Modelling of Solid Waste Management Systems of Dhaka City in Bangladesh

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In the previous chapters of this part, case studies on system dynamics modelling and simulation of some practical problems have been presented. This chapter presents a case study of environmental management of solid waste management system of Dhaka City, Bangladesh. The model of this case study is organised as (1) introduction, (2) dynamic hypothesis, (3) causal loop diagram, (4) stock–flow diagram, (5) model validation, (6) simulation and policy analysis and (7) conclusion to illustrate the system dynamics applications in environmental management based on systems thinking. Population, uncleared waste, untreated waste, composite index and public concern are projected to increase with time for Dhaka City. Simulated composts, CO_2 total, CH_4 and BOD from energy, leachate production and BOD from leachate over a period of 30 years are also presented. Simulated results also show that increasing the budget for collection capacity alone does not improve environmental quality; rather an increased budget is required for both collection and treatment of solid wastes of Dhaka City. This model can be used as a tool to assess and design policy options of solid waste management.

12.1 Introduction

Solid waste consists of the highly heterogeneous mass of discarded materials from the urban community, as well as the more homogeneous accumulation of agricultural, industrial and mining wastes. The principal sources of solid wastes are residences, commercial establishments, institutions and industrial and agricultural activities. Domestic, commercial and light industrial wastes are considered together as urban wastes. The main constituents of urban solid wastes are similar throughout the world, but the quantity generated, the density and the proportion of constituents vary widely from country to country and from town to town within a country according to the level of economic development, geographic location, weather and social conditions. In general, it has been found that as the personal income

rises, kitchen wastes decline but the paper, metal and glass wastes increase; the total weight generated increases but the density of the wastes declines (Rao 1992).

Several disposal methods are being used in various parts of the world, and the most prominent of these are open dumping, sanitary landfilling, incineration and composting. Sanitary landfilling is the main method used in industrialised countries, and open dumping is very common in developing countries like Bangladesh and India.

Open dumping of solid wastes is practised extensively in Bangladesh because it is cheap and requires no planning. Generally, the low-lying areas and outskirts of the towns and cities are used for this purpose.

Sanitary landfilling is a controlled engineered operation, designed and operated according to acceptable standards. It may be defined as a controlled method of disposing of refuse onto or into land while minimising nuisances or hazards to public health or safety. The operation is carried out without environmental damage and in areas already spoiled or in need of restoration.

Incineration involves the burning of solid wastes at high temperatures. If incineration is to become an economical method for solid waste disposal, useful materials and energy must be recovered by the process. Heat can be recovered by putting a waste heat boiler or some other recovery devices on an existing solid waste incinerator. The heat so recovered can be utilised for generating electricity or for space heating purposes. In general, solid waste has about one-third the heating value of coal, but unlike coal it has a very low sulphur content. All types of incinerators produce air pollution. The contributions to global warming by incineration are much less than those of landfill but comparable to those by composting. Yongfeng (2005) reported that municipal solid waste incineration has recently emerged as the method of choice for the primary treatment of municipal solid wastes in many cities in China. Alam and Bole (2001) and Sufian and Bala (2006) reported that there exists high electrical energy recovery potential from urban solid waste of Dhaka City.

In contrast to a sanitary landfill, composting of refuse is an aerobic method of decomposing solid waste. Many types of microorganisms already present in the waste biostabilise the organic matter in the waste and produce a soil conditioner as a result of the process. The organisms include bacteria, which predominate at all stages; fungi, which often appear after the first week; and actinomycetes, which assist during the final stages. Zurbrugg et al. (2002) reported a success story of decentralised collection and composting scheme in Mirpur, Dhaka, Bangladesh. The case of Mirpur shows that composting can be a good alternative to conventional solid waste management options, reducing the amount of waste to be transported and dumped by producing a valuable raw material for fertilisers.

Solid wastes contain significant amounts of valuable materials like steel, aluminium, copper and other metals which, if they are recovered and reused, would reduce the volume of the wastes to be collected and at the same time would yield significant salvage and resale income. In addition, better reclamation techniques will help to save valuable natural resources and turn wastes, which could be

dangerous, into useful products. Some important solid wastes that have been successfully reclaimed are paper, plastics, glass and metals.

Solid waste generation of the Dhaka metropolitan area in 1998 was 3944 tons/ day and 4750 tons/day in 2000. Solid waste generation in Dhaka City is increasing rapidly with rapidly growing population and GDP, and the Japan International Cooperation Agency (JICA) (2005) predicted solid waste generation to increase from 3200 tons/day in 2004 to 4634 tons/day in 2015. Of the total waste produced, nearly 20 % is used for recovery and recycling and about 37 % remains scattered laying around on roadsides, open spaces or drains. The remaining 43 % of the wastes are deposited together in some primary depots from where about 45 % is finally disposed of either by the DCC or community-based organisations (CBOs) in the open landfill sites.

Many studies have been reported on strategies to achieve municipal solid waste management (Pawan et al. 1997; Salvato 1992; Kum et al. 2005). Linear programming, input–output analysis, expert system (a methodology that uses expert knowledge to solve problems of a complex system) and system dynamics have been applied to aid decision-makers in planning and management of solid waste management systems (Everett and Modak 1996; Clayton and McCarl 1979; Barsi 2000; Ming et al. 2000; Heikki 2000; Mashayekhi 1992; Sudhir et al. 1997). Several studies have been reported on life cycle assessment (LCA) of municipal solid waste management systems (Consonni et al. 2005a, b; Velumani and Meenakshi 2007). Consonni et al. (2005a, b) examined environmental impacts and economics of the various strategies using life cycle assessment starting from heat and mass balances. Velumani and Meenakshi (2007) reported life cycle inventory analysis for three different municipal solid waste management scenarios: (i) open landfill; (ii) generation, collection, transportation and sanitary land filling; and (iii) generation, collection, transportation, segregation, incineration, recycling and sanitary land filling for Coimbatore City, India, to aid the decision-makers and planners for integrated management of solid waste management for sustainable development.

Dyson and Chang (2005) emphasised the capability of system dynamics for prediction of solid waste generation, and Sufian and Bala (2006, 2007) and Bala and Sufian (2006) successfully applied system dynamics to model and analyse the policy options of solid waste management system.

Solid waste crisis is emerging in Bangladesh and the majority of the cities are severely affected. The disposal problem is more serious for Dhaka City, the capital of Bangladesh. There is a large gap between the waste generation and management system which results in environmental pollution. To meet this gap, there is a need of a model for solid waste management systems of Dhaka City, Bangladesh. Here the system dynamics model of solid waste management adopted from Sufian and Bala (2006, 2007) is presented, and it has been designed to predict solid waste generation, scientific landfill, incineration, composting and life cycle assessment.

12.2 Dynamic Hypothesis

The dynamic hypothesis is a conceptual model which seeks to define the critical feedback loops and system structure that drive the system's behaviour in the reference mode. When the model based on feedback concept is simulated, the endogenous structure of the model should generate the reference mode behaviour of the system, and thus, the endogenous structure causes the changes in the dynamic behaviour of the system. In system dynamics modelling, causal loop diagrams identify the principal feedback loops of a system, and the causal loop diagram and stock–flow diagram are used to describe the basic cause–effect relationships hypothesised to generate the reference mode of the behaviour over time (Sterman 2000). Solid waste management systems can be represented by causal loop diagram and stock–flow diagram, and the simulation model based on the causal loop diagram and stock–flow diagram would generate dynamic behaviour of the solid generation, uncleared wastes and untreated wastes and composting in the reference mode. The solid wastes and its present management systems in the form of causal loop diagram and stock–flow diagram are hypothesised to generate the observed solid waste generation, uncleared wastes and untreated wastes in the reference mode. In essence there is piling up of uncleared wastes and untreated wastes from the lack of management strategies and fund; this dynamics results from the endogenous consequences of the feedback structure of the solid waste management systems.

