INTEGRATED MUNICIPAL SOLID WASTES MANAGEMENT IN A METROPOLITAN CITY

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CERTIFICATE FROM THE SUPERVISOR/S

*This is to certify that the thesis entitled "**Integrated Municipal Solid Wastes Management in a Metropolitan City**" submitted by **Shri Subhasish Chattopadhyay**, who got his name registered on **27th June, 2011**, for the award of Ph.D. (Engineering) degree of Jadavpur University is absolutely based upon his own work under the supervision/s of **Dr. Amit Dutta** and that neither his thesis nor any part of the thesis has been submitted for any degree or any other academic award anywhere before.*

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Declaration

I declare that the work described in this thesis is entirely my own. No portion of the work referred to in this thesis has been submitted in support of an application for another degree or qualification of this or any other university or institute. Any help or source information, which has been availed in the thesis, has been duly acknowledged.

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ABSTRACT

Waste generation is an integral consequence of human civilization. Initially due to small population, disposed waste was easily assimilated by the nature. At present era exponential growth of population accelerates urbanization and industrialization which result shortage of space and resources. As a consequence of that the huge generation of municipal solid waste (MSW) and its improper management, especially in developing countries, have become a life-threaten issue for the society. Improper management and crude dumping of MSW leads to high emission of GHGs like CH_4, CO_2 and other toxic gases, huge generation of highly polluted leachate and degradation of natural resources like air, water and land. As the existing conventional MSW management is unable to satisfy the goal of sustainable development, integrated MSW management system is required to achieve this goal. A methodology has been developed to find the optimized path to shift towards integrated MSW management approach. In this study a major metropolitan city Kolkata in a developing country, India, is considered to develop this methodology.

In 2012, globally ~3 billion urban population generated 1.3 billion MT/year of MSW @1.2 kg/capita/day and by 2025 this will likely increase to 2.2 billion MT/year from 4.3 billion urban population @ 1.42 kg/capita/day. Presently in India out of 1.21 billion population, ~377 million are urban population. The urban population in India generated ~144 thousand MT/day of MSW during 2013-14. Kolkata municipal area having 9 million total population generate ~3000 MT/day of MSW. In India, to minimize the adverse environmental and social impacts due to existing practice, management and handling rules of MSW has been developed in 2000 and lately it has enhanced in 2016 which has emphasized on integrated management of MSW.

In the study of existing MSW management system of Kolkata, it is found that there is no source segregation, 60% house-to-house collection, 50-55% open vats, 50% operational efficiency of KMC transport system with 30-35% old vehicles, 80% old hired vehicles, informal recycling system, uncontrolled land disposal without having any liner, leachate management and gas collection facility which are causing numbers of environmental and human health hazards to the surroundings. Around 5% recyclables of the garbage is taken out by the informal rag pickers at the households, containers and vat points level. If 5 to 6% of irregular garbage transformation to compost is ignored, rest 95% of the garbage is reaching to the dumping ground, Dhapa. At Dhapa informal rag pickers further segregated out around 4.21% recyclable. So total recovered recyclable is around 9.21% and rest of the garbage is disposed in the landfill along with silt or rubbish.

A significant amount (3106 MT/year) of air pollutants are generated from existing MSW transportation sector of Kolkata. A major greenhouse gas CO_2 emission is the largest (97.84%) then NOx emission is the second largest (1.17%) and other major air pollutants are CO (0.66%), HC (0.19%), PM (0.12%) and SOx (0.02%).

The noise pollution study on existing situation reveals that the group of workers worst affected are the drivers and laborers of bulldozer, pay-loader fed tipper truck and manually loaded tipper truck. All the waste carrying vehicles except new dumper placer are higher than the permissible noise level and replacement of an old dumper placer by a new one effectively reduces the noise level by ~20% in dB(A) scale.

For estimation of landfill gas, site specific composition of MSW for Triangular model results close to the average value of CH_4 recovery. So, the gas generation from MSW in the developing country like India, where bio-degradable and inert wastes are high, 40% weightage to Triangular model and 30% each for IPCC and LandGEM model is recommended. From existing system, 5×10^9 MJ energy can be recovered for 10 years period after scientific closure of the existing open dump site, Dhapa, and installed plant capacity would be limited to only 3 MW. So, flaring of methane is the suitable option considering economic and commercial non-viability of power generation. From the clean development mechanism (CDM) project profit of KMC, apart from environmental benefit, is around 10.2 crores for 10 years. During transition period introduction of the engineered landfill (ELF) with phase wise disposal and closure facilities, with 75% gas recovery efficiency, results reduction of additional 49,74,456 tCO_2-eq. From proposed ELF having CER value of 1,16,21,610 tCO_2-eq, 3.5×10^{10} MJ energy likely to be available and 10MW commercially viable power plants could be supported for 20 years.

HELP model analysis for Kolkata with unlined landfill sites shows ~ (900-1000) L/m^2/year highly polluted leachate generation. Use of a complete top cover system, i.e. use of vegetative cover, top vegetation soil cover (45 cm) to support vegetation, sand layer (15 cm) for lateral drainage and barrier clay layer (60 cm), at post closure reduces the leachate generation by ~96% i.e. only ~43 L/m^2/year generation. Phase-wise landfilling operation can decreases leachate generation by ~33 % even during active period.

EPACMTP model analysis shows that metal concentration appears in the receptor well, 500m away from the disposal ground, after a lag period and then increases rapidly to its peak and remains for several hundred or thousand years. Peak concentration of organics on the other hand remains for around 25 years after the closer of the landfill and then starts decreasing. Therefore during the active period use of bottom liner, leachate collection and treatment are necessity.

Maximum life of liners is 50-100 years. So, in the post filling period, complete cover system is recommended for reduction of leachate generation by ~96% to prevent contamination of precious groundwater due to solid waste disposal.

A generic MSW management linear programming (LP) model is developed considering its different components and economics. Then it is applied to the existing MSW management system and validated. After that it is applied to the proposed integrated MSW management system and compared with the existing to achieve optimized cost effective sustainable solution methodology of MSW management system for developing countries like India.

The analysis of existing MSW management LP model with Kolkata data shows that the ratio of total quantity of waste i.e. garbage and silt or rubbish transported by departmental vehicles and hired vehicles is ~ 37:63 and with respect of only garbage disposal it is 42:58. In existing model departmental vehicles prefers to carry 5% excess waste than the existing practice. Average departmental vehicle running efficiency is only 50% which should have to be improved to minimize cost. Hired vehicles need ~35.8% of the total transportation cost to remove ~63% of total waste quantities. Though hired vehicles are more cost effective yet departmental vehicles are also needed to meet local constraints and better control over the MSW management system.

The validation of the LP model for existing scenario with actual data shows very good (± 10%) results and it indicates ~7% cost minimization is possible in the existing scenario. Further optimization of number of departmental vehicle shows ~27% reduction in total transportation cost and ~19% minimization in total SWM cost are possible in the existing scenario only by reducing the excess number of departmental vehicles to its minimum requirement. As the 50% running efficiency is on lower side, considering work culture and inadequate infrastructure for developing countries, 60% vehicle running efficiency may be considered by which ~3.2% overall SWM cost savings is possible.

Sensitivity analysis shows rate increment in incentive has negligible effect on total cost. However, garbage clearance efficiency by departmental vehicle can be increased by increasing incentive. Fixed running cost and idle cost of departmental vehicles have significant effect on transportation cost of departmental vehicles, so vehicle maintenance staff should be selected judiciously for careful maintenance of the departmental vehicles. Proper attention should also be paid for fixing and reviewing of zone wise transportation cost of silt and garbage for hired vehicle as the transportation cost of hired vehicles has significant effect on total SWM cost. If waste generation is increased by 5%, total SWM cost is increased significantly by ~4% and vice versa. So, proper estimation of waste generation is very important.

In the proposed integrated MSW management system, three engineered landfill (ELF) sites associated with three material sorting facilities, incineration facilities and composting facilities are considered. Proper source segregation of waste will be done by two bin system and after separating out 5% recyclable at source, rest amount of garbage will be transported to central sorting facilities attached with each ELF for further separating out of recyclable materials and segregating for thermal and bioprocessing. Revenue will be earned by the KMC from selling of recyclables. Then treatment and disposal of garbage will be done as per its characteristics. High calorific value of garbage fraction will go for thermal processing (mass burn incineration) and biodegradable fraction for biological processing (windrow composting). Inert and residues from treatment plants will go to engineered landfills having proper bottom liner with leachate collection facilities.

The analysis of proposed integrated MSW management LP model indicates that the total optimum SWM cost for this model with same cost configuration is ~46% lower than the total SWM cost in existing optimized model. In this system ~33% inert material of the total waste will be disposed in the engineered landfill and total ELF running cost is ~21% less because of lesser amount of land filling. In proposed model fuel cost of departmental vehicle is reduced by ~21% and transportation cost of hired vehicle is reduced by ~4%. Total transportation cost is ~6.5% less than the existing model because of lesser distances covered by the vehicles to transport waste to the nearest of three ELF sites in the proposed model.

Total recyclable materials generate a substantial amount of revenue. Revenue from compost is ~1.8 times higher than its production cost, so composting is highly profitable component in the proposed system. So far in integrated SWM, though the O&M cost of incineration and compost plant is high but revenue earning from recyclable and compost reduces the cost of solid waste management by 46% than the existing model. So, generation of compost should not be interrupted and market should be well developed for regular selling of the entire compost product for successful running of integrated MSW management system. Considering sustainability, it is suggested that, higher calorific value materials should be incinerated with proper air pollution equipment.

When the integrated SWM system operates along with fully functional three integrated facilities, the capacity of sorters, incinerators, compost plants and ELFs can be predicted. So, with this methodology capacity of different units of integrated MSW management for proposed plan can be set successfully.

Apart from management and economic gain, pollution minimization potential study of proposed integrated MSW management system also shows encouraging result. In the proposed integrated MSW management system ~25% of air pollution reduction is possible from the waste transportation sector than the same for existing MSW management system.

In the existing system total estimated methane emission from disposal ground is ~9,48,477 MT i.e. 1,99,18,017 MT CO_2-eq . In the integrated MSW management system only ~33% inert will go to engineered landfill after segregation and treatment. So there will be no gas generation from ELF.

Apart from transport sector, comparison study gaseous emissions between the systems shows that in the proposed integrated MSW management overall gaseous emission is increased by 53% from the existing because of higher CO_2 emission (103% increases from existing) both from incineration and composting. On the contrary CH_4 emission is reduced by 89% from the existing system. As CH_4 is 21 times more potential as greenhouse gas than CO_2, substantial amount overall GHG emission reduction (67.3%) can be achieved in proposed integrated MSW management system.

In the existing MSW management system ~87 to 90% mixed waste is being disposed to Dhapa dumping ground from which ~900 to 1000 L/$m^2$of leachate is being generated every year containing high organic and inorganic materials which is polluting the surrounding water resources. In the integrated system as only ~33% of the inert material will go to engineered landfill, direct reduction of leachate generation is ~62%. Adopting phase wise disposal during active period over all leachate generation will be ~25.5%. During post closure period with complete top cover leachate generation will be ~1.5%. So during post closure period of integrated system, around 98.5% leachate generation reduction will be possible than the existing system. Because of only inert material present in the landfill, leachate quality will also improve substantially. Pollutant transport study, using EPACMTP, indicates that at this amount leachate generation all the metals and organic pollutants will be well within the safe limit in the surrounding water resources.

In the proposed integrated MSW management system reduction in total land area requirement will be 37% which will be a substantial amount of cost and valuable land resource saving. As good quality of compost will be produced and will be used also by the local farmers for enhancing the fertility of surrounding agricultural land. So, there will be no chance of heavy metal pollution in the soil and food chain.

Above studies indicates substantial amount of pollution reduction possibilities are there in the proposed integrated MSW management system than the existing system. So, integrated MSW management system not only provides cost effective management but also offers less polluted solution. The study conclusively has delivered a methodology to achieve a sustainable solution of MSW management system in developing countries like India.

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ADB	Asian Development Bank
AIIH&PH	All India Institute of Hygiene and Public Health
ASTDR	Agency for Toxic Substances and Disease Registry
ASTMD	American Society for Testing and Meterials
BOD	Biochemical Oxygen Demand
CDM	Clean Development Mechanism
CER	Certified Emission Reduction
CLR	Cellulose-to-Lignin Ratio
C/N	Carbon / Nitrogen ratio
COD	Chemical Oxygen Demand
COPD	Chronic obstructive pulmonary disease
CPCB	Central Pollution Control Board
CPHEEO	Central Public Health & Environmental Engineering Organisation
DA	Dearness Allowance
DAF	Dilution Attenuation Factor
dB(A)	A-weighted Decibels
DDOC	Decomposable Degradable Organic Carbon
DES	Department of Environmental Sciences
DP	Dumper-Placer
DOC	Degradable Organic Carbon
DOE	Department of Environment
DWS	Drinking Water Standard
ELF	Engineered Landfill

EPA	Environmental Protection Agency (USEPA)
EPACMTP	EPA's Composite Model for Leachate Migration and Transformation Products
EPC	Engineering, Procurement and Construction
FAO	Food and Agriculture Organisation
FOD	First Order Degradation
gcpd	Grams per capita per day
GHG	Greenhouse Gas
GIS	Geographic Information System
GPS	Global Positioning System
ha	Hectare. 1 ha = 0.01 km^2
HELP	Hydrologic Evaluation of Landfill Performance
HRA	House Rent Allowances
ICS	Intermediate/Central Sorting facility
IEA	International Energy Agency
IETC	International Environmental Technology Centre
IMR	Industrial Material Resources
INCHEM	International Programme on Chemical Safety'
IPCC	Intergovernmental Panel on Climate Change
ISWM	Integrated Solid Waste Management
KEIP	Kolkata Environmental Improvement Project
kg	Kilogram
km	Kilometer
kWh	kilowatt-hour
KMA	Kolkata Metropolitan Area

KMC	Kolkata Municipal Corporation
KPH	Kilometer Per Hour
l or lit	Litres
LAI	Leaf Area Index
LCV	Lower Calorific Value
LFG	Landfill Gas
LP	Linear Programming
LPI	Leachate Pollution Index
m^3	Cubic metre
MA	Medical Allowance
MCL	Maximum Contaminant Level
MILP	Mixed Integer Linear Programming
MIS	Management Information System
MoEF	Ministry of Environment & Forests, Govt. of India
MoEFCC	Ministry of Environment, Forests and Climate Change
MPN	Most Probable Number
NREL	National Renewable Energy Laboratory
MSWM	Municipal Solid Waste Management
MSW	Municipal Solid Waste
MT	Metric Tons; 1 MT = 1000 kg
MW	Mega Watt
NEERI	National Environmental Engineering Research Institute
NGO	Non-Government Organisation
O & M	Operation & Maintenance
OECD	Organisation for Economic Co-operation and Development

PCB	Pollution Control Board
PHED	Public Health Engineering Department
RBW	Rapidly Biodegradable Waste
RDF	Refuse Derived Fuel
ROHC	Regional Occupational Health Centre
SBW	Slowly Biodegradable Waste
SPM	Suspended Particulate Matter
SWM	Solid Waste Management
TDS	Total Dissolved Solids
TERI	The Energy and Resources Institute
TKN	Total Kjehldahl Nitrogen
TPD	Tons Per Day
TSS	Total Suspended Solids
ULB	Urban Local Body
UNEP	United Nations Environmental Program
UNCHS	United Nations Human Settlements Programme
UNESCAP	United Nations Economic and Social Commission for Asia and the Pacific
USEPA	United States Environmental Protection Agency
VOC	Volatile Organic Carbon
VRP	Vehicle Routing Problem
WBM	Water Balance Method
WBPCB	West Bengal Pollution Control Board
WHO	World Health Organisation
w.r.t	with respect to

WTE	Waste-to-Energy
Yr	Year

Chapter 1

1. INTRODUCTION

Ever since the ancient times, humans and animals have used the resources of the earth to support life and discarded the useless or unwanted residues called waste (Tchobanoglous et. al., 1997). In those days, the disposal of waste did not pose significant problems as the population was very small and a vast expanse of land was available for the assimilation of such wastes.

However today, serious consideration is being given everywhere to this burgeoning problem of solid wastes. Rapid population growth, rapid urbanization and uncontrolled industrial development are seriously degrading the urban and semi urban environment in many of the world's developing countries, placing an enormous strain on natural resources and undermining effective and sustainable development (Talashikar, 1985). Management of municipal solid waste resulting from rapid urbanization has become a serious concern for Municipal Corporations, Government Departments, Urban Development Authorities, regulatory bodies and also for the public in most of the developing countries. Due budgetary constraints, lack of equipment and planning, lack of awareness, solid waste management services in most of the urban local bodies in developing counties are very poor.

The wastes are strewn over the streets and drains and the cities resort to indiscriminate dumping of domestic, commercial, industrial and bio-medical waste; electrical and electronic equipments without any treatment except recyclable separation by scavengers (Aman Mahar, 2007). This leads to contamination of surface and ground by the leachate. In many of the developing countries like India uncontrolled land disposal of municipal solid waste i.e. crude open dumping is still the main disposal method even today (Singh et al., 2007; CPHEEO, 2016). Physical, chemical and biological processes occurring simultaneously at the dump sites result in waste decomposition as well as generation of highly polluted leachate and hazardous landfill gases. Chemically contaminated leachates are one of the byproducts in landfill degradation reactions (O'Learly and Walsh, 1995). One of the severe problems associated with the open dumps is infiltration of leachate into the surrounding environment, subsequent contamination of the land and water (Walker, 1969; Chian and DeWalle, 1976; Kelley, 1976; Masters, 1998; Kumar et al., 2002). It is essential to protect ground and surface waters and soil from contamination due to leachate percolation in and around dump sites.

Because of the prevailing anaerobic conditions within a biologically active open dumping and landfilling, both of which are known to result in significant greenhouse gases emission, particularly methane that has significantly higher effect on global warming. These sites also produce carbon-di-oxide, water and various trace components such as ammonia, sulfide and non methane volatile organic carbon compounds (VOCs). The 100 year global warming potential of CH_4 is 25 times greater than that of CO_2 (Hettiaratchi, 2007). Landfills are the largest anthropogenic source of atmospheric CH_4 in many developed countries. In Canada, 23 MT of a total of 93 MT (about 25%) of anthropogenic CH_4 emissions in 2001 are from landfills (Environment Canada, 2002).

Additionally one should understand that MSW not only produce CH_4 but also produce significant quantity of major air pollutants like CO_2, PM, SO_x, NO_x, Benzene, Butadiene from the facilities used for associated activities such as transportation vehicles. Epidemiological studies show that vehicular pollutants are responsible for various alarming effects (JoAS, 2009). In SWM system i.e, in collection, storage point, during transportation, processing and disposal site, noise pollution is also a major concerned to the workers associated with these activities which should have to be considered with proper weightage.

As the world races toward its urban future, it is estimated that in 2012, globally about 3 billion urban residents generated waste at a rate of 1.2 kg per person per day (1.3 billion tons per year). By 2025 this will likely increase to 4.3 billion urban residents generating about 1.42 kg/capita/day of municipal solid waste (2.2 billion tons per year). Waste generation rates and characteristics vary as a function of economic affluence; however, regional and country variations can be significant, as can they are within the same city. High-income countries produce the most waste per capita with higher recyclables, while low income countries produce the least solid waste per capita higher biodegradables. Thus, sub-Saharan Africa generates waste at a rate of about 0.65 kg/capita/day, South Asia at 0.45 kg/capita/day, Latin America & Caribbean at 1.1 kg/capita/day and OECD (Organisation for Economic Co-operation and Development) countries at 2.2 kg/capita/day.

The urban growth in India is faster than the average for the country and far higher for urban areas over rural. Due to continuous migration of population from rural areas to towns and cities, in India the share of urban population has increased from 27.84% in 2001 to 31.8% in 2011 and likely to reach 50% by 2030. Presently out of a population of 1.21 billion approximately 377 million urban people are residing in 7,935 towns and cities with 4041 municipal authorities (CPHEEO, 2016). There are three megacities - Greater Mumbai, Kolkata and Delhi, which have a population exceeding 10 million, 53 cities which have more than 1 million population and 415 cities whose population exceeds 0.1 million (Census, 2011; Joshi and Ahmed, 2016; Singh et al., 2011). Accelerating urban population coupled with increasing per capita income and subsequent increase in MSW generation has made many Indian cities deficient in basic infrastructure of SWM services. The urban population in India generated about 1,14,576 MT/day of MSW in 1996; 1,27,486 MT/day during 2011-12; and 1,50,000 MT /day during 2014-15 and likely to reach 260 million tons per year by 2047 (CPCB, 2012; CPCB, 2015; CPHEEO, 2016).

So it has resulted in over stressing of urban infrastructure services including municipal solid waste services due to poor resources and inadequate capacity of the urban local bodies (ULBs). Therefore augmentation of SWM facilities and their operation and maintenance in a sustainable manner by the ULBs would not only require huge capital investment, but also introduction of latest and cost effective technologies.

The problem of urban waste management is significant not only because of large quantities involved, but also its spatial spread across 7935 cities and towns (in 2011) and enormity and variety of problems involved in setting up and managing systems for collection, transportation and disposal of waste. Now, Government has understood the need for integrated solid waste management for sustainable development. Therefore, it is the responsibility upon the ULBs to implement Solid Waste (Management & Handling) Rules, 2000 and 2016 for municipal solid waste management, The Plastic Waste Management Rules, 2016, The Bio-Medical Waste Management Rules, 2016, The E-Waste Management Rules, 2016, Construction and Demolition Waste Management Rules, 2016.

Very few urban local bodies in the country have prepared long term plans for effective solid waste management in their respective cities (CPHEEO, 2016). As for example in metropolitan city like Kolkata, India only some equipments are procured through Kolkata Environmental Improvement Project under the financial assistance of Asian Development Bank (KMC, 2007). Source segregation has implemented only in seven wards out of 144 wards as a pilot project. A small portion of mixed waste is processing through windrow composting but not in a regular manner due to marketing problem of compost etc. Thus, issues related to managing solid waste must be addressed using a holistic approach. Proper municipal solid waste management demands the application of the principles of Integrated Solid Waste Management which includes preventing waste, minimizing the initial generation of materials through source reduction, reusing and recycling and composting to reduce the volume of materials being sent to landfills or incineration (CPHEEO, 2000; ISWA, 2012). Several researchers have used Linear Programming (LP) for modeling SWM system and then tried to optimize the model in order to optimize the entire SWM system (Costi et al., 2004; Najm et al., 2002; Rathi, 2007).

Thus to satisfy the goal of sustainable development, integrated MSW management system is needed and for proper implementation of an ISWM system, there is a need to formulate a mathematical model for the MSW management of a city of a developing country. For this purpose Kolkata, India may be selected to develop the methodology for the developing countries to arrive at the optimum sustainable operating plan for the integrated MSW management system under given set of socio-economic and environmental conditions.

2. LITERATURE REVIEW

In the present chapter, an extensive literature search was carried out on various aspects of municipal solid waste generation; toxicity and health effects from MSW; air pollution from (a) waste transport sector and treatment processes like incineration, engineered landfill, composting and (b) landfill gas; noise pollution from waste transportation vehicle and heavy earth moving vehicles at disposal site; noise exposure to the workers engaged in MSW management system; surface and ground water pollution due to leachate; land pollution from leachate and after effect of use of solid waste for agriculture; integrated system approach and development of model using Linear Programming (LP). On the basis of the literature review, the objective and the scope of the present study were identified.

The functional elements of the SWM system typically include waste generation sources, quantity, composition, segregation, storage; collection; transfer and transportation; sorting; processing or treatment; and final disposal.

2.1 SOURCES AND TYPE OF WASTES

Solid waste is that material which arises from various human activities in solid form and which is normally discarded as useless or unwanted (Tchobanoglous et. al., 1997). It encompasses 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 management of these waste materials is the fundamental concern of all the activities encompassed in solid waste management- whether the planning level is local, regional or sub-regional or state and federal (Tchobanoglous et. al., 1997).

The sources and types of solid waste, along with its composition and rates of generation, are the basic parameters to design and operate the functional element associated with the solid waste management. The sources of solid waste in a community are, in general, related to land use and zoning (Flintoff, 1984). Although any number of source classifications can be developed, the categories such as residential and commercial wastes, institutional wastes, industrial wastes, construction and demolition wastes, municipal services wastes, agricultural wastes, treatment plant wastes, special category wastes are useful (Peavy et. al., 1985).

2.2 MUNICIPAL SOLID WASTE GENERATION

In order to plan the development of waste management facilities information about the quantities and types of wastes generated within and around the municipality, which may be included in the same municipal waste management system, are very important (UNCHS, 1994; Mattsson and Ber, 2004).

Projected increases in quantities of each waste stream should also be estimated in order to plan for future provision of facilities. Knowledge of the composition of the waste stream is also necessary for proper selection of treatment and disposal options (Yedla et. al., 2001; Karar K., 2007).

The main factors such as climate and seasonal variation, finance available locally to municipalities and waste service operators, economy of the region, physical characteristics of the cities, social and religion customs, public health awareness, quality of management and technical capacity, environmental standards required to be achieved etc. influence the composition and rate of production of solid waste (Dong Suocheng et al., 2001; Amponsah and Salhi, 2004).

Accurate information on waste generation is necessary to monitor existing management systems and making regulatory, financial and institutional decisions. The huge amounts of municipal solid waste (MSW) create enormous challenges for all developed or developing countries across the whole economic spectrum. The Table 2.1 shows the per capita MSW generation in different countries (Hoornweg and Bhada-Tata, 2012; Kawai and Tasaki, 2016); Table 2.2 shows the overall issues in Asian countries (UNEP, 1996), which are classified into less developed, developing and developed cities. Both the tables shows waste generation in developed countries is more than the less developed countries. Table 2.3 shows MSW quantities and per capita generation in Indian cities (CPCB, 2012).

Table 2.1 Per capita MSW generations in different countries

Country	Quantity (kg/capita/day)
India	0.34 - 0.37
U.S.A.	1.25 - 2.58
U.K.	1.34 - 1.79
Singapore	0.94 - 1.49
Japan	0.9 - 1.71
China	0.31 - 1.02
Indonesia	0.49 - 0.52

Table 2.2 Overall issues in Asian cities (UNEP, 1996)

	Less developed cities	Rapidly developed cities	Developed cities
Examples	Dhaka, Kathmandu, Karachi.	Beijing, Shanghai, Bangkok, Kualalampur, Manila.	Tokyo, Taipei, Seoul, Hongkong, Singapore, Macao.
Trends	Population growth, urbanization.	Population growth, urbanization, industrialization, economic growth.	Stable population, affluent society, ‘Throw away’ consumption pattern.
Urban Characteristics	Mix of semi-urban and urban areas.	Rapidly urbanizing and sprawling number of irregular settlements such as slums and shantytowns.	Highly urbanized, dense areas.
MSW generation (kg/capita /day)	0.3-0.7	0.5-1.5	>1.0

Table 2.3 Quantities of MSW and per capita generation in Indian cities (CPCB, 2012)

City	MSW generated (MT/day)		
	1999-2000[a]	2004-2005[b]	2010-2011[c]
Ahmedabad	1683	1302	2300
Bangalore	2000	1669	3700
Bhopal	546	574	350
Mumbai	5355	5320	6500
Kolkata	3692	2653	3670
Delhi	5700	5922	6800
Hyderabad	1566	2187	4200
Jaipur	580	904	310
Kanpur	1200	1100	1600
Lucknow	1010	475	1200
Chennai	3124	3036	4500
Surat	900	1000	1200

a EPTRI survey ; b NEERI-Nagpur survey; c CIPET survey

Researchers (Bhide and Shekdar, 1998; Das et al., 1998; Pappu et al., 2007; Srivastava et al., 2015; Kumar et al., 2017) suggest per capita rate of MSW generation in India ranges from 0.2 to 0.6 kg/day; the amount of MSW generated per capita is estimated to increase at a rate of 1–1.33% annually. As per CPHEEO, 2016, during 2013-2014, the average rate of waste generation in India was 0.11 kg/day out of which 82% was collected and only 22.9% was treated. The waste generation rate is between 200-300 gm/capita/day in small towns and cities (population less than 2 lakhs); for cities with a population between 2 to 5 lakhs, the waste generation rate is around 300-350 gm/capita/day; 350-400 gm/capita/day in cities with population 5 lakhs to 1 million; and 400-600 gm/capita/day in cities with population exceeding 1 million. With increasing urbanization and changing lifestyles, Indian cities now generate eight times more MSW than they did in 1947 (Kaushal et al., 2012). Between 2001 to 2011, there has been an almost 50% increase in total MSW generation. India is thus facing a sharp contrast between its increasing urban population and available services and resources.

