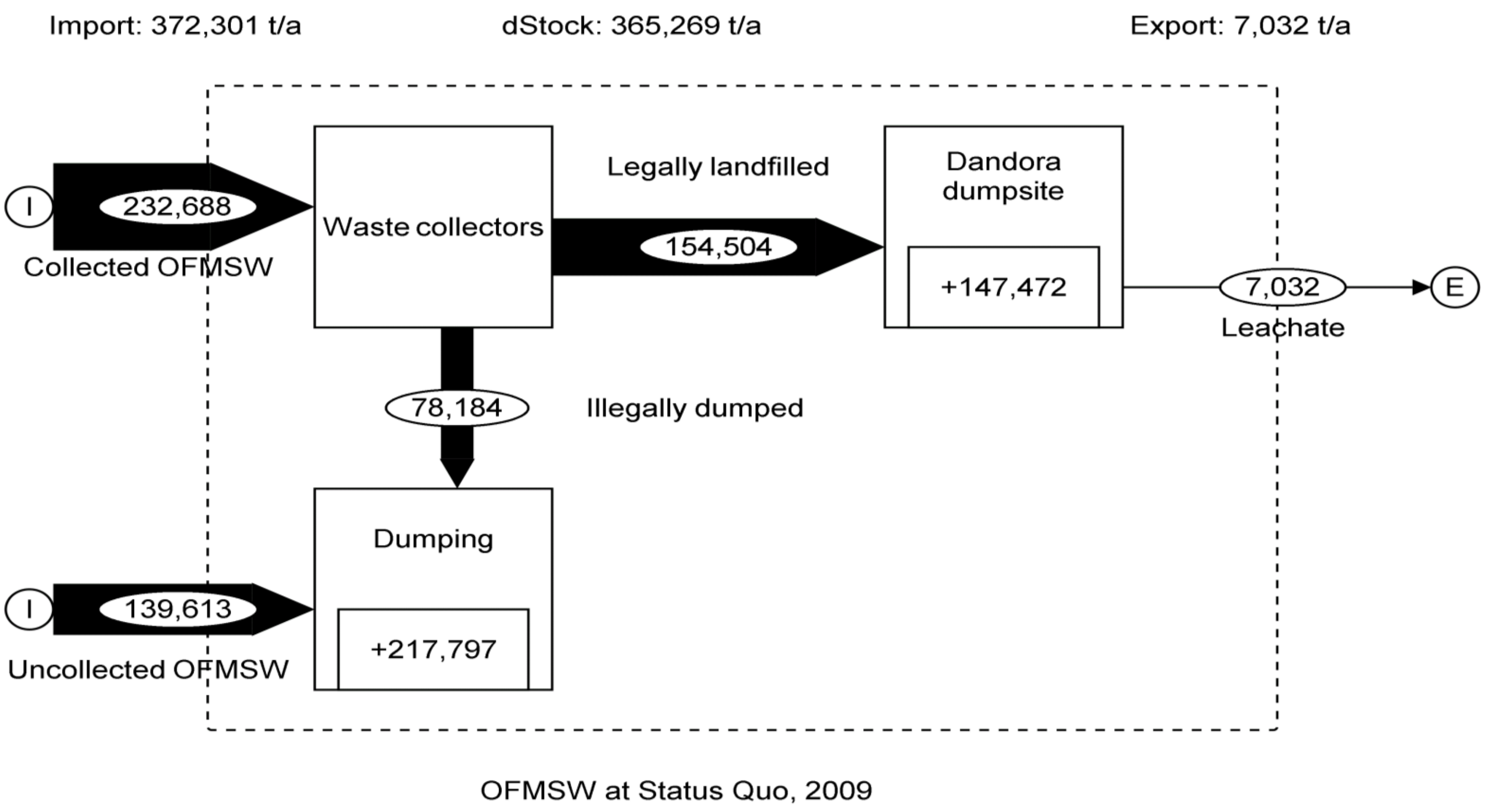

Figure 10: Status quo of OFMSW management (t/yr)