12.3 Causal Loop Diagram

Causal loop diagram of solid waste management systems of Dhaka City, Bangladesh, is shown in Fig. 12.1. Municipal solid wastes increase with population (R1) and solid generation creates public concern and pressure to mitigate the waste (B1). The solid wastes are separated into recyclable wastes and nonrecyclable wastes. Both the uncollected waste and unhygienic disposal of waste create environmental pollution, which gives rise to increase public annoyance and anger, and hence public concern develops to reduce waste generation (B2 and B3). Also, the untreated wastes create public concern and pressure (B4). A higher composite index increases management perception which increases fund allocation for solid waste management (B5). The composite index is defined as

$$\text{Composite Index} = (w_1 \times \text{UNCL} + w_2 \times \text{UNTR}) \times \text{POPR} \qquad (12.1)$$

where

w_1, w_2 = weighting factor ($w_1 = 0.5$ and $w_2 = 0.5$)
UNCL = the ratio of the uncleared waste at any point of time to the base value
UNTR = the ratio of the untreated waste at any point of time to the base value
POPR = the ratio of the population at any point of time to the base value

Fig. 12.1 Causal loop diagram of solid waste management systems of Dhaka in Bangladesh

A higher value of composite index indicates a progressive deterioration in health and environmental quality. A fraction of organic solid wastes from the municipal solid wastes is used for composting, and the remaining portion of the nonrecyclable wastes is used for sanitary landfill and incineration.

Life cycle assessment (LCA) of municipal solid waste management of the Dhaka City is also included in this model. The scope of life cycle assessment is to account for all possible environmental impacts 'from cradle to grave', i.e. along the whole sequence of actions required to bring about and later terminate a given product or an activity. Life cycle assessment of municipal solid wastes starts just at the moment when it is put into the waste bin and ends up when it is disposed. Life cycle assessment assesses the use of resources and releases of emissions to air, water and land and the generation of useful products from the wastes. This is done here by compiling an inventory of relevant inputs and outputs of the system and evaluating the potential impacts of those inputs and outputs in relation to the objectives of the study. To evaluate properly the global warming potential, CO_2 emissions are broken down into a fraction originated by fossil carbon (plastics, rubber or fossil fuel) and a renewable fraction originated from biogenic materials (paper, wood or organic fractions).

12.4   Stock Flow Diagram

The flow diagram of the model was constructed using icon-operated stock and flow symbols of STELLA software. The STELLA flow diagram of the urban solid waste management system is shown in Figs. 12.2a, 12.2b, 12.2c and 12.2d. Fundamental equations that correspond to the major state variable are as follows:
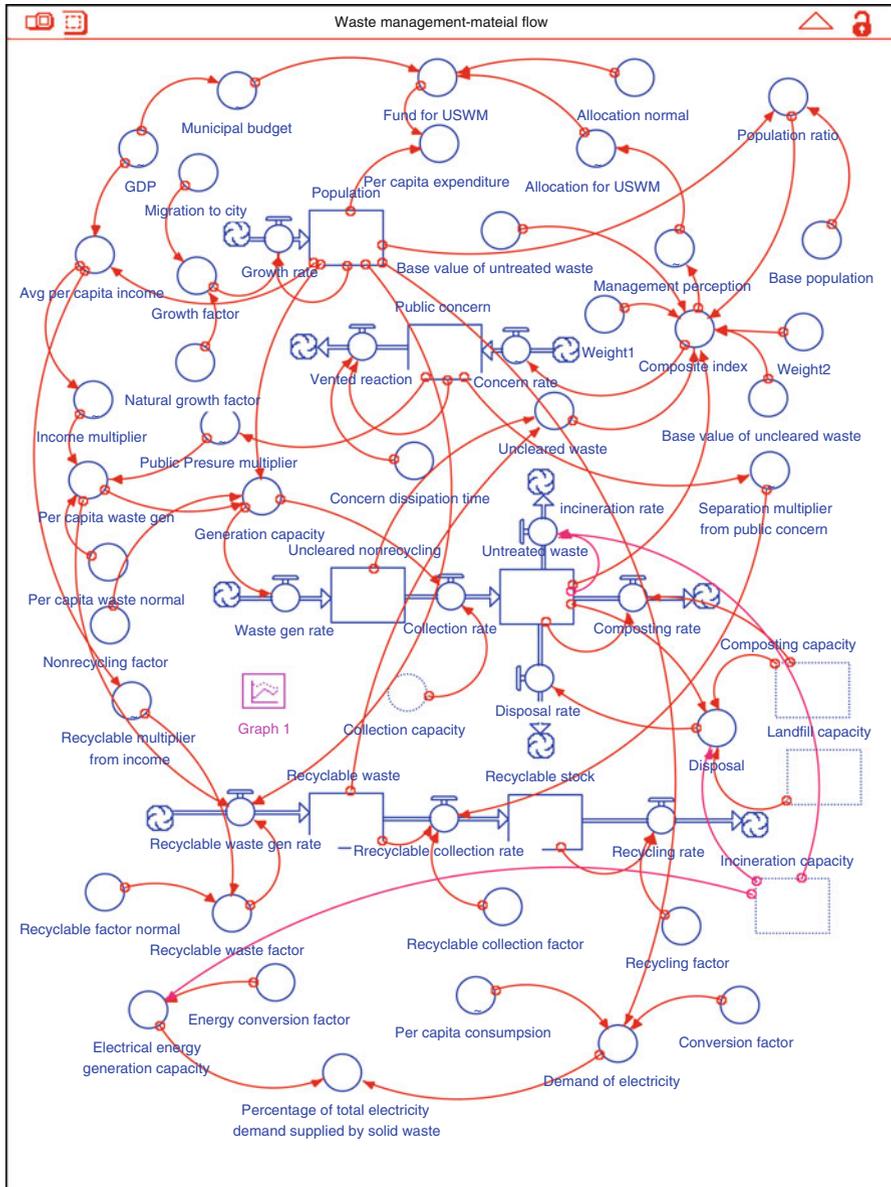
Fig. 12.2a STELLA flow diagram of solid waste management system dynamics—material flow

Fig. 12.2b STELLA flow diagram of solid waste management system dynamics—composting, incineration and landfill

Fig. 12.2c STELLA flow diagram of solid waste management system dynamics—energy flow and emissions
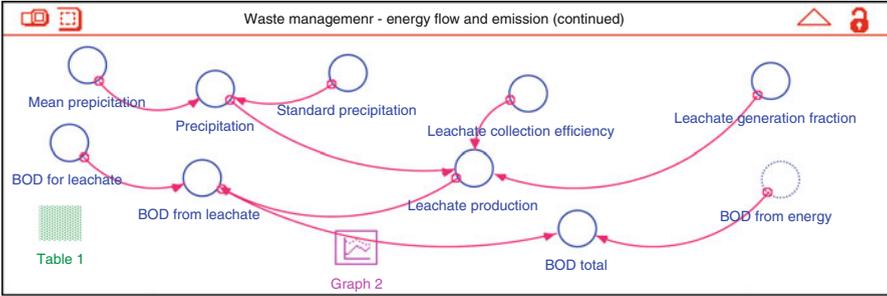
Fig. 12.2d STELLA flow diagram of solid waste management system dynamics—energy flow and emissions

12.4.1 Waste Management–Material Flow

The generated solid wastes consist of uncleared nonrecycling wastes and recyclable wastes.

