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Future Projections of Urban Waste Flows aand their Impacts in African Metropolises Cities

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ABSTRACT: This paper presents future trends of urban wastes and their impacts on the environment of African cities using plausible mitigation scenarios. To accomplish this, an integrated dynamic model for urban waste flows was developed, tested, calibrated and validated. Its parameter sensitivity was analyzed. Using population projection up to 2052 with different levels of technological implementation, policy enforcement and awareness raising, four runs were executed. The "*business as usual*" run showed that with no additional mitigation measures, the environmental quality in Kampala and Dar es salaam Cities deteriorates. The "*more enforcement*" and "*more collection*" scenarios showed good reduction in environmental loads but they perform less well in resource recovery. The "*proper management*" scenario that combines enhanced technological implementation, awareness raising and policy enforcement, produced the smallest environmental loads, and recovered the largest amount of resources. Thus, the city authorities, general public, community based organisations and Non-governmental organizations would have to increase their efforts in finances and commitment to improve the urban environmental quality and increase resource recovery.

Key words: Solid waste, System dynamic, Urban environment, Kampala, Dar es Salaam

INTRODUCTION

The rapid population growth and rapid changes in lifestyles drive the rapid increase in the quantity and changes in the composition of urban solid waste in African cities. Only the business districts and affluent neighbourhoods have generally sufficient and high quality waste management services. The informal settlements have no or poor urban waste collection and management (Spaargaren *et al.*, 2006). Here also sanitation facilities are poorly operated and maintained. This deteriorates the urban environment and poses a public health risk. It is thus, a challenge to urban authorities to ensure adequate provision of urban waste management services to all city residents. Such condition is also observed in other developing countries (Abduli *et al.,* 2007; Nasrabadi *et al.,* 2008; Omran *et al.,* 2009). Kampala City in Uganda is also pressed with poor sanitation, among others by illegal disposal of faecal sludge in storm water drains, frequent sewer overflows and decreasing efficiency of existing wastewater treatment facilities. The solid wastes collection and treatment is inadequate, illustrated by heaps of uncollected solid wastes along road sides. Dar es Salaam in Tanzania faces similar problems. Here the existing sewage treatment facilities do not fulfil national effluent quality standards of Tanzania (DWSC, 2007). Not all solid wastes are adequately collected and treated (ERM, 2004). Future projections for solid waste (KCC 2006a) and wastewater (KSSMP, 2004) generation for Kampala City, and solid waste generation for Dar es salaam City (ERM, 2004) are available. Unfortunately, these projections were done using static models that likely underestimated the increase in urban waste and ignored changes in its composition. Such static models are inappropriate to explore dynamic systems. Thus, a dynamic model is the appropriate alternative to explore the future projection of urban waste production and to assess plausible waste management scenarios for a complex system. Such a model helps to understand large scale complex systems with feedback mechanisms (Dyson and Chang, 2005). This paper presents the development and application of such a model to project trends of urban wastes and assess their consequences on the

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urban environment with different mitigation scenarios. The model is developed, calibrated and tested using data for Kampala City, and validated with data for Dar es salaam City. Sensitivity analyses were also performed.

The proceeding section describes the method and materials used. Section 3 discusses the current urban waste situation, the model calibration, its validation, sensitivity analyses, and the scenarios and results. The final section draws conclusions.

MATERIALS & METHOD

Kampala, Uganda, covers an area of about 150 Km^2 (Matagi, 2002). The population of the city is spread over five divisions and has grown from about 0.8 million in 1991 to about 1.2 million in 2002 at an estimated annual growth rate of 3.8% (UBOS, 2006). The present Kampala administrative boundary (see Fig. 1) is the study area for the 2052 projections of future urban waste flows and their impacts on the environment.

The city is characterised by low lying hills and wet valleys covered with papyrus (Kulabako, 2005). The valley have high water table, which affects the operations of septic tanks as the soak pits gets saturated with water. The climate is tropical with small variations of temperature, humidity and wind throughout the year. The mean annual rainfall is 1180 mm. The rainy season is from March to May and October to November (UBOS, 2008). The surface runoff from the city is drained by the Nakivubo Channel into the Lake Victoria Inner Murchison Bay (IMB) via a wetland (see Fig. 1). The IMB represents the only drinking water source for Kampala residents.

Dar es Salaam, the capital of Tanzania, is located along the coast of Indian Ocean. The city covers an area of about 1400 Km^2 with an estimated population of 2.5 million by 2002 and an annual growth rate of 4.3%(ERM, 2004). The present city administrative boundary used for this study is presented in Fig. 2 Dar es Salaam City is divided into three municipalities, namely: Ilala, Kinondoni and Temeke.

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 1000mm. From March to May the rainfall ranges from 150 to 300mm, and short rains occurs from November to December (Yhdego, 1995).

To establish the quantities of solid wastes generated by different income groups, solid waste generation rates for low-, medium- and high-income households were determined through household surveys for a period of one month. The households were selected using random non-probabilistic sampling, and working only with households that agreed to participate. The solid waste composition was determined at the landfill for a period of nine days,

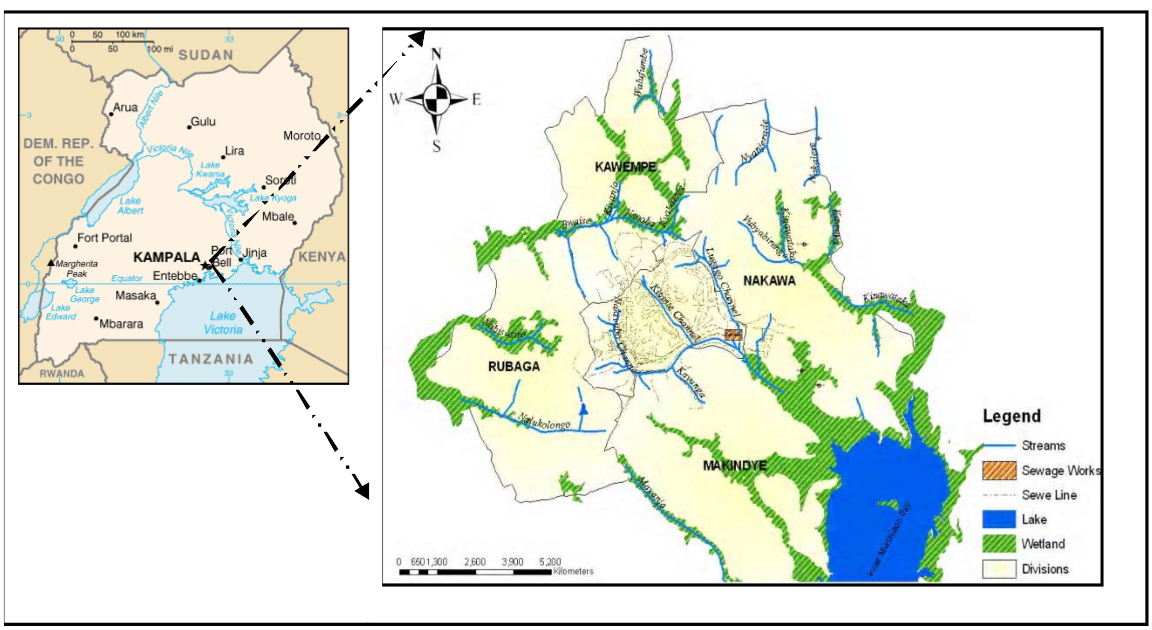


Fig. 1. Map of Kampala showing the divisions, streams, wetlands and sewer coverage

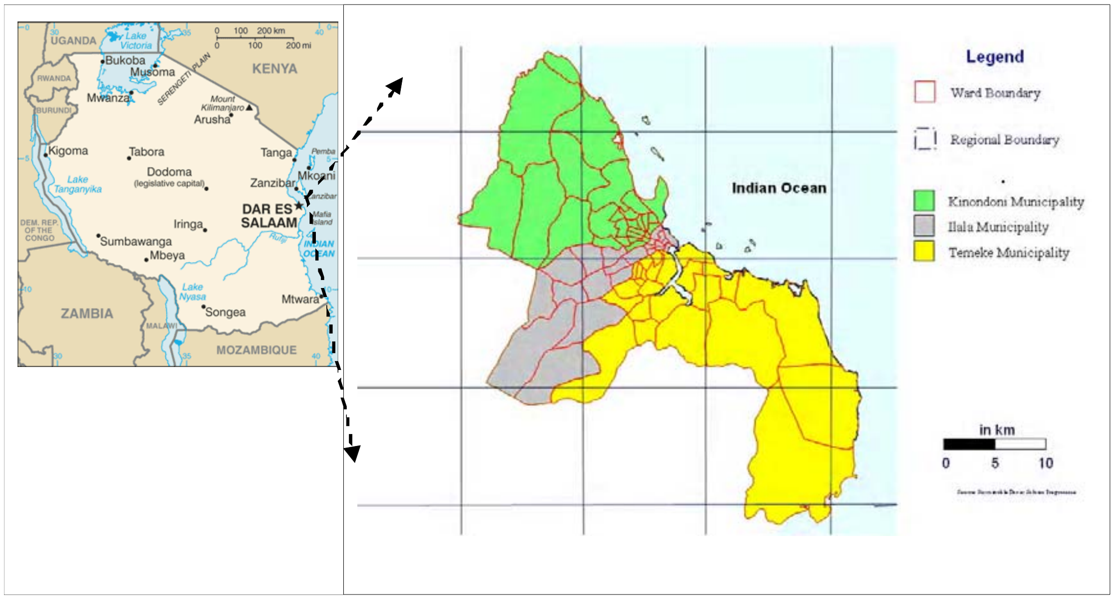


Fig. 2. Map of Dar es Salaam showing the three municipalities

using the method developed by the American Society for Testing Materials (ASTM). The composition analysis was conducted on solid wastes delivered from all five divisions.