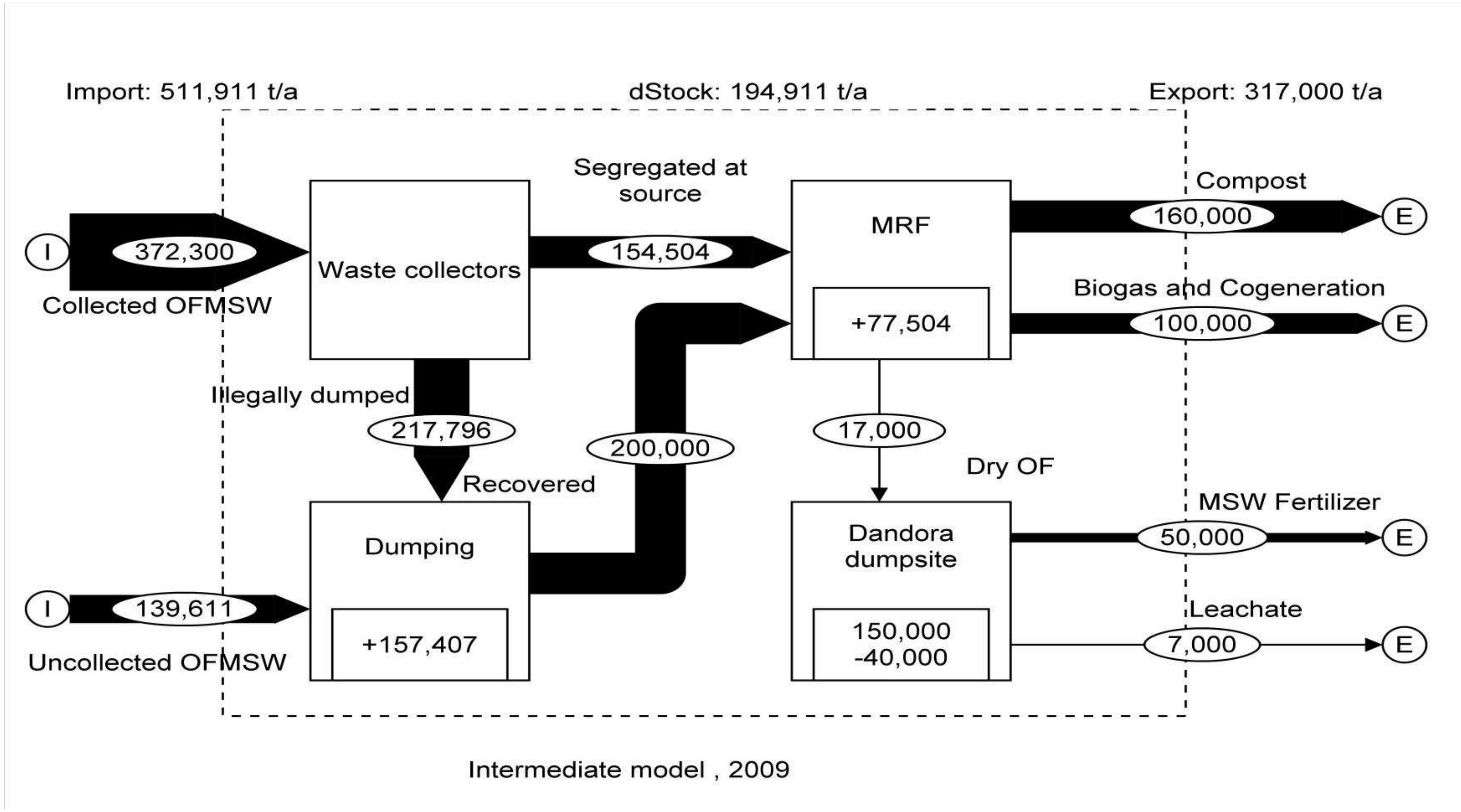

Figure 11: Interim model for sustainability in OFMSW management (t/yr)

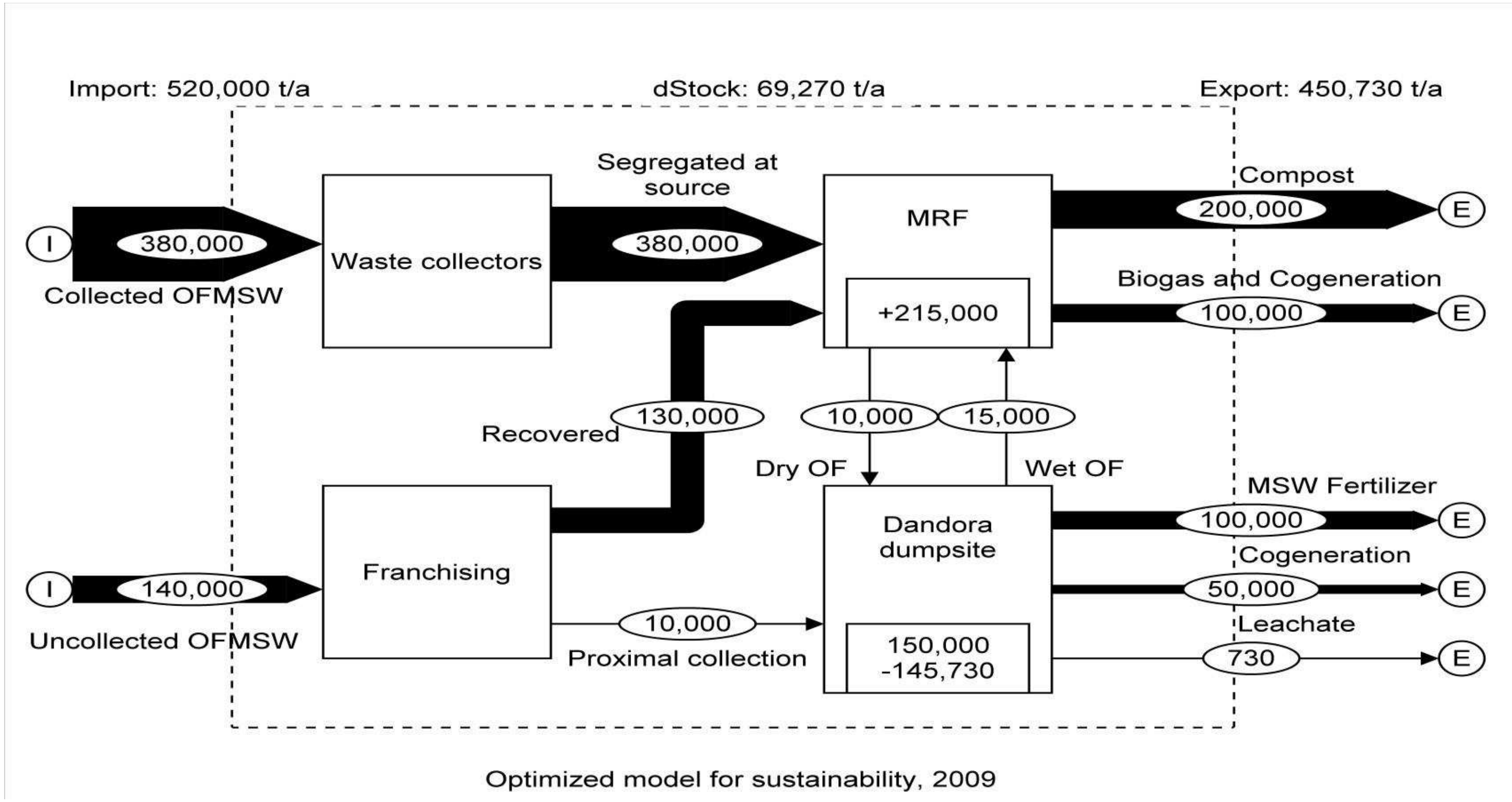

Figure 12: Optimized model for sustainability in OFMSW management (t/yr)

