Simulating Sanitation and Waste Flows and their Environmental Impacts in East African Urban Centres

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This research was conducted under the auspices of the Graduate School for Socio-Economic and Natural Sciences of the Environment (SENSE).

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Richard Oyoo

Thesis
submitted in fulfilment of the requirements for the degree of doctor
at Wageningen University
by the authority of the Rector Magnificus
Prof. Dr M.J. Kropff,
in the presence of the
Thesis Committee appointed by the Academic Board
to be defended in public
on Tuesday 14 October 2014
at 1:30 p.m. in the Aula.

Richard Oyoo
Simulating Sanitation and Waste Flows and their Environmental Impacts in East African Urban Centres,
179 pages.

Thesis, Wageningen University, Wageningen, The Netherlands (2014)
With references, with summarises in English and Dutch

ISBN 978-94-6173-842-4

Acknowledgement

Urban waste pollution of Lake Victoria, driven by rapid population growth and changing life style in the lake's surrounding cities, has become one of the most severe environmental and public health problems in East Africa. Many interventions to address the lake's water pollution have been unsuccessful. These waste flows are poorly documented and this has contributed to the longstanding absence of effective and efficient solutions. To design adequate solutions for these problems, a model representing waste flows through the social and natural systems of East African cities should enable projecting future trends in waste flows and their environmental impacts under different management regimes. This thesis therefore aims to understand, qualify, quantify and model waste flows and their environmental impacts in Lake Victoria's surrounding cities. The resulting model will be applied to search for and assess viable solutions to better manage waste flows, and minimize environmental and human health impacts.

This PhD research has been implemented in the framework of the Partnership Research on Viable Urban Environmental Infrastructure Development (PROVIDE) in East Africa. The project was funded by the Interdisciplinary Research and Education Fund (INREF) of Wageningen University, the Netherlands. I am very grateful to have been able to study waste flows in this context.

I feel indebted to my promoters/supervisors: Prof. Dr. Rik Leemans (Chair of Environmental Systems Analysis Group) and Prof. Dr. Arthur J.P. Mol (Chair of Environmental Policy Group), who have patiently guided me during this research process up to completion of this thesis. Their critical comments on the research design, analysis and scientific writing, have significantly enhanced my knowledge in understanding and diagnosing environmental problems. The academic quality of this thesis was highly improved by their critical and detail refinements of all chapters. Surely, without both promoters/supervisors, this thesis would have stayed just a dream. What I have learnt from both promoters/supervisors will benefit me for my entire lifetime.

Furthermore, my appreciation goes to Dr. Gábor Szántó, coordinator and Dr. Peter Oosterveer, manager of the PROVIDE project, for their advice and timely processing of the research funds to ensure the continuity of my research project.

My gratitude also extends to Prof. Dr. Carolien Kroeze and Dr. José Potting from the Environmental Systems Analysis Group for their useful discussions and contributions to my research. I further appreciate the encouraging and stimulating academic support of Andrè, Arnold, Dolf, Eugenie, Karen, Lars and Nynke. Special thanks go to Wichertje for translating the thesis's summary from English to Dutch. I also owe many thanks to Dr. Bas van Vliet and Prof. Dr. Gert Spaargaren from the Environmental Policy Group for their stimulating discussions during my stays in the Netherlands. Special thanks go to the administrators, Corry Rothuizen from the Environmental Policy Group, and Mathilde Witteveen and Ria Cuperus (RTD) from the Environmental Systems Analysis Group for their support in ensuring that I obtained all the necessary administrative and logistical requirements in time during my stays in the Netherlands.

Further appreciation goes to my PROVIDE colleagues: Aisa Solomon, Christine Majale, Fredrick Salukele, Judith Tukahirwa, Mesharch Katusiimeh and Sammy Letema. Your discussions from different disciplinary perspectives enhanced my understanding of modelling the environmental flows and designing appropriate responses to environmental problems that cover social, technological, economic and environmental aspects. I also extend my appreciation to colleagues at the Environmental Systems Analysis Group, for their company: Alexander, Alexey, Aritta, Cheng, Claudia, Katalin, Lucie, Maryna, Mathias, Roy and Shahid. Not forgetting other PhD researchers: Leah Ombis, Robert Okello and Thomas Odong. Being with you made my stay in Wageningen exciting.

I would like to thank the senior management of the National Water and Sewerage Corporation (NWSC), Uganda, for the support offered to me during my PhD research. Special thanks also go to the senior management of the United Nations African Union Mission in Darfur (UNAMID) for giving me time to travel to the Netherlands to have discussions with my supervisors on the progress of my PhD research. Also, I extend my thanks to staff members (Abu Bangura, Emmanuel Mollel, Esther Mbappe, Maisa Eltaher, Rebecca Kunya-Bagaya, Samah Osman and Yustinian Mulaki) of the Water and Environmental Protection Section, UNAMID, for their moral support.

I also extend my sincere thanks to Alice Aol, Barbra Alwoch, Linda Atim, Miriam Oyugi, Majorine, Nancy Allimadi, Robert Wokorach, Samson Ayonic and Vivian Adoch for their moral support when I was away from home during the months and years of this PhD research program. Lastly, to my late aunt Alice Allimadi, late father, David Oyoo, and my late mother Kelementina Aol Oyoo. You always took pride in my academic success. It is therefore a pity that you all did not live to see this day. Mum, we are what we are today because of the sacrifices that you made.

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Abbreviations

Symbol	Meaning
AC	Acidification
AfDB	African Development Bank
BOD_5	Five-days Biological oxygen demand
BSTW	Bugolobi Sewage Treatment Works
CBO	Community Based Organization
CFU	Coliform Forming Units
DAWASA	Dar es Salaam Water and Sewerage Authority
DPSIR	Driving force-Pressure-State-Impact-Response
EEA	European Environmental Agency
EMCA	Environmental Management and Co-ordination Act
ERM	Environmental Resources Management
GHGs	Greenhouse gases
GWP	Global warming potential
HT	Human toxicity
INREF	Interdisciplinary Research and Education Fund
ISO	International Organization for Standardization
IUWFM	Integrated Urban Waste Flow Model
KCC	Kampala City Council
KCCA	Kampala Capital City Authority
KMC	Kisumu Municipal Council
LC	Local Councillor
LCA	Life Cycle Analysis
LVEMP	Lake Victoria Environmental Management Program
MAPET	Manual Emptying Pit Technologies
MCDA	Multi-criteria Decision Analysis
MDGs	Millennium Development Goals

Symbol	Meaning
MLG	Ministry of Local Government
MoH	Ministry of Health
MSW	Municipal solid waste
MWI	Ministry of Water and Irrigation
NBS	National Bureau of Statistics
NE	Nutrient Enrichment
NEMA	National Environmental Management Authority
NGO	Non-Governmental Organization
NWSC	National Water and Sewerage Corporation
OFMSW	Organic fraction of municipal solid waste
POF	Photochemical ozone formation
PROVIDE	Partnership for Research on Viable Infrastructure Development
PSP	Private Service Providers
RQ	Research question
STW	Sewage Treatment Works
TN	Total Nitrogen
TP	Total Phosphorous
UBOS	Uganda Bureau of Statistics
UNAMID	United Nations African Union Mission in Darfur
UNBS	Uganda National Bureau of Standards
UNESCO-IHE	United Nations Educational, Scientific and Cultural Organization-International Institute for Hydraulic and Environmental Engineering
UN-HABITAT	United Nations Human Settlement Programme
URT	United Republic of Tanzania
VOCs	Volatile organic carbon
WHO	World Health Organisation

Chapter 1 General introduction: simulating sanitation and waste flows and their environmental impacts in East African urban centres

1.1 Background

The rapid population growth and rapidly changing consumption patterns increase waste flows in developing countries' cities, including those in East Africa. Many city authorities in developing countries have failed to adequately collect and treat all the wastes produced in their cities. In East Africa, the peri-urban and slum settlements are often characterised by uncollected municipal solid waste (MSW) along roadsides, on 'waste' land and in storm surface water drains. Sewage overflows and illegal discharges of faecal sludge from on-site sanitation systems into storm surface water drains are also common (Mireri *et al.*, 2007; NWSC, 2008). Water sources are contaminated by faecal matter and are loaded with high amounts of organic matter and nutrients, resulting in water eutrophication (Howard *et al.*, 2003; Kulabako, 2005).

Several studies attribute the cause of these increasing waste flows in the urban environment in East Africa to poor performance of large-scale waste infrastructures, such as centralised sewerage systems and landfills. Such large-scale infrastructures have high operational and maintenance costs (Kansiime and Nalubega, 1999). The heterogeneous spatial settlement patterns and varying local environmental conditions in East African cities also make it unfeasible to adequately collect and treat all waste flows using uniform large-scale centralised waste infrastructures. A robust system that combines a mixture of diverse waste collection and treatment technologies and management regimes, and that matches the spatial settlement structures, specific local environmental and socio-economic conditions, would be a viable solution for managing waste flows in such cities. In literature, such systems are referred to as modernised mixtures (Scheinberg and Mol, 2010; Scheinberg *et al.*, 2011).

The development of such robust waste management systems for the urban centres of Kenya, Tanzania and Uganda—the East African region this thesis focuses on—requires the identification and quantification of urban waste sources and compositions, and the assessment of different waste management options and systems for future effective, efficient and viable waste management. This chapter sets the background to research problems, research questions, and general methodology and approach for such a study. It starts with a typology of waste sources and management in East African cities (section 1.2) and the political, legal and institutional frameworks of the current waste management systems are embedded in (section 1.3). Subsequently, the research problem is defined and the research questions are formulated (sections 1.4 and 1.5, respectively). Finally, the research approach and general methodology are introduced.

1.2 Urban waste typology, sources and management

The principle sources of urban waste in East Africa are households, offices, government institutes, commercial establishments and markets (Kaseva and Mbuligwe, 2005; KCC, 2006). Here, and in the rest of this thesis, urban waste refers to only human excreta and municipal solid waste. This thus excludes waste from industries, agriculture and mining sectors.

For the purpose of discussion in this thesis, the typology of urban waste can be put in four distinct categories:

i. *Organic fraction of municipal solid waste (OFMSW):* This fraction includes food left-overs, remains/processing waste of fruits and vegetables. These wastes originate mainly from households and markets. Much of the OFMSW from markets result from packaging materials (e.g. banana leaves, grasses and potato stalks) used for wrapping fresh foodstuffs, as well as from left-over products that can no longer be sold or consumed. In the rest of this thesis, the organic fraction of municipal solid waste is expressed as OFMSW.

ii. *Recyclable material:* This waste fraction includes paper, glass, plastics, metal and textile. In this thesis, recyclable material refers to the fraction of municipal solid waste that can be salvaged and directly reuse or recycled for making secondary materials. In the rest of this thesis, a recyclable material is expressed as a recyclable.

iii. *Non-biodegradable, inert waste*: This fraction consists of waste materials that are not necessarily toxic to all species, but can be harmful or toxic to humans. This includes for instance construction and demolition waste. In the rest of this thesis, this waste category is referred to as residue or other MSW (i.e. municipal solid waste fractions that are not OFMSW or recyclables). Since the amount of this waste type is small, it is not covered in detail in this thesis.

iv. *Solid and liquid human excreta:* This is largely sourced from households, educational institutes and other common facilities. In the rest of this thesis, solid and liquid human excreta is expressed as human excreta.

The current management of the aforementioned waste categories in Kenya, Tanzania and Uganda are briefly described below. The four types of wastes described above are broadly argued into two categories: human excreta and municipal solid waste as overall category of the first three fractions. This helps to understand the problems of managing waste flows and enables the formulating of the research questions.

a) Solid waste management

Substantial amounts of municipal solid wastes are generated daily in East African cities, of which OFMSW forms the highest fraction. Table 1.1 provides data on municipal solid waste generation rates for seven East African cities. Much of the municipal solid waste originates from households (Table 1.2). The official or formal municipal solid waste management includes storage, collection and transportation of municipal solid waste to a disposal site. Valuable fractions such as paper, plastics, glass bottles and metal are partly collected separately for recycling; only parts of these waste materials end up at the landfills/open dumps. At its generation point, the municipal solid waste is often temporarily stored either on-site or in the immediate neighbourhood (often in skips[1]) prior to collection for final disposal. Skips are often over-filled with municipal solid waste.

Formal municipal solid waste collection percentages are low in many East African cities. In Kampala City for example, less than one fourth of the 1,300 t of municipal solid waste generated daily is collected by official public and private waste collection agencies (Okot-Okumu, 2006). Also, in Kisumu only about 20% of municipal solid waste generated by the urban resident is collected by the municipality and private collectors (Onyango and Kibwage, 2008). Formalised municipal solid waste collection is often concentrated in the business districts and in the more affluent neighbourhoods. In the less affluent areas informal waste collection is also of great importance. Many city residents have also resorted to burying or open burning of their municipal solid wastes or disposing them illegally into the environment.

[1] *Skips are containers used for MSW collection, and they are mainly stationed at the markets and residential areas. They are hauled to landfills by trucks whenever filled.*

Table 1.1. Population versus MSW generation rates and OFMSW for the cities studied.

City	Population growth rate (%)	Population size in 2002	MSW generation (t day^{-1})	OFMSW (%)	Sources
Kampala	3.8	1,208,196	1,300	83	(Oyoo *et al.*, 2011)
Jinja	2.4	86,520	207	75	(Okot-Okumu, 2006)
Kisumu	3.2	280,966**	140	67	(Onyango and Kibwage, 2008)
Mwanza	3.0	476,646	191	78	(Salukele, 2013)
Bukoba	4.0	81,221	32	78	(Mbuligwe *et al.*, 2002)
Musoma	5.8	108,242	54	74	(UN-HABITAT, 2005)
Dar es Salaam	4.3	2,500,000	2,037	64	(ERM, 2004)

**Population size from population census for 1999

Table 1.2. Sources of MSW and their estimated contribution to the MSW load.

Source	Contribution in weight (%)	
	Jinja	**Dar es Salaam**
Households	52	72
Markets	20	3
Commercial establishments	8	2
Industries	3	-
Government institutes	5	-
Others MSW	12	23
Total	**100**	**100**

Note: (-) means value is included in Others MSW. *Sources:* (ERM, 2004; Okot-Okumu, 2006)

The collected municipal solid waste is disposed in landfills/open dumps. Besides recycling, landfilling is the only authorized method to treat municipal solid waste in almost all East African cities (KCC, 2006; Onyango and Kibwage, 2008). These landfills generate leachate containing high concentrations of dissolved and suspended solids. For example, the measured BOD_5 in the untreated leachate of

Kampala's landfill is about 2,100 mg l^{-1}, while that of treated leachate is 298 mg l^{-1} (Mwiganga and Kansiime, 2005). This is much higher than the specified national effluent discharge standard of 50 mg l^{-1} (NEMA, 1999). Such leachate poses a serious environmental threat to the water quality for the groundwater aquifer and Lake Victoria.

b) Human excreta management

The sanitation systems in place fall into two broad types: 'flush-and-discharge' or 'drop and store'. The flush-and-discharge systems, connected to a piped sewerage infrastructure, are used in the business districts and satellite estates of East African cities (Kulabako *et al.*, 2010). The population without access to flush-and-discharge systems uses drop-and-store devices, which are usually on-site pit toilets. A small portion of these on-site sanitation systems are emptied regularly after which the faecal sludge is taken to sewage treatment works (STW) at a fee (DAWASA, 2007; NWSC, 2008). In Kampala City, for example, only about 27% of the faecal sludge from on-site sanitation systems is taken to a sewage treatment works (NWSC, 2008; Oyoo *et al.*, 2011) and in Kisumu it is only about 5% (MWI, 2007). In the poorer and densely built-up areas where vehicular access is impossible, scavengers are employed to empty the pit latrines. The contents of these pit latrines are often dumped in storm surface water drains or in a pit dug nearby.

Table 1.3. Proportions of population served by sewerage in large East African cities.

Tanzania		**Uganda**		**Kenya**	
City	*Population (%)*	*City*	*Population (%)*	*City*	*Population (%)*
Arusha	9	Kampala	5	Kisumu	16
Dar es Salaam	13	Jinja	22	Nairobi	36
Mwanza	9	Entebbe	4		

Sources: (DAWASA, 2007; MWI, 2008; NWSC, 2008)

The percentages of the population served by sewerage systems are generally small in East African cities (Table 1.3). Moreover, sewage overflows and leakage from manholes and broken sewers are frequent. In Kampala City, for instance, about 19% of sewage overflows to the environment. The sewage treatment works are also operating ineffectively. In Kenya, for example, of the thirty-eight (38) sewage treatment works, 40% are overloaded, 6% are operating at design capacity, 42% operating below capacity and 3% are not operating at all (MWI, 2008). The BOD_5 levels in the effluent for the main Kampala's sewage treatment works is reported to be about 120 mg l^{-1} higher than the set effluent quality standard of 50 mg l^{-1} (NEMA, 1999). Most conventional sewage treatment processes violate the stringent environmental standards set by Uganda's National Environmental Management Authority (NEMA). This stringent legislation, coupled with the economic inabilities to meet the requirements by using up-to-date technologies, paralyses many investments in sewage treatment systems.

1.3 Political, legal and institutional framework

The political, legal and institutional frameworks in which waste management infrastructures operate are crucial for the performance of waste management systems. Below, the governing structures for urban waste flows are described for the three East African countries included in this thesis.

a) Kenya's waste policies

The main acts governing Kenya's waste management include the Environmental Management and Co-ordination Act (EMCA) from 1999 (NEMA, 1999), the Water Act from 2002 (MWI, 2002) and the Local Government Act from 1998 (MLG, 1998). EMCA establishes the legal and institutional framework for environmental management, including waste management. It emphasises waste reduction and source segregation, prohibits dangerous handling and disposal of waste to the environment, and facilitates waste recycling. This Act stipulates that any person, whose activities generate waste, shall employ measures essential to minimize waste flowing into the environment through reclamation, recycling and treatment. Nobody shall dispose waste in such a manner that it causes pollution or health risks. Anybody contravening this law is liable, on conviction, to imprisonment for a term of not more than two years or to a fine of not more than one million shillings (around US$ 11,827) or to both (NEMA, 1999). The Water Act shifts the government's responsibility from that of an implementer to a facilitator. It emphasizes on private sector participation in the management and development of sewerage services to serve all urban residents, including low-income households, and to protect the environment (MWI, 2007). The Local Government Act allows cities to have by-laws to regulate and manage all wastes in their jurisdiction (MLG, 1998). These by-laws clearly articulate the segregation of municipal solid waste at source.

The municipal solid waste management in Kenyan cities was previously carried out by the Cleaning Section in the municipal Public Health Department. In 2004, this management role was transferred to the Directorate of Environment, which is responsible for all activities relating to municipal solid waste management within city jurisdictions (KMC, 2007).

The sewerage system management has now been privatized (in line with the Water Act) by shifting the water supply and sewerage services from local authorities to private companies formed by the City Councils. For instance, the sewerage system for Kisumu is managed by the Kisumu Water and Sewerage Company (UN-HABITAT, 2004). With regard to on-site sanitation systems, the Ministry of Public Health and Sanitation is responsible for ensuring their proper installation, operation and maintenance. The constructions, operations and maintenance of the on-site sanitation systems such as septic tanks, eco-san and pit latrines are performed by the individual households.

b) Tanzania's waste policies

The policy documents governing waste management in Tanzania include the Environmental Policy document from 1997 (URT, 1997), the Solid Waste and Hazardous Management Act from 2009 (URT, 2009; URT, 2009), the Public Health Act from 2009 (URT, 2009), the Water Supply and Sanitation Act from 2009 (URT, 2009), and the National Environmental Management Act from 2004 (URT, 2004). These regulations provide principles and guidelines for handling waste from generation up to final disposal. The Solid Waste and Hazardous Waste Management Act requires any person in possession of hazardous waste materials to separate them from other types of waste and then collect, transport and dispose them separately. Tanzania's National Environmental Management Act is the main legislative reference for environmental management, and provides the legal and institutional framework for sustainable management of the environment in Tanzania. It provides guidelines for the prevention and control of pollution, waste management, environmental quality standards, compliance and enforcement. The Water Supply and Sanitation Act 2009 calls for sustainable management and adequate operation of sanitation services, and calls for the establishment of sanitation authorities. This Act ensures that every Tanzanian has access to sanitation services, to promote public health and proper sanitation management (URT, 2009).

The management of MSW in Tanzania's cities primarily lies with city authorities and is supervised by the health departments of city authorities (Yhdego, 1995). The responsibility for managing sewerage systems and on-site sanitation systems lies with the Ministries of Water and Health (Scheelbeek, 2006). The urban water and sanitation authorities are responsible for the collection and treatment of sewage generated in urban centres. For example, the sewerage system for Dar es Salaam is managed by the Dar es Salaam Water and Sewerage Authority (DAWASA), which exclusively focuses on the sewerage systems in business districts and more affluent neighbourhoods (DAWASA, 2007). The on-site sanitation systems are based on self-provisioning by the individual households, but are regulated by the health departments of city authorities (World Bank, 2003).

c) Uganda's waste policies

Uganda's Public Health Act from 1964 (MoH, 1999), its National Environmental Act Cap-153 from 1995 (NEMA, 1999), its 1997 Water Act (MWE, 1997) and its Local Government Act from 1997 (MLG, 1997) are the main legal documents for the management of waste flows. The Public Health Act defines the role of city authorities and their communities with regard to health risks of managing municipal solid wastes' storage, collection, transportation, treatment and final disposal facilities. This act empowers all city authorities to take all lawful, necessary and reasonably practical actions to protect and promote public health in their cities. It is thus the responsibility of city authorities to keep the city clean at all times (MoH, 1999). The Local Government Act decentralizes the operationalization of the country's policies, assigns roles and responsibilities to each municipal governance level and specifies the role of stakeholders (MLG, 1997). The National Environment Act stipulates that all generated waste is disposed or discharged in such a volume and composition that it does not harms the environment (NEMA, 1999). There is also a solid waste management ordinance, defining the procedures for municipal solid wastes' storage, collection, transportation and disposal. This ordinance classifies waste into hazardous and non-hazardous waste. The ordinance prohibits indiscriminate disposal of municipal solid waste to the environment. However, enforcement of these regulations has been challenged by low enforcement capacities and weak punitive measures. For instance, anybody contravening the sections of the Solid Waste

Management Ordinance or sections of the Wastewater Management Regulations is only liable on conviction to imprisonment for a term of not more than six months or to a fine of not more than three hundred sixty thousand Uganda shillings (which equals US$ 144) (KCC, 2000).

The overall management of MSW in Uganda's cities is the mandate of city authorities, such as the Kampala Capital City Authority (KCCA)[2]. The collection and transportation of municipal solid waste in the city is supervised by a Divisional Public Health officer who reports to a Senior Principal Assistant Town Clerk. The central KCCA office is responsible for managing the landfill, but its operations and maintenance have been outsourced to a private contractor (KCC, 2006).

The sewerage systems in big cities, including Kampala City, are operated and maintained by the National Water and Sewerage Corporation (NWSC, 2008). Ensuring adequate installation, operation and maintenance of on-site sanitation systems remains the responsibility of city authorities (AfDB, 2006). However, the construction and the day-to-day operations and maintenance of on-site sanitation systems are done by individual households or government institutes. Where tenants lack adequate sanitation facilities, private entrepreneurs provide common toilets at a fee.

1.4 Problem statement

Although political, legal and institutional frameworks governing waste flows exist in Uganda, Kenya and Tanzania, the waste flows are poorly managed. Uncollected municipal solid wastes are seen along roadsides and sewage overflows are frequent. Large volumes of waste enter the inshore areas of Lake Victoria, polluting the lake's water and causing water eutrophication (Muyodi *et al.*, 2009). Also, high population growth devoid of basic sanitation in slums has exacerbated the influx of waste into the inshore areas of Lake Victoria (UN-HABITAT, 2008). If this trend continues, Lake Victoria's water quality will rapidly deteriorate. Poor water quality has consequences for the economic activities related to the lake and for human health. A model representing waste management flows through the social and natural systems of East African cities would enable the projection of future waste flow trends and their environmental impacts under different waste

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[2] Kampala Capital City Authority is the legal entity, established by the Uganda parliament, and is responsible for the operations of Kampala City. It replaced the former Kampala City Council (KCC).

management regimes, so as to design appropriate responses. But at the moment there exists no coherent model integrating waste flows from different sources via intermediates to treatment and final disposal, and their environmental impacts. We therefore need a model representing the system processes under specific social and natural conditions of East African cities. Such a model, built on adequate local data and knowledge of waste flows as well as modern scientific insights, is necessary to gain better insight into the management of various waste flows in expanding East African cities. A process-based approach, which describes different waste flows at different stages (from generation to disposal) and connects them at different levels of analysis (from localized flows related to one or a few households via neighbourhood or community level up to municipal level), is considered an appropriate strategy to build a model under conditions of data limitations (Biggs *et al.*, 2004).

Models for substance flows, relating different levels of aggregation, have been developed for cities in developed countries (Douglas *et al.*, 2002), but these models might not be appropriate for assessing performance of waste sector for East African cities because of differences in the social and natural conditions. In addition most existing models, simulate only municipal solid waste flows (Tanskanen, 2000; Skordilis, 2004) or only nutrient fluxes (Belevi *et al.*, 2004), separately. The only available model for a city in East Africa is a static model for planning municipal solid waste disposal sites for Dar es Salaam City (Yhdego *et al.*, 1992). This model proved useful in providing optimum solutions for the present situation but is less useful for investigating long term solutions under (rapidly) changing conditions. A dynamic integrated model is required to understand the processes of waste generation, transformation, transport, treatment and final disposal of waste materials, and to design appropriate responses to manage waste flows. Such models can be used to understand and illuminate how driving factors and forces on waste production and management influence the environment and human health. Such models can also make up for data and information deficiencies, for instance, by providing calculated estimates where observations are lacking. In addition, such models can be used to assess scenarios of future waste flows management. They can inform and facilitate the development of future innovative policies and management options, for instance on shifting from end-of-pipe abatement to structural improvements, on preferential social behaviour, on essential technological regime shifts and on required institutional arrangements.

1.5 Objective and research questions

To design appropriate future responses to the growing waste flows and their environmental and human health impacts, better insights in the environmental performance of urban waste infrastructures are needed. The overall objective of this research is twofold: (i) to understand, qualify, quantify and model waste flows and their environmental and human health consequences in cities in East Africa surrounding Lake Victoria; and (ii) to assess solutions for better management of waste flows towards minimizing environmental and human health impacts. To achieve this objective, the following research questions are central in this study:

i. What are the current organic loads to the inshore areas of Lake Victoria from the surrounding cities, and optimal scenarios to minimise organic loads from each city?
ii. What are the likely and possible future waste flows and their environmental impacts when technological, social and economic changes are taken into consideration all together?
iii. To what extent, and how, can waste recycling improve the environmental performance of waste infrastructures in cities in East Africa?
iv. What is the optimal scenario to improve environmental performance of waste infrastructures in cities in East Africa, based on economic, environmental, social and technological criteria?
v. Given the answers to the above four questions, what is the most appropriate scenario to improve the environmental quality of Lake Victoria?

1.6 Research approach and methodology

The waste flows in East African cities—from generation via intermediate stages to treatment and final disposal—are poorly qualified and quantified. This makes designing appropriate responses to minimise impacts of waste flows on the urban environment difficult. These waste flows need to be identified, qualified, quantified, mapped and modelled to understand their dynamics and conversion in space and time. This requires the application of integrated models. However, before explaining environmental system analysis as the main methodology to design such a model and use it for assessing (future) waste management regimes, this section start with explaining the context of this study in a wider research programme called PROVIDE, followed by the introduction of a Driving force-Pressure-State-Impact-Response (DPSIR) type of conceptual framework for this study.

1.6.1 Context of the study

This study is part of a larger research project, the Partnership for Research on Viable Infrastructure Development (PROVIDE) in East African cities. PROVIDE aims to investigate the technological and institutional dimensions of sanitation and solid waste management in East African cities in order to improve the environmental performance of the water and waste sectors. This contributes to achieving some of the Millennium Development Goals (MDGs) on improving access to safe drinking water and basic sanitation, and the lives of at least one hundred million slum dwellers (Meinzinger *et al.*, 2009).

Important issues addressed by the MDGs are: improved governance, technological innovation and diffusion, and enhanced financing mechanisms (Majale, 2011). To attain these MDGs, the future potential waste management options and their consequences on the environment should be explored, using local knowledge. PROVIDE project consists of different projects, covering several aspects of sanitation and municipal solid waste management at different levels and for different urban centres, mostly around Lake Victoria (Figure 1.1). Research carried out in PROVIDE project includes, for examples, the functioning of public and private service provision of solid waste management in Kampala, Uganda (Katusiimeh, 2012); the assessment of sanitary systems—conventional and modernised mixtures—in East African cities (Letema, 2012); the role of non-governmental and community-based organizations in sanitation and solid waste management systems in East African cities (Tukahirwa, 2011); the role of municipal institutional arrangements in modernising solid waste management in urban centres of East Africa (Majale, 2011); and innovative landfill bioreactor systems for municipal solid waste treatment in East Africa (Salukele, 2013). This thesis furthers the knowledge on urban waste systems in East African cities by simulating sanitation and waste flows and their environmental impacts in East African cities. It uses some of PROVIDE case study cities, which were also used in the earlier PROVIDE studies, as empirical bases (Figure 1.1).

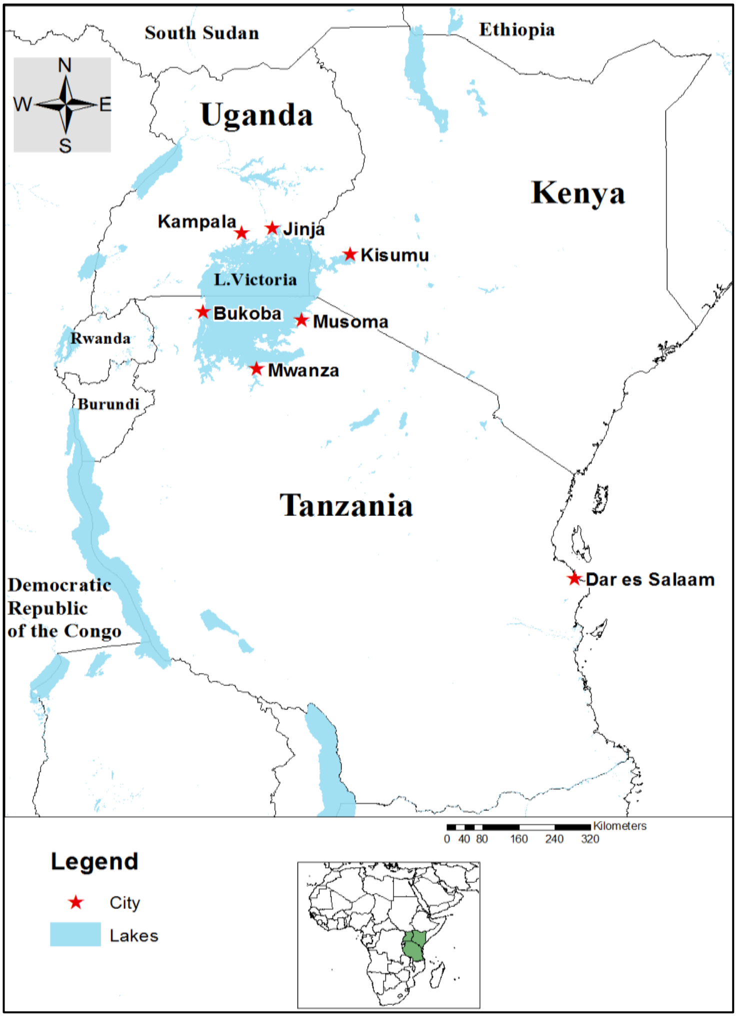

Figure 1.1. Map of East Africa showing the cities studied and inset (Africa).

1.6.2 The study's conceptual framework

Several approaches exist for analysing the structure and dynamics of environmental problems and their impacts. The Driving force-Pressure-State-Impact-Response (DPSIR) framework is one of the most commonly used approaches for analysing environmental problems (EEA, 1999). The DPSIR framework is useful for describing and evaluating the relationship between the origins of, the consequences of and solutions for environmental problems (Millennium Ecosystem Assessment, 2003). It is also helpful for visualising specific problems within a system's approach, conceptualising system elements and their relations in developing mathematical models and enhancing communication between scientists, decision-makers and the public in addressing these problems. The DPSIR framework views societal developments as common drivers (D) that exerts pressure (P) on the environment. This results in the state (S) of the environment. These changes have environmental and human health impacts (I). These impacts trigger society responses (R) that alter the drivers, pressures, state or impacts through preventive, adaptive or curative measures.

The DPSIR framework has been applied, among others, in the Millennium Ecosystem Assessment to illustrate the cyclic consequences of human impact, ecosystem degradation, ecosystem service change, human well-being and societal responses to these changes (Millennium Ecosystem Assessment, 2003).This thesis applies a DPSIR framework to understand waste flows management problems by identifying drivers of waste flows, waste activities exerting pressures on the environment, state of the environment and impacts of waste flows on the environment and human health. Subsequently, this DPSIR variant designs appropriate responses for drivers, pressures, state and impacts to improve the environmental performance of waste sectors in East African cities. The DPSIR framework (as visualized in Figure 1.2) is built by defining the problem of waste management infrastructure, listing key concepts/keywords related to waste flows, and determining the concepts/keywords linked to waste management problems or resulting from these problems. The cause and effect relationship of waste problems are restructured using this framework.

Increasing population growth, increasing economic development and changing consumption patterns are identified as the key drivers of waste production and their flows to the urban environment. These drivers influence the pressures by changing waste composition, use of land for illegal waste disposal, and increasing waste production by households, markets, government institutes and commercial establishments. As the state factors, the environmental pollution by waste and emissions are used as indicators. These emissions cause impacts on the human health and well-being, and the environment. Society then respond by introducing (new and/or more) treatment technology, enhancing and improving waste recycling, involving stakeholders in waste management, and introducing and stringently enforcing waste management policies. The different components of the DPSIR framework (Figure 1.2) are summarised below. Detailed analyses are performed and discussed in chapters 2, 3, 4 and 5.

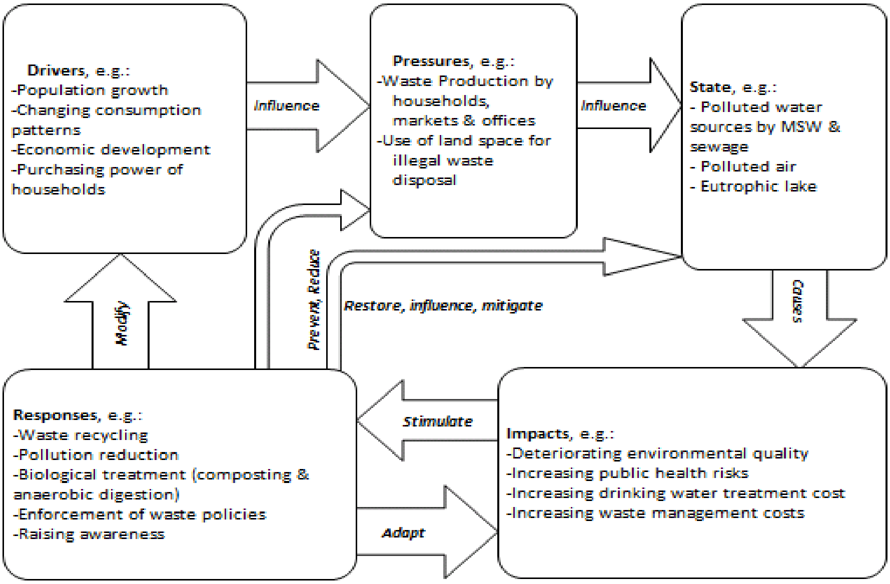

Figure 1.2. DPSIR conceptual framework for waste flows in East African cities.

a) Drivers

Many drivers influence the quantity and quality of wastes. Understanding these drivers is essential for designing interventions that capture and enhance positive impacts, and minimize negative ones. The key direct drivers of waste flows in East African cities are: population size and economic development. Changes in both drivers are projected to increase the demand for food, clean water and energy, which will in turn affect the waste flows (Leemans *et al.*, 2005). Increases in population size increase the waste flows (Hinga *et al.*, 2005). The high urban population growth rates in East Africa are expected to continue for the coming decade (EAC, 2004; Makita *et al.*, 2010), and so do the magnitude of waste flows.

When population growth is coupled with an increase in purchasing power for households and economic development, this may lead to a further increase in the waste flows, all other things remaining constant. Households with high income levels have higher consumption levels than low-income households because of their higher purchasing power. Hence, increasing households' financial income levels increases consumption and waste generation, as most literature indicated. Changing consumption patterns directly influence the waste generation rate

(Sufian and Bala, 2007). But changing consumption patterns also changes the composition of MSW, often lowering the proportion of OFMSW in the MSW.

b) Pressures

The pressures resulting from consumption and waste production processes by households, markets and commercial establishments can be categorised as: (1) use of environmental resources, (2) use of land space for (illegal) waste disposal, and (3) harmful emissions to air, water and soil. The MSW generation rates per capita in East African cities are lower than for developed countries' cities (Mwiganga and Kansiime, 2005), but their collection rates are also low. This results in higher environmental loads per unit of generated waste in East African cities, compared to most European cities (Asase *et al.*, 2009). Also, the establishment of end-of-pipe waste treatment facilities near cities can result in land use conflict between sites for waste treatment and land for food crops production, for housing or for industrial development. Alternatively, waste disposal facilities could be established in remote areas from cities, but this increases the cost and environmental burden, because of increased waste hauling distances (Strauss and Montangero 2002).

c) State

The pressures exerted by waste production and the use of land for illegal waste disposal may lead to unintentional or intentional changes in the state of the environment. In this context, the state of environment reflects the magnitude and concentration of physical phenomena (e.g. temperature), biological phenomena (e.g. fish stocks) and chemical phenomena (e.g. five-days biological oxygen demand [BOD_5], total nitrogen [TN] and total phosphorus [TP]) in a certain area (EEA, 1999). This in turn determines the health, survival, growth and distribution of living organisms in the environment, among which human beings are included. Many East African cities dispose their MSW in unregulated open dumps (KCC, 2006; Mireri *et al.*, 2007; Onyango and Kibwage, 2008). These open dumps/landfills emit methane emissions into the atmosphere as there are no gas collection systems installed in East African landfills. The MSW in landfills also generate leachate containing high organic matter and heavy metals, polluting groundwater if left untreated. Besides that, the emissions from pit-unlined latrines and untreated sewage pollute water sources.

Because of inadequate human excreta collection and treatment, the spring water sources in Kampala, for example, are widely contaminated by faecal matter (Nsubuga *et al.*, 2004). Only 10% of these spring water sources met the stipulated coliform counts of 0 CFU 100 ml^{-1} required by the World Health Organisation (WHO) drinking water quality guidelines (WHO, 2004). Surface waters of streams and Lake Victoria's inshore have high levels of organic matters and nutrients. For instance, the surface water in Nakivubo Channel in Kampala City has a reported BOD_5 level of 173 mg l^{-1} (NWSC, 2006). This channel discharges its water to Lake Victoria Murchison Bay. As a result, the bay has very low dissolved oxygen level of approximately 1.5 mg l^{-1} and it is eutrophic (Muyodi *et al.*, 2009).

d) Impacts

The changes in the quality and functioning of the environmental state impact the well-being of human beings. In East African cities, open dumping/landfilling and on-site sanitation systems are the most used methods for treating MSW and human excreta, respectively. These systems impact the environment and human health. The possible impacts on human health arising from poor waste management include intake of contaminated drinking water and food crops. The OFMSW disposed in landfills is transformed by microorganisms, resulting in polluted leachate that flows to the groundwater and surface water sources. Methane emissions resulting from landfills contribute to global warming if not collected. Additionally, the organic acids produced in the leachate may mobilize heavy metals, which then enter water sources (Brunner and Rechberger, 2004). This deteriorates water quality and increases drinking water treatment costs. For example, the drinking water treatment chemical dosage for Kampala's drinking water treatment works at Gaba has increased exponentially fivefold between 1993 and 2010, because of the deteriorating Lake Victoria Murchison Bay's water quality. The energy usage has also increased because of more frequent cleaning of water filtration systems due to clogging by algae (NWSC, 2006).

e) Responses

Society makes decisions in response to the impacts of waste flows on health and the environment. The responses are taken to prevent, correct or adapt to changes in the state of the environment. An effective response strategy to waste problems involves a combination of interventions at all points in this conceptual framework. Such interventions may seek to modify drivers through policies that affect consumption levels and patterns, population sizes and financial capacities of households (Millennium Ecosystem Assessment, 2003). Also, responses may seek to prevent or reduce pressures exerted on the environment through regulations, for example, by reducing the production of waste via discharge limits, discharge fees, or internal recycling. Responses may also be applied to directly restore the state of the environment, through controlling the physical and chemical environment, for example, by setting water or air quality criteria. In some situations, responses are taken to adapt to the new state of the environment. Additionally, responses may be applied to mitigate the impact of waste flows on the environment and human health by introducing waste treatment technologies. Furthermore, since policies for dealing with environmental degradation are concerned with the future impacts of current actions, applying appropriate responses would require the development of scenarios of changes in pressure, state and drivers related to waste flows, to aid decision-making (Alcamo, 2001).

1.6.3 Environmental system analysis of waste flows

This thesis applies an environmental system analysis approach to understand, identify, qualify, map, quantify and model waste flows in East African cities. Environmental system analysis is useful for analysing complex environmental problems and for evaluating possible solutions for these environmental problems. As elements of environmental system analysis, in this thesis, the system definition, model building, system analysis, scenario analysis, multi-criteria decision analysis and life cycle analysis are performed, to search for and assess viable waste management solutions for East African cities.

As the first step in environmental system analysis, the system boundaries are defined in this thesis. This is then followed by analysing the system elements and their relations, and the identification and description of waste flows. An appropriate system definition is vital for the identification of appropriate solutions to waste flow problems at stake, as well as for model requirements (Jawjit, 2006). In this thesis, the important sources for waste generation and their flow paths and sinks are identified. The current magnitudes for urban environmental loads to Lake Victoria's inshore areas are estimated using a material flow analysis. This provides baseline conditions for calculating the environmental loads. These environmental loads are used to compare the relative performances of different and plausible scenarios for waste management.