In many cases municipalities might not have sufficient budget and management capacity to maintain a complete database of solid waste quantity and quality in support of such needs on a long term basis (Dyson and Ni-Bin Chang, 2005). Above barriers are some of the reasons for the lack of waste generation data in developing countries.

2.2.1 Past Studies on Solid Waste Generation of Kolkata

Study of various reports prepared in the past for Kolkata shows a wide range of variation in generation. Further the modality of quantity estimation has not been spelt out in any of these reports. Total quantity of MSW generation assessed in these reports (ADB, 2005) as explained in Table 2.4.

Table 2.4 Study reports on assessed quantity of MSW generation of Kolkata (ADB, 2005)

Sl. Nos.	Source	Year of estimation	Estimated quantity (MT/d)
1.	Talukdar Committee's Report	1963	2115
2.	Mr. M.G. Kutty's Report	1963	1500
3.	NEERI Report	1970	1640
4.	Task Force(CMDA Report)	1973	1600-1800
5.	Report of CE (MV & CON), CMC	1983	1800
6.	Calcutta Management Association Report (10 Boroughs)	1985-87	1750+200(silt)
7.	Report of Institute of Local Govt. & Urban Studies	1992	3150
8.	Report of CMC	1993	3100-3400
9.	Report of KMC on assessment	1999	2400+200(silt)

2.3 CHARACTERISTICS OF REFUSE

The analysis of refuse is carried out normally to know its physical as well as chemical characteristics which help in designing and selecting the collection, processing and disposal aspects of the system (Flintoff, 1984).

2.3.1 Selection of Sampling Points, Collection and Analysis of Samples

Collection of samples is the first step in estimating the composition of MSW and should be carefully decided to ensure truly representative samples. In general, one sample should be collected randomly from each identified truck (ASTMD, 5231). If more than one sample is needed, should be collected from different parts of the load in the truck.

Sample size of about 200 to 300 lb (in about 100 to 150 kg) is considered optimum as recommended in (ASTMD, 5231). Following are some of the common procedures of samples collection. Often combination of these procedures is also used.

- Obtaining a composite sample from material taken from pre determined points in the load e.g. each corner and middle of each side.
- Coning and quartering.
- Collecting a grab sample from a randomly selected point using a front-end loader.
- Manually collecting a column of waste from a randomly selected location.

In Kolkata as well as in India stratified random sampling method is very difficult because of the complexity in accurately dividing the population into various socio economic groups. Therefore quartering method may be suitable in India as well as in Kolkata (NEERI, 1995).

2.3.2 Composition of MSW

A comparison of the current waste composition in Asian countries (Table 2.5) (IGES, 2001) shows that comparatively developed countries like Japan, China, Korea generates lower percentage of organic waste (17 to 36%) than Sri Lanka, Indonesia, Myanmar (70 to 80%). The composition differs depending on the economic level of cities as well as other factors such as geographic location, energy sources, climate, living standards and cultural habits and the sources of wastes.

Table 2.5 Percentage composition of urban solid waste in selected Asian countries (IGES, 2001)

Country	Organic Waste	Paper	Plastic	Glass	Metal	Others
China	35.8	3.7	3.8	2.0	0.3	54.3
Hong Kong	37.2	21.6	15.7	3.9	3.9	17.6
Indonesia	70.2	10.9	8.7	1.7	1.8	6.2
Japan	17.0	40.0	20.0	10.0	6.0	7.0
Laos	54.3	3.3	7.8	8.5	3.8	22.5
Malaysia	43.2	23.7	11.2	3.2	4.2	14.5
Myanmar	80.0	4.0	2.0	0.0	0.0	14.0
Philippines	41.6	19.5	13.8	2.5	4.8	17.9
Singapore	44.4	28.3	11.8	4.1	4.8	6.6
South Korea	31.0	27.0	6.0	5.0	7.0	23.0
Thailand	48.6	14.6	13.9	5.1	3.6	14.2
Abu Dhabi	22.5	42.4	6.3	4.4	14.0	10.4
Lahore, Pakistan	49	4	9	3	4	31
Sri Lanka	80	8	2	6	1	3

The ratio of paper and plastics including voluminous materials such as food containers and wrapping materials is higher in developed cities. On the other hand wastes in developing cities have a high organic content and a low calorific value. Biological treatments such as composting and bio-gasification are thus most suitable. Physical and chemical characteristics of municipal solid waste in some of the cities in India are shown in Table 2.6.

Table 2.6 Physical and chemical characteristics of municipal solid waste of a few India cities (Srivastava et al., 2015; Gupta et al., 2015)

Description	Delhi	Mumbai	Chennai	Kolkata	Hyderabad
Population (million)	10	13.8	5.8	7.0	4.2
MSW (tons/day)	+5000	+6400	+4000	+3000	+2200
Recyclables (%)	15.52	16.66	16.34	11.48	21.6
Others (including inert) [%]	30.06	20.9	42.32	37.96	24.20
Biodegradable/ Organic (%)	54.42	62.44	41.34	50.56	54.20
Moisture content (%)	49	54	47	46	46
C/N ratio	34.87	39.04	29.25	31.81	25.90
HCV (kcal/kg)	1802	1786	2594	1201	1969

2.4 SOLID WASTE MANAGEMENT SYSTEM

Any municipal solid waste generated in a city or a town, shall be managed in accordance with the following compliance criteria and the procedure.

2.4.1 Collection of Municipal Solid Waste

Collection not only includes gathering of solid waste and emptying containers into a suitable vehicle for storage, but also hauling the waste after collection to the location where the collection vehicle is emptied (Kumar et al., 2009). The location may be a transfer station, a processing station or a landfill disposal site (Dhindaw, 2004). Collection is by far the largest cost element in most MSWM systems, accounting for 60-70% of costs in industrialized countries and 70-90% of costs in developing and transition countries (UNEP/IETC, 1996).

Once waste has been collected, there are three basic alternatives for MSW disposal (Daskalopoulos et al., 1998) (i) direct dumping of unprocessed waste in a sanitary landfill or open dump; (ii) processing of the waste before final disposal (reduce waste volumes); (iii) processing of the waste to recover resources (materials or energy) with subsequent disposal of residue.

2.4.2 Recycling

All recycling systems must have four major components in order to function, namely (Daskalopoulos et al., 1998)

- There must be a consistent and reliable source of the recycled materials,
- Methods for processing the recovered materials must be in place,
- Markets must exist for the reprocessed material,
- Consumer's willingness to participate (Ku et al., 2009).

It is only when all these components function in an economically viable manner that a successful recycling system can exist. The costs and benefits of reclamation must be studied through a life cycle approach (Metin et al., 2003). A successful refuse collection and recycling scheme needs to be both user and operator friendly. There are a number of guiding principles which need to be considered when planning and carrying out service promotion (role of local authority), which include: (i) enhancing motivation/awareness, (ii) incentives to participate, (iii) enhancing convenience, (iv) appealing norms, (v) use of neighborhoods (opportunity structures for participation), and (vi) providing effective information (Read, 1999). To introduce a comprehensive formal waste management system (recycling program), these program can legitimize and support informal waste workers and sweeper system in order to help create sustainable SWM solutions. Educational and community action programs have the potential to reduce the social stigma of working with waste, and raise awareness of citizens and planners of the integral role of waste workers in the city's daily functioning (Gray-Donald, 2001).

2.4.3 Segregation of MSW

Segregation at source is the initial essential step towards successful solid waste management system (Tchobanoglous et. al., 1993). Sorting of waste is mostly accomplished by unorganized sector and seldom practiced by waste producers. Segregation and sorting takes place under very unsafe and hazardous conditions and the effectiveness of segregation is reasonably low as unorganized sector segregates only valuable discarded constituents from waste stream which can guarantee them comparatively higher economic return in the recycling market (Kaushal et al., 2012). On a number of occasions, due to improper handling the segregated materials got mixed up again during transportation and disposal (CPCB, 2013). Municipal authority shall organize awareness programs for segregation of wastes at source and shall encourage re-cycling or re-use of segregated waste materials. Municipal authority shall undertake phased programs to ensure that the community is fully involved in wastes segregation (CPHEEO, 2000; CPHEEO, 2016).

2.4.4 Processing of MSW

Suitable technology (or combination of such technologies) shall have to be adopted to make use of waste for sustainable development and to minimize the burden on landfill (Tchobanoglous and Kreith, 2002).

2.4.4.1 Recycling

Recycling and reuse diverts a significant fraction of municipal waste from being dumped or disposed in landfills — resulting in saving of scarce resources as well as reducing environmental impacts and the burden of waste management on urban local bodies. It is the method of processing non-biodegradable waste to recover commercially valuable materials (e.g. plastic, metal, glass, e-waste, paper).

2.4.4.2 Composting

The organic content of municipal solid waste tends to decompose leading to various smells and odor problems. Composting is the decomposition of organic matter by microorganism in warm moist, aerobic and sometimes in anaerobic environment, yielding humus-rich compost. Composting of waste is, therefore, the most simple and cost effective technology for treating the organic fraction of waste (Asnani, 2006; Gupta et al., 2015).

In most developing countries, lack of economic and environmental motivation means that it will be very difficult, if not impossible, to explicitly promote source segregation of compostable materials. Nevertheless, since the success of composting systems and the quality of compost depend also on the materials that are composted, a separate collection system for compostable would facilitate the production of high quality of compost. Citizens can deliver organic waste to small/decentralized community composting plants. The term decentralized composting is used here for schemes receiving the main organic waste bulk from neighbourhoods where the composting site is located. These facilities will generally be in the range of 2 to 50 tons per day, depending on the size of the community and the proportion of compostable materials in the waste stream. Centralized composting refers to composting of wastes from multiple sources, where the wastes are transported from several points to a facility that can receive 10 to 200 tons per day (Zurbrugg et al., 2004; UNEP/IETC, 1996; IETC, 1999). Despite the aforementioned advantages, composting has the distinction of being the waste management system with the largest number of failed facilities worldwide. The problems most often cited for the failures of composting include: high operation and maintenance costs, high transportation costs, poor quality product as a result of poor pre sorting (especially of plastic and glass fragments), poor understanding of the composting process, technical failure (over-design of machines; failure of equipment), marketing failure, lack of community support (household cooperation) and competition from chemical fertilizers (which are often subsidized) (UNEP/IETC, 1996; Zurbrugg et al., 2004).

Energy can be recovered from the organic fraction of waste (biodegradable as well as non-biodegradable) basically through two methods as follows:

2.4.4.3 Bio-chemical Conversion

The process is based on enzymatic decomposition of organic matter by microbial action to produce methane gas or alcohol (Flintoff, 1984). Biomethanation is the anaerobic fermentation of biodegradable matter in an enclosed space under controlled conditions of temperature, moisture, pH, etc. The waste mass undergoes decomposition due to microbial activity, generating biogas comprising mainly of methane and CO_2 and some digested stabilized sludge. Depending on the percentage of sulphur content in the waste (proteins, sulphates), hydrogen sulphide may also be generated in varying degrees (CPHEEO, 2016). For high moisture and organic contents of Indian wastes, the anaerobic digestion is a suitable option. Small to medium scale plants have been developed especially for cattle manure (Gobar Gas plants). Kitchen and vegetable market wastes can be collected and treated at source if space permits and resulting bio-gas can be used for captive energy use such as lighting, cooking, etc. Biogas systems are currently available to treat wastes of fruit and vegetable origin (Nagori et al., 1988; CPHEEO, 2016). Toilet linked biogas plants have been installed at family, community and institutional levels. Purified biogas (cleaned thoroughly by removing CO_2 less than 5% and H_2S less than 10 ppm) and then used as an environment-friendly automotive fuel. Similarly electricity can be generated from bio-gas for on-site processing or distribution through local electric power grid. The stabilized sludge can be used as soil conditioner. Barik and Paul in 2016 reported that the kitchen food waste can also be used as an innovative raw material for biodiesel production. However, most bio-methanation plants require pre-treatment of waste to obtain a homogenous, digestible, shredded feedstock.

2.4.4.4 Thermo-chemical Conversion

This process entails thermal decomposition of organic matter to produce either heat energy or fuel oil or gas. The thermo-chemical conversion processes are useful for wastes containing high percentage of organic non-biodegradable matter and low moisture content. The main technological options under this category include Incineration and Pyrolysis or Gasification (MWCA, 1989). The objective of Waste-to-Energy combustion is treating waste to reduce its volume; generating energy and electricity only adds value to the process (Annepu, 2012).

(a) Incineration

It is the process of direct burning of wastes in the presence of excess air (oxygen) at temperatures of about 800^0C and above, liberating heat energy, inert gases and ash. Net energy yield depends upon the density and composition of the waste; relative percentage of moisture and inert materials, which add to the heat loss; ignition temperature; size and shape of the constituents; design of the combustion system (fixed bed or fluidized bed), etc. In practice, about 65 to 80 % of the energy content of the organic matter can be recovered as heat energy, which can be utilized either for direct thermal applications, or for producing power via steam turbine-generators (with typical conversion efficiency of about 30 %).

Some basic types of Incineration plants operating in the developed countries in the West, in Japan and Singapore incinerate 90% of its MSW (UNEP, 1999) are as follows:

- Mass Burn
- Modular Combustion Units
- Refuse-Derived Fuel (RDF) based power plants

(b) Pyrolysis

Pyrolysis is a chemical change due to partial combustion of solid wastes in the absence of oxygen. It is also known as thermal where external source of heat is employed. Pyrolysis is an endothermic process and requires heat from an external source. Therefore it is also termed as destructive distillation. It yields gaseous, liquid and solid fractions as follows (Singh et al., 2011; CPHEEO, 2016).

- Gas fraction includes hydrogen, methane, carbon monoxide and carbon di-oxide
- Liquid fraction includes tar or oil stream containing acetic acid, acetone and methanol.
- Solid fraction includes char, consisting of carbon and other inert materials originally present in MSW

The proportion of gases, liquid and char obtained depends upon the temperature at which pyrolysis is carried out. As temperature increases the amount of gaseous component increases while the quantity of liquid and char decreases. The energy content of pyrolytic gases is about 26100 KJ/m^3 and that of pyrolytic tar or oils is 23240 KJ/Kg.

(c) Gasification

It is a process in which partial combustion is carried out in the presence of oxygen but in lesser amount than that is stoichiometrically required for complete combustion. The self-sustaining partial combustion is carried out to obtain combustible gases eg. hydrogen and carbon monoxide, which are used as fuel. The energy content is in the range of 5.2 to 6.0 MJ/m^3. Typically composition of combustible gas, obtained from gasification process contains CO_2 (10%), CO (20%), H_2 (15%), CH_4 (2%), some N_2 and other trace gases. In India, limited gasifiers were installed but they are mostly used to burn agro biomass (Joshi and Ahmed, 2016).

2.4.5 Disposal of MSW

Landfilling shall be restricted to non-biodegradable, inert waste and other waste that are not suitable either for re-cycling or for biological processing and thermal processing. It shall also be carried out for residues of wastes processing facilities as well as for pre-processing rejects from waste processing facilities (Zurbrugg, 1999). Landfilling of mixed wastes shall be avoided unless it is found unsuitable for waste processing (Oweis and Khera, 1990). Under unavoidable circumstances or till installation of alternate facilities, it shall be done following proper norms and shall meet the following criteria:

- Landfill siting and construction shall be done after proper care. However, in respect of cities having population over five lakhs, proper environmental impact assessment shall be conducted before selecting a site.
- Provision for future landfill site shall be included in the land use plan of city or town.
- Landfill site shall comply with the norms to control air and water (ground and surface water) pollution and other environmental norms as laid down in the standards i.e. proper lining, daily cover, leachate collection and treatment system, gas collection system etc.
- Waste at disposal site shall not be burnt. Sites, where waste is to be burnt shall be monitored for compliance.

The mode of waste disposal predominantly through landfilling (simple open dumping) is a conventional, cheap, fast but unhygienic method in many developing countries (Nyns and Gendebien, 1993; Rotich et al., 2005). Illegal dumping (also known as fly dumping, or midnight dumping) is the littering of waste that occurs at abandoned industrial, commercial or residential buildings; vacant plots; and poorly lit areas such as roads and open water bodies (USEPA, 1998). The birds foraging on garbage dumps are known to cause substantial problems for aircrafts operating in the urban areas. The bird strikes have resulted in a great deal of flaws to aviation sector (Cheng, 2015). Open burning of garbage (including plastics) is very common phenomenon in the cities/towns, even in Kolkata which generates toxic emissions such as CO, Cl_2, HCl, dioxin, furans, amines, styrene, benzene, 1,3 butadiene, CCl_4 and acetaldehyde are emanates and pollute the environment. Chinnamine (1992) reported that burning of 1kg. agricultural waste produced about 20-114 gm. Carbon monoxide and 2.1-11.4 gm total suspended particle as smoke. Researchers from the USEPA have reported in the Journal of Environmental Science and Technology that open burning of household waste produces not only considerable quantity of CO and smoke but also a potential source of air borne dioxins and furan emissions. Exposure to certain dioxins has been clearly shown to cause adverse effects in laboratory animals such as immune dysfunction, cancer, hormonal changes and development of abnormalities (Anon, 2000). Using sanitary landfills as a mean becomes significant while public reluctance concerning open dumping and building of (more) incinerators turn out to be apparent (Weng and Ni-Bin Chang, 2001). Sanitary landfills incorporate a full set of measures which include gas control, collection and treatment of leachate and the application of base liners. It also includes daily soil cover on waste, network of monitoring systems; and implementation plans for closure and after care of the site (Kgathi and Bolaane, 2001). A number of general characteristics distinguish a sanitary landfill from an open dump, but these characteristics vary from region to region as well as from site to site.

A 1998 study by TERI (The Energy Research Institute, New Delhi) calculated the land that was occupied by disposed waste from 1947 – 1997. The study measured the land occupied in terms of ‘football fields’ and arrived at 71,000 football fields of solid waste, stacked 9 metres high. Based on the current scenario of 91% of generated waste being landfilled/dumped in India, the study predicted that the waste generated by 2001 will occupy 240 sq km or half the area of Mumbai; waste generated by 2011 will have occupy 380 sq km or 90% of the area of Chennai; waste generated by 2021 will require 590 sq km or the area of Hyderabad (refer to Table 2.7).

Table 2.7 Table showing urban land required for landfilling if MSW is dumped without treatment [Gupta et al., 1998; Ministry of Finance, 2009]

Year/Period	Area of land occupied/required of MSW disposal (sq km)	City equivalent of area
1947-2001	240	50% of Mumbai
1947-2011	380	90% of Chennai
1947-2021	590	Hyderabad
1997-2047	1400	Hyberabad + Mumbai + Chennai

2.5 IMPACTS OF SOLID WASTES ON ENVIRONMENT

Unless properly managed, solid wastes have potential of serious impacts on environment. It can lead to surface and ground water contamination (Fatta et al., 1999; Mor et al., 2006; Motling et al., 2013; Tchobanoglous et al., 1993; Kumar and Alappat, 2005), land pollution and air quality deterioration. Table 2.8 shows important water contaminants and their impact.

2.5.1 Health Effects of Biogas

A number of polluting gases can have a variety of impacts on health. CO_2 and CH_4 are greenhouse gases partially responsible for global warming (El-Fadel et al., 1997a; Talyan et al., 2007; USEPA website).

Table 2.8 Important water contaminants and their impacts

Contaminant	Impacts & Reasons for Concern
Suspended Solids	Can lead to the development of sludge deposits and anaerobic conditions when untreated wastewater is discharged in the adjoining environment.
Biodegradable Organics	Generally measured as BOD and COD. If discharged untreated to the environment their biological stabilization can lead to the depletion of natural oxygen resources and to the development of septic conditions.
Pathogens	Disease vectors communicable diseases can be transmitted by the pathogenic organisms in water.
Nutrients	Both nitrogen and phosphorus along with carbon are essential nutrients for growth. When discharged to adequate environment, there nutrients can lead to the growth of undesirable aquatic life. When discharged in excessive amounts on land, they can also lead to the pollution of ground water.
Priority Pollutants	Organic and inorganic compounds selected on the basis of their known or suspected carcinogenicity, mutagenicity, acute toxicity etc. Many of these compounds are found in wastewater or leachate from landfills.
Heavy Metals	Heavy metals are common in landfill leachate and Wastewater from industrial activities. These may need to be removed if the water has to be reused.

2.5.1.1 Methane

The accumulation of CH_4 in confined spaces or enclosed structures can result in asphyxia, explosions, and fires, which may cause injury or loss of life. The risk of CH_4 gas explosions is highest at ambient concentrations of between 5% and 15%. Underground migration of biogas (lateral migration) can result in its infiltration into buildings and can cause explosions or asphyxia in confined spaces (Williams, 1998; Williams, 2002).

2.5.1.2 CO_2

The green house effect is a natural phenomenon that traps radiation within earth's atmosphere. A higher concentration of green house gases means a warmer climate. CO_2 is considered the predominant green house gas and has the greatest impact on global heat (Lin and Shyu, 1999; Lorenzetti, 2001; Garg et al., 2001).

2.5.1.3 Organic Compounds at Low Concentrations

A number of organic compounds are toxic, including several VOCs, which can cause health problems following chronic exposure. These include, for example, aplastic anemia; teratogenic and fetotoxic effects; damage to the liver, lungs, and kidneys; nervous system damage; and various cancers, such as leukemia and myelomas (Škulte´tyova, 2011). It is important to note, however, that these effects are associated with high concentrations, which are not necessarily found in proximity to landfills. Those at greatest risk are landfill workers, particularly operators of heavy equipment used to compact the waste.

Other major air pollutants and their impacts are shown in Table 2.9.

Table 2.9 Major air pollutants and their impacts

Pollutants	Impacts
Suspended Particulate Matter (SPM)	Aggravates lung illness, corrodes metals, causes grime on belongings and buildings, obscures vision. (Peavy et al., 1979).
Sulfur Oxides	Acid rain (Bresser, 1990; Porteous, 1992).Corrodes metals, causes acute and chronic leaf injury, attacks a wide variety of trees, irritates upper respiratory tract, destroys paint pigments.
Nitrogen Oxides	Acid rain (Mellanby, 1989; Porteous, 1992). Irritate eyes and nose, creates brown haze, causes visible leaf damage, stunts plant growth, corrodes metals.
Carbon Monoxide	Causes headaches, dizziness and nausea, reduces oxygen level in blood, impairs mental processes. (Chatterjee, 1994). (Peavy et al., 1979).
Hydrocarbons	Causes cancer, retards plant growth (Peavy et al., 1979).

2.6 STANDARDS

Environmental impacts of poorly managed wastes have been studied all over the world. It is now well known that a large number of disease vectors and water borne diseases spread due to poor collection and disposal practices of solid waste. To control the adverse impact of ambient air quality, leachate water quality and noise quality, certain standard regulations have been laid down throughout the world. Table 2.10, 2.11, 2.12, 2.13 and 2.14 shows standards, which are followed in India for ambient air quality, leachate water quality and noise quality respectively.

Table 2.10 Ambient air quality standards (CPCB, 2009)

Area/land use	SO_2 (μg/m^3)		NO_X as NO_2(μg/m^3)		CO		PM_{10} (μg/m^3)	
	Annual Avg.	24 hours	Annual Avg.	24 hours	1 hourly	8 hourly	Annual Avg.	24 hours
Industrial Area, Residential, Rural and other areas	50	80	40	80	4.0 mg/m^3	100.0 μg/m^3	60	100
Ecologically Sensitive	20	80	30	80	4.0 mg/m^3	100.0 μg/m^3	60	100

Table 2.11 Ambient noise standards [CPCB Noise Pollution (Regulation and Control) Rules, 2000]

Area code	Category of area	Limits in db(A), L_{eq}	
		Day	Night
A.	Industrial	75	70
B.	Commercial	65	55
C.	Residential	55	45
D.	Silence zone	50	40

Note:

1. Daytime is reckoned in between 6.00 a.m. and 9.00 p.m.
2. Nighttime is reckoned in between 9.00 p.m. and 6.00 a.m.
3. Silence zone is defined as areas up to 100 m around such premises as hospitals, educational institutions and courts. The silence zones are to be declared by the competent authority.
4. Mixed categories of areas should be declared as one of the four above-mentioned categories by the competent authority and the corresponding standards shall apply.

Table 2.12 Noise limits for automobile (CPCB, 2000)

Sl. Nos.	Category of vehicles	Noise limits in dB (A)
1.	Motorcycle, scooter and three wheeler	80
2.	Passengers cars having maximum 9 seats	74
3.	Passenger vehicles having more than 9 seats and vehicle weight more than 3.5 MT	78 (engine power < 150 KW) 80 (engine power > 150 KW)
4.	Passenger/commercial vehicles having more than 9 seats	76 (vehicle weight < 2 MT) 77 (vehicle weight > 3 MT but < 3.5 MT
5.	Commercial vehicles used for transport of goods having vehicle weight exceeding 3.5 MT	77 (engine power < 75KW) 78 (engine power > 75KW but < 150KW) 80 (engine power > 150 KW)

Table 2.13 Leachate water quality standards (CPCB, 2000)

Constituents	Indian standards (1993)		WHO	
	Desirable	Maxm. Permissible	Desirable	Maxm. Permissible
pH	6.5-8.5	6.5-9.5	7.0-8.5	6.5-8.2
Total Hardness	300	600	100	500
Calcium	75	200	75	200
Magnesium	30	100	-	150
Sodium	-	100	-	80
Chloride	250	1000	200	600
Copper	0.05	1.5	0.05	1.5
Iron	0.30	1.0	0.10	1.0
Manganese	0.10	0.5	0.05	0.5
Cadmium	0.01	N.R.	-	0.1
Lead	0.10	N.R.	-	0.1
Zinc	0.05	0.15	0.05	0.15
Chromium	0.05	N.R.	-	0.0

All values except pH are in mg/l.   NR – No Relaxation.

Table 2.14 Standards for disposal of leachate (CPHEEO, 2016)

Parameters	Permissible limits		
	Inland Surface water	Public sewers	Land disposal
Suspended solids	100	600	200
Dissolved solids (inorganic)	2100	2100	2100
pH	5.5-9.0	5.5-9.0	5.5-9.0
Ammonical nitrogen	50	50	-
Total Kjeldahl Nitrogen	100	-	-
BOD	30	350	100
COD	250	-	-
Arsenic	0.20	0.20	0.20
Mercury	0.01	0.01	-
Lead	0.10	1.00	-
Cadmium	2.00	1.00	-
Chromium	2.00	2.00	-
Copper	3.00	3.00	-
Zinc	5.00	15.0	-
Nickel	3.00	3.00	-
Cyanide	0.20	2.00	0.20
Chloride	1000	1000	600
Fluoride	2.00	1.50	-
Phenolic Compounds	1.00	5.00	-

All values except pH are in mg/lt.

2.7 SOLID WASTE MANAGEMENT AND HEALTH RISK

Municipal solid waste possesses a number of potential hazards due to various factors. Many of them - like pathogenic organisms, insects, rodents, birds, air borne litter, water pollution, etc. can be controlled by proper waste management (Flintoff, 1984).

In India ground water pollution from dumping sites remains one of the most serious potential hazards, which have not been properly looked into. The degree of the contamination threat to ground water supplies from landfills depends on several factors: toxicity and volume of the contaminant generated at each site, the nature of the geologic medium underline the site, and the dominant hydrologic condition in the area.

The least expensive and most widely used waste management option for both municipal and industrial waste has been the engineered landfill. In any geographic area other than arid zones, the fill is subjected to percolating rain water or snow melt which eventually flows out the bottom of the landfill site and moves into the local ground water system. These percolated waters known as leachates can contain large amount of inorganic and organic contaminants.

Plastic products have become an integral part in the daily life of human as a basic need. It produced on a massive scale worldwide and its production crosses 300 million tons per year globally (Suaria et al., 2016). It is worth to mention that usage of plastic packaging and products has increased multifold in the last one decade due to its low price and convenience, however general public is not aware about its detrimental impact on the human and environment on littering and dumping.

In India approximately 12 million tones plastic products are consumed every year, which is expected to rise further. It is also known that 50-60% of its consumption is converted into waste (Farshi et al., 2017). Main usage of plastic is in the form of carry bags, packaging films, wrapping materials, fluid containers, clothing, toys, household applications, industrial products, engineering applications, building materials etc. It is true that conventional (petro based) plastic waste is non biodegradable and remains on landscape for several years polluting environment ethics because life cycle of plastic waste is incomplete and ultimately it is dumped on the landfill sites and other places. According to researchers, experiments show that micro plastics damage metabolism and food chain of aquatic creatures (Carbery et al., 2018). Indiscriminate littering and non biodegradability of plastic waste raise several environmental issues such as choking of drains, making land infertile, and on ingestion by livestock and wild life lead to death. During polymerization and manufacturing process toxic fugitive emissions are released. Lead and Cadmium and DEHP [di(2-ethylhexyl)Phthalates] commonly used in LDPE, HDPE, PP, PET etc and other metal based additives which are used during manufacturing and recycling of plastics are toxic and known to leach out in the environment (Wagner et al., 2009). A schematic diagram showing potential health risk associated with solid waste has been depicted in Figure 2.1 (AIIH&PH, 1990).