Table 16: Tabulated Summaries of OFMSW, N, P and K

	OFMSW t/d	OFMSW kg/ha/d	OFMSW kg/cap/yr	OFMSW t/yr
Total generated	1,020	84,020	118.63	372,300
Collected	638	52,553	90.13	232,688
Uncollected	383	31,507	44.49	139,611
Illegally dumped	214	17,644	24.91	78,182
Landfilled	423	34,868	49.23	154,504
Uncollected + illegal dumping	597	49,152	69.4	217,797

	N kg/ha/d	N kg/cap/d	N t/yr	N loss kg/ha/d	N loss kg/cap/yr
Total generated	882	1.25	3,908	617	0.87
Collected	552	0.4	1,245	197	0.42
Uncollected	331	0.47	1,467	162	0.23
Illegally dumped	185	0.26	820	130	0.18
Landfilled	366	0.52	1,622	256	0.36
Uncollected + illegal dumping	516	0.73	2,286	361	0.51

	P_2O_5 kg/ha/d	P_2O_5 kg/cap/d	P_2O_5 t/yr	P2O5 loss kg/ha/d	P_2O_5 loss kg/cap/yr
Total generated	1,924	2.72	8,525	481	0.68
Collected	203	0.87	2,721	154	0.22
Uncollected	722	1.02	3,199	181	0.26
Illegally dumped	404	0.57	1,790	101	0.14
Landfilled	799	1.13	3,540	200	0.28
Uncollected + illegal dumping	1,126	1.59	4,989	282	0.4

	K_2O kg/ha/d	K_2O kg/cap/d	K_2O t/yr	K2O loss kg/ha/d	K_2O loss kg/cap/yr
Total generated	1,008	1.42	4,467	1109	1.57
Collected	631	0.45	1,427	354	0.45
Uncollected	378	0.53	1,675	416	0.59
Illegally dumped	212	0.3	939	233	0.33
Landfilled	418	0.59	1,852	460	0.65
Uncollected + illegal dumping	590	0.83	2,614	649	0.92

5.3.1 Discussion and Results of the MFAs

The scenarios presented by the three MFAs are modeled on the base year 2009 in tonnes/year of OFMSW in a system boundary defined as the system of waste management of Nairobi. The two input flows are decoupled to clarify the impact of collection versus that of non-collection from the 51% of total MSW. The input flow *Collected OFMSW* is collected from waste generators by waste collectors previously confirmed as the NCC, Creative Consolidated and other private firms, herein grouped together. In this study, the negative externalities such as leaching at the process *Dumping* are not modeled but rather assumed to be contained as stock in this process*. Table 16* in the previous page allows a comparison of nutrients in different units for analysis in this section and the MFAs.

The first MFA in *Figure 10* is populated with figures at status quo as calculated in the previous chapters. Due to non-collection, the input flow is directly connected to the process *Dumping* which creates a stock since it is not remediated. The flow is managed by *Waste collectors* who collect, transport and dispose of this waste stream. Unfortunately, the collected waste diverts into two flows from process P1 into *Illegally dumped* and *Legally landfilled* as a consequence of a limited capacity allowed at the landfill, fully exploited by the latter flow. The former flow leads to *Dumping* and increases the stock. The process *Dandora dumpsite* receives the latter flow into stock and produces an export flow *Leachate.*

The status quo of waste management in Nairobi is planned as a two-pronged system focused on sanitation by collecting waste from the generators and disposing it in the Dandora landfill. However, due to a lack in capacity, a gap is created and exploited through extreme dumping as represented in the flows *Uncollected OFMSW* and *Illegally dumped*. The worrying factor is the rate of illegal dumping around the city, as the yearly dumped stock is estimated at 218,000 t/yr. The sole positive aspect to this flow is the implication that some of the waste is valorized through animal feeds, domestic biogas production and compost and that the decaying OFMSW is mostly on land and may seldom affect the hydrologic cycle. Consequently, the impacts of this flow are far less than the flow to the dumpsite.

The flow to the dumpsite creates an immense stock of nutrients at 148,000 tonnes yearly. This stock of nutrients is reduced at a rate of 7,000 tonnes/year in leachate. To reflect on the figures more elaborately, this is the equivalent of 1,600 t/yr of nitrogen, 3,500 t/yr of phosphorus and 1,800 t/yr of potassium flowing into the landfill and 0.4 kg/cap/yr of N and 0.3 kg/cap/yr of P. As a result, the leachate leads to high nitrification of the adjacent Nairobi River and the implication of heavy metals which accumulate as trace elements in the nutrient cycle is undeniably alarming considering the rate of nutrient loss to the dumpsite. As seen in *Table 16*, the dumpsite is injected with at least half of the per capita amount of nutrients in waste and about 30% of nitrogen, 75% of phosphorus and an increment of 52% in potassium levels is retained by the dumpsite while 70% N and 25% P is lost through leaching.

Through the nutrient balance model in chapter *4*, the calculations revealed a nutrient loss of 0.2 kg/capita N and 0.9 kg/capita P loss into the landfill while 0.4 and 0.3 kg/capita/year of N and P respectively leach into the river. The total import of nutrients into the system was approximately 372,000 t/yr while the export was 7,000 t/yr thus leaving a stock within the waste streams of 365,000 t/yr.

The implications of this vary from heavy dependence on mineral and chemical fertilizer inputs from local and international sources to uncontrolled pollution without mitigation. As phosphorus is a both a finite and lithophylic element, it is hard to recover it in good quality and quantity once it escapes into another cycle such as the hydrologic cycle. This was explained in the spirals and cycles observation mentioned in section *4.3*. For these few reasons, it can be concluded that the current model of waste management of collection and disposal is not efficient and neither is it adequate in utilizing the nutrients available in the OFMSW. Subsequently, a study model to propose ways of sustainable nutrient balance was built as seen in Figure 12.