Uncleared nonrecycling waste is increased by waste generation rate and decreased by collection rate, and it is expressed as

$$\begin{aligned} \text{Uncleared\_nonrecycling}(t) = & \ \text{Uncleared\_nonrecycling}(t-dt) \\ & + (\text{Waste\_gen\_rate} - \text{Collection\_rate}) * dt \end{aligned} \quad (12.2)$$

Nonrecyclable waste generation depends on the population, per capita income and GDP. The nonrecyclable waste generation rate, i.e. waste capacity, is computed from population, per capita waste generation and nonrecycling factor as

$$\text{Generation\_capacity} = \text{Population*Nonrecycling\_factor*Per\_capita\_waste\_gen} \quad (12.3)$$

The waste collection rate depends on collection capacity and generation capacity. IF generation capacity is greater than collection capacity THEN collection rate is collection capacity ELSE it is generation capacity, and it is expressed as

$$\begin{aligned} \text{Collection\_rate} = & \ \text{IF}(\text{Generation\_capacity} > \text{Collection\_capacity}) \\ & \text{THEN}(\text{Collection\_capacity})\text{ELSE}(\text{Generation\_capacity}) \end{aligned} \quad (12.4)$$

Recyclable waste is increased by recyclable waste generation rate and decreased by recyclable collection rate, and it is expressed as

$$\begin{aligned} \text{Recyclable\_waste}(t) = & \ \text{Recyclable\_waste}(t-dt) \\ & + (\text{Recyclable\_waste\_gen\_rate} \\ & - \text{Recyclable\_collection\_rate}) * dt \end{aligned} \quad (12.5)$$

The recyclable waste generation rate is computed from population, average per capita income and recyclable waste factor as

$$
\begin{aligned}
&\text{Recyclable\_waste\_gen\_rate} \\
&= \text{Population*Per\_capita\_waste\_gen*Recyclable\_waste\_factor}
\end{aligned}
\tag{12.6}
$$

The recyclable collection rate depends on recyclable waste, recyclable collection factor and separation multiplier from public concern, and it is computed as

$$
\begin{aligned}
&\text{Recyclable\_collection\_rate} \\
&= \text{Recyclable\_waste*Recyclable\_collection\_factor*Separation\_multiplier\_from\_public\_concern}
\end{aligned}
\tag{12.7}
$$

The portion of the uncleared nonrecycling wastes and recyclable wastes that are not collected is termed as uncleared wastes. Uncleaned and untreated wastes create nuisance which causes public concern. This concern is reduced by vented reaction. The public concern is expressed as

$$
\begin{aligned}
\text{Public\_concern}(t) = {}& \text{Public\_concern}(t - dt) \\
&+ (\text{Concern\_rate} - \text{Vented\_reaction}) * dt
\end{aligned}
\tag{12.8}
$$

Concern rate increases with composite index and it is non-linearly related with composite index. This relationship is expressed by a graphical function:

Concern_rate = GRAPH(Composite_index)
(0.00, 1.00), (25.0, 1.11), (50.0, 1.25), (75.0, 1.35), (100, 1.42), (125, 1.47), (150, 1.50)

Concern decreases with time and it is expressed as

$$
\text{Vented\_reaction} = \text{Public\_concern/Concern\_dissipation\_time}
\tag{12.9}
$$

Public concern in turn creates public pressure to reduce the waste generation, and the effect of public pressure resulting from public concern is expressed as a multiplier. The public pressure multiplier is non-linearly related to public concern, and it is expressed as

Public_pressure_multiplier = GRAPH(Public_concern)
(1.00, 1.01), (2.50, 1.04), (4.00, 1.08), (5.50, 1.15), (7.00, 1.25), (8.50, 1.35), (10.0, 1.50)

Untreated waste is increased by collection rate and decreased by composting rate, disposal rate and incineration rate, and it is expressed as

Untreated_waste(t) = Untreated_waste$(t - dt)$
+ (Collection_rate − Composting_rate − Disposal_rate − incineration_rate) * dt

$$(12.10)$$

IF untreated waste is greater than composting capacity THEN composting rate is composting capacity ELSE it is untreated waste, and it is expressed as

Composting_rate =   IF(Untreated_waste > Composting_capacity)
×THEN(Composting_capacity)ELSE(Untreated_waste)

$$(12.11)$$

IF untreated waste plus incineration capacity is greater than composting capacity THEN disposal rate is the MIN of (i) (untreated waste plus incineration capacity >composting capacity) and (ii) (landfill capacity) ELSE it is zero, and it is expressed as

Disposal_rate
= IF((Untreated_waste + Incineration_capacity) > Composting_capacity)
THEN(MIN((Untreated_waste + Incineration_capacity − Composting_capacity),
Landfill_capacity)) × ELSE(0)

$$(12.12)$$

IF untreated waste is greater than incineration capacity THEN incineration rate is incineration capacity ELSE it is untreated waste, and it is expressed as

incineration_rate =   IF(Untreated_waste > Incineration_capacity)
THEN(Incineration_capacity)ELSE(Untreated_waste)

$$(12.13)$$

Both uncleared wastes and untreated wastes create nuisance and increase environmental concern. Composting index is an environmental indicator and it is defined by the following expression:

Composite_index
= (Weight1*Uncleared_waste/Base_value_of_uncleared_waste
+ Weight2*Untreated_waste/Base_value_of_untreated_waste)*Population_ratio

$$(12.14)$$

Recyclable stock increases by recyclable collection rate and decreases by recycling rate. It is expressed as

$$\text{Recyclable\_stock}(t) = \text{Recyclable\_stock}(t - dt)$$
$$+ (\text{Recyclable\_collection\_rate} - \text{Recycling\_rate}) * dt$$

$$(12.15)$$

Recycling rate is a fraction of recyclable stock and it is expressed as

$$\text{Recycling\_rate} = \text{Recyclable\_stock*Recycling\_factor} \qquad (12.16)$$

12.4.2 Waste Management: Composting, Incineration and Landfill

Composing capacity is increased by increasing capacity and decreased by depreciation and it is expressed as

$$\text{Composting\_capacity}(t) = \text{Composting\_capacity}(t - dt)$$
$$+ (\text{Increasing\_capacity} - \text{Depriciation\_rate}) * dt$$

$$(12.17)$$

Increasing capacity is computed from desired treatment capacity, existing composting and correction time, and it is expressed as

$$\text{Increasing\_capacity} = (\text{Desired\_treatment\_capacity} - \text{Composting\_capacity})$$
$$/\text{Correction\_time\_for\_treatment\_plant}$$

$$(12.18)$$

Depreciation rate is computed from composting capacity and its average life, and it is computed as

$$\text{Depriciation\_rate} = \text{Composting\_capacity/Average\_plant\_life} \qquad (12.19)$$

Incineration capacity is increased by incineration capacity rate and decreased by depreciation, and it is expressed as

$$\text{Incineration\_capacity}(t) = \text{Incineration\_capacity}(t - dt)$$
$$+ (\text{Incineration\_capacity\_rate} - \text{Depreciation\_rate}) * dt \qquad (12.20)$$

Incineration capacity rate is computed from desired incineration capacity, existing incineration capacity and correction time, and it is expressed as

$$\text{Incineration\_capacity\_rate} = (\text{Desired\_incineration\_capacity} - \text{Incineration\_capacity})$$
$$/\text{Correction\_time\_for\_inc}$$

$$(12.21)$$

Depreciation rate is computed from incineration capacity and its average life, and it is computed as

$$\text{Depreciation\_rate} \ = \ \text{Incineration\_capacity}/\text{Average\_inc\_life} \qquad (12.22)$$

Landfill capacity is increased by landfill capacity rate and decreased by landfill rate, and it is expressed as

$$\begin{aligned}\text{Landfill\_capacity}(t) \ = \ & \text{Landfill\_capacity}(t - dt) \\ & + (\text{Landfill\_capacity\_rate} - \text{Landfill\_rate}) * dt \quad (12.23)\end{aligned}$$

Landfill capacity rate is the landfill development and it is expressed as

$$\text{Landfill\_capacity\_rate} \ = \ \text{Landfill\_development} \qquad (12.24)$$