After estimating current environmental loads a dynamic integrated model is developed—based on locally available waste flows data combined with scientific literature—for exploring the consequences of different and plausible waste management scenarios. The model is developed by adopting an integrated assessment modelling approach. This model is used to quantify environmental loads and impacts of scenarios for managing waste flows. Scenarios are plausible alternative futures and outcomes under particular assumptions, and can be used as a systematic method for thinking creatively about the range of choices that need to be made (Rotmans *et al.*, 2000). In this study, I am particularly concerned with scenarios that deal with variations in waste flows under different management regimes (i.e. different technologies, management programs, enforcement strategies and payment schemes) and their environmental impacts.

The scenarios are further evaluated using a multi-criteria decision analysis to determine the optimal waste management scenario. To this end, the scenarios are appraised against economic, environmental, social, technological and general criteria, simultaneously. Multi-criteria decision analysis is a useful tool for analysing complex environmental problems featuring high uncertainty, conflicting multidimensional objectives (economic, social, environmental, general and political) and different data types (qualitative and quantitative data), which can lead to selection of robust solutions (Morrissey and Browne, 2004; Crown, 2009).

Finally, an environmental impact assessment for waste recycling is done to understand the impact of waste recycling on the performance of the waste sector in East African cities. To do so, an emission inventory is compiled within the system boundaries. Necessary data from scientific literature and field surveys are used. Life cycle analysis (LCA), combined with scenario analysis, is applied to quantify the potential contribution of waste recycling on the environmental performance of the waste sector in East African cities.

1.7 Outline of the thesis

This thesis is structured through sequential steps that are taken in addressing the overall objective and research questions (Figure 1.3). The research questions (RQ) are inside the boxes and abbreviated as RQ1, 2, 3, 4 and 5. Chapter 2 analyses and estimates the organic loads to Lake Victoria's inshore from large cities, and assesses the pollution abatement strategies. Six scenarios combining different organic treatment options are assessed on their contribution to the reduction of organic loads relative to the baseline load for each city. Chapter 3 presents the development and application of a dynamic model for wastes generation, transportation, treatment and their environmental impacts. A waste flows dynamic model for East African cities is developed, calibrated, validated and tested. This model is subsequently applied to project future waste flows and their environmental impacts in four scenarios. Chapter 4 presents the determination of an optimal scenario for managing waste flows in Kampala City. Four scenarios are appraised, using expert multi-criteria assessments on a set of economic, environmental, technological, social and general criteria. In Chapter 5, the potential local, regional and global environmental impacts of waste recycling in East Africa are assessed, using four scenarios for Kampala as a case study city. To conclude, in Chapter 6, the findings of chapters 2, 3, 4 and 5 are discussed, the research questions are answered and final conclusions are drawn with respect to effective and necessary measures to improve the environmental performance of waste flows and Lake Victoria's environmental quality. Basically, the last chapter provides us with elements for viable modernized mixtures of waste management systems in East African cities.

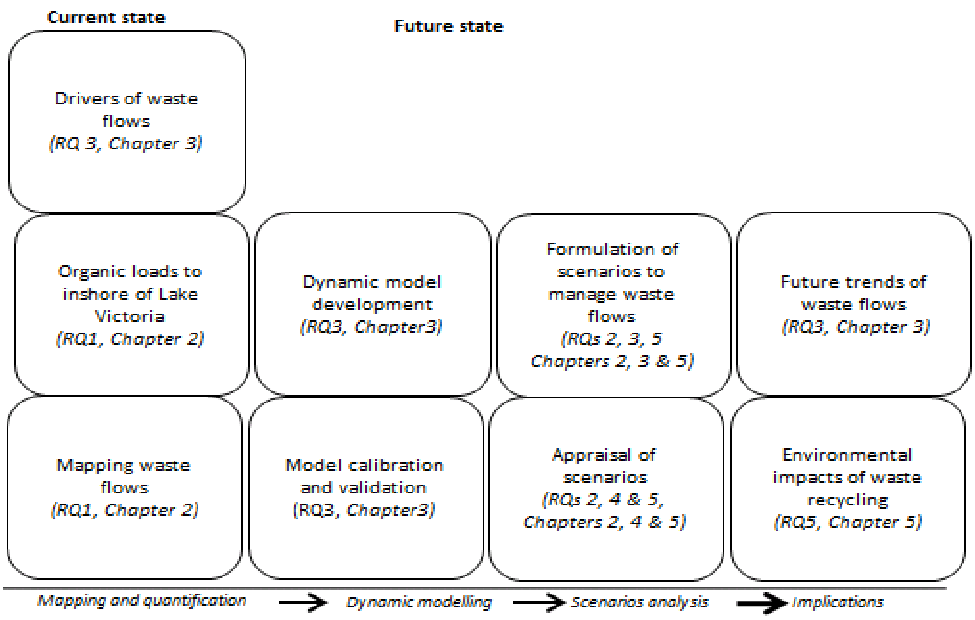

Figure 1.3. Overview of sequential steps in the different chapters of this thesis; from mapping and quantification to study's implication.

Chapter 2 Urban organic waste loads and pollution abatement strategies for cities surrounding Lake Victoria[3]

Abstract

Lake Victoria, which is the largest African lake, supports livelihoods of about forty million people. The lake's water quality and resources are threatened by urban organic waste pollution. This study assessed the organic loads to Lake Victoria's inshore for six cities and evaluated plausible scenarios to reduce these loads. A box model was developed, calibrated, validated, tested and applied to assess the current organic and nutrient loads for each city, and how each scenario performed in reducing these loads. The scenarios are evaluated for specific local conditions in each city. The estimated annual five-days biological oxygen demand, total nitrogen and total phosphorus loads to the lake's inshore by 2011 amounted to 23 kt, 4 kt and 2 kt, respectively. Kisumu had the highest organic loads, followed by Kampala, Mwanza, Musoma, Bukoba and Jinja. Based on experts' scores and model outputs, the composting scenario and the scenario that combines diverse local organic waste treatment options performed best in reducing organic and nutrient loads to the lake. Sensitivity analysis showed that these outcomes are robust.

Key words: Solid waste; human excreta; anaerobic digestion; composting; multi-criteria.

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[3] This chapter is based on an article submitted for publication to *Journal of Environmental Management*, as: Oyoo R., R. Leemans and A.P.J. Mol, "Urban organic waste loads and pollution abatement strategies from cities surrounding Lake Victoria".

2.1 Introduction

Lake Victoria, shared by Kenya (6%), Uganda (43%) and Tanzania (51%), is important because of its economic, social and aesthetic values to the people of these and other neighbouring countries. They depend on the lake for fish, drinking water and livelihoods. Unfortunately, the lake is being threatened by siltation, agricultural runoffs and urban waste (Muyodi *et al.*, 2010). Urban waste massively deteriorates the lake's inshore water quality and is thus a key concern. Urban waste here refers to MSW and human excreta produced in urban areas.

Several studies have reported both on the lake's pollution and the initiatives implemented by the Lake Victoria Environmental Management Program (LVEMP) to mitigate these pollutions (Scheren *et al.*, 2000; LVEMP, 2001). These studies aggregated domestic and industrial waste (such as from breweries and dairy and industries), agricultural runoffs and urban runoffs to the lake's inshore. They recommended organic loads reduction to the lake's inshore by pre-treating industrial effluent, rehabilitating existing sewerage and their treatment works, and increasing MSW collection rates. But these recommendations ignored local conditions and possibilities, and didn't integrate the physical waste flows with socio-economic and environmental conditions in each city. This is vital for designing measures to minimise organic loads from the cities to the lake's inshore. Also, the recommendations are generic and may be unsuitable for all the cities surrounding Lake Victoria considering the large differences in their environmental conditions and socio-economic development levels. Policy makers therefore have difficulties to select and apply measures to minimize organic loads and to protect Lake Victoria's water quality.

To understand the magnitudes in organic loads to the lake's inshore for the surrounding cities, and design effective pollution abatement measures, quantifying pollution loads at a city level is essential. Therefore, this paper assesses scenarios for local organic waste treatment for six cities to minimise organic loads to Lake Victoria's inshore. The paper addresses the following questions: (1) What are the current organic loads to Lake Victoria's inshore for the six cities studied? and (2) What are the optimal organic waste treatment scenarios to minimise organic loads for each city?

All urban organic waste sources are identified through literature reviews and field surveys. A box model is developed and calibrated with waste flows for Kampala, and validated with waste flows for Kisumu. This model is then used to assess the current organic load to the lake's inshore and assess the effectiveness of each scenario to reduce BOD_5, TN and TP with respect to the baseline loads. These three parameters are used as indicators for water quality as they are part of the national water quality standards for regulating effluent discharges from industries and STWs (NEMA, 1999). The BOD_5, TN and TP reduction scenarios are appraised against specific local conditions for each city. The evaluation of the scenarios for specific local contexts with the same sets of criteria is innovative. A robust and sustainable organic waste management system for each city can then be selected.

2.2 Method

This section provides the methods for estimating the baseline loads for the cities to the lake's inshore, assessing scenarios' performances in reducing organic loads and evaluating scenarios against urban specific criteria for each city.

2.2.1 Modelling

The estimations of the environmental loads to Lake Victoria's inshore and the model's calibration, validation and sensitivity analyses are described below.

a) Estimating total nitrogen, total phosphorus and five-days biological oxygen demand loads to the lake's inshore

The six selected cities are Kampala, Jinja, Kisumu, Mwanza, Bukoba and Musoma. These cities are 'big' waste generators (Table 2.1) and this threatens Lake Victoria's inshore water quality. The TN, TP and BOD_5 loads are assessed using a box model (Figure 2.1). This model simulates waste fluxes between different compartments. This approach is effective to estimate pollution loads where data from pollution monitoring programs are unavailable. The organic waste produced in base year 2011 in each city is taken as the functional unit for estimating TN, TP and BOD_5 loads. The baseline BOD_5 fluxes for Kampala are provided in Figure 2.1.

Table 2.1. Demographic data for selected cities surrounding Lake Victoria.

City	Population size in 2002	Growth rate (% $year^{-1}$)	Projected population size 2011
Kampala	1,208,196	3.8	1,700,850
Jinja	86,520	2.4	107,300
Kisumu	280,966**	3.2	412,500
Mwanza	476,646	3.0	635,730
Bukoba	81,221	4.0	116,420
Musoma	108,242	5.8	182,430

**Population size for 1999 census. *Sources*:(NBS, 2003; UBOS, 2007; Onyango and Kibwage, 2008).

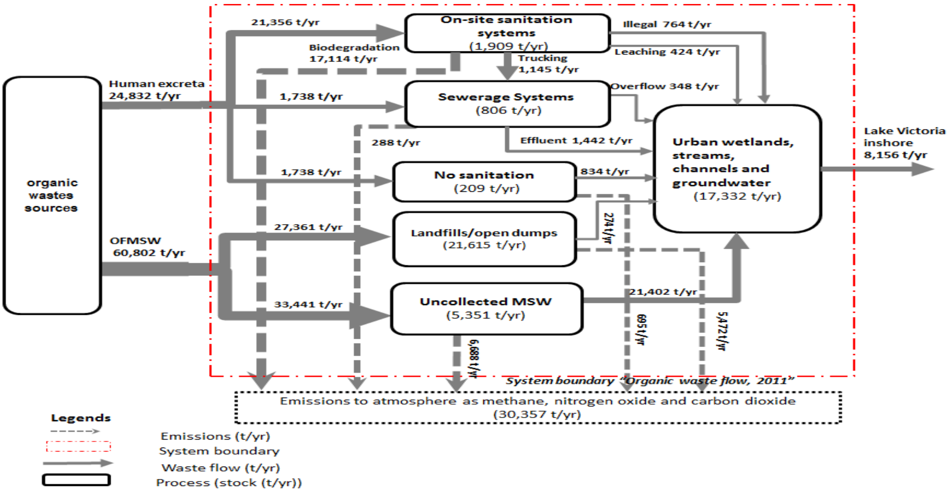

Figure 2.1. Schematic flow diagram of organic waste-flow model from points of generation up to the lake's inshore, indicating Kampala's baseline BOD_5 flows.

Based on 50% water content of the OFMSW (Montangero and Strauss, 2002), the environmental loads from MSW generated for each city are estimated as population size times percentage OFMSW times the per capita MSW generation rate times percentages of TN, TP and BOD_5 in OFMSW (Table 2.2). The environmental loads for uncollected MSW before entering the lake's inshore are estimated as total loads for MSW generated times the fraction of uncollected MSW. To account for emissions of CH_4, CO_2 and NO_x due to biodegradation and denitrification of organic matter, and phosphorus adsorption on soil, the environmental loads in uncollected MSW are multiplied by a factor 0.8, 0.7 and 0.4 for TN, TP and BOD_5, respectively (Finnveden, 1999). Adsorption here refers to the attachment of phosphorus on soil particles in the sub-surface. As the aforementioned factors are influenced by environmental conditions, a sensitivity analysis is performed to assess their influence on the environmental loads to the lake's inshore. The loads from landfilled MSW are estimated as the total loads for MSW times the fractions of landfilled MSW that leaches (Finnveden *et al.*, 1995).

Table 2.2. BOD_5, TP and TN generation rates in fresh human excreta and proportions in OFMSW (Montangero and Strauss, 2002; Gumbo, 2005).

Parameter	OFMSW (% dry weight)	Fresh human excreta (kg cap^{-1} year^{-1})
TN	1 – 2	3.7
TP	0.4- 0.8	1.1
BOD_5	30 – 40	14.6

For each city, the TN, TP and BOD_5 loads resulting from human excreta are estimated using population size as a proxy. The environmental load from on-site sanitation is closely associated with the density of on-site sanitation systems, the number of people using the systems and the geologic conditions (Barrett *et al.*, 1999). The loads for sewerage, on-site sanitation and open defecation are estimated by multiplying total load for human excreta generated by each respective fractions of the population using the different sanitation systems. The load for faecal sludge from on-site sanitation taken for further treatment at the STW is estimated as the faecal sludge load in on-site sanitation times the fraction of faecal sludge taken to the STW. The per capita BOD_5, TN and TP loads in faecal sludge are as, shown in Table 2.3. Faecal sludge quality is influenced by storage duration, ambient temperature, groundwater intrusion and emptying frequency (Montangero and Strauss, 2002). In Kampala, on-site sanitation systems are distributed as: 78% pit latrines, 20% septic tanks and 2% public toilets (NWSC, 2008). Since Kampala is the largest among the studied cities and has a high proportion of pit latrines, the per capita loads for pit latrines are used for computing the faecal sludge loads. The fraction of faecal sludge emptied is assumed highest in Kampala as its groundwater table is high. This fills on-site sanitation systems very fast (NWSC, 2008). The TN, TP and BOD_5 loads for sewage overflows are estimated by multiplying the TN, TP and BOD_5 loads collected by sewers by a fraction of the overflowed sewage from sewers.

Table 2.3. Faecal sludge characteristics for on-site sanitation facilities (Mara, 1978; Montangero and Strauss, 2002; Gumbo, 2005).

Parameter	Unit	Septage	Public toilet sludge	Pit latrine
BOD_5	kg capita^{-1} year^{-1}	0.4	5.8	2.9
TN	kg capita^{-1} year^{-1}	0.3	2.9	1.8
TP	kg capita^{-1} year^{-1}	1.1	1.1	1.1

The TN, TP and BOD_5 loads for the STW are estimated by multiplying influent load with the so-called *penetration factor*. This factor refers to the percentage of the pollutant leaving systems that is untreated, and provides an insight into the potential reduction of pollutants by treatment systems (Scheren *et al.*, 2000). The higher the penetration factor the larger the pollution load to the environment. Penetration factors vary between 0 and 1; with a high value indicating low pollutant removal efficiency. The BOD_5,TN and TP reduction efficiencies for

Kampala's STW are, for example, 60%, 30% and 30%, respectively (NWSC, 2008). Hence, their respective penetration factors are 0.4, 0.7 and 0.7. Kampala's STW has the highest pollution reduction efficiency among all STWs' of the included six cities (LVEMP, 2001). For this reason, the STWs penetration factors (Table 2.4) are assumed to be between 0.4 for Kampala's STWs, and 1 for no STW for Bukoba and Musoma. The TN, TP and BOD_5 loads to the water from on-site sanitation are estimated as the product of their on-site sanitation loads and the fraction lost by biodegradation, nitrification, denitrification and leaching. Organic matter is degraded under predominantly anaerobic conditions, producing carbon dioxide and methane. Organic shows the highest degradation rate followed by nitrogen compounds. Phosphorus has no degradation metabolisms towards the atmosphere (Nalubega *et al.*, 2001). The removal efficiency for BOD_5 in unsaturated subsoil by filtration, sorption and biodegradation processes is about 90% (Gill *et al.*, 2008). The fractions of TN, BOD_5 and TP leached from on-site sanitation to the water are each set at 10% (Elisabeth, 2005; Meinzinger *et al.*, 2009). Here, leaching refers to movement of TN, TP and BOD_5 from on-site sanitation to the water through a permeable medium.

Table 2.4. Penetration factors for STWs for the cities studied.

City	BOD_5	TN	TP	Remarks
Kampala	0.4	0.7	0.7	This study
Jinja	0.5	0.8	0.8	This study
Kisumu	0.8	0.8	0.9	This study
Mwanza	0.7	0.8	0.8	Assumed value since it is a pond based STW
Musoma	1.0	1.0	1.0	No STW
Bukoba	1.0	1.0	1.0	No STW

The net TN, TP and BOD_5 loads after pre-filtration by wetlands are estimated as each load before entering the wetlands times wetlands' penetration factors of TN, TP and BOD_5. The penetration factors of TN and TP for wetlands in Table 2.5 are estimated using the relationship listed in Table 2.6. Different wetland systems have different retention capacities. In this thesis, the penetration factors of BOD_5 stem from North American temperate wetlands, which range from 0.3 to 0.5 (Richardson and Nichols, 1985). This is because all reported penetration factors for tropical wetlands are for constructed wetlands, which have controlled loads. Temperate wetlands are active even at low temperatures (Jokerst *et al.*, 2011), implying that the penetration factors applied can provide an estimate of BOD_5

loads for comparison of baseline loads across the studied cities. This is then followed by a sensitivity analysis on the BOD_5 degradation rate for wetlands.

Table 2.5. Penetration factors for wetlands for the cities studied.

City	Wetlands sizes (km^2)	BOD_5	TN	TP	Remark/source
Kampala	5	0.3	0.4	0.6	(Kansiime and Nalubega, 1999)
Jinja	5	0.3	0.6	0.4	(Kelderman *et al.*, 2007)
Kisumu	23	0.6	0.8	0.8	(Sitoki *et al.*, 2010)
Mwanza	Not available	0.9	0.9	0.8	Wetland drained (Kassenga, 1997)
Musoma	30	0.5	0.8	0.8	Small wetland (Kassenga, 1997)
Bukoba	50	0.5	0.7	0.6	Small wetland (Kassenga, 1997)

Table 2.6. Nutrient penetration factors for wetlands (most likely values) based on Scheren *et al.* (2000).

Loading (g m^2 $year^{-1}$)	N	P
2	No value	0.4
10	0.3	0.6
50	0.7	0.8
500	0.9	0.8

b) Calibration, validation and sensitivity analysis

A box model for waste flows from points of generation via the treatment systems and wetlands up to the lake's inshore, including fractions lost to the environment, is developed in Microsoft excel. The model is parameterised using literature values and field measurements for STWs' performances for Kampala. The sewage inflows to the STW are measured hourly for 11 hours for a week, and that for sewage ponds are determined daily using float method for three days. The influent and effluent samples are collected on hourly basis each day and once a week for a period of one month. From the daily collected influent and effluent samples, composite samples are prepared for the influent and effluent. The composite samples are analysed for BOD_5, TN and TP levels using standard analytical procedures (Greenberg *et al.*, 1980). Based on the influent and effluent qualities and their flows, the BOD_5, TN and TP loads for the respective influent and effluent are computed. The influent and effluent loads are then used to compute the STW's performance in reducing the BOD_5, TN and TP loads by subtracting the effluent loads from influent loads. The amount of overflowed sewage from sewers is estimated as average sewage overload times the number of occurrence of sewage overflows per month.

The model is calibrated and validated with the respective waste flows for Kampala and Kisumu. TP is selected as the parameter to calibrate and validate the model, because, unlike TN, large fluxes of TP to surface water from the selected cities come from domestic waste. Also, cyanobacteria in surface water can fix atmospheric nitrogen (Smith *et al.*, 2006). This process is excluded from this model, implying that using TN as a major calibrating parameter will create some uncertainty in model's results. The TP input from sediment into the water column is also not considered, since the wave effect along Lake Victoria's inshore is minimal to re-suspend the sediment (Sitoki *et al.*, 2010).

According to Scheren *et al.* (2000), the atmospheric depositions and agricultural land runoffs of TP and TN into the entire Lake Victoria accounts for about 90% and 94%, respectively. The remaining fractions are for municipal wastewater, urban runoff and industrial effluent entering the lake via the bays. Even though the proportion of municipal waste load to the lake's inshore is low, this study still focused on the municipal waste because previous studies did not assessed organic loads reduction options for the cities to the lake's inshore by considering the local socio-economic and environmental conditions for each city. Also, the lake's inshore are being used as drinking water sources for Lake Victoria's surrounding cities. The water quality in the lake's inshore is deteriorating, and this trend is most likely to continue with the current rapid population growth and lifestyles changes, if urban waste is improperly managed in these cities. Moreover, the groundwater aquifers in these cities are unsuitable for drinking water supply because about 90% of sanitation systems in these cities are on-site systems that pollutes the groundwater quality (Kulabako, 2005; Mireri *et al.*, 2007; Oyoo *et al.*, 2011). Also, with the current economic hardship in these cities, harvesting drinking water from the lake's inshore further from the city is unfeasible in the near future.

The TP and TN loads for domestic organic waste to the lake's inshore from surrounding cities are higher than for industries. The aggregated waste flows for food processing industries are small compared to waste flows for households in the cities assessed. The collection and treatment of waste flows for households is inadequate. Some industries, for examples, Uganda Breweries and Nile Breweries in Uganda, have established their own wastewater treatment systems. These wastewater treatment systems have aeration and anaerobic digestion units, which reduces large proportions of N and P in the influent. Therefore, the TP and TN loads for industries are assumed to be negligible. This is also supported by the Ministry of Water and Environment of Uganda report, which states that urban settlements contribute 72% of nutrient loads to Lake Victoria on the Uganda side compared to 13% by industries and 15% by fishing villages (Nyenje *et al.*, 2010).

A sensitivity analysis is conducted to assess the robustness of the outcomes for the model for the variables assumed to be most uncertain. Sensitivity analysis is a systematic procedure to determine which parameters have the greatest influence on the results (Leemans, 1991; Björklund, 2002). Sensitivity analyses are performed for the leaching rate from on-site sanitation systems, penetration factors of pollutants for the STWs and the wetlands, and loss of nutrients and organic from uncollected MSW. These variables are varied by doubling and halving their best estimate values, and the net TN, TP and BOD_5 loads are estimated. Results are compared with baseline loads for each city.

2.2.2 Scenarios for organic loads reduction

Six scenarios, including current conditions, are designed by combining different organic waste treatment options. These scenarios are based on current sanitation systems in use and locally available organic waste treatment technologies in the region. The MSW composition, waste treatment technologies and sanitation systems are assigned different proportions of OFMSW and human excreta to be treated in each scenario. The proportions of OFMSW and human excreta to be treated in the designed scenarios are the same for each city. These future scenarios aimed at producing organic loads with minimal environmental impacts on the water quality in the lake's inshore by 2025. The overall organic load reduction for each future scenario is estimated by comparing it to the baseline conditions for each city. The scenarios assessed are:

1. *Scenario 1* (business-as-usual) represents current MSW and human excreta management systems for the six cities studied, as summarised in Tables 2.7 and 2.8.

Table 2.7. Municipal solid waste collection rates for the cities studied.

City	MSW collection rate (%)	Disposal method	Source
Kampala	45	Landfilling	(Oyoo *et al.*, 2011)
Jinja	40	Open dumping and composting	(Okot-Okumu and Nyenje, 2011)
Kisumu	20	Open dumping	(Onyango and Kibwage, 2008)
Mwanza	80	Open dumping	(Salukele, 2013)
Bukoba	60	Open dumping	(Mbuligwe *et al.*, 2002)
Musoma	52	Open dumping	(UN-HABITAT, 2005)

Table 2.8. Sanitation systems and faecal sludge management for the cities studied.

Cities	Population served			Faecal sludge trucked to STW (%)	Sewage overflow (%)	Faecal sludge illegally disposed (%)	Sources
	Sewerage (%)	On-site (%)	No Sanitation (%)				
Kampala	7	86	7	16	20	20	(Oyoo *et al.*, 2011)
Jinja	26	70	4	4	12	10	(NWSC, 2005)
Kisumu	16	81	3	8	17	20	(Mireri *et al.*, 2007)
Mwanza	7	80	13	8	15	20	(Rwabigene, 2002)
Bukoba	0	85	15	0	0	30	(Dominika, 2010)
Musoma	0	90	10	0	0	30	(UN-HABITAT, 2005)

2. *Scenario 2* represents the aerobic composting of OFMSW, treating human excreta by STWs and on-site sanitation. The on-site sanitation systems include septic tanks, pit-lined latrines and eco-san toilets used to store and to partially treat human excreta at the points of generation (Nsubuga *et al.*, 2004). The STWs' reduction efficiencies for BOD_5, TN and TP are provided in Table 2.9. The OFMSW is sorted and 80% is composted. The remaining 20% of OFMSW is disposed together with the residues at the landfills. The fractions of population using sewerage in each city are maintained as in Scenario 1. The remaining population are served by on-site sanitation because these cities are sprawling and many new settlements are located far away from existing sewers (Mireri *et al.*, 2007; NWSC, 2008; Oyoo *et al.*, 2011).

3. *Scenario 3* assumes 80% of sorted OFMSW is co-treated with 50% of human excreta from on-site sanitation systems (after six months storage), using anaerobic digestion. The co-treating of faecal sludge and OFMSW is advantageous because the two materials complement each other. The human excreta is relatively high in nitrogen content and moisture, and the OFMSW is relatively high in organic carbon content and has good bulking quality (Montangero and Strauss, 2002). The remaining 20% of OFMSW is disposed at the landfills. The fractions of the human excreta collected by sewers and treated at the STWs, are maintained as in Scenario 1 (i.e. existing sewerage coverage and STW for each city). The remaining fractions of human excreta neither treated by STWs nor co-treated with OFMSW in each city (e.g. 43% for Kampala City) are treated using on-site sanitation.

Table 2.9. Sewage treatment works efficiencies for the cities studied.

City	STW pollutant removal efficiencies (%)			Remarks
	BOD_5	TN	TP	
Kampala	60	30	30	This study
Jinja	50	20	20	(NWSC, 2005)
Kisumu	20	20	10	This study
Mwanza	30	20	20	(Rwabigene, 2002)
Musoma	0	0	0	No STW
Bukoba	0	0	0	No STW

4. *Scenario 4* represents landfilling of OFMSW, and partial treatment of human excreta using on-site sanitation (e.g. septic tanks and pit-lined latrines), and full treatment by the STWs. Here, all the OFMSWs generated are collected and disposed at the landfills. The fractions of human excreta treated by the STW in each city are maintained as in Scenario 1. The STWs' efficiencies in removing pollutant loads are maintained as in Scenario 2. The human excreta generated by the remaining population in each city is stored and partially treated on-site, prior to collection and final treatment at the STWs.

5. *Scenario 5* assumes sewerage coverage expanded to serve an additional 20% of the population in each city. Sewage overflow is reduced to 5% through timely and regular maintenance of sewerage networks. Much of the sewage overflows in these cities are the combination of blocking of the sewerage systems because of illegal dumping of MSW in sewer manholes and too much storm water (Mireri *et al.*, 2007; MWI, 2007; NWSC, 2008).

Faecal sludge emptied from on-site sanitation systems increases to 30% using a combination of light tools and trucks that can easily access densely built areas. The STWs' performances in each city enhance to reduce BOD_5 by 70% and nutrients by 40%. The current levels of OFMSW collected and disposed at the landfills in each city are maintained as in Scenario 1.

6. *Scenario 6* combines all the organic treatment options to match with the settlement patterns, and local environmental and socio-economic conditions specific to each city. The OFMSW is sorted and 80% is co-treated with 50% of partially digested human excreta from on-site sanitation systems using anaerobic digestion. The remaining 20% of OFMSW is collected and disposed in the landfills. The STWs' performances enhances by 50% compared to the business-as-usual scenario. Sewage coverage increases by 10%. Sewage overflow reduces to 5% and faecal sludge emptied from on-site sanitation facilities increases to 20%. For Kampala, the combined waste treatment options are landfill, anaerobic digestion and a sewerage system. Jinja, Mwanza and Kisumu have their waste treatment options comprising of composting, sewerage and anaerobic digestion. Bukoba and Musoma have no sewerage, so their organic waste treatment systems consist of composting, anaerobic digestion and on-site sanitation.

2.2.3 A multi-criteria analysis of organic load reduction scenarios

The steps below are applied to appraise five organic load reduction scenarios against urban specificities.

a) Selected criteria

Scenarios 2 to 6 are evaluated for availability, affordability, social acceptability, flexibility and feasibility. Availability represents the physical presence of effective waste treatment options in the city. Affordability represents the costs for implementing and operating the waste management systems, for which capital investment and operational costs play an important role. Social acceptability represents the acceptance of the waste management systems from people of all quarters. Implementation of new sanitation concepts may encounter social resistance by specific groups in society (Balkema *et al.*, 2002). Flexibility refers to the extent to which technical elements of waste management systems are resilient, robust and easily adaptable to changing conditions. For example, upgrading an existing waste treatment system to handle additional hydraulic and/or organic loads should require minimal changes to the infrastructure. Feasibility is related to the implementation possibilities of the system with respect to local environmental and socio-economic conditions, which can restrict the use of some waste technologies.

b) Multi-criteria analysis

In each city, eight local experts, who understand the local conditions in their cities, are selected to score Scenarios 2 to 6 on the five selected criteria through face to face questionnaires. These experts are related to institutions that provide MSW collection and sanitation services in their cities. All experts had an academic background and experience in the field of environmental sciences, social sciences or environmental engineering. The eight experts are selected for each city in such a way that disciplinary diversity is guaranteed. The explanations and assumptions for each of the scenario, the criteria and their definitions, and the scales of the scores are presented on paper to the experts. All experts studied the scenarios carefully prior to scoring.

Equal weights (i.e. 20%) are assigned to all the five criteria that were scored by the experts. The scores on the five criteria done by the eight experts for each scenario are averaged to get mean scores. The ranking of each scenario against the selected criteria was based on a simple qualitative performance scale ranging from, for example, highly unfeasible, unfeasible, acceptable, feasible to very feasible. These scores are converted into numerical values: 0, 25, 50, 75 to 100. The overall performance for each scenario S_i is computed by a linear approach, represented by Equation 2.1 (Crown, 2009).

$$S_i = w_1 s_{i1} + w_2 s_{i2} + \cdots + w_5 s_{i5} = \sum_{j=1}^{5} w_i s_{ij} \qquad \text{Equation 2.1,}$$

where s_{ij} is the preference score for scenario *i* on criterion *j* and w_i is the weight for each criterion. The preference score is calculated as the average score of the scores for each scenario against each criterion performed by the eight experts. Since, the weights for the criteria are assumed equal, w_i remains constant, and so Equation 2.1 simplifies to:

$$S_i = s_{i1} + s_{i2} + \cdots + s_{in} = \sum_{j=1}^{5} s_{ij} \qquad \text{Equation 2.2}$$

To determine to what extent changing the weights of criteria influence the overall ranking for the scenarios, a sensitivity analysis is performed. The weights for the separate criteria are systematically varied up and down to examine the impacts of the relative weights on the total scores of each criterion and scenario. For example, the weight for the criterion “availability” is increased from 20% to 60%, and simultaneously, the weights for the four other criteria are decreased from 20% to 10%, respectively, so that the total weight remained 100%. Besides, the standard deviations for all criteria and scenarios are determined for each city. This indicates the spread of individual scores from the mean score for each city.

2.3 Results and discussion

2.3.1 Model’s calibration, validation and sensitivity analyses

The calibrated model estimates about 1.0 kt TP load into Lake Victoria’s Murchison Bay, a little below the measured 1.2 kt TP. The slight difference is likely explained by the release of phosphorus from the sediments into the water, an input that is excluded in this model. Lake Victoria’s Murchison Bay is eutrophic, implying its bottom water is anoxic and much of the phosphorus (P) in sediments is released into the water (Correll, 1998). Also, the wetlands penetration factor of TP used in our model is based on a study by Kansiime and Nalubega (1999) assuming that wetlands have most of their papyrus intact. Papyrus effectively takes up nutrients from water. Over the years, the Nakivubo wetlands have been drained for agriculture, resulting in a reduced retention time for nutrients in the systems (Kansiime *et al.*, 2005). Hence, the wetland penetration factor of phosphorus used most likely underestimates TP load. Nonetheless, this estimated TP load adequately explains the contribution from domestic organic waste for the city to the lake’s inshore.

The calculated TP load for Lake Victoria’s Winam Gulf is less than the measured TP load. This difference is probably explained by the input P from the sediments and other sources, which are excluded in this model. The shallow depths and large surface area for this bay allows for daily mixing of the water leading to re-suspension of P from the lake bottom, contributing to the high concentration of P in the water (Gikuma and Hecky, 2005). However, considering that only P inputs from MSW and human excreta are estimated, the model still performs within an error of 10%, which makes it appropriate to estimate the baseline loads as well as assess the effectiveness of organic loads reduction scenarios for each city.

The sensitivity analysis performed on the leaching and degradation rates show that the estimations for BOD_5 loads is very sensitive (Figure 2.2a and c). This indicates that the estimates for the leaching and organic degradation rates are critical for accurate estimation of BOD_5 loads. Also, sensitivity analysis on penetration factors of pollutants for the STWs and the wetlands influences all variables (Figure 2.2b). This means that accurate estimates for penetration factors of pollutants are essential to reduce uncertainties of the model results. More field data is required to estimate precise values for penetration factors to minimise the uncertainty of the model results. This in turn improves the understanding of the waste flows and designing of appropriate policies to reduce organic loads for cities surrounding Lake Victoria.

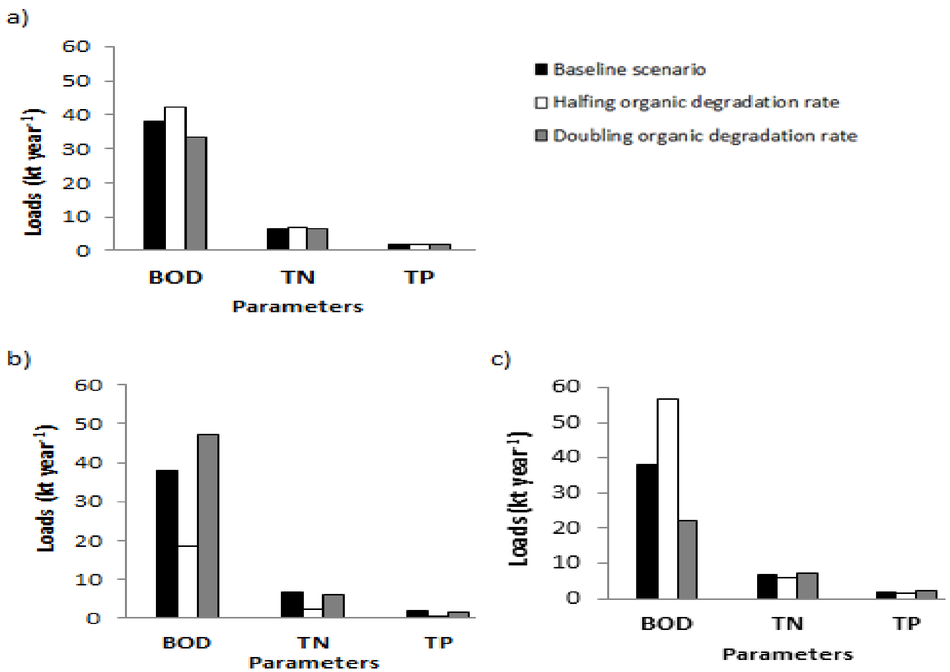

Figure 2.2. Plots for sensitivity analyses: (a) leaching rate from on-site sanitation systems, (b) penetration factor and (c) organic degradation rate.

2.3.2 Baseline organic and nutrient loads to Lake Victoria's inshore

The estimated baseline BOD_5 loads before pre-treatment by wetlands for the cities assessed are higher for MSW stream than in human excreta. These BOD_5 loads from MSW for all the cities studied ranges from 1 to 22 kt $year^{-1}$, and from human excreta they ranges from 0.5 to 10 kt year^{-1}. The high BOD_5 loads from MSW are attributed to the low MSW collection efficiencies in these cities despite their low generation rates (Table 2.10). The MSW generation rates for these cities are comparable to rates reported for other developing countries' cities (e.g. Ogwueleka (2009) reports that Lagos generates about 0.6 kg capita^{-1} day^{-1}). However, these rates are lower than for developed countries' cities (e.g. Al Sabbagh *et al.* (2012) reports that developed countries' cities generates approximately 1.1 kg capita^{-1} day^{-1}). The high fractions of OFMSW for these cities also explain the high BOD_5 loads from MSW. Also, the percentages of OFMSW for these cities are comparable to those reported for other developing countries' cities (Dagadu and Nunoo, 2011), but higher than those for developed countries' cities (e.g. London, Canada (Asase *et al.*, 2009)). The key reason for these high fractions is that many households are too poor to purchase goods that increase the fractions of non-food waste in the MSW composition.

Table 2.10. Municipal solid waste data for the cities studied.

City	Generation rates (kg cap^{-1} day^{-1})	OFMSW (% wet weight)	Source
Kampala	0.6	83	(Oyoo *et al.*, 2011)
Jinja	0.6	75	(Okot-Okumu and Nyenje, 2011)
Kisumu	0.5	67	(Onyango and Kibwage, 2008)
Mwanza	0.4	78	(Salukele, 2013)
Bukoba	0.4	78	(Mbuligwe *et al.*, 2002)
Musoma	0.5	74	(UN-HABITAT, 2005)

Conversely, the TN and TP loads from human excreta are higher than from MSW for all the cities assessed. The TN loads from human excreta ranges from about 0.1 to 2.0 kt year^{-1} and TP loads from about 0.1 to 1.0 kt year^{-1}, and TN loads from MSW ranges from about 0.05 to 0.95 kt year^{-1} and TP loads from approximately 0.03 to 0.48 kt year^{-1}. The high TN and TP loads from human excreta is because of high ratio of improperly constructed, operated and maintained on-site sanitation systems as well as high proportion of population without access to sanitation (see Table 2.8). On-site sanitation systems are the most used in all the cities assessed, because of the stagnant development of sewerage systems, while the urban expansion continues. This has also been reported in other cities in the region (e.g. Dar es Salaam City (DAWASA, 2007)). The low proportion of faecal sludge trucked from on-site sanitation systems to STWs compared with the amount of faecal sludge stored on-site also contributes to the high nutrient load to the environment. This low collection rate is because of vehicular inaccessibility in densely built-up areas and financial inability of the low-income households to pay fees to empty faecal sludge from their toilets (NWSC, 2008).

The annual net loads to Lake Victoria's inshore after pre-treatment by wetlands, amount to about 4 kt TN, 2 kt TP and 23 kt BOD_5. The values for TN and TP are comparable to the values reported by LVEMP (2001), which are 4 kt TN, 2 kt TP except for BOD_5, which is 18 kt and is less than the estimate obtained in this study. The increased BOD_5 load is probably attributed to the low MSW collection rates in the cities surrounding Lake Victoria (Mwiganga and Kansiime, 2005; Mireri *et al.*, 2007). Also, the declining wetlands' vegetation along the lake's shoreline in the cities studied to pre-filter the organic loads in surface water prior to entry to the lake's inshore explains the increased BOD_5 loads (Kyambadde *et al.*, 2004). This model applied penetration factors of pollutants derived from literature, which may have overestimated the organic loads. More so, it is assumed that all the waste generated by city residents in the studied cities flows towards the lake's inshore, which may not be necessarily true for all the cities studied.

The TP loads for our model and that for LVEMP (2001) are similar, most likely because of the high BOD_5 loads in the wetlands, causing anaerobic conditions. Under anaerobic conditions, iron will be dominantly present in Fe^{2+} form, which has hundred times lower phosphorus binding capacity than the Fe^{3+} form (Kelderman *et al.*, 2007). This results in more phosphorus available in the water column. The concentration of phosphorus in the water can also be reduced through uptake by water weeds and sedimentation of phosphorus attached on sediments to the lake's bed. These processes are not included in this model.

As shown in Figure 2.3, the net TN and TP loads to Lake Victoria's inshore are highest for Kampala, followed by Kisumu, Mwanza, Musoma, Bukoba and Jinja except BOD_5 is highest for Kisumu. This ranking has also been reported by LVEMP (2001). The LVEMP study also included industrial waste, which is omitted in this study. The patterns of BOD_5 loads for this thesis is similar to the findings from Scheren *et al.* (2000), who also reported the highest BOD_5 loads to Lake Victoria from the Kenya side, which in this study is represented by Kisumu. The annual BOD_5 loads reported by Scheren *et al.* (2000) from Kenya, Uganda and Tanzania sectors are 8 kt, 5 kt and 4 kt, respectively. Their study included also organic waste from industries and agricultural runoff. But this study only estimated urban organic loads to Lake Victoria's inshore from households since organic waste in the cities studied is mainly from households, and less from industries and agriculture runoffs (Nyenje *et al.*, 2010).