The model in *Figure 10* is open, thus a flexible approach to use the available resources to enhance capacity to collect and divert the OFMSW from the landfill and into valorization is possible. As part of the aims of a successful waste management system is to minimize cost, the new models consider this school of thought.

The intermediate model in *Figure 11* is modestly adjusted to a higher input of OFMSW in anticipation of more participation in the system as well as population growth from the base year 2009. As shown, waste production does not decrease and this reflects in the growing amount of OFMSW. Since the city is still in a modus of implementing new waste management strategies as included in the model, the cost is scaled down by reassigning some assets.

The asset imported into the system is represented by the process *MRF* (P4). As the only additional asset, this process represents a number of activities within it. The material recovery facility is charged with sorting, segregating of waste and valorizing it. It is a central distribution platform that is both flexible and can be established in various areas of the city. The MRF is thus the recipient of all diverted waste streams of OFMSW for the allocation into processes that produce compost, biogas and cogeneration. The MRF thus receives all diverted flows previously attached to the dumpsite for the main reason of resource recovery. As the MRF acts as an intermediary to handle the 51% of bulk organic waste, the landfill can be shut under recovery and construction of the WtE plant. This complimentary approach further builds capacity for the expansion of MSW management facilities as the city expands into a metropolis.

In the intermediate model in Figure 12, the stock within the system is reduced to 195,000 t/yr as increased operational capacity reduces dumping from 218,000 to 157,000 t/yr in dumping and the introduction of the MRF further diverts collection for valorization. A simulated increase in collection of the full 1,020 t/d (372,300 t/yr) results in a 140,000 t/yr increase in dumping and the uncollected flow is maintained at around 140,000 t/yr.. An increased collection and complete diversion to the MRF alleviates this potential problem as shown by the flow *Recovered* since efforts by CBOs and other private firms are introduced to increase collection and transport to a facility without a collection limit, the MRF. This process is also propagated by the increasing awareness and participation of source separation and improved collection services to the areas that were previously not serviced. The MRFs now replace Dandora dumpsite as the default disposal point and they convert the organic waste to availability of compost, biogas and cogeneration materials. This can be done on site or off site but in this case, it is done on site to cut down on transportation costs and space. Since composting and biogas and cogeneration take time (14 days to a year), the stock in the MRF represents this and finished products for distribution in the form of compost.

The Dandora dumpsite (P3) however holds stocks in this model for producing MSW fertilizer from fractions diverted to it from the MRF (P4) as well as previous stock in the status quo model. The link between these two processes is the flow F10 that represents the dry organic fraction residue produced by the MRFs which is used to produce MSW fertilizer combined with the nutrients retrieved from the dumpsite during its recovery. As a result, more capacity can be retrieved from urban mining as represented in the export of MSW fertilizer. The processes within the Dandora dumpsite are only for MSW fertilizer production. Leachate management is assumed to start at the next stage of recovery after dumpsite recovery through urban mining and nutrient recycling avail enough capacity.

The stocks within the system are due to cumulative waste management and resource transformations. The former MFA consists mainly of negative stocks since no valorization takes hold. The intermediate model however, considers the nutrient resources from OFMSW that the first model reveals. The potential is stored in stocks in the latter model due to mostly manufacturing of MSW fertilizer, composting processes, collection and segregation, biogas digestion and storage of the usable products made from the recovered organic fraction. In this model, an equivalent of 2 kg/capita/yr of nitrogen and 4 kg/capita/year phosphorus are recaptured from waste. This translates to approximately 868 t/d of exports or 3,000 t/yr N, 8,500 t/yr P and 4,500 t/yr K. That is 1.3 kg/capita/yr N, 3kg/capita/yr P and 1 kg/capita/yr K. The leachate still exports the equivalent of 1,600 t/yr of nitrogen, 3,500 t/yr of phosphorus and 1,800 t/yr of potassium flowing into the landfill and 0.4 kg/cap/yr of N and 0.3 kg/cap/yr of P.

As the intermediate model is an interim measure to salvage nutrients from waste streams, another model to streamline and improve this system for the long term while using the available resources is modeled in *Figure 12*. This optimized model thus moves the stocks from the generators environment and into the waste management system completely by the efficiency of franchising and segregation at full scale coverage of the city. The collection capacity is slightly adjusted upwards to show growing collection capacity and the import flow *uncollected OFMSW* remains decoupled to show the capacity that was previously unmanaged. The waste collectors and franchising are not combined because the number of the franchisees and capacities are unknown at this point. However the combined effort moves the total 520,000 t/yr OFMSW from generators without leaving uncollected stock. The increased efficiency from this point is the *Proximal collection* flow into the Dandora dumpsite. This flow ensures the generators closest to the dumpsite receive services through the dumpsite thus saving more energy and costs. This fraction is transferred from the dumpsite to the MRF as the flow *Wet OF* every time the flow *Dry OF* is delivered, thus cutting down double transport costs.

At this stage, recovery and product exports have reduced the amount of OFMSW creating leachate and thus a reduction of leachate. The dumpsite also has less accumulation of stock as most of it is exported in the flows of MSW fertilizer and cogeneration. The stocks in the system are now reusable or recycled products that can propagate the nutrient cycle thus establishing sustainability and a sustainable NB.

From the intermediate model, 70% N and 25% P is lost through leaching while 30% of N and 75% of P is available for MSW fertilizer production at the landfill. At the optimized model in *Figure 12*, the amount of leachate contains approximately 7% N and 2% P therefore saving 63% N and 23% P from loss into Nairobi River. At least half of the per capita amount of nutrients in waste and about 30% of nitrogen and 75% of phosphorus and 52% increment in potassium levels retained at the dumpsite are put back into circulation, thereby closing the nutrient cycle.