IF Disposal is less than Landfill capacity THEN Landfill rate is Disposal ELSE it is Landfill capacity, and it is expressed as

$$\text{Landfill\_rate} \ = \ \begin{aligned}&\text{IF}(\text{Disposal} < \text{Landfill\_capacity})\text{THEN}(\text{Disposal}) \\ &\text{ELSE}(\text{Landfill\_capacity})\end{aligned} \qquad (12.25)$$

The landfill development is non-linearly related to time and it is expressed as

Landfill_development = GRAPH(TIME)
(0.00, 175500), (3.00, 252000), (6.00, 366750), (9.00, 460250), (12.0, 558000), (15.0, 647250), (18.0, 732250), (21.0, 791750), (24.0, 855500), (27.0, 893750), (30.0, 915000)

The number of trucks for collection of wastes increases with increase rate and decreases by discard rate, and it is expressed as

$$\begin{aligned}\text{No\_of\_truck}(t) \ = \ & \text{No\_of\_truck}(t - dt) \\ & + (\text{Truck\_increase\_rate} - \text{Truck\_discarded\_rate}) * dt \quad (12.26)\end{aligned}$$

The truck increase rate is computed from the desired number of trucks, number of trucks and correction time as

$$\text{Truck\_increase\_rate} \ = \ \begin{aligned}&(\text{Desired\_number\_of\_truck} - \text{No\_of\_truck}) \\ &/\text{Correction\_time\_of\_truck}\end{aligned} \qquad (12.27)$$

The truck discard rate is calculated from number of trucks and average life of a truck:

$$\text{Truck\_discarded\_rate} \ = \ \text{No\_of\_truck}/\text{Avg\_life\_of\_truck} \qquad (12.28)$$

The number of trucks for landfill increases with increase rate for landfill and decreases by discard rate for landfill, and it is expressed as

$$
\begin{aligned}
\text{Trucks\_for\_landfill}(t) = {}& \text{Trucks\_for\_landfill}(t - dt) \\
& + (\text{Truck\_increase\_rate\_for\_landfill} - \text{Truck\_discarding\_rate\_for\_landfill}) * dt
\end{aligned}
$$
(12.29)

The truck increase rate for landfill is computed from the desired number of trucks for landfill, number of trucks for landfill and adjustment time for landfill as

$$
\begin{aligned}
& \text{Truck\_increase\_rate\_for\_landfill} \\
& = (\text{Desired\_number\_of\_trucks\_for\_landfill} - \text{Trucks\_for\_landfill}) \\
& \quad / \text{Adjustment\_time\_for\_landfill}
\end{aligned}
$$
(12.30)

The truck discard rate for landfill is calculated from the number of trucks for landfill and average life of a truck:

$$
\text{Truck\_discarding\_rate\_for\_landfill} = \text{Trucks\_for\_landfill} / \text{Average\_life\_of\_truck}
$$
(12.31)

The total fund required is computed from the fund required for disposal, processing and collection as

$$
\begin{aligned}
\text{Total\_fund\_required} = {}& \text{Fund\_required\_for\_disposal} \\
& + \text{Fund\_required\_for\_processing} \\
& + \text{Total\_fund\_required\_for\_collection}
\end{aligned}
$$
(12.32)

The total fund required for collection is the sum of collection cost and cost of the truck, and it is expressed as

$$
\begin{aligned}
\text{Total\_fund\_required\_for\_collection} = {}& \text{Collection\_cost\_per\_year} \\
& + \text{Fund\_for\_truck}
\end{aligned}
$$
(12.33)

12.4.3 Waste Management: Energy Flow and Emissions

BOD total is the sum of BOD from energy and BOD from leachate, and it is expressed as

$$
\text{BOD\_total} = \text{BOD\_from\_energy} + \text{BOD\_from\_leachate}
$$
(12.34)

BOD from energy is the sum of BOD collection, BOD from the glass, BOD from the landfill, BOD from the metal, BOD from the paper and BOD from the plastic, and it is expressed as

$$\text{BOD\_from\_energy} = \text{BOD\_Collection} + \text{BOD\_glass} + \text{BOD\_landfill}$$
$$+ \text{BOD\_metal} + \text{BOD\_paper} + \text{BOD\_plastic} \qquad (12.35)$$

where

$$\text{BOD\_Collection} = \text{Fuel\_consumption\_for\_collection*BOD\_for\_diesel} \quad (12.36)$$

$$\text{BOD\_glass} = \text{Glass*BOD\_factor\_glass} \qquad (12.37)$$

$$\text{BOD\_landfill} = \text{Fuel\_consumption\_for\_landfill*BOD\_for\_diesel} \qquad (12.38)$$

$$\text{BOD\_metal} = \text{metal*BOD\_factor\_metal} \qquad (12.39)$$

$$\text{BOD\_paper} = \text{Paper*BOD\_factor\_paper} \qquad (12.40)$$

$$\text{BOD\_plastic} = \text{Plastic*BOD\_factor\_plastic} \qquad (12.41)$$

BOD from leachate is computed from leachate and BOD for leachate as

$$\text{BOD\_from\_leachate} = \text{Leachate\_production*BOD\_for\_leachate} \qquad (12.42)$$

where

Leachate_production
$$= \text{Leachate\_collection\_efficiency*Leachate\_generation\_fraction*Precipitation}$$
$$(12.43)$$

CH_4 total is the sum of CH_4 from collection, CH_4 from the glass, CH_4 from the metal, CH_4 from the paper, CH_4 from the plastic and CH_4 from the landfill, and it is computed as

$$\text{CH}_4\_\text{total} = \text{CH}_4\_\text{Collection} + \text{CH}_4\_\text{glass} + \text{CH}_4\_\text{metal} + \text{CH}_4\_\text{paper}$$
$$+ \text{CH}_4\_\text{plastic} + \text{CH}_4\_\text{landfill} \qquad (12.44)$$

where

$$\text{CH}_4\_\text{Collection} = \text{Fuel\_consumption\_for\_collection*CH}_4\_\text{for\_diesel} \quad (12.45)$$

$$\text{CH}_4\_\text{glass} = \text{Glass*CH}_4\_\text{factor\_glass} \qquad (12.46)$$

$$\text{CH}_4\_\text{landfill} = \text{Fuel\_consumption\_for\_landfill*CH}_4\_\text{for\_diesel} \qquad (12.47)$$

$$\text{CH}_4\_\text{metal} = \text{metal*CH}_4\_\text{factor\_metal} \qquad (12.48)$$

$$\text{CH}_4\_\text{paper} = \text{Paper*CH}_4\_\text{factor\_paper} \qquad (12.49)$$

$$CH_4\_plastic = Plastic*CH_4\_factor\_plastic \qquad (12.50)$$

CO_2 total is the sum of CO_2 from collection, CO_2 from the glass, CO_2 from the landfill, CO_2 from the metal, CO_2 from the paper and CO_2 from the plastic, and it is expressed as

$$CO_2\_total = CO_2\_collection + CO_2\_glass + CO_2\_landfill + CO_2\_metal$$
$$+ CO_2\_paper + CO_2\_plastic \qquad (12.51)$$

where

$$CO_2\_collection = Fuel\_consumption\_for\_collection*CO_2\_for\_diesel \quad (12.52)$$

$$CO_2\_glass = Glass*CO_2\_factor\_glass \qquad (12.53)$$

$$CO_2\_landfill = Fuel\_consumption\_for\_landfill*CO_2\_for\_diesel \qquad (12.54)$$

$$CO_2\_metal = metal*CO_2\_factor\_metal \qquad (12.55)$$

$$CO_2\_paper = Paper*CO_2\_factor\_paper \qquad (12.56)$$

$$CO_2\_plastic = Plastic*CO_2\_factor\_plastic \qquad (12.57)$$

12.5   Model Validation

The various ways of validating a system dynamics model, such as comparing the model results with historical data, checking whether the model generates plausible behaviour and checking the quality of parameter values, were considered. Some of the parameters have been derived from studies in other areas and some were the results of expert guesswork. To judge the plausibility of the model, the behaviour of the key variables in the base run was examined.