The quantity of solid wastes disposed at landfills was computed from the daily disposal data recorded at the landfill. This was done to estimate the proportion of solid wastes that are collected and treated at the landfill. To assess the net amount of solid wastes finally disposed, the amount of recyclables salvaged (before and at the landfill) was estimated. Since the weights of recyclables are not measured at the landfill, the amount of recyclables salvaged at the landfill was determined by interviewing the scavengers and KCC officials. The amount of recyclables collected at the source of waste generation was estimated by interviewing the recycling industries and local communities.

The organic load reduction of the leachate treatment plant at the landfill was estimated by mass balancing the influent and effluent organic loads. The influent and effluent quality data used for the mass balance was determined in the laboratory using standard analytical procedure (Greenberg *et al.*, 1980). The organic solid composted at the source of waste generation was determined by interviewing KCC officials, local communities and through literature review.

The institutional arrangements and relevant policies on solid waste management were reviewed to understand causes for the increased amount of uncollected solid waste within Kampala City. Physical observation on solid waste management from households up to the disposal site was conducted to supplement the literature 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 amount of faecal sludge disposed at treatment plants was estimated from the disposal records. The records contain truck capacity and type of waste disposed. The amount of sewage overflowing from sewers was estimated by computing the product of average time taken to clear the blockage, the number of blockages and the average sewage overflow rate during such a blockage.

To assess the treatment plant performance as well as the environmental compliance of the final effluent to the national effluent discharge standard, the influent and effluent qualities measurements were done for a period of four months using standard procedures (Greenberg *et al.*, 1980). A mass balance was performed on the influent and effluent loads to determine the organic load removal efficacy by the existing sewage treatment plants.

The Integrated Urban Waste Flow Model (IUWFM) is developed on the assumptions below.

1. The population size of the three income groups are assumed to vary as a function of a net constant growth rate. Against the background of continuing socio-economic development in Kampala, it is assumed that the numbers of high- and medium-income people

loosing their wealth are negligible such that the population size of these groups do not decline in absolute term. The population of the low-income group will increase due to higher birth rates and more immigration of the rural poor to the urban centre in search for jobs. However, the use of a constant net growth rate for a long simulation period (e.g. fifty years) may not be realistic owing to the fact that birth rates may change due to improved standard of living, increased confidence of children survival to maturity, improved status of women or increased use of birth control measures. Nevertheless, since scenarios are designed to shows plausible future trends (and not predictions), the assumption of a constant net growth rate is reasonable for understanding feedbacks and interactions within the system.

2. Given the socio-economic status and development level for Kampala City, 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 fifty years the effect of specific population saturation density can be neglected. This is because as population pressure increases and land gets limited high-density building may develop leading to increase in population saturation density. In contrast the conversion of residential areas to commercial establishments will result in a decrease in population saturation density.

3.The number of inhabitants in a given geographical area drives the net amount of urban wastes generated in that location. Thus, population size is used as a proxy to estimate the quantity of urban waste generated. Furthermore, the $capita^{-1}$ Biological Oxygen Demand (BOD), Total Nitrogen (TN) and Total phosphorus (TP) in human excreta are assumed to be independent of the socioeconomic status and the variation among individuals to be minimal (Mara, 1976). The specific wastewater load introduced to on-site sanitation system is assumed to be in the same range as discharge to sewer despite the difference in water usage.

4. Because of frequent flooding of low lying areas in rainy season, on-site sanitation facilities are emptied within a period of one month. But in dry areas septic tanks can function for more than 10 years for a household without empting if properly operated and maintained (Franceys *et al.*, 1992). As the population settled in low lying areas is much less than those in dry areas, a retention period of eight years is assumed for faecal sludge before emptying. This is supported by experience provided by cesspool truck operators on the frequency of emptying a specific facility.

5.Due to the poor operations and maintenance of on-site sanitation facilities in slums and illegal discharge of faecal sludge, it is assumed that 20% of the human excreta stored in on-site sanitation systems is lost to the environment (NWSC, 2008). The amount of the organic matter lost through conversion to CO_2 and CH_4 from on-site sanitation is assumed 4%, as the system is partly covered.

6. The rate of sludge accumulation in sewerage ponds ranges from about 0.03 to 0.04 $m^3 hd^{-1} year^{-1}$. When the pond is half full of sludge it is desludged. This is done once every 10 to 15 years for a properly operated sewage pond (Mara, 1976). In this model, it is assumed that 1% of the sludge is removed monthly. This may not be realistic for poorly operated and managed ponds as is more often the case now.

7. For the computation of the Bugolobi Sewage Treatment Works (BSTW) threshold, it is assumed that the plant will be in operation up to 2017. The threshold is the feasible maximum capacity for wastewater treatment plant, and is only indicative of the technical constraints that compartment imposes. For example, the threshold limit for BOD load is the product of the design wet weather flow of 34,000 $m^3 day^{-1}$, concentration of 430 mg l^{-1} and life time of 15 years from 2002 onwards. The wet weather flow is the peak flow that occurs in a combined sewerage system (sewage and storm water) during rainy season (Mara, 1976).

8. The composting of solid waste is assumed home composting with negligible leachate production. This is because during composting the water produced at the degradation of organic matter is depleted from the compost bed by the removal of heat in the form of vapor (Szanto, 2009).

9. All components of the waste are assumed to be oxidised at the same rate and constant with time based on first-order kinetics. However, 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 this model, the proportion of readily biodegradable organic solid wastes converted to CO_2 and CH_4 is assumed 10%, and the fraction of paper and board degraded assumed 5% (Dalemo *et al.*, 1997). The organic material discharged to the environment is further degraded. Based on organic mass balance for Nakivubo channel, it is assumed that degraded BOD, TN and TP in the water environment are 30%, 10% and 10%, respectively (NWSC, 2008). The degradation is assumed independent of the temperature due to the small temperature variation in Kampala.

The IUWFM is composed of four subsystems, namely: ‘Population’, ‘Solid waste’, ‘Sanitation’ and ‘Environment’ as shown in Fig. 3.

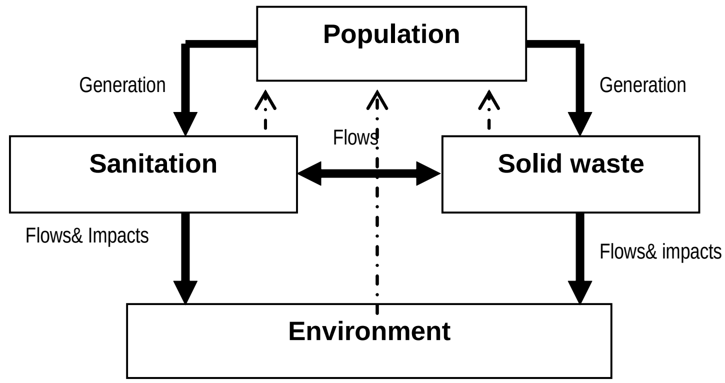


Fig. 3. Structure of the IUWFM

The population subsystem drives the generation of both solid wastes and human excreta, which flows to the different compartments. These flows are controlled by their threshold limits. At threshold points, any addition of waste 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 such as organic compost, plastic, paper and metals improves the well-being of the population. These feedbacks are indicated using dotted lines (see Fig. 3).

The IUWFM calculates the waste flows in a selected geographical region for a defined spatial system and time using the mass conservation principle. Mass balances 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 waste lost from treatment plants and on-site sanitation, and fractions illegally disposed.

Presented in Fig. 4 is the IUWFM built in SIMILE software environment. This software combines system dynamic and object-based paradigms. This provides a close correspondence between the objects in the real world and the objects in the model (Muetzelfeldt and Masshede, 2003).