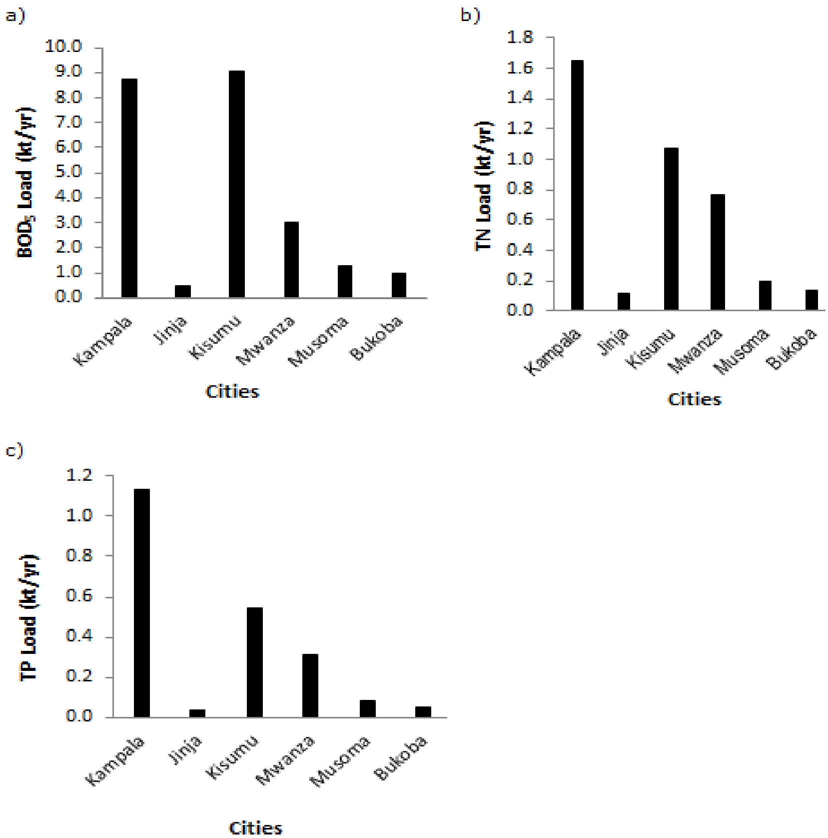

Figure 2.3. Net loads to the inshore areas of Lake Victoria (a) BOD_5; (b) TN; and (c) TP.

The current trend of urban expansion against the stagnated sewerage expansion in the studied cities is likely to continue for at least two more decades, and this will rapidly deteriorate Lake Victoria's inshore water quality. More collection of faecal sludge in densely built-up areas, using small size vacuum trucks and light tools such as vactug and MARPET, and transport to STWs is required to reduce the illegal disposal of faecal sludge to the environment. Also, on-site sanitation systems such as septic tanks and pit-lined latrines for storage and partial treatment of human excreta on-site are needed for these cities to reduce these loads. Jinja has the lowest net TN, TP and BOD_5 loads because of a small population size and/or a good pollution filtering function of the Kirinya wetlands. These wetlands reduces TP, TN and BOD_5 loads from sewage effluent from Jinja's STW and urban surface water runoff prior to discharge to Lake Victoria's inshore (Kelderman *et al.*, 2007).

High BOD_5 loads in surface water have consequences for water quality and aquatic species. When BOD_5 load is larger than the ability of the receiving water to supply new oxygen, then dissolved oxygen levels will decrease, and in extreme cases lead to total anoxia. Exposure to a dissolved oxygen concentration below 2 mg l^{-1} for several days may kill fish. The excessive inputs of TP and TN result in eutrophication. Eutrophication can result in the development of mono-specific blooms of cyanobacteria, which disrupt the normal phytoplankton succession patterns and virtually alter all interactions between organisms within an aquatic community (Smith *et al.*, 2006). Abundant algae populations blocks the water filters in the water treatment plants. This interrupts drinking water production and also increases the energy usage because of more frequent cleaning of the water filtration systems (Okello *et al.*, 2010).

2.3.3 Organic loads' reduction to Lake Victoria's inshore

Different but possible scenarios for minimising organic loads to Lake Victoria's inshore in all the cities studied were assessed using a box model. The model's outputs for each scenario were compared with the baseline loads for each city to calculate the percentage reduction in organic loads. The results (Figure 2.4) show that Scenario 3 (anaerobic digestion) reduces BOD_5 and TP by respectively 49% and 27% in the cities studied except Mwanza. Mwanza has a high MSW collection rate (i.e. 80%). Improved control of domestic wastes reduces BOD_5 loads, often associated with occurrence of water borne diseases. Scenario 2 (composting) and Scenario 3 (anaerobic digestion) perform similarly for BOD_5, TN and TP loads reduction for all the cities assessed. Scenario 4 (landfilling) reduces organic and nutrient loads for other cities better than it does for Mwanza. Mwanza already has a high MSW collection efficiency, such that any additional increase in amount of MSW collected contributes minimally to BOD_5 load reduction. Instead more collection and treatment of human excreta is required for Mwanza to reduce the nutrients loads.

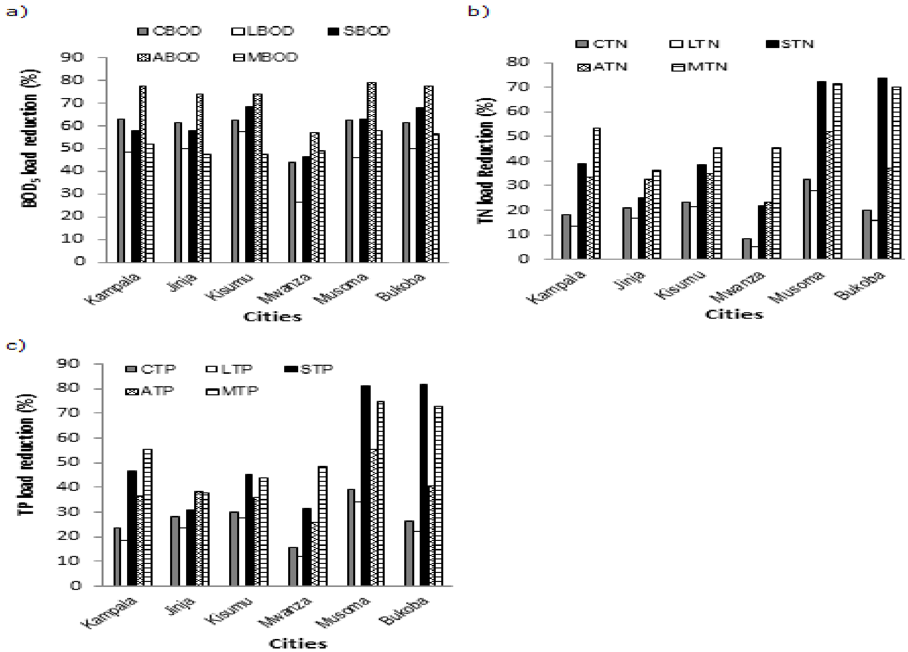

Figure 2.4. Percentage load reduction for different scenarios relative to the baseline scenario for each city: (a) BOD_5; (b) TN; and (c) TP. Where $CBOD_5$, $ABOD_5$, $LBOD_5$, $SBOD_5$, and $MBOD_5$ stands for BOD_5 Scenario 2, BOD_5 Scenario 3, BOD_5 Scenario 4, BOD_5 Scenario 5, BOD_5 Scenario 6, respectively. Similarly, CTN, LTN, STN, ATN, MTN, correspond to TN; and CTP, LTP, STP, ATP and MTP correspond to TP.

Scenario 5 for sewerage improvement reduced environmental loads by only about 18% in all cities studied except Mwanza. The load reduction by Scenario 5 for Mwanza is about 46% indicating much effort for the organic load reduction should be on adequate collection and treatment of human excreta, because MSW collection rate is already high. The poor performance of Scenario 5 for other cities is because of low proportions of population served by sewerage. The low economic development level and the high heterogeneity in settlement patterns in the cities studied restrict the expansion of sewers to serve all city residents.

Scenario 6 performs better than other scenarios for Kampala and Mwanza, because of the high settlement heterogeneity that requires mixtures of diverse treatment options to match with the settlement patterns. Besides pollution prevention, Scenarios 2, 3 and 6 also produce compost, digestate and biogas, and also reduce the environmental impact of disposal sites through diversion of OFMSW from landfills, as OFMSW is largely to blame for the polluting leachate and methane generation. These scenarios also, extend the landfill's capacity as OFMSW is kept out of the landfills thus providing additional volume for incoming MSW. The compost and digestate when properly applied on farm land, replenishes the soil humus layer with organic matter and nutrients, contributing to sustainable resource management.

However, the compost produced from MSW can possibly be contaminated by toxic substances because of lack of source sorting of MSW. The digestate also contain pathogenic microorganisms, such as bacteria, viruses, protozoa and helminths (Andersen *et al.*, 2012), which can infect end-users. These pathogens in the digestate must therefore be inactivated through co-composting the digestate and OFMSW together to combine the effects of heat and time. A composting temperature of 70 ^{o}C for one to two hours would kill all the pathogens (Tchobanoglous *et al.*, 1993).

Because of the heterogeneity of settlement patterns and varying local conditions within each city and across all cities, treatment of all organic wastes using a single approach is impossible. The settlement patterns, socio-economic conditions and levels of environmental infrastructure development differ within each city. Each city requires different combinations of organic treatment options that fit their spatial settlement patterns, and local environmental and social conditions, to adequately treat all organic wastes. Application of such mixed waste systems to treat organic waste in East African cities will make the treatment of organic waste flexible as well as increase access to the waste treatment facilities by urban residents, particularly the urban poor.

2.3.4 Scenarios' performances for each city local specificities

This section addresses the assessment of organic loads reduction scenarios based on the evaluation scores produced by the experts. The analysis of the results for the performances of the scenarios for each city presented in Table 2.11 show that Scenarios 2 and 6 are the most optimal to produce minimal organic loads in all cities studied. These scenarios are flexible and feasible to implement in the heterogeneous spatial settlements reflected in these cities. Besides, Scenario 2 requires a low level of expertise and can be performed at a household or a community level. However, community composting facility may prove to be unsustainable, because it operates at a relatively large-scale. This demands more resources, which may not be affordable by the low-income households, who form the bulk of the urban population. Scenario 5 performs poorly in all the cities studied because of the spread out of human settlements far away from sewers. This makes provision of sewerage services to all city residents unfeasible in the near future. The terrain in some of the cities also makes it very expensive to extent the sewer system to serve the population settled on hilly areas. For example, the informal settlers in Mwanza are located on hill slopes, which make it very expensive to lay sewers, considering the limited waste management budget. Bukoba and Musoma do not have sewerage, and it is unlikely they will have them in the near future, as their budgets for waste management are low to develop sewerage systems.

Further analysis of the scores for the experts against each criterion shows that Scenario 4 scores high on availability in Kampala as a landfill already exists and treats about 45% of MSW generated (Oyoo *et al.*, 2011). The other cities scores moderate on this aspect because they have open dumps that can be upgraded to landfills by introducing leachate collection systems. Scenario 2 scores high on availability only for Jinja, because composting is being practiced on a large scale. A composting plant has been established at the open dump site. Meanwhile Scenario 3 performs poorly in criterion 'availability' for all cities assessed, because treatment of organic waste using anaerobic digestion processes is new in the region, and is only being piloted in Kisumu, Kenya (Letema, 2012).

With regard to criterion 'affordability', small-scale systems score better than large-scale systems. Scenario 2 scored highly on affordability in all the cities except in Jinja. Jinja has a large-scale composting facility, requiring centralised collection and transportation of OFMSW from points of generation to the composting facility. This increases operational costs. Large-scale systems such as landfilling and sewerage are very unaffordable because their investment, operation and maintenance costs are high. These systems, for examples, conventional centralised large-scale STWs and centralised composting facilities require external power supply for their operations (van Buuren, 2010) and may not be affordable for these cities, considering their low economic performances. Furthermore, the cost recovery introduced for MSW collection makes Scenario 4 inaccessible to many low-income households, as they are financially unable to pay waste collection fees.

With regard to the criterion 'social acceptance', Scenarios 4 and 5 are very socially acceptable in all the cities studied because of the low involvement of households in their operations and maintenance. Scenario 4 treats unsorted MSW and thus does not need waste sorting, which needs active participation of households. Conversely, Scenarios 2 and 3 need active households' participation in terms of waste sorting in order to produce good quality compost. This probably explains their low social acceptances by the urban residents in all the cities studied.

Considering flexibility and feasibility criteria, small-scale systems are more flexible than large-scale systems, and they fit well into informal settlements (van Buuren, 2010). The small-scale systems are easy to modify when there are additional changes in the requirements. Scenarios 2, 3 and 6 are considered to be more flexible than other scenarios, since they are applicable at the household or community level. The heterogeneity in the spatial settlement patterns in all the cities studied make Scenario 6 more feasible when compared to the other scenarios. The sewerage match well with the planned settlements, meanwhile anaerobic digestion and on-site sanitation systems fit well into informal settlements, where water consumption is only about 18 litre $capita^{-1}$ day^{-1} and buildings are constructed in irregular pattern (Paterson *et al.*, 2007).

The sensitivity analysis performed to assess the robustness for the ranking of the six scenarios show that the choice of the scenarios for all the cities studied remains unchanged even when the weights for the criteria are doubled or halved. Scenario 6 still performs best in Kampala and Kisumu on all the criteria in spite of doubling and halving their weights. Similarly, Scenario 2 still performs best in Jinja, Mwanza, Bukoba and Musoma. This suggests that the weighting of the criteria have no effects on the ranking of the six scenarios assessed. Therefore, applying Scenarios 2 and 6 to treat organic waste for the six cities studied would produce minimal environmental loads to Lake Victoria's inshore.

Also, in comparing scores for the experts among the cities it proved that the standard deviations for Jinja (65±5.5), Musoma (58±2.8) and Bukoba (58 ± 4.5) are slightly higher than those for Kampala (62±2.8), Kisumu (64±0.8) and Mwanza (62±1.2). Nonetheless, the standard deviation values for all the cities studied are relatively small, indicating insignificant difference in the judgement among the groups of experts for the six cities studied. Therefore, the scoring of the six scenarios for all the cities studied can be performed by the same experts.

Table 2.11. Estimating functionality of proposed scenarios for the cities studied.

		Criteria					
Cities	**Scenarios**	**Availability**	**Affordability**	**Social acceptance**	**Flexibility**	**Feasibility**	**Total score**
Kampala	Scenario 2	+++	++++	+++	+++	++++	**85**
	Scenario 3	-	++	-	++	+	40
	Scenario 4	+++	+	+++	-	++	65
	Scenario 5	++	-	++++	-	-	35
	Scenario 6	+++	++	++	+++	++++	**85**
Jinja	Scenario 2	+++	+++	++++	+++	++++	**90**
	Scenario 3	-	++	-	++	-	25
	Scenario 4	++	+++	++	++	+	70
	Scenario 5	++	++	++	+	+	60
	Scenario 6	++	++++	++	++	+++	80
Kisumu	Scenario 2	++	+++	++	++	+++	85
	Scenario 3	+	+	-	++	++	50
	Scenario 4	++	+	++	-	+	50
	Scenario 5	++	-	+++	-	+	45
	Scenario 6	++++	+++	+++	+++	++++	**90**
Mwanza	Scenario 2	++	+++	++	++	+++	**85**
	Scenario 3	+	++	-	+	+	45
	Scenario 4	++	+++	+++	++	+++	75
	Scenario 5	++	-	++	-	-	30
	Scenario 6	+++	+++	+++	+++	+++	75
Musoma	Scenario 2	+++	+++	++	+++	+++	**90**
	Scenario 3	+	+	-	++	+	40
	Scenario 4	++	++	++++	+	+	60
	Scenario 5	-	-	++	-	-	15
	Scenario 6	++	++	++	+++	+++	85
Bukoba	Scenario 2	++	+++	++	+++	++++	**85**
	Scenario 3	+	+	-	+++	+	50
	Scenario 4	++	+	+++	+	+	65
	Scenario 5	-	-	++	-	-	15
	Scenario 6	++	+	+++	++	+++	75
Weight		**20**	**20**	**20**	**20**	**20**	

Note: Conversion of score: ++++ =100; +++ = 75; ++= 50; + =25; - = 0

Availability: (++++) scenario treats more than 50% of generated waste in a given city; (+++) scenario treats between 30 and 40% of generated waste but can be upgraded; (++) scenario treats below 30% and cannot be upgraded; (+) scenario available in the region but not in use; (-) scenario not available in region.

Affordability: (++++) scenario has low investment, operation and maintenance costs, (+++) scenario has high investment cost but low operation and maintenance costs, (++) scenario has low investment cost but high operations and maintenance cost, (+) scenario has high investment, operation and maintenance costs, (-) scenario has high investment, operations and maintenance costs and require external funding to supplement the waste management budget for its operations and maintenance.

Social acceptance: (++++) scenario can co-treat OFMSW and human excreta for reuse with no institutional support, (+++) scenario can treat OFMSW and human excreta for reuse with minimal institutional support, (++) scenario can co-treat OFMSW and human excreta but no resources recovered, (+) scenario treats only a single waste stream (-) scenario requires institutional support for its operations.

Flexibility: (++++) scenario adapts easily to new conditions and requirements, and treats both human excreta and OFMSW, (+++) scenario adapts easily to new conditions but cannot treat both waste streams, (++) scenario adapts to new conditions with moderate modification, (+) scenario adapts to new requirements and conditions but with major modification, (-) scenario cannot adapt easily to new requirements and conditions.

Feasibility: (++++) scenario fits easily to existing settlement patterns, (+++) scenario fits partly to existing settlement patterns, (++) scenario can fit to existing settlement patterns with minor modification, (+) scenario can fit to existing settlement patterns but major modification, (-) scenario cannot fit to existing settlement patterns.

The one-way ANOVA test indicates that there is a statistically significant difference in the mean scores between the different cities [F (5, 43) = 6.67, p = 0.01]. The ranking of the scenarios for each city depends on experts for each city. This could probably be explained by the small size of the experts considered for each city. However, this test does not tell us which specific groups differed. This can only be assessed by performing post-hoc tests. Such a test was not performed in this study, because our study aimed at establishing if there is an overall mean difference between groups.

2.3.5 Weighted performance

The analysis of results for the weighted performance assessment of the scenarios per criterion for all the cities studied (Figure 2.5) show that for criterion 'availability', Scenario 5 is regarded the best because four cities have sewerage systems. This is followed by Scenario 4 (landfilling) because landfills and open dumps exist in the cities studied and they can be further developed by introducing leachate and gas collection systems so as to treat the OFMSW generated by the city residents in an environmentally sound manner. Scenarios 2, 3 and 6 are weakly available on the ground in all the six cities studied.

For criterion 'affordability', Scenario 5 is regarded worst because of the high installations, operations and maintenance cost associated with large-scale centralized waste management systems like sewerage. Such large-scale system requires external energy to operate them. Meanwhile Scenarios 2, 3, 4 and 6 are moderately affordable as they can be established in small-scale, thereby requiring low operation and maintenance cost. More so, these scenarios can be easily established in the cities studied, because they fit well in the heterogeneous settlement patterns reflected in these cities.

In social acceptance, Scenario 5 is regarded very highly socially acceptable followed by Scenarios 2, 4 and 6. On the other hand, Scenario 3 is socially unacceptable because of the negative attitude towards use of compost produced by combined treatment of OFMSW with human excreta. For example, in Kisumu, Kenya, it is a taboo for men to handle human feces (Drangert *et al.*, 2002). This makes the use of compost produced from co-composting of human excreta and OFMSW to be socially unacceptable for agricultural production.

In flexibility, Scenario 3 is considered very flexible because of the existence of septic tanks that can be modified to anaerobic digesters. The anaerobic digesters can be used to co-treat human excreta and OFMSW together, producing valuable byproducts such as digestate and biogas. Scenario 5 is considered very inflexible as it requires properly planned settlements to ensure installation of sewerage to serve all the city residents.

With regard to feasibility, Scenarios 2, 3, 4 and 6 are very feasible to implement in the existing local environmental and socio-economic conditions for the cities studied. Scenario 5 is considered very unfeasible because of the low economies in most of the cities assessed.

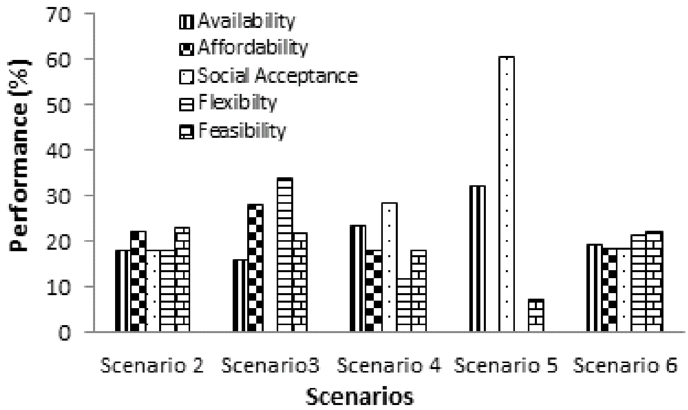

Figure 2.5. Weighted performance scores of the scenarios for all cities studied.

2.3.6 The study's limitations

This study had little field data for all the cities studied. The wetlands penetration factors of pollutants for estimating the organic and nutrient loads to the lake's inshore are derived from reviewed literature. Despite the little amount of field data, the results of the study showed an increasing trend for the urban organic loads to Lake Victoria's inshore. Moreover, the trend of our results is comparable with the results of studies carried out by Scheren *et al.* (2000) and LVEMP (2001), indicating that the results of our study are reliable and robust.

Also, in our study we assigned equal weights to all the criteria, which may have not captured the importance of each individual criterion considering the complexity of managing the human excreta and OFMSW combined together.

However, the sensitivity analysis performed on the role of equal weights for the criteria, by doubling and halving the weights for the individual criterion, as well as the standard deviation analysis showed that the ranking of the scenarios did not change. Therefore, applying the most optimal scenario for each city would produce minimal organic loads to Lake Victoria's inshore.

2.4 Conclusions

Estimating organic pollution loads and abatement measures for a trans-boundary lake system is a complex task, because of differences in geophysical, political and social settings across these cities in the different countries. Based on population sizes, waste compositions and penetration factors of pollutants for artificial and natural systems, the organic and nutrient loads to Lake Victoria's inshore for six cities are estimated. This provided insights on the magnitude of organic loads to the lake's inshore for the cities studied. Future potential organic waste treatment scenarios are designed and their efficiencies relative to baseline loads are assessed. The scenarios are also appraised against local urban specificities. Our results show that the BOD_5 loads to Lake Victoria's inshore increased by 39% compared to the reported value of 2001. This deteriorates the water quality with consequences for human health and livelihoods related to the lake. More effort on increasing composting of organic waste and reinforcing waste collection and monitoring are required for all the six cities studied, to minimise organic loads to Lake Victoria's inshore. Our study also indicated that the local experts' judgment is a useful method to select the appropriate waste management scenarios. The experts selected Scenarios 2 (composting) and Scenario 6 (mixed systems) as the optimal scenarios for minimal organic and nutrient loads to the lake's inshore. Scenario 2 is optimal for Mwanza, Jinja, Bukoba and Musoma; meanwhile Scenario 6 is optimal for Kampala and Kisumu. Sensitivity analysis shows that this selection of scenarios is robust. Thus, integrating and optimising diverse organic waste treatment options, and matching them with the heterogeneous settlement patterns and the local conditions of the individual cities would minimise organic loads to Lake Victoria's inshore.

Acknowledgment

This paper was prepared within the framework of the PROVIDE program and was funded by the INREF of Wageningen University, the Netherlands.

Chapter 3 Projections of urban waste flows and their environmental impacts for African metropolises using a system dynamics approach[4]

Abstract

The rapid population growth and lifestyle changes drive the increasing urban waste flows in African cities. Only the central business districts and affluent neighbourhoods have adequate urban waste management services. The informal settlements are characterized by poor sanitation and inadequate municipal solid wastes collection. This paper presents future trends of urban waste flows and their environmental impacts using four plausible urban waste management scenarios for fifty years into the future. To accomplish this, a dynamic box model integrating waste flows from generation up to final disposal, and their environmental impacts, is developed, tested, calibrated and validated. A sensitivity analysis is also done. The future scenarios (business-as-usual, enhanced technological implementation, policy enforcement and awareness-raising) are implemented in the model. The 'Business-as-usual' scenario showed a continued deterioration of the urban environment in Kampala and Dar es Salaam cities. The 'More enforcement' and 'More collection' scenarios reduced environmental loads but they performed poorly in resource recovery. The 'Proper management' scenario combining increased technological innovation, awareness-raising and enforcement, resulted in the smallest environmental loads and recovered the most resources. Thus, to improve the urban environmental quality and increase resource recovery, the East African city authorities should stimulate efforts to intensify and diversify waste management.

Keywords: Urban waste; dynamic modelling; impacts; urban environment; scenarios.

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[4]This chapter has been published as: Oyoo R, R. Leemans, and A. P. J. Mol (2011). Future Projections of urban waste flows and their environmental impacts in African Metropolises Cities. *International Journal of Environmental Research* 5: 705-724

3.1 Introduction

The rapid population growth and lifestyle changes drive the rapid increase in the quantity of urban waste generated in African cities. Only the central business districts and affluent neighbourhoods have generally sufficient and high quality waste management services. The informal settlements have no or poor MSW collection services (Scheinberg *et al.*, 2011). Here, sanitation facilities are also poorly operated and maintained. This deteriorates the urban environment and poses public health risks. It is thus a challenge for urban authorities to improve and to ensure adequate provision of waste management services to all urban residents inclusive of the urban poor.

Kampala City in Uganda like other large African cities is pressed with poor sanitation, illegal disposal of faecal sludge in storm water drains, frequent sewage overflows and decreasing treatment efficiency of existing sewage treatment facilities. The MSW collection is inadequate, evident by uncollected MSW along roadsides. Also, Dar es Salaam City in Tanzania faces similar problems. Here, the existing STWs do not fulfil the set national effluent quality discharge standards of Tanzania (DAWASA, 2007). In addition, MSW is not adequately collected, and indiscriminate dumping of MSW to the environment is a common practice (ERM, 2004).

The future projections for MSW (KCC, 2006) and municipal wastewater (NWSC, 2008) generation for Kampala, and MSW for Dar es Salaam (ERM, 2004) have been done in the past. Unfortunately, these projections were done using static models. The structure of these models is simply an expression of cause-effect or an illustration of trend extension, to verify the inherent systematic features that are recognized as related to the observed database (Dyson and Chang, 2005). As a result, they likely underestimated the increase in urban waste and ignore changes in its composition. Such static models are inappropriate to explore dynamic systems. A dynamic model that can project the future urban waste production and assess the performances of plausible waste management scenarios is the most appropriate alternative.

Adequate waste management services can be attained by having in place waste management solutions that are environmentally friendly, socially acceptable, economically affordable, and resilient to socio-economic, political and environmental changes. In designing and assessing future solutions to waste management, an integrated system dynamics model is useful. Such a model can help to identify weak points in current waste management systems and to develop mitigation measures to prevent environmental and health problems (Light, 1990). It also enhances the understanding of large scale complex feedback systems (Dyson and Chang, 2005). Hence, the objective of this paper is to develop and use such a model to project trends of waste flows and assess their consequences on the environment, under different mitigation scenarios. The model is developed, calibrated and tested using data for Kampala, and validated with data for Dar es Salaam and Kisumu cities. Sensitivity analyses are performed on key processes and input parameters.

3.2 Method

3.2.1 Study Areas

a) Kampala

Kampala, the capital city of Uganda, covers about 150 km^2 (Matagi, 2001). The population of the city is spread in five divisions and has grown from about 0.8 million in 1991 to 1.2 million in 2002 at an annual growth rate of 3.8% (UBOS, 2006). The present Kampala administrative boundary (Figure 3.1) is the study area for the 2052 projections of future trends of waste flows and their environmental impacts.

The city is characterised by low lying flat top hills and wet valleys covered with papyrus (Kulabako, 2005). The valleys have a high water table and are frequently flooded in the rainy season. This affects the environmental performances of on-site sanitation such as pit latrines and septic tanks in terms of groundwater quality protection. The climate is tropical with small variations of temperature, humidity and wind throughout the year. The dry season is from December to March and June to July. The mean annual rainfall is 1,180 mm with two peaks: March to May and October to November (UBOS, 2008).

The main existing sewerage managed by the NWSC serves about 80,000 people (NWSC, 2008). The sewage from this system is treated at the Bugolobi Sewage Treatment Works (BSTW), and the effluent discharged to the Nakivubo Channel surface water. This channel drains to Murchison bay of Lake Victoria. This bay represents the only drinking water source for Kampala residents. There are also five smaller sewerage systems serving about 20,000 people. The sewage from these systems is treated using sewage ponds.

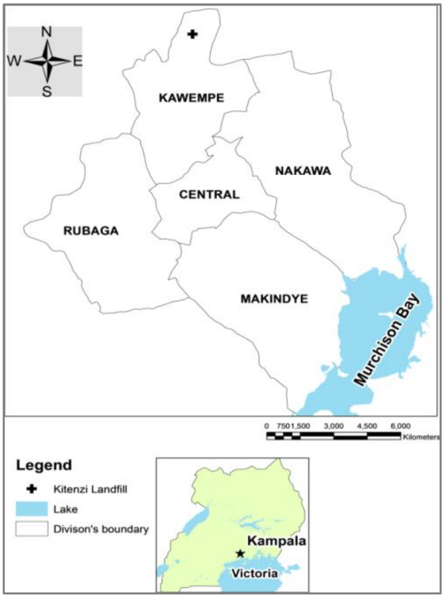


Figure 3.1. Map of Kampala's divisions and inset (Uganda).

b) Dar es Salaam

Dar es Salaam, the capital city of Tanzania, is located along the coast of the Indian Ocean. It covers about 1,400 km^2. In 2002 the city had an estimated population of 2.5 million and an annual growth rate of 4.3% (NBS, 2003). The current administrative boundary for the city used for this study is presented in Figure 3.2. The city has gentle slopes and valleys. The climate is moist monsoon, with cold weather from April to October, and hot and humid from November to March. The temperature ranges from 13^{o}C to 35^{o}C. The average humidity is 96% in the morning and 67% in the afternoon. The annual rainfall is about 1,000 mm (Yhdego, 1995).

There are nine sewage ponds serving the Ilala, Kinondoni and Temeke municipalities. The University College of Dar es Salaam owns and operates its own sewage pond. Of the nine sewage ponds, four have facilities for dumping faecal sludge, but only two are operational (DAWASA, 2007).

Figure 3.2. Map of Dar es Salaam's municipalities and inset (Tanzania).

3.2.2 Model's inputs data

The estimations of MSW and sanitation data for calibrating, validating and testing the model are described below.

a) Municipal solid waste

To establish the quantities of MSW generated by different income groups, the daily MSW generations by high-, medium- and low-income households are measured for a period one month at points of generation. In each income group, five households were selected using random non-probabilistic sampling, and working only with households that agreed to participate. The MSW composition analyses were conducted for a period of nine days, using the method developed by the American Society for Testing Materials. The composition analysis was performed on MSW collected daily from all the three income groups.

The quantity of MSW disposed at landfills was computed from the daily MSW disposal records at the landfill. This was done to estimate the proportion of MSW that is collected and treated at the landfills. To assess the net amount of MSW finally disposed, the amounts of recyclables salvaged (before and at the landfill) were estimated. Since the weights of recyclables are not measured as they are transported out of the landfill, the amount of recyclables salvaged at the landfill was determined by interviewing ten scavengers and four KCCA officials. Similarly, the amount of recyclables collected at the source of waste generation was estimated by interviewing the six small-scale recyclers and ten persons in the communities involved in waste recycling.

The reduction of organic load by the leachate treatment plant was estimated by subtracting effluent organic load from influent organic load. The influent and effluent quality data was determined in the laboratory using standard analytical procedure (Greenberg *et al.*, 1980). The influent and effluent flows were measured using flow meters. The amount of OFMSW composted by the households was determined by interviewing fifteen KCCA officials performing MSW collection (three from each division), twenty five households (five from each division) and through literature review for MSW management in Kampala.

The institutional arrangements and relevant policies governing MSW in urban towns in Uganda were reviewed to understand causes for the increased amount of uncollected MSW in Kampala. Physical observation on MSW management from households up to the landfill was done to supplement the literature data, to map the MSW flows.

b) Sanitation data

To establish the proportion of human excreta treated with the different sanitation systems in Kampala, the sanitation coverage was obtained through literature review and consultation of city authorities. The daily volume of faecal sludge collected from on-site sanitation and taken for further treatment at the BSTW was estimated from the faecal sludge disposal records. These records contain truck capacities and sources of the faecal sludge disposed. The amount of overflowed sewage from sewers was estimated as average sewage overload times number of occurrence of sewage overflows per month. Much of the sewage overflow is the combination of blocking of the system, because of dumping of MSW in sewer manholes and too much storm water.

To assess the STW performance as well as the environmental compliance of the final effluent to the specified national discharge quality standards, the influent and effluent qualities measurements were performed for four months using standard procedures (Greenberg *et al.*, 1980). The influent and effluent loads including faecal sludge taken to STW helped to determine the organic load removal efficacy by the existing STW. The faecal sludge load to STW was computed as faecal sludge quality (i.e. concentrations for BOD_5, TN and TP) times the daily volume of faecal sludge delivered at the STW. Faecal sludge quality was measured for a composite sample prepared from faecal sludge samples taken from fifteen trucks for different sources, using standard analytical procedures.

3.2.3 Model's assumptions and design

This subsection describes the model's assumptions and its design structure.

a) Model's assumptions

The assumptions below were applied for developing an Integrated Urban Waste Flow Model (IUWFM) for projecting future waste flows and their environmental impacts in East African cities.

1. The population sizes of the three income groups are assumed to vary as a function of a net constant growth rate. The net growth rate is the difference between the sum of the birth rate and immigration rate minus the sum of migration and mortality rates. Against the background of continuing socio-economic development in Kampala, it is assumed that the high- and medium-income people losing their wealth are negligible such that the population sizes of these groups do not decline in absolute term. For instance, in 1999 about 15% of the population in Kampala lived below the poverty line (Wairagala, 2005). The population size of the low-income group will increase, because of higher birth rates and increased immigration of the rural poor to the urban centre in search for jobs. Hence, using a constant net growth rate for long simulation periods (e.g. 50 years) may be unrealistic owing to the fact that birth rate may change, because of improved standards of living, increased confidence of children survival to maturity, improved status of women or increased use of birth control measures. Nevertheless, since the scenarios are designed to show plausible future trends (and not predictions), applying a constant net growth rate is reasonable for understanding feedbacks and interactions within the system.

2. Given the current socio-economic status and development level of Kampala, the high-, medium- and low-income groups are assumed to have saturation population densities of 50, 250 and 450 persons ha^{-1}, respectively (NWSC, 2008). But for long simulation periods of 50 years the effect of specific population saturation density can be neglected. This is because as population pressure increases and land becomes limited, high-density

buildings may develop. This means an increase in population saturation density. However, the conversion of residential areas to commercial establishments will lead to a decrease in population saturation density.

3. The number of inhabitants in a given geographical area drives the net amount of waste generated in that location. Thus, population size is used as a proxy to estimate the quantity of waste generated. Furthermore, the per capita BOD_5, TN and TP in human excreta are assumed to be independent of the socioeconomic status, and the variation among individuals to be minimal (Mara, 1976). Also, the specific wastewater loads introduced to on-site sanitation are assumed to be in the same range as those emitted to the sewer although there is a difference in the amount of water used.
4. Because of frequent flooding of low lying areas in the rainy season, on-site sanitation, such as pit latrines and septic tanks, are emptied after every four to six months (NWSC, 2008). But in dry areas faecal sludge in septic tanks can stay for more than ten years if properly designed, operated and maintained (Paterson *et al.*, 2007). Since the proportion of population settled in the low lying areas are much less than those in dry areas, a retention period of eight years is assumed for faecal sludge in on-site sanitation prior to its collection and transportation to STWs. This is supported by field experience provided by cesspool truck operators in Kampala on the frequency of emptying a specific on-site sanitation facility.
5. Because of the poor operations and maintenance of on-site sanitation, particularly in slums, and illegal discharge of faecal sludge into storm surface water drains, it is assumed that 18% of the faecal sludge from on-site sanitation is disposed to the environment (NWSC, 2008). Additionally, the amount of organic matter lost through conversion to CO_2 and CH_4 from on-site sanitation is assumed to be 4% per month. Properly designed and operated on-site sanitation reduces about 60% BOD_5 in the effluent. As the effluent passes through unsaturated soil, the BOD_5 in the effluent is further reduced, in total by about 90% (Elisabeth, 2005). Hence, it is assumed that 10% of the effluent BOD_5 load from on-site sanitation leaches into the groundwater. The ratios of N and P from on-site sanitation leaching into the groundwater are set at 30% and 10%, respectively (Nalubega *et al.*, 2001).

6. The rate of sludge accumulation in pond systems is assumed to be approximately 0.03 – 0.04 m^3 hd^{-1} $year^{-1}$. The desludging of ponds is required when the pond is half full with sludge. This is done once every ten to fifteen years in properly operated sewage ponds (Mara, 1976). In this model, it is assumed that 1% of the sludge is removed monthly. This may be unrealistic for poorly operated and managed ponds as is more often the case now.

7. For the computation of the STW threshold, it is assumed that the plant will be in operation up to the year 2017. This is because the BSTW is located in an industrial area, which has been earmarked for future industrial expansion (NWSC, 2008). The threshold is the feasible maximum capacity for a STW, and is only indicative of the technical constraints that a compartment imposes. For example, the threshold limit for BOD_5 load at the BSTW is estimated as the product of the design wet weather flow of 34,000 m^3 day^{-1}, BOD_5 concentrations of 430 mg l^{-1} and a life time of fifteen years from 2002. The wet weather flow is the peak flow that occurs in a combined sewerage system (sewage and storm water) during the rainy season (Mara, 1976).

8. Based on the organic carbon fluxes for the BSTW, it is assumed that 10% of the total carbon is lost to the atmosphere by conversion to CO_2, as the BSTW is a conventional aerobic treatment system. The sludge production is assumed to be 40% of the total organic carbon load to the STW. The remaining 50% organic carbon load is discharged to the Nakivubo Channel.

9. The composting treatment, which is the biological breakdown of organic matter by microorganisms under aerobic conditions, is assumed to be 100% home composting (Szántó, 2009). The resulting compost is used in gardens. The leachate production is assumed negligible, because during composting processes, the water produced at the degradation of organic matter is depleted in form of vapour by the generated heat.

10. All components of the waste are assumed to be oxidised at the same rate, and are constant with time. This follows first-order kinetics, but it is unlikely that all components of waste are oxidised at the same rate. For example, in waste stabilization ponds, as the retention times increases the rate constant decreases (Mara, 1976). In landfills, aerobic and anaerobic biological processes may take place. Landfills with very low compaction do allow aerobic processes to convert OFMSW to CO_2 and water (Ehrig, 1982). In this

model, the proportion of OFMSW converted to CO_2 is assumed to be 10%, and the fraction of papers degraded is assumed to be 5% (Dalemo *et al.*, 1997). Nitrogen losses from composting processes vary with the degradation conditions. The loss of nitrogen during composting amount to about 50% of the initial amount of nitrogen present (Strauss *et al.*, 2003). The organic load discharged to the environment is further degraded. Based on the analysis in Nakivubo channel surface water, it is assumed that the degraded BOD_5 and TN, and the settled TP are 30%, 10% and 10%, respectively (NWSC, 2008).

c) Model's design

The IUWFM is composed of four subsystems, namely: 'Population', 'Solid waste', 'Sanitation' and 'Environmental', as shown in Figure 3.3.

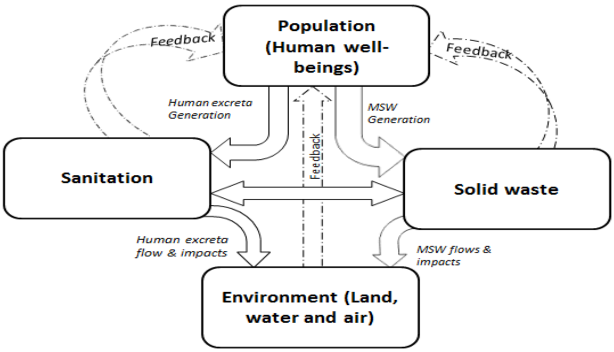


Figure 3.3. Design structure for IUWFM.

The population subsystem drives the generation of both MSW and human excreta, which then flows to the different compartments. These flows are controlled by threshold limits. At threshold points, any addition of waste flow to the compartment results in overflow to the environment. The fraction lost to the environment is translated to impacts, which in turn affect the well-being of the population. The resources recovered from the waste (e.g. compost, plastics, papers and boards, and metals) are reused by the local population, often after a simple processing. These feedbacks are represented by dotted lines. The environmental subsystem is also linked to the population subsystem by a dotted line to depict the impacts of the environment on human beings.

The IUWFM calculates the waste flows in a selected geographical region for a defined timespan based on the principle of mass conservation. The waste fluxes are calculated throughout the system including the fraction lost to the environment. This gives the opportunity to identify environmental measures – such as technological enhancement and policy enforcement – that control urban waste lost during collection and transportation, and from treatment facilities and on-site sanitation, as well as fractions illegally disposed to the environment.

Illustrated in Figure 3.4 is the conceptual flow diagram for IUWFM built in SIMILE software environment. This software combines system dynamics and object-oriented based paradigms. This provides a close correspondence between the objects in the real world and the objects in the model (Muetzelfeldt and Masshede, 2003).