## 12.6   Simulation and Policy Analysis

Computer projections of population, solid waste generation, uncleared waste and untreated waste for Dhaka City are shown in Fig. 12.3. Dhaka City had a population of 4.375 million in 1995 and approaching 12.082 million by 2025. The population growth rate of the city is higher than the average value of the whole country. This might be due to the fact that for job opportunities or other attractive factors, there is a rapid population inflow into the city. More population means more waste, and more waste means more resources needed for waste management. The waste generation increases from 1.027 million tons in 1995 to 4.257 million tons in 2025. An estimate of waste generation is crucially important to collection services and disposal facilities. It is clear from the figure that uncleared waste increases from
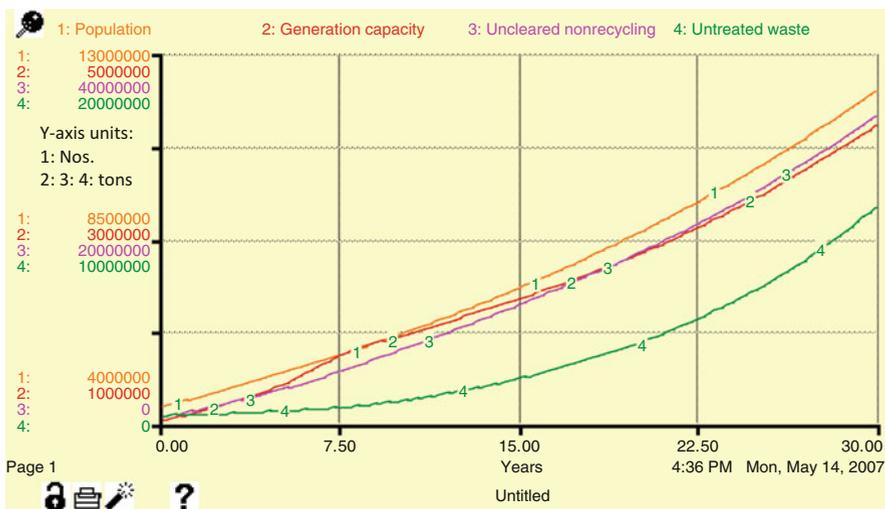
Fig. 12.3 Population, solid waste generation, uncleared waste and untreated waste of Dhaka City for a time horizon of 30 years

519,681 tons in 1995 to 33.183e + 006 tons in 2025, and untreated waste increases from 376,321 tons in 1995 to 11.65e + 006 tons in 2025. The uncleared waste of Dhaka City is increasing with time because of an inadequate collection capacity to transport the wastes to the dumpsites. Untreated waste is also increasing with time due to the lack of treatment facilities.

Figure 12.4 shows simulated incineration capacity, composting capacity, landfill capacity, electrical energy generation potential and composite index for a time horizon of 30 years. For a policy of introduction of incineration plant, composting and sanitary landfill, the landfill capacity increases from 150,000 tons in 1995 to 907,729 tons in 2025, incineration capacity increases from 150,000 tons in 1995 to 0.190e + 006 tons in 2025, corresponding electrical energy generation capacity increases from 66,750 MWh in 1995 to 84,556 MWh in 2025 and composting plant capacity increases up to 15 years, and then it becomes almost constant. The electrical energy recovery from urban solid waste generation of Dhaka City can supply a significant portion of the consumption requirement of electrical energy of the city. Hence, adoption of the policy for electricity from urban solid waste of Dhaka City should be dictated by the economy of adoption of the technology of electricity generation from the solid waste and environmental implications. The composite index increases from 0.86 in 1995 to 101.47 in 2025. The rapid increase in composite index with time means that the quality of the environment is deteriorating rapidly with time. In the early period (0–7.5 years), the composite index is very low with a very small growth rate, while in the later period, it increases very rapidly. The rapid increase in the composite index with time means that the quality of the environment is deteriorating rapidly with time.
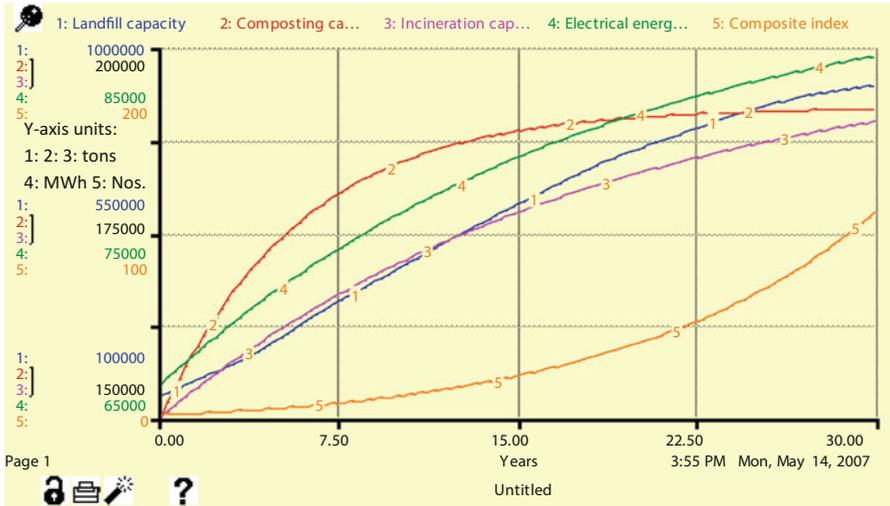
Fig. 12.4 Simulated landfill capacity, composting capacity, incineration capacity and electricity generation potential from solid waste and composite index for a time horizon of 30 years
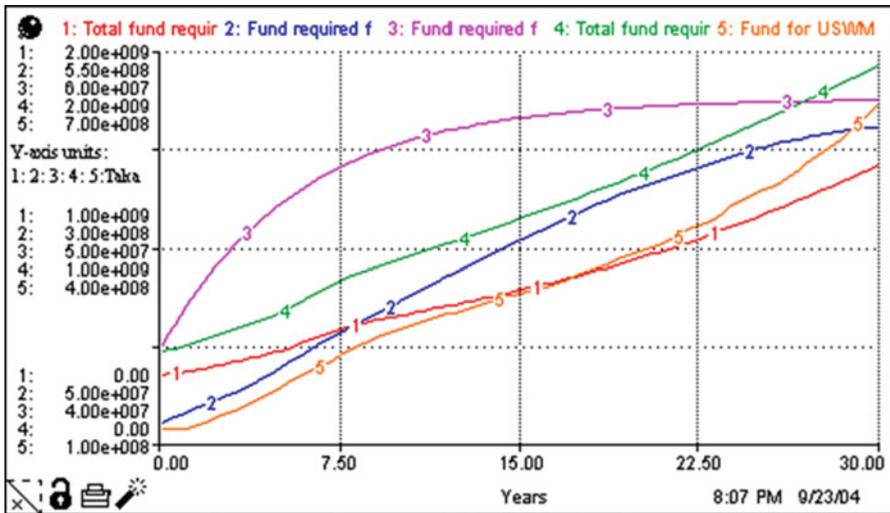
Fig. 12.5 Simulated total fund required for collection, fund required for disposal, fund required for processing, total fund required and fund for USWM for a time horizon of 30 years (one US $ = Taka 70.00)

Thus, solid waste management system is sustainable in the short run and becomes unsustainable in the long run.