"We cannot conceive of matter being formed of nothing, since things require a seed to start from…Therefore there is not anything which returns to nothing, but all things return dissolved into their elements."

William Shakespeare

6 Conclusion

Just as a nutrient cycle, sustainability is a long-term process. The models and research indicate nutrients are contained in stocks of urban mines such as landfills and the processes to establish sustainability take time. Using the cycles and spirals perspective, the return to start of a nutrient flow takes a long time however the start is achieved at another similar point in time. This way the nutrient cycles are closed as brilliantly postulated by Brunner (2013).

The first research question whether nutrients can be retrieved from MSW steams to sustain anthropogenic metabolism by capping on the losses from waste disposal is captured by the use of the NB model and enhanced later by MFA. The hypothesis is proved true resultant of organic waste streams terminating at the Dandora dumpsite and just as in most systems, what goes in will come out. This study OFMSW flows to waste streams and the landfill present the potential for reuse of these nutrients based on the NPK indicators. As it is at least 51% of the MSW, it also shows a positive resource for diversion and reuse from normal waste streams to the landfill. The resource is as immense as the population and sustainability is ensured through food production from the recapture of nutrients in waste back into the anthropogenic cycle by the methods simulated in the intermediate and optimized MFA models of this study.

The second research question on MSW streams potential for nutrient recovery to explain how sustainable NB can be implemented using the indicators NPK was also answered through modeling and decoupling OFMSW and UFMSW. Through the quantification and analysis of OFMSW, calculations in the Nutrient Balance section of this paper revealed the nutrient concentrations at each stage of the processes in Nairobi's WMS and by concentrating on the dumpsite, a positive indication of 30% N, 70% P and an increment of 52% K was revealed in the landfill in just a year. The breakdown in the tables showed that from generation to disposal there was a huge potential to recover these nutrients from ending up as pollution stock.

As illustrated by the last two MFAs, the potential for nutrient resources for sustainability are indicated by the stocks primarily in *Dumping* and *Dandora* *dumpsite.* The installation of an asset as the process *MRF* was an essential modification of the system to enhance sustainability and valorization in waste management which then enables recovery and the removing of waste stock from the generators' environment and into the WMS processes. The nutrient balance tool was essential in analyzing and accounting for nutrients that are either causing damage or lacking and thus the indicator of an excess or dearth of nutrients. The NPK indicators are important agricultural nutrients and essential to survival and propagation of the anthroposphere and thus key. The rarity and complexity of N and P in direct usable form enhances their importance in this study.

The third part of this thesis was to discuss the theoretical approaches and models to simulate a sustainable nutrient balance. This was shown in the MFA by modeling three scenarios; status quo, an intermediate model and an optimized model. Using the potential of particular OFMSW streams that contain the biggest portions and present opportunities for recovery, the approach of diversion and resource recovery to direct exports from the system in usable form achieved this goal. The modeling from the intermediate to optimized model revealed a time series from medium to long-term targets respectively since the stocks also take time for conversion while urban mining is also time dependent. The study confirms the notions of high volumes of OFMSW from generators particularly in HHs, restaurants and markets since these are the singular groups that generate high volumes of organic waste. These sources account for about 30% to 62% of total OFMSW retrieved at source, thus indicating the importance of source segregation. The models utilize this to enhance better outputs from the waste management system and by employing the cost effective methods within the existing strategy laid down in the ISWM of 2010.

On losses of nutrients in the flows within OFMSW waste streams, the single greatest portion can be captured at collection and later at the landfill. The second group of potential areas is the collective dumping flows and in order to maximize the nutrient capture, collection is most necessarily the point of action. On a per capita basis, the same indications from largest concentrations are at the collection and dumpsite from the status quo model against the latter two models. A suggestion would be at least two days of the week dedicated to collection of OFMSW; Monday and Thursday.

The dumping situation on the other hand cannot be overlooked as long as there are slums and unless there is willingness to pay for collection and possibilities for binning and segregation of waste is enhanced. However, incentives through subsidized collection services by the city are capable of retardation of the dumping flow. Pricing is as important as the success of this model system and the confidence of the citizen and willingness to access the service for a reasonable charge is essential. The individual effort also has a big impact on the system as the per capita indicators tabulated in this study (summarized in *Table 16*) show that the individual capacity to bin waste properly after segregation is paramount in saving costs and recovery of both UFMSW and OFMSW. This is a key impact area for volume reduction and capacity management in the waste treatment and disposal aspects. As the citizen produces between 1 and 3 kilograms of NPK yearly in waste, the potential for nutrient recycling in large populations is an asset towards food security and environmental management through sustainability. Thus as proposed by other studies, invigorated collection by the more efficient groups and firms such as CBOs that operate in challenging areas are more cost effective and have better access while rolling out the franchising model. The key factor would be to enhance their capacity by complimentary points of collection for larger capacity transport to handle the waste.

Education and sensitization of the citizens is a fundamental approach for the success of any model of sustainability. As an energy and nutrient source, OFMSW can achieve both with the byproducts of each process being reusable in the system. As 51% of all waste flows are organic matter, the individual contribution to MSW volumes at 1.57 kg per day reveals that 0.8 kg/capita/day is exclusively OFMSW and thus the impact on nutrient flows to waste streams in Nairobi is quantified as between 1 kg to 3 kg/capita/yr NPK or 119 kg/capita/yr of generated OFMSW containing essential nutrients for animal and plant development. Of this input into the WMS, between 0.3 to 0.7 kg/capita/yr NPK per capita is lost to leaching at the landfill as observed in the summary of tables of this study.