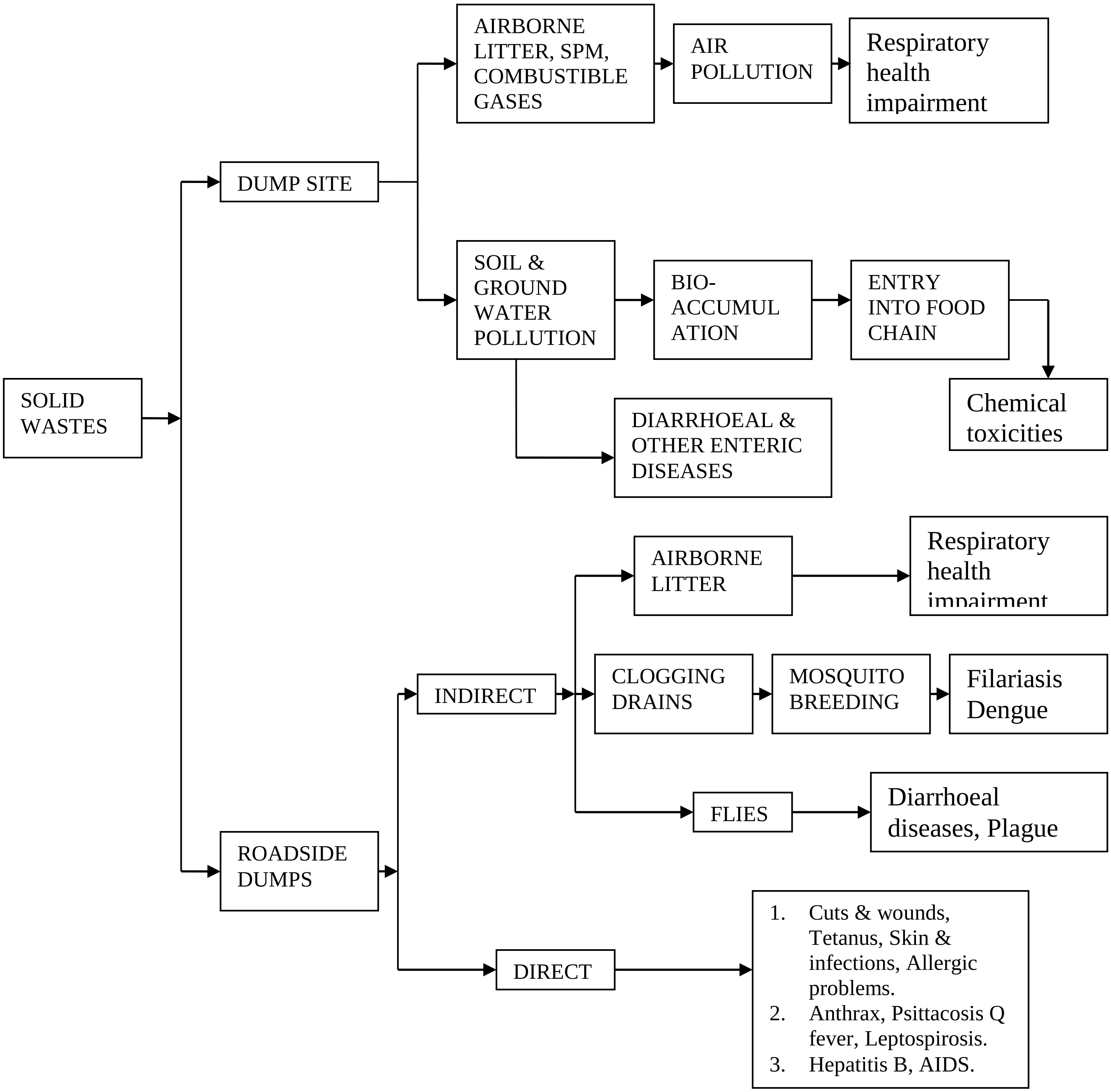


Figure 2.1 Potential health risks associated with solid wastes

2.7.1 Specific Diseases in Relation to Solid Waste

The epidemiologists of certain infectious agents are such that they pose more than an average risk of some specific diseases among waste handlers (McGranahan and Songsore, 1994). Table 2.15 has summarized the health problems experienced by waste handlers in developing countries (Woolveridge and Clare, 1994).

Table 2.15 Health problems of waste handlers (Woolveridge and Clare, 1994)

Reference	Health Problems Identified
Arer, 1989	Presence of helminthes, poor nutritional status, prevalence of parasites, retarded growth
Dr. Cuyper, 1992	Bronchitis, cuts
Furedy, 1992	Backache, cuts
Gunn and Oses, 1992	Lead and mercury poisoning, tetanus, gunshot wounds, battering, impaired pulmonary function, stunting, malnutrition (from low calorie intake and parasites), skin disorders, skeletal deformities from carrying heavy loads
Hunt, 1994	Fever, skin problems, colds infectious diseases, parasitic diseases, diseases of the respiratory system, diseases of the ear and mastoid process, mental and behavioral disorders, scabies, possible increased susceptibility to tuberculoses.
Klyaju, 1986	Diarrhoea, worms, dysentery, cold, stomach trouble, sore eyes, fever, para-typhoid, headache
Kungskulum, 1991	Headache, diarrhea, respiratory problems, skin diseases, cuts (including needlestic injuries)
Nath et. al., 1990	Respiratory diseases, diarrhoea, viral hepatitis, protozoal and helminthic infestation, skin disease, lower immunization rates than control group, poor nutritional status
Yiedgo, 1991	Eye irritation, tuberculoses, diarrhea, dysentery, coughing, malaria, scabies, headache

A study was instituted by CPCB on assessment of health status of conservancy staff and other community associated with handling of solid waste management. The study was taken up at Kolkata through Chittaranjan Cancer Research Institute and at Chennai with the assistance of Sri Ramchandra Medical College. The objective of the study is to assess health status of each target group involved in handling of municipal solid waste (MSW). Health assessment studies at Kolkata included clinical examination of 732 individuals of which, 376 were conservancy workers, 151 rag pickers and 205 controls. The findings of the study are tabulated below (Table 2.16):

Table 2.16 Health problems of associated with conservancy staff and ragpickers in Kolkata (CPCB, 2006)

Parameter	Con	RP	MSW	Implication
Upper respiratory symptoms	43	82	93	*Infection in nose, throat*
Lower respiratory symptoms	32	80	89	*Infection in lung*
Impaired lung function	43	84	71	*Breathing problem*
Sputum neutrophilia	13	53	64	*Infection, Inflammation*
Elevated AM number	12	65	85	*High PM_{10} exposure*
Larger and multinucleated AM	8	23	32	*Sustained high pollution load*
Multinucleated giant cell	2	5	10	*Bacterial infection*
Curschman's spiral	2	4	5	*Obstruction in airways*
Goblet cell hyperplasia	2	16	25	*Elevated mucus production*
Elevated siderophage count	6	34	44	*Covert lung hemorrhage*
Elevated micronucleus count	8	68	82	*Chromosome break*
Low hemoglobin, RBC in blood	17	32	45	*Anemia*
Leukocytosis	7	26	34	*Infection*
Elevated platelet count	12	62	75	*Cardiovascular rish*
High platelet P-selectin	9	55	87	*Do*
Low CD 4+high CD8+cells	11	42	78	*Altered immunity*
Low CD20+high CD56+cells	12	54	89	*Do*
Sputum eosinophilia	11	28	36	*Allergy, asthma*

Con=Control, RP=Ragpickers, MSW=conservancy staff of Kolkata Municipal Corporation, AM=Alveolar Macrophage

2.8 AIR POLLUTANTS FROM VEHICLE EMISSION AND THEIR HEALTH EFFECTS

The atmosphere is a complex, dynamic natural gaseous system that is essential to support life on planet Earth. Apart from natural sources, air pollution is the human introduction into the atmosphere of chemicals, particulates, or biological materials that cause harm or discomfort to humans or other living organisms, or damage the environment. Air pollution is often identified with major stationary sources, but the greatest source of emissions is actually mobile sources, mainly automobiles (JoAS, 2009). Apart from criteria pollutants from automobiles, carbon dioxide, which contributes to global warming, has recently gained recognition as pollutants by climate scientists.

The principal pollutants emitted by petrol-fuelled vehicles are carbon monoxide (CO), unburnt hydrocarbons, nitrogen oxides (NO_x) while those from diesel vehicles are particulate matter (PM), nitrogen oxides (NO_x), polycyclic aromatic hydrocarbons (PAH) and sulphur dioxide (SO_2). Petrol vehicles also emit benzene (BENZ) and Butadiene (BUTDN) (Holman, 1999). Carbon monoxide decreases the oxygen carrying capacity of blood, NOx, PM_{10} and SO_2 affects the respiratory system while some PAH's are carcinogens (Marilena and Elias, 2008). Carbon dioxide is a major contributor to the greenhouse effect and climate change. Any car produces twice its weight in carbon dioxide each year. About 30% of all CO_2 emissions in Canada come from road vehicles. Vehicles also contribute to smog and acid rain, producing 19% of nitrogen oxides, 23% of volatile organic compounds (which together create ground level ozone, a major component of smog) and 37% of the total carbon monoxide released each year as a result of human activity (Environment Canada., 2002). Amounts of sulphur oxides continue to decrease as low sulphur fuels gain market penetration.

Particulate matter is a component of smog, deposited as soot. Local emissions dominate the concentration of SO_2, NO_2 and PM_{10} (particulate matter less than 10 microns). The major sources of emissions affecting Kolkata area include mobile sources along with contributions from industrial sources, coal-fired power plants and domestic heating (Gupta et al., 2008). Particulate matter (PM) can accumulate in the upper atmosphere and affect climate change. The production of PM_{10} is associated particularly with the combustion of carbon-based and sulphur-based chemicals such as gasoline and diesel. Researchers (Karar and Gupta, 2006; Karar et al., 2006a) have found Cr, Zn, Pb, Cd, Ni, Mn and Fe in the PM_{10} concentrations in Kolkata. The health effects of PM are varied and may be dependent on the size, shape, and chemical composition of the particles. PM_{10} of Kolkata is about 52% of total particulate matter (PM) at residential area and 54% at industrial area (Karar et al., 2006b). Exposure has been linked with mild symptoms such as coughing and wheezing, with exacerbation of pre-existing lung diseases like bronchitis and Chronic obstructive pulmonary disease (COPD), and with serious health effects including cancer, heart attacks and strokes (Zoidis, 1999). Sulphur and nitrogen oxides and acid aerosols will irritate the lungs and exacerbate pre-existing lung diseases. Several studies were carried out in Kolkata by different institutes and organizations, which highlighted the impacts on our health because of the precarious state of the Kolkata air quality. It has been found that residents of Kolkata have not only showed much higher Alveolar Macrophage (AM) count in their deep sputum but also increase in the percentage and total number of neutrophils and eosinophils-cells. The AM count was found to rise with increasing level of particulate pollution in the workplace (Mylius and Gullvag, 1986). Large increase in neutrophils and eosinophils in the sputum of urban individuals suggest inflammation of lung and allergic lung reaction in large number of residents of Kolkata. This is more pronounced among the people exposed to vehicular emission like traffic policemen, hawkers etc (WBPCB, 2001). In another study of biological monitoring of lead in juvenile blood, it was found that blood lead level of students of Kolkata in the age group 10-12 years had a higher lead content than the village student (ROHC, 1999).

Presence of appreciable concentration of Polycyclic Aromatic Hydrocarbons (PAH) was found in the ambient air of Kolkata, some of which are known to have potential in carcinogenic activities. The concentration of Benzo (a) Pyrene was observed to be much higher than other PAH in the atmosphere of Kolkata and its potential for pronounced carcinogenic activity is well known (Chakraborty, 1998). Emission factors of specified pollutant based on vehicle distribution weighted by type, age and operating mode are taken from CPCB (CPCB, 2000a)

Air pollution is usually concentrated in densely populated metropolitan areas, especially in developing countries like India, monitoring of where environmental regulations are generally relatively less. High vehicular density, insufficient road space, low traffic speed, bad road condition, rapid growth in vehicle population have led to a deterioration of the atmospheric condition over Kolkata, a city with one of the highest population densities of India at 24,760 persons per square km. Kolkata has been placed among the 41 most polluted cities of the world with respect to suspended particulate matter (SPM) levels, according to Global Pollution and Health a report published in 1996 by WHO and UNEP. The major sources of air pollution in the city are automobile exhausts (50%), industrial emission (48%) and domestic cooking (2%). During 2010, the contribution from automobile sector to the air pollution load would rise to 55% (Gopalakrishnan, 1997).

A large numbers of highly polluting old vehicles are presently plying on the city streets. Stationary vehicles with running engines release more pollutants than the moving ones. Similarly automobiles running at an optimum speed of 60 km/h emit less pollutant than the relatively slow moving vehicles. The latter point seems to have a significant impact on the air pollution scenario of Kolkata because of the fact that the average vehicular speed in the city is much less for several reasons. The most important point in this regard is inadequate road space (6% of total area against 25-30% expected) coupled with high vehicular density that often leads to traffic jams particularly at peak hours. In addition, adulteration of fuel is a burning problem; both gasoline and diesel are reported to be adulterated with kerosene and solvents resulting in higher emission of pollutants (DOE, 2002; Majumdar et. al., 2008). In this context proper management of transport in each sector is essential for minimization of air pollutants in a city like Kolkata for sustainable development; Municipal Solid Waste (MSW) management is one such sector. The transport sector of MSW management system is a small part of the total automobile transport in Kolkata, but this work is a part of the total MSW management system to minimize the potential environmental impact from MSW sector. Knowledge of estimation will facilitate to optimize the minimum MSW transport emissions.

Not much research has been carried out worldwide linking the contribution of MSW conservancy transportation vehicles with air pollution. Jovičić et al. (2011), in their research had mainly focussed attention on route optimisation by GIS/GPS to increase fuel efficiency of conservancy vehicles. They had used COPERT computer programme to predict vehicle emissions for heavy duty diesel vehicles conforming to EURO I standard, assuming emission of CO_2 for typical municipal vehicle (with Euro 1 engine) is 900 g/km. However detailed calculations with stoichiometric equations for different pollutants are missing in this work. Vilms et al. (2015) had investigated the amount of air pollutants (CO_2, CO, HC, NOx, PM and CO_2-eq) formed in the city centre of Tallinn (Estonia), when the present waste collection system with conservancy trucks is applied. Calculation of air pollutants generated was carried out according to the amount of the burnt fuel emitted by municipal trucks complying present EURO III norms and future EURO V requirements. The authors have then compared the present system waste transportation involving trucks with a proposed pneumatic waste transportation system which may eliminate the noise and exhaust gases generated by garbage trucks, the dropped or leached waste from vehicles; in addition to that, visual disturbance of seeing garbage trucks would be eliminated. In India, Chattopadhyay et al. (2010), had presented a detailed work on the different pollutants (PM, CO, CO_2, SO_2, NOx, benzene, butadiene) emitted into the atmosphere from the different vehicle fleets employed by KMC for waste transportation of Kolkata city.

2.9 NOISE POLLUTION FROM TRANSPORTATION SECTOR AND THEIR HEALTH EFFECTS

Due to rapid urbanization and industrialization, high density of traffic in Kolkata, India has resulted in increased noise levels in the environment leading to noise pollution. Human ear is sensitive to a range of intensity from 0 to 180 dB(A). Noise pollution can cause annoyance and aggression, hypertension, high stress levels, tinnitus, hearing loss and other harmful effects, myocardial infarction, headaches, fatigue, stomach ulcers and vertigo (Franssen et al., 2004). Traffic noise, especially because of the increasing no. of vehicles on the limited road surface (only 6% Kolkata surface is available for roads) is a major cause for the noise pollution.

After vehicular emission, noise pollution is the second most hazardous pollutant of environment from the health point of view (Kumar, 2005). According to the EPA (USA), noise pollution can be broadly defined as "unwanted or offensive sounds that unreasonably intrudes into our daily activities”. Noise pollution can be divided into two categories viz. natural and man-made. Natural causes of noise pollution are air, volcanoes, seas, rivers, exchanging voices of living organs including man and animals (PSCST, 2010).

The intensity of sound is measured in decibels (dB). This is on logarithm scale which means that 50 dB (A) sounds would be ten times louder than 40 dB (A). Human ear is sensitive to an extremely wide range of intensity from 0 to 180 dB(A), 0 dB(A) being the threshold of hearing, whereas 140 dB(A) marks the threshold of pain. Experts believe that continuous noise level in excess of 90 dB(A) can cause loss of hearing and irreversible changes in nervous system (Field, 1993; Kryter and Karl, 1994).

The net effects of high traffic intensity in noise pollution in the city are well known facts. A study (Kumar, 2005) conducted jointly by Central Pollution Control Board (India) and State Pollution Control Board, Kolkata, West Bengal, in 1994-95 shows that the traffic of Kolkata contributes a major part of the noise pollution and the noise levels at the road crossings are much higher. The improved socio-economic status of urban population coupled with inadequacy of public transport has encouraged personalized means of transport. This craze for owning vehicles in urban centers, has led to considerable noise and air pollution, especially in big cities (Table 2.17) (Maithani et al., 2007).

Table 2.17 Noise levels (dB(A)) in major Indian cities

City	Day	Night
Delhi	83	77
Kolkata	82	75
Mumbai	80	71
Chennai	77	73

Earlier there was no specific legislation in India to deal with the problem of excessive noise. Keeping in view the serious health hazard due from noise, the Government thought it fit to enact a special law in regulation to control noise pollution. The enactment of the Noise Regulation Rules 2000 under Sec. 3 of Environmental Protection Act, 1986, is seen as a comprehensive legislation in controlling the increase of the noise level in industrial (75 dB(A)), commercial (65 dB(A)) and residential zones (55 dB(A)). The rules mention the creation of silence zones (50 dB(A)) 100 meters from school, courts, educational institutions and hospitals. Noise limits for passenger or commercial vehicles with gross vehicle weight in the range of 4 MT to 12 MT and above 12 MT are 89 dB(A) and 91 dB(A) respectively (MoEF, 2002). Noise monitoring data collected in Kolkata Municipal Corporation area since 1989 indicate that both day time and night time ambient noise level by far exceeds the prescribed limit (82 - 94 dB(A)). Even in declared silence zone the recorded figure stands at 65 - 80 dB(A), nearly equaling the figure prescribed for industrial zone (Environment Department, 2002).

The noise of road vehicles is mainly generated from the engine and from frictional contact between the vehicle and the ground and air. In general, road-contact noise exceeds engine noise at speeds higher than 60 km/hr (Singh and Davar, 2004).

Unfortunately not much literature is available where the contribution of waste management sector to ambient noise pollution has been quantified. Chattopadhyay et al., (2014) had presented a study of the noise pollution from municipal solid waste (MSW) management sector of the megacity of Kolkata, India. Kolkata is one of the largest MSW generators (~3000 MT/day) having high traffic density and restricted road space. The purpose of this study was to prepare the noise level inventory from different types of collection points, transportation sector and landfill site in present situation. Though the workers are found in several cases exposed to noise level beyond regulatory limit but in no case the surrounding noise level exceeds the regulatory limits.

2.10 LANDFILL LEACHATE

Although waste management hierarchy considers landfilling as a last option, the worldwide trend is still in favor of controlled sanitary landfilling, as the preferred means of disposing both municipal and some solid industrial waste. In spite of many advantages, as the cheapest option in terms of capital and exploitation costs, the major drawback of landfilling resides in the generation of heavily polluted leachates, whose quantity, volumetric flow rate, and chemical composition are highly variable. In addition, landfill outputs induce impacts and risks in the environment, forcing authorities to impose more and more stringent constraints**.**

The generation of leachate is caused principally by precipitation percolating through waste deposited in a landfill and has extracted dissolved and suspended materials. Additional leachate volume is produced during the decomposition of carbonaceous material producing a wide range of other materials including methane, carbon dioxide and a complex mixture of organic acids, aldehydes, alcohols and simple sugars. The leachate from landfills contains toxic chemicals including volatile organic compounds (VOCs), nitrogen compounds, inorganic macro components (common cations and anions including sulfate, chloride, iron, aluminium, zinc and ammonia), heavy metals (Cr, Cd, Pb, Ni, Cu, Hg) , and xenobiotic organic compounds such as halogenated organics, (PCBs, dioxins, etc) (Tchobanoglous, 1993; Kjeldsen et al., 2002; Kathpalia and Alappat, 2003; Mor et al., 2006).

Factors affecting quality of leachate are waste composition, elapsed time, ambient temperature, available oxygen and moisture. These factors govern various chemical and biochemical reactions during the waste decomposition. The quantity of leachate produced is affected to some extent by decomposition reactions and initial moisture content; however, it is largely governed by the amount of external water entering the landfill. Factors affecting quantity of leachate are precipitation, ground water intrusion, refuse condition and final cover design. (Owesis and khera, 1990)

2.10.1 Composition of Leachate

When water percolates through the waste, it promotes and assists process of decomposition by bacteria and fungi. Leachate composition may vary widely within the successive aerobic, acetogenic, methanogenic, stabilization stage of the waste evolution. The acidogenic phase occurs when the landfill containing large amounts of biodegradable organic matter is a few years old, resulting the so-called young leachate with high values of COD and biological oxygen demand (BOD) levels, while the ratio BOD/COD is higher than 0.7 and pH is at low value due to the high concentrations of volatile fatty acids. Acidic fermentation is enhanced by a high moisture content or water content in the solid waste. The methanogenic phase is specific to landfills older than 10 years and the leachate generated is referred to as old. Methanogenic microorganisms, developed in the waste, degrade volatile fatty acids which are converted to biogas (CH_4, CO_2), while pH > 7, and the ratio BOD/COD is stabilized on levels < 2.

Refractory (non-biodegradable) compounds become the dominant organic fraction in the leachate (Renou et al., 2008; Schiopu and Gavrilescu, 2010). Table 2.18 compares leachate composition in the early and later stages of waste degradation (Tchobanoglous et al., 1993). Leachate is generally characterized by a strong odor and dark brown color and contains high levels of pollutants (e.g., a BOD of 10000 mg/L, compared to 100–200 mg/L for typical municipal wastewater).

Table 2.18 Typical data on the composition of leachate from new and mature landfill (Tchobanoglous et al., 1993)

Constituents	New Landfill (less than 2 yrs), mg/L		Mature Landfill (greater than 10 yrs), mg/L
	Range	Typical	
BOD_5	2,000-30,000	10,000	100-200
TOC	1,500-20,000	6,000	80-160
COD	3,000-60,000	18,000	100-500
Total Suspended Solids	200-2,000	500	100-400
Organic Nitrogen	10-800	200	80-120
Ammonia Nitrogen	10-800	200	20-40
Nitrate	5-40	25	5-10
Total Phosphorous	5-100	30	5-10
Ortho phosphorous	4-80	20	4-8
Alkalinity as $CaCO_3$	1,000-10,000	3,000	200-1,000
pH	4.5-7.5	6	6.6-7.5
Total Hardness as $CaCO_3$	300-10,000	3,500	200-500
Calcium	200-3,000	1,000	100-400
Magnesium	50-1,500	250	50-200
Potassium	200-1,000	300	50-400
Sodium	200-2,500	500	100-200
Chloride	200-3,000	500	100-400
Sulphate	5-1,000	300	20-50
Total Iron	50-1,200	60	20-200

A large number of hazardous compounds were found in leachate from 12 Swedish municipal landfill sites. More than 90 organic and metal organic compounds and 50 inorganic elements were detected in these sites. Compounds detected include halogenated aliphatic compounds, benzene and alkylated benzenes, phenol and alkylated phenols, ethoxylates, polycyclic aromatic compounds, phthalic esters, chlorinated benzenes, chlorinated phenols, PCB, chlorinated dioxins and chlorinated furans, bromated flame-retardants, pesticides, organic tin, methyl mercury and heavy metals. Average heavy metal concentrations in leachate were found out as Cr 15.3µg/L, Cu 23µg/L, Hg 0.028µg/L, Pb^{2+} 4.43µg/L and Cd 0.44µg/L (Oman and Junestedt, 2008).

Chattopadhyay et al. (2009), Motling (2014) and De et al. (2017) had reported the landfill leachate quality of Dhapa landfill site in Kolkata city during the past years. The results of their researches are tabulated below in Table 2.19.

Table 2.19 Physico-chemical parameters of leachate collected from uncontrolled landfill at Dhapa, Kolkata

Parameters	Range as per Chattopadhyay et al. (2009)	Range as per Motling (2014)	Range as per De et al. (2017)	Leachate discharge standards to inland surface water (MoEFCC, 2016)
pH	7.48-8.00	7.8-9.0	7.8-8.6	5.5-9.0
Alkalinity	2900-3590	–	Not reported	–
Total solids	10051-14727	–	Not reported	–
TDS	Not reported	4300-30900	2320-15700	–
Total organic solids	2750-7000	Not reported	Not reported	–
Total inorganic solids	7543-7785	Not reported	Not reported	–
COD	3427-16000	2496-21120	1200-13200	250
BOD_5	2075-7000	3408-14539	525-6440	30
NH_4	Not reported	192-1230	168-4210	50
TKN	Not reported	238-1900	631-9139	100
Cd	0.04-0.05	Not reported	0.006-2.11	2.0
Cr	0.43-0.85	0.82-27.12	0.104-10.43	2.0
Fe	Not reported	2.6-14.7	0.8-11.25	–
Hg	0.002-0.009	0.005	0.16-2.65	0.01
Mn	Not reported	Not reported	0.68-3.90	–
Ni	0.6-0.73	0.22-4.45	0.2-0.77	3.0
Pb	0.07-0.08	0.48-12.98	0.37-1.14	0.1
Zn	0.16-0.85	0.4-7.76	1.00-25.14	5.0
Cu	0.06-0.28	0.17-3.4	0.14-0.68	3.0
As	0.005-0.009	0.02-0.36	0.0045-0.5610	0.2
Chloride	1234-3408	1060-3700	2103-6735	1000
Nitrate	2.16-3.31	Not reported	9.45-59.2	–
Fluoride	0.36-0.86	Not reported	0.2-2.53	2.0

All concentrations in mg/l except pH

2.10.2 Environmental Impact of Leachate

The presence of moisture and rainwater leach the pollutant chemicals produced during degradation to dissolve and flow into the groundwater and surface water reserve thereby affecting the flora and fauna of the water body. The dump sites virtually become a breeding ground for all kinds of diseases. Besides this, it leads to formation of secondary pollutants like H_2S, and other hydro sulfurous gaseous pollutants reacting with bacteria present in the waste in the presence of moisture and temperature. CH_4 which is one of such toxic gases produced leads to fire hazards (Sahu, 2007). Pathogenic microorganisms that might be present in it are often cited as the most important, but pathogenic organism counts reduce rapidly with time in the landfill, so this only applies to the freshest leachate.

There has been a serious concern about the possible contamination of soils, ground and surface waters when the wastes are, thus, disposed. A study conducted in the city of Hyderabad clearly showed how soil, surface water as well as ground water have been polluted due to open landfills (Rao and Shantaram, 2003). Consumption of leachate-contaminated ground water may lead to, among other things, heavy metal toxicity such as impaired renal function and possibly cancer.

Leachate streams running directly into the aquatic environment can severely diminish bio-diversity and greatly reduce populations of sensitive species. Where toxic metals and organics are present this can lead to chronic toxin accumulation in both local and far distant populations. Rivers impacted by leachate are often yellow in appearance and often support severe overgrowths of sewage fungus. The leachate from the Mavallipura illegal solid waste dump near Bangalore is allowed to stagnate in a ditch next to the dump and slowly finds its way into surface and ground water aquifers. Over the years all drinking water sources in the vicinity have been adversely affected, and the threat looms large of contaminating the Arkavathy river, a major drinking water source of Bangalore (ESG, 2011).

2.10.2.1 Heavy Metals

Dumping of electronic goods, electro plating waste, painting waste, used batteries, etc. in MSW landfills results in increased concentration of heavy metal in leachates which in turn pollute the groundwater. Electronic goods contribute around 70% of the heavy metals in landfills. India is importing electronic waste specially computers having high lead, mercury and cadmium concentration from Singapore, South Korea and US for disposal (Esakku et al., 2003). Further some small scale industries dumps their wastes in MSW landfills which is also an eminent source of heavy metals.