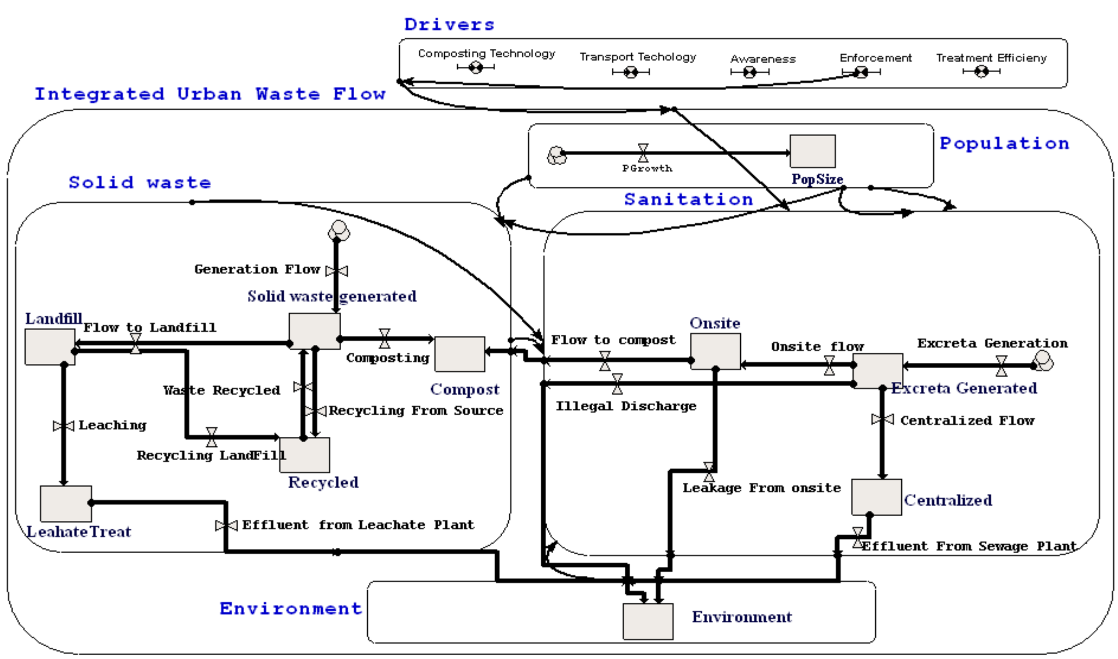


Fig. 4. IUWFM representation in SIMILE

The boxes/compartments represent stock variables where urban wastes are generated, stored or transformed. The processes in the boxes are described by empirical relationship between inputs and outputs. The flow from one box to another is modelled as 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 economic factors. The urban waste load to the environment is the cumulative environmental burden due to losses from the other compartments.

The human excreta (from the sanitation subsystem) and the organic solid waste fraction (from solid waste subsystem) are combined in the compost compartment by co-composting. Composting is the biological decomposition and stabilization of organic substrates, under condition that allow development of thermophilic temperatures as a result of biologically produced heat to produce a final product that is stable and free of pathogens (Szanto, 2009). The compost is used as soil conditioner, but this may be rejected due to cultural reasons. For instance, in Kisumu, Kenya, it is a taboo for men to handle human faeces (Drangert *et al.*, 2002). Also due to health reason people may fear to use compost. But this can be (partly) overcome by awareness campaigns and the provision of incentives. To compute the combined organic load from the human excreta and solid waste, the organic fraction in solid waste is further expressed in terms of BOD, TN and TP. In a wet organic solid waste, the BOD, TN and TP contents are in the ratios of 0.297, 0.003 and 0.002 respectively (NWSC, 2008). The urban waste flows are influenced by technology, awareness and enforcement, represented as

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

Where, UW_{t+1} is the urban waste flow at time t; FE, FA and FT are enforcement, awareness 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, and 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 urban 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 and reuse. These 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 mimic changes in enforcement, awareness and technology. For example, expanding sewerage and ensuring houses close to the sewer are connected would reduce the proportion of excreta stored in on-site sanitation system. This in turn reduces the organic load to the environment. Enhanced enforcement reduces illegal dumping of septic sludge or better and timely emptying of septic tanks.

The outputs for IUWFM are the cumulative quantities of solid wastes disposed in landfill, compost produced, environmental loads in terms of BOD, TN and TP. The BOD is an indicator of the amount of oxygen that will be removed from the water by organic matter (Straskraba and Tundisi, 1999). High BOD discharges in water depletes dissolved oxygen (DO) and can result in massive fish kills (Gilbert, 1991). In terms of water quality, TN and TP are considered pollutants if their presence in water are in concentrations sufficient to cause algal bloom (Mufide *et al.*, 2008). Algae add colour and changes water taste reducing its acceptability as a domestic water source.

This model computes the population sizes for the parishes, different income groups (low-, medium- and high-income) and aggregated population. The population sizes of the three income groups are controlled by their population saturation densities. As the population density increases up to the saturation point, the population of high density areas moves to the neighbouring parishes with low population density. At this stage population growth is no longer exponential. This subsystem is initialised with the 2002 population census data (UBOS, 2006), and validated with the population estimated by the Uganda Bureau of Statistic (UBOS). The model output is shown in Table 1.

Table 1. IUWFM and UBOS aggregated population projections for Kampala City

Model	Estimated population	
Year	**2010**	**2015**
IUWFM	1,605,900	1,921,900
UBOS (UBOS 2007)	1597,900	1,923,900

The projected population figures using this model differ slightly from the UBOS projection because of application of population saturation densities. This is neglected in the UBOS model. But the IUWFM yields relatively good results for short periods and is useful to project population at division/parish level.

The quantity of solid wastes generated is estimated by computing the product of population sizes and their capita^{-1} solid waste generation rates. This is initiated in the generation box and subsequently distributed to the other compartments (landfill, recycling, compost and environment) (see Fig. 4). The flows are divided into three streams, namely: organic solid, recyclables (metal, plastic, paper and board) and others (textile and construction wastes). The organic solid waste is separated because of the potential for co-composting with human excreta. The recyclables are lumped since their percentages are small. These flows are explicitly computed as fractions of generated solid wastes. This subsystem is parameterised with the parameters shown in Table 2.

The sanitation subsystem is initialised by multiplying population size with the daily capita^{-1} human excreta generation rate, and then distributed to the different compartments (centralised sewage, on-site sanitation and compost). This subsystem computes the organic loads that characterise the quality of different types of wastewater that changes during the different stages of processing. These loads are explicitly computed as fractions of generated human excreta. The flow from on-site sanitation to the centralised sewage system is modelled to mimic the fraction of human excreta emptied by trucks. This subsystem is parameterised with data shown in Table 3.

The environmental compartment, which is the sink to the urban waste materials is limited to soil, surface water, ground water and wetlands. The urban wastes lost from the different compartments are aggregated to calculate the load to the environment. This load is

Table 2. Parameters and variables use in the solid waste subsystem

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

Table 3. Parameters and variables use in the calibration of the sanitation subsystem

Parameter	Unit	Value	Reference
BOD	g capita^{-1} d^{-1}	40	(Mara,1976; Bekithemba,2005)
TN	g capita^{-1} d^{-1}	10	(Mara,1976; Bekithemba,2005)
TP	g capita^{-1} d^{-1}	3	(Mara,1976; Bekithemba,2005)
Proportion of population served by on-site sanitation	%	86	(KSSMP,2004; UBOS,2006)
Proportion of population served by Centralised sewerage	%	7	(NWSC,2006; UBOS,2006)
Proportion of population with no access to sanitation	%	7	(NWSC,2006; UBOS,2006)
Leaks from on-site sanitation	%	18	(NWSC,2008)
Vacuum truck collection	%	17	Computed
Sewage treatment efficiency	%	60	Measured
Centralised Sewage BOD threshold	MTonnes	79	Computed
On-site sanitation BOD threshold	MTonnes	1.5×10^5	Computed

translated to the impact on the environment measured by the BOD, TN and TP loads. The load is computed at parish level as load density by dividing the organic load by the area of the parish. The parishes close to or with fragile ecosystems, such as wetlands and surface water, are assigned a unique code. The environment indicators can be represented graphically as 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.

RESULTS & DISCUSSION

The solid waste generation rates by the low-, medium- and high-income households are estimated to be 0.46, 0.63 and 0.68 Kg capita^{-1}day^{-1}, respectively. The overall mean solid waste generation rate by household is about 0.59 Kg capita^{-1} day^{-1}. This is in the range of early estimates obtained in previous studies. Matagi (2002) estimated a solid waste generation rate of 0.55 Kg capita^{-1} day^{-1} and the Lake Victoria Environmental Management Program estimated a range of 0.5-0.8 Kg capita^{-1} day^{-1}(LVEMP, 2001). But the Kampala Solid Waste Management Strategy (KSWMS) estimated a solid waste generation rate of 1 Kg capita^{-1} day^{-1} (KCC 2006b) twice the value obtained in this study. This is attributed to the inclusion of solid wastes generated by markets and commercial establishment. Table 4 provides the solid waste composition analyses done on the solid waste dumped at the landfill from the divisions of Kampala City.

Table 4. Composition of solid waste in Kampala City

Solid waste type	Composition (%)
Paper and board	5.3
Glass	1.1
Metal	0.9
Plastic	7.7
Organic	83.2
Textiles	0.4
Construction	1.5
Total	100.0

The analyses show organic solid waste being the largest fraction, followed by plastic, paper and board. The large organic fraction is explained by the consumption of fresh food stuffs such as unripe bananas (matoke), potatoes and vegetables. The high proportion of plastic and paper wastes are attributed to increased commercial activities.

Presently, solid waste generated is stored either on-site or in the immediate neighbourhood in skips[1] before transportation to the landfill. Where solid waste collection points are lacking, empty plots, road sides and storm drains are convenient places to dump waste. The solid waste collection is done by KCC and Private Service Providers (PSPs). About 700 tonnes day^{-1} of solid wastes is disposed in the landfill at Kitenzi. These solid wastes are mainly from the business district and affluent residents where PSPs are actively involved. Solid waste from low-income households is rarely collected as they cannot afford to pay for the solid waste collection. Approximately, 200 tonnes month^{-1} of recyclable items are scavenged from the landfill, and sold to recycling industries.

The Uganda Constitution (1995), Public Health Act (UG, 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 solid waste management. These legal instruments are governed by various ministries and there is no one synchronizing agency.