This thesis also linked sustainability to resource recovery and proposed methods of accomplishing this phenomenon. An analysis of the different studies on waste management in Nairobi revealed some inconsistencies of research. However, the differences were marginal. The use of a nutrient balance was invaluable to draw conclusions on the concentrations of nutrients after loss and gave further evidence of points of investigation. As the model relied heavily on approximations, the results are not conclusive but are indicative of areas of research.

As a tool for policy making, the models in this study can enhance the efforts for reaching the goals of waste management. The method is however requisite of more data and development but it acts as a framework to form inquiry and research into the study focus. Some data sets could improve the research significantly especially in developing this theoretical model. This aspect can be a benefit for sustainable nutrient management, resource recovery from landfills in urban mining and in landfill recycling. The inputs are however, highly dependent on reliable data and laboratory work with a probable need to consider more factors and a methodology for landfills. This can then support routine testing and can impact the land use patterns of landfills in developing countries. Furthermore, the nutrient balance can be used for target reviews.

With a potential of at least 50% reduction from landfilling, the cost of transportation is positively impacted and the benefits are forthcoming from nutrient replenishment in soil, composting, biogas production, sustainable food production and even animal feeds. The potential to recycle the Dandora landfill is thus presented through the recovery of materials and nutrients by the proposed diversion to MRFs. The diversion however should be rigorously supported by the waste generators through segregation of wastes to provide the SWM process with cleaner selection of waste for valorization. A sustainable nutrient balance can thus be achieved in time. The issue of affordability is thus reduced when segregation, proper management of collection and reuse of wastes is done by diversion from landfills. The improved models of this study are scalable for either smaller or larger areas and they can be distributed across the city and in the outskirts with careful planning. This means that as Nairobi develops into a metropolitan region, the factors of integration affecting OFMSW can be integrated and enhanced especially since periurban areas and the outskirts of the present boundary are suitable locations for MRFs.

To conclude, the amount of nutrients in the dumpsite can be quantifiable and processes to recover them implemented. However, the process is a long-term affair and requires proper planning and analysis. The immediate issue is thus to divert the continued flow of OFMSW from waste streams to the landfill and to valorization. This will effectively reduce the costs of transportation and increase capacity for waste storage in the landfill. The notion that the Dandora landfill is at capacity is thus contestable as there are other options to explore rather than a “wasteful” abandonment of one landfill type for another without a solution. Thus, the sustainability models remain as the best options for Nairobi, yet.

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Appendices

Appendix I

Tables with Constituency and respective slums data approximations in 2008 from Pamoja Trust Research for Nairobi, (Pamoja Trust, 2008) The tables were used to compile slum population statistics.

Constituency/Ward	Settlement	Persons	HHs	Land ownership	Land (acres)	River	Established
Westlands							
Highridge	Maasai	183	61	Private	20	Gaitathuru	1968
	Suswa	1,820	150	Road reserve	0.25		1963
	Deep Sea	1,600				Gaitathuru	
Kitusuru	Kaptagat	1,600	400	Road reserve	2	Gaitathuru	30/03/1970
	Kibagare	15,000	3,000	Rail and road reserve	4		1972
Kangemi	Waruku	420	60	NCC	0.5		1966
Karura	Mji wa Huruma	2,065	413	NCC	5	Ruaka	1979
Kitusuru	N or NITD (Native Industrial Training Department)	1,800	275	Veterinary Department	2.5		1974
Kitusuru	Nduboini	800	160	Government	3		1976
Karura	Githogoro	17,000	2,000		17		1991
Total Westlands		**42,288**	**6,519**		**54.25**		

Constituency/Ward	Settlement	Persons	HHs	Land ownership	Land (acres)	River	Established
Starehe							
	Bondeni	10,000		Government/ Riparian	18	Nairobi	1960
	Corner Mbaya	12,000	600	NCC	10		1979
	Ghetto	2,365	813	NCC	(1.4ha) 3.5		
	Gitathuru	986	314	NCC	5.3	Gitathuru	
	Grogon Huruma	350		NCC	(2.14ha) 5.3		1977
	Kahonoki	17,000	3,000	NCC	20		1977
	Kambi Moto	1,241	539	NCC	(0.4ha) 1		1975
	Kosovo	25,000	3,200	Government/Police	12	Mathari	2001
	Kwa Kariuki	7,000	1,000	Private	4		
	Madoya	3,000	400	Private	4	Gitathuru	
	Mahiira	1,174	384	NCC	(1.19ha) 3		1978
	Mlango Kubwa-Tsunami	2,000	300	Private	3		
	Mathare 3A	2,500	1,000	Private	4	Nairobi	
	Mathare 3C	2,800	1,000	Private	15	Nairobi	
	Mathare 4B	12,000	4,000	Government	10	Mathari & Nairobi	
	Mathare Gitathuru	1,000	305	Government/Police		Mathari/ Gitathuru	1976
	Mathare Kiamutisya	1,700	3,900	Government	13	Nairobi	
	Mathare Mashimoni	3,500	1,550	Government/ Airforce	5	Nairobi	1952
	Mathare No. 10	4,000	700	Private	7	Nairobi	
	Mabatini	1,200	386	Road reserve	2		
	Redeemed	798	259	NCC	(0.72 ha) 1.8		1978
	Village 2	20,000	400	Private/ NCC	20		
		117,114	7,628				
Total Starehe		**131,614**	**24,050**		**165.1**		