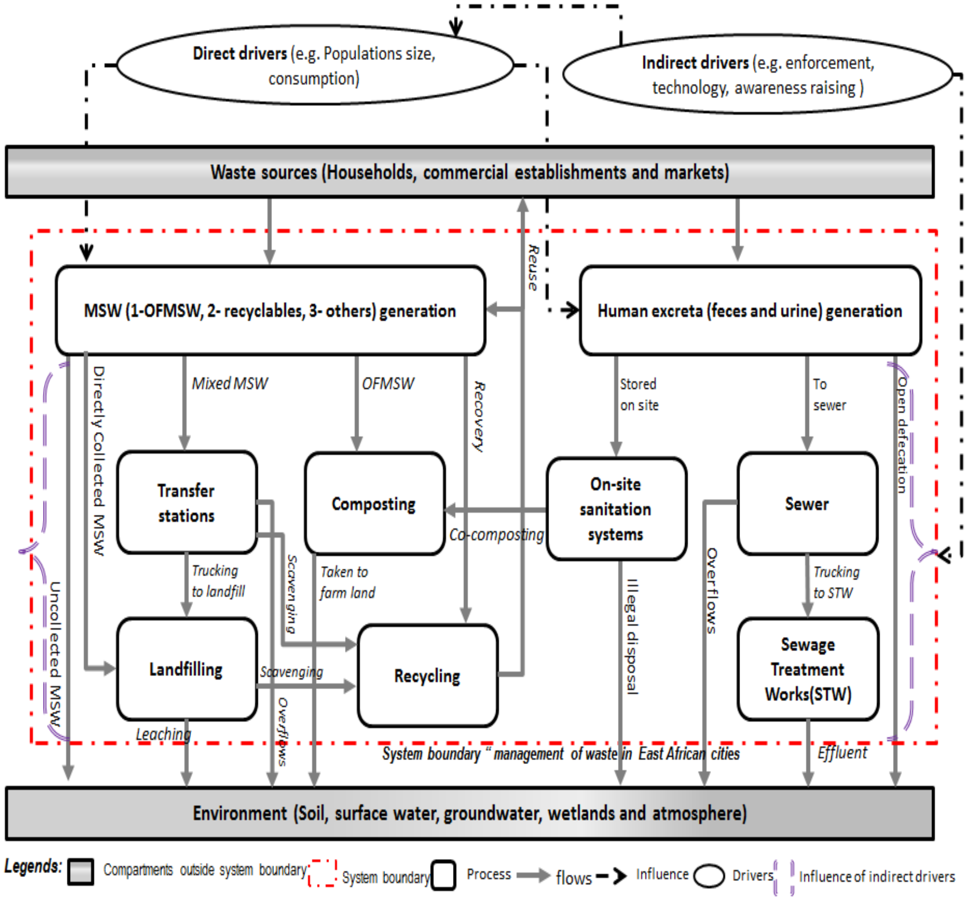


Figure 3.4. Conceptual flow diagram for IUWFM.

The boxes/compartments represent stock variables where wastes are generated, stored or transformed. The fluxes are calculated for each compartment by subtracting outputs from inputs. The flow from one compartment to another is modelled as a fraction, and is represented by an arrow. The size of the arrow is determined by the different variables that mimic the effectiveness of urban waste management via a combination of environmental, socio-political and economical factors. The waste load to the environment is the cumulative environmental burden due to the waste lost from the other boxes/compartments.

The faecal sludge (partially treated fresh human excreta from the sanitation subsystem) and the OFMSW (from the solid waste subsystem) are co-treated in the compost compartment by co-composting. Co-composting refers to composting of two or more kinds of organic materials together, in this case, faecal sludge and OFMSW. Co-composting of faecal sludge and OFMSW is advantageous because the two materials complement each other. The human excreta is relatively high in nitrogen and moisture content, and the OFMSW is relatively high in organic carbon content and has good bulky quality. Both waste materials can be converted to a soil conditioner (Montangero and Strauss, 2002). Also, if in a sanitation system the urine and feces are separated at points of generation; the urine can be diluted with water and directly used as organic fertiliser in agricultural lands. The feces can be aerobically co-composted with OFMSW or dried separately, and later applied as organic fertiliser. However, in Kampala, treated feces cannot easily be transferred to agricultural lands because urban farmers are too small to be able to apply reusing treated feces. The cultural perception by some communities can affect its success. Also, because of health reasons people may fear to use the compost produced from the human excreta. This however can be (partly) overcome by awareness-raising and giving incentives. To compute the combined organic loads for the human excreta and MSW, the OFMSW is expressed as BOD_5, TN and TP. Dry OFMSW has BOD_5, TN and TP contents of 40%, 2% and 0.8%, respectively (Montangero and Strauss, 2002).

The urban waste flows are influenced by technology, awareness and enforcement, represented as in Equation 3.1.

$$UW_{t+1} = (FE, FA, FT)UW_i \qquad \text{Equation 3.1,}$$

where, UW_{t+1} is the waste flow at time t; *FE, FA* and *FT* are enforcement, awareness-raising and technology variables, respectively; and UW_i is the current state of the urban waste flow. These factors influence urban waste flows either positively or negatively. A positive influence is when an increase in one element causes an increase in another, whereas a negative influence is when an increase in one element causes a decrease in another. The technology factor is linked to collection, transportation and treatment processes. This is important because a large proportion of the waste is not adequately collected and treated due to lack of or inappropriate technological application. Enforcement changes the behaviour of actors in handling waste, and awareness factors influence negative attitudes of the residents towards waste management. The three variables are modelled by simple multiplication factors ranging from 1 to 5. Level 1 is the current situation and level 5 provides a theoretical maximum efficiency. Increasing these efficiencies reduces the volume of untreated waste flowing to the environment. This mimics changes in enforcement, awareness and technology. For example, expanding sewerage and ensuring houses close to the sewer are connected would reduce the proportion of human excreta stored in on-site sanitation as well as reduce organic loads to the environment. Enhanced enforcement reduces illegal dumping of faecal sludge or better and timely emptying of septic tanks.

The outputs for IUWFM are the cumulative quantities of MSW disposed in landfill, compost produced, and BOD_5, TN and TP loads to the environment. BOD_5 is an indicator of the amount of oxygen required by aerobic microorganisms to decompose the organic matter in a sample of water (e.g. water polluted by sewage). It is used as one indicator of the degree of water pollution (Straskraba and Tundisi, 1999). High BOD_5 loads in surface water have consequences for water quality and aquatic species. When the BOD_5 load is larger than the ability of the receiving water to supply new oxygen, then dissolved oxygen levels will decrease, and in extreme cases lead to total anoxia. In terms of water quality, TN and TP are considered pollutants if their presence in water are in concentrations sufficient to cause eutrophication. Eutrophication is intense algal bloom in surface water (Banar *et al.*, 2008). Algae add colour, changes water taste and reduces acceptability of water as a drinking water source.

The different subsystems for the IUWFM model are described below.

a) Population subsystem

Population sizes drive the effects of waste on the urban environment. The three population groups are linked together by flows of people moving into and out of the different classes. The population sizes of these groups are controlled by their population saturation densities. The population density has implications on the quantity of waste generated and cost required to treat the waste to protect the environment from pollution. Highly populated areas produce relatively more MSW per ha than sparely populated area (Massimiliano *et al.*, 2008). This implies more need for resources such as refuse collection trucks, waste collection light tools and manpower to adequately collect and treat all MSW generated. Also, highly populated areas may imply greater scarcity of land such that pressure is placed to preserve land to build waste treatment facilities. However, high density areas can be relatively cheap in terms of MSW collection because of economies of scale as the costs are spread over all households.

Similarly, for the high-density settlement, economies of scale can make simplified sewerage (also known as condominial sewerage) cheaper than on-site sanitation technologies. A simplified sewerage is technically feasible and economically appropriate sanitation option available for low-income, high-density urban settlements. This system can provide an equivalent level of service and health benefits as conventional sewerage. In simplified sewerage, the conservative design codes are relaxed, to reduce the pipe diameters, gradients and depths, while maintaining sound physical design principles. The simplified sewer network is very flexible, with pipes often laid inside a housing block, in the front garden, or under the pavement, rather than in the centre of the road as with conventional sewerage. This results in considerably less disruption to existing structures, and cost savings in excavation, backfills and pipe quality (Paterson *et al.*, 2007).

This model computes the population sizes for the parishes, different income groups (low-, medium- and high-income) and aggregated population. As the population increases, the density also increases up to the saturation point. At the saturation point, movement of population to the neighbouring parishes takes place because of the limited available space. This means that population growth is no longer exponential when the population saturation densities are reached.

This subsystem is initialised with the 2002 population census data (UBOS, 2007), and validated with the population estimated by the Uganda Bureau of Statistics (UBOS). The output of this model is, as shown in Table 3.1.

Table 3.1. Aggregated projected population values for Kampala City.

	Estimated populations	
Model	**2010**	**2015**
IUWFM	1,605,900	1,921,900
UBOS	1597,900	1,923,900

Source: (UBOS, 2007)

The projected population sizes using this model differ slightly from the UBOS projection because of applying the population saturation densities in our model. This is neglected in the model for the UBOS such that the population size continues to grow exponentially. But IUWFM yields relatively good results for short periods and is useful for projecting population at division/parish level.

b) Solid waste subsystem

The quantity of MSW generated is estimated by computing the product of population sizes and their per capita MSW generation rates. The process is initiated in the generation box and subsequently distributed to the other compartments (i.e. landfill, recycling, compost and environment), as shown in Figure 3.4. The waste flows are divided into three streams: OFMSW, recyclables (i.e. metal, plastic, glass and papers) and others MSW fractions (i.e. textile and construction wastes). The OFMSW is considered separately from other fractions because of the potential to co-compost with human excreta. The recyclables are combined together because their percentages are very small compared to the percentage for OFMSW. These flows are explicitly computed as fractions of generated MSW. The compartments are controlled by their threshold limits. For example, the threshold limit for the landfill is its maximum capacity. This subsystem is parameterised with the parameters provided in Table 3.2.

Table 3.2. Parameters and variables used in the solid waste subsystem.

Parameter	Unit	Value	Sources
Population growth rate	%	3.8	(UBOS, 2006; UBOS, 2007)
Initial population (2002)	Persons	1,208,196	(UBOS, 2007)
Design capacity of landfill	Mt	2	(KCC, 2005)
Estimated compost by 2052	Mt	22	Computed

c) Sanitation subsystem

The sanitation subsystem is initialised by multiplying population size with the daily per capita human excreta generation rate, and distributed to the different compartments (i.e. sewerage and on-site sanitation systems). The faecal sludge in on-site sanitation systems flow to the compost compartment, where co-composting of OFMSW and faecal sludge is performed.

This subsystem computes the organic loads that characterise the quality of different types of wastewater that is subject to change during the different stages of processing. These loads are explicitly computed as fractions of generated fresh human excreta. The flow from on-site sanitation systems to the centralised sewerage is modelled to mimic the fraction of faecal sludge emptied by trucks from on-site sanitation systems and taken for further treatment at the STW. This subsystem is parameterised with the field and literature data, as shown in Table 3.3.

Table 3.3. Parameters and variables used to calibrate the sanitation subsystem.

Parameter	Unit	Value	Sources
BOD_5	g capita^{-1} d^{-1}	40	(Mara, 1976; Gumbo, 2005)
TN	g capita^{-1} d^{-1}	10	(Mara, 1976; Gumbo, 2005)
TP	g capita^{-1} d^{-1}	3	(Mara, 1976; Gumbo, 2005)
Proportion of population served by on-site sanitation	%	86	(UBOS, 2006)
Proportion of population served by centralised sewerage	%	7	(UBOS, 2006)
Proportion of population with no access to sanitation	%	7	(UBOS, 2006)
Fraction of BOD_5 leached into the groundwater from on-site sanitation	%	10	(Montangero and Strauss, 2002)
Fraction of TN leached into the groundwater from on-site sanitation	%	30	(Nalubega *et al.*, 2001)
Fraction of TP leached into the groundwater from on-site sanitation	%	10	(NWSC, 2008)
Proportion of faecal sludge collected from on-site sanitation by vacuum truck and taken to the STW.	%	27	Computed
BOD_5 removal efficiency from influent by STW	%	60	Measured
TN removal efficiency from influent by STW	%	30	Measured
TP removal efficiency from influent by STW	%	20	Measured
Proportion of sludge produced as fraction of STW influent	%	40	Assumed
Centralised sewage BOD_5 threshold	Mt	79	Computed
On-site sanitation BOD_5 threshold	Mt	1.5×10^5	Computed

d) *Environmental subsystem*

The environmental compartment, which is the sink for the urban waste materials is limited to soil, surface water, groundwater, wetlands and air. The wastes lost from the different compartments are aggregated to calculate the load to the environment. This load is translated to the impact on the environment. The environmental impacts are characterised by the BOD_5, TN and TP loads. The load is computed at a parish level as load intensity by dividing the organic load by the area of the parish. The parishes close to fragile ecosystems, such as wetlands and surface water, are assigned a unique code. The impacts are represented graphically as a time series plot or on a spatial map as load intensities. The spatial display is plotted by extracting the data for a particular time step.

3.3 Results and discussion

3.3.1 Municipal solid waste and its management

The analysis of results for the MSW data for Kampala used for calibrating the solid waste subsystem is discussed below.

a) *Municipal solid waste generation and composition*

The MSW generation rates by the low-, medium- and high-income households in Kampala are estimated to be 0.46, 0.63 and 0.68 kg cap^{-1} day^{-1}, respectively. The MSW generated by markets is about 45 t day^{-1}. The overall mean MSW generation rate by households is about 0.59 kg $capita^{-1}$ day^{-1}. This is in the range of early estimates obtained in previous studies. For examples, Matagi (2001) estimated a MSW generation rate of 0.55 kg $capita^{-1}$ day^{-1} and the LVEMP estimated a range of 0.5 to 0.8 kg $capita^{-1}$ day^{-1} (LVEMP, 2001). But the Kampala Solid Waste Management Strategy reported a MSW generation rate of 1 kg $capita^{-1}$ day^{-1} (KCC, 2006). This is twice the value obtained in this study, because the MSW generated by markets and commercial establishments are also included to the MSW produced by households. This is considered separately in this study.

Table 3.4 provides the MSW composition for Kampala. The analyses show OFMSW as being the highest fraction in the MSW composition, followed by plastic, paper and board. The high OFMSW is explained by the high consumption of fresh foodstuffs such as matoke (i.e. unripe bananas), potatoes, fruits and vegetables. For example, preparing 1 kg of matoke produces about 3 kg of OFMSW. The high proportions of plastics and papers in the MSW composition are attributed to the increased generation of packaging materials from commercial establishments. Generally, commercial establishments provide plastic bags at a free cost to customers to carry purchased goods.

Table 3.4. Municipal solid waste composition values for Kampala City.

Category	Composition (%)	Standard deviation
Paper and board	5	2.6
Glass	1	0.4
Metal	1	0.4
Plastic	7	1.8
OFMSW	83	5.2
Textiles	1	0.5
Construction	2	0.6
Total	**100**	

b) Municipal solid waste management

The MSW generated is stored either on-site or in the immediate neighbourhood in skips before transportation to a landfill. Where MSW collection points are lacking, empty plots, roadsides and storm surface water drains are convenient places to dump MSW. The daily amounts of MSW collected, uncollected, composted/buried and recycled, are displayed in Figure 3.5. The MSW collection activity is performed by KCCA and Private Service Providers (PSPs). The MSW collected is mainly from the business district and affluent residents where PSPs are actively involved. The MSW from the low-income households is rarely collected as they cannot afford to pay for the MSW collection fee. The recyclables salvaged from sources of waste generation, transfer stations, in trucks and at a landfill are sold to the small-scale recycling industries.

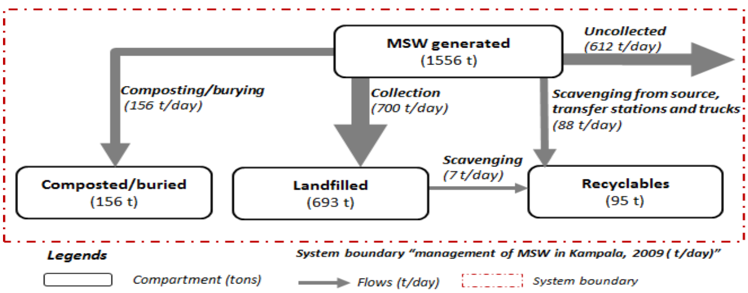


Figure 3.5. Kampala's daily MSW loads in the various compartments.

3.3.2 Sanitation coverage and management

There are two main sanitation systems in use in Kampala. These are: (1) off-site sanitation where domestic wastewater generated is carried away by sewers and treated in a centralised STW before discharge to the environment; and (2) on-site sanitation where domestic wastewater generated is stored at the point of generation, and the organic matters in the waste are partially degraded.

About 5% of the fresh human excreta generated in Kampala is treated at the BSTW. There are also five smaller sewerage systems using ponds based sewage treatment systems, treating about 2% of the generated human excreta. Approximately, 7% of population have no access to sanitary facilities, and they practices open defecation. Areas with no off-site sanitation have on-site sanitation such as septic tanks, unlined pit latrines and pit-lined latrines, which serves about 86% of Kampala's population. Pit latrines are the commonest on-site sanitation used in Kampala. About 80% of the pit latrines are of the traditional unimproved type and do not meet the basic criteria of hygiene and accessibility to the children and disabled persons (NWSC, 2008). Subsequently, spaces around the houses are used for excreta disposal especially by the children. In these cases, the excreta disposed ends up in storm surface water drains or in MSW dumps.

The on-site sanitation systems are emptied whenever full, using vacuum trucks. However, poor accessibility to some of these facilities (due to the dense settlement and no/narrow roads) for desludging by trucks and associated costs results in most of the latrine contents being disposed to adjacent dug unlined pits or in storm surface water drains (Kulabako, 2005). Of the 86% of the human excreta stored in on-site sanitation, about 27% of the faecal sludge is emptied and co-treated with fresh human excreta at the BSTW, 55% of the faecal sludge is retained on-site and 18% is illegally disposed to the environment (NWSC, 2008).

3.3.3 Policy, legal and institutional framework

The Uganda Constitution (1995), Public Health Act (MoH, 1995), National Environmental Act Cap, 153 (1995) (NEMA, 1995), Local Government Act (1997) and Kampala Solid Waste Management Ordnance, are the principle policy documents governing waste management in Uganda. These legal instruments are governed by various ministries and there is no one synchronizing agency.

There are three ministries in charge of sanitation and waste management. These are the Ministry of Local Government concerned with MSW and on-site sanitation; the Ministry of Health, dealing with the on-site sanitation; and the Ministry of Water and Environment for the sewerage systems. The communication among these ministries with regard to waste management is poor. This makes it very difficult to create a comprehensive sanitation and waste management plan for the entire city. The Ministry of Water and Environment, represented by the NWSC, exclusively focuses on sewerage systems in the business district and affluent neighbourhoods in large cities, including Kampala. A sewerage system contributes to the wealthy appearance of the city and is therefore considered as very important. Poorer areas are left to the Ministry of Local Government and Ministry of Health, which focus on the coverage of on-site sanitation systems.

The collection and transportation of MSW within the city lies with the administrative divisions of KCCA, and is headed within each division by a Divisional Public Health Officer. Presently, other key actors in MSW management within the division (such as community development, education and public relation officers) are excluded. This makes MSW management a health problem rather than an environmental concern. In addition, the Local Councillors (LC1s) are not active in ensuring compliance of solid waste management ordinance at households, despite their closeness to the communities. Their active involvement can change the negative attitudes of the communities towards MSW management and encourage public participation. For instance, in Katanga slum in Kampala, every household pays a monthly fee for MSW collection, which is used to fuel the KCCA's trucks to transport MSW to the landfill.

Although MSW management fits well with the concerns of the community, the Community Based Organisations (CBOs) and the local Non-Governmental Organisations (NGOs) that are involved in MSW management activities are not supported by the KCCA. The KCCA standpoint is that PSPs have a main role in MSW collection for all the city residents. Unfortunately, the low-income households are unable to pay for this service. Thus, about 55% of MSW generated remains uncollected. By providing support to CBOs and NGOs, the access to MSW services by low-income households can be improved (Massoud *et al.*, 2003; Tukahirwa *et al.*, 2010).

3.3.4 Model calibration and validation

The results for the model's calibration and validation are discussed below.

a) Calibration

This model was calibrated using annual amounts of MSW disposed in a landfill from 2002 to 2006. As the output of a stock variable in SIMILE is cumulative, the annual cumulative masses of MSW disposed in a landfill were used. The calibration exercise was done by varying the fraction of MSW flowing to a landfill. This was arrived at by matching the plot of the simulation result to that of the measured MSW, as shown in Figure 3.6. Since the actual masses of MSW are taken before dumping, the degrading, recycling and leaching rates within a landfill were set at zero.

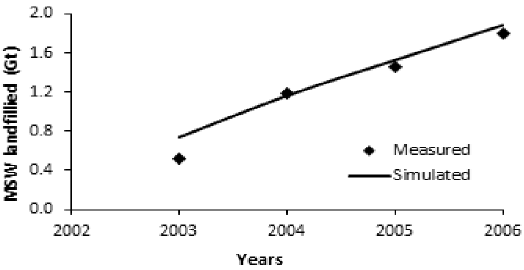


Figure 3.6. Plots for measured and simulated MSW disposed in a landfill.

Both plots show a gentle increase in time in cumulative amounts of MSW disposed in a landfill. To further assess the degree of fitting of the two curves, the actual annual cumulative amounts of MSW disposed in a landfill were plotted against the simulated cumulative amounts of MSW. The variance of the simulated values to the measured values, given by R^2 is, as shown in Figure 3.7.

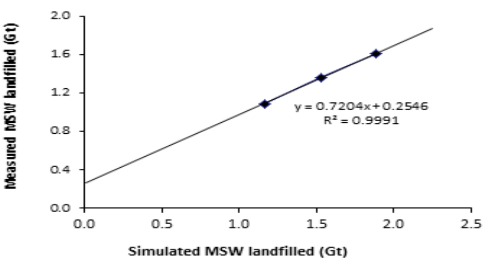


Figure 3.7. Plot for measured against simulated MSW disposed in a landfill.

The R^2 from the plot shows a high correlation value of 0.99 illustrating a good fit for the model simulation to the actual measurement of MSW disposed in a landfill.

b) Validation

This model was validated using demographic, MSW and sanitation data for Dar es Salaam (Tables 3.5 and 3.6). Dar es Salaam is about nine times bigger than Kampala, and it is as densely populated as Kampala.

Table 3.5. Municipal solid waste and sanitation data for Dar es Salaam City.

Parameter	Unit	Value	Source
MSW generation rate	kg capita^{-1} d^{-1}	0.8	(ERM, 2004)
MSW taken to a landfill	%	44	(ERM, 2004)
Proportion of MSW recycled	%	9	Health Officer
MSW illegally disposed to environment	%	38	(ERM, 2004)
OFMSW treated by composting process	%	9	Health Officer
Fraction of population using on-site sanitations	%	90	(DAWASA, 2007)
Fraction of population using centralised sewerage	%	7	(DAWASA, 2007)
Fraction of population with no access to sanitations	%	4	(DAWASA, 2007)

Table 3.6. Municipal solid waste composition values for Dar es Salaam City.

Category	Composition (% in wet weight)
Paper and board	8
Textile	1
Plastic	5
Metal	2
Glass	3
Leather/rubber	1
Ceramic/Stone/soil	1
OFMSW	64
Other	15
Total	**100**

Source: (ERM, 2004)

The result for the model validation is presented in Figure 3.8. The plots indicate both the simulated and the measured MSW disposed at the dump sites for Dar es Salaam.

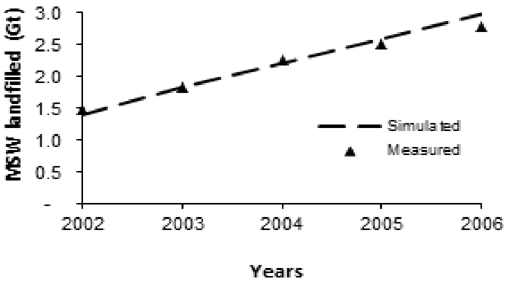


Figure 3.8. Dar es Salaam's simulated and measured MSW quantities disposed in dumps.

The plot shows a gently increasing trend for both simulated and measured cumulative amounts of MSW disposed at the dump sites. To determine the degree of validation, the variance R^2 was computed by plotting the simulated amounts of MSW against the measured amounts of MSW disposed in the dump sites (Figure 3.9). With an R^2 value of 0.99, the fit was good.

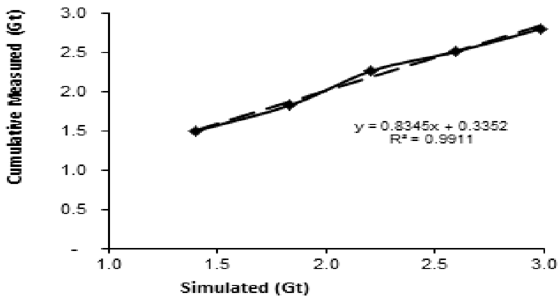


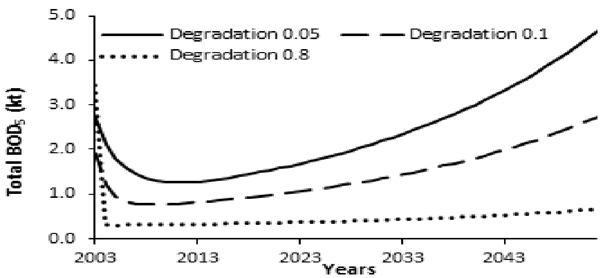
Figure 3.9. Plot for measured MSW disposed verse simulated for Dar es Salaam City.

3.3.4 Sensitivity analysis

The sensitivity analysis estimate the rate of change in the output of a model with respect to changes in inputs and/or parameters. It is performed to learn whether the model's general pattern of behaviour is strongly influenced by changes in the uncertain parameters (Ford, 1999). Such knowledge is important to evaluate the applicability of the model to accurately project the future trends, determine parameters for which it is important to have more accurate values and to understand the behaviour of the system. In this study, sensitivity analyses were done for the different processes/parameters for waste management. These parameters are: degradation rate, landfill threshold, composting threshold, on-site sanitation threshold, centralised sanitation threshold, recycling rate, composting rate, collection rate, vacuum truck emptying rate and leaching rate.

A comparison was made between a simulation using default parameter values and a simulation in which the parameter values are drastically changed. The change in the simulation results is measured by the change in BOD_5, TN and TP loads. Examples of studied sensitivities for the case study of Kampala are presented in Figure 3.10.

a)



b)

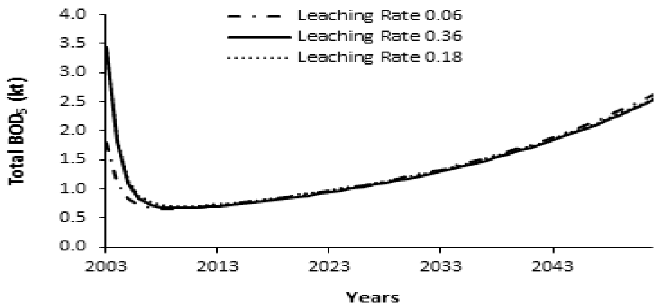


Figure 3.10. Plots for sensitivity analyses for changing rates, a: degradation rate; b: leaching rate.

From the sensitivity analyses results, the degradation rate is found to be sensitive to the model outputs. The graph reveals the changes of uncertainty change over time. There is little uncertainty in the BOD_5 in the first few years, and by the year 2051, the range of uncertainty extends from about 0.5 to 4.5 kt BOD_5. This implies that a small difference in the degradation rate can lead to large changes in the width of uncertainty interval. The further we look into the future, the larger the uncertainty becomes. However, the model outputs show a similar pattern, with the middle simulation being the base case. They show BOD_5 loads decreasing from 2003 to 2009 and increasing from 2009 to 2051. This implies that the model's general tendencies are robust across wide variations in the numerical estimates of uncertain parameters. Thus, the underlying structure of the model is robust. A model is robust when it generates the same general pattern despite the great uncertainty in parameter values (Ford, 1999). In contrast, the leaching rate from on-site sanitation systems is sensitive to the model output. The estimation of the degradation rate in the model has a big play in the model's output. This is explained by the high amount of readily biodegradable organic matter in the waste stream. Based on this result, the waste fluxes for the Nakivubo channel were calculated to improve the degradation rate estimate.

3.3.5 Waste management scenarios

Many environmental processes unfold over long time spans, which require assessments that look for 50 years or more to seek a new insight on how decisions taken today may affect the future. This can be explored by using scenarios. Scenario are plausible and often simplified description of how the future may develop based on a coherent and internally consistent set of assumptions (Monika and Henrichs, 2007). For this study, four urban waste management scenarios are developed. These are: 'Business-as-usual', 'More enforcement', 'More collection' and 'Proper management'. They are described below.

a) Business-as-usual

This scenario assumed that no additional mitigation measures are put in place to reduce the amounts of MSW generated, to prevent illegal dumping of MSW into the environment or to improve existing waste infrastructures. The MSW transported to a landfill continues falling from collection trucks, because of improper use of truck's covers to prevent the falling of MSW from the trucks. Also, there are no access roads in informal settlements for MSW collection trucks. The rates for MSW collection and OFMSW composting remain low. The on-site sanitation facilities in slums are poorly designed and operated resulting in faecal sludge overflow to the surrounding environment. The current environmental performances of the existing STW and leachate treatment plant (LTP) in reducing BOD_5, TN and TP in the influent are maintained. The respective influent BOD_5, TN and TP reductions by STW are 50%, 30% and 30%. The LTP's performances in reducing BOD_5, TN and TP are 60%, 40% and 60%, respectively. The fractions for BOD_5, TN and TP leached from on-site sanitation are 10%, 30% and 10%, respectively. The numbers of enforcement officers on the ground to ensure compliance of solid waste management ordinance and sanitation regulation are inadequate. Also, LC1s are not active in ensuring compliance of solid waste management ordinance and public health regulations at household level. The CBOs and NGOs have limited resources, and they are not supported by the public sector to effectively carry out waste management activities. The level of awareness on environmental and health benefits derived from resources recovery is low among the urban residents. Thus, this scenario continues the current status quo, as shown in Figure 3.11. The values for the flows for leaching from on-site sanitation, STW effluent and LTP effluent are calculated by the model. Therefore, the values for these flows are not indicated in Figure 3.11.

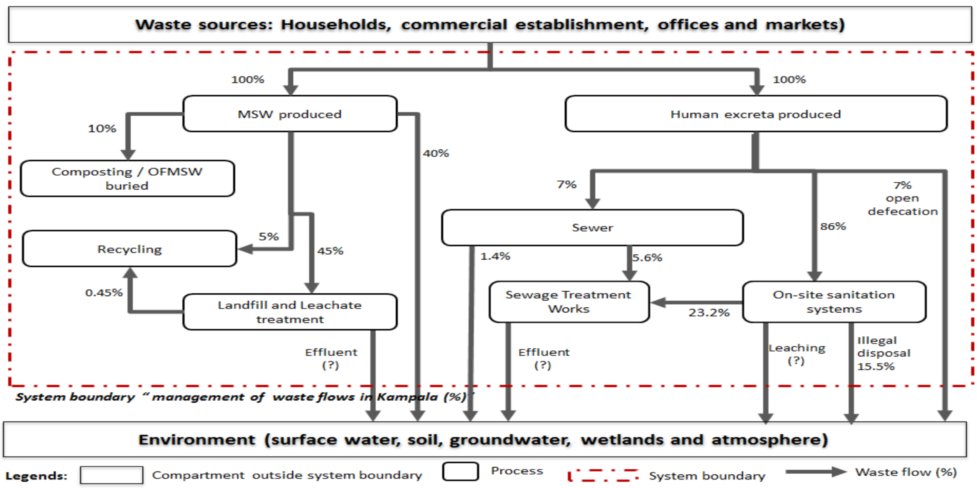


Figure 3.11. Urban waste flows in the 'Business-as-usual' scenario.

b) More enforcement

The 'More enforcement' scenario assumed that the existing solid waste management ordinance and public health regulations are enforced by 70%. In this case, the numbers of enforcement officers are increased by 30% to prevent any illegal MSW dumping into the environment, all houses within the radius of 60 m to a sewer are connected to sewers as per the National Public Health policy (MoH, 1964; MoH, 1995). This is to increase the amount of human excreta treated at the STWs. All on-site sanitation facilities are emptied in time whenever full. The performances for STW and LTP in reducing influent BOD_5, TP and TN, and the proportions for BOD_5, TP and TN leached from on-site sanitation are maintained as in the 'Business-as-usual' scenario. This strategy is calculated to reduce the amounts of MSW and human excreta flowing to the environment by about 45% and 15%, respectively. Additionally, the operational budget for LC1s is increased by 30% to ensure full implementation of solid waste management ordinance and sanitation regulations at household level. The LC1s are also to ensure prompt payment or physical participation by households in waste management. The organic materials used to package fresh foodstuffs brought to markets are reduced by 10% by use of fines. The level of awareness is enhanced by 15% more than in the 'Business-as-usual' scenario. As the amount of MSW disposed at collection points will increase, the numbers of skips and trucks to transport MSW are increased by 5% more than in the 'Business-as-usual' scenario. The skips are placed within walking distance from the houses to reduce illegal dumping of MSW. Also, MSW collection points are accessible by trucks. This scenario is illustrated, as shown in Figure 3.12. The flows' values for LTP effluent, STW effluent and leaching from on-site sanitation are calculated by the model, and their values are not indicated in Figure 3.12.

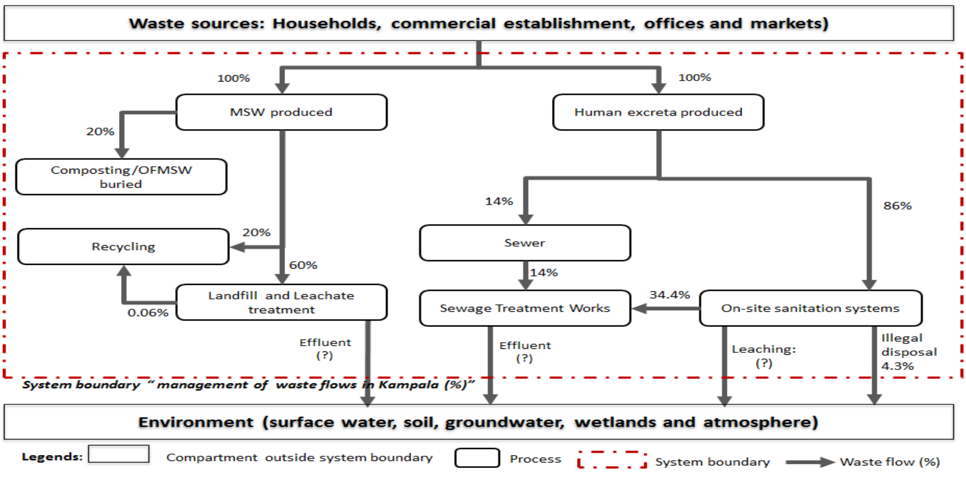


Figure 3.12. Urban waste flow in the 'More enforcement' scenario.

c) More collection

This scenario focused on collection and transportation of waste. It assumed that the collection and transportation of wastes is enhanced by 70%. Here, the quantities of skips are increased by 30% more than in the 'Business-as-usual' scenario, and they are positioned within walking distances for all residents without a door-to-door collection. The skips are emptied in time to prevent MSW overflows to the surrounding environment. The service coverage by PSPs is 20% more than in the 'Business-as-usual' scenario. The KCCA's trucks are assumed to serve the low-income residents and public places. Furthermore, the capacity of CBOs to collect MSW is enhanced by 10% by providing low cost tools such as wheelbarrows and animal drawn carts. The unlined pit latrines are replaced with properly designed and functioning pit-lined latrines, septic tanks and eco-san toilets. The LTP's performances in reducing influent BOD_5, TN and TP, and leaching rates for BOD_5, TN and TP from on-site sanitations are maintained as in the 'Business-as-usual' scenario. The STW's performances in reducing influent BOD_5, TP and TN are 65%, 60% and 60%, respectively.

The faecal sludge collection is increased by introducing light faecal sludge empting tools like vacutug and manual pit emptying technology (MAPET) for use in densely built-up areas. Also, neighbourhood or communal septic tanks systems are constructed such that multiple houses are connected to them. These communal septic tanks are constructed along roadsides, where vacuum trucks can empty them. Three faecal sludge treatment facilities are constructed to serve a population of about 150,000 people (NWSC, 2008). The effluent from the pond is discharged into the wetlands. The phosphorus and nitrogen in the effluent are partly taken up by wetlands' plants (Kansiime and Nalubega, 1999). The treated sludge is dried for about ten weeks and used as organic fertiliser (NWSC, 2008).

Given a high organic strength in faecal sludge (e.g. NH_3 level exceeding 2 g l^{-1}), anaerobic ponds - with or without prior solids removal in separate settling units - are considered a feasible option as primary units in pond treatment schemes in warm climate (Montangero and Strauss, 2002). Use of facultative ponds for faecal sludge treatment may often be impossible, because of the high ammonia levels in the sludge. Excessive ammonia concentrations impair or suppress algal growth, necessary for the operation of waste-stabilization ponds (Franceys *et al.*, 1992).

The composting of OFMSW and recycling of other recyclables is set to 10%. The level of awareness is increased by 10% higher than in the 'Business-as-usual' scenario. The enforcement is enhanced by 10% by increasing operational funds for LC1s. This scenario is as shown in Figure 3.13. The flows' values for leachate effluent, STW effluent and leaching from on-site sanitation to the water are calculated by the model, and so their values are not indicated in Figure 3.13.

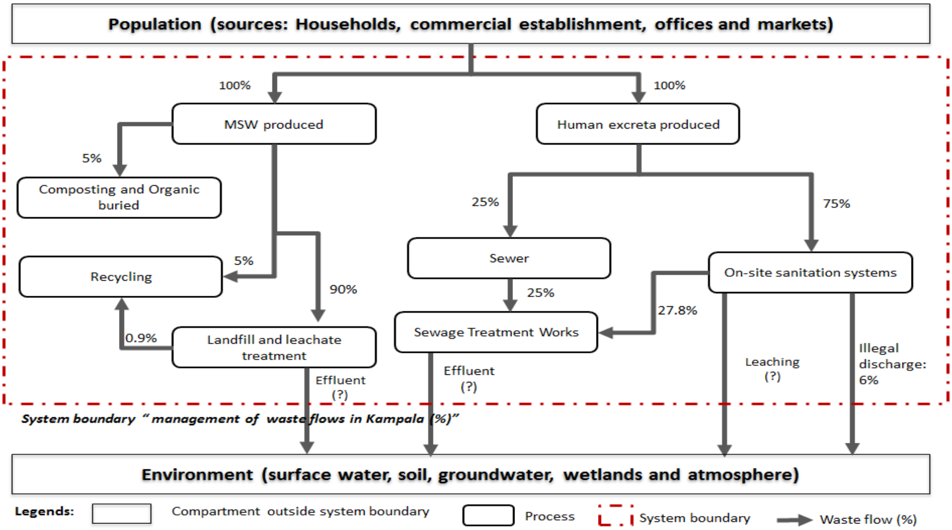


Figure 3.13. Urban waste flows in the 'More collection' scenario.

d) Proper management

Presented in Figure 3.14 is the waste flow for the 'Proper management' scenario. It is assumed that the technological enhancement is increased by 60%. Here, 50% of the technological enhancement is on increased implementation of aerobic composting technologies such as windrows (i.e. organic wastes are piled up in heaps or elongated heaps) and static piles. These technologies are open systems, and can be implemented at household level or community level. The OFMSW is co-composted with faecal sludge, and subsequently used as soil conditioners. The faecal sludge from on-site sanitation is mixed with two or three times its volume of OFMSW. It is turned several times in the first few weeks to keep it aerobic (Montangero and Strauss, 2002). The performance of existing waste treatment facilities is enhanced by 10%. Here, the STW's performances in reducing influent BOD_5, TP and TN are 70% each. The LTP's performances in reducing influent BOD_5, TP and TN are 90%, 80% and 80%, respectively. The fractions for BOD_5, TN and TP leached from on-site sanitation to the water are 10%, 30% and 10%, respectively. The numbers of enforcement officers to ensure compliance of solid waste management ordinance and sanitation regulations are increased by 20% higher than in the 'Business-as-usual' scenario. The level of awareness is enhanced by 20% compared to the 'Business-as-usual' scenario. The link between the low-income, and medium- and high-income groups established such that recyclables generated by medium- and high-income groups are collected by the low-income group at the sources of MSW generation, instead of salvaging from a landfill and skips. The current transport capacity is maintained. As illustrated in Figure 3.14, the flows' values for the LTP's effluent, STW's effluent and leaching from on-site sanitations to the water are not provided. These values are calculated by the model.

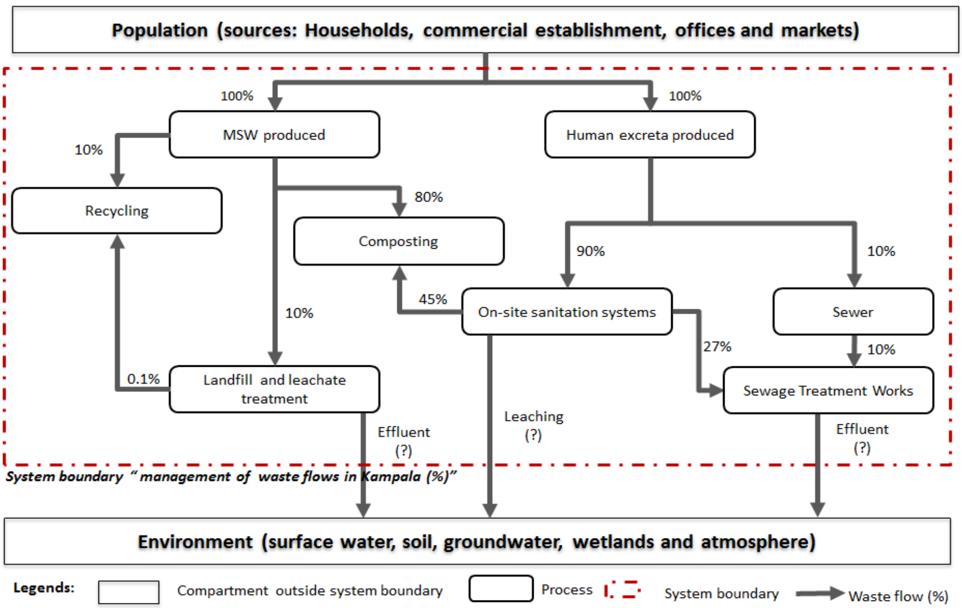


Figure 3.14. Urban waste flow in the 'Proper management' scenario.