The collection and transportation of solid waste within the city lies with the administrative divisions of KCC, and is headed within each division by a Divisional Public Health Officer (DPHO). Other key actors in solid waste management within the division – such as community development, education and public relation officers – are excluded. In addition, the Local Councilor 1s (LC1s) are not active in ensuring compliance of solid waste management ordinance at households. Their active involvement can change the behavior of actors towards solid wastes management and encourage public participation.

Though solid waste 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 solid waste management activities are not supported by KCC. The KCC standpoint is that PSPs have a main role in solid waste collection for all the city residents. Unfortunately, the low-income households are unable to pay for this service. Thus, about 45% of solid waste generated remains uncollected. By providing support to CBOs and NGOs, the access by low-income households to solid waste management services can be improved (Massoud *et al.*, 2003; Tukahirwa *et al.*, 2010).

There are two main sanitation systems in use in Kampala city. These are: (1) off-site sanitation system where wastewater generated is carried away by sewers and treated in a centralised plant before being discharged to the environment; and (2) on-site sanitation systems where wastewater is stored at the point of generation and undergoes there some degree of decomposition.

About 5% of the wastewater generated is treated at the BSTW. Five smaller sewer systems using pond based treatment system treat about 2% of the generated wastewater. About 87% of the population use on-site sanitation system such as septic tanks, pit latrines and ventilated improved pit (VIP) latrines. The on-site sanitation facilities are emptied whenever full, using vacuum trucks. On-site facilities that are inaccessible by trucks or unlined are manually emptied, and the content dumped in storm water drains or buried nearby. Approximately 200 m^3day^{-1} of faecal sludge is emptied and treated at the BSTW, 400 m^3day^{-1} stored on-site and 130 m^3day^{-1} illegally disposed to the environment (NWSC, 2008).

This model was calibrated using data of solid wastes disposed in the landfill at Kitenzi from 2002 to 2006. Because the stock variable in SIMILE is cumulative, the annual cumulative masses of solid wastes disposed were used to calibrate the model. The calibration was done by varying the proportion of solid wastes flowing to the landfill. This was arrived at by matching the plot of the simulation result to that for the measured solid wastes as depicted in Fig. 5. Since the masses of solid wastes are taken before dumping, the degrading, recycling and leaching rates within the landfill were set at zero.

Both plots showed a gentle increase in time in cumulative masses of solid wastes disposed in the landfill. To further assess the degree of fitting of the two curves, the actual annual cumulative amounts of solid wastes disposed at the landfill were plotted against the simulated cumulative masses of solid wastes. The variance of the simulated values to the measured values, given by R^2 is shown in Fig. 6.

The R^2 showed a high correlation value of 0.99 illustrating a good fit for the simulation to the actual measurement of solid wastes disposed at the landfill. This model was validated using demographic, solid wastes and sanitation data for the city of Dar es Salaam, Tanzania, presented in Table 5 and Table 6. Dar es Salaam is about nine times bigger than Kampala, and is as densely populated as Kampala.

The result for the validation is presented in Fig. 7, indicating both simulated and measured plots.

The plot shows a gently increasing trend for both simulated and measured cumulative solid wastes disposed at dump sites. To determine the degree of validation, the variance R^2 was computed by plotting simulated values against the measured values (see Fig. 8). With an R^2 value of 0.99 the fit was good.

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 if 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, determine parameters for which it is important to have more accurate values and understand the behaviour of the system. In this study a sensitivity analysis was done for the different processes/parameters for urban waste management. These are: degradation rate, landfill threshold, composting threshold, on-site sanitation threshold,

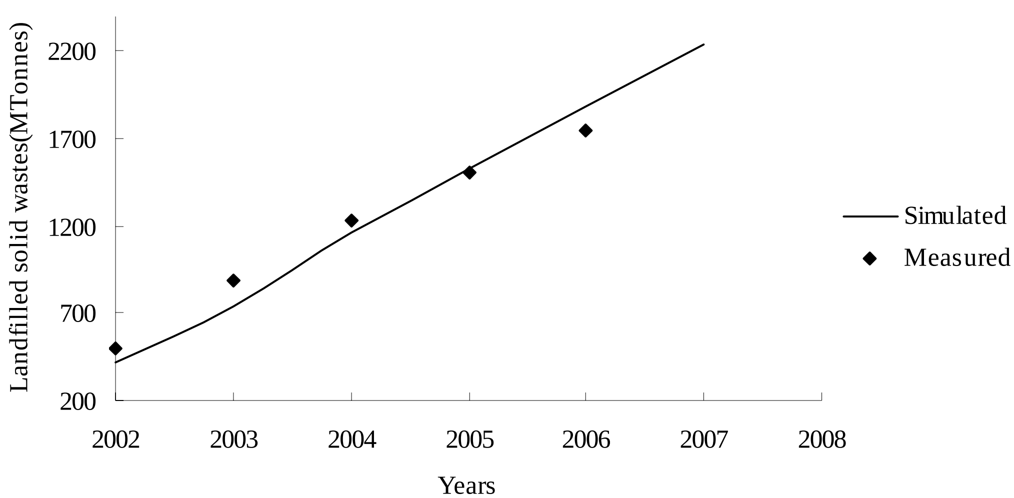


Fig. 5. Plots for measured and simulated solid waste disposed at the landfill

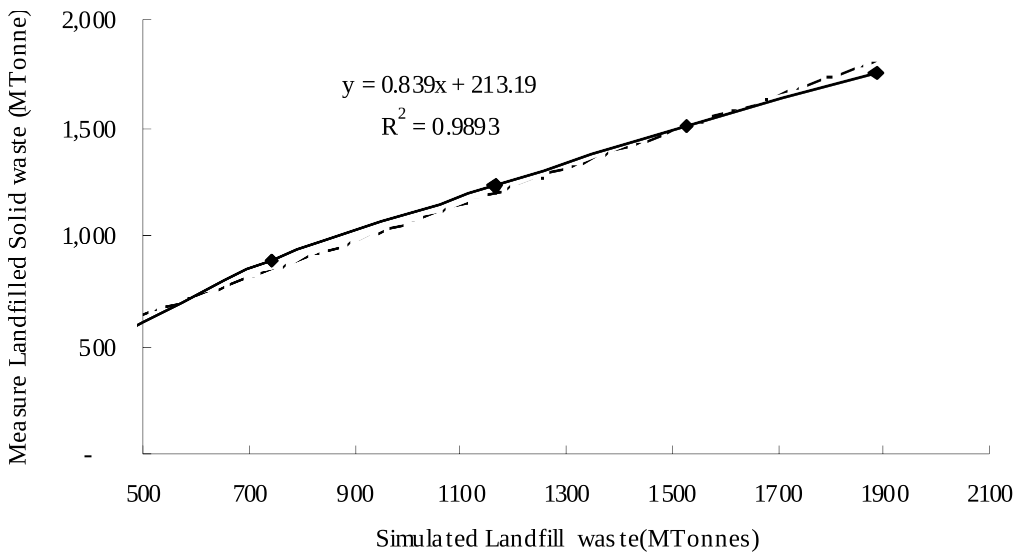


Fig. 6. Plot for measured against simulated solid waste disposed in the landfill

Table 5. Solid waste and sanitation data for Dar es Salaam City

Parameter	Unit	Value	Source
Solid waste generation rate	Kg Capita^{-1}day^{-1}	0.815	(ERM, 2004)
Solid waste taken to landfill	%	44	(ERM,2004)
Solid waste recycled	%	9	Health Officer
Solid waste illegally disposed	%	31.2	(ERM,2004)
Solid waste composted	%	9	Health Officer
Solid waste buried or burnt	%	25	Health Officer
Proportion of population using on-site sanitation	%	90	(DWSC,2007)
Proportion of population using centralised Sanitation	%	7	(DWSC,2007)
Proportion of population with no sanitation	%	4	(DWSC,2007)

Table 6. Solid waste composition for Dar es Salaam City

Category	Composition 2006 (%)
Paper and board	8
Textile	1
Plastic	5
Metal	2
Glass	3
Leather/rubber	1
Ceramic/Stone/soil	1
Organic	64
Other	15
Total	**100**