Constituency/Ward	Settlement	Persons	HHs	Land ownership	Land (acres)	River	Established
Makadara							
	Barclays	2,000	200	Government	3		2000
	Commercial	6,000	900	Private	1.25	Ngong	
	Fuata Nyayo & Kisii	9,000	1,500	Private/ NCC	3		1988
	Hazina	13,000		Kenya Railways	6		1988
	Kabiirira	3,500	530	Dumpsite	3		1976
	Kaloleni (Agare)	10,000	2,000	NCC/Kenya Railways	4		1976
	Kanato	10,000	500	Government	3		
	Kenya Wine	10,000	500	Riparian reserve	7	Ngong	
	Kingston	4,500	288	Private/High voltage electricity way-leave	2		1980
	Lunga Lunga	15,000	2,800	High voltage electricity way-leave	9		1960
	Maasai	3,000	750	High voltage electricity way-leave	2		1998
	Mariguini	3,502	2,652	NHC (National Housing Corporation)	6.7		1983
	Maziwa	15,000	800	Government	3		1960
	Mukuru Kayaba	40,000	2,000	Kenya Railway/High voltage electricity way-leave	20	Ngong	1960
	Shimo la Tewa	3,000	950	NCC	3		1986
	Sinai	30,000	7,200	Kenya Pipeline, Kenya Railways	15-20		1980
	Site	15,000	6,000	Dumpsite	7		1996
	Kisii	10,000	3,000	Dumpsite	4		1988
Total Makadara		**202,502**	**32,570**		**86.95**		

Constituency/ Ward	Settlement	Persons	HHs	Land ownership	Land (acres)	River	Established
Lang'ata							
*Kibera/Kibra = 100 acres	City Cotton - Wilson	1,600	270	Moi Education Complex	1		
	Kuwinda	7,000	1,400	Government	5		1978
	Mitumba	5,280	1,008	Unknown	7		1992
	Plot 10	650	130	Government/Kenya Prisons	1.5		1978
	Quarry, Raila Estate	9,000	1,800		8		1990
	Riverside Mbagathi	18,000	2,700	Government	13		
	Soweto East	50,000	13,000		15		
	Laini Saba*	60,000	10,000	Government	50		
	Mashimoni*	25,000	4,000	Government	7		
	Shilanga*	35,000	7,000	Government	6		
	Lindi*	50,000	8,000	Tribal	20		
	Kichinjio*	10,000	3,000	Government/Kenya Railways	8		
	Makina*	50,000	9,000	Government	20		
	Kambi Muru*	40,000	10,000	Government	8	Otiende	
	Gatwikira*	70,000	7,000	Quarry	40	Kyahiti	1940
	Soweto West Kianda*	40,000	7,500	Government	40		1977
	Kisumu Ndogo*	35,000	6,100	Government	30		1964
Total Lang'ata		**506,530**	**91,908**		**279.5**		

Constituency/Ward	Settlement	Persons	HHs	Land ownership	Land (acres)	Established
Dagoreti						
Kawangware	Congo	8,000	2,500		7	
Ruthimitu	Dagoreti Center	246	65	Native land trust	1	1960
Ruthimitu	Gachui	378	130	Native land trust	(0.0049 sq.km) 1.2	1970
Kawangware	Gatina	20,000	5,000	Private	20	1964
Waithaka	Kabiria			Private		
Kawangware	Kabiro	5,000	3,000	Private	10	
Mutuini	Kaburi	268	82	Native land trust	0.75	1979
Mutuini	Kamwanya	766	263	Native land trust		1950
Mutuini	Kandutu	495	160	NCC	(0.00914 sq.km) 2.26	1969
Mutuini	Kanguku	402	142	NCC	(0.021 sq.km) 5.2	1960
Kawangware	Kanunganga	3,000	1,200	Private	5	
Ruthimitu	Kareru	296	93	NCC		1970
Kawangware	Kawangware Sokoni	101	27	NCC	0.12	1962
Kawangware	Kawangware Coast	32	11	NCC	0.25	1982
Kawangware	Kawangware Kiambooni	49	9	NCC	1	1988
	Kinyanjui	3,000	1,000	Private	12	
Mutuini	Kirigu	185	68	NCC	(0.00254 sq.km) 0.63	1960
Ruthimitu	Kware	1,342	391	NCC	(0.05676 sq.km) 14	1969
Mutuini	Muria Mbogo	207	66	NCC	(0.17512 sq.km) 43	
Kawangware	Muslim	12,500	1,500	Private/ NCC	(0.19359 sq.km) 48	1973
	Mutego	170	32	Kenya Railways		1969
Mutuini	Njiku	776	249	NCC	(0.0066 sq.km) 1.6	1965
Waithaka	Pipeline	164	53	NCC	(0.00065 sq.km) 0.16	1979
Kawangware	Kawangware	25,000	6,000	Private	15	
Golf Course	Toi Market	3,500			6	1980
	Wanyee Close					
Ruthimitu	Gatharani	312	95	Private/ Jehovah Witness	(0.068 sq.km) 15	1977
	Riruta Githembe					
	8.4% of Dago	20,099	2,041		(0.6 sq.km) 15/1.6% of Dago	
Total Dagoreti		**86,189**	**22,136**		**209.17**	

Constituency/ Ward	Settlement	Persons	HHs	Land ownership	Land (acres)	River	Established
Kamukunji							
Bahati	Buruburu City Carton/ Buruburu Riverbank Settlement	6,000	702	NCC/Private	30	Nairobi	1958
Eastleigh	Garole	3,000	400	Government	3		1980
Pumwani	Gikomba	10,000		Government	5	Nairobi	
Kariokor	Mwariro/Riverside Market	400		NCC	2		1998
Eastleigh South	Kinyago and Kanuku	20,000	18,000	NCC	4.2	Nairobi	1963
	Eastleigh	600		Private			
	Majengo (Sofia, Mashimoni, Gatanga and Digo)	25,000	4,350	Government/Private	25	Nairobi	1921
Eastleigh South	Zawadi	9,000	340	Private	10	Nairobi	2000
	New Akamba Dancers	400	34	Private		Nairobi	1967
	Kiambiu	17,000	2,400	Government/Private	20	Nairobi	1959
	City Carton Biafra	792	198	Government	0.5	Nairobi	1970
	Eastleigh Muungano	600	60	Unkown	2.5		1987
Total Kamukunji		92,792	**26,484**		**102.2**		