3.3.6 Scenarios results

The analysis of the results for the scenarios for Kampala and Dar es Salaam cities are discussed below.

a) Kampala

Table 3.7 provides the outputs for the four scenarios with the BOD_5, TN, and TP loads to the environment and MSW disposed in a landfill measured as wet weight. The compost produced is estimated as dry weight, based on assumption that organic waste contain about 50% water content (Montangero and Strauss, 2002).

Table 3.7. Simulation outputs for the four scenarios by 2052.

Parameter	Unit	Business -as-usual	More Enforcement	More collection	Proper management
Total BOD_5 Load to environment	Mt	310	192	230	150
Total TN Load to environment	Mt	8	4	2	6
Total TP Load to environment	Mt	3	2	2	2
Total compost produced	Mt	1,100	3,850	2,550	11,000
Total MSW landfilled	Mt	130	2,200	300	44

The ‘Business-as-usual’ scenario shows the highest BOD_5, TN and TP loads to the environment. This is attributed to indiscriminate dumping of MSW, illegal discharge of faecal sludge, sewage overflows and leaching from unlined pit latrines. The indiscriminate dumping of MSW and illegal faecal sludge disposal is because of inadequate numbers of enforcement officers to ensure compliance of solid waste management ordinance and sanitation regulations. For example, the Public Health Act (1964) states that every house must have a toilet, but this is not the case on the ground (MoH, 1964). The ‘Proper management’ scenario shows the smallest BOD_5 and TP loads to the environment. This is explained by the high compost production owing to increased implementation of composting technologies.

The projected future trends for the four scenarios are presented in Figure 3.15. Parameters of the different scenarios are plotted on the same graph so as to compare the effect of the different strategies assumed in the scenarios.

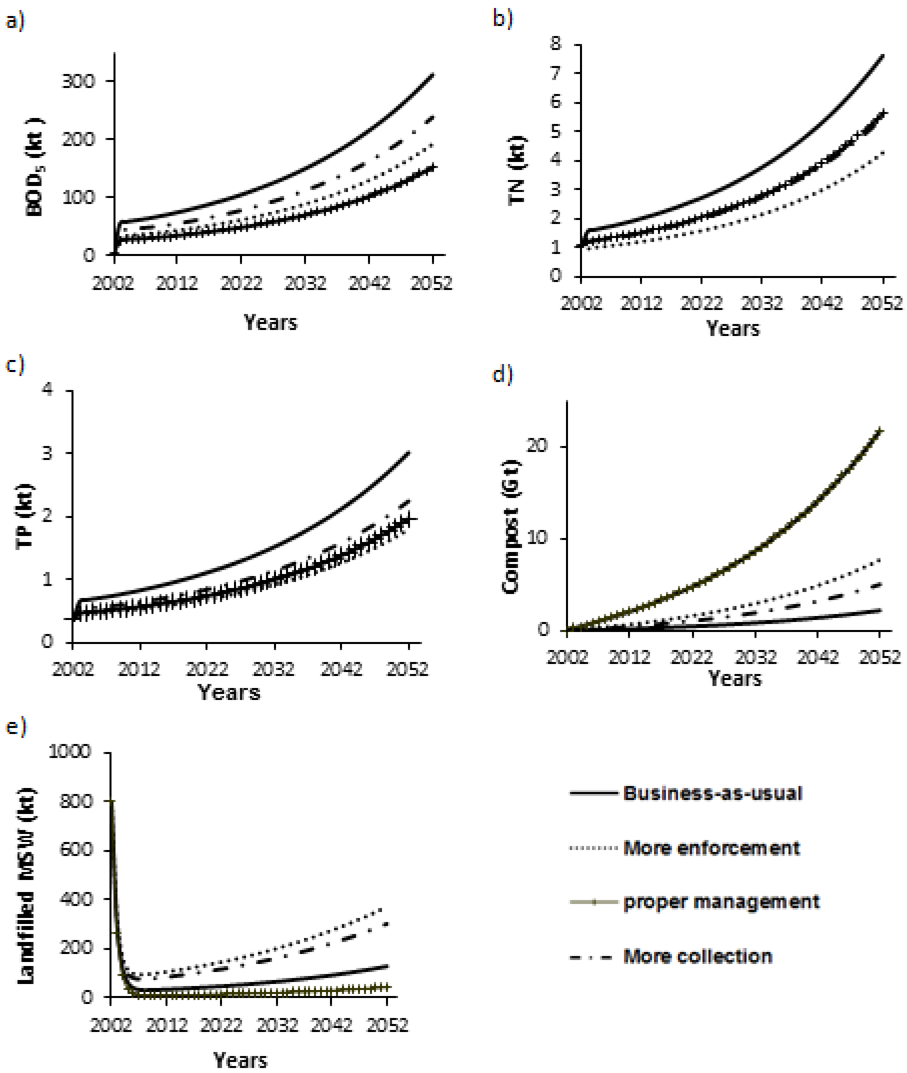


Figure 3.15. Simulation plots for Kampala City, a: BOD_5; b: TN; c: TP; d: compost; e: MSW Landfilled.

The estimated total BOD_5 loads after 50 years in the ‘Business-as-usual’ scenario increased by 370% compared to the year 2008 BOD_5 loads. This is attributed to an increase in population size coupled with inadequate mitigation measures to halt the increasing environmental loads. But the accumulated quantity of MSW disposed in a landfill by 2052 is less than the designed capacity (2 Gt). This is explained by the rapid breakdown of readily biodegradable OFMSW that constitutes the highest fraction (i.e. 83%) in the MSW composition. Additionally, the BOD_5, TN and TP loads to the environment by 2052 will be 30 times more than the present state (i.e. year 2008). This will have severe negative consequences on the environment and human health. Also, the scenario shows that, the amount of compost produced by 2052 is low compared to the amount of OFMSW generated, because of the low level of peri-urban agriculture.

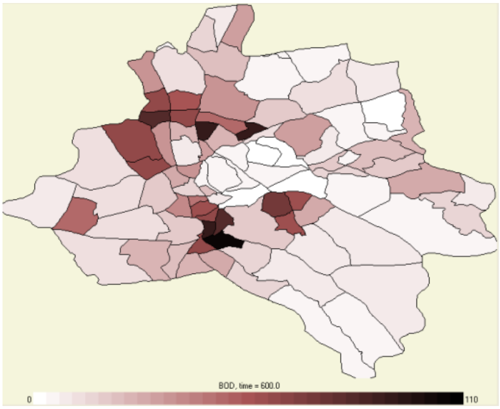
The 'More enforcement' scenario shows a BOD_5 load reduction to the environment by about 40% compared to the 'Business-as-usual' scenario. This is because of increased numbers of enforcement officers and active participation by LC1s in ensuring environmental compliance. Strong enforcement of an effective policy and legal framework leads to reduced indiscriminate dumping of MSW and illegal disposal of human excreta to the environment. This requires availability of appropriate technologies that are economically affordable, environmentally effective and socially acceptable, to implement waste management activities. This scenario also shows increased amounts of compost produced and MSW disposed in a landfill. The increased amount of MSW disposed in a landfill fills a landfill within four years, resulting in more need for land for expansion purposes. This makes treatment of MSW by a landfill expensive because of the appreciating land value.

The 'More collection' scenario estimated 26% reduction of accumulated organic loads in the environment by 2052 compared to the 'Business-as-usual' scenario. This is because of the increased numbers of skips, use of wheelbarrows and animal-drawn carts to collect MSW in densely built-up areas, and increased coverage by PSPs. The use of MAPET and vacutug to empty faecal sludge in densely built-up areas, and construction of three additional faecal sludge treatment plants also explain the reduction in environmental loads. Moreover, the involvement of CBOs and NGOs in MSW collection and recycling activities reduce the environmental loads. This however would require an awareness campaign to ensure active involvement by the public in waste management. In comparison to the 'More enforcement' scenario, this scenario registered a lower reduction of organic load to the environment. This is because the 'More enforcement' scenario focused on reducing illegal disposal of MSW that accounts for about 40% of the total MSW generated.

The 'Proper management' scenario shows that by 2052 the total BOD_5 load over 50 years is reduced by about 51% compared to the 'Business-as-usual' scenario. This is attributed to increased implementation of co-composting technologies, increased removal of faecal sludge from densely built-up areas and increased access to toilets by the growing slum population. This increased compost matches well with the promotion of urban agriculture and/or transportation of the compost to rural farmland. However, compost produced from MSW is often of low quality because of presence of toxic substances (Massoud *et al.*, 2003). This can affect its acceptability for food crop production. The level of toxic substances in compost can be reduced by implementing waste sorting. This can be done by bringing facilities for waste recovery closer to the sources of waste generation to encourage households to sort their wastes (Curran *et al.*, 2007). Additionally, decentralising composting to household level and promoting urban/peri-urban agriculture would encourage households to sort their wastes. The composting can be by windrows composting method or establishment of small-scale composting enterprises in the parishes. The latter is applicable for densely built-up areas. The composting enterprises can be motivated by paying them for each ton of OFMSW diverted from the landfill. Finally, to convince people of the importance of investing in their sanitary facilities, education and training programs should be provided to them, their living conditions should be improved and settlement permission should be provided by the responsible authorities.

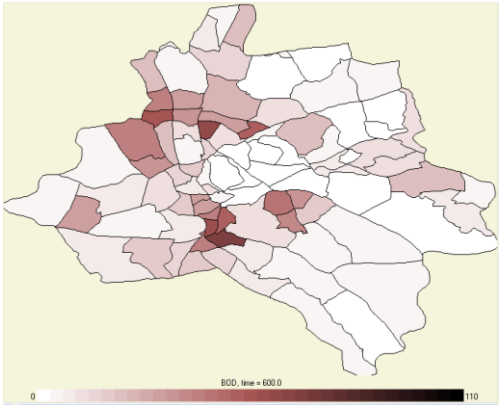
Presented in Figure 3.16 is the spatial BOD_5 load intensity at parish level for the four different scenarios. The spatial plots (Figure 3.16) show that the BOD_5 intensity in the 'Business-as-usual' scenario ranges from about 0.5 to 110 t ha^{-1}. Parishes that have effective MSW collection and sewerage collection and treatment systems registered low BOD_5 intensity. Also, parishes with low population show low BOD_5 load intensity because of low amounts of urban waste per ha. However, parishes occupied by low-income earners show high BOD_5 intensities because of inadequate MSW and illegal discharge of faecal matter to the environment. More so, these parishes have mainly unlined pit latrines that can have their content leaching easily into the groundwater. This high BOD_5 intensity indicates the need for increased provision of sanitary facilities and MSW collection and treatment facilities. The 'More enforcement' scenario shows a reduction in BOD_5 load intensity across the parishes in the range of approximately 0.5 to 68 t ha^{-1}. The 'More collection' scenario indicates a BOD_5 load intensity ranging from approximately 0.7 to 86 t ha^{-1}. The ‘Proper management’ scenario demonstrates the best results with a BOD_5 intensity ranging from approximately 0.5 to 50 t ha^{-1}.

a)



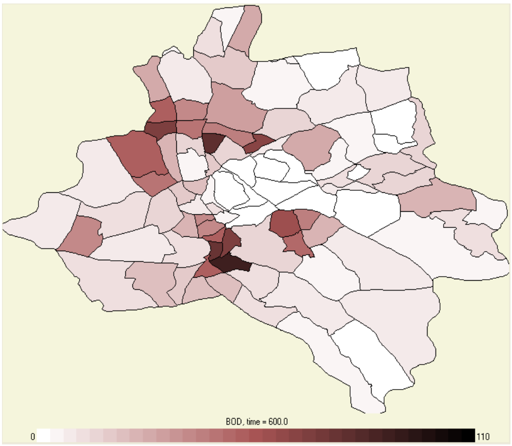
Business-as-usual (BOD_5 0.5 - 110 t ha^{-1})

b)



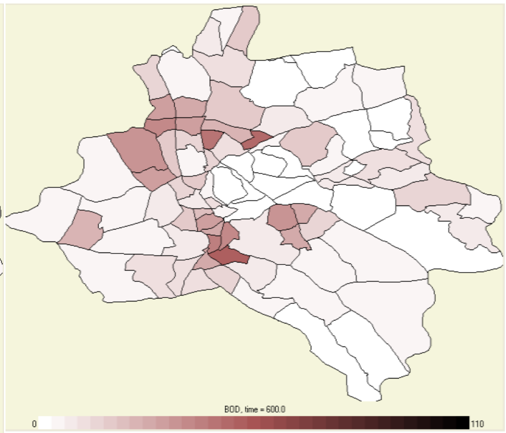
More enforcement (BOD_5: 0.5 - 68 t ha^{-1})

c)



More collection (BOD_5: 0.7 - 86 t ha^{-1})

d)



Proper management (BOD_5: 0.5 - 50 t ha^{-1})

Figure 3.16. BOD_5 spatial distribution maps for Kampala City, a: ‘Business as usual’; b: ‘More enforcement’; c: ‘More collection’; d: ‘Proper management’.

b) Dar es Salaam City

The scenarios formulated for managing waste flows for Kampala were also simulated for Dar es Salaam. The plots of the scenarios are, as shown in Figure 3.17.

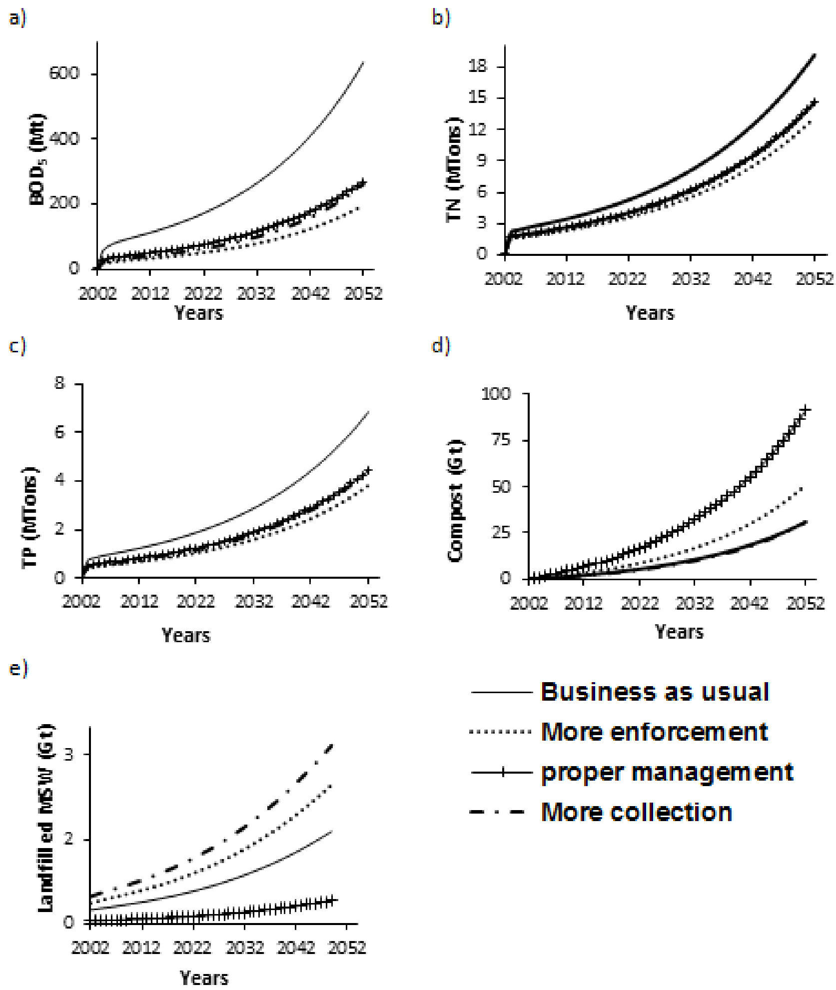


Figure 3.17. Simulation plots for Dar es Salaam City (a: BOD_5; b: TN; c: TP; d: compost; e: MSW Landfill).

The plots show that with no measures put in place to reduce waste production, to increase waste collection rate and treatment efficiency, the BOD_5 load to the urban environment will increase, as shown in the 'Business-as-usual' scenario. The 'More enforcement' scenario indicates a major reduction of organic load to the environment by 2052 because of reduced illegal dumping of MSW. This also explains the increased amount of MSW disposed in the dump sites compared to the 'Business-as-usual' scenario. The 'Proper management' scenario shows a significant reduction of organic load to the environment and of MSW disposed in the dump sites as compared to the 'Business-as-usual' and the 'More collection' scenarios. Also, compost production was high, resulting in increased organic recycling.

In comparison to Kampala, the plots are similar except for the indifference of outputs for the 'More collection' and 'Proper management' scenarios for Dar es Salaam (with respect to BOD_5, TP and TN). This is because the problem associated with MSW management in Dar es Salaam is because of illegal dumping of MSW into the environment. Hence, 'More enforcement' scenario explains the higher reduction in the environmental loads when compared to the other scenarios.

3.4 Conclusion

This study shows the use of system dynamics modelling to understand and project the future waste flows and their environmental impacts in East African metropolises. Presently, waste flows in Kampala and Dar es Salaam are poorly managed with little formal resource recovery from the waste streams. The 'Business-as-usual' scenario shows that with no additional measures put in place to improve waste management in both Kampala and Dar es Salaam cites, the waste management situation rapidly deteriorates, with negative consequences for human health and the environment. The 'Proper management' scenario that integrates increased implementation of co-composting technologies of OFMSW with faecal sludge, increased waste collection, increased numbers of enforcement officers and increased awareness-raising, provides the best strategy to improve the urban environmental quality, as well as resources recovery. The 'More enforcement' and 'More collection' scenarios reduced the negative impacts on the environment but they performed less well in resource recovery. Thus, to improve the urban environmental quality and increase resource recovery, the city authorities, NGOs, CBOs and the general public would have to increase their efforts and involvement. It is also noted that with this modelling approach, it is possible to understand the behaviour of a complex system such as the waste management with limited available data. However, there are limitations in the predicted values since the scenarios are based on assumptions that may change. Hence, the scenario results just show the probable paths that can be followed if the assumptions in those scenarios are implemented.

Acknowledgment

This paper was prepared in the framework of the PROVIDE, and funded by the INREF of Wageningen University, the Netherlands.


MERCUR

Chapter 4 Determining an optimal waste management scenario for Kampala, Uganda[5]

Abstract

The state of environmental quality in Kampala City is deteriorating. The city needs a novel waste management approach to improve the environmental quality in its heterogeneous settlement patterns. Earlier, an integrated dynamic waste flow model was applied to project the future waste flows and their impacts on the environment of Kampala, using four waste management scenarios. These scenarios were 'Business-as-usual', 'More enforcement', 'More collection' and 'Proper management'. The robustness of the scenario results was determined using a Multi-Criteria Decision Analysis approach. Twenty-four criteria were identified and grouped as environmental, economic, social, technological and general. Equal weights were assigned to these five sets of criteria. The four scenarios were evaluated against all criteria, and a sensitivity analysis was performed on the role of the equal weights on the choice of the scenarios. The results showed that the 'Proper management' scenario, which integrates diverse technologies and management programs matching with the local context, is the most optimal approach to improve Kampala's environmental quality. Scenarios that emphasized more on waste collection but less on resource recovery were ranked middle. The scenario maintaining the status quo performed worst. Application of a mix of diverse local technologies and management programs, and matching with the settlement patterns is the most optimal solution to improve Kampala's urban environmental quality.

Key words: Municipal solid waste; faecal sludge; urban waste; multi-criteria; scenario; East Africa.

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[5] This paper has been published as: Oyoo R, R. Leemans and A.P.J Mol (2013). Determining an optimal waste management scenario for Kampala, Uganda. *Waste Management & Research, 31 (12) 1203-1216*

4.1 Introduction

The increasing waste flows and their management has become a pressing issue to city authorities in developing countries. The informal settlements are characterised by heaps of uncollected MSW in their neighbourhoods and illegal discharges of faecal sludge into storm surface water drains. This degrades the urban environment and poses public health risks (Patel *et al.*, 2010).

Kampala, the capital city of Uganda is typical in this context, as it faces the aforementioned waste management problems. MSW collection is inadequate, as the cost of the transporting fleet makes up a very high share in the available MSW management budget (KCC, 2006). The city exhibits a wide disparity in settlement patterns between the high- and low-income households. This implies that no single waste management solution is adequate to collect and treat all the generated wastes in the city. Having robust waste management systems that integrates a mix of different technologies, economies and socio-political dimensions, matching with the physical and human systems for a specific local condition, would be the appropriate system for managing waste flows in such a city. Such solutions are often referred to as Modernised Mixtures (Scheinberg and Mol, 2010; Scheinberg *et al.*, 2011). Viable waste management solutions should comply with environmental, technological, social and economic factors (Morrissey and Browne, 2004). It is possible to assess such solutions using a dynamic model to project the future waste flows and their environmental impacts.

Earlier, projections for waste flows and their impacts for Kampala were simulated for four waste management scenarios using an IUWFM (Oyoo *et al.*, 2011). This model integrates waste flows from generation up to final disposal and their environmental impacts. It is driven by the local population growth and influenced by technological development, awareness enhancement and regulation enforcement. The environmental impacts are estimated by the BOD_5, TN and TP loads. These three parameters indicate water quality level. They are part of the water quality standards for regulating effluent from STWs (NEMA, 1999).

The four scenarios evaluated were 'Business-as-usual', which represents the status quo; 'More collection', which lays more emphasis on technological enhancement in the local MSW and human excreta management; 'More enforcement', which emphasises the enforcement of regulations; and 'Proper management', which integrates a mix of diverse technologies, awareness enhancement and regulation enforcement. The IUWFM results for these scenarios were only defined in terms of environmental effects. However, there was also a need to appraise them against multiple criteria, as waste management systems are too complex to be understood and assessed in one dimension. A multi-criteria decision analysis (MCDA) was applied to evaluate the four scenarios against a range of environmental, economic, social, technological and general criteria.

The MCDA is used to analyse complex problems featuring high uncertainty, conflicting multidimensional objectives and different data types, leading to robust solutions (Morrissey and Browne, 2004; Crown, 2009). It has been applied, among others, in agricultural (Havlikova and Kroeze, 2006; Hajkowicz, 2007), industrial (Zopounidis, 2009), technology (Chiadamrong, 1999; Chan *et al.*, 2000; Bollinger and Jacques, 2008), energy (Akash *et al.*, 1999) and waste management (Kapepula *et al.*, 2007; Generowic *et al.*, 2011) studies. It has also been applied to compare waste management scenarios for Sydney, Australia in conjunction with a life cycle analysis (LCA) tool (El Hanandeh and El-Zein, 2010). In this study, MCDA was applied to evaluate the four waste management scenarios to verify the robustness of the results obtained using an IUWFM. This innovative approach provides a rapid appraisal of scenarios under limited time and resources, facilitating quick selection of an optimal waste management system for developing countries' cities in which the available resources are often inadequate for data collection. We assessed the robustness of the IUWFM's results for the waste management scenarios in Kampala with regard to economic, environmental, technological, social and general criteria. The results should also be applicable to other similar large and medium size East African cities.

4.2 Method

4.2.1 Scope and characteristics of the field of study

The selected scope of this study is the management of both the MSW and human excreta within the administrative boundary of Kampala City. By 2002, the city had a population of about 1.2 million with an annual growth rate of 3.8% (UBOS, 2007). This gives a projected population of 1.7 million in 2011. The MSW generation rate is about 0.59 kg capita^{-1} day^{-1} (Oyoo *et al.*, 2011) and is comparable to other developing countries' cities but is modest when compared with developed countries' cities (Collivignarelli *et al.*, 2010). The MSW composition is typical of developing countries' cities (Table 4.1). The OFMSW is high, which means very dense waste and high moisture content, as opposed to relatively less dense waste with low OFMSW in developed countries' cities. High amount of OFMSW may suggest that composting should be seen as a 'baseline' technology rather than landfilling. Currently, landfilling is the only authorised MSW disposal method, but open dumping, open burning, recycling and composting are also practiced to unknown extents. About 45% of MSW generated is disposed in a landfill, and only 11% of recyclables are informally recovered daily (Oyoo *et al.*, 2011).

Table 4.1. Municipal solid waste composition values for Kampala City.

Category	Composition (% in wet weight)
OFMSW	83
Plastic	7
Paper and board	5
Construction	2
Glass	1
metal	1
Textiles	1
Total	**100**

Source: (Oyoo *et al.*, 2011)

The sanitation solutions used are off-site, on-site and open defecation. The estimated proportions of these sanitation systems are: 86%, on-site; 7%, off-site; and 7%, open defecation (UBOS, 2006). About 27% of faecal sludge from on-site sanitation is trucked to the BSTW daily (Oyoo *et al.*, 2011). The on-site sanitation facilities located in densely populated slums are never emptied by trucks because of vehicular inaccessibility. These facilities are emptied manually by scavengers, and their contents discharged into storm surface water drains or buried in unlined pit. This pollutes the groundwater and surface water quality.

4.2.2 Establishing multi-criteria decision analysis

Multi-criteria decision analysis is a powerful tool for evaluating a complex system. It was selected to evaluate the four waste management scenarios because of its capability to handle complex problems involving economic, social, environmental, general and political objectives (Ekmekçioĝlu *et al.*, 2010), which are typically found in waste management systems. It also assesses both qualitative and quantitative data without the need to convert them to the same unit (Hajkowicz, 2007).

The steps involved in MCDA are: (1) identifying the problem, (2) formulating scenarios, (3) identifying criteria, (4) assigning weights to criteria, (5) scoring scenarios against selected criteria, (6) computing performances for scenarios, (7) examining results, (8) conducting a sensitivity analysis on selected criteria weights and (9) taking decisions (Crown, 2009). In this study, only steps 3 to 9 were performed. Steps 1 and 2 are a part of a scenario analysis established in the previous study by Oyoo *et al.* (2011). The rest of the steps are described below including the summary for the scenarios formulated in Chapter 3.

a) Waste management scenarios

Four waste management scenarios are appraised against five sets of criteria. The four scenarios were previously assessed using IUWFM. The assessment results showed that if no additional mitigation measures are put in place to improve waste management in Kampala, the environmental quality in Kampala would increasingly deteriorate. If 'More collection' or 'More enforcement' scenarios would be applied, the result would be a good reduction in environmental loads but with a few resources recovered. Applying 'Proper management' scenario integrating a mixture of diverse local waste technologies and management programs matching with the different spatial settlement patterns and local context would produce small environmental loads and recover a large amount of resources (Oyoo *et al.*, 2011). The scenarios assessed are:

1. *Business-as-usual:* represents the current status quo.
2. *More enforcement:* represents enforcement of sanitation regulations enhanced by 70%. Here, 30% increased numbers of enforcement officers, 30% increased monetary operational budget to LC1s to enforce public health regulations at households, and 10% reduced OFMSW from packaging materials for foodstuffs brought to markets by charging an environment tax on fresh foodstuffs transporters. Awareness-raising and waste collection tools each increased by 15% as compared to 'Business-as-usual' scenario. The numbers of skips and trucks for MSW collection increased by 5%. It is anticipated that the amounts of MSW and human excreta flows to the environment would be reduced by about 45% and 15%, respectively.
3. *More collection:* represent waste collection and transportation to disposal sites enhanced by 70%. Here, 20% increased collection tools, 20%

increased service coverage by private service providers, and 30% increased faecal sludge collection and sewage treatment lagoons. Awareness-raising and regulation enhancement each increased by 15%, higher than in the '*Business-as-usual*' scenario. The enforcement of MSW ordinance is enhanced by 10% by provision of additional funds to LCs and Public Health Officers. It is anticipated that MSW and human excreta loads to the environment would be reduced by about 86% and 85%, respectively.

4. *Proper management:* represents mixture of diverse treatment technologies and different management regimes matched and optimised with the specific local conditions. Technology is enhanced by 60%; here 50% is for new technologies such as anaerobic digesters and waste recyclers, and 10% increased performance of existing waste treatment systems. Numbers of enforcement officers and awareness raising each increased by 20% compared to the *'Business-as-usual'* scenario. It is anticipated that, about 80% of resources would be recovered from waste and waste flow to the environment would be reduced by 90%.

b) Criteria selection

Decision making in waste management system is a complex process, partly because it requires the consideration of multiple criteria, which may conflict with each other. For example, locating a new site for a landfill at minimal cost is feasible, but it could compromise groundwater quality protection. The selection of criteria can be done through stakeholders' interviews and literature reviews (Garfì *et al.*, 2011).

The latter was applied for this study. Twenty-four criteria were selected and grouped as economic, environmental, social, technological and general criteria. This was done to aid the process of checking whether the selected criteria were appropriate to the problem, to ease the calculation of criteria weights as the number of criteria was high, to facilitate the scoring of the scenarios on the criteria and to examine the overall results at the level of the objectives. These criteria were assessed on their usefulness, measurability, completeness, avoidance of redundancy, prevention of double counting and mutual independence of preferences (Crown, 2009).

The selected criteria are explained below in five different groups.

(1) Economic criteria

Economic criteria are often not only expressed as the cost of the system but can also include impacts of the system on the local economy (van Buuren, 2010). The selected economic criteria for this study are operations, maintenance and investment costs, which specify the costs of the system and less so, the economic impact on the local economy.

i) Operations and maintenance costs

This refers to the funds spent on waste management activities such as collection, transportation and treatment, and services and repairs done on equipment to ensure their continuity. This cost is important for the sustainability of waste management systems (Panagiotis *et al.*, 2009). Waste management systems with high operations and maintenance costs are unsustainable where the available operational budget is limited. The operations costs are measured by fuel usage and wages. These indices change with fleet size, and they can discriminate between the four scenarios. The higher the fleet size, the higher the fuel usage and wages required to operate the fleet. Fuel usage is also linked to CO_2 emissions, which are a part of the environmental criteria. However, since CO_2 emissions reduction due to decreased fuel usage is a non-monetary benefit, it is assumed to be an economic criterion to avoid double counting. Double counting should be avoided, because then indicators are likely to be given more weight in the overall decision than merited (van Buuren, 2010).

ii) Investment costs

Investment costs comprise the purchase of land and vehicles, to install treatment facilities and transport the waste to treatment sites. Waste treatment facilities require land space of varying size. For example, small-scale on-site systems use less land space than large-scale centralised systems. High land requirement implies more costs to establish the waste facility. During the installation, operations and closure phases of a waste facility, the landscape can be negatively impacted. This causes land to fall under environmental criteria. However, since the prevention of impacts from waste treatment installation on the landscape is a non-monetary benefit, land is considered an economic criterion.

Similarly, vehicles are chosen, because the larger the waste volume, the greater the capacity in terms of vehicles required to ensure that all wastes are collected.

On-site or semi-centralised waste treatment systems require the transportation of waste from them to disposal sites only when they are filled, unlike large-scale centralised off-site systems, where wastewater is conveyed to STWs by sewers.

(2) Environmental criteria

The environmental criteria are important for protecting the environment from pollution and conserving natural resources for the current and future generations. The environmental criteria selected are as follows.

i) Prevention of emissions to surface water

The impact of emissions on surface water is measured by the BOD_5, TN and TP levels. These indicators best measure the impacts of waste on surface water quality, and they can qualitatively discriminate between different waste systems. For example, anaerobic digesters do not release TP and TN into the water, because they are sealed off, and so, they score higher in the emission prevention than does a centralised conventional sewerage system (van Buuren, 2010).

ii) Prevention of emissions to the soil and groundwater

The prevention of emissions to the soil and groundwater is linked to the pollution by waste facilities. It is selected, because groundwater is a potable water source for the majority of low-income households in Kampala and also in other developing countries' cities. It can discriminate groundwater quality difference among the four scenarios. For instance, landfilling has a higher pollution potential impact on groundwater than composting treatment. When considering the efficiency of waste systems in preventing groundwater pollution, this criterion falls under technological criteria. But it is considered an environmental criterion to avoid double counting.

iii) Prevention of emissions to air

The prevention of emissions to the air is measured by the levels of NO_x [NO_x is a generic term used for nitrogen monoxide (NO) and nitrogen dioxide (NO_2)], CO_2 and CH_4 emitted. These indicators express the impact of the different waste systems on the environment in the best way, and they can differentiate among the four scenarios. NO_x emissions react with NH_3 and volatile organic carbons (VOCs) to form toxic products that can cause health problems. This causes NO_x to be considered a social criterion. NO_x is also emitted from vehicles, contributing to local air pollution, and it is thus considered an environmental criterion as well.

Similarly, the amounts of CO_2 and CH_4 emissions depend on the waste systems. For example, landfilling unsorted MSW emits higher amounts of CO_2 and CH_4 than composting or properly sealed anaerobic digestion (Gomes *et al.*, 2008). During waste transportation, CO_2 is also emitted from fossil-fuel combustion, which is a part of economic criteria. However, here CO_2 emission is assumed to be due to breakdowns of OFMSW, making it an environmental criterion.

iv) Resource Recovery

The indices for resource recovery are energy generation, and nutrients and recyclables recovery. The nutrients and recyclables recovery refers to valuable waste materials that can be recovered from waste. The energy generation refers to the potential amount of energy that can be recovered by a waste disposal method (Ekmekçioĝlu *et al.*, 2010). These indicators are selected because of the increasing need for resource conservation. Waste systems that recover more materials are more environmentally sustainable than those that mainly dispose of waste. Effective resource recovery would lead to a financial benefit, and, thus, make this criterion fall under economic criteria. But, since financial accounting does not completely express the value of recovered resources, the resource recovery is assumed to be an environmental criterion (van Buuren, 2010).

(3) Technological criteria

Proper technology is essential for the success of waste management systems. The technological criteria selected are as follows.

i) Reliability

Reliability is an indication of the sensitivity of the process to malfunctioning equipment (Gumbo, 2005). The sensitivity to irregular maintenance and dependence on external supplies and services are the indicators selected for reliability. Usually, in developing countries, irregular maintenance is common, so sensitivity to irregular maintenance can distinguish among the four scenarios. Technologies that are sensitive to irregular maintenance, for example, sewerage systems with a high risk of clogging, because of the transportation of solids and intermittent water supply, are less reliable than on-site sanitation like septic tanks and pit latrines. On-site sanitation like septic tanks can withstand long periods without maintenance, since the solids are removed after septic tanks are filled up.

The dependence on external suppliers and services includes assessment of energy, chemicals, spare parts and maintenance services. This criterion is important for developing countries in which available operational funds are limited for managing waste systems. Waste systems that depend on external supplies and services like conventional STWs are less reliable than septic tanks, which do not depend on external supplies.

ii) Flexibility and adaptability

The flexibility and adaptability refers to efforts rather than costs needed to modify waste technology when new conditions are set because of increasing or decreasing capacity and in anticipation of legislative changes. It is assessed by the easiness to adapt to new requirements, which refers to the efforts required to adapt a system to a new condition. Developing countries' cities often have very limited operational budgets available; therefore, easiness to adapt to new requirements is vital for discriminating viable waste technologies. For example, on-site or community-scale waste treatment systems are more adaptive to new requirements than large-scale treatment systems.

(4) Social criteria

Social criteria are important, because the acceptance of waste management systems by end-users is paramount in having a resilient and sustainable system. The social criteria selected are as follows.

i) Institutional support

Institutional support refers to the involvement of public sectors in ensuring the smooth operations of waste systems. In developing countries' cities, waste systems that require low institutional support are vital because of limited available operational funds, as opposed to developed countries' cities. Some waste systems require much more institutional support for their success than others, and so, institutional support can distinguish among the four scenarios. For example, centralised waste systems need more institutional support than semi-centralised or on-site waste systems.

ii) Awareness-raising to end-users

This concerns the training of the end-users and familiarizing them with the technologies used, to ensure their sustainability. It is selected, because different waste management systems differ in their operations and maintenance. Some waste management systems require a permanent effort made towards increasing awareness, and are thus, less manageable than waste management systems that need less effort. Awareness-raising may also be required if the system requires special attention. For example, discharging toxic substances into anaerobic digestion can pollute digestate, making them unusable as organic fertiliser.

iii) Community involvement

Community involvement is related to the active participation of communities in the operations of waste systems. It is selected, because some waste systems need community participation to ensure their success. This criterion can therefore, distinguish among the four scenarios. For example, waste systems that involve source sorting require higher community involvement than mixed waste systems.

iv) Job creation

Job creation refers to the potential job opportunities offered by the waste systems to the local community. It is chosen because of the high unemployment rate in cities in developing countries. A waste management system that employs many people is more beneficial to the community for improving their living conditions than a waste management system that employs very few people. If staff wages are considered, then job creation would fall under economic criteria. More employees not only make a service that is higher in wage costs, but also indicate that the applied technologies are less technology intensive, therefore, less prone to failure due to lack of maintenance. Of course, the number of employees should then be viewed in terms of company size.

v) Public health

Public health is an aspect of social progress that may fall under technological criteria. But all waste systems are designed with the aim of health protection and the promotion of hygiene, implying that public health as a technological criterion cannot discriminate between waste systems (van Buuren, 2010). Public health is placed as a social criterion, because the end-users and their social practices are directly influenced by public health quality. The indicators for public health criterion are prevention of health risk exposure to users and waste workers.

Though waste management systems are designed to prevent exposure of health risks to users and workers, not all waste systems are equally adequate in this respect. The level of adequateness is qualitatively measured as risk of exposure to health hazards by users and waste workers. For example, anaerobic digestion of human excreta and OFMSW has a higher health risk to users than centralised off-site treatment of wastes. Also, waste systems that combine all MSW streams together have a high potential of causing harm to waste workers.

(5) General criteria

The general criteria are important for the working environment and institutional framework under which the scenarios are to be implemented and operated. The general criteria selected are as follows.

i) Requirement for legal authorization

The requirement for legal authorization is related to legal instruments and incentives that facilitate the implementation of waste management systems. Some waste management systems require incentives and legal support to ensure their success. For instance, anaerobic digestion of human excreta and OFMSW with reuse would require incentives in the form of subsidies and the application of the 'polluter pays principle' to encourage waste sorting. Such legal requirements make it possible to differentiate among the four scenarios.

ii) Time and ease of implementation

This refers to the time needed to implement the waste program. Different waste systems have different durations to implement them because of differences in complexity. For example, large-scale centralised waste systems require a longer duration for implementation than decentralised or semi-centralised waste management systems. In this case, a shorter duration implies a higher score.

All the selected criteria described above including their preference directions are summarized in Table 4.2. The preferred directions refer to the desired performance of the criteria in assessing the scenario. For example, low fuel usage is desirable, whereas high fuel usage is undesirable. This implies that the lower the fuel usage in a given scenario, the stronger the preference.

Table 4.2. Criteria selected for evaluating the scenarios.

Set of Criteria	**Criteria**	**Weights (%)**	**Preferred direction**
Economic		20	
Operation and maintenance cost	Fuel		Low
	Maintenance		Low
	Wages		Low
Investment cost	Land		Low
	Vehicles		Low
Environmental		20	
Prevention of emissions to surface water	BOD_5		Low
	TN and TP		Low
Prevention of emissions to air	CO_2		Low
	NO_x		Low
	CH_4		Low
Prevention of emissions to soil and groundwater			Low
Resource recovery	Energy generation		High
	Nutrient and recyclables		High
Technological		20	
Reliability	Sensitivity to irregular maintenance		Low
	Dependency to external supplies and services		Low
Flexibility	Ease to adapt to new conditions and requirements		High
Social		20	
Institutional support			Low
End-users awareness			Low
Community involvement			High
Job creation	Number of people employed		High
Prevention of Health risks exposure	Prevention of exposure of health risks to users		High
	Prevention of exposure of health risks to workers		High
General		20	
Legal authorization	Number enforcement officers		Low
Time and ease of implementation	Duration		Low

BOD_5: five-days biological oxygen demand; TN: total nitrogen; TP: total phosphorus; CO_2: Carbon dioxide; NO_x: nitrogen monoxide + nitrogen dioxide; CH_4: methane

c) *Scoring and weighting*

Scoring involves the assessment of the expected consequences of a scenario against selected criteria. The scoring of each scenario happens by assigning a numerical score on each criterion related to the preference scale. A more preferred scenario scores higher on the scale, and a less preferred scenario scores lower. In this study, questionnaires were distributed to twelve individuals to score the four scenarios against the twenty four criteria. The twelve people were randomly selected, and they were asked to fill in the questionnaires as well as indicate their professions. Before filling the questionnaires, the four scenarios were explained to all the participants, pointing out their assumptions and consequences. The evaluators consisted of a community development officer, a solid waste engineer, two health officers, a gender officer, five environmental officers and two representatives from households (one was from the informal settlements, representing the low-income households and another was from the high-income planned settlements, representing the high-income households). The environmental officers are involved in raising awareness and ensuring solid waste and sanitation compliance by the communities at the administrative divisions.

Criteria were weighted to convert all the scores to a common scale. A weight is a value that reflects the relative importance of a criterion with regard to other criteria. For example, some people may consider the economic criterion to be more important than the environmental criterion; consequently, the economic criterion will have a greater weight than the environmental criterion. In this study, equal weights were initially assigned to the five sets of criteria (see Table 4.2), and in each set, the weight was equally divided among its criteria. The overall preference score for each scenario, $s_{i,}$ was computed using Equation 4.1.

$$S_i = w_1 s_{i1} + w_2 s_{i2} + \dots + w_n s_{in} = \sum_{j=1}^{n} w_i s_{ij} \qquad \text{Equation 4.1,}$$

where s_{ij} is the preferences score for scenario *i* on criterion *j*, w_i is the weight for each criterion and n is the number of criteria.

Sensitivity analyses were performed to see whether changing the weights and the different groups of respondents would influence the relative scores and preferences for scenarios. The weights for the five sets of criteria were systematically varied up and down to investigate the relative impacts of the weights on the overall scores of the four scenarios. For example, the weight for the economic criterion was increased from 20% to 60%, whereas simultaneously, the weights for other sets of criteria were decreased from 20% to 10%, respectively, so that the total weight remained 100%. Another sensitivity analysis was performed with regard to the different group of respondents while maintaining equal weights for the five sets of criteria.