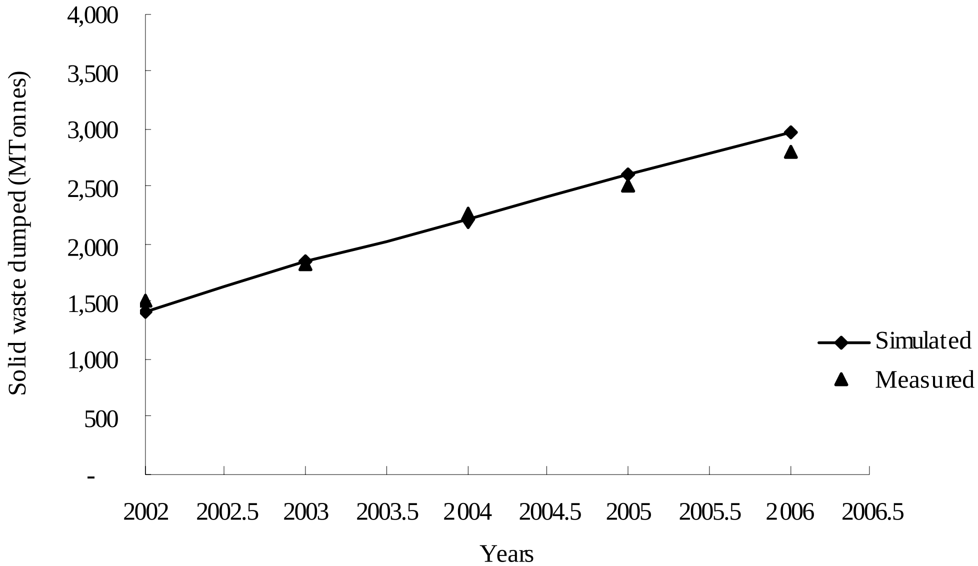


Fig. 7. Plots for simulated and measured solid waste dumped for Dar es Salaam

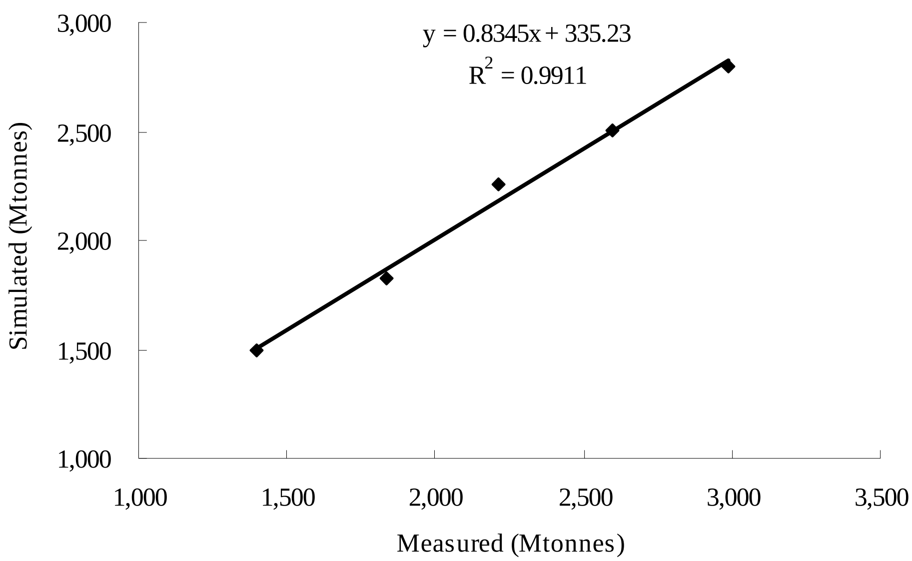


Fig. 8. Plot for measured solid waste verse simulated at dump site for Dar es Salaam City

centralised sanitation threshold, recycling rate, composting rate, collection rate, vacuum truck emptying rate and leaking rate from on-site sanitation. 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, TN and TP loads. Examples of studied sensitivities for the case study of Kampala City are presented in Fig. 9.

From the sensitivity analyses, the degradation rate is found to be sensitive to the model outputs. The leaking rate from on-site sanitation is not sensitive to the model output. The graph reveals how uncertainty changes over time. There is little uncertainty in the BOD in the first few years, the range of uncertainty extends from around 500 Tonnes BOD to 4500 Tonnes BOD. This implies that a small difference in the degradation rate can lead to large change in the width of uncertainty interval. The further we look into the future, the larger the uncertainty becomes. But the model outputs show a similar pattern, with the middle simulation being the base case. The plot shows BOD loads decreasing from 2003 to 2009 and increasing from 2009 to 2051 implying that the model is robust. A model is robust when it generates the same general pattern

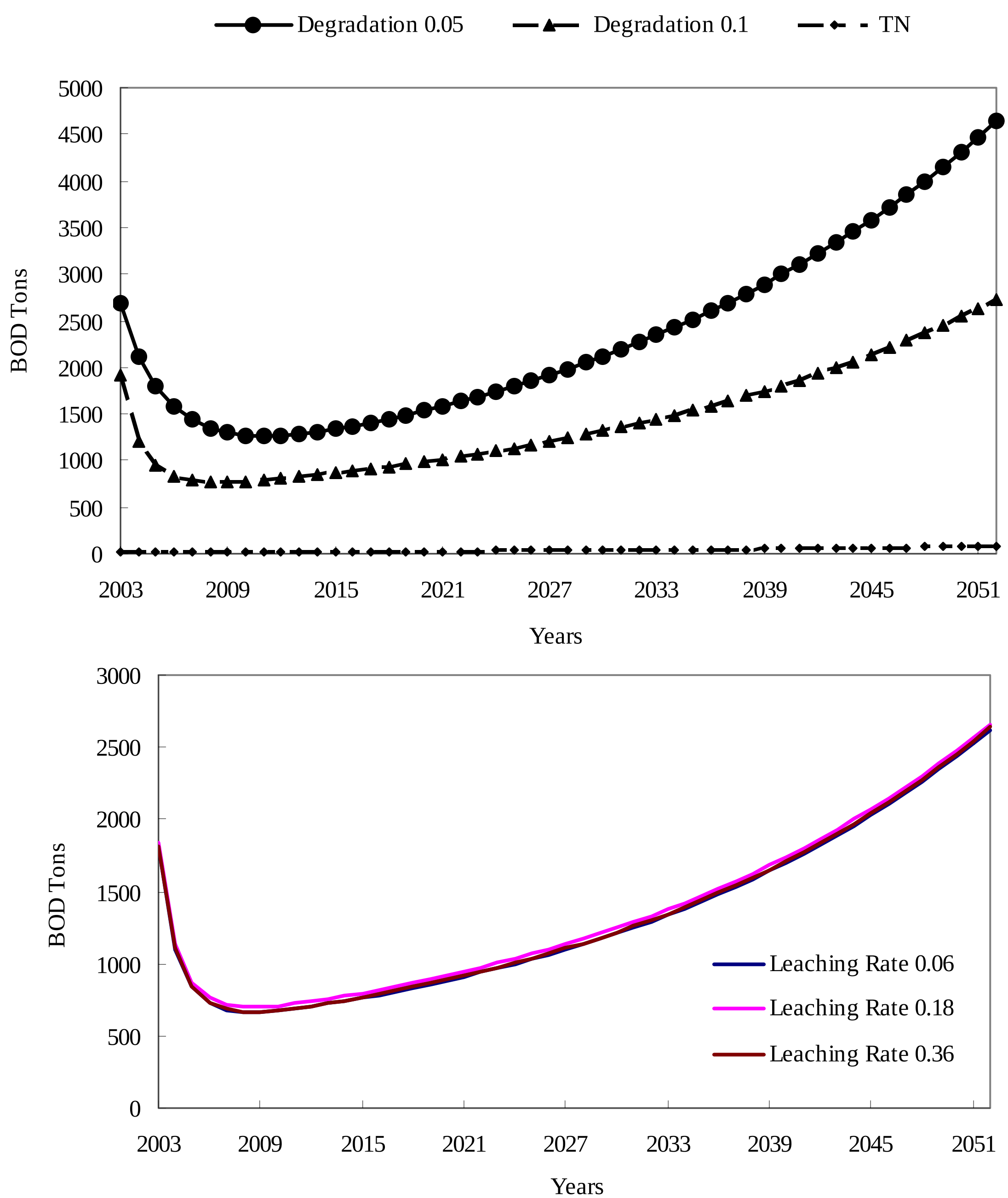


Fig. 9. Sensitivity analysis plots (a: degradation rate; b: leaking rate)

despite the great uncertainty in parameter values (Ford, 1999). 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 organic fraction in the waste stream. Based on this result a mass balance was done for the Nakivubo channel to improve on the degradation rate estimate.

Many environmental processes unfold over long time spans that 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. Scenarios are plausible and often simplified descriptions of how the future may develop based on a coherent and internally consistent set of assumptions (Monika and Henrichs, 2007). For this study four plausible scenarios were developed: *"business as usual"*, *"more enforcement"*, *"more collection"* and *"proper management"*.

This scenario assumed that no additional mitigation measures are put in place to reduce the amounts of solid wastes generated and to eliminate indiscriminate dumping. The vehicular accessibility to informal settlements for refuse collection is still problematic. The proportion of solid waste treatment by composting is still low. The on-site sanitation facilities in slums are poorly operated and maintained leading to their overflow. The treatment efficacies of the existing waste facilities are maintained. The numbers of enforcement officers on the ground to ensure environmental compliance are inadequate. The LC1s are not active in ensuring environmental compliance. The CBOs and NGOs have limited resources, and they are not supported by the public sector in carrying out waste management activities. The level of awareness on environmental and health benefits derived from resources recovery is low. Thus, this scenario continues the current status quo as presented in Fig. 10.

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 is increased by 30% to prevent any illegal waste dumping, all houses with septic tanks within a radius of 60m to a sewer are connected, and on-site sanitation facilities are emptied in time. This strategy is expected to reduce the amounts of solid wastes and human excreta flow to the environment by about 45% and 15% respectively. Additionally, the budget for LC1s is increased by 30% to ensure full implementation of solid waste ordinance and sanitation regulation at household level. The organic packaging materials for fresh food stuffs brought to markets reduced by 10% by taxing the transporters. The level of awareness on composting and recycling is enhanced by 15% compared to *"business as usual"*. Since the quantity of solid wastes disposed in central collection points will increase, the numbers of skips and trucks to transport solid wastes are increased by 5%. These skips are placed within walking distance to reduce illegal dumping, and are accessible by trucks. This scenario is summarised in Fig. 11.