Table 2.20 Heavy metal sources and adverse health effects

Metal	Source	Effects
Chromium	Leather tanning, explosives, ceramics, paint pigments, photography, wood preservation, fertilizers, dyes and paints.	Mainly Cr^{6+} damages the kidneys, liver and blood cells. It can also alter genetic materials and can cause birth defects, infertility, tumor formation and cancer. Other effects of Cr^{6+} includes skin rashes, upset stomachs and ulcers, respiratory problems, weakened immune systems, lung cancer and even death.
Mercury	Fluorescent and other lights, batteries, electrical switches, relays, barometers and thermometers.	Extremely toxic. Mercury can cause both chronic and acute poisoning. A potent neurotoxin that can affect the brain, liver and kidneys, and cause developmental disorders in children. Can bio-concentrate up in the food chain.
Lead	Lead-acid batteries, consumer electronics, glass & ceramics, plastics, soldered cans and pigments	Damage nervous connections (especially young children could show slight deficits in attention span and learning abilities) and cause blood and brain disorders. Long-term exposure: plumbism, brain and kidneys damage and ultimately cause death. In pregnant women, high levels of exposure to lead may cause miscarriage. Chronic, high-level exposure has shown to reduce fertility in males.
Cadmium	Metal alloys such as solder, electroplating, nickel plating, engraving, and especially nickel-cadmium batteries.	Alzheimer's and other brain disorders. Increased salivation, dry throat, choking, abdominal pain, headache, vomiting, chest pain and anemia. Cadmium is extremely toxic even in low concentrations, and will bioaccumulate in organisms and ecosystems. A potent enzyme inhibitor, teratogenic in many animal species and carcinogenic to humans.
Copper	Electrical wiring, and water pipes, agricultural pesticide	Children under one year of age are more sensitive to copper than adults. Long-term exposure (more than 14 days) to copper in drinking water which is much higher than 1,000 µg/l has been found to cause kidney and liver damage in infants.

Heavy metals tend to be more soluble in acidic water. In aquifers and soils that have pH buffering capacity and under oxidizing conditions they are readily absorbed or exchanged by clays, oxides and other minerals. But the typical fatty acid content of landfill leachate creates acidic conditions favorable for dissolution of heavy metals. These heavy metals do have a serious problem for the environment since they cannot be biodegraded and remain in the soil or water only and may affect humans and livestock. Heavy metals like manganese, mercury, lead, arsenic, cadmium, copper, nickel, chromium are either toxic or carcinogenic in nature. Unlike organic pollutants, heavy metals do not decay and thus one of the largest problems associated with the persistence of heavy metals is the potential for bioaccumulation and bio-magnifications (Nguyen et al., 2013). Source and effects of some heavy metals are given in Table 2.20.

CPCB conducted studies on heavy metal concentration in raw MSW from 59 cities of India. The result indicated that average concentration of lead was in the range of 47 to 185 mg/kg, 36-63 mg/kg for nickel, 1.5 to 6.5 mg/kg for cadmium and 0.01 to 0.23 mg/kg for mercury (CPCB, 2010).

A study on heavy metal contents in fine fraction of MSW collected from Perungudi dumping ground near Chennai reveled that chromium concentration varies between 110 to 261 mg/kg with a mean value of 140 mg/kg. Lead content varies between 53 to 112mg/kg with a mean value of 86 mg/kg. Mercury content ranges between 0.039 to 0.78 mg/kg with an average of 0.29 mg/kg. Cadmium and Copper content ranges between 0.82 to 1.77 mg/kg and 75 to 217 mg/kg respectively and their mean value is 1.29 and 113 mg/kg respectively. From the same sampling stations leachates were collected and analyzed for these heavy metals. Average concentration of chromium, mercury, lead, cadmium and copper varied between 5.9 -200μg/L, 1.7-8.3μg/L, 299-606, 8-26μg/L and 8-137 μg/L respectively (Esakku et al., 2003). Urban solid wastes generated in Hyderabad city contains average chromium 25mg/kg, cadmium 2mg/kg, lead 135mg/kg and copper 113 mg/kg (Rao and Shantaram, 2003).

2.10.2.2 Organics

Leachate contains high BOD and COD but with time it biodegrades. Fresh leachate contains 2000 to 30,000 mg/L BOD and 3,000 to 60,000 mg/L COD but leachate from a matured landfill (after 10 to 15 years) reduces to 100-200mg/L and 100-500 mg/L respectively. Gas production from landfill also continues for around 15 years. Thus highly degradable organic fraction of the waste is not a problem in long term. But like heavy metals some organic compounds are toxic in nature and are resistant to biodegradation. Presence of even trace amounts of such compounds like benzene, toluene, vinyl chloride, phenol, chloroform etc in drinking water is harmful to human health. Organics also encompasses refractory compounds like humic and fulvic acids along with small amounts of volatile acids (Chian and DeWalle, 1977). Some of these organic constituents are also carcinogenic.

Adsorption is the most common way in which the trace organic constituents in the leachate are removed as it moves through a porous medium. Biodegradation rates can occur but to lesser extent. Typical data on characteristics of leachate is given in Table 2.18 (Bagchi, 2004; Tchobanoglous et al., 1993). Studies conducted by Indian Institute of Technology, Delhi, NEERI, Nagpur, and some State Pollution Control Boards have shown ground water contamination potential beneath landfills (CPHEEO, 2000). A range of values for the first-order biodegradation rate constant for selected organics under anaerobic groundwater environments as recommended for input into the EPA's Composite Model for Leachate Migration and Transformation Products (EPACMTP) are also given in Table 2.21 (SRC, 1997; EPA, 1999).

Table 2.21 Typical range of organics in landfill leachate

Organics	Concentration (mg/L)		Biodegradation Rate (day^{-1})		
	Minimum	Maximum	Minimum	Mean	Maximum
Acetone	170	11,000	0.0037	-	0.037
Benzene	2	410	0	0.0033	0.038
Toluene	2	1600	0.00099	0.059	0.30
Chloroform	2	1300	0.004	0.08	0.25
Phenol	10	28,800	0.0013	-	0.032
Vinyl Chloride	0	100	0.00033	0.0073	0.0845

Source and adverse health effects of organics

Acetone is used in industrial solvent and chemical intermediate, paints, varnishes and lacquers and is used as a solvent for cements in the leather and rubber industries. Disposal of agricultural and food waste, animal waste, atmospheric wet deposition, household septic tank effluents and chemical waste disposal sites are some source of acetone. It has low acute and chronic toxicity. EPA reported that there is currently no evidence to suggest a concern for carcinogenicity. High doses exposure affects central nervous system but it is not a neurotoxicant. It has been categorized by the U.S.EPA as a Group D carcinogen (inadequate evidence to classify) (DES, 2005; MassDEP, 2010).

Chloroform present in soil may come from improper land disposal of waste material containing chloroform or other chlorine-containing compounds that are broken down to form chloroform. Pesticide manufacturing plants; pulp and paper mills; food processing industries; paint stores (as a result of using chloroform-containing solvents for lacquers, gums, greases, waxes, adhesives, oils, and rubber). Chloroform affects the central nervous system, liver, and kidneys (INCHEM, 2010).

Toluene is used as a solvent, especially for paints, coatings, gums, oils and resins, and as raw material in the production of benzene, phenol and other organic solvents and in the production of polymers and rubbers. It is nephrotoxic, neurotoxic, hepatotoxic, and results in decreased respiratory function (Eco-USA, 2011).

Benzene is used for making plastics, rubber, resins and synthetic fabrics like nylon and polyester, solvent in printing, paints, dry cleaning, etc. The major sources of benzene in drinking water are discharge from factories; and leaching from gas storage tanks and landfills (INCHEM, 2010). Benzene is a well-established human carcinogen. It can induce anemia, it is fetotoxic, but not found to bio-concentrate or bio-accumulate in aquatic or terrestrial organisms (EPA, 2011).

Vinyl Chloride is not known to occur naturally although it has been found in landfill gas and groundwater as a degradation product of chlorinated hydrocarbons deposited as solvent wastes in landfills. Originate from degradation of higher chlorinated aliphatic hydrocarbons, such as trichloroethylene and tetrachloroethylene (Davis and Carpenter, 1990). It received increased attention as a groundwater contaminant as it is both toxic and carcinogenic to humans. Its adverse health effects also include decreased fertility.

Phenol is mainly a man-made chemical, although it is found in nature in animal wastes and organic material. The largest single use of phenol is to make plastics, but it also is used to make nylon and other man-made fibers, resins. It also is used as a as a disinfectant, and in medical products. Phenol will stay in the air, soil, and water for much longer times if a large amount of it is released at one time, or if a steady amount is released over a long time. Phenol has been found in materials released from landfills and hazardous waste sites, and it has been found in the groundwater near these sites. Repeated exposure to low levels of phenol in drinking water has been linked with diarrhea and mouth sores in humans; consuming very large amounts of phenol has resulted in death (Eco-USA, 2011).

2.10.3 Estimation of Landfill Leachate

Amount of leachate generated depends on several factors like climate conditions, stage and age of landfill and waste and site specific parameters. In the absence of leachate collection or liner system, leachate can contaminate soil, surface water and ground water. Both the quality and quantity of leachate generated during the active and closure of landfill are important in managing a landfill and treatment of the leachate. Thus estimation of leachate quantity is an important factor for providing leachate collection and treatment facility, for designing liner system or to estimate its adverse impact. Direct quantification of leachate in case of a new landfill or existing landfills with no leachate collection system is not possible. The only method available for such cases is estimation of leachate quantity by modeling the site water balance on the basis of wide range of assumptions.

Variety of water balance methods is available to enable estimation of leachate from a landfill. The following water balance analysis methods are being used for leachate estimation or prediction from a landfill (i) Simplified manual method (MBALANCE), (ii) Leachate Estimation and Chemistry Model (LEACHM), (iii) UNSAT model, (iv) Soil Cover model, and (v) Two Dimensional water flow and solute transport in variably saturated porous media (HYDRUS2D) model. These models take in to account the significant water balance processes like precipitation, runoff and evapotranspiration. Several other models available are MOBYDEC, PREFLOW, FILL, HELP have been published and some of them widely used (Tränkler et.al., 2001).

2.10.3.1 Water Balance Method (WBM)

The potential for the formation of leachate can be assessed by preparing a water balance on the landfill. The water balance involves summing the amounts of water entering the landfill and subtracting the amounts of water consumed in chemical reactions and the quantity leaving as water vapour. The potential leachate quantity is the quantity of water in excess of the moisture-holding capacity of the landfill material.

2.10.3.2 HELP Model

The EPA-sponsored Hydrologic Evaluation of Landfill Performance (HELP) computer program is a quasi-two-dimensional hydrologic model of water movement across, into, through and out of landfills. The model accepts weather, soil and design data and uses solution techniques that account for the effects of surface storage, snowmelt, runoff, infiltration, evapotranspiration, vegetative growth, soil moisture storage, lateral subsurface drainage, leachate recirculation, unsaturated vertical drainage, and leakage through soil, geomembrane or composite liners. Landfill systems including various combinations of vegetation, cover soils, waste cells, lateral drain layers, low permeability barrier soils, and synthetic geomembrane liners may be modeled. The program was developed to conduct water balance analyses of landfills, cover systems, and solid waste disposal and containment facilities. As such, the model facilitates rapid estimation of the amounts of runoff, evapotranspiration, drainage, leachate collection, and liner leakage that may be expected to result from the operation of a wide variety of landfill designs. The primary purpose of the model is to assist in the comparison of design alternatives as judged by their water balances (Schroeder et al., 1994). The basic water balance equation used is:

Precipitation = Runoff + Evapotranspiration + Leakage + Change in water storage.

The potential leachate quantity is the quantity of water in excess of the moisture-holding capacity of the landfill material. The model uses daily climate data, landfill design data and soil data including waste characteristics. The model estimates daily runoff, evapotranspiration, drainage, and leachate and liner leakage (if present). The model is applicable to open, partially closed, and fully closed sites, and is a rapid and economical tool for screening landfill design alternatives.

The HELP model simulates hydrologic processes for a landfill by performing daily, sequential water budget analysis using a quasi-two-dimensional, deterministic approach. It is being used widely in engineering practice to predict leachate generation at landfills. In fact, its use has become compulsory for existing site evaluation and setting up of new landfill facilities (El-Fadel et al., 1997b). It accounts for snow melt, lateral drainage, freezing conditions taking into consideration the properties and composition of landfill cover.

A study was carried out to investigate the applicability of the HELP model in arid areas, by construction of two 35×25 m test cells in Kahrizak landfill in Tehran and monitoring the real leachate generation from each one for a period of one year. A comparison was made between values calculated by HELP model and the recorded values. In cell 2 leachate recirculation took place while cell 1 was operated without any recirculation The average field capacity and saturated hydraulic conductivity of the waste were tested and found to be 27.6 (v/v) and 0.084 cm/sec. Based on monitored values total amount of 94.9 m^3 leachate is produced in the modeling period in cell-1 while in cell-2 the this value reached 105 m^3 while 164 m^3 of leachate was recirculated over the cell. In the same period the amount of precipitation over the cells amount to around 334 m^3 (based on precipitation data from nearest stations). The model results for cell-1 show production of 99.7 m^3 in modeling period in cell-1 and 201.9 m^3 in cell-2. The results gained by study in cell-1 without any recirculation shows that the leachate prediction in arid areas can be predicted with a good accuracy in annual basis but when the infiltration of water to waste body increase due to leachate production, the model tends to underestimate water storage capacity of landfill and deviates from real values (cell-2). (Shariatmadari, et al., 2010).

Manandhar et al. (2009) had compared the actual leachate percolation values obtained by lysimeter with values predicted by HELP model in their research on the water management of a landfill in Nepal. The leachate production as an effect of climatological factors has been assessed and the evaluation as well as applicability of the model has been discussed. The trend of leachate generation in HELP simulation and actual data seem to be similar in October–December season, but in June–September, the trend shows higher percolation rate in actual data than model. Their study results have raised issues like effect on water balance by the variation of short-term rainfall into percolation.

HELP version 3 was examined under the humid climate of Germany in an extensive validation study. The aim of the research was to put the validation results of HELP model to practice by showing the potential and limitations of applying the HELP model for surface cover systems. A German enhancement of the HELP model, HELP 3.50 D, was developed, which fixes certain errors and enhances some processes (Berger, 2002). Berger (2000) further opines “The HELP model is a suitable tool for experts in hydrology; but good knowledge of the model and its behaviour and critical review of the simulation results are essential.”

A study presents comparative analyses of the results obtained by WBM and HELP model for landfill leachate generation from a landfill in the municipality of Centar Zupa in Macedonia. WBM is used to assess possible leachate generation volumes on an annual level for two scenarios: average annual precipitations and for historical data of annual values of precipitations for the period 1960-1985. For the first scenario maximal production of leachate was around 5500 m^3/year and for the second scenario estimated maximum annual leachate rates was 9500 m^3/year. Leachate generation rates were highly correlated to the annual sum of precipitation. The results from HELP model showed that the average amount of annual leachate generation is around 9000 m^3 (Katerina et al., 2010).

Muthukumara et al. (2015) had attempted to validate the applicability of HELP model in their study for Udapalatha open dumpsite in Central Province, Sri Lanka. Input weather data (rainfall, temperature, relative humidity, wind velocity, solar radiation) and site specific data (area, depth, profile characteristics) were obtained from nearby weather stations and site investigations, respectively. Model output leachate was validated with changes in four groundwater level percussion boreholes which were installed at the dumpsite. The trends in temporal changes in water level in monitoring well and model-estimated leachate were similar.

In India also HELP model has been employed for simulating the hydrologic processes in a secured landfill site in an industrial area of Ankleshwar in the Bharuch district of Gujrat (Jose and Majumdar, 2003).

2.10.4 Ground Water as a Drinking Water Source

Groundwater is the major source of drinking water in both rural and urban India. It is also an important source of water for agricultural and industrial sector. In India almost 61% of the water needs are fulfilled with ground water; in Maharashtra the dependence on the ground water is ~65% (Iqbal and Gupta, 2009). According to some estimates, it accounts for nearly 80 % of the rural domestic water needs, and 50 % of the urban water needs in India (Kumar and Shah, 2011). Usually the ground water is considered as less polluted as compared to the surface water, due to the reduced exposure to the external environment. But lack of sanitation, improper waste management like leachate from unscientific disposal of solid wastes also contaminates groundwater leading to increased pollution levels. Further during the past two decades, the water level in several parts of the country has been falling rapidly due to an increase in extraction.

For the last 300 years Kolkata has also experienced a huge population growth and demand of water, mainly for domestic purpose, has increased by many folds. Domestic water supply is done mainly from the Hoogli River through the Tala pumping stations and the Garden Reach pumping stations. In spite of this surface water sources a huge amount of water is drawn from the groundwater aquifers below Kolkata for drinking water purpose. This exploitation is so huge that permanent depletion of water level has occurred in the groundwater of Kolkata. Moreover if this limited available source of water gets polluted due to unscientific solid waste dumping then undoubtedly it will lead to a serious drinking water problem in the city (Aktar et al., 2010; Sengupta, 2009).

2.10.5 Contamination of Groundwater by Landfill Leachate

Groundwater pollution has been an issue of concern for environmentalists, since the pollution could be hardly reformed. The best accepted option is to avoid the possibility of polluting the ground water sources. Historically, it was believed that the natural filtering, resulting from water percolation through the subsurface, provides sufficient protection from contamination of groundwater. But today pollution of groundwater resources has become a major problem and hazardous substances leaking from industrial and municipal landfills are one of the major contaminant sources.

As discussed earlier, in the absence of leachate collection system or in case of unlined landfills, leachate migrates downward through the underlying vadose zone and finally reaches the aquifer (Dutta et al., 2014). Moreover leachates also move laterally from the peripheral leachate drains to contaminate surrounding surface water bodies. Various studies has revealed clear link between landfill leachates and groundwater- surface water pollution. The major concern with the movement of leachate into the subsurface aquifer below unlined and lined landfills is the fate of the constituents found in the leachate. Heavy metals and trace organics are the two constituents of greatest interest as they are highly persistent in nature.

A contaminated groundwater system in the carbonate terrain of Missouri has been investigated to determine pollution of spring originates from nearby sanitary landfill operations. Three diagnostic criteria: nitrogen-phosphorus ratios, chemical response to rainfall variation and correspondence of dilution ratios for conservative pollutants clearly indicate the landfill to be the principal source. Lithium bromide tracer testing clearly established hydraulic connection between the landfill and spring **(**Murray et al., 1981).

Niininen et al., (1994) had investigated the quality of landfill leachates and their effects on groundwater for four landfills sites (Joutsa, Kouvola, Kuopio and Lappeenranta) in Finland. Some organic contamination of groundwater was observed in the vicinity of four landfills studied.

A study was conducted in order to evaluate the effect of leachate from a landfill in the Seri Petaling in Malaysia. This landfill was a mature landfill whereby the pH was around 7.3 to 7.5 for well 1 and 5.7 to 6.1 for well 2. Overall, the concentrations of groundwater's pollutants in sampling well 1 were higher than sampling well 2 due to the distance from landfill site. At well 1, the concentration of the pollutants was increasing. Ammonium-nitrogen (NH_3-N) concentration increased from 1.2 mg/L in August 1998 to 208 mg/L in January 1999. Nickel concentration was higher at well 1. Iron and copper concentrations in well 2 still exceed the limits of Raw Water Quality Criteria. The experimental results indicate that the underground water quality was greatly affected by the leachate, since most of the parameters examined showed increased concentration at well 1 (Yusoff and Al-Hawas , 2008).

Compositions of landfill leachate and groundwater pollution were studied at Ibb city, Yemen. The leachate was sampled at three different locations at the landfill, i.e. at the landfill itself and at 15 and 20 m downstream of the landfill. The leachate and groundwater samples were collected during wet season, due to the excessive generation of leachate during this season. The leachate at this landfill is most likely in methanogenic phase, based on the alkaline pH value recorded (pH=8.2). In the leachate lead concentration varied from 0.0008 - 5 mg/L, chromium from 0.01-1.8 mg/L, cadmium from 0.0001 – 0.4 mg/L and copper from 0.004 – 10 mg/L. in the ground water, Cu concentration was the highest concentration of heavy metals with a variation of 3.5-5.7 mg/l, whereas the lowest concentration of heavy metals was recorded for Cr with a value of 0.131- 0.133 mg/l. Lead also varied from 0.183-1.85 mg/L while Cd was not detected. These boreholes were affected by the migration of leachate from the body of the landfill to the groundwater (Sabahi et al., 2009a; Sabahi et al., 2009b).

Yusof et al. (2009) studied the effect of municipal landfill leachate on river water in reference to the effect of controlled and uncontrolled landfills in Malaysia. River water in the vicinity of the uncontrolled landfill was observed with highest concentration of organics and ammoniacal nitrogen in comparison to controlled landfills. Heavy metals like Fe, Zn, Cr, Cd, Cu, Pb, Mn were present in high values exceeding the standard limits of Malaysia. Parameswari and Mudgal (2014) estimated the concentrations of heavy metals like Cd, Cr, Pb, Zn, and Fe in groundwater in and around the landfill site in Chennai, Tamil Nadu, India. Pb was present in majority of the sampling stations beyond the standard value of BIS. Moreover Cd and Cr were also observed in some of the sampling stations clearly indicating the effect of landfill leachate in groundwater.

Studies conducted by Indian Institute of Technology, Delhi, NEERI, Nagpur, and some State Pollution Control Boards have shown ground water contamination potential beneath sanitary landfills in India (CPHEEO, 2000).

Leachate and groundwater samples were collected from Gazipur landfill-site at Delhi and its adjacent area to study the possible impact of leachate percolation on groundwater quality. The leachate contains high BOD around 19000 mg/L, COD 27200mg/L, and TDS 27956 mg/L. Heavy metal like Cu concentration was 0.93 mg/L, Cr 0.29 mg/L, Cd 0.06 mg/L, Pb 1.54mg/L and phenol concentration was 0.02mg/L. The moderately high concentrations of Cl^-, NO^{3-}, SO_4^{2-}, NH_4^+, Phenol, Fe, Zn and COD in groundwater, likely indicate that groundwater quality is being significantly affected by leachate percolation. The presence of Total Coliform (TC) and Faecal Coliform (FC) in groundwater warns for the groundwater quality and thus renders the associated aquifer unreliable for domestic water supply and other uses (Mor et al., 2006). Some organic compounds are toxic in nature and are resistant to biodegradation. Presence of even trace amounts of such compounds like benzene, toluene, vinyl chloride, phenol etc in drinking water is harmful to human health.

Groundwater in Ankleshwar Industrial Estate in Bharuch district in Gujarat is highly contaminated. The contamination is a result of more than 3,000 industrial units in the estate: around 270 million litres of liquid waste and 50,000 tonnes of solid waste are generated annually. This often becomes a problem for people living in villages around the industrial estate because they depend on groundwater to meet their daily needs. Even crops growing on contaminated soil absorb the pollutants (Varshney, 2008).

Another study was conducted to find the concentration of metal ions in the ground water samples at Naregaon dumping area in Aurangabad during summer, monsoon and winter season. Water samples were collected from the dug wells and bore wells, around the dumping site. Average concentrations of copper, chromium and cadmium during summer were found to be 0.0065mg/L, 0.0064 mg/L and 0.0074 mg/L. During monsoon due to dilution effect it reduced to 0.0059mg/L, 0.0059mg/L and 0.0065mg/L respectively. During winter average concentration 0.0069mg/L for copper, 0.0073 mg/L for chromium and 0.0079 mg/L cadmium i.e. highest of all season. From the obtained results it was evident that at present the metal ion concentration is not at the levels which could be hazardous for humans. But still the study clearly points out that the concentration of the metal ions is increasing with respect to the vicinity to the dumping site and continued practice of waste dumping in the similar way may result in further increments of metal ions aggregation and pollution of groundwater sources (Iqbal and Gupta, 2009).

Sampling and analysis of leachate from Bhalaswa landfill, Delhi and groundwater samples from nearby locations clearly indicated the likely contamination of groundwater due to landfill leachate. The results of simulation studies carried out for the migration of Chloride from landfill shows that the simulation results are in consonance with the observed concentration of Chloride in the vicinity of landfill facility. The leachate from Bhalaswa landfill was found to be having a high concentration of chlorides, as well as Dissolved Organic Carbon (DOC), COD. High concentrations of heavy metals (Mn, Ni, Cu, Zn, Pb) were also observed, which is hazardous for health (Jhamnani and Singh, 2009).

A study has been conducted on the water quality in the vicinity of the Mavallipura illegal solid waste dump, near Bangalore. Special focus has been given on heavy metals in water. For the following parameters, one or more samples had concentrations higher than the desirable limit or maximum permissible limit (according to IS 10500 standard) odour, taste, turbidity, total hardness, chloride, TDS, cadmium, lead, alkalinity, calcium, magnesium and MPN coliform (ESG, 2011)

Groundwater monitoring by Bhalla et al. (2011) near Jamalpur (Punjab) landfill site has clearly shown that the leachate generated from the municipal solid waste landfill site is affecting the groundwater quality in the adjacent areas through percolation in the subsoil.

Central Pollution Control Board's Zonal Office Kolkata took an attempt to monitor and evaluate the present scenario of dumping sites of KMC at *Dhapa-Bantala* area, at three different locations. Site (A) is the site where dumping was made earlier about 50 years ago and is an old dumping site. The area was reported to be irrigated by storm water and sewage canal. Presently it is used for recreational purposes. Site (B) includes biomedical waste dumping area. It is the designated area for the hospital waste. Site (C) is an old dump site comprising 11 villages, considering its gravity of the health related aspects especially for the groundwater used for their drinking purposes. Suction Lysimeters were used for collecting samples of soil water out flux or leachates from unsaturated and saturated soils at different depths. The physico-chemical characteristics of water sources at CMC village, P.C. Chandra Green Project, Sonar Bangla and Science City in the nearby vicinity which are extensively used for drinking purposes were tested at depths 46 m to 168 m. Though the concentration of heavy metals in leachate are above the critical limit, but probably due to their low mobility or complex formation with the organic substances, groundwater contamination is restricted. But at the same time it is an established fact that leachate contains high concentration of organic and inorganic pollutants and hence may contaminate the surface and groundwater sources. (Saha et al., 2003; Basak, 2011).

De et al. (2017) had detailed seasonal variation of groundwater quality near the uncontrolled dumping ground at Dhapa, Kolkata. The groundwater in this area was found to be unsuitable for drinking water purposes while it can be used for irrigation during pre-monsoon season only. Another study by De et al. (2016) reveals leachate generated from the Dhapa MSW uncontrolled landfill site demonstrated that it was in its methanogenic phase with intermediate biodegradability, having a leachate pollution index (LPI) of 34.02 for the active dumping ground and 31.80 for the closed dumping ground at Dhapa. LPI was formulated using Delphi Technique by Kumar and Alappat (2003, 2005) to evaluate the leachate contamination potential of different landfills on a comparative scale using an index.

Thus the above studies revealed that the ground water in and around the uncontrolled landfill is being polluted by the leachate. Hence, the goal of ground water protection efforts must necessarily be the control or management of these sources, to ensure that release of pollutants will be sufficiently attenuated within the subsurface to prevent significant impairment of ground water quality at points of withdrawal or discharge. This goal can be effectively achieved only if control and management options are based on definitive knowledge of the transport and fate of pollutants in the subsurface environment. Such knowledge is required for establishment of criteria for design, operation and location of new potential sources of pollution. Knowledge of transport and fate is also required for assessing the probable impact on ground water quality by existing polluting sources.

2.10.6 Leachate and Contaminant Transport in Subsurface Strata

When rain water seep into the ground, it becomes the part of subsurface or ground water. First the water percolates down through cracks and pores of soil and rock to a region called unsaturated or vadose zone as it contains both air and water in the void spaces between the soils. Water in this zone is unavailable for human use. In the next saturated zone, all spaces between the soil particles are filled with water. This water is the available groundwater and the upper boundary of saturated zone is the water table. Thus an aquifer is a saturated geologic layer with high permeability of water. Below this aquifer generally there is a confining bed which is a relatively impermeable layer of hard rock that greatly restricts the movement of ground water. This type of aquifers is known as unconfined aquifers. Aquifers can also be present in between two confining layers and are called confined aquifers. Unconfined and confined aquifers are shown in Figure 2.2.