4.3 Results and discussion

4.3.1 Comparison of the viewed scenarios

The results for the four scenarios appraised against the five sets of criteria are presented in Figure 4.1 and Table 4.3. Overall 'Proper management' scenario is ranked the highest. The 'Business-as-usual' scenario is ranked lowest, whereas the 'More enforcement' and 'More collection' scenarios are ranked in the middle. The 'Proper management' scenario performed best in most criteria because of its mix of diverse waste collection and treatment technologies from small-scale to large-scale systems and extra management programs aiming at both low-cost resource recovery and the reduction of environmental loads. The scenario that considers the integration of the diverse waste collection and treatment technologies and different management approaches to match with the heterogeneous settlement patterns performed best. This finding is comparable to other studies. For example, Wilson *et al.* (2012) in their assessment of solid waste management in twenty mega cities, found that there is no "one size fits" solution to manage waste in cities in developing countries. Rather there is strength in diversity. They mentioned that many cities have deployed a wide variety of ideas to manage waste, some of which draw upon tradition; some are firmly embedded in local culture and habits, some aim at changing habits and attitudes.

The 'Business-as-usual' scenario performed worst because of the high pollution loads caused by a huge quantity of uncollected wastes and the low efficacies of the existing treatment technologies in pollution reduction, as well as high operations and maintenance costs of old waste management equipment. Like other cities in developing countries such as Nairobi, Delhi and Dhaka, waste collection services do not necessarily extend to the peri-urban areas (Kapepula *et al.*, 2007). This is contrary to cities in developed countries, where waste collection services is irrespective of the social status of the citizens (Wilson *et al.*, 2012).

The MSW collection in developing countries' cities is largely restricted to the business districts and affluent neighbourhoods, explaining the huge amount of uncollected MSW. The 'More enforcement' and 'More collection' scenarios performed relatively well because of the reduced emissions, reduced health risks to the residents and waste workers, and job creation for the low-income households.

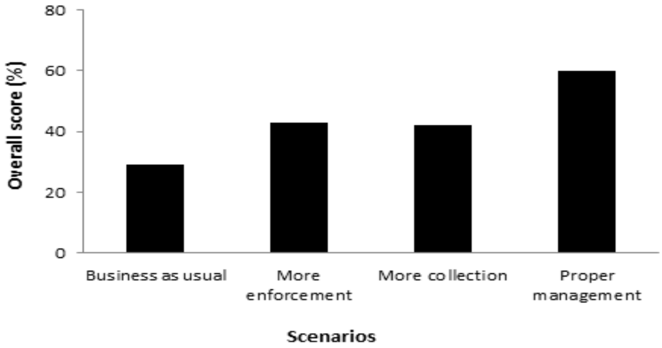


Figure 4.1. Overall performance scores for the scenarios.

The analyses by criteria groups for the four scenarios are, as shown in Figure 4.2. The results show that 'Proper management' scenario scored highest on economic criterion. This is explained by the low cost that would be required to modify the existing septic tanks to anaerobic digesters to treat both human excreta and OFMSW together. In addition, the integration of small-scale and large-scale waste management systems lowers the operational and investment costs compared with the application of only large-scale centralised waste systems. The 'Business-as-usual' scenario scored lowest, most likely because of the high cost involved in the maintaining and operating the old solid waste collection fleets for KCCA and the existing sewerage. The latter can be explained by its high dependency on external supplies and services.

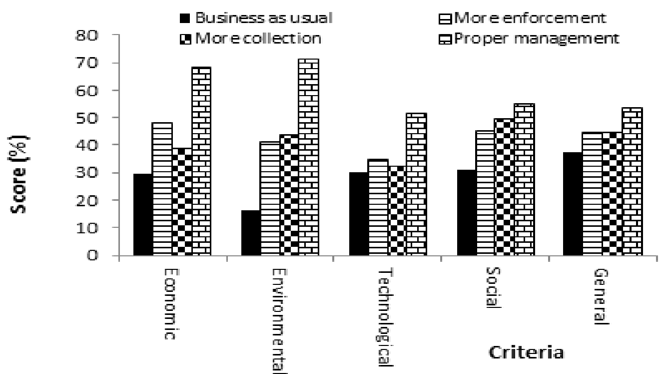


Figure 4.2. Performance scores by criteria groups for the scenarios.

The 'Proper management' scenario performed best in the environmental criteria because of the higher rates of energy and nutrient generation, and the associated credits gained from avoided emissions. This is in line with the waste management hierarchy which stipulates that waste recycling has higher environmental benefits than landfilling (El Hanandeh and El-Zein, 2010). For example, the compost produced from organic waste can substitute the chemical fertiliser as organic fertiliser for farmland. This leads to avoided emission associated with the production of chemical fertiliser (Bernstad and la Cour Jansen, 2011). Also, the production of paper from paper waste reduces the use of virgin fibre, leading to reduction in deforestation. Forests are sinks for CO_2 because they take in CO_2 for processing food during photosynthesis, offsetting the Greenhouse gases (GHGs) emissions from other sources (Yoshida *et al.*, 2012).

The 'More collection' and 'More enforcement' scenarios performed moderately because of the combination of reduced direct flows of untreated urban wastes to the environment and the limited resource recovery involved. The 'Business-as-usual' scenario performed worst, because of its high pollution load as well as little resources recovered.

The 'Proper management' scenario exhibited excellent performance on technological criterion because of the high reliability of an integrated mix of small- and large-scale waste collection and treatment technologies that fits well into a heterogeneous spatial settlement patterns in the city. In this case, the technological set up is not totally dependent on external supplies and services. Technologies that are independent of external supplies and services are resilient to socioeconomic changes, and can therefore operate normally in all seasons (van Buuren, 2010; Letema, 2012). The other scenarios scored low values, because they largely depend on external supplies and services for their smooth normal operations.

With regard to the social criteria, the 'Business-as-usual' scenario performed worst. This is attributed to its high health risk to both residents and waste workers. The other scenarios performed better on this aspect because of their positive contributions towards reduced health risks to users of waste facilities and waste workers, as well as job creation for low-income households and high community involvement in waste management.

The 'Business-as-usual' scenario performed well in the general criteria. This is because the waste management systems are already in place, and, therefore, no time is required to implement them. On the other hand, the other waste management scenarios performed poorly in the general criteria. This calls in the need for increased numbers of enforcement officers to ensure compliance of sanitation and solid waste management regulations by the city residents as well as incentives to motivate residents to recycle their wastes.

4.3.2 Sensitivity analysis

The results for the sensitivity analyses showed that even if the weight for each individual criterion is doubled or halved, the ranking of the scenarios remains unchanged (Figure 4.3). The 'Proper management' scenario still performs best in most of the criteria except for the technological criterion. This is because of the sensitivity of composting processes to toxic substances. Doubling the weights for the economic and environmental criteria improves the performance for the 'Proper management' scenario better than the other scenarios.

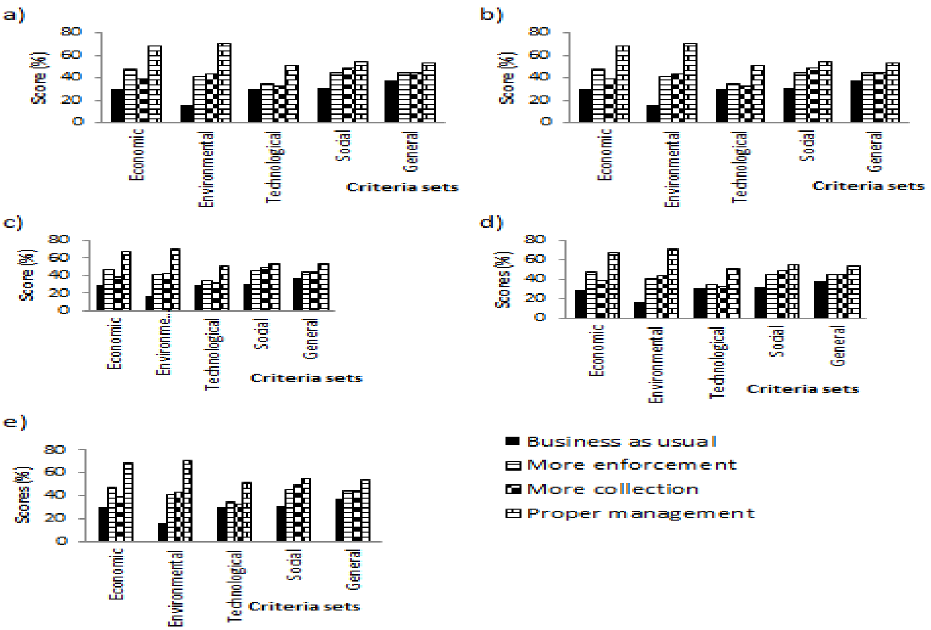


Figure 4.3. Sensitivity analyses outputs for different criteria. a) Increased economic criteria from 20% to 60%; b) increased environmental criteria from 20% to 60%; c) increased technological criteria from 20% to 60%; d) increased social criteria from 20% to 60%; and e) increased general criteria from 20% to 60%.

The performance for the 'More collection' scenario decreases due to increased investment, operations and maintenance costs. Doubling the weight for the social criterion improves the performance for the 'More collection' scenario because of reduced public health risks. This means that incorporating health protection measures in waste treatment by-products leads to the social acceptance of such a waste management system by end-users. Meanwhile doubling the weight for the general criterion only improves the 'Business-as-usual' scenario since this system already exists and does not require time to implement.

The sensitivity analyses results for changing the different groups of respondents also showed that the 'Proper management' scenario performed better than other scenarios with the exception of the social criterion evaluated by environmental officers (Figure 4.4). The respondents from the households preferred the technological option under the 'Business-as-usual' scenario to manage waste. This is possibly because households prefer to get rid of wastes from the living environment than to reuse or recycle them because of health risks. With regard to the respondents with a health background, both the 'More enforcement' and the 'Proper management' scenarios performed equally well on the social and general criteria.

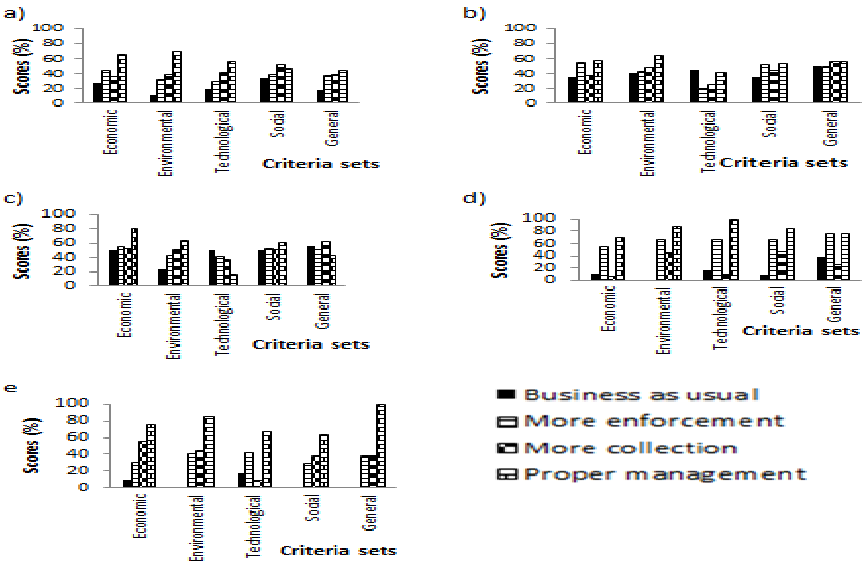


Figure 4.4. Sensitivity analyses outputs for equal weights but different respondents. a) Environmental officers; b) Health officers; c) Households; d) solid waste engineer; and e) Community officer.

Table 4.3. Detail performance evaluation matrix scenario (i) by using the selected criteria for the four scenarios.

Criteria group	Sub-criteria	Weight (w)	Scenarios							
			Business as usual		More enforcement		More collection		Proper management	
			Score (S1)	Weighted average S1*w	Score (S2)	Weighted average S2*w	Score (S3)	Weighted average S3*w	Score (S4)	Weighted average S4*w
Economic										
Operation and maintenance cost	Fuel	4.0	2.5	10.0	3.5	14.0	2.3	9.2	3.4	16.0
	Maintenance	4.0	2.2	8.8	2.5	10.0	2.5	10.0	3.9	15.6
	Wages	4.0	2.0	8.0	2.6	10.4	2.8	11.2	3.9	15.6
Investment cost	Land	4.0	1.9	7.6	3.1	12.4	2.3	9.2	3.5	14.0
	Vehicle	4.0	2.3	9.2	2.9	11.6	2.9	11.6	3.4	13.6
Sub-total		***20.0***		***43.6***		***58.4***		***51.2***		***74.8***
Environmental										
Prevention of emission to surface water	BOD	2.5	1.5	3.8	3.2	8.0	3.2	8.0	4.0	10.0
	TN and TP	2.5	1.5	3.8	3.2	8.0	3.2	8.0	4.0	10.2
Prevention of emission to air	CO_2	2.5	1.8	4.5	2.4	6.0	2.4	6.0	3.4	8.5
	NO_x	2.5	1.8	4.5	2.3	5.8	2.8	7.0	3.6	9.0
	CH_4	2.5	1.8	4.5	2.8	6.3	2.6	6.5	3.9	9.8
Prevention of emission to soil and ground water		2.5	1.7	4.3	2.7	6.8	3.3	8.3	3.5	8.8
High resource recovery	Energy generation	2.5	1.5	3.8	2.5	6.3	2.4	6.0	4.3	10.8
	Recovery of recyclables	2.5	1.6	4.0	2.4	6.0	2.1	5.3	4.1	10.3
Sub-total		***20.0***		***33.0***		***53.0***		***55.0***		***77.0***
Technological										
Reliability	Sensitivity to irregular maintenance	6.7	2.1	14.0	2.2	14.7	2.3	15.3	2.9	19.3
	Dependency of external supply	6.7	2.0	13.3	2.5	16.7	1.9	12.7	2.8	18.7
Flexibility	Easy of adaptation to new conditions	6.7	2.5	16.7	2.1	16.7	2.7	18.0	3.5	23.3
Sub-total		***20.0***		***44.0***		***48.0***		***46.0***		***61.3***
Social										
Community involvement		3.3	2.8	9.3	3.1	10.3	3.4	11.3	2.8	9.3
Institutional support		3.3	2.4	8.0	2.9	9.7	3.1	10.3	2.9	9.7
End-users awareness		3.3	1.8	6.0	3.0	10.0	2.8	9.3	3.0	10.0
Job creation	Number of people employed	3.3	2.8	9.3	3.0	10.0	3.4	11.3	3.5	11.7
Health risk exposure	Prevention of exposure to users	3.3	2.0	6.7	2.3	7.7	2.5	8.3	3.4	11.3
	Prevention of health risk exposure to waste workers	3.3	1.7	5.7	2.6	8.7	2.7	9.0	3.6	12.0
Sub-total		***20.0***		***45.0***		***56.3***		***59.7***		***64.0***
General										
Required legal authorizations	Number enforcement officers	10	2.5	25.0	2.8	28.0	3	30.0	3.6	36.0
Time and ease of implementation	Duration required	10	2.5	25.0	2.8	28.0	2.6	26.0	2.7	27.0
Sub-total		***20.0***		***50.0***		***56.0***		***56.0***		***63.0***
Overall preference scores		**100.0**		**215.6**		**271.7**		**267.9**		**340.1**

4.3.3 Potential of integrating diverse technologies in Kampala's waste management system

The integration of diverse waste technologies and management programs to manage waste flows in Kampala could improve its urban environmental quality.

This would involve the establishment of small-scale, semi-centralised/decentralised waste management systems such as communal MSW collection points, communal septic tanks and anaerobic digesters in informal settlements as well as large-scale centralised waste systems, for example, sewerage in planned settlements. Such a mix of diverse waste technologies could also fit in other developing countries' cities such as Kathmandu, Nepal (Ronteltap *et al.*, 2009) and Phnom Penh, Cambodia (Seng *et al.*, 2010) having heterogeneous settlement patterns. But such an approach may be economically unviable for developed countries' cities where settlement patterns are uniform (Hara *et al.*, 2010).

The combined treatment of human excreta and OFMSW appear to be technically feasible, but its implementation may be unfeasible because of the fear to use compost. This is associated with health risks and cultural taboos (Drangert *et al.*, 2002; NWSC, 2008). Such fear could be overcome by increasing awareness, incorporating health protection measures in co-composting treatment and providing incentives in the form of subsidies to transport the compost from urban to rural farm lands. This reduces the urban ecological footprint (Kim, 1998). Funds for such subsidies could possibly be obtained from agricultural research funds and the KCCA. The KCCA could benefit from the prolonged landfill's lifespan because of the reduced amounts of MSW landfilled. This also saves the KCCA millions of dollars in avoided MSW collection, transportation and disposal costs.

Application of compost produced from MSW on farmland can have a major constraint because of its poor quality. This is largely because of a lack of proper segregation of MSW at the source, which contaminates the feedstock of the co-composting process. This calls for source sorting of OFMSW at the households and markets. In Dhaka City, the local professionals have implemented organized collection of source-separated OFMSW from households and markets, and established community-based composting facilities using the funding from the clean development mechanism (Wilson *et al.*, 2012). Such an arrangement could also be borrowed and applied in Kampala to manage the OFMSW.

The promotion of the co-composting of human excreta with readily biodegradable OFMSW at the household or community levels would further ensure the involvement of the communities in waste management. This would lead to a decentralised waste management as well as a reduction in the workload for the KCCA in the actual management of MSW. Consequently, investments are reduced in the new centralised municipal infrastructure to an enormous extent. However, the effective implementation of co-composting treatment would require an enabling environment in the form of regulations on MSW separation at sources to reduce the risk of contamination of compost. Also, the Ministry of Agriculture would need to develop compost quality standards for agricultural purposes to guide the farmers.

4.3.4 Study limitations

The number of the selected criteria was quite high compared with other waste management systems studied (Cheng *et al.*, 2003; Generowic *et al.*, 2011). This is because of the complexity of the urban waste system, combining human excreta and MSW in the local context in East African cities. Such a large number of criteria leads to an extra analytical effort in assessing input data and could make the communication of the analysis more difficult. However, in this study, the overall preference scores for the four scenarios were clearly distinguished. Thus, the most optimal waste management scenario for Kampala was easily selected.

Being a static model, the MCDA is not optimally suited for dynamic systems like waste systems (Borsuk *et al.*, 2008). This is because human judgment sometimes tends to be biased in its assessment of alternatives that can more readily be linked to what is familiar, and to be overly influenced by recent, memorable, or successful experiences. Such judgment may not fit well with scenarios that focus on long-term projections as in the case of this study. Nevertheless, the MCDA provided a useful insight into the possible barriers to the four scenarios and how best to improve the waste management systems in Kampala.

Comparing this study to other similar studies, for example, the comparative analysis of solid waste management in 20 mega cities (Wilson *et al.*, 2012), and integration of environmental and human health risk assessment for industries using hazardous materials (Topuz *et al.*, 2011), the public health, environmental and resource conservation were considered as separate criterion. However, in this study, the latter two were merged into one, and public health was weighted 20% of the social criteria. The latter two are combined in one criterion to avoid double counting, and public health criterion is weighted 20% of social criteria since it focuses on the reuse of by-products but not technological effectiveness in health prevention. But still a mix of diverse waste technologies and different management programs presented by the 'Proper management' scenario performed best as also reported in other studies (e.g. Wilson *et al.* (2012)).

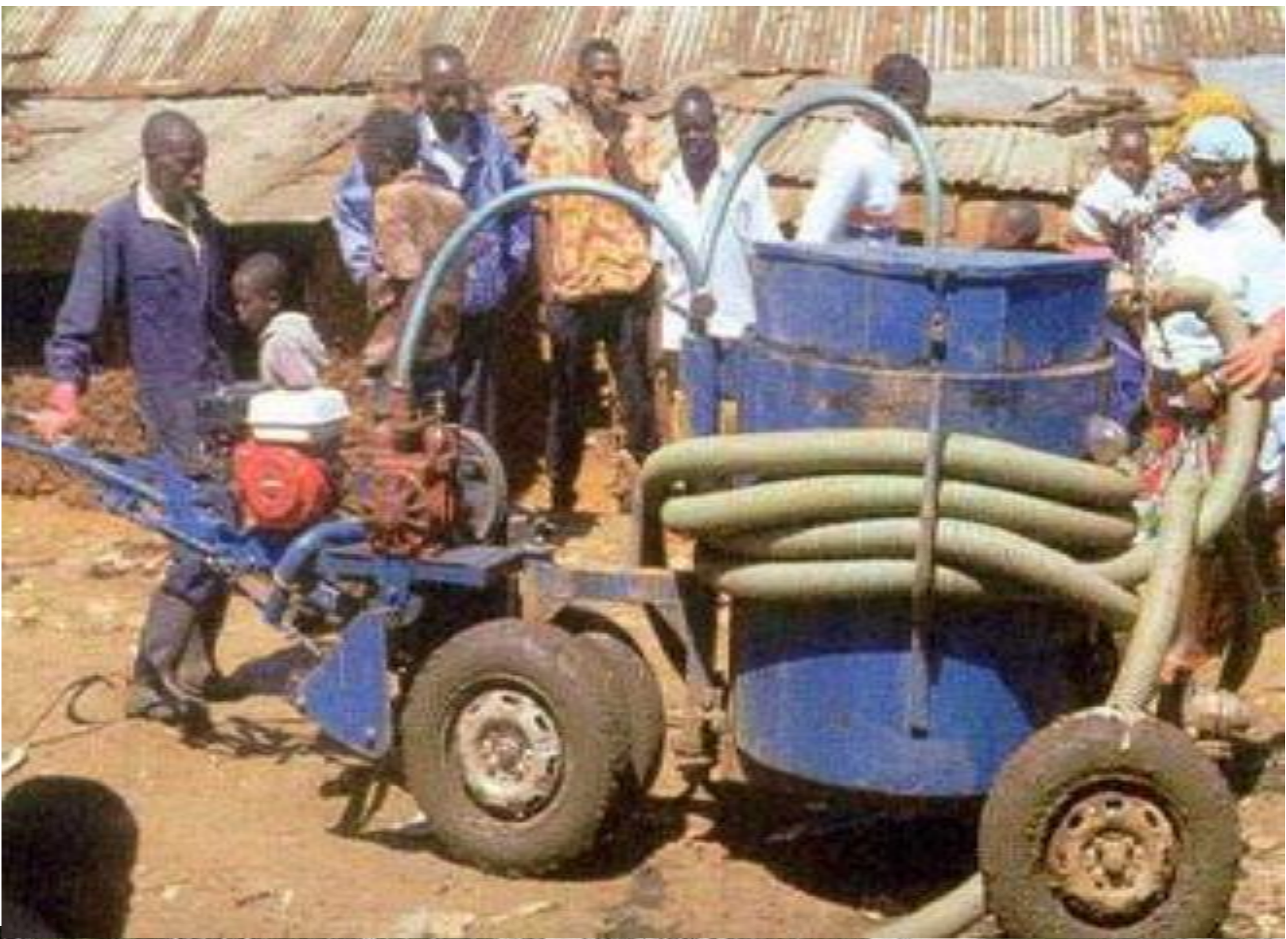
The equal weights assigned to all the criteria, with 'general' criteria having only two sub-criteria compared to other criteria, could have effectively given a much higher weight to the 'general' criteria. However, sensitivity analyses showed that the ranking of the scenarios remains unchanged even after doubling the criteria weights. Hence, assigning equal weights does not have an effect on the overall ranking and choice for the scenarios. This led to increased confidence in decision-making to select the most appropriate waste management scenario for Kampala.

4.4 Conclusions

Multi-criteria decision analyses can have a positive contribution in both the process of decision-making, selecting the appropriate waste management systems, and understanding the effect of economic, social, environmental, technological and the 'general' criteria on the waste management systems. Although the large number of the selected criteria complicates decision making, this study shows that the complexity of waste management systems justified this approach. The equal weights for each set of criteria may have weakened the analysis, but the sensitivity analysis shows that the ranking of the scenarios is robust. This ranking applies in this case and not necessarily in each future analysis. The mix of approaches reflected in the 'Proper management' scenario is a key solution to improve the environmental performance of waste systems. The management of waste in a developing country's city is a complex issue, as the heterogeneous settlement patterns are unlikely to accept a single solution to be applied to adequately collect and treat all the waste flows. A mix of diverse waste technologies and different management regime matching different settlement patterns is the most optimal approach to manage waste flows in Kampala, to improve its urban environmental quality.

Acknowledgments

This paper was prepared in the framework of the PROVIDE program, and funded by the INREF of Wageningen University, the Netherlands.




LHD

Chapter 5 Environmental impacts of urban waste recycling in East Africa: The case of Kampala, Uganda[6]

Abstract

Improper management of waste flows in East African cities has become an environmental and public health concern to the city authorities. We assessed the environmental impacts of waste recycling in Kampala City, using four designed waste management scenarios, namely: (1) Scenario S1 representing the status quo, (2) Scenario S2 maximizing landfilling, (3) Scenario S3 combining composting, resource recovery, landfilling and sewerage, and (4) Scenario S4 combining anaerobic digestion, resource recovery, landfilling and sewerage. These scenarios are quantitatively assessed on environmental impacts of global warming, acidification, nutrient enrichment, photochemical ozone formation, water source pollution and resource recovery. Sensitivity analyses are performed to assess the robustness of the ranking of the scenarios. Results show that scenarios incorporating resource recovery performed better than those without. Scenario S4 combining anaerobic digestion, resource recovery, landfilling and sewerage performed best on all environmental impact categories. Sensitivity analyses show that this assessment result is robust. Hence, integrating waste recycling to form part of the formal waste management system in Kampala would considerably reduce the environmental impacts of waste flows. The similarities in municipal solid waste compositions, generation rates, sanitation systems and settlement patterns across these cities, implies that enhancing waste recycling and integrating it to form part of the formal waste management systems for these cities would produce minimal environmental impacts.

Key words: Emissions; human excreta; solid waste; composting; anaerobic digestion; and landfilling.

[6] This paper is has been accepted for publishing in *Habitat International* as: Oyoo R., R. Leemans and A.P.J Mol. "Comparison of Environmental performance for different waste management scenarios in East Africa: The case of Kampala, Uganda" DOI 10.1016/j.habitatint.2014.07.012

5.1 Introduction

The rapid population growth and lifestyles changes in East African cities drive the increased urban waste flows. This puts pressure on the environment and poses public health risks since not all waste flows are collected and treated adequately. Urban waste in this context refers to MSW and human excreta produced in urban areas. Both MSW and human excreta contain readily biodegradable organic matter, which makes it possible to solve problems related to them.

The large and medium sized cities surrounding Lake Victoria such as Kampala and Kisumu have low MSW collection efficiencies. Consequently, large amounts of urban waste flows to Lake Victoria's inshore, deteriorating the lake's water quality (Muyodi *et al.*, 2009). Groundwater sources in these cities are also contaminated by faecal matter, from poorly constructed, operated and maintained on-site sanitation systems (Machiwa, 2001; Kulabako, 2005; Mireri *et al.*, 2007). Hence, there is an urgent need to minimize the waste flows to the environment in these cities. Recycling waste would reduce waste flows to the environment.

Kampala City in Uganda has both formal and informal waste management systems. Waste management in this context refers to the management of both MSW and human excreta. Thus, in this thesis, waste management stands for urban waste management and the term "waste" refers to "urban waste". The formal waste management system refers to waste management activities performed by public entities, legally authorized private service providers (PSPs) (Katusiimeh *et al.*, 2012) or legally recommended on-site sanitation systems. The informal waste management systems refer to waste management activities, which are unregulated, unregistered, unrecognized by urban authorities as being part of the formal waste management systems or casual activities performed by individuals, families or community enterprises that are engaged in value-adding activities on small-scale with minimum capital inputs (Klundert and Lardinois, 1995; Scheinberg *et al.*, 2011). Examples, of the informal waste management activities in Kampala are recycling, open burning and open dumping. These informal activities are performed to unknown extents (KCC, 2006).

The lack of quantifiable data makes it difficult to comprehensively assess the environmental performance of waste flows for Kampala. Earlier study by Oyoo *et al.* (2011) projected the future waste flows and their impacts on Kampala's environment for four waste management scenarios, using a dynamic model. Their study indicated a deteriorating urban environment if the waste management status quo continues. They recommended a mix of diverse technologies and management regimes, fitting the spatial settlement patterns as the optimal solution to manage Kampala's waste flows. Also, Oyoo *et al.* (2013) appraised the same scenarios for environmental, economic, social, technological and general criteria, using multi-criteria analysis. Their study still recommended for a mix of diverse technologies and management regimes as the optimal solution to manage Kampala's waste flows. However, both studies did not integrate the local, regional and global scales all together to assess the environmental impacts of waste flows in Kampala. An integrated approach is therefore required to assess the total environmental impacts of the waste management systems, to design suitable measures, so as to improve the environmental performance of waste flows. Assessing the potential environmental impacts for waste flows on local, regional and global scales concurrently is then essential.

Studies assessing local, regional and global environmental impacts of waste management systems have been performed, using life cycle analysis (LCA). LCA is an environmental assessment tool for assessing the cradle-to-grave impacts of products and services (ISO, 1997), but the methodological framework also allows for the analysis of waste management systems. For example, Banar *et al.* (2008) applied the approach to determine the optimum MSW management strategy for Eskisehir, Turkey. Their study recommended composting as the best option to manage MSW for Eskisehir, because of its low environmental impacts. Bernstad and la Cour Jansen (2011) and Andersen *et al.* (2012) also used a similar approach to compare environmental impacts for composting, landfilling and incineration of MSW. Both studies recommended for composting treatment of MSW, because of its low environmental impacts. However, the results for these studies are difficult to generalize for East African cities, because of the difference between MSW characteristics and emission factors used in these studies and those for East African cities. Also, results for LCA studies differ according to the study goals, assumptions and method used (Ralph *et al.*, 2009). But a similar approach can be used to assess the potential environmental impacts of waste management systems for Kampala.

This paper assesses the environmental impacts of the current and potential future systems to manage waste flows, in order to determine the most environmentally preferred waste management system for East African cities, exemplified with Kampala. The following research question was examined: To what extent and how can resource recovery from waste improve the environmental performance of waste management systems in Kampala? The potential environmental impacts of four waste management scenarios are assessed and compared. Scenario here refers to a combination of different waste treatment options. The use of LCA and scenario analysis to assess the environmental impacts of waste recycling for Kampala, a city in a developing country, is innovative; since such a study has never been published for East African cities. This study also provides science-based information for Kampala Capital City Authority (KCCA) and other city authorities in East Africa for managing waste flows in their cities.

5.2 Methods

5.2.1 System description and boundaries

We studied the current and three potential future systems to manage waste flows for Kampala; a metropolis with a population size of 1.2 million and an annual growth rate of 3.8% by 2002 (UBOS, 2007). The city's projected population in 2011 stood at 1.7 million. The city has a MSW rate and compositions comparable to other cities in the region (see Tables 5.1 and 5.2). The OFMSW forms the highest portion. Systematic MSW sorting and recycling is not implemented, although materials with high resale values such as metals, plastics, and papers are recycled by the informal recycling sector. About 45% of MSW generated is collected and disposed at the landfill daily, using 74 trucks. These trucks use about 0.1 L t^{-1} km^{-1} of diesel to transport MSW to the landfill. Also, 0.7 L t^{-1} of diesel is used to compact MSW at the landfill site. Approximately, 86% of the population uses on-site sanitation systems, 7% uses sewerage and 7% practices open defecation (NWSC, 2008).

Table 5.1. Municipal solid waste data for the selected cities in East Africa.

Urban	Generation rate (kg capita^{-1} day^{-1})	OFMSW (%)	Source
Kampala	0.6	83	(Oyoo *et al.*, 2011)
Jinja	0.6	75	(Okot-Okumu and Nyenje, 2011)
Kisumu	0.5	67	(Onyango and Kibwage, 2008)
Mwanza	0.4	78	(Salukele, 2013)
Bukoba	0.4	78	(UN-HABITAT, 2005)
Musoma	0.5	74	(UN-HABITAT, 2005)

Table 5.2. Municipal solid waste compositions values for Kampala City.

Waste category	Percentage (in wet weight)		
	(Matagi, 2001)	(Mwiganga and Kansiime, 2005)	(Oyoo *et al.*, 2011)
Paper and board	5	6	5
Glass	1	4	1
Metal	3	-	1
Plastic	2	3	8
OFMSW	83	78	83
Construction debris	-	2	2
Street sweepings	6	-	-
Industrial	-	2	-
Others MSW	-	5	-
Total	**100**	**100**	**100**

Note: (-) means value included in Others MSW

Illustrated in Figure 5.1 is the schematic flow diagram for the waste flows through the formal and informal waste management systems in Kampala. Such a flow diagram allows for an adequate assessment of the waste management process as a whole, and an assessment of the total potential environmental impacts for the waste management systems. The process starts from the moment material ceases to have value (becomes waste), and terminates when waste becomes inert material or emissions. The products derived from waste processes such as biogas, compost, digestate and recyclables as well as other emissions are placed outside the system boundary for the waste flows. The environmental impacts of these products downstream are not included in this study.

The formal waste management activities in Kampala are landfilling, sewerage and on-site sanitation. The sewerage and landfilling are placed in one box because both are formalised large-scale centralised systems for treating human excreta and MSW, respectively. In Kampala, the MSW landfilled is covered with soil daily. The landfill processes produce landfill gases, consisting of methane and carbon dioxide, the principle products of anaerobic decomposition of OFMSW. Other components of landfill gas include nitrogen, ammonia, nitrogen oxide and volatile organic carbons (Tchobanoglous *et al.*, 1993). The landfill in Kampala does not have a landfill gas collection system, implying that all the landfill gases produced are released to the atmosphere (KCC, 2006). The landfill processes generate about 0.15 m^3 leachate ton^{-1} MSW and 250 Nm^3 biogas ton^{-1} OFMSW (McDougall *et al.*, 2001). These emissions include biogenic CO_2, CH_4 and N_2O (Gentil *et al.*, 2011).

The sewerage processes emits about 0.22 kg CH_4 kg^{-1} BOD_5 (Van Amstel, 2012). The on-site sanitation is also a source of nitrate (NO_3) leaching into surface and ground water. How much NO_3 is leached depends on the soil permeability.

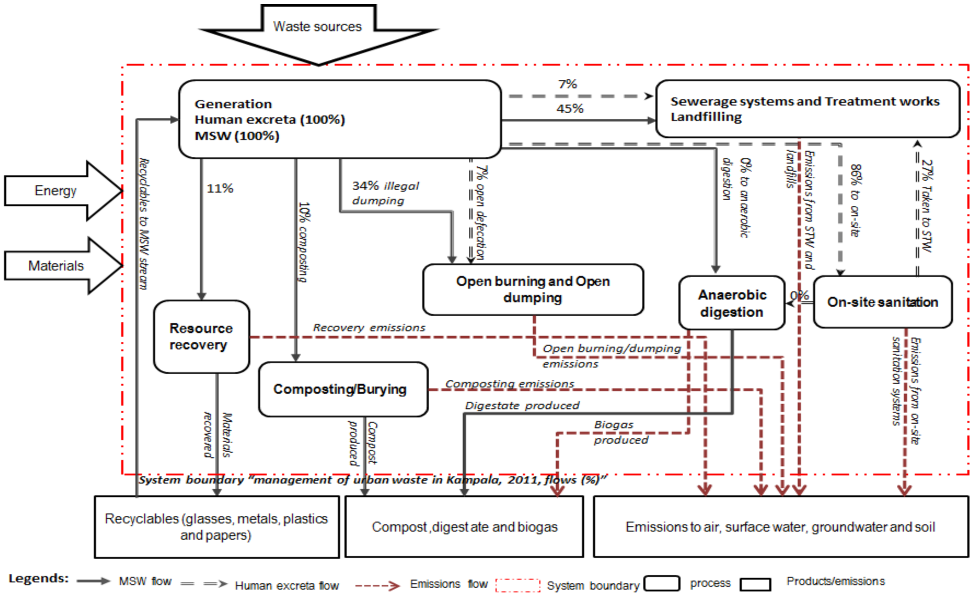


Figure 5.1. Kampala's waste flows through the formal and informal waste management activities, and the associated emissions and co-products.

The informal waste management activities in Kampala include:

1. *Open waste dump*: this system does not adopt any technical measures to control gases and leachate. Like landfills, open waste dumps emit methane emissions and other landfill gases to the atmosphere. But since open dumps are not covered and compacted with soil as is the case in Kampala, the quantity of methane produced is small as compared to a landfill. The landfill gases released might migrate off-site and cause odour. Also, the leachate produced can contaminate the groundwater aquifers. This is of concern for Kampala's groundwater aquifer, because of the high groundwater table (Kulabako, 2005).

2. *Composting:* this is the biological decomposition of OFMSW into a stable humus-like product. It is considered an informal activity because it is not supported by the KCCA as a mean to improve Kampala's urban

environment. Composting processes are aerobic, emitting carbon dioxide, ammonia, nitrogen oxide, VOCs, sulphur dioxide (SO_2) and methane (Andersen *et al.*, 2010). They are net energy user because oxygen must be supplied for waste conversion. Composting offer relatively simple operation and, if properly operated, can significantly reduce the volume of the OFMSW (Tchobanoglous *et al.*, 1993). OFMSW contains approximately 0.55 - 1.1 N kg capita^{-1} year^{-1}, 0.2 – 0.4 P kg capita^{-1} year^{-1} and 16 - 22 C kg capita^{-1} year^{-1} (Strauss *et al.*, 2003).

3. *Open waste burning* causes emissions of NO_x, CO, SO_2, CO_2 and VOCs formed during combustion (Forbid *et al.*, 2011).

5.2.2 Scenarios

Four scenarios for managing waste flows are designed by combining different waste treatment options. In each scenario, the MSW composition, treatment technologies and sanitation categories are assigned different percentages for OFMSW, human excreta and resources recovered. It is assumed that the MSW composition remains identical in all the four scenarios such that it has no influence when comparing their environmental performances. Because of the high moisture content (55 - 75%wt.) in the MSW, incineration is not considered as part of the alternatives for the scenarios. The scenarios assessed are:

1. Scenario S1 represents the current waste management system.
2. Scenario S2 represents landfilling of all MSW. Landfilling is considered, because it is the only authorized disposal method for MSW in East African cities, including Kampala. The time boundary of a landfill system is set at a 100 years, when biogas formation from OFMSW has stopped (Finnveden, 1999). The proportion of population served by a sewerage system is maintained at 7% as in Scenario S1, and the rest uses on-site sanitation, because human settlements in Kampala are sprawling outwards and many new houses are far from the existing sewers (NWSC, 2008).
3. Scenario S3 assumes source sorting of MSW into OFMSW, other recyclables and MSW residues (i.e. fractions neither recyclable nor OFMSW). Here, 60% of the sorted OFMSW is treated by home composting or community-composting facilities located within walking distance. The composting method considered is windrow. Windrow refers to a pile of

biodegradable organic waste material subjected to decomposition (Kumar, 2011). Each household can have its own windrow. The organic waste pile is frequently turned to improve porosity and oxygen content, remove moisture, and redistribute cooler and hotter portions of the pile (Gajalakshmi and Abbasi, 2008). This is manually performed, and so no external input of energy is required. The leachate produced during the composting process is assumed negligible, since the leachate is depleted from the compost bed by vaporization (Szántó, 2009). The recyclables (i.e. metal, glass, paper and plastic) are recycled to produce secondary materials. Because of limited data on resource recovery, a recovery rate for materials in MSW is set at 30%. The emissions resulting from transportation of recyclables are neglected since their fractions are quite small compared to OFMSW. The MSW residues, including 40% OFMSW, are landfilled but no landfill gas utilization. The management for the human excreta is as in Scenario S2.

4. Scenario S4 assumes source sorting of MSW. Because of the high percentage of population using on-site sanitation (86%) and high percentage of OFMSW (83%) in the MSW composition (Oyoo *et al.*, 2011), 60% of sorted OFMSW is co-digested with 50% of faecal sludge trucked from on-site sanitation (e.g. pit latrines and septic tanks) by anaerobic digestion off-site. Anaerobic digestion converts organic waste to digestate, and CO_2, CH_4, NH_3 and H_2S emissions. This offer the benefit of energy recovery in the form of methane biogas and thus, net energy producers. The treatment considered in this scenario is a two stage high-solids anaerobic/aerobic processes. The first stage is the high-solids (25 - 30%) anaerobic digestion of organic waste, producing CH_4 and CO_2 under thermophilic conditions (54 - 56^{o}C) and thirty days hydraulic retention time. The second stage is the aerobic composting of the anaerobically digested solids, producing a humus-like product known as digestate (Tchobanoglous *et al.*, 1993). The digestate and biogas are used locally. Using the same conversion efficiency as landfill gas engines; biogas generates electricity of about 190 kWh ton^{-1} MSW (McDougall *et al.*, 2001). The digesters are assumed to be properly sealed, preventing escape of gases to the air. The fractions of resources recovered, MSW disposed at a landfill and population using sewerage are as in Scenario S3.

5.2.3 Impact assessment

There is lack of reliable emissions data for waste flows in developing countries' cities, including Kampala. This makes comprehensive assessment of the total environmental impact of waste systems in such cities problematic. In this study, generic average emission factors obtained from literature and waste flow data got from field surveys and literature are used to estimate the potential environmental impacts of the four scenarios. The waste flows produced in the base year 2011 are taken as the functional unit to estimate the potential environmental impacts.

The emissions are estimated using traditional emission factor–based estimations that apply a fixed emission rate of a given pollutant for a given source, relative to units of activity. The equation uses an average emission factor (F) and an activity level (A), to calculate emissions (E), given by $E=F*A$. This method is traditionally used to quantify pollutant levels in air, water and soil, at high aggregation levels (e.g. city scale in this study). The approach is simple and input data needed to calculate emissions are easily available (Havlikova and Kroeze, 2006). However, its simplicity may give rise to large uncertainties in emission estimates as it does not consider spatial and temporal variabilities of emissions. Pinder *et al.* (2004) showed how important it is to consider temporal and spatial variability when estimating ammonia emissions. This may also hold true for other emissions.