This scenario focused on collection and transportation of urban waste. It assumed that the collection and transportation of urban wastes is enhanced by 70%. In this case, the numbers of skips is increased by 30%, and they are positioned at walking distance for all residents and accessible by trucks. The skips are emptied in time to avoid solid wastes overflows. The service coverage by PSPs is increased by 20% compared to *"business as usual"*. KCC serves low-income residents and public places as well as monitor the operations of PSPs. The capacity of CBOs to collect solid waste is enhanced by 10% by providing wheel barrows and carts. The pit emptying is increased by introducing Vacutug and manual pit emptying technology (MAPET) for use in densely built-up areas. Three faecal sludge treatment facilities are constructed to serve a population of about 150,000 as per Kampala City master plan (NWSC, 2008). Organic solid composting and level of awareness each increased by 10%. The enforcement of solid waste ordinance is enhanced by 10% through addition of more funds to LC1s and Public Health Officers (PHOs). This scenario is presented in Fig. 12.

Presented in Fig. 13 is the urban wastes 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 composting technologies such as windrows, aerobic and anaerobic digestions. The performance of existing waste treatment facilities is enhanced by 10%. The number of enforcement officers to ensure compliance of solid waste ordinance and sanitation regulations increased with 20%. The level of awareness enhanced by 20% compared to *"business as usual"*. Low-income and medium/high-income groups are 'connected' such that recyclables generated by medium/high-income groups are collected by low-income group at the source.

Table 7 provides the outputs for the four mitigation scenarios. The BOD, TN, TP, compost and solid wastes disposed in landfills are measured as wet weight.

The "*business as usual*" run showed the highest BOD, TN and TP loads to the environment. This is caused by indiscriminate solid wastes disposal, illegal faecal sludge discharge, sewage overflows and leaks from unlined pit latrines. This is caused by inadequate numbers of enforcement officers to ensure environmental compliance. For example, the Public Health Act (1964) states that every house must have a toilet, but this is not the case on the ground (Government, 1964). The *"proper management"* scenario showed the smallest BOD, TN and TP loads to the environment attributed to increased implementation of composting technologies.

The projected future trends for the four scenarios are presented in Fig. 14 with parameters plotted in the same graph for different scenarios. This is done to enable easy comparison of the effect of the different strategies in the scenarios.

The estimated total BOD loads after 50 years in the *"business as usual"* scenario increased by 370% compared to 2008 BOD loads. This is attributed to an increase in population size coupled with inadequate mitigations to halt the increasing environmental loads. Additionally, the quantity of solid wastes disposed at the landfill by 2052 is less than the designed capacity (2000 Mtonnes). This is explained by the rapid breakdown of readily biodegradable organic solid wastes that constitutes the highest fraction (83%) in