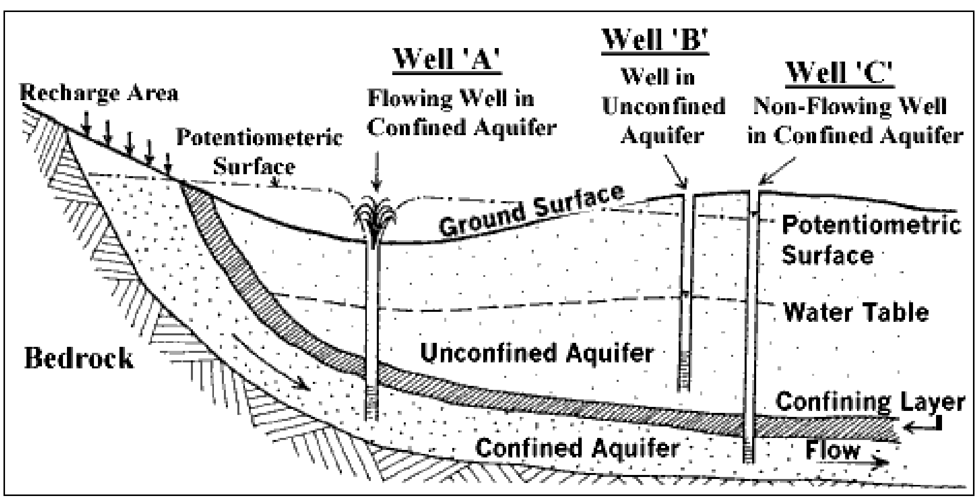


Figure 2.2 Unconfined and confined aquifers

The thickness and hydraulic conductivity, K of the aquifers layers are very important as they govern the three-dimensional flow of groundwater.

Under normal conditions, leachate is found in the bottom of landfills. From there, its movement in unlined landfills is downward through the underlying strata until it eventually reaches the saturated zone, although some lateral movement may also occur, depending on the characteristics of the surrounding material. Leachate then follows along the hydraulic gradient of the groundwater system. The rate of seepage of leachate from the bottom of landfill can be estimated using Darcy's Law:

$$Q = -KA(dh/dl)$$

Where, $Q =$ leachate discharge per unit time, $K =$ coefficient of permeability, $A =$ cross-sectional area through which the leachate flows, $dh/dl =$ hydraulic gradient, $h =$ head loss and $l =$ length of flow path.

The minus sign in Darcy's law arises from the fact that the head loss, dh, is always negative. The coefficient of conductivity is also known as the hydraulic conductivity, the effective conductivity, or the seepage coefficient.

There are many factors which cause the subsurface transport of contaminants. The mechanisms of transport of contaminants in ground water include advection, dispersion, diffusion, adsorption and ion exchange, decay, chemical reaction and biological processes. Advection represents the movement of a contaminant with the bulk fluid according to the seepage velocity in pore space. Dispersion is the combined result of two mass transport processes in porous media namely mechanical dispersion and molecular diffusion. The mass transport phenomenon occurs mainly due to heterogeneities in the medium that cause variation in flow velocities and in flow path, which is referred as mechanical dispersion. Diffusion is defined as the movement of constituent molecules in an environmental medium from areas of high constituent concentrations toward areas with lower constituent concentrations. This process occurs as a result of concentration gradients. Diffusion can occur both in the absence or presence of advective flow. The combined effects of mechanical dispersion and molecular diffusion make the solute spread to an even larger area than pure advection. Adsorption and ion exchange occur at the interface between the solid and liquid phases, the solute in the liquid may be adsorbed by the solid. Adsorption attenuates or retards a dissolved contaminant in ground water. The mass in the solid may also get into the liquid by dissolution or ion exchange. The chemical and biochemical reaction that can alter contaminant concentration in groundwater are acid-base reactions, solution-precipitation reactions, oxidation-reduction reactions, ion pairing or complexation**,** microbiological processes and radioactive decay (ESG, 2011).

To solve a ground water prediction problem, the most reliable way is to conduct a field test and directly observe the state of the aquifer. Unfortunately this is unrealistic because the performing field test for all conditions is not feasible always, further it involves high costs. Therefore, modeling method becomes the most feasible way for solving the problem. Many types of model have been used for simulating ground water flow and pollutant transport (Mohan and Muthukumaran, 2004; Mirbagheri et al., 2009).

A two-dimensional numerical model has been developed for quantifying groundwater inputs and associated contaminant discharge from a landfill facility situated south of Beirut, Lebanon, with capacity of 2000 ton/day into the nearest aquifer. It is established on finite difference-finite volume solution of two-dimensional advection-diffusion-linear sorption with first order decay equation. Leachate quantity and potential percolation into the subsurface in this project was estimated using the HELP model. Contaminant transport simulation of leachate to the nearest aquifer has been done. A comprehensive sensitivity analysis to leachate transport control parameters was also conducted. Sensitivity analysis suggest that changes in source strength, aquifer hydraulic conductivity, and dispersivities have the most significant impact on model output indicating that these parameters should be carefully selected when similar modeling studies are performed. (Rouholahnejad and Sadrnejad, 2009).

2.10.6.1 EPACMTP

Fate and transport of constituents of leachate in the subsurface unsaturated zone and in the aquifer can be modeled using EPA's Composite Model for Leachate Migration and Transformation Products (EPACMTP). The EPACMTP code is capable of simulating the fate and transport of dissolved contaminants from a point of release at the base of a waste disposal unit (landfill), through the unsaturated zone and underlying groundwater, to a receptor well at an arbitrary downstream location in the aquifer. Thus it simulates the impact of the release of constituents present in waste that is managed in land disposal units and establishes regulatory levels of concentrations for those constituents. It takes into account various site specific, constituent specific, unsaturated zone specific and aquifer specific parameters. Deterministic or Monte Carlo methodology can be used to model continuous or finite source.

Sastry and Isukapalli (1999) has performed a case study for characterization of uncertainty in estimated maximum concentration of tritium in a receptor well and the estimated time of occurrence of the maximum concentration using EPACMTP. The main source for the contamination is a hypothetical landfill unit in the southern United States. The variability and uncertainty associated with the hydrogeologic parameters and with the physical properties of the landfill unit are considered to characterize the uncertainty in the calculated concentrations of tritium.

An assessment of the potential for ground water impacts caused by leaching from industrial material resources (IMRs) used as pavement materials in roadway construction has been done using US EPA’s Industrial Waste Management Evaluation Model (IWEM) v2 (beta), which relies on Version 2.2 of the EPACMTP code. Comparison with field data showed that 90^{th} percentile concentrations predicted by IWEM at a monitoring well adjacent to a highway test section constructed with IMRs were higher than measured concentrations, which suggests that the prediction by IWEM is conservative. Parametric analysis showed that concentrations at an adjacent monitoring well decrease as the depth to ground water increases and the initial leachate concentration decreases. Predicted concentrations were insensitive to the thickness of the IMR layer and exposure duration but sensitive to the aquifer hydraulic conductivity and thickness (Li and Benson, 2009).

Analysis of liner leakages due to leachate heads were done for a landfill in Florida. To predict the behavior of the leachate head on the liner for a ‘typical’ Florida leachate collection system and to estimate leakage rates HELP model has been used. The EPACMTP was used to conduct a Monte Carlo analysis of contaminant transport and potential receptor well contaminant concentrations. The fate and transport of benzene was modeled. Receptor well contaminant concentrations were calculated for composite and double liner systems. Temporal variations in the leachate head on the liner and the associated variations in the leakage rate were found to have a pronounced effect on the calculation of receptor well concentrations (Reinhart and Mc Creanor, 1999)

Solid waste generation and its management is a big challenge in the developing and thickly populated countries like India. Open dumping of MSW is polluting air, soil, surface and ground water and thus posing a high health and environmental risk. From the available characteristics study of leachate it is found that it contains high BOD, COD, TSS, toxic heavy metals and refractory organic substances. Kolkata also receives considerable amount of rainfall and so undoubtedly huge amount of polluted leachate is generated from the open dumping ground at Dhapa, situated at the eastern fringe of the city. As there is no liner or leachate collection or treatment, it is contaminating the surface and ground water.

There has been some work on estimation of leachate generation by different methods (like WBM and HELP model) all over the world and in very limited places in India. Further some light has to be thrown on leachate transport through the subsurface strata and its ability to contaminate ground water because still it is a major source of drinking water all over India. Thus as all over the country numerous open dumpsites exists, which pose threat to the precious surface and ground water. So a detailed study should be done to estimate leachate generation and it's adverse effects to bring out preventive solutions. Leachate constituent fate and transport model like EPACMTP has been used in some places around the world. But no such study exists for Kolkata and so it demands some detailed study for the existing scenario and to provide future solutions.

2.11 LANDFILL GAS GENERATION AND ENERGY RECOVERY

Solid waste placed in the landfills undergoes a number of simultaneous and interrelated biological, chemical and physical changes. Organic waste decomposition leads to the production of landfill gas (LFG) mainly consisting of methane (CH_4) and carbon dioxide (CO_2). According to Falzon, 1997, methane production in landfills typically begins 6 to 12 months after waste placement, then rises to a maximum shortly after landfill closure and finally gradually declines over a period of 30-50 years. Now, it is of common understanding that LFG should be considered either as a significant source of pollution and risk if migrating uncontrollably to the air and ground, or as a potential environment-friendly renewable power source (Pembina Institute, 2003). One ton of household waste has a methane gas production potential of 180 to

250 cubic meters over a period of 15 to 20 years (Thompson and Tanapat, 2004; Tanapat et al., 2003). There are two possible solutions for dealing with LFG emissions. In case of low methane ratios, LFG should be extracted and flared or oxidized in biofilters. On the other hand, in case of high methane content, LFG evidently becomes a valuable energy source, as it can be used to fuel engines producing electricity or generate thermal energy. More specifically, it can be used as a supplementary or primary fuel to increase the production of electricity, as a pipeline quality gas and vehicle fuel, or even for supply of heat and carbon dioxide for greenhouses and various industrial processes. Reported technologies that utilize LFG include internal combustion (IC) engines, gas turbines, fuel cells and boiler systems (Tsatsarelis et al., 2006a; Tsatsarelis et al., 2006b). However, use of landfill gas may not be practical in all situations because of (i) high impurities: H_2S in landfill gas, cause corrosion in IC engine, (ii) low gas production rate from landfills, (iii) less organic content in landfills, (iv) high investment cost, (v) lack of skilled labour.

Clean development mechanism (CDM) is a project-based mechanism for promoting technology transfer and investment from developed countries to the developing countries to reduce the green house gas (GHG) emissions (UNESCAP, 2003). Global warming is a worldwide problem that will affect both the developed and the less developed nations. Following energy and agriculture, landfill is the third biggest emission source (Goldstein et al., 2007). Landfills are estimated to account for around 13% of the total global anthropogenic methane emission which is equivalent to around 818 million metric tons of CO_2 ($MMtCO_{2}$-eq) (Ahn et al., 2002). According to the estimates from the GHG emission inventory in India in 1998, LFG generated a waste disposal site in India accounts for about 7 to 8% of the GHG emission, being estimated to be 69 $MMtCO_{2}$-eq (KEIP, 2007b). In addition to GHG reductions, the capture and use of landfill gas provides the ancillary benefits of limiting odors, controlling damage to vegetation, risk from explosions, fires and asphyxiation, and smog while providing a potential source of revenue and profit (Smith et al., 2001). Despite these many benefits, landfill gas recovery is essentially an ‘end of pipe’ solution, which does not actively tackle the root cause of waste generation, unlike composting.

In India, there are few cases where LFG is collected and treated because such projects require additional costs and have not been technically spread within the country (KEIP, 2007b). Methane escaping from landfill sites will react with other pollutants in strong sunlight to produce ground level ozone and thereby contribute to photochemical smog (Goldstein et al., 2007). Methane is explosive within the range of 5% to 15% concentration in air (Ahn et al., 2002). In previous decades, the United States environmental protection agency (USEPA) documented at least 40 explosions or fires caused by migrating landfill gas, including 10 accidents causing injuries or deaths. More recent accidents are less common due to better landfill gas management (ATSDR, 2001). More importantly, this methane can travel through porous ground or layers of trash, appearing up to one kilometer away (NREL, 2008).

A landfill methane model is a tool that can be used to estimate methane generation rate, methane oxidation rate and total methane emission from landfill. Methods and models for predicting LFG generation first appeared in the early 1970's. In most of the developing countries the dominant disposal method is open dumping compared to the wide use of engineered landfills (ELF) in the western countries due to lack of finances of the Government, rapid population growth, and increasing urbanization (Visvanathan, 2006; Barton et al., 2008). In India approximately 90% of the generated waste in municipalities and urban areas are dumped in landfills, which have environmental impacts in the form of pollution to soil, ground water, air and contribution to global warming (Chattopadhyay et al., 2007a). In the existing open dump site Dhapa of Kolkata, there is no gas recovery and controlling system, no detailed study has been carried out to know the amount of different gases generated from landfill. If landfill generated gases could be collected or flared it would have positive impact on the environment (Chattopadhyay et al., 2009a). The study of the estimation of methane generation, annual entrapment and its recovery from existing open dump site and proposed engineered landfill with phase wise closure facilities is required. Recovered methane from existing and proposed ELF site can be an alternative environment-friendly renewable source of energy through the systematic recovery and utilization of landfill gas generated during anaerobic decomposition of MSW.

2.11.1 Landfill Gas Generation

Gas production is a function of many variables including physico-chemical composition of waste, environmental variables like pH, temperature, moisture content, nutrients, climate etc, and landfill methodologies. There are two stages in a landfill, its active stage, where MSW is being disposed of and other is its post closure period. The usual composition of landfill gas (% by volume) consists of about 47.7% methane, about 47.7% carbon dioxide, 0.1% carbon monoxide, 0.01% hydrogen sulphide, 0.5% trace components, 3.1% nitrogen, 0.8% oxygen and 0.1% hydrogen (Khan and Ashan, 2000; Tchobanoglous et al., 1993). According to the EPA, methane is 21 to 25 times more efficient at trapping heat than carbon dioxide (CO_2). Nitrous oxide (N_2O) is 310 times more efficient than CO_2. Per fluorocarbons (PFCs) and hydro fluorocarbons (HFCs) have anywhere from around 1,000 to 10,000 times more potential than CO_2 (Ewall, 1999).

In many landfills, the available moisture is insufficient to allow for the complete conversion of the biodegradable organic constituents in the MSW. The optimum moisture content for the conversion of the biodegradable organic matter in MSW is of the order 50 to 60%. Also in many landfills, the moisture that is present is not uniformly distributed. When the moisture content of the landfill is limited, the gas production curve is more flat and extends over a longer period of time. The production of landfill gas over extended periods of time is of great importance with respect to the management strategy to be adopted for post closure maintenance (Tchobanoglous et al., 1993). The gas production from the anaerobic decomposition of the rapidly biodegradable waste (RBW) vary from five years or less (some highly biodegradable wastes are decomposed within days of being placed in a landfill) and the same for slowly biodegradable waste (SBW) in MSW vary from 5 to 50 years. Following closure, a landfill continues to emit GHG, possibly for several hundreds of years (Borjesson et al., 2004). Since in India, MSW contains more rapidly bio-degradable waste (RBW) and high moisture (~50%), therefore, after closure, effective gas generation period between 15 to 50 years can be considered.

Landfill operators, energy recovery project owners and energy users need to assess the volume of gas produced and recovered over time from a landfill. Recovery and energy equipment sizing, project economics, and potential energy uses depend on the peak and cumulative landfill gas yield. The composition of the gas (percent methane, moisture content) is also important to energy producers and users. Proper landfill management can enhance both yield and quality of gas.

2.11.2 Landfill Gas Lateral Migration and Recovery

Lateral landfill gas migration through soil depends on various factors such as composition of waste, construction of landfills, climate, temperature, permeability and water content of the surrounding unsaturated zone and geological properties of surrounding strata. The methane oxidation is also an important factor. There have been some studies on landfill gas migration in soil and methane oxidation, but most were in temperate zone (Mohsen and Farquhar, 1979).

Boeckx and Cleemput (1996) examined the influences of moisture contents and soil temperature on the methane uptake capacity of the neutral landfill cover soil. Soil moisture contents of 10 to 25% w/w gave a maximum CH_4 oxidation rate. In wet condition, CH_4 consumption is slower because of limited gas diffusion. It is difficult to predict the gas migrating distance as it depends on many factors. Although distances greater than 1,500 m. have been observed, these are exceptional. More typically migration plumes extend for about 150 m.

Collection efficiency is a measure of the ability of the gas collection system to capture generated landfill gas. Since the gas generation rate from landfill cannot be measured directly, therefore it is estimated by mathematical models. Flare station records indicate that approximately 1% of the recovered gas is vented during routine and unscheduled maintenance annually (USEPA, 2004). Gas collection efficiency depends on type of disposal facility, collection system design, extent of collection system covers to waste volume, waste characteristics, collection system operation etc. Several practical factors influence the possibility of capturing the quantity of LFG generated. The most important are (i) LFG losses to the atmosphere through the surface or through lateral gas migration (ii) Pre-closure loss due to decomposition of organic material (iii) Boundary effects causing incomplete anaerobic decomposition of the near surface layer (e.g., air intrusion due to gas extraction) (iv) Other losses such as washout of organic carbon via leachate (Johannessen, 1999). Achievable collection efficiencies for engineered landfill sites and open and controlled dumpsites are ~60-90% and ~30-60% respectively (NEERI, 2006).

Most developed countries have policies that will constrain and potentially reduce future growth in methane emissions from landfills, such as expanded recycling and composting programmes, increased regulatory requirements to capture and combust LFG and improved LFG recovery technologies (USEPA, 2008). However, developing regions in Asia and Eastern Europe are projected to experience steady growth in landfill methane generation because of expanding populations, combined with a trend away from unmanaged open dumps to sanitary landfills with increased anaerobic conditions conducive to methane production (IEA, 2009).

Energy needs to be conserved to protect the environment from drastic changes, to save the depleting resources for future generations. Countries all over the world have started to ponder over a new energy policy with a possibility of having no or limited impact. Power generation from renewable energy sources results low carbon emissions but it needs high capital cost for setting up a plant. Non-renewable energy sources are available in nature only in limited amount in the form of fossil fuels, natural gas, oil and coal. These are apparently cheap, easy to use but cannot be reproduced i.e. leads to resource depletion. These also cause global warming and serious health effect. Out of many forms of renewable energy, landfill gas to energy (LFGE) projects are win-win opportunities that create partnerships within the community, by involving citizens, nonprofit organizations, local governments and industry in sustainable community planning. These projects go hand-in-hand with community and corporate communities and lead to cleaner air, increased use of renewable energy, economic development, improved public welfare and safety, and reductions in GHGs (Goldstein et al., 2007).

2.11.3 Methodology of Gas Emission Estimation

Several models to predict methane emissions originating from landfills have been proposed or are recommended by national governments. Landfill gas models can be broadly classified into zero-order, first-order, second-order, multiphase, or a combination of orders. The most common type of models use single-phase or multiphase first order kinetics that describe the decay of biodegradable waste and the production of methane. Most methane production models are based on MSW. They are therefore not much suitable for situations with lower amounts of organic waste. Emission model validation along with assumptions for extraction efficiency and methane oxidation has been carried out using LFG extraction field-data in most cases. Only two studies (Oonk and Boom, 1995; Huitric and Soni, 1997) have validated models using whole site methane emission measurements. Major uncertainties were introduced due to the differences between the default waste categories in the model and the actual data. The definitions of waste categories can differ between countries. A specific problem with former landfills is that very often the data on waste amounts and waste composition are not available. In that case assumptions have to be made that obviously increases the uncertainty of the estimate.

The EPER Germany, SWANA are zero order models in which CH_4 production rate is assumed to be constant against time. This assumption causes a vivid inaccuracy in the results (Scharff and Jacobs, 2006; SWANA, 1998). First order models have a linear relation with maximum potential of CH_4 production per unit weight of waste as well as exponential relation with decay rate and time. In 1994, a study (Oonk et al., 1994) was performed at several landfills in the Netherlands.

Both first order and multi-phase models showed low mean relative errors in contrast to zero order models. On the basis of this study the Dutch government used the single-phase first order model to calculate national methane emissions from landfills. The Anglo-Welsh Environment Agency prefers Gas Sim, a first order multiphase model, LFG estimation (Scheepers and Van Zanten, 1994). Afvalzorg is also a first order multiphase model and based on Netherlands waste characteristics. LandGEM is recommended by the USEPA and the model is based on US waste composition, inert material and other non-hazardous wastes. It is user friendly in spreadsheet environment (USEPA, 2005). Complex mathematical models like Halvadakis (El-Fadel et al.,1989) which follows the carbon in methane production chain from solid carbon to aqueous carbon, acidogenic and methanogenic biomass carbons, acetate carbon, carbon in CO_2 and then carbon in methane. Model is too difficult to be calibrated and used.

Landfill air emission estimation model (USEPA, 1998), based on first order decay (FOD) reaction, is probably the most widely used model. Output of the model is compare reasonably well with more complex models and recommended by intergovernmental panel on climate change (IPCC) for calculating methane emissions from landfills (IPCC, 1996).

2.12 INTEGRATED SOLID WASTE MANAGEMENT (ISWM)

Proper municipal solid waste management (MSWM) involves the application of the principle of Integrated Solid Waste Management (ISWM) (Beukering et al., 1999; CPHEEO, 2000; ISWA, 2012; Klundert and Anschutz, 1999; UNEP, 2009; UN-HABITAT, 2010; CPHEEO, 2016). ISWM is the application of suitable techniques, technologies and management systems covering all types of solid wastes from all sources to achieve the twin objectives of (a) waste reduction and (b) effective management of waste still produced after waste reduction. ISWM is a comprehensive waste prevention, recycling, processing and disposal program. An effective ISWM system considers how to prevent, recycle, and manage solid waste in ways that most effectively protect human health and the environment. It involves evaluating local needs and conditions, and then selecting and combining the most appropriate waste management activities for those conditions. The major ISWM activities are waste prevention, segregation, recycling and composting, incineration and subsequently disposal in properly designed, constructed, and managed landfills. An effective integrated solid waste management system depends upon the correlation between functional elements (generation, segregation, storage, collection, transportation, processing and disposal) and strategic aspects (social awareness, participation, technology, governance and financial resources). The strategic aspects provide strength to the ISWM system (Gupta and Misra, 2014). With increasing population and changing lifestyles, there is continuous escalation in solid waste generation worldwide and the existing techniques and facilities are ineffective in managing the solid wastes especially in developing countries like India — an easily-implementable and economically feasible ISWM system that can effectively address and manage solid wastes is the need of the hour.

Recognizing this fact, the EPA has developed a national strategy for integrated solid waste management. The intent of this plan is to assist local communities in their decision making by encouraging those strategies that are the most environmentally acceptable. The EPA ISWM strategy suggests that the list of the most to least desirable solid waste management strategies should be (i) reducing the quantity of waste generated (ii) reusing the materials (iii) recycling and recovering the materials (iv) combusting for energy recovery (v) landfilling. That is, when an integrated solid waste management plan is implemented for a community, the first means of attacking the problem should be reducing the waste at the source. The action minimizes the impact of natural resource and energy reserves.

Reuse is the next most desirable activity, but this also has a minimal impact on natural resources and energy. Recycling is the third option, and should be undertaken when most of the waste reduction and reuse options have been implemented. Unfortunately, the EPA confuses recycling with recovery, and groups them together as meaning any technique that result in the diversion of waste. As previously defined, recycling is the collection and processing of the separated waste, ending up as new consumer product e.g. compost. Recovery is the separation of mixed waste, also with the end result of producing new raw materials for industry.

The fourth level of the ISWM plan is solid waste combustion, which really should include all methods of treatment. The idea is to take the solid waste stream and to transform it into a nonpolluting product. The conversion may be by combustion, but other thermal and chemical treatment methods may eventually prove just as effective. Finally, if all of the above techniques have been implemented and/or considered, and there is still waste left over (which there will be), the final solution is landfilling. At this time there really is no alternative to landfilling (except disposal in deep water - which is now illegal), and therefore, every community must develop some landfilling alternative.

While this ISWM strategy is useful, it can lead to problems if taken literally. Communities must balance the above strategies to fit their local needs. All the options have to be juggled and the special conditions integrated into the decision. The economics, history, politics, and aspirations of the community are important in developing the recommendations.

2.13 OPTIMIZED MODEL OF INTEGRATED SOLID WASTE MANAGEMENT

Solid waste management is a multidisciplinary field requiring information about the physical, environmental, social, and economic implications of a SWM system. The ISWM approach is designed to minimise the initial generation of waste through source reduction, then through reusing and recycling to further reduce the volume of materials being sent to processing and landfills, compared to the conventional approach of simply focusing on disposal of solid waste. System analysis, a discipline that harmonises these ISWM strategies provides interdisciplinary support for SWM decision-making.

Anderson (1968) was the first to propose a mathematical model to optimise the waste management system. His LP model considered only waste flows from transfer station to landfill sites and tends to minimise the partial costs involved in a SWM system. Since then, several researchers have developed solid waste management models as decision-support tools for processing technology selection, siting and sizing of waste processing facilities, vehicle or manpower management and overall system optimisation.

Different models of waste planning have been researched and applied in the SWM field in the following decades. The primary considerations involved are cost control, environmental sustainability and waste recycling. The techniques employed include linear programming (Christensen and Haddix, 1974; Fuertes et al. 1974; Jenkins 1982; Jacobs and Everett 1992), mixed integer linear programming i.e. MILP (Badran and El-Haggar 2006; Huang et al. 1997), multi-objective programming (Sushi and Vart 1989; Chang et al. 1996), nonlinear programming (Huang et al. 1995a; 1995b), as well as their hybrids, which involve probability, fuzzy set and inexact analysis (Li and Huang 2009; Huang and Cai 2010; Piresa et al. 2001). Due to complexity of the problem, research reports on nonlinear programming problems for solid waste management are scarce; some exceptions are Or and Curi (1993), Sun et al. (2013). In some of the works (Huang et al. 1995a; 1995b), the nonlinear objective functions are converted into linear functions or simplified into quadratic functions under some adopted conditions and assumptions.

Linear programming is the most basic form of SWM modeling; the objective function is linear and the constraints comprising of equalities and inequalities are linear too. Cost is generally taken as the most appropriate objective function. The downside of LP models are that they may involve too many variables and constraints which affect computational time. In *mixed integer linear programming* models, some of the variables are constrained to be integers. *Inexact analysis* often treats the uncertain parameters as intervals with known lower and upper bounds and unclear distributions. In real-life problems, while the available information is often inadequate and the distribution functions are often unknown, it is generally possible to represent the obtained data with inexact numbers that can be readily used in the inexact programming models. However, traditional binary analysis methods for inexact linear programming and inexact quadratic programming involve unavoidable simplifications and assumptions, which often increased the chance for error in the problem solving process and adversely affected the quality of the results. Moreover, a more complex model often increases error in the solution and often produces less optimal results (Jin et al. 2017).

Daskalopoulos et al. (1998) had developed a MILP model for the management of different MSW streams, taking into account their rates and compositions, as well as their adverse environmental impacts. Using this model, the authors have identified optimal combination of technologies for handling, treatment and disposal of MSW in a more economical and environmental-friendly way. In this model, the optimal MSW flows to different types of treatment alternatives are determined by minimising a linear cost function. Constraints for the objective function are the capacity-constraints of the treatment plants and landfill site. Environmental costs were calculated based on greenhouse gas emissions and their global warming potentials. However, the model does not cover collection and transportation costs, which accounts for nearly 70-80% of total MSW management costs in developing economies.

Badran and El-Hagar (2006) had proposed a MILP model for optimal management of municipal solid waste at Port Said, Egypt. The idea is to choose a combination of collection stations from the possible locations in such a way as to minimise the daily transportation costs from the districts to the “collection stations”, and then from the collection stations to the composting plants and/or landfills. The constraints for the objective function (i.e. cost) are the capacity constraints for collection stations, composting plants and landfills. However, recycling, incineration and RDF plants as well as regulatory and environmental constraints have not been considered in this model.

Najm et al. (2002) had introduced optimisation techniques to design least cost solid waste management systems, considering variety of management processes. Their LP model accounts for solid waste generation rates, composition, collection, transportation, treatment, disposal as well as potential environmental impacts of various MSW management techniques. Environmental costs were determined based on the value that the society places on environmental damage which was assumed equal to the cost of abatement and remediation of potential pollution.

Costi et al. (2004) had proposed a mixed integer, non-linear decision model to plan the municipal solid waste management, defining the refuse flows that have to be sent to recycling /processing/ disposal units, suggesting the optimal number, the types and the siting of the plants. The objective function takes into account all possible economic costs, whereas constraints arise from minimum requirements for recycling, incineration process requirements, sanitary landfill conservation and mass balance. The model has been formulated considering stringent European legislation guidelines for MSW management concerning waste minimisation, recycling, energy and material recovery, and final disposal at landfill. Regulatory, technical and environmental constraints had been comprehensively covered in their model. The authors in their research had included waste flows from RDF-plant and stabilised organic matter treatment plant to incinerator. A very similar type of model was presented by Fiorucci et al. (2003), except that Costi et al. (2004) had incorporated the environmental impacts of solid waste management system as well in their model.