The standard impact categories assessed are global warming potential (GWP), acidification (AC), photochemical ozone formation (POF), nutrient enrichment (NE) and human toxicity (HT). Global warming potential refers to the potential effect of the emissions of CO_2, CH_4 and N_2O from waste and the associated activities on increasing the temperature in the lower atmosphere on a global scale. Here, wherever CO_2, CH_4 and N_2O are emitted they contribute to the same effect and thus the impact is global. Photochemical ozone formation refers to the effect of the emissions of VOC, NO_x, C_2H_4 and CO from waste on a regional or local scale. Local refers to impacts caused by human activity within a radius of 25 km. “Regional” refers to impacts caused by human activity outside a radius of 25 km but not effecting globally. Acidification refers to potential impact of emissions of SO_2, NO_x and NH_3 from waste and associated activities on a local or regional scale. Nutrient enrichment refers to potential impact of NO_3, NH_3 and NO_x emissions on the enrichment of aquatic ecosystems with nutrients on local or regional scale leading to water eutrophication. Human toxicity refers to potential human health risk connected to exposure from the environment via air, soil and drinking water as a result of SO_2 and NO_x emissions to the environment on a local scale.

Also, resource conservation and water sources pollution are assessed. The resource conservation refers to the recovery of resources from waste, to substitute the use of virgin materials at a local scale. Water source pollution refers to the contamination of the water sources by nitrogen from the waste on a local scale. These environmental impact categories are chosen because the emissions from waste flows may be detrimental to Lake Victoria's water quality, aquatic life and human health.

The estimation of the environmental impact categories are described below.

a) Estimating global warming potential, acidification, photochemical ozone formation, nutrient enrichment and human toxicity

The GWP, AC, POF, NE and HT are estimated by computing emissions for the contributing substances for the different waste management activities (Tables 5.3 and 5.4), and then weighting with their characteristic factors provided in Table 5.5. The biogenic CO_2 emissions are accounted as neutral to GWP since they originate from organic matter generated by an equivalent biological uptake of CO_2 during plant growth (IPCC, 2006). The emissions from sewerage and on-site sanitation are excluded as they are the same in all the four scenarios. Moreover, the estimated potential impacts for sewerage and on-site sanitation (Table 5.6), based on an average water consumption of 41 litre capita^{-1} day^{-1} (World Bank, 2005), a wastewater density of 1000 kg m^{-3} and impact factors from ecoinvent database (Frischknecht *et al.*, 2007), are quite low compared to that for MSW. Therefore, the environmental impacts of the on-site sanitation with respect to AC, NE, GWP, HT and POF are also ignored. The emissions from vehicles are estimated on the basis of fuel consumption.

Table 5.3. Emission factors (kg t^{-1}) for recyclable materials**.**

Parameter	Glass	Fe	Al	Paper	PET	PE	PP	PS	PVC
CO_2	278	595	518	–1,300 to –2,900	163	163	942	942	942
CH_4	0.83	1.29	2.71	0.01	0.02	0.02	0.02	0.02	0.02
NO_x	1.69	1.77	0.62	5.44	0.08	0.08	0.08	0.08	0.08
VOCs	0.17	0.02	0.30	23.89	6.98	6.98	6.98	6.98	6.98
SO_2	0.43	2.98	2.88	9.99	0.00	0.00	0.00	0.00	0.00

Abbreviations: PET, polyethylene terephthalate; PE, polyethylene; PP, polypropylene; PS, polystyrene; and PVC, polyvinyl chloride. Source: (Hanandeh and El-Zein, 2010)

Table 5.4. Emission factors (kg t^{-1} MSW) for different processes.

Process	CH_4	N_2O	NO_x	VOC	CO	SO_2	NH_3	CO_2
Burning	–	–	1.42[a]	4277[b]	–	0.92[a]	–	–
Landfilling	204[c]	0.13[c]	107[c]	17[d]	–	–	3.4[d]	–
Composting	4[e]	(0.30–0.55)[f]	(0.03–0.27)[f]	1.4	(0.07–0.13)	–	370[e]	–
Anaerobic digestion	–	–	0.19[g]	–	–	0.003[h]	–	–
Diesel used (g/kg fuel)	6.91[j]	0.02[j]	50[k]	6.5[k]	15[k]	20[k]	–	3150[j]

[a]Zhao *et al.* (2011), [b]Forbid *et al.* (2011), [c](Wang *et al.*, 1997; Barton and Atwater, 2002 ; Hanandeh and El-Zein, 2010), [d]Tchobanoglous *et al.* (1993),[e]Adhikari *et al.* (2010),[f]Andersen *et al.* (2010),[g]Banar *et al.* (2008), [h]Valerio (2009), and [i]Abduli *et al.* (2011)

Table 5.5. Environmental impacts for standard categories and their typical contributing substances, sources: (Tabata *et al.*, 2011; Zhao *et al.*, 2011).

Impact Categories	Geographical scale	Contributing substances	Contribution equivalents of substances
GWP	Global	CO_2	1 kg CO_2-eq.kg^{-1}
		CH_4	21 kg CO_2-eq.kg^{-1}
		N_2O	310 kg CO_2-eq.kg^{-1}
AC	Regional/local	SO_2	1 kg SO_2-eq.kg^{-1}
		NO_x	0.72 kg SO_2-eq.kg^{-1}
		NH_3	1.88 kg SO_2-eq.kg^{-1}
NE	Regional/local	NO_3	1 kg NO_3-eq.kg^{-1}
		NH_3	3.64 kg NO_3-eq.kg^{-1}
		NO_x	1.35 kg NO_3-eq.kg^{-1}
POF	Regional/local	C_2H_4	1 kg C_2H_4-eq. kg^{-1}
		CO	0.04 kg C_2H_4-eq.kg^{-1}
		VOC	0.5 kg C_2H_4-eq.kg^{-1}
HT	Local	SO_2	0.096 kg $C_6H_4Cl_2$-eq.kg^{-1}
		NO_X	1.2 kg $C_6H_4Cl_2$-eq.kg^{-1}

b) *Estimating water sources pollution*

The impact of waste emissions on water sources is related to the consumption of scarce resources, and it is not an environmental impact category. So the potential impact of waste emissions on water sources is not directly compared with those of other standard impact categories. The TN emissions to water sources from the collected and uncollected MSW, the sewerage and on-site sanitation are estimated as the fractions of TN that have leached into the water sources.

Table 5.6. Computed potential impacts for sewerage, on-site sanitation and landfill.

Impact category	Unit	Impact factor (Frischknecht *et al.*, 2007)	Sewerage	On-site sanitation	Landfills (t^{-1} MSW)
AC	kg SO_2-eq.t^{-1}wastewater	0.0031	0.000	0.003	87
NE	kg PO_4-eq.t^{-1} wastewater	0.0130	0.001	0.012	138
GWP100	kg CO_2-eq.t^{-1} wastewater	0.4170	0.019	0.253	3815
HT	kg $C_6H_4Cl_2$-eq.t^{-1} wastewater	0.6033	0.042	0.561	113
POF	kg C_2H_4-eq.t^{-1}wastewater	0.0001	0.000	0.000	8

c) *Estimating resources recovery*

Many waste management systems produce co-products, which substitute the use of goods (virgin materials, chemical fertiliser and electrical energy) in downstream activities. This results in avoided environmental impacts related to the production of goods using “normal means of production”. In this study, the environmental impacts for the production of the goods are estimated using SimaPro 7.3 software (Table 5.7) (Goedkoop *et al.*, 2010), and they are subtracted from the total environmental impacts for the waste management system, to calculate the net environmental impacts (Bernstad and la Cour Jansen, 2011).

The compost and digestate are assumed to substitute the nitrogen and phosphorus in the chemical fertiliser at a replacement ratio of 1:1. That is 1 kg of nitrogen in organic fertiliser replaces 1 kg of nitrogen in chemical fertiliser. Similarly, biogas used for cooking is assumed to replace an equal energy amount of diesel fuel. The recyclable materials replace an equivalent amount of virgin materials, but their avoided impacts are not computed, because of lack of reliable data.

Table 5.7. Impacts for fertiliser production and electricity generation from diesel (Frischknecht *et al.*, 2007).

Impact categories	Unit	Diammonium phosphate, as N	Diammonium phosphate, as P_2O_5[a]	Electricity, diesel energy
AC	kg SO_2-eq.	0.0093	0.0442	0.0001
NE	kg NO_3-eq.	0.0029	0.0360	0.0001
GWP100	kg CO_2-eq.	2.7889	1.5697	0.4140
HT	kg $C_6H_4Cl_2$-eq.	2.2631	1.3244	0.0470
POF	kg C_2H_4-eq.	0.0004	0.0018	0.0001

[a] Note that P_2O_5 contains 0.44 kg P, and 1 kg P requires 2.3 kg P_2O_5 to be produced.

d) *Projecting future environmental impacts*

In order to understand how resource recovery would impact the environmental performance of the waste flows in the future, the projection for waste flows is performed and the GWP impacts are assessed for the four waste management scenarios. The future waste generation is estimated using population size for a given geographical area, as a proxy. The amount of MSW generated is estimated as population size times per capita MSW generation rate. Similarly, the amount of human excreta produced is estimated as population size times per capita human excreta generation rate. The future MSW composition (in terms of percentage of OFMSW) and generation rates (Table 5.8) are assumed to change in accordance with economic growth. These values are derived from MSW data for medium- and high-income cities in Asian countries (Table 5.9).

5.2.4 Sensitivity analysis

Because of the uncertainty associated with the use of average emission factors, which are time and location dependent, a sensitivity analysis is performed to assess the robustness of the ranking of the scenarios. A sensitivity analysis is performed by doubling and halving the amount of OFMSW recovered for Scenarios S3 and S4. But the same amount of OFMSW is maintained for Scenarios S1 and S2, since Scenario S1 is a baseline and Scenario S2 is designed to treat all MSW generated.

Another sensitivity analysis is performed by considering that the purchasing power of households would improve, resulting in generation of more non-food wastes. This is because over the years, the MSW compositions for Kampala have shown an increasing trend of non-food waste (Table 5.2). The MSW compositions for high-income Asian countries' cities (Table 5.9) are used for estimating the environmental impacts, because the MSW generation rates for low-income Asian countries and those for East African cities are similar.

Table 5.8. Municipal solid waste data derived from cities in Asian countries (World Bank, 1999).

Year	Generation rates (kg cap^{-1} day^{-1})	MSW Composition (%)
2009	0.6	83
2014	0.6	83
2019	0.7	60
2024	0.8	58
2029	0.9	30
2034	1.5	30
2039	2.0	28
2044	2.5	28
2049	3.0	20

Table 5.9. Municipal solid waste data of various income Asian countries (World Bank, 1999).

	Low-income countries[a]	Middle-income countries[b]	High-income countries[c]
MSW generation rate (kg $cap^{-1}d^{-1}$)	0.6 (0.5–0.9)	0.7(0.5–1.1)	1.6 (1.1-5.1)
MSW Composition (%)			
OFMSW	41	58	28
Paper	5	15	36
Plastic	4	11	9
Glass	2	2	7
Metal	1	3	8
Others MSW	47	11	12

[a]Nepal, Bangladesh, Myanmar, Vietnam, Mongolia, India and Sri Lanka
[b]Indonesia, Philippines, Thailand and Malaysia
[c]Republic of South Korea, Hong Kong, Singapore and Japan

5.3 Results and discussion on scenarios

5.3.1 Comparison of environmental profiles

This section compares the environmental profiles of the four scenarios with regard to the GWP, AC, NE, POF and HT. The GWP profiles for the four scenarios (Figure 5.2) shows that Scenario S2 (landfilling) has the highest GWP, followed by Scenario S1 (business-as-usual), Scenario S3 (composting) and Scenario S4 (anaerobic digestion). This ranking has also been reported in similar studies, where landfilling has the highest value of GWP, followed by incineration, composting and anaerobic digestion (Mendes *et al.*, 2003; Hong *et al.*, 2010). The values of GWP for landfills reported in the literature range from 900 kg CO_2-eq.t^{-1} (Mendes *et al.*, 2003) to 6,990 kg CO_2-eq.t^{-1} (Banar *et al.*, 2008). In our study, the estimated value of GWP is 3,830 kg CO_2-eq.t^{-1}, four times higher than the value stated by Mendes *et al.* (2003), but lower than the value estimated by Banar *et al.* (2008). The relatively high value estimated from our study is because of high emissions of methane from the biological decomposition of a large amount of OFMSW disposed in a landfill. Meanwhile the GWP reported by Banar *et al.* (2008) is higher than our estimate because biogenic carbon dioxide emissions are also included in their estimate. This is omitted in our study. From this study's results, controlling methane emissions is essential to reduce GWP for landfills. Capturing methane emissions for use as an energy source is a potential option to reduce the GWP for landfills (Hong *et al.*, 2010). The methane emissions from Kampala's landfill could be captured to generate electricity, supplementing electricity supply from the national grid for use at a landfill site.

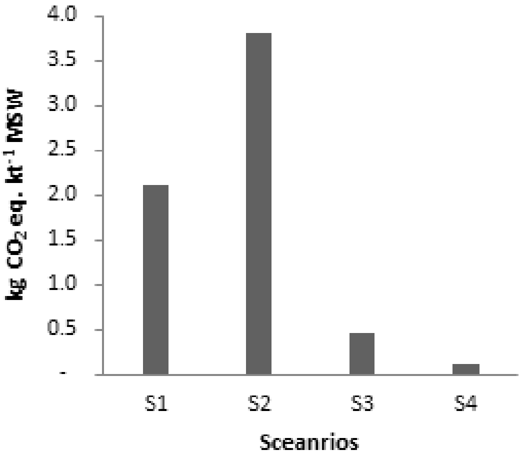


Figure 5.2. GWP profiles for the scenarios.

Scenario S1 indicated a lower GWP than Scenario S2, because the amount of MSW landfilled is small, and MSW disposed in open dumps releases mainly biogenic carbon dioxide. Similarly, Scenario S3 had a low GWP value, because a large portion of GHGs emissions from composting processes are biogenic carbon dioxide and the emissions resulting from transportation of OFMSW to composting facilities are assumed to be zero, as the composting treatment is performed on-site. Scenario S4 produced the least GWP value because methane emissions are burnt to produce biogenic carbon dioxide (IPCC, 2006). Biogas burning may emit between approximately 1 - 4 g CO_2-eq.kWh^{-1} of fugitive methane emissions depending on the technology used (Bernstad and la Cour Jansen, 2011). However, in our study anaerobic digesters are considered to be properly sealed, and so the fugitive methane emissions are zero.

Scenario S3 indicates high environmental impacts of AC and NE (Figure 5.3a and b) because of high emissions of ammonia from the composting processes. The importance of ammonia emissions from the composting processes with regard to these impact categories have also been reported by other authors (e.g. (Banar *et al.*, 2008; Bernstad and la Cour Jansen, 2011)). Conversely, Scenario S4 produced the least environmental impacts of AC and NE because of the sealed environment of anaerobic digesters. The only substances contributing to these impact categories in Scenario S4 are from fossil-fuel combustion. Compared to other studies, Banar *et al.* (2008) also found the environmental impacts of acidification and nutrient enrichment are lowest for anaerobic digestion processes.

The large impact of acidification and nutrient enrichment for Scenario S3 poses a threat to Lake Victoria's water quality, which may result in loss of biodiversity. However, treatment of exhaust gas from composting processes offers an opportunity to reduce the values of AC and NE, to minimize the environmental burden of Scenario S3 for these two impact categories. Previous studies have estimated NO_x and NH_3 removal efficiencies by odour removal devices in closed composting facilities to range from 95 to 98% (Mendes *et al.*, 2003; Sironi *et al.*, 2007). However, the handling of exhaust gas is not considered in this study. This handling might decrease the estimated benefit of Scenario S3 because of the emissions from the cleaning of the composting facilities.

With respect to POF, Scenario S1 has the highest environmental burden (see Figure 5.3c). The VOCs emissions from open burning are the main substances responsible for a high value of POF in Scenario S1. Recovery of resource from waste reduces the emissions of NO_x and VOCs, as illustrated by the good performances of Scenarios S3 and S4 with regard to this impact category. Like POF, Scenarios S1, S3 and S4 (incorporating recovery of resources) performed better than Scenario S2 with respect to HT. Scenario S2 has the highest environmental burden in this impact category, because of high NO_x emissions (see Figure 5.3d).

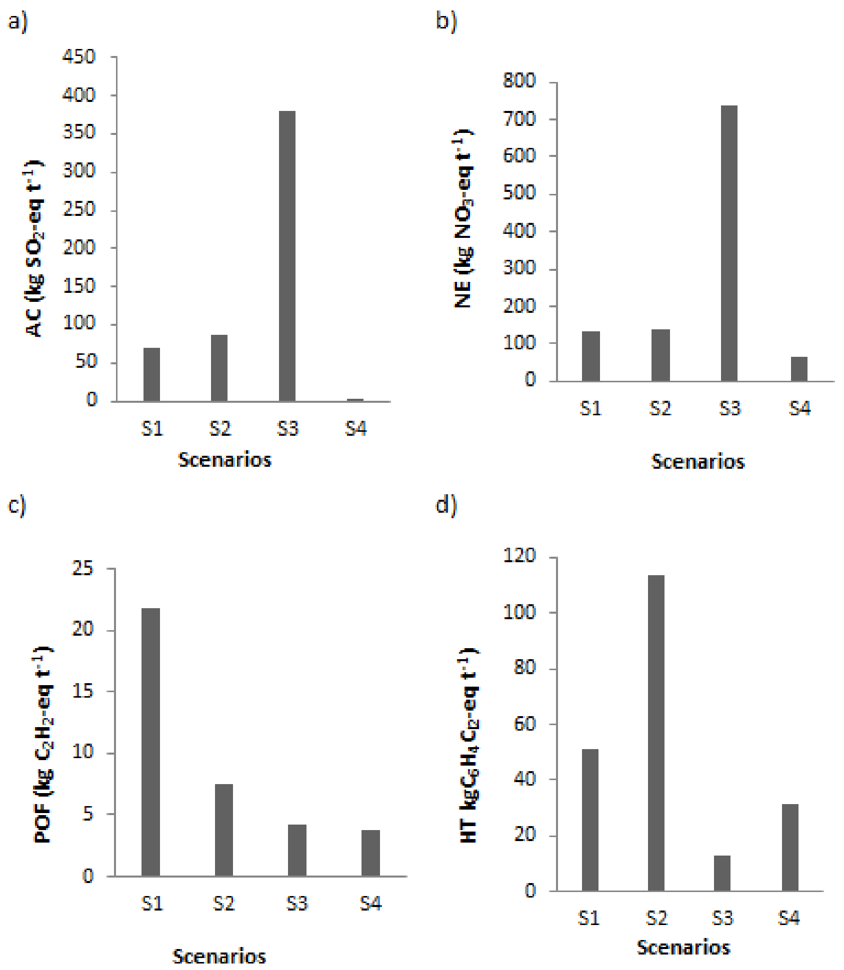


Figure 5.3. Profiles for the Scenarios: a) AC, b) NE, c) POF and d) HT.

5.3.2 Comparison of water sources pollution

Scenario S1 indicates the highest TN load to the water sources, followed by Scenarios S2, S3 and S4 (Figure 5.4). The high TN load into the water sources for Scenario S1 is attributed to the high proportion of unlined pit latrines, which are improperly operated and maintained. This is also supported by a study by Cronin *et al.* (2007), linking contamination of groundwater in developing countries' cities to poorly constructed and operated on-site sanitation facilities, particularly in areas with high water tables. This is typical for Kampala.

Scenario S3 shows a lower TN load to the water sources as compared to Scenarios S1 and S2, because the leachate generated is assumed negligible. Also, Scenario S4 produced the least TN load to the water sources. This low TN load into water sources can be practically achieved when the digestate is properly applied on farm land. Compared to Scenario S1, Scenario S4 reduced the TN loads to the water sources by about 81%. This implies that co-digestion of faecal sludge and OFMSW in a properly constructed digester, and followed by proper application of the digestate on farm land reduces the leaching of nitrogen to the water sources. This ensures better water quality for the urban residents, particularly for the low-income households who directly use untreated water for their domestic needs (Kulabako *et al.*, 2010).

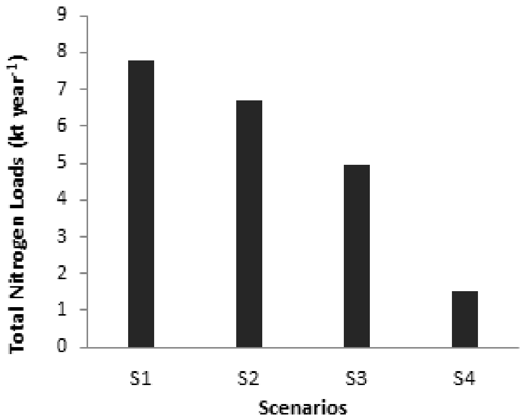


Figure 5.4. Total Nitrogen loads to water sources for the different scenarios**.**

5.3.3 Comparison of energy requirement

As illustrated in Figure 5.5, Scenario S2 shows the highest energy requirement for waste collection and treatment. This is because all the MSW generated is to be collected and disposed at a landfill. Scenarios S1, S3 and S4 show comparatively lower amounts of energy required to operate MSW management facilities, because of a low amount of MSW to be transported to a landfill. More so, Scenario S3, which consists largely of composting processes performed on-site, contains little vehicular transportation of OFMSW. The used windrow composting method does not require external energy, since the turning of the compost is performed manually. Moreover, there is no transportation of the compost and digestate to rural farm land as both products are assumed to be used locally. Similarly, Scenario S4 requires less external energy inputs for operating anaerobic digestion (Edelmann *et al.*, 2002).

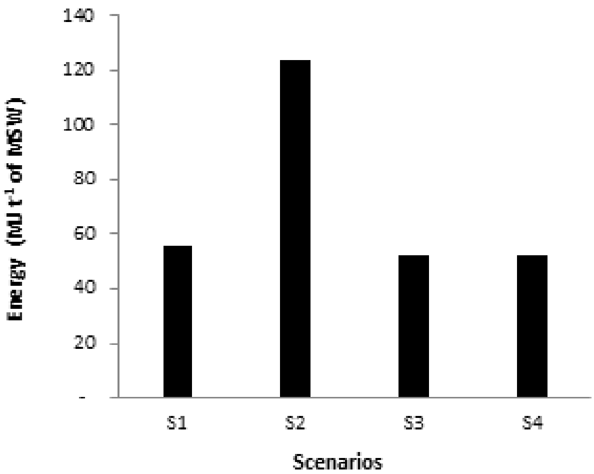


Figure 5.5. Energy requirement profiles for the Scenarios**.**

5.3.4 Comparison of resource recovery

The analysis of the results shows that all the scenarios recovering resources from waste performed well. Scenarios S3 and S4 have a high potential for resource recovery because of the production of compost, biogas and recyclable materials. The recovered resources from waste contribute to avoided emissions and avoided use of virgin materials, resulting in minimal environmental impacts. For example, the production of paper from paper waste reduces the use of virgin fibre, leading to reduction in deforestation. Forests are sinks for CO_2 because they take in CO_2 for processing food during photosynthesis, offsetting the GHGs from other sources (Harrison, 2001). Also, recycling of paper waste leads to avoidance production impact. Additionally, the recovered resources from waste reduce the amount of MSW to be finally disposed at a landfill. This prolongs landfill's lifespan. This is important for Kampala and other East African cities as suitable parcels of land in the periphery of the cities are becoming scarce because of urban expansion for settlement and industrial development.

Recycling of phosphorus is a hot issue now because of its foreseen scarcity. The supply horizon for phosphorus has been estimated at only 50 - 100 years (Andersen *et al.*, 2012). Scenario S3 (composting) and Scenario S4 (anaerobic digestion) return phosphorus and nitrogen elements back to the soil for food production. This is important for Kampala as the growing population will need a constant food supply to feed them. Scenario S3 produces about 149 t N year^{-1} and 54 t P year^{-1}, substituting equivalent amounts of nitrogen and phosphorus in chemical fertiliser when used on farm land. This contributes to a reduction in the total environmental impacts of Scenario S3, by avoiding the emissions associated with the production of chemical fertiliser (Bernstad and la Cour Jansen, 2011).

Scenario S4 championed all other scenarios in resource recovery. It derives energy out of the waste first, and then stabilised the residues to get a nutrient-rich end products. Scenario S4 produced about 3 GJ t^{-1} of energy and is comparable to the values reported by Bernstad and la Cour Jansen (2012), in the range of 2 – 4 GJ t^{-1}, but lower than values reported by Hanandeh and El-Zein (2010) of 6 – 17 GJ t^{-1}. This is because only 60% of OFMSW is anaerobically digested, whereas the comparison is based on total MSW produced. The avoided materials in Scenario S4 are chemical fertiliser and fossil-fuel. The substitution of chemical fertilisers and fossil-fuel with digestate and biogas, respectively, are equally important for the avoidance of negative environmental impacts from Scenario S4. The benefits from the recovered energy and organic fertiliser, reduced MSW loads to a landfill and reduced environmental impacts are good incentives to motivate the implementation of Scenario S4. However, digestate contains pathogenic microorganism, which can infect the end-users. The digestate must be aerobically stabilised before using on farm lands by co-composting digestate and OFMSW to combines the effects of heat and time, to inactivate the pathogens. A composting temperature of 70^{o}C for 1-2h can inactivate the pathogens in the digestate (Montangero and Strauss, 2002).

Scenario S2 ranks the worst since no co-product is produced to substitute downstream activities, resulting in no avoided environmental burden. However, it has the potential to produce biogas that can be collected to generate electricity. Scenario S2 can produce approximately 208 Nm^{3} biogas ton^{-1} MSW landfilled, which can be converted to electricity using a landfill biogas engine. The conversion efficiency for a landfill biogas engine ranges between 20 and 30% (El Hanandeh and El-Zein, 2010). Using a conservative efficiency value of 20%, electricity production is approximately 412 kWh t^{-1} MSW. This requires the KCCA to invest in a biogas collection system and a biogas engine to produce the electricity. The income generated from the energy production can pay back part of the investment cost.

5.3.5 Comparison of Global Warming Potential

In terms of GWP, Scenario S2 performed worse than other scenarios, as shown in Figure 5.6. With no resource recovery measures being implemented, the GWP increased and the waste management system will risk collapsing. The increased GWP will result in climate change. Climate change is the enhanced greenhouse effect attributed to human influence (Arena *et al.*, 2003). The increases in GWP in Scenario S2 call for the need for landfill gases to be collected and treated adequately. Conversely, Scenario S1 performed better than Scenario S3 and Scenario S4, because of the low amount of MSW disposed in a landfill and thus lower fossil-fuel used for transporting MSW to a landfill. More so, large amounts of OFMSW are disposed at the open dumps, emitting biogenic carbon dioxide, neutral to GWP (IPCC, 1996).

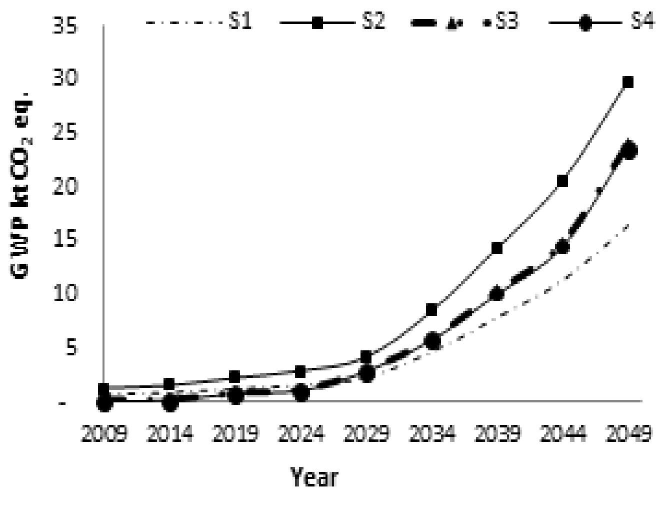


Figure 5.6. Projected impact of GWP for the Scenarios.

5.3.6 Sensitivity analysis

The results of sensitivity analysis, through varying the amount of OFMSW recovered for all the scenarios, revealed that the ranking of the four scenarios remains unchanged (Figure 5.7). Doubling the amount of OFMSW recovered does decrease the GWP for Scenario S3 and Scenario S4, while halving the amount of OFMSW recovered increases the GWP for Scenario S3 and Scenario S4. At full recovery of OFMSW (i.e. 100%), the GWP value for Scenario S4 becomes negative, implying anaerobic digestion of organic waste leads to avoided environmental impact of GWP. Conversely, the environmental impacts of AC and NE increase with increased recovery of OFMSW for Scenario S3, because of an increased level of ammonia emissions. This suggests that controlling ammonia emissions is essential for producing minimal environmental impacts of acidification and nutrient enrichment for Scenario S3.

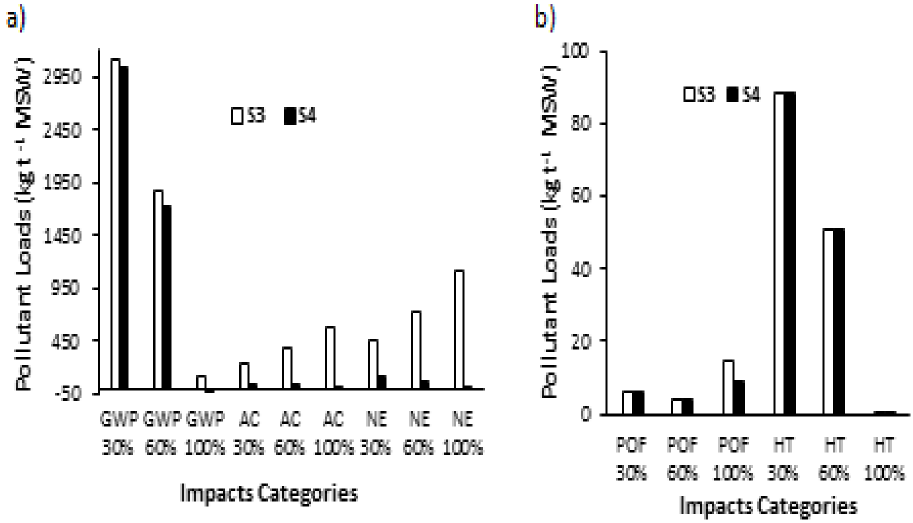


Figure 5.7. Sensitivity analyses outputs: (a) GWP, NE and AC; (b) POF and HT.

5.3.7 Limitations of the study

This study investigated several environmental problems and comparatively assessed the total potential environmental impacts for four waste management scenarios. However, because of data limitations, generic average emission factors derived from literature are used in this study. These average emission factors may not fully represent the studied system, but our study showed environmental impact trends that are comparable to similar studies in other developed countries' cities (Mendes *et al.*, 2003; Banar *et al.*, 2008). Furthermore, sensitivity analyses showed that despite changing the OFMSW in the MSW composition, the ranking of the scenarios remains unchanged. This implies that there is a possibility of generalizing the implication of this study's results to other East African cities, considering the similarities in their MSW compositions and settlement patterns.

5.4 Conclusions

As economic development in Kampala continues to rise, so does the environmental burden of managing waste flows. This study compared the environmental impacts on global warming, nutrient enrichment, acidification, human toxicity, photochemical ozone formation, water sources pollution and resource conservation for the current and three future scenarios for managing Kampala's waste flows, based on emission factor-based estimations. The approach proved useful for comparing the total potential environmental impacts of waste management systems in developing countries' cities, where emissions data is lacking and/or inadequate. Based on the assessment results for Kampala, this study shows that scenarios recovering organic waste and recyclables from waste produced minimal environmental impacts of global warming potential and the water sources pollution. Business-as-usual scenario and a scenario maximizing landfilling perform poorly for environmental impacts of global warming potential, photochemical ozone formation and human toxicity. A scenario with considerable composting treatment performs worst on the environmental impact of acidification and nutrient enrichment because of high ammonia emissions. Integrating anaerobic digestion, resource recovery, landfilling and sewerage performs best in all environmental impact categories. Sensitivity analysis indicates that the assessment results are robust. Therefore, recovering resource from waste would lead to minimal environmental impacts of waste flows. Integrating resource recovery into the formal waste management system in Kampala is likely to yield significant environmental benefits. The similarities in municipal solid waste compositions, sanitation systems and human settlement patterns across East African cities, imply that this study's results can be generalized to them.

Acknowledgment

This paper was prepared within the framework of the PROVIDE and was funded by the INREF of Wageningen University, the Netherlands.

Chapter 6 General discussion and final conclusions

6.1 Introduction

This thesis is part of the output project for Partnership for Research on Viable Infrastructure Development (PROVIDE). The project consisted of different sub-projects for sanitation and solid waste management at different levels. This thesis focused on simulating sanitation and waste flows to understand waste flows' trends and their environmental impacts under different waste management regimes. By understanding the current and future waste flows and their environmental impacts, appropriate responses can be developed and implemented, to minimise the environmental and societal impacts of waste sector in East African cities.

As discussed in Chapter 1, waste flows in cities surrounding Lake Victoria are poorly managed and this severely deteriorates the lake's water quality with consequences for ecosystems, human health and economic activities dependent on the lake (Muyodi *et al.*, 2010). Improving access to waste infrastructures with proper environmental performances to all city residents is therefore a top priority on the development agenda. The East African city authorities have been directing their efforts to increase the proportion of the population with access to waste infrastructures as well as to enhance the waste infrastructures' environmental performances.

To effectively improve environmental performances for waste infrastructures, an integrated dynamic model representing the systemic processes for generating and controlling waste flows is needed. Such a model can be applied to project the future trends in waste flows and their environmental impacts under different management regimes. So far, a coherent dynamic model specifically integrating waste flows from different sources to final disposal and their environmental impacts did not exist for East African cities. Nevertheless, to understand the process for waste flows and their environmental impacts, developing a process-based model, which describes different waste flows at different stages and connects them at different levels of analysis, is a suitable strategy. This is appropriate for the obvious data limitations in East African cities (Biggs *et al.*, 2004).

Against the above described background, this thesis focuses on the understanding, quantifying, mapping and modelling waste flows processes in East African cities, and to develop suitable measures to improve Lake Victoria's water quality. Henceforth, five research questions were formulated to address the thesis's objective:

i. What are the current organic loads to Lake Victoria's inshore from surrounding cities, and optimal scenarios to minimise organic loads from each city?

ii. What are the likely and possible future waste flows and their environmental impacts when technological, social and economic changes are taken into consideration all together?

iii. To what extent, and how, can waste recycling improve the environmental performance of waste infrastructures in East African cities?

iv. What is the optimal scenario to improve environmental performance of waste infrastructures in East African cities, based on economic, environmental, social and technological criteria?

v. Given the answers to the above four questions, what is the most appropriate scenario to improve Lake Victoria's environmental quality?

In the remaining part of this chapter, the answers to the five research questions are presented, discussed and reflected upon in Sections 6.2, 6.3, 6.4, 6.5 and 6.6, respectively. The innovations, strengths and limitations of this study are discussed in Section 6.7. The direction for future research is provided in Section 6.8 and the final conclusions are given in Section 6.9.

6.2 Current urban organic loads to Lake Victoria's inshore

This section answers the first research question on minimising current organic loads to Lake Victoria's inshore. Based on the study presented in Chapter 2, the current urban organic loads for six cities surrounding Lake Victoria are evaluated. The lack of adequate field data made it difficult to quantify for the cities in question, the absolute net organic loads entering Lake Victoria's inshore. Nevertheless, the approach used by Scheren *et al.* (2000) to quantify net organic loads to Lake Victoria's inshore was adopted. This method is effective for estimating environmental loads where pollution monitoring programs are unavailable, as is the case for the cities studied. Scheren *et al.* (2000) used a parsimonious but comprehensive approach to estimate the net organic loads to Lake Victoria's inshore by multiplying population size, pollution intensities and pollutant penetration factors for natural and artificial systems. This approach is also applied in this thesis to quantify the net organic loads for each city to Lake Victoria's inshore. In this thesis, the projected population size for each city is used as a proxy to estimate total nitrogen, total phosphorus and five-day biological oxygen demand loads. The net environmental loads for each city after pre-filtration by wetlands are estimated as the product of each load before entering the wetlands and wetlands' penetration factors of pollutants.

The analysis shows that the annual net loads to the lake's inshore after pre-treatment by wetlands, amount to approximately 4 kt TN, 2 kt TP and 23 kt BOD_5. The values for total nitrogen and total phosphorus are comparable to the values reported by LVEMP (2001), which are 4 kt TN, 2 kt TP except for BOD_5, which is about 18 kt and is less than the estimate obtained in this study. The annual net environmental loads for the cities studied ranged from approximately 0.1 to 1.5 kt TN, 0.03 to 1.0 kt TP and 0.5 to 10 kt BOD_5. The nutrient loads are highest for Kampala, followed by Kisumu, Mwanza, Musoma, Bukoba and Jinja. Jinja has the lowest environmental loads because of its small population size and/or a good pollution filtering function of the Kirinya wetlands prior to the entry of urban runoffs to Lake Victoria's inshore (Kelderman *et al.*, 2007). The patterns of five-days biological oxygen demand loads for this thesis compare poorly with findings for Scheren *et al.* (2000), who reported the highest BOD_5 load to Lake Victoria's inshore from the Kenya side, while this thesis found the highest loads coming from Kampala, Uganda. The annual five-day biological oxygen demand loads reported by Scheren *et al.* (2000) from Kenya, Uganda and Tanzania are 8 kt, 5 kt and 4 kt, respectively. An explanation to the found difference may arise as their study included also organic waste from industries and agricultural runoff. This thesis however only estimated urban organic loads from households to Lake Victoria's inshore, and not from industries and agricultural runoffs.

The trend of increased environmental loads to Lake Victoria's inshore is explained by (i) the deteriorating environmental performances of large-scale urban environmental infrastructures, (ii) low municipal solid waste collection rates, and

(iii) declining urban wetlands vegetation along Lake Victoria's shoreline (Scheren *et al.*, 2000). Also, these cities were sprawling whereas the sewerage expansion stagnated (NWSC, 2008). This implies that a high proportion of the population is using on-site sanitation. Most of the on-site sanitation facilities are poorly constructed, operated and maintained. This pollutes groundwater and poses a threat to Lake Victoria's water quality since the groundwater table around the lake is high (Nalubega *et al.*, 2001; Howard *et al.*, 2003; Kulabako, 2005). The current trend of urban expansion against the stagnated sewerage expansion is likely to continue for at least two more decades, and this will further deteriorate Lake Victoria's water quality.

The increased environmental loads to Lake Victoria's inshore from surrounding cities calls for more collection and improved treatment of urban organic waste to minimise the environmental loads. Based on the results for different scenarios, the scenario mixing and optimising diverse organic treatment options, and matching with heterogeneous settlement patterns, local environmental and social-economic conditions specific to each city produced minimal environmental loads. The reduction of environmental loads for the cities studied ranged from 27% to 66% for five-day biological oxygen demand, 16% to 61% for total nitrogen and 21% to 63% for total phosphorus. The scenario that included anaerobic digestion reduced five-day biological oxygen demand and total phosphorus loads by respectively 48% and 20% in the cities studied, except for Mwanza. Mwanza has a high municipal solid waste collection rate (80%). The scenario for sewerage improvement reduced environmental loads by only about 20% in all cities because of low proportions of population served by sewerage in the cities studied. The low economic development level and the high heterogeneity in settlement patterns in the cities studied restrict sewers expansion to serve all city residents.

Based on the scenario results, the heterogeneity of settlement patterns and varying local environmental and socio-economic conditions within each city makes treatment of organic wastes using a single approach impossible. The settlement patterns, socio-economic conditions and levels of environmental infrastructure development apparently differ within each city. Each city therefore requires different combinations of organic treatment options that fit their city-specific spatial settlement arrangements and local environmental and socio-economic conditions to adequately treat all the organic wastes. Application of such mixed treatment systems will make the treatment of organic waste flexible as well as increase access to the waste treatment facilities by urban residents, particularly the urban poor. This drives towards minimal environmental loads.

6.3 Future waste flows trend and their environmental impacts

This section addresses the second research question on future waste flows and their environmental impacts in East African cities. Here, a box model describing waste flows from different sources via different stages up to treatment and final disposal, and their environmental impacts, is constructed. The model's relationships, parameters and variables are based on reviewed literature and field surveys. Four steps are performed to develop a model to understand the various relationships between components of the waste flows system. These steps are: (1) identification of waste typologies, sources and pathways, (2) identification of links between the environment and waste flows, (3) selection of environmental indicators and (4) assessment of impacts of waste flows on the environment.

The model captured waste flows through the formal and informal waste management activities practiced in Kampala, Kisumu and Dar es Salaam. These cities have similar waste management activities and they are comparable to other cities in the region and even other developing countries' cities. Such similarities make the model adaptable to other developing countries' cities. Organic fraction of municipal solid waste and human excreta flows are combined to project the future waste flows and their environmental impacts. This is contrary to developing countries' models that focused either on solid waste stream only (Belevi *et al.*, 2004) or on human excreta only (Montangero *et al.*, 2007). Treating organic fraction of municipal solid waste and human excreta together is a logical, acceptable and beneficial approach, since organic fractions of municipal solid waste and proportions of on-site sanitation systems are high for East African cities and other developing countries' cities (Oyoo *et al.*, 2011; Wilson *et al.*, 2012).

Scenario analyses for different waste management strategies, capturing different pollution reduction strategies, were explored using the model. The scenarios are: (1) 'Business-as-usual', representing the waste management status quo; (2) 'More enforcement**'**, enhancing enforcement success of the existing solid waste management ordinance and public health sanitation regulations by 70%, reducing organic packaging materials by 10%, increasing awareness-raising efforts by 15%, and increasing collection skips and trucks by 5% compared to the 'Business-as-usual' scenario; (3) 'More collection' scenario, increasing waste collection and transportation by 70%, increasing composting technology, level of awareness-raising and enforcement of regulations by 10% each; and (4) ‘Proper management’ scenario, integrating diverse technologies and measures, and matching them to specific local conditions, enhancing technological development level by 60%, and increasing enforcement and awareness-raising each by 20% compared to the ‘Business-as-usual’ scenario.