Figure 12.5 shows the simulated total funds required for collection, landfill and treatment, total fund required and fund for USWM for a time horizon of 30 years.
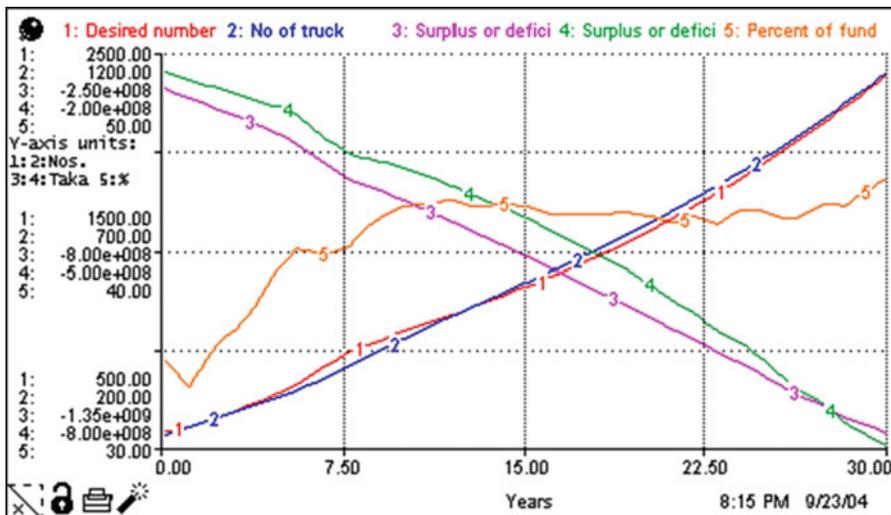
Fig. 12.6 Simulated desired number of trucks, number of trucks used, surplus or deficit budget, surplus or deficit budget for collection and percent of fund available for collection for a time horizon of 30 years
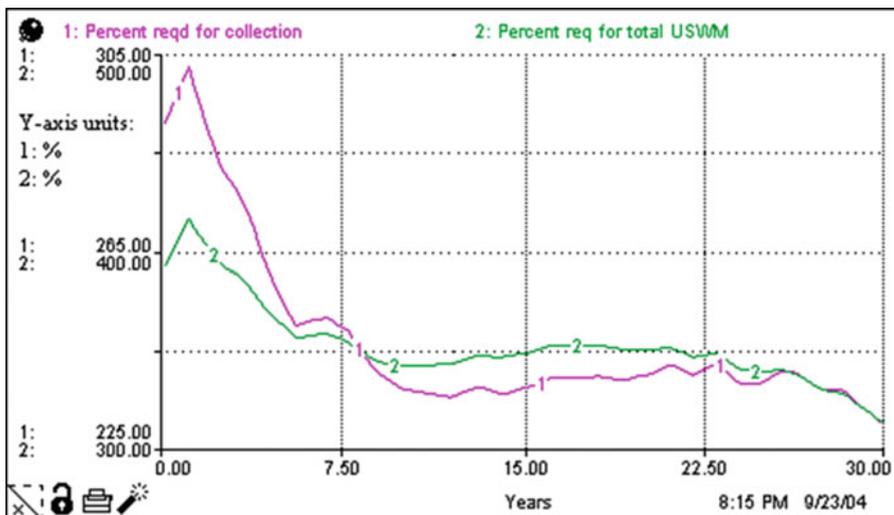
The simulated total fund required for collection, total fund required and fund for USWM are increasing with time. The fund required for collection increases from Tk 3.46e + 008 in 1995 to Tk 14.15e + 008 in 2025 since the generation of solid waste increases. The fund required for disposal also increases from Tk 7.50e + 007 in 1995 to Tk 45.38e + 007 in 2025. The fund required for waste treatment is increasing up to 15 years. After 15 years, the fund required for treatment is more or less constant at a value of Tk 5.70e + 007. This is because of the fact that the capacity utilisation of the treatment plant is fulfilled. The fund required for landfill is also increasing until towards the end of the simulated period. These are due to the facts that treatment capacity and landfill capacity are approaching the proposed desired treatment capacity and proposed desired landfill capacity, respectively. Logically, the total fund required increases from Tk 4.660e + 008 in 1995 to Tk 19.27e + 008 in 2005, and the total fund required for solid waste management increases from Tk 1.18e + 008 in 1995 to Tk 6.16e + 008 in 2005. Thus, increased funds are needed for both collection and solid waste management.

Figure 12.6 shows the simulated desired number of trucks, number of trucks used, surplus or deficit total budget, surplus or deficit budget for collection and percent of fund available for collection for a time horizon of 30 years. The desired number of trucks increases from 575 in 1995 to 2384 in 2025, whereas the number of trucks used increases from 230 in 1995 to 1148 in 2025. There is always a gap between the desired number of trucks and number of trucks used. Thus, the collection service at Dhaka City is deteriorating rather than improving. Moreover, the transportation of the waste to the dumpsite is not properly managed. Wastes are seen flying from the trucks during transport. Since the population and wastes

generated are increasing with time, the desired number of trucks is also increasing. The number of trucks never equals the desired number of trucks, since the policy was to reduce the shortage in number of trucks which is dynamic. This indicates that more funds are required to mitigate the shortage of trucks and to meet the collection cost. The patterns of the change of deficit of the budget and the budget for collection decrease with time, but the percent of fund available for collection increases from almost 34 % in 1995 to 39 % in 2000 and then gradually increases to 43.5 % in 2005 and then almost remains constant. Thus, there is high shortage of fund for collection particularly for trucks for collection.

Figure 12.7 shows the simulated percent of fund increase required for only total waste collection and total USWM for a time horizon of 30 years. Initially the required budget for collection is 291 %. The budget requirement for collection decreases from 291 to 254 % sharply within 5 years; then it gradually decreases to a constant value of 238 % within 10 years and it continues up to 25 years. After 25 years, it decreases gradually. But for total urban solid waste management, the required budget for total waste management is 415 %. Then, the budget requirement decreases gradually from 415 % to an almost constant value of 340 % within 10 years. The initial jumps of the budgets for total waste collection and total urban solid waste management are due to the introduction of treatment plant and landfills for solid waste disposal.

Figure 12.8 shows simulated composts, i.e. nitrogen, potassium and phosphorus, and composite index. Composts available from solid waste increase from 0.150e +006 tons in 1995 to 0.191e+006 tons in 2025. Nitrogen, potassium and phosphorus increase from 3600 tons in 1995 to 4602 tons in 2025, from 2550 tons in 1995 to 3260 tons in 2025 and from 1800 tons in 1995 to 2301 tons in 2025, respectively,