Rathi (2007) had developed a linear programming model to integrate different options and stakeholders involved in MSW management in Mumbai. Different economic and environmental costs associated with MSW management were considered. In the model, the author had taken into account community compost plants, mechanical aerobic compost plants and sanitary landfills as waste processing/disposal options while environmental costs were primarily taken from California Integrated Waste Management Board (1991) literature. Shortcomings in this model include non-consideration of waste-to-energy treatment plants and certain costs taken directly from foreign literature.

Rawal et al. (2012) had divided the study area into zones — each zone has a ward which is the ‘waste centre’ or ‘waste source’. They proposed a VRP (Vehicle Routing Problem) method that first minimised MSW collection vehicle routes. The optimised collection points were further utilised in the development of optimised model formulations. They compared two models — one, integer-linear (IL) programming program, where variables are the number of trucks and the other, mixed integer linear (MIL) program where variables are the amount of waste actually transported. However, in this model, stabilised organic material plant construction and operation cost and environmental costs have been excluded.

Although sufficient literature is available worldwide linking ISWM and operations research, yet not much work has been carried out in India in this field. Again, most of the ISWM mathematical models proposed in developed countries lacks in collection and transportation constraint details, although a major fraction of total SWM budget is spent on this.

From the foregoing discussion it is evident that waste generation is an integral consequence of human civilization and at present era as a result of exponential growth of population and civilization, huge generation of municipal solid waste (MSW) and its improper management, especially in developing countries, has become a life-threaten issue for the society. As the existing conventional MSW management is unable to satisfy the goal of sustainable development, integrated MSW management system is needed to achieve this goal. Thus, for proper implementation of an ISWM system, there is a need to formulate a mathematical model for the SWM of a municipality, taking into account waste generation rates, composition, segregation, transportation modes, recycling, processing techniques, revenues from waste processing — simulating actual waste management as closely as possible — this will help as a decision support tool to select the best-suited, optimised system from various sets of solutions.

3. OBJECTIVE AND THE SCOPE OF THE PRESENT STUDY

Objective of the present study is to develop an integrated MSW management system considering its different components and socio-economic conditions and present optimized sustainable solution of MSW for metropolitan cities in developing countries like India. Kolkata city is considered for the study.

The study envisages to encompass the following aspects:

- Study of different aspects of existing MSW management system of Kolkata city
- Estimation of air and noise pollution from existing transportation sector for MSW management system
- Estimation of Landfill gas generation, CDM benefit and power generation potential from existing MSW management system
- Estimation of landfill leachate generation and its pollution potential from existing MSW disposal ground at Kolkata
- Development of a generic MSW management linear programming (LP) model
- Application of the MSW management LP model for the validation and study of existing MSW management of Kolkata
- Application of the MSW management LP model for the study of proposed integrated MSW management of Kolkata
- Comparison between the existing MSW management system and the proposed integrated MSW management system from model study to achieve optimized cost effective sustainable solution methodology of MSW management system for developing countries like India

Though this study is based on solid waste management, socio-economic conditions and other data of Kolkata city area as an example, yet the municipal solid waste management problem and its solution methodology presented here are quite generic in nature and can be successfully implemented to any city in a developing country.

4. EXISTING SYSTEM OF MUNICIPAL SOLID WASTE MANAGEMENT IN KOLKATA

Management of MSW resulting from rapid urbanization has become a serious concern for Kolkata Municipal Corporation. It is a multi-disciplinary approach for embracing the waste collection, transfer, haulage and disposal and its impact is wide. Figure 4.1 shows the location of wards, boroughs, KMC head quarter, garages and dhapa disposal site in Kolkata.

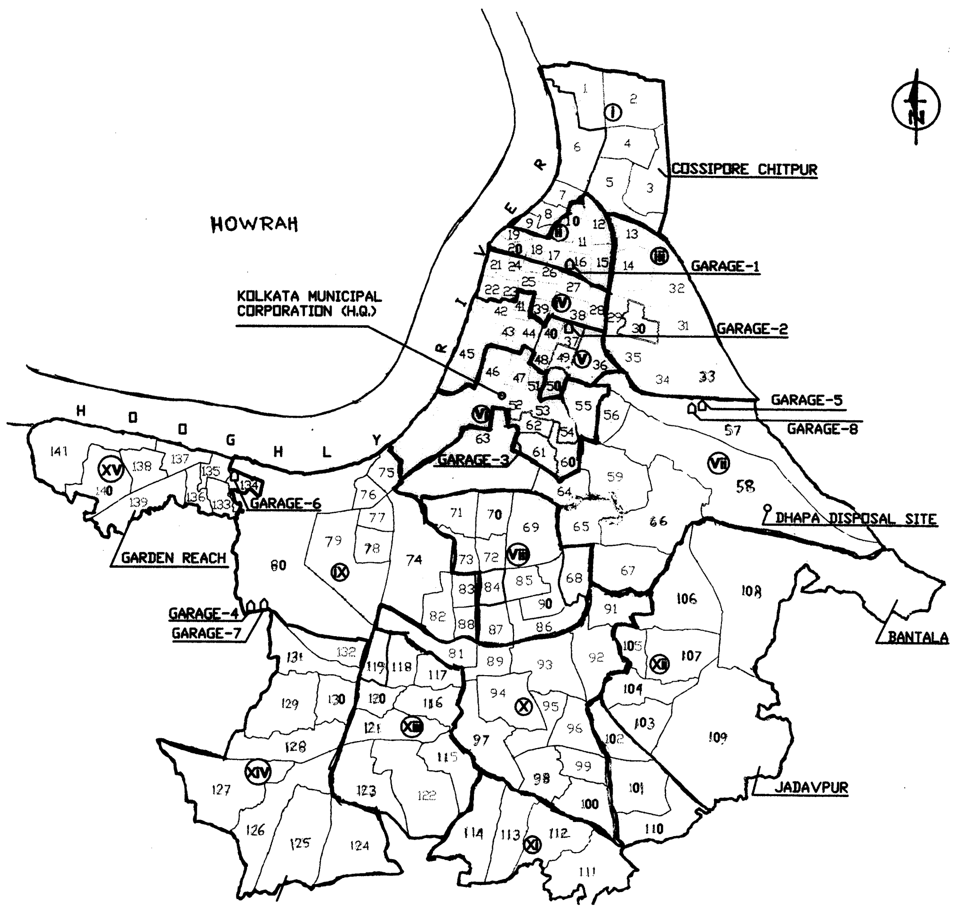


Figure 4.1 Map shows location of wards, boroughs, KMC (Head Quarter), garages and Dhapa disposal site in Kolkata

Kolkata of about 187.33 sq.km KMC area comprising of 15 Boroughs and 141 electoral wards, has 9 million total population including floating population of approximately 3.4 million and population living in slum and urban poor is about 20,00,000 having waste generation @ 470 gm/capita/day for resident population and 250 gm/capita/day for floating population. Cluster wise population data as per Census 2001 as well as projected population upto 2035 for Kolkata city is given in Annexure 4.1. The total MSW generation is about 3000 MT/day, in which ~90% is garbage and ~10% is inorganic silt or rubbish (Chattopadhyay et al., 2007 b).

4.1 PHYSICAL AND CHEMICAL CHARACERISTICS OF CITY GARBAGE

The analysis of garbage is carried out normally to know its physical as well as chemical characteristics. Refuse characteristics depend upon a number of factors such as food habits, cultural traditions, socio-economic factors and climatic conditions. Refuse characteristics vary not only from city to city but even within the same city itself and also seasonally. In Kolkata as well as in India stratified random sampling method is very difficult because of the complexity in accurately dividing the population ratio various socio economic groups. Therefore, quartering method may be suitable in India as well as in Kolkata (NEERI, 1995). The physical and chemical characteristics enable us to decide the desired frequency of collection, precautions to beataken during its transportation and method of processing and disposal. Table 4.1 shows variation of physical composition of garbage of MSW at Kolkata during 1970, 1995 and 2005.

Table 4.1 Variation in garbage composition at Kolkata during 1970, 1995 & 2005

Sl. No.	Parameters	1970	1995	2005
1	Biodegradable	40.36	44.29	50.56
2	Green coconut shells	4.95	8.51	4.5
3	Paper	3.17	4.64	6.07
4	Plastics	0.64	3.22	4.88
5	Metals	0.66	0.43	0.19
6	Glass & Crockery	0.38	1.72	0.34
7	Coal	6.08	3.10	-
8	Inert	40.76	26.82	29.6
9	Others*	3.00	7.27	3.86

All values are in percent by wet weight * Bio-resistant and synthetic material

Average biodegradable fraction is higher than the biodegradable fraction is found in the year 1970 and 1995. Since the refuse has high organic fraction it is suggested that the same may be composted as organic manure to be used for agricultural purposes. The above comparison also reveals that day to day use of plastic and paper are increasing. Moreover, use of coal is decreasing as mainly utilization of domestic gas increased. Table 4.2 shows variation of chemical composition of garbage of MSW at Kolkata during 1970, 1995 and 2005.

Table 4.2 Variations of garbage composition (Chemical Parameters) at Kolkata during 1970, 1995 and 2005

Sl. No.	Parameters	1970	1995	2005
1	Moisture	42.84	61.57	46
2	pH	7.31	6.33	0.3 – 8.07
3	Loss of Ignition	35.24	46.78	38.53
4	Carbon	19.58	25.98	22.35
5	Nitrogen as N	0.55	0.88	0.76
6	Phosphorous as P_2O_5	0.57	0.58	0.77
7	Potassium as K_2O	0.40	0.93	0.52
8	C/N Ratio	35.60	29.53	31.81
9	Calorific Value Kcal/kg	549.32	648.91	1201

All values are in percent by dry weight basis except pH and Calorific Value.

From comparative study of chemical composition it is seen that the value of moisture content increased during 2005 which is probably due to presence of higher proportion of fresh and unprocessed vegetable wastes. Though the calorific value has doubled during the year 2005 but it is still not suitable for incineration. The C/N ratio has increased and is ideal initial ratio for composting (CPHEEO, 2000).

The physical composition and characterization of Kolkata garbage is presented in Table 4.3; from these tables, composition of recyclable materials is computed as shown in Table 4.4.

Table 4.3 Average physical composition of garbage in KMC area

Total Compos-tables	Recyclables				Others including Inert						Total
	Paper	Plastic	Glass	Metal	Inert	Rubber and Leather	Rags	Wooden matter	Coconut	Bones	
50.56	6.07	4.88	0.34	0.19	29.60	0.68	1.87	1.15	4.50	0.16	100.00
50.56	11.48				37.96						100.00

(All values are expressed in percentage on wet weight basis)

Table 4.4 Proportion of recyclable materials in garbage in Kolkata at present

	Materials					Total
	Paper	Plastic	Glass	Metal	Rubber & leather	
Original Composition	6.07[@]	4.88	0.34	0.19	0.68	12.16
Recyclable portion at source and at landfill site	5.00 (82%)	3.38 (70%)	0.27 (80%)	0.15 (80%)	0.41 (60%)	9.21[*]

[*]Out of this 9.21%, about 5% is recycled at household level and 4.21% is recycled by ragpickers in the existing system

The schematic diagram of existing garbage management system is shown in Figure 4.2.

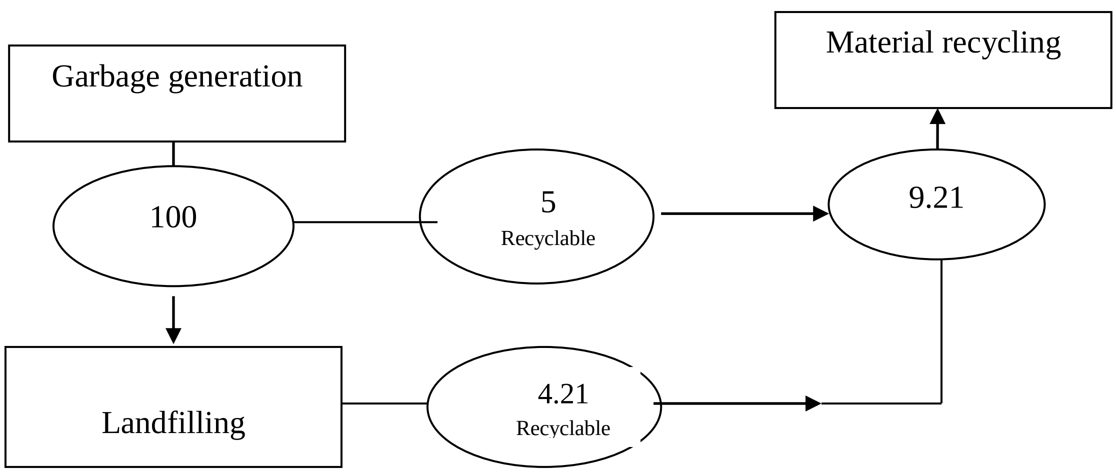


Figure 4.2 Materials flowchart for existing MSW (garbage) management system

Existing municipal solid waste management system is basically open dumping of waste without any liner and gas collection system. Around 5% recyclables of the garbage is taken out by the informal rag pickers at the household, container and vat points level. If 5 to 6% of irregular garbage transformation to compost is ignored, rest 95% of the garbage is reaching to the dumping ground, Dhapa. At Dhapa informal rag pickers further segregated out around 4.21% recyclable. So total recovered recyclable is around 9.21% and rest of the garbage is disposed in the landfill along with silt or rubbish.

4.2 COLLECTION, STORAGE AND TRANSPORTATION

4.2.1 Collection and Storage

The collection, transportation and disposal of MSW are the most pressing problems of the city today. As such, it comprises an extremely complex set of operations, which has to take place on an enormous scale. It is a general situation that household wastes are tipped haphazardly in and around the roadside dustbins. Apart from the unaesthetic consideration of such a system the major disadvantage is that the inadvertent mixing of various fractions of urban solid waste leave little scope for effective recovery of recyclable and removal and transport of problematic fermentable. However in Kolkata the major constituent of domestic waste (garbage) is on an average 1775 MT, market and commercial waste (garbage) 941 MT and silt and debris 231 MT (Chattopadhyay et al., 2007b). Waste generation is 2947 MT/d and may be considered approximately 3000 MT/d. Cluster wise solid waste generation- Cluster – I (Borough I to IX)-Av. 790 gpcd (623.97 to 1235.97 gpcd) and Cluster - II (Borough X to XV)-Av. 360 gpcd (262.80 to 523.91 gpcd). The field staffs commence their work at 5 am and continue till 12.00 noon with a break of half an hour in between.

- Street sweeping and cleaning: After the first mastering, conservancy workers carry out sweeping and cleaning of roads and pavements and there after remove the collected garbage to the assigned vat or containers. This task is completed by about 7.30 am.
- Residential, commercial, slums and office complexes: 7.30 am onwards the conservancy workers move on to their assigned areas with their hand carts giving whistle signal, calling the residents to bring their garbage. This process continues till 10.30 Am. Garbage thus collected is taken to the nearest vat or container from where vehicles pick up the garbage and transport the same to the disposal ground. Presently this process of "House-to-House" collection facilities of garbage is available in 141 wards. On an average "House-to-House" collection covers around 60% of the houses. The main difficulty is in the commercial areas where it is difficult to enforce discipline.
- Big hotels and restaurants have their own vat, collected and transported regularly by KMC or Private vehicles on charge basis. Other dispose their waste on the road or nearby vat by KMC or own sweeper. In case of own market vat wastes are collected regularly. In

roadside or unauthorized market, the waste is dumped on the road and collected by KMC street sweeper.

As the implementation of KEIP project is going on, the scenario of collection points is changing from time to time. Emphasis has given towards containerized system. At present total collection points are around 650, having 365 containers, 20 DL and 265 vat points i.e., 55% Container; 45% Vat and others. Collected waste is transported directly to the dumping ground at Dhapa by both private own vehicles and departmental (KMC) vehicles. As the existing dumping ground is about 10 KM distance from the centre of the city so at present KMC does not have any transfer station. However, to improve the collection efficiency and transportation system in Kolkata city, KMC has piloted the use of stationary compactors (10.5 Cu.M) and movable compactors (14 Cu.M) for secondary waste collection. The stationary compactors, when coupled with hook loaders, provide high transport efficiency for waste. In order to synchronize the system with the existing primary collection system, the stationary compactors are installed with a tip cart mechanism. The tip cart mechanism proved to be flexible for manual feeding, wheel barrow feeding and feeding by small battery operated hydraulic dumpers.

4.2.2 Experiences on Segregation Scheme

Pilot scheme for segregation of waste at sources covering domestic as well as commercial area was launched in the year 1999 for the ward no. 7, 8, 22, 23, 32, 42, 59, 65, 68, 69, 81, 82, 83, 86, 87, 90, 91, 92, 93 and 95 but failed due to neither authorization letters were issued to the NGOs, most of the residents did not pay the charges to NGOs engaged for the services, role of KMC sweepers and NGOs staff was not well defined etc. The Indian Plastic Federation in association with KMC, West Bengal Pollution Control Board (WBPCB), and others was tried to launch a Waste to Wealth project in the city to divert waste plastic materials at source to recycling units considering that the residents would be paid to dispose plastic in the same way they would be paid to dispose other substances like newspapers, bottles and cans. The project has not yet been implemented. Based on the past experience, KMC has again introduced the pilot project in 7 wards (Wards 33, 47, 64, 103, 110, 115 and 130) and the rest wards are to be covered up gradually.

4.2.3 Transportation

Currently private owned manually loaded trucks transport all silt or rubbish and 60% (approx.) of daily-generated garbage. For remaining 40% garbage, carried by departmental (KMC) vehicles, four types are in vogue - manual loaded vehicles, pay loader vehicles and two types of containerized vehicles. There are 5 main vehicle garages and three subsidiary garages from where conservancy vehicles operate to transport garbage from their assigned areas to the disposal ground (Figure 4.1). One of the garages is a specialized one dealing all heavy earth moving equipment viz. pay loaders and bulldozers and their associated vehicles. All the garages are equipped with repair and maintenance facilities like washing, servicing, fueling, petty store, small machine shops etc.

During implementation of KEIP project the status of departmental solid waste carrying vehicles and landfill operation equipments has modified. Emphasis has given towards replacement of older vehicles by new vehicles. At present total Departmental waste carrying vehicles ~ 200; Dozer - 3 operating, 2 procured; Pay Loader - 10 operating, 3 procured. Average daily no. of vehicles used: 105 (Dept.) and 205 (Hired).

4.2.4 Deficiencies in the Present Collection, Storage and Transportation System

(i) At present there is no source segregation system in KMC area.

(ii) House-to-house collection covers 60% area.

(iii) About 50 – 55% of collection points are in the form of open vat (Masonry or RCC) and the waste is lifted daily. However no. of collection points remains in bad condition due to lack of awareness, citizen dropping the waste haphazardly at the collection point after the clearance is done.

(iv) Dumper placer containers and KMC vehicles are not washed daily or periodically even once in a week. This results in heavy corrosion giving ugly appearance and reduced life.

(v) 30 to 35% of KMC vehicles are more than 7 years old. The operational efficiency is just above 50%.

(vi) Fuel consumption is not monitored as kilometer-reading meters of all vehicles are damaged and fuel is issued on trip basis, which is very high.

(vii) In newly added areas (Borough XI – XV) under KMC jurisdiction, as still some open space is there, large quantity of waste is disposed off in open canal and drains or dumped into low-lying areas instead of collecting and transporting to Dhapa waste disposal site.

(viii) Compactors do not receive the silt or rubbish, tree branches etc and hence requires separate storage facilities.

(ix) In case of breakdown of the machines and electrical failure collection system totally hangs up.

(x) Since compactor receives mixed waste therefore, recyclable materials cannot be segregated and reused after compaction.

4.3 TREATMENT AND DISPOSAL OF MUNICIPAL SOLID WASTE

4.3.1 Treatment (Composting)

Initially mechanized compost plant of 700 TPD capacities was installed by KMC in collaboration with M/S Eastern Organic Fertilizers (India) Pvt. Ltd. with a technical back up of M/S Excel Industries Pvt. Ltd. At present the plant operation is done by M/s Eastern Organic Fertilizers (India) Pvt. Ltd. with capacities of 500 TPD. The existing compost plant of KMC is located at Dhapa and 'Windrow method' is used for processing of compost.

4.3.2 Deficiencies in the Existing Compost Plant

Mechanized compost plant of 700 TPD capacity started functioning from April 2000. But it is not fully functional since 2003 due to mixed waste with high inert content (though having organic content ~50%) and the problem of marketing of the compost. At present it processes ~150 TPD garbage during non-monsoon period.

4.3.3 Disposal

About 95% of the waste in the world is land filled or dumped into a hole in land or directly on the riverbanks or into the sea. Due to many technical and economic reasons, landfill will remain the most suitable option for most countries. Crude dumping is mostly followed in India and other developing countries especially in small and medium-size cities. In Kolkata the major disposal ground Dhapa is in the eastern fringe of the city with an average distance of 10 km from the collection points. Total area of the Dhapa landfill site is 21.4 ha. As it is almost exhausted, additional 13.6 ha. has been acquired. One of the severe problems associated with the open dumps is infiltration of leachate into the surrounding environment and subsequent contamination of the land and water. Three bulldozers are deployed daily at the disposal ground for spreading and leveling the garbage and silt. Computerized weighbridges of five 30T capacities have been installed for checking and recording of weights. Fig. 4.3 shows the monthly MSW disposal at Dhapa landfill site for 2000 to 2007.

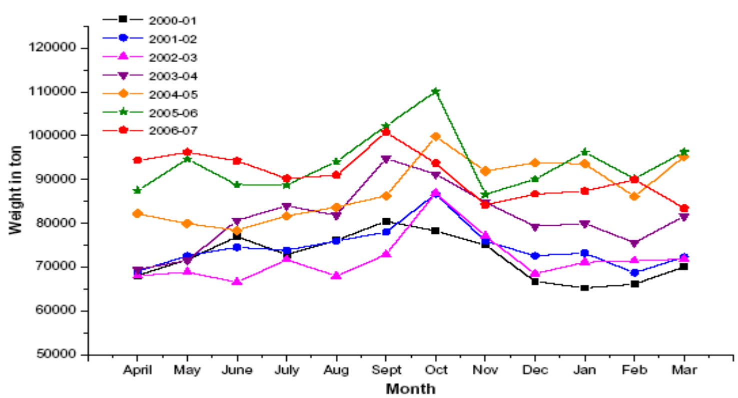


Figure 4.3 Monthly municipal solid waste disposal records from 2000 to 2007

4.3.4 Soil Reclamation Potential at Dhapa Landfill

Landfill reclamation, commonly referred to as landfill mining, has been gaining some popularity in the past few years as a means of expanding landfill capacity and avoiding the high cost of acquiring additional land or developing new sites. The U.S.EPA has reported that reclamation projects have been successfully implemented at municipal landfills across the United States since 1980s (KEIP, 2007b). Experience also exists in other countries such as the Netherlands, Canada and the UK to name a few (KEIP, 2007b). Despite the success of many programs landfill reclamation is considered a relatively new approach to managing landfill capacity and no comprehensive database is readily available in India. Three locations were selected to carry out test pit mining with a view to extracting and analyzing decomposed landfilled material for the purpose of determining the suitability of this material for use as landfill cover. The locations were selected where waste had not been deposited for a number of years (around 15 years) and the organic fraction were believed to be sufficiently decomposed to potentially fit for recovery of the residual soil. Results from the geotechnical laboratory analysis of representative samples of material passing through the 50 mm screen, reveals that this waste is not suitable as a low permeability final cover which is used for final closure. Rather this material would be more suited as a growing medium for the cover's vegetative layer including the stabilization of slides slopes. As a daily cover the material would be suitable in dry weather but may be very soft during wet conditions due to the high silt content. A sandier material would be more preferable.

4.3.5 Waste to Energy (WTE) Project

In a feasibility study of WTE project with MSW of Kolkata, Mass Burn technology has been considered rather than advanced costly systems like gasification, pyrolysis, plasma etc. and RDF due to non-availability of local market (KEIP, 2007a). For Mass Burn system three options have been considered – (i) for maximum waste throughput; (ii) for a selected high calorific value waste stream; and (iii) for selected waste after implementation of new infrastructure.

It is not feasible financially to burn the MSW generated in Kolkata in its current composition for energy recovery. A tipping fee or other form of financial support in the order of Rs 5200 per MT plus profits and contingencies would be required (KEIP, 2007a). The most attractive option financially is for WTE to be part of a fully integrated system, and receive waste that has been sorted or preprocessed, so that the waste is dry and has a high heating value. In this case, a tipping fee or financial support of about Rs 3900 per MT would be required (plus profit and contingencies) (KEIP, 2007a). It can be concluded from the above that WTE does not appear to be feasible as a waste reduction technology at this time either for a large scale mixed MSW facility or for a smaller scale, selected waste facility. Therefore, waste to energy is not considered as a waste treatment and reduction option at this time.

4.3.6 Clean Development Mechanism (CDM) Opportunities

It may be assumed that 50% of the methane generated is recovered by a future landfill gas (LFG) collection system (i.e., collection efficiency of 50%). Utilization or flaring of methane is an attractive option for reduction of GHG, i.e. getting benefit of CDM. Since the estimated landfill gas generation and recovery are heavily dependent on the condition of the existing landfill at Dhapa, detailed assessment of LFG generation, collection and flaring system are essential to know the degree of certainty regarding economic benefits accruing due to greenhouse gas emission reductions.

Energy recovery by utilizing the landfill gas generation from existing disposal site and proposed engineered landfill site is studied.

4.3.7 Deficiencies in the Present Disposal System

(i) Maximum safe life of Dhapa disposal site is less than a year if the land presently occupied by unauthorized cultivators is not taken over and developed for Engineering Landfill.

(ii) The method of operation of Dhapa waste disposal site is uncontrolled without providing earth cover, liner and leachate collection and treatment.

(iii) Not many studies have been carried out to determine the effect of landfill operations on the surrounding environment and ground water. No Environmental Impact Assessment studies have been carried out by KMC.

(iv) Rag picking carried out at Dhapa site for recycling and reuse of recyclable waste is most unorganized, hazardous and unhygienic way, affecting seriously the health and safety of rag pickers.

4.4 EXISTING RECYCLING SYSTEM

Though totally unorganized, recycling systems are often well established in developing countries. The existing recycling system in India and other developing countries is pointed below:

- Newspapers, old bottles, metals are sold from or reused in households
- Waste pickers sort recyclable or saleable materials from the refuse heaps in containers or vats
- Waste collectors spend 25 – 30% of their time sorting saleable materials from the refuse both at the collection points and disposal ground.
- Communities living in the vicinity of the dumping site or disposal ground scavenge for their lively hood.
- Waste pickers and waste collectors sell the assorted materials to middle man buyers who often perform some simple sorting and cleaning
- Middlemen buyers sell to whole sellers or big dealers and hence back to primary industries.

Table 4.5 gives an indicative list of major items and the prices that the waste pickers commanded for them. Table 4.6 shows pick able items at the Dumping Ground (KEIP, 2007a).

Table 4.5 Rag pickers price list

Items	Market Price / Kilogram
Dry paper	Rs. 3.60
Wet paper	Rs. 1.50
Cardboard/Cartons	Rs. 6.00
Metal	Rs. 5.00
Rubber	Rs. 2.00
Glass	Rs. 3.00
Textiles/Rags	Rs. 3.00
Leather	Rs. 1.50
Rigid plastic	Rs. 12.00
Soft plastic	Rs. 5.00

Table 4.6 Pickable items at the dumping ground

Items	% Availability
Paper	0.9
Cardboard/Cartons	0.3
Metal	0.2
Coconut Shells	1.1
Glass	0.3
Textiles/Rags	0.2
Leather	0.1
Rubber	0.3
Wood	0.2
Rigid plastic	0.3
Soft plastic	0.9

4.5 EXPENDITURE IN SOLID WASTE MANAGEMENT

KMC spends 70.12% to 75.62% of the total budgetary allocation on primary collection of the solid waste, 20.00% to 24.68% on transportation and 4.38% to 6.36% for the final disposal of the solid waste. It is seen that most of the budget allocation is spent for operation and maintenance of primary collection, transportation and disposal system. Very nominal percentage is used for capital expenditure of the three systems. Fig. 4.4, Fig. 4.5 and Fig. 4.6 shows trend of capital expenditure, trend of O & M expenditure and year wise expenditure respectively.