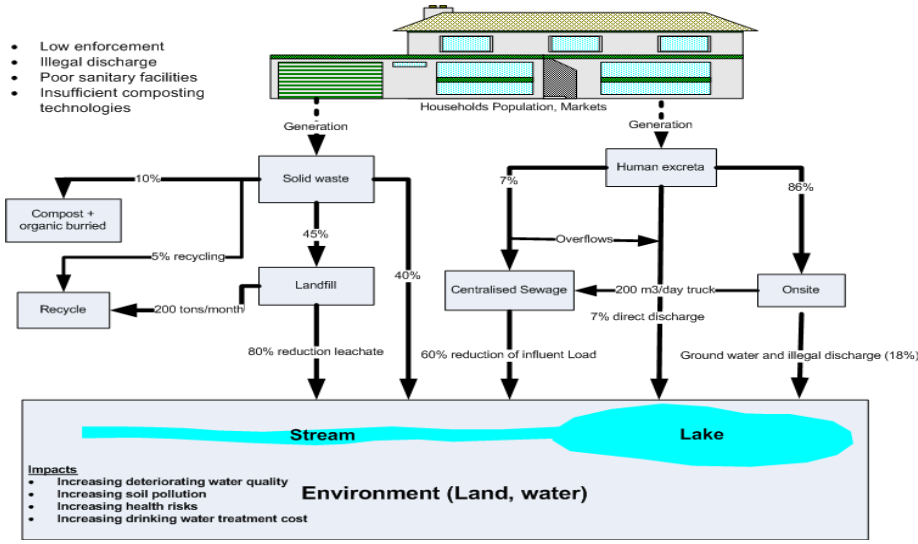


Fig. 10. Urban waste flows in the "Business as usual" scenario

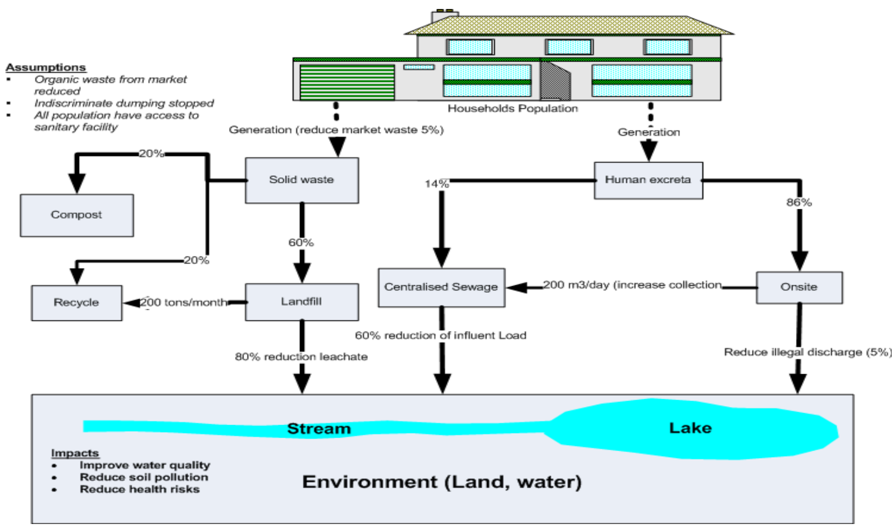


Fig. 11. Urban waste flow in the "more enforcement" scenario

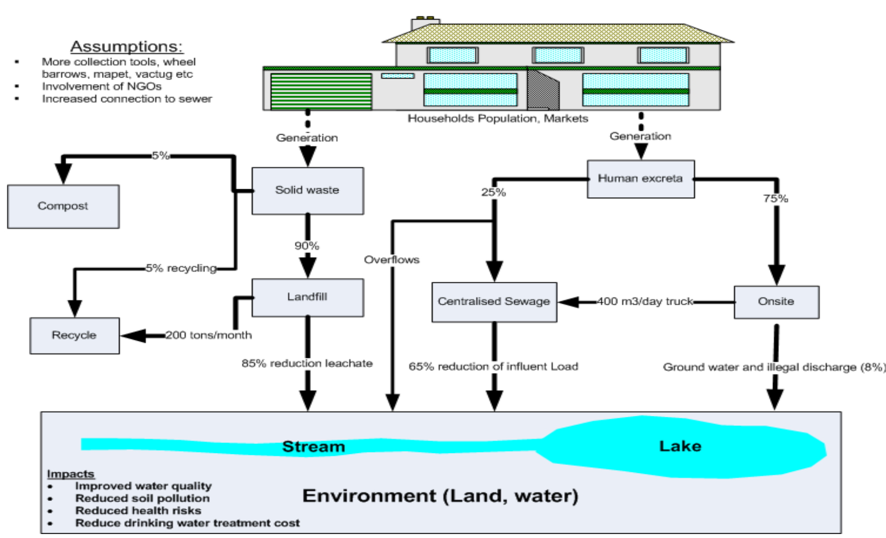


Fig. 12. Urban waste flows in the "More collection" scenario

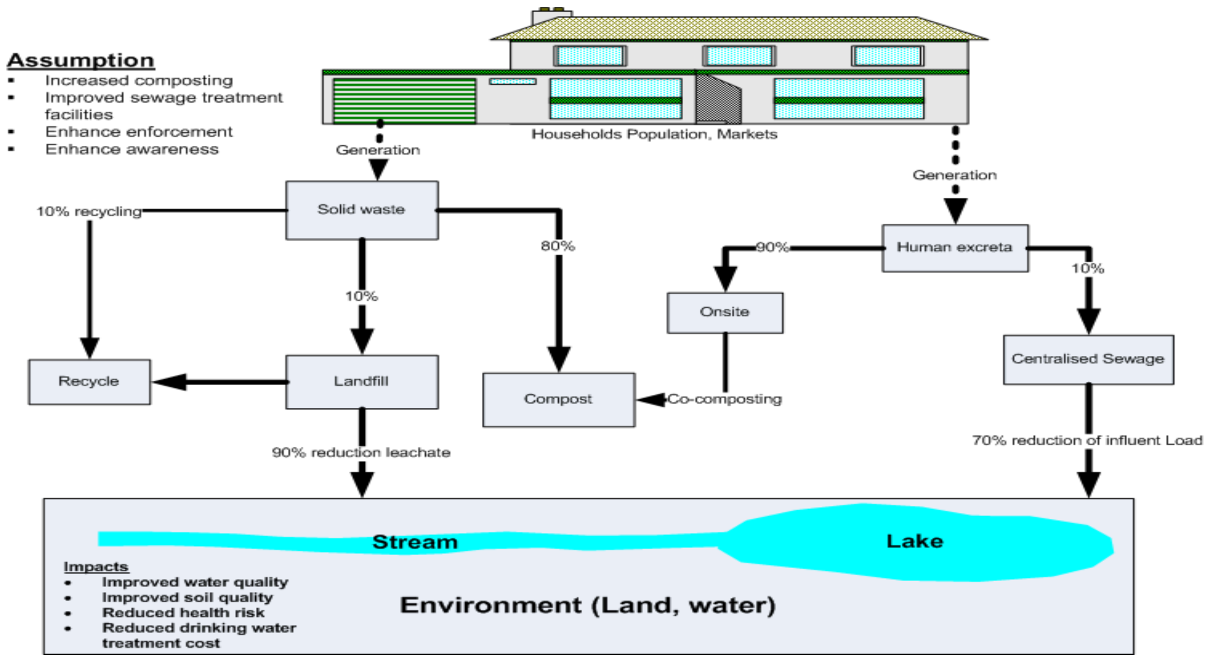


Fig. 13. Urban waste flow diagram for proper management scenario

Table 7. Simulation output for the four scenarios by 2052

Parameters	Unit	Business as usual	More Enforcement	More collection	Proper management
BOD	Mtonnes	310	192	230	150
TN	Mtonnes	7.6	4.3	2	5.6
TP	Mtonnes	3	1.8	2	2
Compost	Mtonnes	2,200	7,700	5,100	22,000
Solid wastes in landfill	Mtonnes	130	2200	300	44

solid waste. The scenario also showed that the BOD, TN and TP loads to the environment by 2052 will be 30 times more than the present state (2008). This will have severe negative consequences on the environment and human health. On the other hand, the amount of compost produced by 2052 is low compared to the amount of organic solid waste generated.

The *"more enforcement"* scenario showed a BOD load reduction to the environment by about 40% compared to *"business as usual"*. 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 solid wastes and human excreta. But this requires availability of appropriate technologies that are economically affordable, environmentally effective and socially acceptable to implement waste management activities. This scenario shows increased amounts of compost and solid wastes disposed at the landfill. This increased amount of landfilled solid wastes fills up the landfill within four years resulting in a demand for land to expand the landfill. This makes treatment of solid wastes by landfilling expensive due to 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"*. This is because of the increased numbers of skips, use of wheelbarrows and carts to collect solid wastes in densely built-up areas, and increased coverage by PSPs. Also the use of MAPET and Vacutug to empty faecal sludge in densely built-up areas, and construction of three additional faecal sludge treatment plants explains the reduced environmental loads. The involvement of CBOs and NGOs in solid waste collection and recycling activities contributes to the reduced environmental loads. But this requires an awareness campaign to ensure active involvement of the public in waste management. In comparison to the *"more enforcement"* scenario,

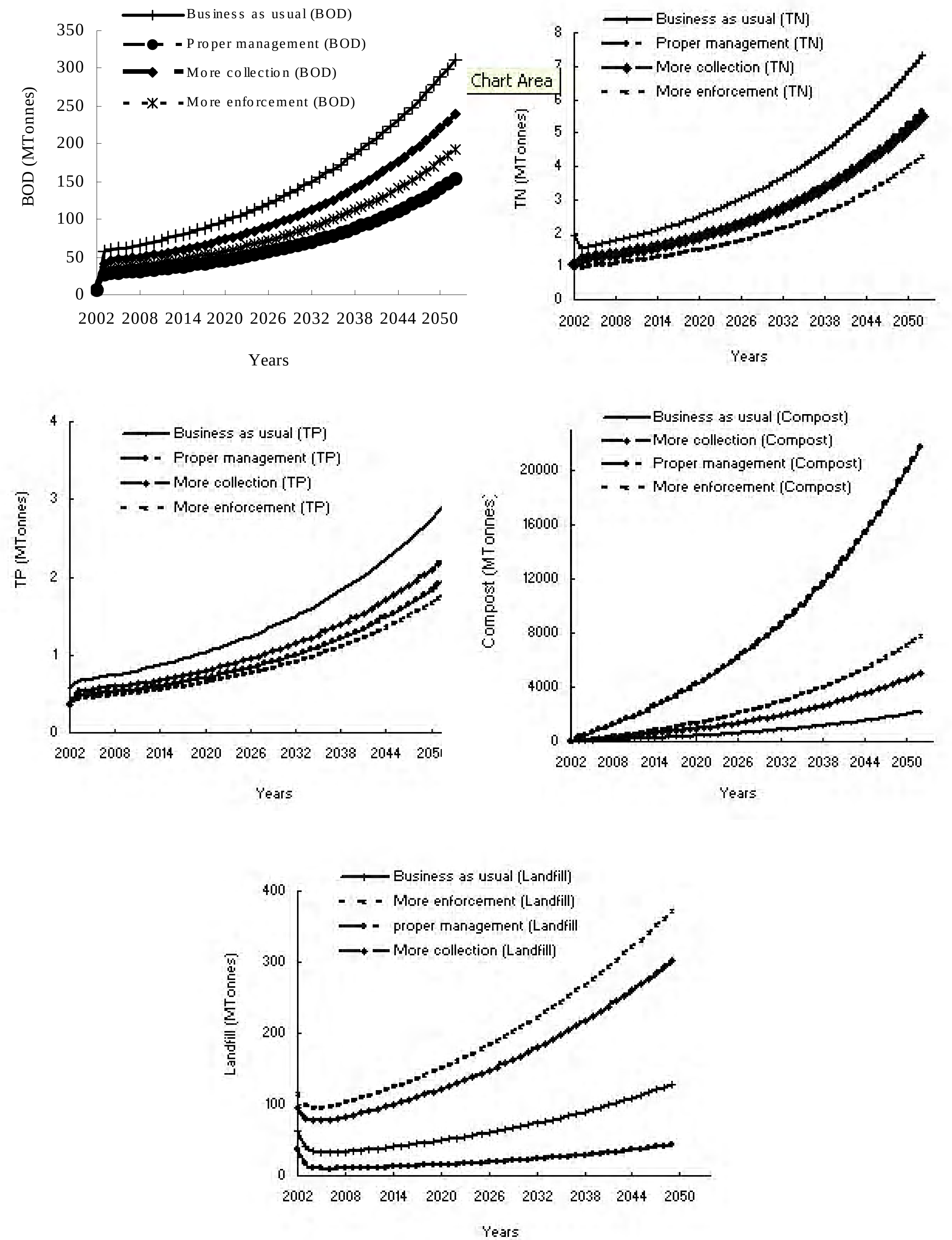
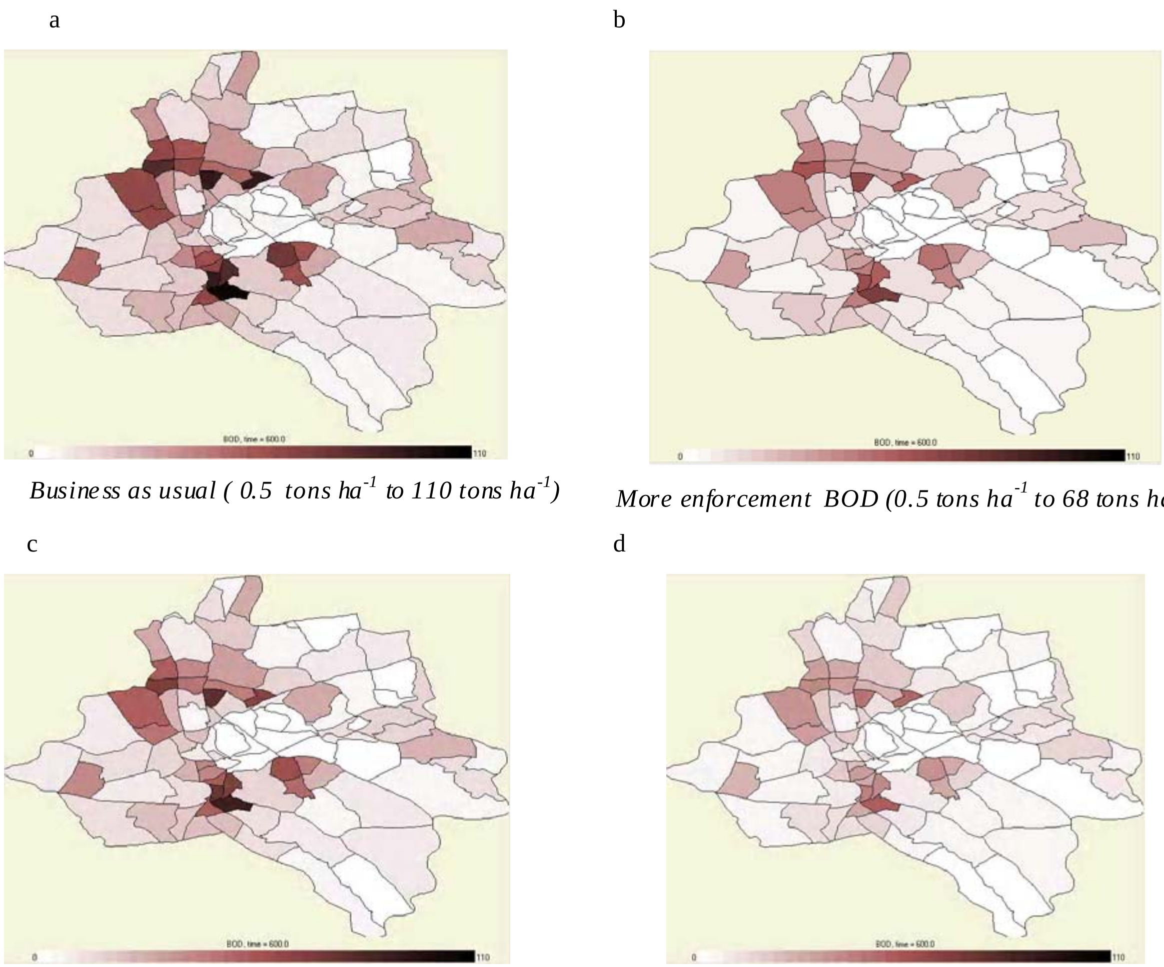


Fig. 14. Simulation plots for the four scenarios for Kampala City (a: biological oxygen demand; b: Total Nitrogen; c: Total Phosphorous; d: compost; e: Landfill)

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 solid waste that accounts for about 40% of the total solid waste generated.