Fig. 12.7 Simulated percent of fund increased required for only total waste collection and total USWM for a time horizon of 30 years
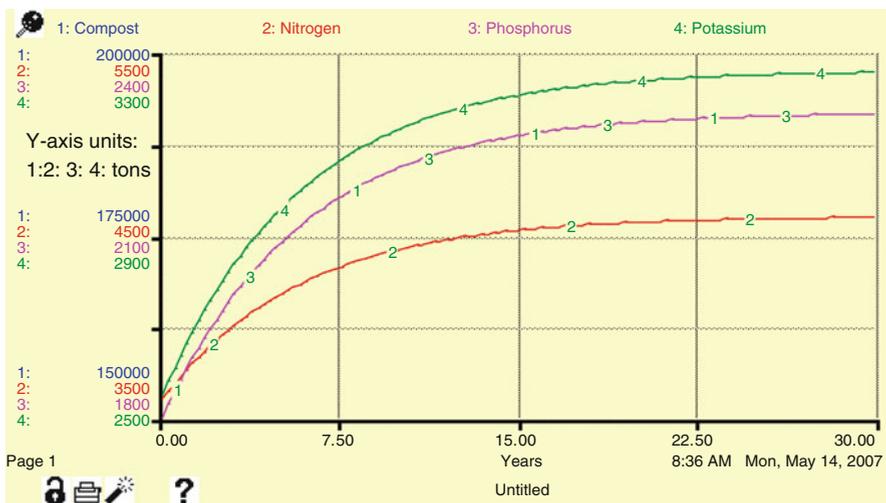
Fig. 12.8 Simulated compost, nitrogen, phosphorus and potassium for a time horizon of 30 years
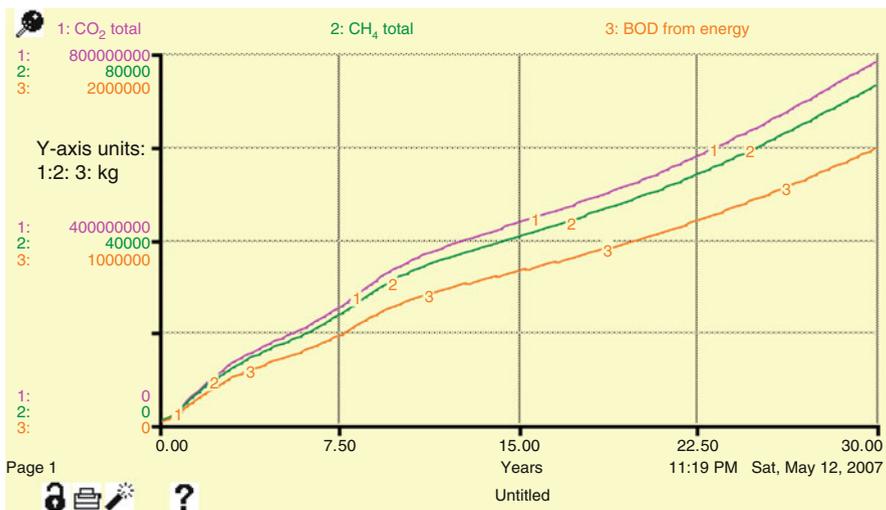

Fig. 12.9 Simulated CO_2 total, CH_4 total and BOD from energy for a time horizon of 30 years

and follow the production pattern of the composts. There is a significant contribution of organic fertilisers from the compost from composting of solid waste. This compost is a good-quality organic fertiliser for garden vegetables and other crops, and it is approved by the Bangladesh Agricultural Research Council (BARC).

Figure 12.9 shows simulated CO_2 total, CH_4 and BOD from energy. Simulated CO_2 total increases from 5.153e + 006 kg in 1995 to 78.112e + 007 kg in 2025. CH_4
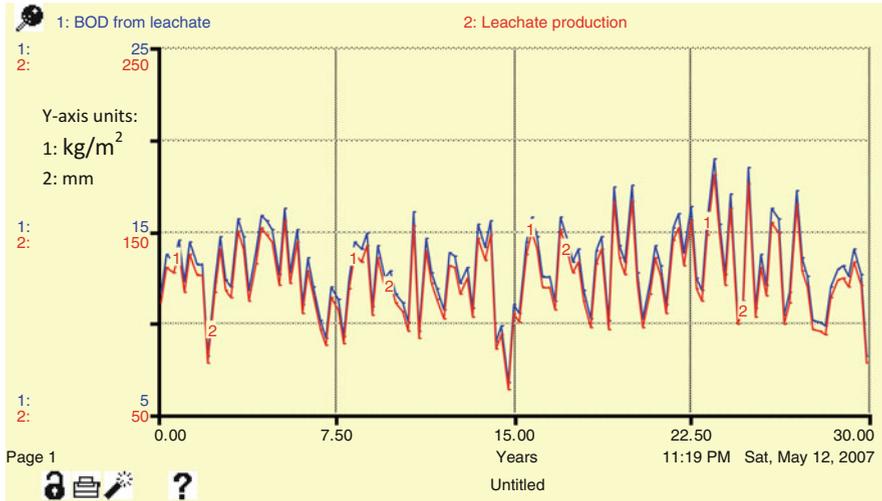
Fig. 12.10 Simulated leachate production (mm) and BOD (kg/m^2) from leachate for a time horizon of 30 years

total increases from 412 kg in 1995 to 72,884 kg in 2005 and BOD from energy increases from 8136 kg in 1995 to 1.48e + 006 kg in 2025. The increase of these emissions with time is due to the increase in solid waste generated. However, the intensity of production of these emissions is moderately low due to the proposed introduction of the composting, incineration plant and sanitary landfill.

Figure 12.10 shows the simulated leachate production and BOD from leachate for a time horizon of 30 years. The simulated leachate production shows fluctuations which are mainly due to the fluctuation in the annual rainfall. BOD from leachate follows the pattern of leachate production. However, BOD from leachate lies between 100 mm and 150 mm.

In order to obtain insight into the effect of the alternative policy options, the following two policy options are considered:

Policy 1: Increasing the collection capacity and assessing its impact on uncleared waste, untreated waste, number of trucks and composite index.

Policy 2: Increasing the collection capacity, treatment capacity and landfill capacity and assessing its impact on uncleared waste, untreated waste, number of trucks and composite index.

Policy 1: Figure 12.11 shows the simulated uncleared waste, untreated waste, number of truck and composite index for increase in collection capacity for a time horizon of 30 years. From the figure it is observed that if we increase the collection capacity by doubling the truck increase rate, the uncleared waste decreases and untreated waste increases, but the composite index remains unchanged as compared with the base scenarios discussed earlier. This means
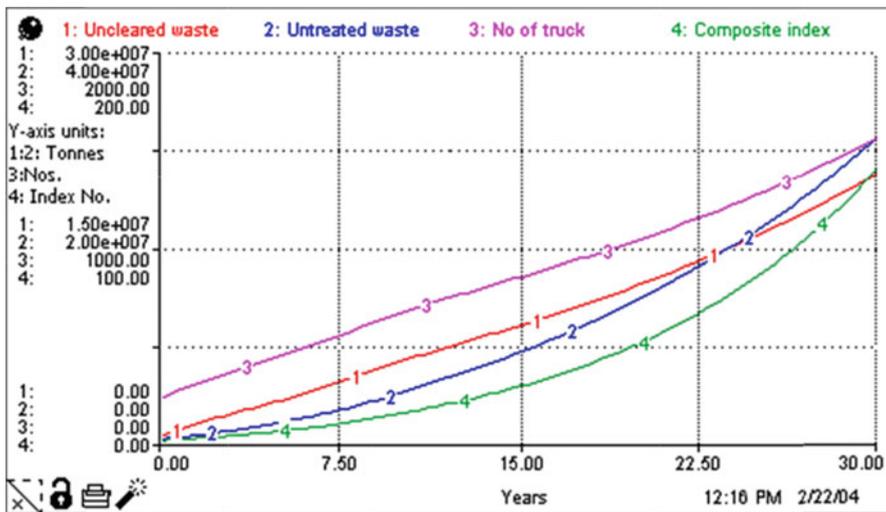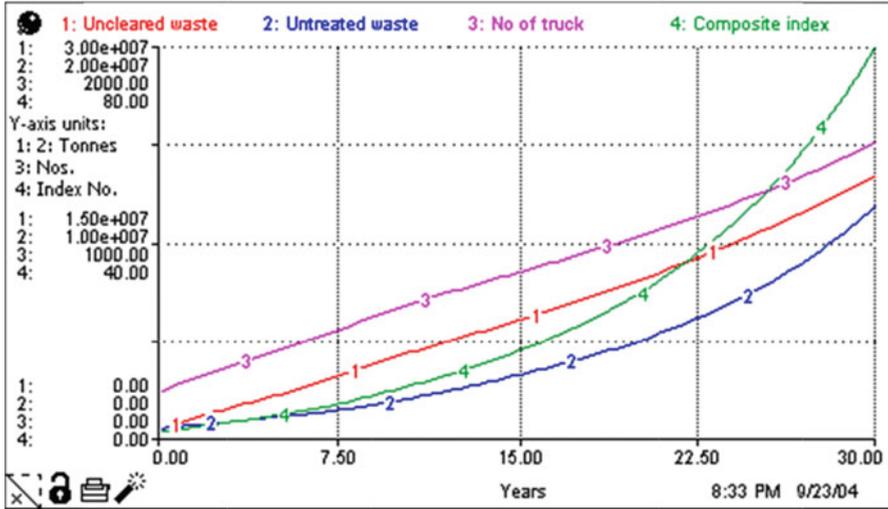
Fig. 12.11 Simulated uncleared waste, untreated waste, number of trucks and composite index with increase in collection capacity for a time horizon of 30 years

that increasing collection capacity alone does not improve the environmental quality because composite index is the indicator of environmental quality.