Constituency/Ward	Settlement	Persons	HHs	Land ownership	Land (acres)	River	Established
Kasarani							
Kasarani	Mathare 4A	20,000	5,000	Government	20	Mathari	1940
Mathare North	Ruaraka Akamba Dancers Squatters Village	400	50	NCC	1		
	Jathiani/Gomongo	6,000	270	Private	8		1964
Kasarani	Beth Village	15,000	1,300	Government	5		
Kasarani	Dumpsite	700	120	Government	3		
	Gathecha/Chewa	15,000	300	Private	14		
Ruaka	Ngunyumu	9,800	2,300	Government/Private	10	Gitathuru	
Roysambu	Jua Kali Marurui	3,500	600	Government/Private			1990
Mwiki	Gitumba	4,000	300	Government	10	Nairobi	
Mwiki	Shape Corner	2,500	1,000	Government	10	Nairobi	2003
Kasarani	Kwale	3,000	350	Government	3		
Kahawa	Githurai Majengo	170		Private	0.05		1954
Kahawa	Kamae	8,000	2,500	University/Private	1040		1960
Roysambu	Zimmerman B (Power)	800	290	KPLC			1963
Kasarani	Muthokinjo (Kumi kumi)	600	200	Road reserve	2.5		1978
Kariobangi	Kariobangi Light Industries	800	270	NCC	1		
Mathare North	Janwani (Gomongo)	5,000	600	Government/Dumpsite	10		1980
Kahawa	Soweto Kahawa	3,000	1,000				
	Quarry Squatters				30		1963
Total Kasarani		**98,270**	**16,450**		**1167.55**		

Constituency/ Ward	Settlement	Persons	HHs	Land ownership	Land (acres)	River	Established
Embakasi							
Embakasi	Pipeline	20,000	20,000	Private	12		
Embakasi	Mukuru Sisal	10,000	2,700	Private/ NCC	5		
Embakasi	Embakasi	8,000	1,500	Private			2000
Kariobangi South	KCC	10,000	150	Private	9		
Njiru	Maili Saba	27,000	3,000	Government	30		
Umoja	Mohra Moldada	1,000	340	Private	5	Ngong	1931
	Kyang'ombe	10,000	1,500	Private	5		
Embakasi	Embakasi Sokoni	12,000	700	NCC	3		
Embakasi	Kayole Soweto	10,000	1,600	NCC	20	Ngong	1978
Umoja	Matopeni	15,000	1,875	Private	10		1997
	Mukuru kwa Reuben						
	Mukuru kwa Njenga						
	Mukuru Sinai	7,000					
Total Embakasi		**130,000**	**33,365**		**99**		
Grand Total		**1,290,185**	**253,482**		**2163.72**		

Appendix II

Data from 2009 population census on Nairobi

Administrative area	Population total	No. of HHs	Land Area (Sq.Km)	Density (Persons per Sq.Km)
Kangemi	21,081	5,950	5	3,933
Kawangware / Riruta North	24,413	7,512	4	5,261
Riruta South (Satellite)	17,165	4,716	5	3,433
Waithaka	7,365	1,640	4	1,521
Uthiru / Ruthi Mitu	8,140	1,789	6	1,218
Mutuini	7,627	1,623	4	1,588
Kilimani	45,111	10,601	24	1,805
Dagoreti Total	130,902	33,831	56	2,325
Karen / Langata	13,112	2,081	74	176
Kibera / Woodley	63,353	11,769	7	8,515
Golf Course / Nairobi Hill	16,670	2,371	6	2,835
Nairobi South and West	28,997	4,635	11	2,432
Industrial Area	9,314	1,198	10	849
Mugumoni	11,750	1,684	124	94
Kibera Total	143,196	23,738	234	610
Embakasi	13,502	3,071	62	217
Dandora	22,672	6,253	162	139
Harambee	16,257	3,034	0	20,321

Lumumba	13,544	2,620	1	11,286
Makadara	11,931	3,683	1	10,285
Kaloleni	5,120	1,039	0	8,000
Administrative area	**Population total**	**No. of HHs**	**Land Area (Sq.Km)**	**Density (Persons per Sq.Km)**
Maisha / Makongeni	16,606	4,151	0	27,676
Mbotela	14,073	3,532	0	43,978
Bahati	10,670	2,963	0	20,519
Maringo	13,083	3,218	0	32,707
Uhuru	23,813	4,466	1	12,149
Makadara Total	161,271	38,030	235	686
Shauri Moyo / Muthurwa	18,858	5,049	1	14,286
Pumwani	14,403	4,413	0	36,007
Ziwani / Kariokor	8,521	1,945	0	12,530
Pangani	17,223	4,088	1	10,251
City Centre	18,402	3,147	1	15,863
Nairobi Central	8,859	1,888	1	7,382
Spring Valley	18,559	5,011	23	788
Karura	11,031	3,320	36	298
Parklands	23,965	5,461	2	6,886
Ngara West	10,044	2,507	1	8,100
Ngara East	16,335	4,020	1	13,173
Pumwani	166,200	40,849	72	2,280

Roysambu / Kahawa	36,958	7,458	46	663
Ruaraka / Kasarani	29,881	9,784	16	1,829
Kariobangi	43,349	12,926	12	3,437
Mathare	68,456	20,802	2	29,006
Administrative area	**Population total**	**No. of HHs**	**Land Area (Sq.Km)**	**Density (Persons per Sq.Km)**
Eastleigh	53,562	13,056	7	7,439
Kasarani	226,206	64,026	85	2,655
Nairobi	827,775	200,474	684	1,210
Karura	4,429	813	5	817
Ruaka (Rwaka)	6,958	1,456	7	871

*Karura and Ruaka were not indicated as part of Nairobi in 1999