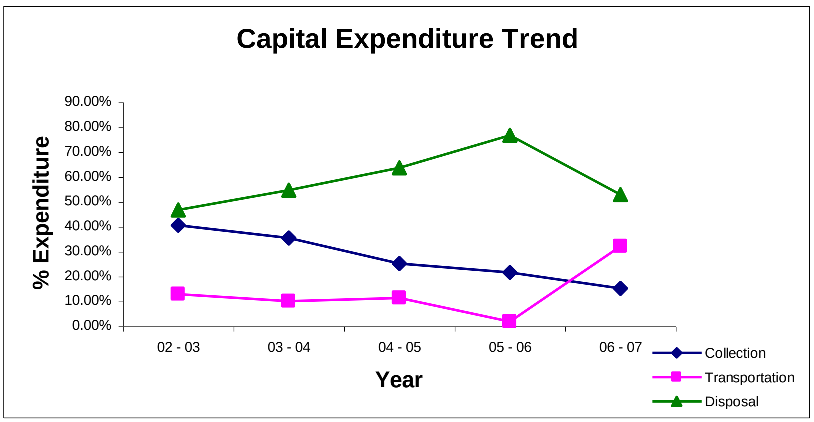


Figure 4.4 Trend of capital expenditure

The percentage of expenditure on collection, transportation and disposal is more or less same throughout the years as operation and maintenance cost dominates the expenditure. So there is almost no reflection of variation of capital expenditure on the total percentage allocation. In near future capital expenditure in treatment and disposal facilities must be increased for sustainable management of MSW in Kolkata.

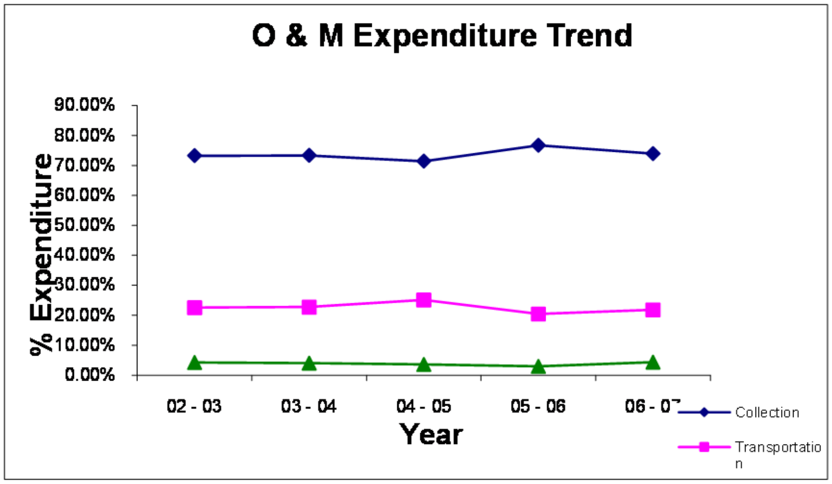


Figure 4.5 Trend of O & M expenditure

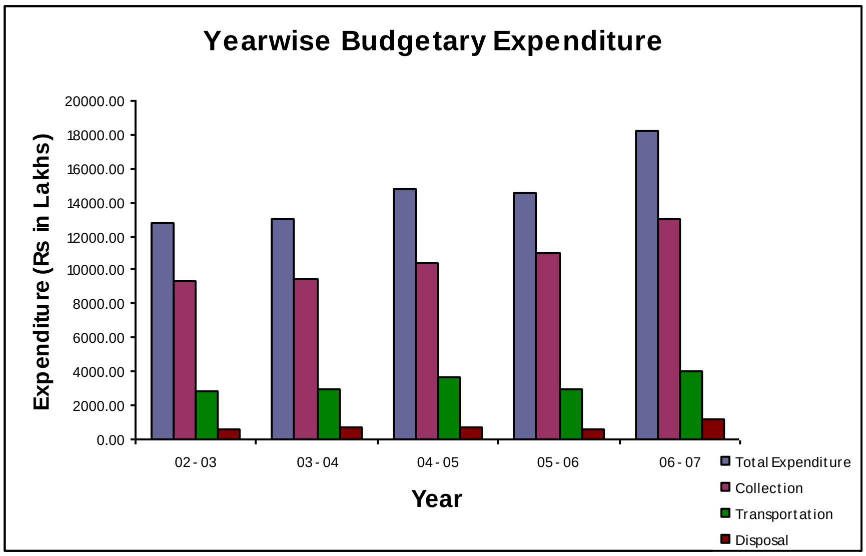


Figure 4.6 Year wise budgetary expenditure

4.6 OBSERVATION ON ABOVE STUDY

The huge generation of MSW in Kolkata has become a life-threaten issue for the society as the urban local bodies, though committed to their services, are finding it difficult to manage properly due to the growing magnitude of problems.

No source segregation, 60% house-to-house collection, 50-55% open vats, 50% operational efficiency of KMC transport system with 30-35% old vehicles, 80% more than 20 years age old hired vehicles, less collection efficiency in newly added areas, informal recycling system are the most pressing problems of the city today. In many of the developing countries like India, uncontrolled land disposal of MSW is a common practice even today. So, the unregulated waste dumps without having liner and leachate management facility cause a number of environmental and human health hazards, the most significant of them being the groundwater contamination. Mechanized compost plant of 700 TPD is practically inoperative since 2003 due to the problem of mixed waste (having high inert content, though contents ~50% organic) and marketing of the compost resulting non-viability of economic operation of the plant. At present it processes ~150 TPD garbage during non-monsoon period. The mixed waste having low calorific value (800 to1000 Kcal /kg) and high inorganic content (30%) is not at all suitable for incineration or WTE project. Though, under Kolkata Environmental Improvement Programme (KEIP) certain modifications and improvement of solid waste management services have been done, but not sufficient enough to mitigate the present and future problem of solid waste management of Kolkata.

With a target of 100% collection, transportation, treatment and disposal, KMC would need to prepare a macro plan first which identifies the quantum of waste generated in the city and the broad strategy to be adopted to manage the system. This is followed by a micro or locality wise plan, which details out the route, timing, equipment and manpower, and how they are to be deployed.

Stresses should be given on the capacity building of the existing solid waste management framework. In collection and transportation sectors emphasis on segregation at house hold level, 100% door-to-door collection, transformation of open vats into closed containerization system, proper management of departmental vehicles, change of old private vehicles to new mechanically operated vehicles are necessary. For processing and disposal - transformation of informal to formal recycling system, construction of new engineered landfill site with liner and leachate collection facilities, enhancement of composting system, CH_4 recovery system for CDM benefit, multiple disposal sites to cope with the rapid expansion of certain areas. In future, Management Information System should have to be incorporated to play a crucial role to make Kolkata solid waste management system sustainable.

4.7 AIR POLLUTION FROM TRANSPORTATION SECTOR

The purpose of this study is to assess the gaseous pollutants generation from transportation sector of MSW management of Kolkata for better urban planning keeping in mind minimization of air pollution from it. Average 3000 MT/day of wastes are transported from the city, to the landfill sites, situated at the outskirts of the city. Waste transportation is a major part of MSW management and this generates a large amount of pollution in the urban atmosphere. Carbon monoxide, particulate matter, NO_X and hydrocarbon emissions from motor vehicles are of increasing concern and probably present the greatest long-term threat to air quality of Kolkata. Motor vehicle population in Kolkata doubles in every six years. With this rate of growth it is unlikely that even the introduction of the most stringent control measures would reduce overall emissions and ambient concentrations from this source. Therefore, urban management plan must include traffic as well as pollution management plans optimizing the routing for sustainable development.

4.7.1 Distance from Borough Center to Disposal Site

There are five main vehicle garages and three subsidiary garages from where conservancy vehicles operate to transport garbage from their assigned areas to the disposal ground at Dhapa. Average distances from borough centre to Dhapa are shown in Table 4.7. It is located at the eastern fringe of the city in ward 58 of borough 7.

Table 4.7 Average distance from borough to Dhapa (KEIP, 2005)

Borough	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
Distance (KM)	9	7.5	5	7.5	7	7	3.5	6.5	9.5	7	8	3	10	11.5	13.5

4.7.2 Basis and Steps of Estimating Different Parameters

4.7.2.1 Garage Wise Availability of Different Types of Departmental Vehicles and their Daily Trips

(1) Identification of different types of vehicle availability (total and in operation) in different garages;

(2) Calculation of average weight carried by each type of vehicles and their fuel consumption.

4.7.2.2 Calculation of Borough Wise Total Distance Covered by the Each Type of Departmental and the Private Vehicles and Their Fuel Requirements

(1) Calculation of total waste generation in different boroughs (kg/day) from recorded KMC data at disposal ground;
(2) Borough wise waste carried by each type of departmental vehicles and private vehicles;
(3) Calculation of total distance covered by each type of vehicles with its average weight carrying capacity, numbers of trips / day and distance of borough centre to disposal ground, Dhapa (km);
(4) Fuel requirement is estimated from its distance wise fuel consumption (loaded and unloaded conditions) and total distance covered.

4.7.2.3 Calculations of Weighted Average of Pollutants (CO, NOx, HC, PM, Benz, Butdn Etc) Emission Factor of the Vehicles and Estimation of Pollutants Emission from them

(1) Identification of year wise vehicular status from KMC data and emission factors of different pollutants (CPCB data);
(2) Calculation of weighted average of pollutant emission factors for each type of vehicles (gm/km);
(3) Estimation of pollutants emission from the weighted average of emission factors and distance covered.

4.7.2.4 Calculation for CO_2 and SO_2 Emission from the Departmental and Private Vehicles

(1) CO_2 generation is calculated from fuel consumption, its carbon % and utilization of carbon as CO;

(2) SO_2 emission is calculated from fuel consumption, its sulphur %.

4.7.3 Garage Wise Vehicle Status in MSW Transportation System

KMC owned vehicles (departmental) and private vehicles carry solid waste for disposal to Dhapa. Eight garages are there for stationing the departmental vehicles (Table 4.8). Though these garages station other types of vehicles also but only the MSW carrying vehicles are considered for calculation of pollutant emissions. Around 50% of departmental vehicles are more than 10 years old. Through KEIP, new dumper placers have been procured to make the system containerized as per MSW (Management and Handling) Rule 2000. In the existing system a considerable number of old hand loaded vehicles still exist for quick removal of solid waste. Old age vehicles and inadequate man power leads to around 50% operational efficiency.

Table 4.8 Garage wise vehicle (departmental) status of existing MSW transportation system

Garage	Vehicle type	No. of vehicles available	Average no. of vehicles in operation
Dist I	Dumper Placer (big)	20	8
	Dumper placer (small)	1	1
	Hand Loaded Tipper Truck	18	10
	Pay Loaded Tipper Truck	1	1
Dist II	Dumper placer (big)	13	6
	Hand Loaded Tipper Truck	17	10
Dist III	Dumper placer (big)	17	8
	Hand Loaded Tipper Truck	12	10
	Pay Loaded Tipper Truck	1	1
Dist IV	Dumper placer (big)	18	9
	Hand Loaded Tipper Truck	17	10
Dist V	Dumper placer (big)	5	3
	Hand Loaded Tipper Truck	5	5
	Pay Loaded Tipper Truck	26	10
Dist VI	Hand Loaded Tipper Truck	5	2
Dist VII	Dumper placer (small)	7	4
	Hand Loaded Tipper Truck	4	4
Dist VIII	Dumper placer (small)	8	4
	Hand Loaded Tipper Truck	4	3

Table 4.9 shows the average weight carrying capacity per trip and fuel (diesel) consumption of departmental and private vehicles. Kilometer-reading meters of most of the old departmental vehicles are damaged and fuel is issued on trip basis, which is very high. Most of the hired vehicles are also very old and their fuel consumption is considered as that of tipper truck.

Table 4.9 Average weight carrying capacity and fuel consumption of departmental and private vehicles

Type of vehicle	Average weight carrying capacity in MT/trip	Fuel consumption in km/l
4.5 m^3 Dumper Placer (D.P.) (small)	2.0	4.875
7.0 m^3 Dumper Placer (D.P.) (big)	2.8	4.0
8.00 m^3 Hand Loaded Tipper Truck (H.L.)	4.0	3.85
11 m^3 Pay Loaded Tipper Truck (P.L.)	7.0	2.0
Open Truck (Private/Hired)	4.8	3.75

Table 4.10 shows borough wise total weight carried and distance covered by each type of departmental and private vehicles. Total weight carried by departmental and private vehicles is 40 % and 60 % but distance covered is ~60 % and 40 % respectively. In case of departmental vehicles with respect to weight, distance running is more (ref. Fig.4.1) as dumper placers carry less amount of weight per trip due to the capacity constraint of the containers. Dumper placers, small and big, actually carry 1.75 MT/trip and 2 MT/trip respectively which is less than their average carrying capacity of 2 MT/trip and 2.8 MT/trip depending upon the filling up of the containers. The Hand Loaded Tipper Truck also actually carries around 3 MT/trip instead of its carrying capacity of 4 MT/trip. Though it is a concern of more fuel consumption vis-à-vis greater pollution generation, yet daily clearance with containerized system is essential for efficient solid waste management. Detail calculation of borough wise emission status of departmental vehicle is given in Annexure 4.2.

Table 4.10 Borough wise MSW transportation status

Br No.	Departmental Vehicle						Private Vehicle (Open Truck)	
	Types of vehicle	Total waste carried (MT)	Actual wt. %	Actual wt. (MT)	No. of trips/day	Tot. dist cov.(km)	Actual wt.(MT) and wt.%	Tot. dist cov. by truck(km)
1	D.P.(big)	124.17	20.93	41.56	20.78	374.04	74.38	278.91
	D.P.(small)		0.59	1.17	0.66	12.00	(37.46 %)	
	H.L.		28.14	55.87	18.62	335.16		
	P.L.		12.88	25.57	3.65	65.74		
2	D.P(big)	84.67	27.75	51.93	25.96	389.45	102.48	320.26
	H.L		17.49	32.74	10.91	163.78	(54.76 %)	
3	D.P.(big)	121.74	33.03	65.95	32.97	329.73	77.83	162.15
	D.P.(small)		2.12	4.24	2.42	24.21	(39.02 %)	
	H.L.		25.83	51.56	17.19	171.87		
4	D.P.(big)	93.58	40.50	68.42	34.21	513.15	75.37	235.53
	H.L.		14.88	25.16	8.39	125.80	(44.62 %)	
5	D.P(big)	100.01	5.23	10.75	5.38	75.26	105.61	308.01
	H.L		6.01	12.36	4.12	57.68	(51.60 %)	
	P.L		37.16	76.41	10.92	152.82		
6	D.P.(big)	76.20	10.82	29.16	14.58	204.09	193.16	563.39
	H.L.		12.02	32.37	10.79	151.06	(71.72 %)	
	P.L.		5.44	14.67	2.09	29.34		
7	D.P.(big)	87.57	7.58	23.04	11.52	80.64	358.90	315.72
	H.L.		3.29	10.02	3.34	23.38	(71.21 %)	
	P.L.		17.92	54.50	7.78	54.50		
8	D.P.(big)	86.80	30.37	60.90	30.45	395.86	113.67	307.85
	H.L.		12.92	25.90	8.63	112.23	(56.71 %)	
9	D.P.(big)	124.94	20.16	58.84	29.42	558.98	166.98	660.95
	H.L.		22.64	66.09	22.03	418.57	(57.20 %)	
10	D.P.(big)	76.44	20.78	76.43	38.22	535.01	291.40	849.93
11	D.P.(small)	62.20	58.19	56.60	32.34	517.47	35.06	116.87
	H.L.		5.76	5.60	1.87	29.87	(36.05 %)	
12	D.P.(small)	58.96	59.45	51.00	29.14	174.86	26.83	33.53
	H.L.		9.27	7.96	2.65	15.92	(31.28 %)	
13	D.P.(small)	71.04	33.98	54.70	31.26	625.14	89.94	374.75
	H.L.		10.15	16.34	5.45	108.93	(55.87 %)	
14	D.P.(small)	55.79	22.33	30.96	17.69	406.94	82.85	397.00
	H.L.		17.91	24.83	8.28	190.36	(59.76 %)	
15	H.L.	0.03	0.14	0.03	0.01	0.27	22.21	124.93

4.7.4 Total Emission of Pollutants from Departmental and Private Vehicles

Average age of the four types of departmental vehicles is shown in Table 4.11. In case of private vehicles 50% vehicles are estimated to be within 1991-1995 and the rest are within 1996-2000. As per order of the Honourable High Court at Kolkata, commercial vehicles, more than 15 years old, are being gradually phased out or converted to Bharat Stage III compliant from September, 2009. In compliance with the court order the present status of private vehicle change till recently is 30% in the range of year 1996-2000; 40% in the range of 2001-2005 and rest 30% in the range of 2006-2010.

Table 4.11 Year wise distribution of the departmental vehicles

Year	No. of departmental vehicles			
	D.P. (Big)	**D.P. (Small)**	**Hand Load**	**Pay Loader**
1986-1990	0	1	32	0
1991-1995	0	2	21	6
1996-2000	11	6	22	8
2001-2005	31	7	7	13
2006-2010	31	0	0	1

Weighted average of the emission factors of the pollutants from the vehicles is done with the help of year wise distribution of no. of vehicles and their respective emission factors (CPCB, 2000a) of the pollutants (Table 4.12).

Table 4.12 Vehicle wise weighted average of emission factors of the pollutants

Type of vehicles	Weighted average of emission factors of pollutants in gm/km					
	CO	**HC**	**NOx**	**PM**	**BENZ**	**BUTDN**
D.P.(big)	3.566	0.921	6.277	0.29	0.004	0.0008
D.P. (small)	4.29375	1.168	7.6875	0.70375	0.00588	0.0011
Hand Load	5.07	1.55	8.93	1.21	0.008	0.0016
Pay Loaded	4.25	1.162	7.557	0.684	0.0058	0.0011
Open Truck (Private)	5.00	1.495	8.95	1.15	0.008	0.0015

The calculated borough-wise emission of pollutants from the department and hired vehicles are shown in Table 4.13. Density of the fuel is considered 820 kg/m^3. Percentage of carbon and sulphur assumed by weight are 87% and 0.035% respectively. Emission Factors of NO_x for above type of vehicles are more than CO and others because of diesel engine. The nano-particles comprise only 1 to 20% of the total particulate mass emitted from a diesel vehicle, but may constitute more than 90% of the total number of the emitted particles (Kittelson, 2001). Apart from Benzene and Butadiene, PM emission is less. Reduction of PM emission is basically not in nano-particulate range and so, number of PM emitted does not reduce effectively. From April'2010 the specification of maximum sulphur in diesel will be reduced to 50 ppm to control the SO_2 emission in the Indian cities. Detail calculation of borough wise emission status of departmental vehicle is given in Annexure 4.2.

Table 4.13 Estimated Borough wise emission status from departmental and private vehicles

Br. No	**Type of Vehicle**	**PM (gm/d)**	**CO (gm/d)**	**CO_2 (gm/d)**	**SO_2 (gm/d)**	**NOx (gm/d)**	**HC (gm/d)**	**BENZ (gm/d)**	**BUTDN (gm/d)**
1	D.P.(big)	108.47	1333.83	242507.45	53.68	2347.85	344.49	1.0	0.30
	D.P(small)	8.45	51.54	6359.74	1.41	92.28	14.02	0.07	0.01
	H.L.	404.60	1695.31	224524.59	49.72	2986.05	518.29	2.67	0.09
	P.L.	44.97	279.41	85547.13	18.87	496.83	76.39	0.38	0.09
	Hired Open Truck	320.75	1394.56	192362.68	42.69	2496.26	416.95	2.23	0.42
2	D.P.(big)	112.94	1388.76	252495.22	55.89	2444.46	358.68	1.56	0.31
	H.L.	197.58	827.89	109643.44	24.34	1458.19	253.10	1.30	0.27
	Hired Open Truck	368.30	1601.31	220880.66	49.02	2866.34	478.79	2.56	0.48
3	D.P.(big)	95.62	1175.81	213779.22	47.31	2069.72	303.68	1.32	0.26
	D.P.(small)	17.03	103.93	12824.84	2.85	186.08	28.27	0.14	0.03
	H.L.	207.43	869.12	115104.40	25.56	1530.82	265.71	1.37	0.28
	Hired Open Truck	186.47	810.76	111834.54	24.82	1451.26	242.42	1.30	0.24
4	D.P.(big)	148.81	1829.89	332698.90	73.64	3221.04	472.61	2.05	0.41
	H.L.	151.81	636.10	84241.93	18.70	1120.37	194.46	1.00	0.20
	Hired Open Truck	270.83	1177.50	162421.88	36.05	2107.73	352.07	1.88	0.35
5	D.P.(big)	21.83	268.37	48793.96	10.80	472.40	69.31	0.30	0.06
	H.L.	69.60	291.63	38622.76	8.58	513.66	89.16	0.47	0.09
	P.L.	104.53	649.48	198850.06	43.86	1154.85	177.57	0.89	0.17
	Hired Open Truck	354.21	1540.05	212431.27	47.15	2756.69	460.47	2.46	0.46
6	D.P.(big)	59.19	727.77	132317.75	29.29	1281.04	187.96	0.82	0.16
	H.L.	182.33	763.97	101177.38	22.48	1345.59	233.56	1.21	0.24
	P.L.	20.07	124.69	38175.23	8.42	221.71	34.09	0.17	0.03
	Hired Open Truck	647.90	2816.95	388563.49	86.24	5042.33	842.27	4.51	0.85
Br.	**Type of**	**PM**	**CO**	**CO_2**	**SO_2**	**NOx**	**HC**	**BENZ**	**BUTDN**

No	Vehicle	(gm/d)	(gm/d)	(gm/d)	(gm/d)	(gm/d)	(gm/d)	(gm/d)	(gm/d)
7	D.P.(big)	23.39	287.56	52282.64	11.72	506.18	74.27	0.32	0.07
	H.L.	28.21	118.21	15656.40	3.47	208.22	36.14	0.19	0.04
	P.L.	37.28	231.64	70922.29	15.64	411.89	63.33	0.32	0.06
	Hired Open Truck	363.08	1578.62	217750.85	48.33	2825.72	472.01	2.53	0.47
8	D.P.(big)	114.80	1411.62	256652.09	56.81	2484.79	364.58	1.58	0.32
	H.L.	135.46	567.60	75171.96	16.69	999.73	173.53	0.89	0.17
	Hired Open Truck	354.03	1539.24	212319.54	47.12	2755.24	460.23	2.46	0.46
9	D.P.(big)	162.10	1993.32	362412.61	80.21	3508.72	514.82	2.23	0.44
	H.L.	505.16	2116.84	280350.98	62.26	3728.48	647.16	3.34	0.67
	Hired Open Truck	760.10	3304.77	455853.05	101.17	5915.54	988.13	5.29	0.99
10	D.P.(big)	155.15	1907.85	346871.75	76.77	3358.26	492.74	2.14	0.43
	Hired Open Truck	977.41	4249.63	586184.37	130.10	7606.83	1270.64	6.80	1.27
11	D.P.(small)	364.17	2221.88	274168.23	60.93	3978.03	604.40	3.04	0.57
	H.L.	36.03	150.97	19993.46	4.44	265.89	46.15	0.24	0.05
	Hired Open Truck	134.40	584.35	80604.01	17.89	1045.99	174.72	0.93	0.18
12	D.P.(small)	123.06	750.79	92644.04	20.59	1344.21	204.23	1.03	0.19
	H.L.	19.22	80.52	10662.94	2.37	141.80	24.62	0.12	0.03
	Hired Open Truck	38.56	167.67	23127.36	5.13	300.12	50.13	0.27	0.05
13	D.P.(small)	439.94	2684.21	331217.59	73.61	4805.79	730.17	3.68	0.69
	H.L.	131.47	550.90	72959.44	16.20	970.31	168.42	0.86	0.17
	Hired Open Truck	430.97	1873.77	258463.22	57.36	3354.04	560.26	3.00	0.56
14	D.P.(small)	286.39	1747.31	215609.03	47.92	3128.37	475.31	2.39	0.45
	H.L.	229.73	962.57	127481.54	28.30	1695.42	294.28	1.52	0.31
	Hired Open Truck	456.56	1985.02	273810.12	60.77	3553.19	593.52	3.18	0.60
15	H.L.	0.33	1.41	187.48	0.04	2.49	0.44	0.00	0.00
	Hired Open Truck	143.67	624.67	86164.98	19.12	1118.15	186.77	1.00	0.19
	Total g/day	**10554.39**	**56051.57**	**8325680.49**	**1846.33**	**99676.95**	**16085.32**	**81.01**	**15.23**
	Total MT/yr.	**3.85**	**20.46**	**3038.87**	**0.67**	**36.38**	**5.87**	**0.03**	**0.01**

Total pollutant generation from MSW transportation sector of Kolkata is around 3,106 MT/year. CO_2 emission is the largest (97.84%) due to high amount of carbon present in hydrocarbon is converted into CO_2 during burning. CO_2 is a major greenhouse gas, which causes global warming. NOx emission is the second largest (1.17%) and higher than CO (0.66%) and HC (0.19%) because along with fuel NOx, high temperature combustion in diesel engine also generates more thermal NOx. It causes acid rain and photochemical oxidants. SOx generation

(0.02%) is much less compare to NOx due to stringent permissible sulphur percentage in diesel fuel. Though the emission percentage of PM is less (0.12%) but it has significant effect on respiratory system due to the presence of higher fraction of nano-sized particles. The emission of unburnt hydrocarbons from diesel vehicle is usually less than the petrol driven vehicles.

From Table 4.13 it is seen that Borough 9 generates maximum pollutants (around 409.94 MT/Year) as departmental and private vehicles cover maximum distance i.e., 1638.50 Km/day (table 4.10). In Borough 15, total pollutant emission is lowest (around 32.28 MT/Year) as part of the waste is dumped in the local Garden reach dumping site.

4.7.5 Pollutant Contribution from Departmental and Private Vehicles

The percent contributions of departmental vehicle and hired vehicle in generation of total major pollutants (PM, CO, SO_2, NOx, and HC) are shown in Fig 4.7. Result shows that total emission of the departmental vehicle is 58%. Around 109 no. of departmental vehicles carry only 40% of the total waste as the capacity of container is less and no. of trips i.e. distance covered are more (60%). In case of the private vehicles (open truck) the total emission is 42% from around 205 no. of vehicles which carry 60% of the total waste.

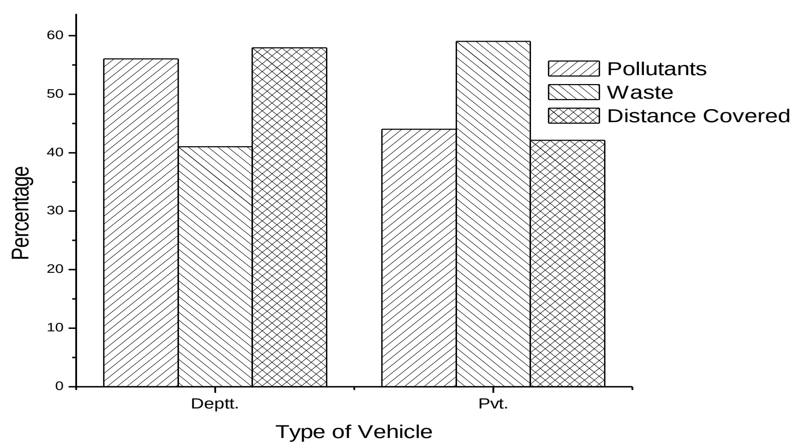


Figure 4.7 Pollutant contributions, waste carried and distance covered by departmental and private vehicles

4.7.6 Borough Wise Emission Trend from Departmental and Private Vehicles

Out of 15 boroughs, pollutant emission from MSW transportation is higher in borough 9 and 10, which is around 13.20% to 11.20%, influenced by waste generation, landfill distance and sharing of waste by departmental and private vehicles. Borough wise total emissions of major pollutants are shown in Figure 4.8. Contribution of borough 12 and 15 are negligible (around 1.52% and 1.04%) in comparison to others. Borough 12 is adjacent to Dhapa and around 15% of waste is dumped locally. In borough 15, as it is far from Dhapa, part of the waste is dumped in the local Garden Reach dumping site.