The scenario results show that by 2052 in Kampala, the annual environmental loads for the different scenarios will range from 150 to 310 Mt BOD_5, 2 to 8 Mt TN, 2 to 3 Mt TP, compost produced from 1 to 11 Gt and municipal solid waste landfilled from 44 to 2,200 Mt. The ‘Business-as-usual’ scenario indicates that with no additional measures put in place to reduce, prevent and treat waste flows, the urban environmental quality rapidly deteriorates with negative consequences on human health. After 50 years, the estimated annual five-day biological oxygen demand load increased by 370% compared to the baseline load for the year 2008. Municipal solid waste landfilled is less than the landfill’s designed capacity (2 Gt). This is because huge fractions of organics are illegally dumped into the environment. The ‘More enforcement’ scenario shows a reduction in BOD_5 loads by about 40% compared to the ‘Business-as-usual’ scenario, implying strong enforcement of an effective policy reduces illegal waste dumping. This requires ensuring that adequate and appropriate waste collection and treatment technologies are in place. The amount of municipal solid waste to be landfilled fills the available landfill’s space within four years. This will demand for more land to expand or develop a new landfill, making waste treatment by landfill expensive because of the appreciating land value. The ‘More collection’ scenario indicates 26% reduction of five-day biological oxygen demand loads compared to the ‘Business-as-usual’ scenario. This is attributed to increasing application of low-cost waste collection and transportation technologies, and satellites faecal sludge treatment facilities. The highest five-day biological oxygen demand load reduction (50%) is achieved by enhancing enforcement, awareness-raising and technological development as reflected in the ‘Proper management’ scenario.

The ‘Proper management’ scenario shows that recycling of organic waste would lead to a substantial reduction of environmental loads. This is because organic wastes constitute more than 70% of municipal solid waste in East African cities (Onyango and Kibwage, 2008; Oberlin and Szántó, 2011; Okot-Okumu and Nyenje, 2011; Oyoo *et al.*, 2011). The recycling of organic waste fits well with the promotion of urban agriculture. However, because of no source sorting of waste, municipal solid waste often contain glass, plastics and toxic substances that can contaminate the compost (Gumbo, 2005). To ensure that good quality compost is produced, waste should be sorted at the source, into biodegradable organic waste, recyclables and residues. Once segregated, the biodegradable organic wastes are composted, recyclables are taken to recycling industries and the residues are disposed at landfills. The composting can be performed by home composting, using windrows or small-scale community composting facility. The latter is applicable for densely built-up areas. Small-scale composting enterprises can be motivated by paying them for each ton of organic waste diverted from the landfill. Education and training programs to urban residents on the benefits of composting are necessary to encourage them to compost their organic wastes.

6.4 Waste recycling as a strategy for waste minimization

To answer the research question on improving environmental performance of waste infrastructures in East African cities, a life cycle analysis approach combined with scenario analysis was applied to evaluate the potential environmental impacts of waste recycling in Kampala. Such a combination of life cycle analysis and scenario analysis is useful for systematically determining and identifying all the relevant processes contributing to the total potential environmental impacts of waste from the system, and exploring future trends of waste flows and their environmental impacts. In this thesis, the following scenarios are assessed: (1) Scenario S1, representing the current status quo, (2) Scenario S2, maximizing landfilling, (3) Scenario S3, combining composting, recycling, landfilling and sewerage, and (4) Scenario S4, integrating anaerobic digestion, recycling, landfilling and sewerage. These scenarios are quantitatively assessed on environmental impacts of global warming, acidification, nutrient enrichment and photochemical ozone formation using traditional emission factor–based estimations. This approach is simple, reliable and the input data needed to compute emissions is readily available (Havlikova and Kroeze, 2006). It is also useful for estimating emissions for developing countries' cities where data are lacking. This facilitates fast decision-making, yet average emission factors are applied instead of varying emissions. Emission factors can change with changing local environmental conditions, and this can lead to a different ranking of the scenarios with regard to their performances in minimizing environmental impacts.

Analysis of the results for the scenarios shows that a combination of anaerobic digestion, recycling, landfilling and sewerage produced minimal environmental impacts in all impact categories. The assessed impacts ranges from approximately 118 to 3,815 kg CO_2-eq.t^{-1} for global warming potential, 32 to 381 kg SO_2-eq.t^{-1} for acidification, 65 to 735 kg NO_3-eq.t^{-1} for nutrient enrichment, 4 to 218 kg C_2H_2-eq.t^{-1} for photochemical ozone formation and 31 to 113 kg $C_6H_4Cl_2$-eq.t^{-1} for human toxicity. Landfilling produced the highest global warming potential with a value of about 3,815 kg CO_2-eq.t^{-1}. This value is higher than the global warming potential value of 900 kg CO_2-eq.t^{-1} for a landfill reported by Mendes *et al.* (2003) and lower than the 6,990 kg CO_2-eq.t^{-1} reported by Banar *et al.* (2008). The relatively high global warming potential value estimated for this thesis compared to the value reported by Mendes *et al.* (2003) is explained by high methane emissions from biodegradation of a large amount of landfilled organic waste. The global warming potential value reported by Banar *et al.* (2008) is higher than the value estimated in this thesis since biogenic carbon dioxide emissions are also included in their estimate. This is omitted in this thesis because biogenic carbon dioxide emissions are neutral to global warming, as they originate from organic matter generated by an equivalent biological uptake of carbon dioxide during plant growth (IPCC, 2006). If the current trend for landfilling of waste continues, then the landfill's contribution to global warming will increase drastically because of production and emissions of methane. Controlling methane emissions is essential in reducing the global warming contribution of landfills. Capturing methane for use as an energy source is a potential option to reduce the global warming potential for landfills (Hong *et al.*, 2010).

Recycling of waste preserves natural resources. For example, the production of paper from paper waste reduces the use of virgin fibres, possibly leading to reduced deforestation. Forests absorb carbon dioxide during photosynthesis. This can offset greenhouse gases from other sources (Harrison, 2001). Additionally, waste recycling reduces the amount of municipal solid waste to be finally disposed at landfills, prolonging landfills' lifespans. This is important for East African cities since suitable parcel of lands in the periphery of the cities are becoming increasingly scarce because of rapid urban expansion for human settlement and industrial development. Recycling organic waste also returns nitrogen and phosphorus into the soil. This reduces environmental impacts by avoiding the emissions associated with the production of chemical fertiliser

(Bernstad and la Cour Jansen, 2011). Nonetheless, composting processes cause high acidification and nutrient enrichment because of their high ammonia emissions. This can pose a threat to the water quality for Lake Victoria. The importance of ammonia emissions from composting processes for acidification and nutrient enrichment have also been reported by other authors (e.g. Banar *et al.* (2008) and Bernstad and la Cour Jansen (2011)). These impacts can easily be reduced substantially by using advanced emissions control technologies in composting processes. Sironi *et al.* (2007), for example, estimated ammonia removal efficiencies of odour removal devices in closed composting facilities to be about 95%. These reduction technologies can be explored for large-scale composting plants. When considering East Africa's low economic development status and poor investment climate, application of large-scale composting plants with advanced emissions reduction technologies might be impossible for the near future. Small-scale or home composting technologies seem the most viable solutions for managing organic waste in East African cities because of their minimal environmental impacts and low investment costs.

6.5 Optimal system for managing waste flows in East African cities

This section addresses the forth research question on the optimal scenario to improve environmental performances of waste infrastructures in East African cities. Four scenarios, namely: The 'Business-as-usual', 'More collection', 'More enforcement' and 'Proper management' scenarios are appraised against economic, environmental, social, technological and general criteria, simultaneously. Several multi-criteria analysis approaches exist in literature. This thesis applied the rating approach since it is a flexible weighted scoring decision making tool that facilitates the setting of priorities and making decision (Oyoo *et al.*, 2013). An alternative approach is the distance-to-target approach, which measures the distance between the calculated present day environmental loads and a defined target level (Jawjit, 2006). This approach is not chosen, since no targets are set for the reduction for waste flows in East African cities.

The analysis shows that the 'Proper management' scenario, combining enforcement enhancement, awareness-raising, and enhancement of the implementation of diverse waste collection and treatment technologies, performed best on all assessed criteria. This is because of its mix of diverse technologies from small-scale to large-scale systems and extra management approaches aiming at both low-cost resource recovery and the reduction of environmental loads (Oyoo *et al.*, 2013). This finding is comparable to the other studies viewed. For example, Wilson *et al.* (2012) in their assessment of municipal solid waste management in twenty mega-cities mentioned that no single waste management approach can treat all the wastes in cities in developing countries, because of their heterogeneity in spatial settlement patterns. The scenarios emphasizing more on waste collection but less on resource recovery are ranked in the middle. The 'Business-as-usual' scenario, maintaining the status quo, performed worst on all assessed criteria. These results show that incorporating multiple technologies and measures is important for designing a suitable waste management system that is robust and accessible by all city residents. This improves waste flows management, particularly primary waste collection, and such management improvements require both social and technical considerations (Scheinberg *et al.*, 2011).

6.6 Implication of study results for Lake Victoria's performance

This section addresses the fifth research question on improving Lake Victoria's environmental performance. The section integrates findings for the four previous research questions, which all consistently conclude that integrating a mixture of diverse waste treatment technologies, enforcement enhancement and awareness-raising, and matching with the specific local context of a city, produce the least environmental impacts. This means that mixing and optimising diverse waste management approaches, and fitting them to the specific local conditions, is a suitable strategy to manage waste flows in cities surrounding Lake Victoria to better the lake's environmental performance. A better performance in this context refers to improvement of Lake Victoria's water quality. The waste management system is taken to be appropriate when the criteria for a modernised mixture approach (i.e. flexibility, ecological sustainability, accessibility and resilience to socio-political changes) are fulfilled (Scheinberg *et al.*, 2011).

The modernized mixture approach optimises environmental infrastructures performance by integrating diverse technologies, economies and socio-political dimensions to fit the physical and human systems at a specific local condition (Scheinberg and Mol, 2010; Scheinberg *et al.*, 2011). This conceptual approach is very helpful for searching appropriate interventions along one or more dimensions. The approach considers that environmental infrastructure services need to address access for the poor, the robustness of the systems, the low levels of technological capabilities, and institutional support of waste infrastructures. The modernized-mixed waste system in this thesis is attained by organising all waste systems in such a way that an optimal mix of scales, strategies, technologies and decision making structures are considered. This results in a configuration that takes the best features out of both conventional centralised and generally perceived modern system, and alternative decentralised systems (Scheinberg and Mol, 2010).

A mixture of diverse and optimised waste management systems is flexible for managing waste flows in East African cities because of their heterogeneous settlement patterns. These cities have a sharp differentiation between high-income and low-income settlements in terms of population densities, public infrastructures, housing stocks, and the reach of water, transport and energy utilities (Makita *et al.*, 2010). This calls for a shift from the centralised-decentralised model of waste management to a modernised mixture approach of waste systems. For example, the modernised mixture approach to manage organic solid waste produced in these cities can be done through applying small-scale compositing or home-composting facilities in densely built-up informal settlements, as well as by using a centralised composting facility or landfill for planned settlements where door-to-door waste collection can be effected. Likewise, human excreta can be managed by a combination of centralised or satellite sewerage systems for planned settlements, and on-site sanitation for informal and peri-urban settlements. The on-site sanitation can be supported by intermediate light faecal sludge emptying and collection tools to complement the conventional vacuum trucks. Application of such light tools can transform insanitary manual emptying to hygienic and acceptable service provisioning in slums, as they can easily manoeuver through narrow paths (NWSC, 2008). The collected faecal sludge can be treated separately to enhance reusability of bio-solids. Separate treatment of faecal sludge is suitable for anaerobic digestion as the waste is concentrated (Lettinga *et al.*, 1997). Given the low economic development level for East African cities, on-site sanitation systems will remain dominant in the next two decades, because of their high accessibility and flexibility. Therefore, enhancing the use of properly constructed on-site sanitation in East African cities will lead to minimal environmental impacts on Lake Victoria.

Furthermore, a mixed and optimised waste system tailored to the needs of the end-users and to the specific local conditions is considered to be ecologically sustainable. Such waste systems provide opportunities to introduce technologies that recover nutrient and/or energy as well as minimise environmental and human health impacts, by minimising entry of pathogens into the water cycle (Werner *et al.*, 2009). Waste management in East African cities and those in other developing countries' cities are largely focused on collection. Concerns about environmental protection and pollution avoidance are less important than the need to clean up business districts and affluent neighbourhoods (Scheinberg and Mol, 2010). By applying a mixture of waste management systems both the needs for the low- and high-income households with regard to waste management will be addressed. For instance, a combination of human-powered tools (e.g. wheelbarrows and animal-drawn carts) and engine-powered means (e.g. trucks) matching the heterogeneous settlement patterns can be applied for municipal solid waste collection. Likewise, a combination of communal septic tanks and centralised sewage treatment systems can be applied for human excreta treatment in informal and planned settlements, respectively.

The increasing trend of rural-urban migration implies a shift of recoverable nutrients to cities. Nutrients should be recovered and ploughed back to peri-urban farm lands. This increases agricultural productivity, contributing to food security. However, applying technologies that lead to re-use of product may face some challenges in their implementation and operations to achieve the desired objective. The cultural perception by some communities can affect the success of applying co-composting technologies, for example, anaerobic digestion with the aim of producing organic fertiliser. Also, because of health reasons people may fear to use the compost produced from human excreta. Awareness-raising campaigns and capacity building measures are helpful in overcoming such constraints. Also, new regulations and institutional arrangements for technologies, and linking their products to rural areas are necessary.

A mixed and optimised waste management system is considered robust to socio-political changes because not all the different waste systems are linked to the political framework of a city. For instance, the on-site sanitation systems and home-composting facilities are managed at household level, and they are not directly influenced by the political framework for the city. Meanwhile the large-scale centralised systems like landfills and sewerage are managed at city level and they are linked to the political framework for the city. Also, the large-scale waste systems require huge budgets for their operations and maintenance. Such a huge budget to carry out adequate waste management is rarely available in developing countries' cities, including those in East Africa. This has an impact on the environmental performances of large-scale centralised waste infrastructures in protecting the environment. The centralised municipal solid waste collection system for Kampala, for example, has failed several times whenever a change occurs in the political leaderships for the city (KCC, 2006). This is attributed to changes in priorities by the politicians, which leads to reallocation of funds from the waste sector to other sectors (and vice versa).

6.7 Thesis's innovations, strengths and limitations

This research successfully applied environmental systems analysis approach to understand the current and future waste flows, and their environmental impacts in East African cities surrounding Lake Victoria. The study examined the combination of both human excreta and municipal solid waste to solve their interrelated problems, as they both contain readily biodegradable organic matters. This is an innovative approach for East African cities, as their municipal solid waste is predominantly organic and on-site sanitation systems are the main option for managing human excreta. Also, the study extended the normal life cycle analysis approach with scenario analysis to assess the environmental impacts of waste recycling in East African cities, exemplified with Kampala. Additionally, the organic waste reduction scenarios were appraised against specific urban criteria for each city surrounding Lake Victoria using a single set of criteria. The study produced an integrated dynamic box model, which was applied to search for, and assess, the different future potential and feasible scenarios for managing waste flows under different regimes. This box model can also be adapted to study the waste flows dynamics and their environmental impacts in cities in the region and even other developing countries' cities with comparable characteristics to the cities assessed in this thesis.

Despite the thesis's methodological innovations and strengths, the primary data collection to accurately model a system representing the processes for waste flows was limited for all the studied cities. Collecting primary data at city level was difficult, but the availability of waste flow data for Kampala and Dar es Salaam provided a unique opportunity to model their waste flows and generalise this approach to the other East African cities. Furthermore, no data was available on specific consumption patterns for the case study cities. Nonetheless, by analysing the major factors influencing waste flows, and linking them to other literature, reasonable assumptions can be made for the development of an integrated dynamic box model, but proper validation remains difficult. To test these assumptions and understand the dynamics of waste flows, local studies on waste flows, their impacts and strategies to mitigate them are needed. Nevertheless, the limited available data was applied to test and validate the model. The model was successfully applied to simulate plausible future scenarios for waste management under different waste flow regimes. The results showed an increasing trend of urban organic and nutrient loads to Lake Victoria's inshore, and a deteriorating tendency of urban environmental quality, if no actions are taken to prevent, reduce or treat waste flows. This trend is comparable to findings reported in many other studies, such as Scheren *et al.* (2000), LVEMP (2001) and Muyodi *et al.* (2009).

Another limitation is that the environmental impacts of waste flows are not explicitly calculated, but rather, estimated based on generic average emission factors. Emission factors can change spatially and temporally because of specific or changing local environmental conditions. This variation is ignored in this thesis. Pinder *et al.* (2004), however, showed how important it is to include temporal and spatial variability when estimating ammonia emissions. This may also hold true for other emissions. Ignoring such variations can lead to some uncertainties in the actual quantification of results, and thus misinterpretation of results by end-users. However, the sensitivity analysis performed on the effect of changing waste composition showed no change in the ranking of the scenarios with respect to minimal environmental impacts. Additionally, the simulated trends are distinct. This confirms that the model is robust across wide variations in the numerical estimates of emission factors.

Also, this thesis assumed population size to increase with a net constant growth rate. Application of a constant net growth rate for a long simulation period (e.g. 50 years) may be unrealistic because birth rates may change due to improvement in the standard of living, increased confidence of children survival to maturity, improved status of women or increased use of birth control measures. This has consequences on the study's waste production estimates, which may be overestimated. However, the number of inhabitants in the given geographical areas for the cities drives their net amount of urban wastes generated. Therefore, population size is only used as a proxy to estimate the quantity of urban waste generated. Since scenario analyses are performed to show plausible future trends (and not predictions), the application of a constant net growth rate is reasonable to understand feedbacks and interactions within the system for the coming decades.

Furthermore, all environmental systems analysis studies are prone to uncertainties (Walker *et al.*, 2003). The important uncertainties for this thesis are model inputs and parameter values. The input uncertainty includes measurement errors for model's inputs. Due to lack of data, some model inputs are approximated from literature values. For example, waste production was estimated based on population growth and waste generation rates. This thesis explicitly considered parameter uncertainty by evaluating the values of constants used in the model. Some of these constants are not specific to local conditions for East African cities. The sensitivity analysis showed that with changes up to 30%, results are comparable to the baseline and literature values. This indicates the model is relatively robust.

Additionally, stakeholder participation in the design of scenarios is excluded because of limited resources. Participatory scenario analysis requires several cycles of storyline writing, quantification and scenario review by several participants, which makes the exercise costly (Alcamo, 2001; Mietzner and Reger, 2004). Stakeholder involvement ensures that different views and opinions are incorporated in scenarios. This leads to the development of more sustainable and legitimate waste management solutions (Alcamo, 2001). Nonetheless, scenarios capturing different pollution reduction strategies derived from literature, showed an improved urban environmental quality. This is in agreement with the recommendations stated in similar studies performed by, for example, LVEMP (2001) and Muyodi *et al.* (2009).

Despite the limitations for the study, the analysis clearly improved insights in the dynamics of waste flows and their consequences on the urban environment, so as to improve the water quality for Lake Victoria. Although many processes remain to be studied and refined, the analyses have revealed some important aspects that need to be considered when projecting impacts of waste flows on the urban environment in East Africa.

6.8 Future research

To gain more insights on the dynamics of waste flows and their environmental impacts in East African cities, a more in-depth analysis of uncertainties is essential. Uncertainty analysis can be done qualitatively (e.g. expert judgement) and/or quantitatively (e.g. error propagation). These approaches are not extensively used in this thesis. The analysis of uncertainty associated to model inputs needs to be explored, to identify processes that require field measurements to address the uncertain and important processes. It is worth noting that environmental systems analysis procedures can reduce uncertainty through iteration. Iterating loops associated with system definition can reduce context uncertainty, and iterating loops associated with model building can reduce model uncertainty, inputs uncertainty, parameter uncertainty and results uncertainty (Jawjit, 2006). These iteration approaches are not fully applied, and so they need to be explored to improve the model results to enable better planning for future waste flows management.

The lack of adequate data for waste flows and associated socio-economic parameters for all the studied cities suggest the need for city authorities in East Africa to allocate more resources to develop comprehensive waste flow databases. Data on pollution intensities for surface water runoffs, consumption patterns, seasonal waste production rates, waste generation rates by different income groups, fractions of waste components in dry weight, and emission factors specific to each city are required. Such data can be collected by engaging undergraduate and postgraduate students. Acquisition of such data would eliminate approximation of model inputs from literature values and this reduces uncertainties in the actual quantification of results. This leads to fine tuning of waste management options to improve water quality for Lake Victoria.

As Lake Victoria’s shoreline is shared by three countries, creating a common definition of waste typologies is vital for regional policy for protecting the lake’s water quality. This thesis limits the definition of urban waste to only municipal solid waste and human excreta. To better match policy needs at regional level, waste studies need to include also industrial and agricultural wastes. Therefore, future research should qualify and quantify the waste flows for industrial and agricultural sectors to Lake Victoria’s inshore. This will enable better planning for the future protection of Lake Victoria’s water quality from pollution by waste.

6.9 Final conclusions

This research shows that the present state of waste management in East African cities surrounding Lake Victoria is very poor, and there is a need for urgent action by city authorities and the general public to improve the environmental performance of the waste sector in these cities. The organic loads for the cities surrounding Lake Victoria to the lake's inshore increased by 39% compared to the reported loads of 2001 by the LVEMP. The lake's water quality has deteriorated; impacting on human health, ecosystems and economic activities dependent on Lake Victoria. The integrated modelling approach and the scenario results indicate that if no mitigation measures are put in place to reduce, prevent or treat the various waste flows, the urban environmental quality deteriorates rapidly. Applying a mix of diverse technologies and different management regimes, and matching them to the heterogeneous spatial settlement patterns, and local socio-economic and environmental conditions in East African cities, will lead to minimal environmental impacts and high environmental benefits.

The research also shows that waste flows management in East African cities is complex, as the spatial heterogeneous settlement patterns are unlikely to accept a single approach to adequately collect and treat all the various waste flows. The sharp differentiation in settlement patterns, socio-economic conditions and level of urban environmental development between the low- and high-income settlements in these cities makes it impossible to apply a single uniform, high-technological and large-scale waste management system to manage the various waste flows. The evaluation of scenarios using a multi-criteria analysis shows that a mixture of diverse waste collection and treatment technologies and different management approaches, fitting the heterogeneous settlement patterns, is the most optimal solution to manage the various waste flows in East African cities, to produce minimal environmental impacts and to enhance human health.

The presented research quantified the current and future environmental loads and impacts of the different waste flows under different management regimes. This contributes to the development of an integrated policy support, which aims at strengthening the sustainable management of waste flows in East African cities. Such integrated analysis forms the basis for improving the urban environmental quality in these cities, and thus improving Lake Victoria's water quality and the well-being of humans depending on the lake.


16 2:50AM

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Summary

Urban waste flows are often linked to the wider surroundings of the urban areas, and they degrade the environment and pose public health risks, when improperly managed. Many city authorities in developing countries including those in East Africa have been unsuccessful to adequately provide waste collection and treatment services to all the urban residents including the urban poor in their cities. In many East African cities, uncollected municipal solid wastes are seen along roadsides and in storm surface water drains, and sewage overflows and illegal disposal of faecal sludge to the environment are common seen in the informal settlements. Large volumes of waste flows from the surrounding cities of Lake Victoria enter the lake's inshore, polluting its water and causing eutrophication. Also, the groundwater sources in areas with high water table are contaminated with faecal coliforms. Poor water quality has consequences for ecosystems, human health and economic activities related to the lake. There is therefore an urgent need for effective and efficient management of the various waste flows in surrounding cities of Lake Victoria in East Africa, to safeguard the lake's water quality from pollution by urban waste.

To manage the various waste flows effectively, the current and future trends for the waste flows and their environmental impacts need to be assessed. A model representing waste management flows through the social and natural systems of East African cities would enable the projection of the future waste flows trends and their environmental impacts under different waste management regimes, in order to design appropriate responses. A process-based approach, describing different waste flows at different stages and connecting them at different levels of analysis is considered a suitable strategy to build a model under conditions of data limitations. Such a model would enable proper understanding, qualifying and quantifying of waste flows and their environmental impacts in expanding East African cities.

This research is part of the PROVIDE project, which aims to investigate the technological and institutional dimensions of sanitation and municipal solid waste management in East African cities, to improve the environmental performance of water and waste sectors. This study contributes to the PROVIDE project by

focusing on simulation of sanitation and waste flows through the natural and social systems in East African cities, to understand, qualify and quantify the current and future trends for waste flows and their environmental impacts. It then applies the box model to search for and assess solutions for better management of various waste flows, to minimise environmental and human health impacts. Specifically, the study assesses the current organic loads to Lake Victoria's inshore from its medium and large size surrounding cities; project the likely and possible future waste flows and their environmental impacts when technological, social and economic changes are all taken into consideration together; assesses the impact of waste recycling in improving the environmental performance of waste sector in East African cities; determines the optimal scenario for improving environmental performance of waste sector in East African cities when economic, environmental, social, technological and the 'general' criteria are integrated; and examines the most suitable system for better management of waste flows to minimize pollution of Lake Victoria' s water and human health impacts.

The objective for thesis is addressed through sequential steps. Having presented the current knowledge on waste flows for East African cities in Chapter 1, the environmental loads to Lake Victoria's inshore for medium and large size cities, and the pollution abatement strategies are presented in Chapter 2. The results show that the annual organic load to Lake Victoria's inshore increased twofold in 2011 since the reported loads of 2001 by the LVEMP. Kampala had the highest organic loads, followed by Kisumu, Mwanza, Musoma, Bukoba and Jinja. Also, the environmental performances for the different but plausible future scenarios relative to the baseline load for each city show composting scenario, and scenario integrating and optimising mixture of diverse organic waste treatment options produced minimal environmental loads. Additionally, the evaluation results for the scenarios against local urban specificities show that the optimal scenarios for the reduction of organic loads are specific for each city due to their differences in local conditions across the cities assessed.

Next, Chapter 3 projects the future waste flows and their environmental impacts for African metropolises using a system dynamics approach. Simulation runs for plausible waste management scenarios indicate that with no additional measures to prevent, to reduce and to treat the various waste flows, the urban environmental quality deteriorates rapidly with negative consequences for human

health and economic activities related to Lake Victoria. Scenarios stressing for more collection and treatment reduced environmental loads but performed less well in resource recovery. Scenario combining technological development, awareness-raising and enforcement enhancement, produced the smallest environmental loads and recovered the largest resources. Applying a mixture of diverse waste collection and treatment technologies and different management approaches, fitting the heterogeneous spatial settlements patterns leads to minimal environmental impacts.

Chapter 4 evaluates the performances for four plausible scenarios against criteria of economic, environmental, technological, social and general, simultaneously. Evaluation results show that a scenario mixing diverse waste collection and treatment technologies and different management approaches, and matching with the local social and natural systems in each city is ranked best. Scenarios laying emphasis on more waste collection and treatment, but less on resource recovery are ranked middle. Scenario maintaining the status quo is ranked worst. The study concludes that applying mixture of diverse waste collection and treatment technologies and management styles, and matching with the local social-economic and environmental conditions is the most optimal system to manage the various waste flows, to produce minimal environmental impacts.

Chapter 5 assesses the environmental impacts of waste recycling in East African cities using the normal life cycle analysis extended with scenario analysis. The potential environmental impacts of four future scenarios for different waste management regimes are estimated. The impacts categories estimated are global warming, acidification, nutrient enrichment, photochemical ozone formation, water sources pollution and resource recovery. The assessment results show that a combination of anaerobic digestion, recycling, landfilling and sewerage systems produced minimal environmental impacts. Thus, integrating waste recycling to form part of the formal waste management system is likely to improve the environmental performance of waste sector in East African cities.

To conclude, Chapter 6 combines the findings in Chapters 2, 3, 4 and 5, to help improving the environmental performance of waste sector in East African cities. The research quantified the current and future environmental loads and their impacts for different responses for managing waste flows under different regimes. This contributes to the development of an integrated policy support

approach, which aims at strengthening the sustainable management of waste in East African cities. This forms the basis for improving the urban environmental quality in these cities. Also, in agreement with modernised mixture approach, this study conclude that applying mixture of diverse waste collection and treatment technologies and different management approaches, and matching with the settlement patterns, and local social and environmental conditions in each city will have positive impacts on the environmental quality for East African cities. Therefore, mixtures of diverse collection and treatment technologies and different management strategies are required to manage the various waste flows, to produce minimal environmental impacts, and thus, safeguard Lake Victoria's water quality from pollution by waste, and improve the well-being of humans.

Samenvatting

Stedelijke afvalstromen beïnvloeden vaak de wijdere omgeving van stedelijke gebieden. Ze degraderen het milieu en vormen een risico voor de volksgezondheid wanneer ze onjuist beheerd worden. Veel stedelijke overheden in ontwikkelingslanden, inclusief die in Oost-Afrika, zijn er niet in geslaagd effectieve afvalinzamelings- en –verwerkingsdiensten aan te bieden aan hun burgers. In veel Oost-Afrikaanse steden is niet opgehaald huishoudelijk afval te zien langs bermen; ook komen overlopende rioleringssystemen veel voor in de informele stadswijken. Grote stedelijke afvalstromen rondom het Victoriameer stromen in de kustwateren van het meer, met watervervuiling en eutrofiëring als gevolg. Ook zijn de grondwaterbronnen in gebieden met een hoge grondwaterstand vervuild met fecale E. coli bacteriën. Een slechte waterkwaliteit heeft gevolgen voor ecosystemen, menselijke gezondheid en economische activiteiten die verbonden zijn aan het meer. Er is daarom een grote behoefte aan een effectief en efficiënt beheer van de diverse afvalstromen in Oost-Afrikaanse steden rond het Victoriameer, om zo het meer te behoeden voor stedelijke vervuiling.

Om de verschillende afvalstromen effectief te beheren, is kennis van de huidige en toekomstige trends voor afvalstromen en hun milieueffecten essentieel. Een model dat afvalstromenbeheer in sociale en natuurlijke stedelijke systemen in Oost-Afrika beschrijft, zou het mogelijk maken trends van toekomstige afvalstromen en hun effecten op het milieu onder verschillende afvalbeheerregimes te onderkennen om te komen tot passende oplossingen. Een procesgebaseerde benadering die verschillende afvalstromen in verschillende stadia beschrijft en ze op verschillende analyseniveaus verbindt, is een geschikte strategie om een model te bouwen om afvalstromen en hun milieueffecten in uitbreidende steden in Oost-Afrika te begrijpen, karakteriseren en kwantificeren, vooral als er beperkte data voorhanden zijn.

Dit onderzoek maakt deel uit van het PROVIDE-project dat tot doel heeft het onderzoeken van de technologische en institutionele aspecten van afvalverwerking en huisvuilbeheer in Oost-Afrikaanse steden, teneinde de milieuprestaties van urbane water- en afvalsectoren te verbeteren. Dit proefschrift draagt bij aan PROVIDE door zich te concentreren op geïntegreerde dynamische modellering van afvalstromen in natuurlijke en sociale systemen in Oost-Afrikaanse steden, om de huidige en toekomstige trends voor afvalstromen en hun milieueffecten te begrijpen, karakteriseren en kwantificeren. Een compartimentenmodel is ontwikkeld en vervolgens toegepast om oplossingen voor beter beheer van diverse afvalstromen te onderzoeken en vast te stellen hoe de effecten op milieu en menselijke gezondheid kunnen worden geminimaliseerd. Deze studie (i) bepaalt de huidige organische belastingen naar de kustwateren van het Victoriameer vanuit zijn middelgrote en grote omringende steden; (ii) beschrijft de waarschijnlijke en mogelijke afvalstromen en hun milieueffecten wanneer technologisch, sociale en economische veranderingen gezamenlijk in aanmerking worden genomen; (iii) bepaalt het effect van afvalrecycling op het verbeteren van de milieuprestaties van de afvalsector in Oost-Afrikaanse steden; (iv) bepaalt het optimale scenario voor het verbeteren van milieuprestaties van de afvalsector in Oost-Afrikaanse steden als economische, sociale, technologische en algemene criteria worden geïntegreerd; en (v) onderzoekt het meest geschikte system voor beter beheer van afvalstromen om vervuiling van het Victoriameer en humane gezondheidseffecten te minimaliseren.

De huidige kennis over afvalstromen in steden in Oost-Afrika wordt gepresenteerd in Hoofdstuk 1. Vervolgens worden de milieubelasting van kustwateren van het Victoriameer vanuit middelgrote en grote steden en de strategieën voor het terugdringen van vervuiling gepresenteerd in Hoofdstuk 2. De resultaten tonen dat de jaarlijkse organische belasting van de kustwateren van het Victoriameer in 2050 twee maal zo hoog kan worden als in 2000. De stad Kampala veroorzaakte de hoogste organische milieubelasting, gevolgd door Kisumu, Mwanza, Musoma, Bukoba and Jinja. De milieuprestaties van de verschillende, maar aannemelijke, toekomstscenario's ten opzichte van de basisbelasting door elke stad tonen dat zowel een composteringsscenario als een scenario dat verschillende afvalverwerkingsmogelijkheden integreert en optimaliseert, een minimum aan organische belasting veroorzaken. Bovendien blijkt uit de evaluaties van de scenario's met lokale stedelijke kenmerken dat optimale scenario's voor het terugdringen van organische belasting specifiek zijn voor elke stad, vanwege verschillen in lokale omstandigheden.

Hoofdstuk 3 beschrijft en analyseert de toekomstige afvalstromen en hun milieueffecten voor Afrikaanse metropolen door middel van een dynamische systeembenadering. Simulaties voor aannemelijke afvalbeheerscenario's geven aan dat, als er geen aanvullende mitigatiemaatregelen worden genomen ter voorkoming, vermindering en verwerking van afvalstromen, de stedelijke kwaliteit snel zal verslechteren met negatieve gevolgen voor menselijke gezondheid en economische activiteiten gerelateerd aan het Victoriameer. Scenario's die de nadruk leggen op meer inzameling en verwerking, verminderden de milieubelasting, maar presteerden minder goed in het terugwinnen van grondstoffen uit afval. Een scenario dat technologische ontwikkeling combineert met bewustzijnsverhoging en versterken van handhaving, resulteert in de laagste milieubelasting en hoogste terugwinning van grondstoffen. Toepassen van een combinatie van diverse afvalinzamelings- en –verwerkingstechnieken en verschillende beheermethoden die passen bij de heterogene ruimtelijke nederzettingen leidt tot minimale milieueffecten.

Hoofdstuk 4 beoordeelt de prestaties van vier aannemelijke scenario's met behulp van economische, milieu, technologische, sociale en algemene criteria tegelijkertijd. De resultaten laten zien dat een scenario het best scoort als het verschillende afvalinzamelings- en verwerkings-technologieën, en beheermethoden combineert en aanpast aan de lokale sociale en natuurlijke systemen in elke stad. Scenario's die de nadruk leggen op meer afvalinzameling en verwerking, maar minder op terugwinning van grondstoffen uit afval presteren middelmatig. Een scenario dat de status quo handhaaft, presteert het slechtst. De conclusie van dit proefschrift is dat de toepassing van een combinatie van verschillende afvalinzamelings- en -verwerkingstechnologieën en beheerstijlen, aangepast aan de lokale omstandigheden, het meest optimale system is om de verschillende afvalstromen te beheren en milieueffecten te minimaliseren.

Hoofdstuk 5 beoordeelt de milieueffecten van afvalrecycling in Oost-Afrikaanse steden, gebruik makend van een normale levenscyclusanalyse en uitgebreid met scenarioanalyse. De mogelijke milieueffecten van vier toekomstscenario's voor verschillende afvalbeheersystemen zijn geschat. De geschatte effectcategorieën zijn opwarming van de aarde, verzuring, eutrofiëring, fotochemische ozonvorming, vervuiling van waterbronnen en terugwinnen van grondstoffen uit afval. De resultaten tonen aan dat een combinatie van anaerobe vergisting, recycling, afvalstortingen en rioleringssystemen de laagste milieueffecten sorteert. Integratie van afvalrecycling als onderdeel van het formele afvalbeheersysteem zal waarschijnlijk de milieuprestaties van de afvalsector in Oost-Afrikaanse steden verbeteren.

Tot slot combineert Hoofdstuk 6 de bevindingen in de eerdere hoofdstukken om de milieuprestaties van de afvalsector in Oost-Afrikaanse steden te helpen verbeteren. Het onderzoek kwantificeert de huidige en toekomstige milieubelasting en de milieu- en gezondheidseffecten voor verschillende vormen van afvalstroombeheer. Deze geïntegreerde beleidsondersteunende aanpak richt zich op het versterken van duurzaam beheer van afval in Oost-Afrikaanse steden. Het vormt de basis voor verbetering van de milieukwaliteit in deze steden. Overeenkomstig de zogenoemde 'Modernised Mixtures'-benadering, concludeert dit proefschrift dat het toepassen van een combinatie van uiteenlopende afvalinzamelings- en verwerkingstechnologieën en verschillende beheer-methoden, aangepast aan de stedelijke patronen en de lokale sociale en milieuomstandigheden in elke stad, positieve effecten zal hebben op de milieukwaliteit van deze steden. Combinaties van uiteenlopende inzamelings- en verwerkingstechnologieën en verschillende beheerstrategieën zijn vereist om diverse afvalstromen te beheren, milieueffecten te minimaliseren en daardoor het Victoriameer te beschermen en het welzijn van mensen te verbeteren.

Publications

Papers published are:

1. **Oyoo R, R. Leemans and A.P.J Mol (2011).** Projections of urban waste flows and their impacts for African metropolises using a system dynamics approach. *International Journal of Environmental Research* 5: 705-724.

2. **Oyoo R, R. Leemans and A.P.J Mol (2013)**. Determining an optimal waste management scenario for Kampala City, Uganda. *Waste management & Research*. 31 (12) 1203-1216.

3. **Oyoo R., R. Leemans and A.P.J Mol (2014).** Comparison of environmental performance for different waste management scenarios in East Africa: The case of Kampala, Uganda. *Habitat International.* DOI 10.1016/j.habitatint.2014.07.012.

Educational program

The SENSE Research School declares that **Mr Richard Oyoo** has successfully fulfilled all requirements of the Educational PhD Programme of SENSE with a work load of 48 ECTS, including the following activities:

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- Advanced Statistics

Other PhD and Advanced MSc Courses
- Social Theory & the Environment. Introduction into Ecological Modernisation Theory
- Integrated environmental assessment pollution management
- PROVIDE Introductory course on sanitation and solid waste management in East Africa

Management Skills Training
- Co-organizing the PROVIDE workshop for Lake Victoria's surrounding cities and their roles in the pollution of the lake, Kisumu, Kenya, 21-24 November 2007

Oral Presentations
- *The background problems of waste flows in East African cities, concept proposal for integrated modelling of sanitation and solid waste flows in East African Urban centres.* PROVIDE Inception Workshop, 20 December 2006, Wageningen, The Netherlands
- *Projections of solid waste flows and their environmental impacts in East Africa, case of Kampala, Uganda.* PROVIDE Symposium, 21-24 November 2007, Kisumu, Kenya
- *Future projections of sanitation and solid waste flows and their environmental impacts on Kampala, Uganda.* 10th WATERNET/WARFSA/GWP-SA -SYMPOSIUM, 28-30 October 2009, Entebbe, Uganda
- *Projections of sanitation flows and their environmental impacts in East Africa, case of Kampala, Uganda.* PROVIDE Symposium, 3-6 October 2008, Arusha, Tanzania
- *Projections of sanitation and solid waste flows and their environmental impacts in East Africa, case of Kampala, Uganda.* PROVIDE Symposium, 20-25 June 2009, Kampala, Uganda
- *Determining an optimal waste management scenario for Kampala, Uganda.* PROVIDE Symposium, 19-23 September 2011, Arusha, Tanzania

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About the Author

Richard Oyoo was born on the 3rd of October 1972 in Gulu, Uganda. After his secondary and advanced levels education, he joined Makerere University, Uganda in 1992, and graduated in 1995 with a BSc (Hons) degree in Industrial Chemistry. His BSc-thesis was on optimizing the performance of rapid gravity sand filters at the Gaba water treatment plants in Kampala, Uganda.

In 1997, he was employed by the National Water and Sewerage Corporation (NWSC), and in 1998, he was offered a grant from the Netherland Fellowship Program for a master degree in Water and Environmental Resources Management at the UNESCO-IHE, the Netherlands, which he completed in 2000. His MSc-thesis was on modeling the transportation and fate of pesticides in Danish surface water streams. In 2001, he studied the lake water management at the International Lake Environmental Committee, Japan. In 2002, he was seconded by the NWSC to work on a project for the Municipal and Industrial Waste Component for Lake Victoria Environmental Management Program with Mott MacDonald in Cambridge, United Kingdom. In this period, he modelled pollutant’s dispersion in Lake Victoria’s Murchison Bay in Uganda, siltation of flood control pond system for Kuala Lumpur City, Malaysia and optimization of sewage ponds performance for Mexico City.

In 2006, he started a master program in Software Engineering at Makerere University, Uganda. The same year he was offered a research grant from Wageningen University, the Netherlands for a sandwich PhD on sanitation and waste flows in East African cities, with the Environmental Systems Analysis Group and the Environmental Policy Group. In 2007, he returned to Uganda for data collection and also continued with his master program in Software Engineering, which he completed in 2008. His MSc-thesis was on development of a 3-Tier Web-based Water Quality Database, case study of the NWSC.

In 2009, he got employed by the UNAMID, Sudan to head the Environmental Protection Unit. He continued with his PhD research and defended it on the 14th of October 2014 in Wageningen University, the Netherlands. His special research interest is on improving water and waste management, to improve the livelihoods of the urban poor and to protect the environment from pollution by waste.

Funding

The research described in this thesis is part of a larger research project, Partnership for Research on Viable Infrastructure Development (PROVIDE), which was financially support by the Interdisciplinary Research and Education Fund (INREF) of Wageningen University, the Netherlands. I am very grateful for the funding I received throughout the entire study period.