The *"proper management"* scenario showed that the total BOD load over 50 years is reduced by about 50% compared to the *"business as usual"*. 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 farm land. However, compost produced from municipal solid waste is often of low quality due to the presence of toxic substances (Massoud *et al.*, 2003). This can affects its acceptability for food crop production. The level of toxic substances in compost can be reduced by implementing waste sorting at source. This can be done by bringing facilities for waste recycling closer to the generated waste (Curran *et al.*, 2007). Additionally, decentralising composting to household level and promoting urban/peri-urban agriculture would encourage households to sort the waste. The composting can be by windrows 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 waste materials diverted from the landfill.
Presented in Fig. 15 is the spatial BOD load intensity at parish level for the four different scenarios.

The spatial plots show that the BOD intensity in the *"business as usual"* scenario ranges from about 0.5 tons ha^{-1} to 110 tons ha^{-1}. Parishes that have effective solid waste collection and sewerage systems registered low BOD intensity. Also parishes with low population show low BOD load intensity because of low amount of urban waste generated ha^{-1}. However,



a: *Business as usual (0.5 tons ha^{-1} to 110 tons ha^{-1})*

b: *More enforcement BOD (0.5 tons ha^{-1} to 68 tons ha^{-1})*

c: *More collection (BOD 0.7 Tons ha^{-1} to 86 Tons ha^{-1})*

d: *Proper management (BOD 0.5 tons Ha^{-1} to 50 Tons Ha^{-1})*

Fig. 15. BOD spatial distribution maps for the four scenarios (a: *"business as usual"*; b: *"more enforcement"*; c: *"more collection"*; d: *"proper management"*)

parishes occupied by low-income earners show high BOD intensities due to inadequate solid waste collection and illegal discharge of faecal matter. More so, these parishes have mainly unlined pit latrines that can easily leak to the groundwater. This high BOD intensity indicates the need for increased provision of sanitary facilities and solid waste collection. The *"more enforcement"* scenario shows a reduction in BOD load intensity across the parishes in the range of about 0.5 tons ha^{-1} to 68 tons ha^{-1}. The *"more collection"* scenario indicates BOD load intensity ranging from 0.7 tons ha^{-1} to 86 tons ha^{-1}. The *"Proper management"* scenario demonstrates the best results with BOD intensity ranging from 0.5 tons ha^{-1} to 50 tons ha^{-1}.

The scenarios formulated for urban waste management for Kampala were also executed for Dar es Salaam. The outputs of these scenarios are shown in Fig. 16.

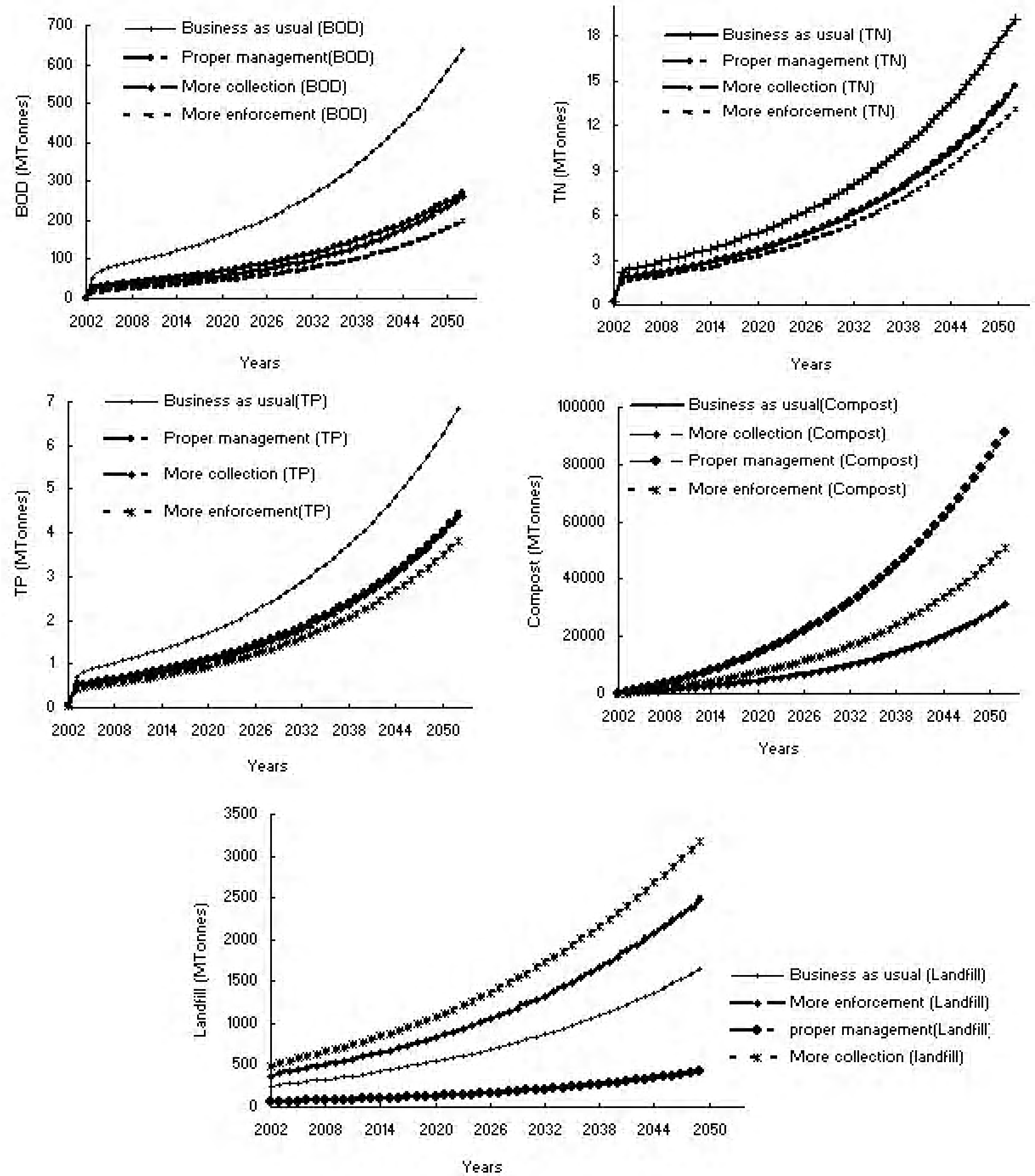


Fig. 16. Simulation plots for the four scenarios for Dar es Salaam City (a: biological oxygen demand; b: Total Nitrogen; c: Total Phosphorous; d: compost; e: Landfill)

The plots show that with no additional mitigation measures, the BOD load to the environment will increase as presented in the *"business as usual"* scenario. The *"more enforcement"* scenario indicates a major reduction of organic load to the environment by 2052 due to reduced indiscriminate dumping of solid waste. This also explains the increased amount of solid wastes disposed in landfills. The *"proper management"* scenario shows a significant reduction of organic load to the environment and of solid wastes disposed at the landfill in comparison to the *"business as usual"* and *"more collection"* scenarios. Also compost production was high.

In comparison to Kampala City, 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, TP and TN loads). This is because the problem associated with solid waste management in Dar es Salaam is indiscriminate solid wastes disposal. This explains why the *"more enforcement"* scenario showed high reduction in the environmental loads compared to the other scenarios.

CONCLUSION

This study used system dynamics modelling to understand and project future urban waste generation and its impacts on the urban environment. Presently, urban waste in Kampala and Dar es Salaam is poorly managed with little resource recovery. The *"business as usual"* scenario showed that with no additional measures for urban waste management in both Kampala and Dar es Salaam, the urban waste situation rapidly deteriorates, with negative consequences for human health and the environment.The *"proper management"* scenario that integrates increased implementation of composting technologies, increased urban waste collection, increased numbers of enforcement officers and increased awareness 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 quality of the urban environment and increase resource recovery, the city authorities, NGOs, CBOs and the general public would have to increase their efforts both in the sense of finances, capacity and general involvement. It is also noted that with this modeling approach it is possible to understand urban waste management with limited data. However, there are limitations in the predicted values since scenarios are based on assumptions that may change. Thus, scenarios just show probable paths that can be followed when the assumptions in the scenarios are implemented.

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