Policy 2: Figure 12.12 shows the simulated uncleared waste, untreated waste, number of trucks used and composite index with increase in collection capacity, treatment capacity and landfill capacity for a time horizon of 30 years. From Fig. 12.12, it is observed that if we increase collection capacity, treatment capacity and landfill capacity by doubling the truck increase rate, treatment capacity increase rate and landfill capacity increase rate, respectively, the uncleared waste decreases in a similar fashion as in policy 1, but the untreated waste and the composite index also decrease as compared to policy 1. Increased composite index is the sign of environmental quality deterioration, and decreased composite index is the sign of environmental quality improvement. This implies that the increased budget allocation for both clearing and treating the wastes is essential for improving the environmental quality of Dhaka City.

Energy from the waste as well as from the incineration reduces greenhouse gas emission. An analysis of CO_2 equivalent emission per kWh of electricity produced by energy from waste showed that global warming potential of emission from waste is less than coal, fuel and even natural gas.

Finally, in the short run the proposed policy is for sustainable development. But in the long run, it appears to be a dream unless population control within the carrying capacity of the city is achieved, and the treatment plants with energy and material recovery are realised.

Fig. 12.12 Simulated uncleared waste, untreated waste, number of trucks and composite index with increased collection capacity, treatment capacity and landfill capacity for a time horizon of 30 years

12.7 Conclusions

Population, solid waste generation and electrical energy generation possibility from the solid waste for Dhaka City are increasing with time. The electrical energy recovery from urban solid waste generation of Dhaka City can supply a significant portion of the consumption requirement of electrical energy of the city. Adoption of the policy for electricity from urban solid waste should be dictated by the economy of adoption of the technology of electricity generation from the waste and environmental implications. There exists a potential for organic fertilisers for composting of solid waste, and this compost is a good-quality organic fertiliser for garden vegetables. A policy of introduction of incineration, composting and sanitary landfill is assessed. The intensity of production of the emissions is moderately low due to the proposed introduction of the composting, incineration plant and sanitary landfill. The proposed system is sustainable in the short run but becomes unsustainable in the long run. This model can be used as a tool to assess and design policy options.

Exercises

Exercise 12.1 What is meant by solid waste? Why modelling and simulation of solid waste management systems is important?

Exercise 12.2 Draw the causal loop diagrams of solid waste management systems consisting of solid waste generation and disposal in the form of limited landfill, composting and open dumping.

Exercise 12.3 Draw stock–flow diagram of solid waste management systems consisting of solid waste generation and disposal in the form of limited landfill, incineration, composting and open dumping and simulate the model for solid waste generation, landfill, composting and open dumping.

Exercise 12.4 Simulate the model in Exercise 12.3 for increasing collection and treatment capacity and also analyse the simulated results.

Exercise 12.5 Simulate the model including incineration in the model in Exercise 12.3 and assess the contribution of CO_2, CH_4 and BOD from the solid waste management system.

References

Alam MJ, Bole B (2001) Energy recovery form municipal solid waste in Dhaka city. In: Proceedings of the international conference on Mechanical Engineering, 26–28 December 2001, Dhaka, pp I 125–130

Bala BK, Sufian MA (2006) A. Modeling of urban solid waste management: the case of Dhaka city. J Agric Mach Bioresour Eng 4(1&2):17–25

Barsi HB (2000) An expert system for landfill leachate management. Environ Technol 21 (2):157–166

Clayton KC, McCarl BA (1979) Management of solid waste systems including non-metropolitan areas, with emphasis on resource recovery. North Cent J Agric Econ 1(1):61–72

Consonni S, Guigliano M, Grosso M (2005a) Alternative strategies for energy recovery from municipal solid waste Part A: mass and energy balances. Waste Manag 25:123–135

Consonni S, Guigliano M, Grosso M (2005b) Alternative strategies for energy recovery from municipal solid waste Part B: emission and cost estimates. Waste Manag 25(2005b):137–148

Dyson B, Chang NB (2005) Forecasting municipal solid waste generation in a fast growing urban region with system dynamics modeling. Waste Manag 25(7):669–679

Everett JW, Modak AR (1996) Optimal regional scheduling of solid waste systems. J Environ Eng 122(9):785–792

Heikki TJ (2000) Strategic planning of municipal solid waste management. Resour Conserv Recycl 30(2):111–133

JICA (2005) The study on solid waste management in Dhaka city, clean Dhaka master plan, final report, Japan International Agency, Pacific Consultants International, Yachiyo Engineering Co., Ltd.

Kum V, Sharp A, Harnpornchai N (2005) Improving the solid waste management in Phnom Penh city: a strategic approach. Waste Manag 25:101–109

Mashayekhi AN (1992) Transition in the New York state solid waste system: a dynamic analysis. Syst Dyn Rev 9(1):23–47

Ming ZG, Zhong YX, Yue ZP, Cheg GH, He HGG, Hemelaar L (2000) Environmental input – output model and its analysis with a focus on the waste management sectors. J Environ Sci 12 (2):178–183

Pawan S, Sikka P, Maheshwari RC, Chaturvedi P (1997) Management of municipal solid waste. Bio energy for rural energization. Department of Science and Technology. IIT, New Delhi, India, pp 205–209

Rao CS (1992) Environmental pollution control engineering and sanitation. Willey Eastern Limited, New Delhi, pp 396–414

Salvato JA (1992) Solid waste management. Environmental engineering and sanitation, 4th edn. Willey, Hoboken, pp 662–766

Sterman JD (2000) Business dynamics: systems thinking and modeling for a complex world. Irwin McGraw Hill, New York

Sudhir V, Srinivasan G, Muraleedharan VR (1997) Planning for sustainable solid waste management in urban India. Syst Dyn Rev 13(3):223–246

Sufian MA, Bala BK (2006) Modeling of electrical energy recovery from urban solid waste system: the case of Dhaka city. Renew Energy 31(10):1573–1580

Sufian MA, Bala BK (2007) Modeling of urban solid waste management: the case of Dhaka city. Waste Manag 27:858–868

Velumani A, Meenakshi P (2007) Life cycle inventory analysis of emissions from existing municipal solid wastes management scenarios in coimbatore city. In: Proceedings of the international conference on Sustainable Solid Waste Management held on 5–7 September 2007, Chennai, India, pp 75–82

Yongfeng NIE (2005) Development and prospects of municipal solid waste (MSW) incineration in China. Front Environ Sci Enfin China 2(1):1–7

Zurbrugg C, Drescher S, Sinha M, Enaetullah I (2002) Decentralized composting in Dhaka, Bangladesh: production of compost and its marketing. In: Proceedings of ISWA 2002 Annual Congress, Istanbul, Turkey, 8–12 July 2002

Bibliography

Bala BK (1998) Energy and environment: modeling and simulation. Nova Science Publisher, New York

Bala BK (1999) Principles of system dynamics. Agrotech Publishing Academy, Udaipur

Cavana RY, Maani KE (2000) A methodological framework for systems thinking and modelling (ST&M) interventions. Ist international conference on systems thinking in management. Internet

Diaz R, Warith M (2005) Life cycle assessment of municipal solid wastes: development of the WASTED model. Waste Manag 25(7):669–679

Forrester JW (1968) Principles of systems. Wright-Allen Press/MIT, Cambridge, MA