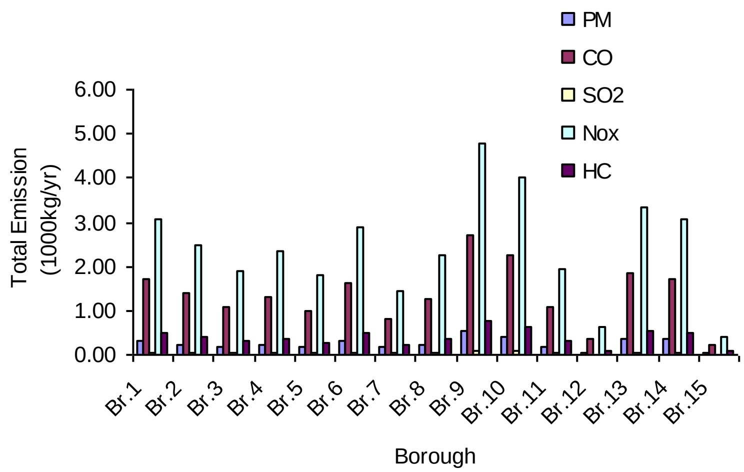


Figure 4.8 Borough wise major pollutant emissions from both departmental and private vehicles

4.7.7 Contribution to Total Pollutant Emissions from Departmental and Private Vehicles

Pollutant generation of CO_2 from the departmental vehicles is 58.17% (1768 MT/Year) and NOx is 54.65% (19.88 MT/Year) (Fig.4.9) because of higher distance covered.

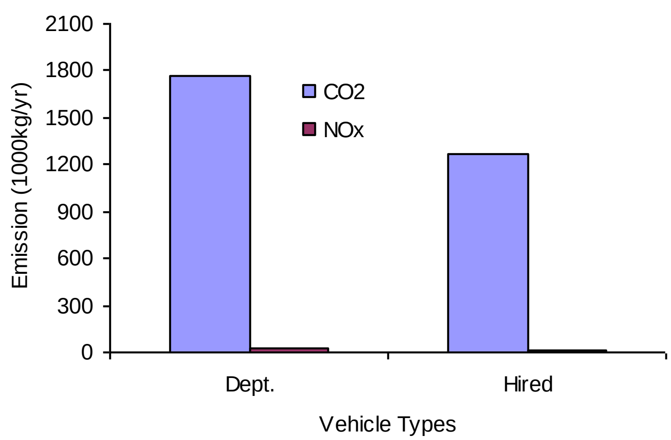


Figure 4.9 Total CO_2 and NOx emissions from departmental and private vehicles

The total pollutant emissions like HC, CO and SO_2 (Fig.4.10) from departmental vehicles are around 53% to 58% whereas PM emission from private vehicles is around 55%, as trucks emit more PM.

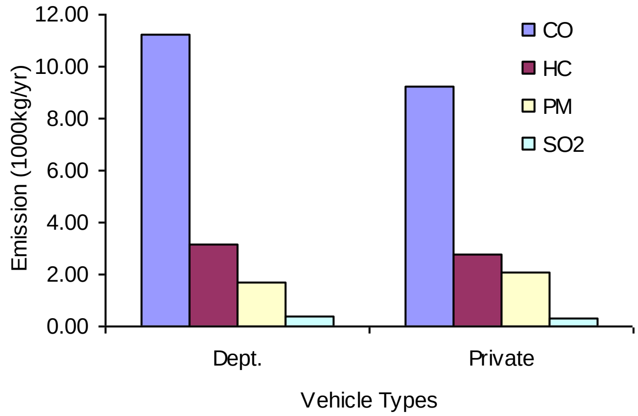


Figure 4.10 Emissions of total CO, HC, PM and SO_2 from departmental and private vehicles

Figure 4.11shows benzene and butadiene emissions from departmental vehicles are higher as higher distance is covered. Though their amount is less compared to other pollutants, yet their health impacts are significant because of their carcinogenic nature.

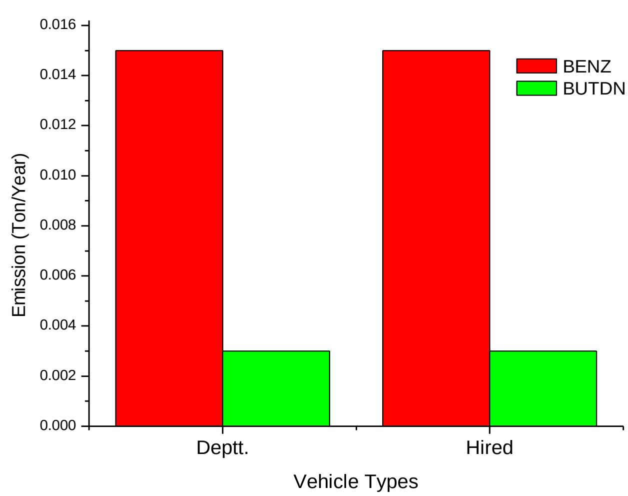


Figure 4.11 Emissions of total Benzene and Butadiene from departmental and private vehicles

Fig.4.12 shows that total CO_2 emission from private vehicles (truck) is more than individual departmental vehicle type. However, departmental vehicles as a whole emit around 18% more total CO_2 emission than private vehicles.

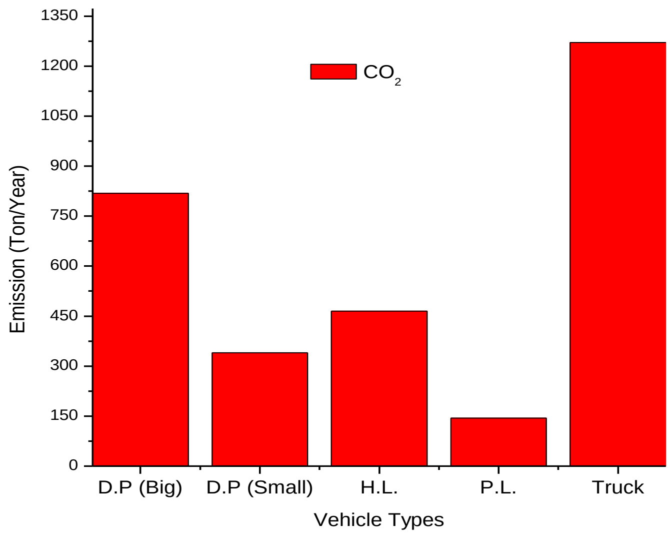


Figure 4.12 Total CO_2 emissions from each type of departmental and private vehicles

Fig.4.13 shows the emission of major pollutants from private vehicle and individual departmental vehicle. Private vehicles emit more major pollutants than the individual departmental vehicle but as a whole departmental vehicle emit around 51.5%.

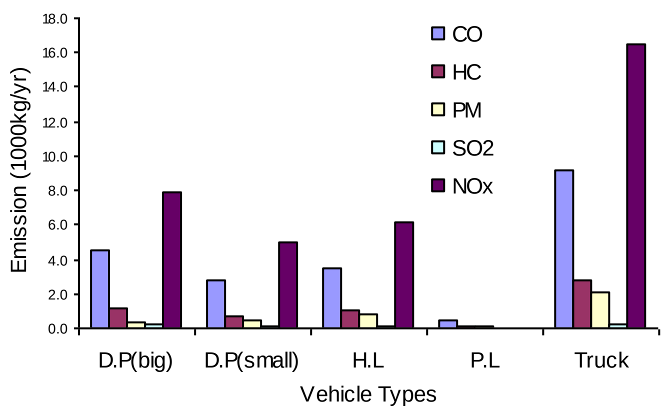


Figure 4.13 Major pollutants emission from each type of departmental and private vehicles

4.7.8 Observation on Results

Considering the synchronization of waste transportation system with the type of collection points, it can be said that in solid waste management, the KMC has some obligatory responsibility to containerize the municipal solid waste and transport by the Dumper Placer. This is inevitable for the present solid waste management system of KMC. The departmental vehicles carry less amount of solid waste and make more numbers of trips due to the capacity of the containers being much lower than that of open trucks. More number of trips means more distance covered i.e. higher fuel consumption which results in more air pollution. Slow road speed affects not only traffic flow but also results in huge fuel waste and aggravates the vehicular pollution. It is suggested that solid waste conveyance system should avoid the peak traffic hours to reduce air pollutant generation and the obnoxious odor problem of MSW during that period.

Total pollutant generation from MSW transportation sector of Kolkata is around 3106 MT/year. A major green house gas CO_2 emission is largest (97.84%) due to high amount of carbon in hydrocarbon is converted into CO_2 during burning. NOx emission is the second largest (1.17%) and higher than CO (0.66%) and HC (0.19%) because of high temperature combustion in diesel engine generates more thermal NOx. It causes acid rain and photochemical oxidants. SOx generation (0.02%) is much less compare to NOx due to stringent permissible sulphur percentage in diesel fuel. Though the emission percentage of PM is less (0.12%) but its polluting effect is significant due to the presence of higher fraction of nanoparticles. The emission of unburnt hydrocarbons from diesel vehicle is usually less than the petrol driven vehicles. Out of 15 boroughs, pollutant emission from MSW transportation is higher in borough 9 and 10, which is around 13.20% and 11.20%. This is the combined effect of waste generation, distance from disposal landfill and proportion of waste carried by departmental and private vehicles. Emissions from borough 12 and 15 are negligible (around 1.52% and 1.04%) in comparison to others. While the total pollutant emissions (CO, HC and SO_2) from departmental vehicles is around 53% to 58%, the PM emission from private vehicles are around 55% as truck emits more PM. Benzene and butadiene emissions from departmental and private vehicles are almost same but the quantity is less compared to other pollutants, yet the impacts are significant because of their carcinogenic nature.

The estimated pollutants generation from MSW transport sector is considerable and cannot be ignored as it is a part of the Kolkata city as well as global air pollution problem. In order to minimize air pollution, we have to minimize the pollution generation from MSW transportation sector. This may be achieved by (i) minimization of overall trips, through optimization of route scheduling, (ii) introducing fuel efficient vehicles, (iii) use of less pollutant fuel, (iv) reduction of ~20% pollution loads generated by vehicles by following proper periodical inspection and maintenance schedule of vehicles, and (v) replacing old vehicles, that have crossed their age limit. More stringent norms for fuels also help in reduction of the pollutants. Reduction of sulphur content limit to 50 ppm in diesel for urban areas from April'2010 can reduce total emission of SO_2 by around 86%. As per Honourable High court, commercial vehicles more than 15 years old are gradually phased out from September, 2009.

4.8 NOISE POLLUTION

Waste transportation is a major part of MSW management and this generates a large amount of air and noise pollution in the urban atmosphere (Chattopadhyay et al., 2010). Noise pollution inventory will facilitate assessing and minimizing environmental impact from MSW transport sector. The purpose of this study is to prepare the noise level inventory from different types of collection points, transportation sector and landfill site in present situation. Objective of this study is also to determine the extent of noise pollution in the work place affecting the working personnel; i.e., the noise level to which employees are exposed.

4.8.1 Study Areas and Methodology Used

Vehicular noise pollution is from the departmental and private vehicles engaged in transporting the waste along with bulldozers continuously pushing waste for leveling and dressing to make next day's waste disposal site. Hence, landfill sites, different types of collection points and various types of departmental and private vehicles engaged for transportation of garbage in loaded and unloaded conditions are implicated in this noise inventory study.

Short-term exposure to excessive noise can cause temporary hearing loss and exposure to noise over a longer period of time can lead to permanent loss of hearing. The level of noise allowed by noise standards in most countries is generally 85-90 db(A) over 8 hour workday (although some countries recommend that noise levels lower than this). Exposure to higher noise levels may be allowed for periods of less than eight hours. For example, workers should not be exposed to noise levels above 95 db(A) for more than 4 hours per day. Therefore, the Leq of the noise exposure for an employee needs to be monitored and controlled ensuring that it does not exceed

85-90 db(A). Workers should never be exposed to more than 140 db(A) of impulse noise (usually a very loud noise that occurs only once) at any time (NIOSH, 1998). So, it is also necessary to determine how long the employees specially engaged in removal of solid waste are exposed to the noise.

Noise level measurement was carried out using a portable precision sound level meter (Model: SL-4001, M/s LUTRON, Taiwan). The sound level meter was frequently calibrated at 94 dB(A) via external sound calibrator for accurate measurement as per IS: 7194, 1994. The noise level read-out from the instrument was in dB(A) (decibel). The Sound Level Meter (SLM) was placed at 1.5 m above the ground and at 2 m horizontal distance from the noise sources as in many noise measurement studies (Piccolo et al., 2005) the device was set at a height ranging from 1.2 m to 1.5 m and at horizontal distances between 1.5 m to 3.5 m. The SLM was set at appropriate ranges at the place of noise monitoring. The noise levels were monitored for 10 to 15 minutes with 10 seconds interval at each location and in each operational variance (Bedi, 2006; Hakan and Derya, 2008). As all the readings are in dB(A), it has to be converted to Leq, the (energy) equivalent sound level.

4.8.2 Results and Discussions

4.8.2.1 Storage Points

Waste collected from the sources of waste generation is temporarily stored in different types of storage points and the facility is so designed that the system synchronizes with the system of primary collection as well as transportation of waste. Presently there are 650 storage points, out of which 365 are mild steel container points, 265 are vat points i.e. masonry or concrete made intermediate or temporary storage points and the rest 20 are direct loading points i.e. directly loaded on the vehicles (Chattopadhyay et al., 2007a). Noise generated due to the activities at the storage points, affects the conservancy staffs who are daily engaged for the collection system and also the surrounding residents. All three types of storage points are investigated. Their representative locations selected are at (i) Vivekananda Park as container point in ward number 86 under borough VIII (ii) Ballygunge Circular Road as payloader operated storage point (open vat) in ward number 69 under borough VIII and (iii) 27, Topsia Road as open vat storage point with manual loading system in ward number 66 under borough VII.

Operation of hydraulically operated dumper placer at the container point (Vivekananda Park) is around 60 to 75 minutes per day during working hours (Figure 4.14). Leq for idling and operating state are 62.8 dB(A) and 82.6 dB(A) respectively. The baseline noise level in this location is relatively higher as it is close to a park where players play cricket and there is frequent movement of students etc. In idling condition 65 dB(A) is exceeded in only 14% of the sampling duration i.e. L14 is 65 dB(A). In operating condition L50 is 81 dB(A). Noise generation from payloader operated storage point at 62, Ballygunge Circular Road (Figure 4.15), where the payloader operation was for filling an 11 m3 tipper truck, is also calculated. The baseline noise data was also collected when the operation was not going on. This particular point is located close to busy roads with light, medium and heavy vehicles plying. Loading operation by the payloader continues for around 60 to 100 minutes per day during the working hours. In this area 65 dB(A) is exceeded for 94% of the loading time. Leq for idling condition (non operating) is 77.06 dB(A) and 75 dB(A) persists for 32% of idling time. During operation Leq is 88.96 dB(A) whereas 75 dB(A) persists for 96% of the time. Field data and result are shown in Table A-4.2 of Annexure 4.3. In case of the open vat point at 27, Topsia Road where garbage is manually loaded in the open truck, the Leq in operating condition is 45.98 dB(A) and in non-operating condition is 45 dB(A). Though manual loading continues for 2 to 4 hours in each open vat points, its noise level is low. However it may be mentioned that to comply with the Municipal Solid Wastes (Management and Handling) Rules’ 2000 (CPHEEO, 2000), for avoiding manual handling, all open vat points are to be gradually converted to containerized system. Though the payloader vat points are the noisiest, conversion of large payloader vat points to containerized storage points is constrained by the high volume of waste generation and severe space problem.

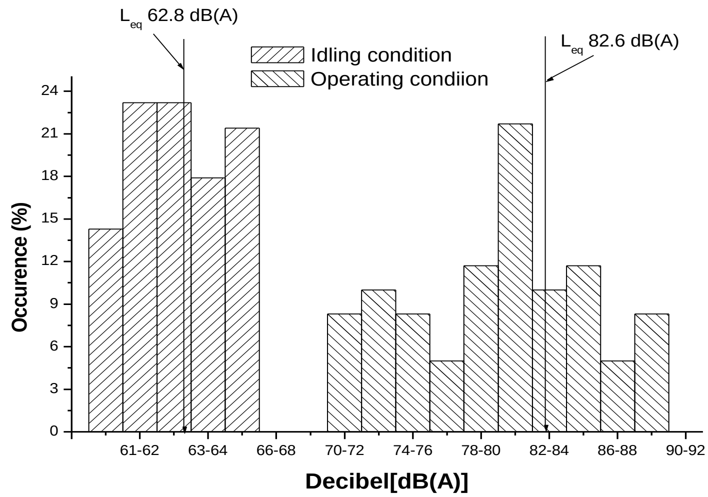


Figure 4.14 Noise level at containerized storage point (Vivekananda Park)

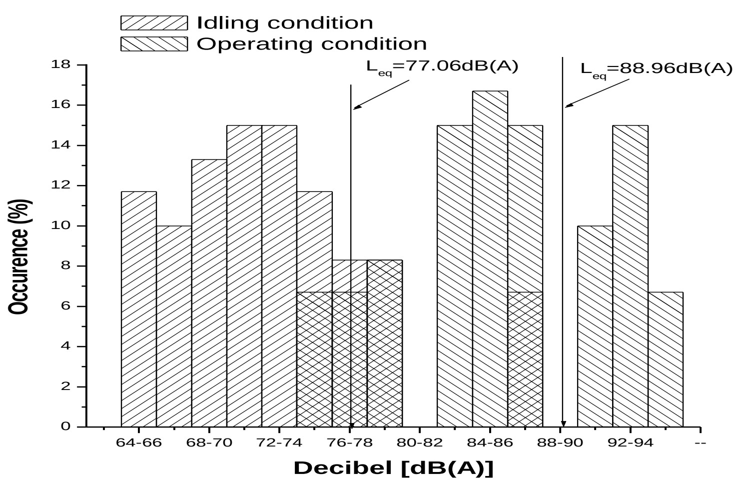


Figure 4.15 Noise level at payloader operated storage point (62, Ballygunge Circular Road)

4.8.2.2 Noise Measurements of Loaded and Empty Run of Garbage Transport Vehicles

At present around 110 departmental vehicles are engaged in carrying of waste. This consists of 9 numbers of 4.5 m^3 dumper placer, 34 numbers of 7 m^3 dumper placer, 55 numbers of 7 m^3 hand loaded tipper truck and 12 numbers of 11 m^3 payloader tipper truck. In addition to this 205 numbers of hired open trucks transport the remaining 60% of total generated waste (Chattopadhyay et al., 2009). As per the order of The Honourable High Court, commercial vehicles older than 15 years old are gradually being phased out from

September, 2009. So, all types of transportation vehicles, (under loaded and empty condition), and bulldozers in running condition are considered for noise measurement.

The noise level Leq values are 82.59 dB(A) and 81.43 dB(A) from a typical new dumper placer during loaded run and empty run (Figure 4.16). Field data and result are shown in Table A-4.3 of Annexure 4.3. Leq for a representative old dumper placers for the corresponding conditions are found to be 104.31 dB(A) and 100.1 dB(A). Majority of the old dumper placers are already replaced and supplemented by new ones with financial assistance of Asian Development Bank (ADB) with a view to containerization of waste as compliance criteria of Municipal Solid Waste (Management and Handling) Rules' 2000. Even if this replacement reduces 20% noise level in dB(A) scale, still noise level of 75 dB(A) prevails for 80% of the total working hours. This calls for special arrangements like ear muff, to protect against any health damage to the drivers and laborers.

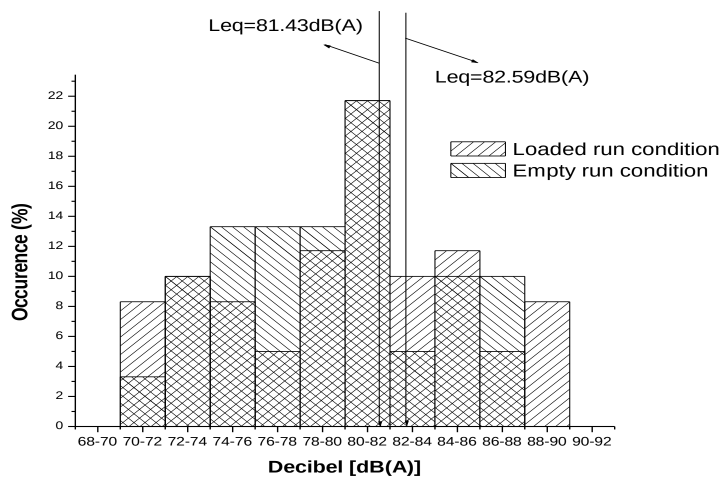


Figure 4.16 Noise level in dumper placer

Leq during loaded run of the 11 m3 tipper truck and while empty run for a typical representative case is found to be 99.96 dB(A) and 89.24 dB(A) respectively. Field data and result are shown in Table A-4.4 of Annexure 4.3. For manually loaded 7 m3 tipper truck Leq for loaded and empty conditions are 94.74 dB(A) and 87.86 dB(A) respectively. Field data and result are shown in Table A-4.5 of Annexure 4.3. L90 values for mechanically loaded and manually loaded tipper trucks are 83 dB(A) and 89 dB(A) respectively. In empty condition for both the cases 75 dB(A) prevails 88% of the running time. Leq for loaded and empty condition of old open trucks are 92.27 dB(A) and 86.04 dB(A) respectively. Field data and result are shown in Table A-4.6 of Annexure 4.3. In both the cases L100 is 75 dB(A). In compliance with the said court order, vehicles older than 15 years are being phased out and new vehicles are being inducted in fleet. For the new vehicles, side walls are additionally raised by 2 ft in order to increase the carrying capacity. Interestingly, these vehicles have higher Leq (102.41 dB(A)) in empty condition compared to loaded condition (101.74 dB(A)). This is due to free vibration of the higher side walls of the truck. All waste carrying vehicles except new dumper placer are found to have noise level above the limit (89 dB(A)) set by the Motor Vehicles Act. Bulldozers are used in dumpsites for regular dressing and leveling. Leq is 102.71 dB(A) for the bulldozer in operation and its L89 is 90 dB(A) while idling. Field data and result are shown in Table A-4.7 of Annexure 4.3. Such high noise levels may causes loss of hearing as well as irreversible damages in nervous system for the bulldozer operators.

4.8.2.3 Garage

KMC has 9 garages where washing, servicing, repairing, fueling of vehicles are done. Petty store and small machine shop facilities are available in these garages. Noise measurement was carried out at Dhapa garage as a representative case. In the open location outside the garage where the vehicles are repaired the noise levels Leq and L40 were 80.26 dB(A) and 75 dB(A) respectively. The Leq and L60 values are 82.09 dB(A) and 75 dB(A) when hammering is done inside the covered garage shade. Field data and result are shown in Table A-4.8 of Annexure 4.3.

4.8.2.4 Landfill Site

Dhapa disposal ground (21.4 ha. area with two separate disposal facilities for departmental and hired vehicles) is in the eastern fringe of the Kolkata city, at a distance of 10 km from the city centre and 2.5 km from Eastern Metropolitan bypass junction. Computerized weighbridges (4 numbers x 30 t) are used for checking and recording weights. The departmental dumpsite area in the working hours bustle with dumper placers, tipper trucks and bulldozers in operation and the waste pickers continuously search recyclable materials. The Leq at the centre of the open active landfill area is comparatively less (~72 dB(A)). For around 60% of the total working hours the prevailing noise level is 65 dB(A). The background noise level i.e. without any activity in the landfill area, Leq is ~55 dB(A). Field data and result are shown in Table A-4.9 of Annexure 4.3.

In the private dump site (where only hired vehicle dispose waste) noise measurement is done while two vehicles are weighed simultaneously on two weigh bridges; vehicles stand in a queue for weighing and empty vehicles returning after unloading of garbage. Leq during the activity period and corresponding background noise level at different locations are shown in Table 4.14. Field data and result are shown in Table A-4.10 and Table A-4.11 of Annexure 4.3.

L_{eq} does not rise much at the junction of E. M. Bypass during the activity hours. This is due to the busy roads where movements of other vehicles always continue. There is a substantial rise in noise level during active period in other locations.

Table 4.14 Comparison of L_{eq} in landfill site

Location	**L_{eq} for active period (dB(A))**	**L_{eq} for background (dB(A))**
Junction of E. M. Bypass	79.14	76.73
Office room (inside) nearby weigh bridge	70.86	55.00
Main road	82.91	53.16
Approach road	76.73	46.25
Private dump site	78.42	53.95
In front of weigh bridge	76.06	54.29

4.8.2.5 Noise Exposures to the Workers Related to SWM Activities

Workers are exposed to noise from many sources: equipment, vehicles, or tools, to name a few. Higher noise level can damage hearing when exposure continues over extended periods of time. Permissible exposure for 8 hours vary between 85 dB(A) and 90 dB(A) (Noise pollution Rules' 2000). Exposure of drivers and workers daily engaged in waste transportation involves (i) starting from garage to waste collection point, (ii) loading at the storage point, (iii) transportation of waste load to Dhapa, (iv) unloading at Dhapa dump site and after several trips (vii) return to garage from Dhapa dump site. Eight hour noise exposure to drivers and workers in dumper placer, L_{eq} is 81.44 dB(A) and 75 dB(A) prevails 95% of the total working hours (Figure 4.17). This is within the range of personal noise level exposure.

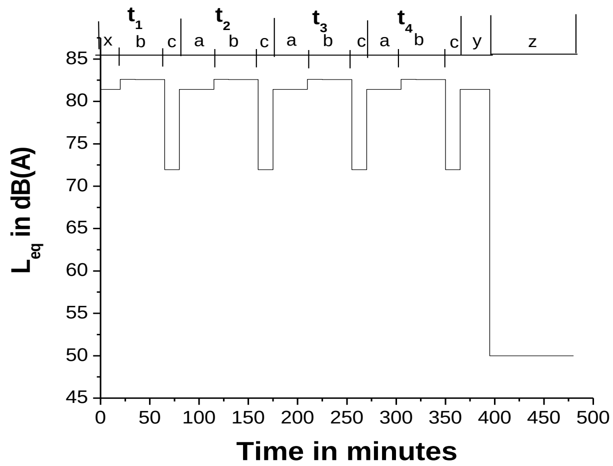


Figure 4.17 Exposure to noise in Dumper Placer vehicle

(x = Garage to collection point; b = Loading time at the collection point and collection point to Dhapa dump site in garbage loaded condition; c = Unloading time at Dhapa; a = Return from Dhapa to collection point for next trip; y = Return from Dhapa to garage; z = Rest period within garage; t_1 = 1st trip; t_2 = 2nd trip; t_3 = 3rd trip; t_4= 4th trip)

In case of the tipper truck, L_{eq} (95.15 dB(A)) is more than dumper placer and 85 dB(A) prevails 95% of the working hours which is quite high for the personal noise level exposure (Figure 4.18). Noise exposure over eight hours in case of open truck (Figure 4.19), L_{eq} (85.25 dB(A)) is more than dumper placer but is lower than that for payloader fed tipper truck. The L_{71} is 85 dB(A). Among the waste carrying vehicles the noise exposure level in the tipper truck is maximum and it is minimum in case of dumper placer.

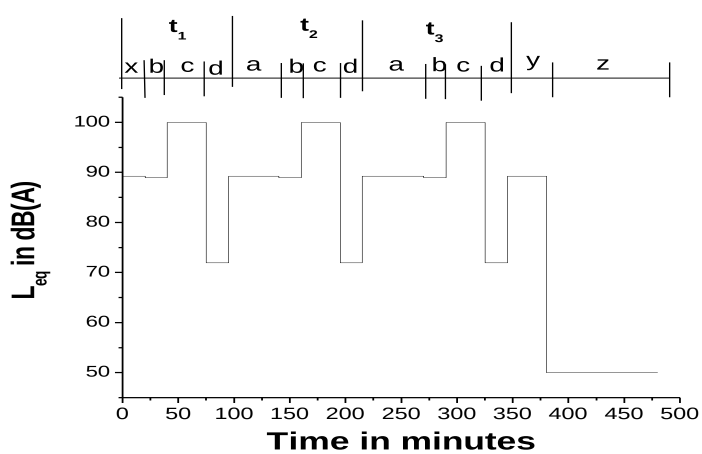


Figure 4.18 Exposure to noise in payloader fed tipper truck

(x = Garage to collection point; b = Loading time at the collection point; c = collection point to Dhapa dump site in garbage loaded condition; d = Unloading time at Dhapa; a = Return from Dhapa to collection point for next trip; y = Return from Dhapa to garage; z = Rest period within garage; t_1 = 1st trip; t_2 = 2nd trip; t_3 = 3rd trip)

Noise exposure for the bulldozer operator is very high (Leq 101 dB(A)) as shown in Figure 4.20. Noise level of 85 dB(A) prevail for 88% of total working hours. Bulldozer operators should essentially use ear protective gears. Activity at the disposal sites starts from 6.00 A.M. and large number of vehicles from different vat points reach the site at a time. In the initial phase of the day the bulldozers continuously run to make space for unloading of waste from the vehicles. In the mid span of the working hours, vehicular load reduces and operators take rest for 15 minutes after every hour of operation. At the end of the working hours vehicular load is minimum as few vehicles reach from distant vat points and market vats. In this period the operator gets more rest. Noise exposure level of employees' who are engaged for allocation of the vehicles at unloading points of the dump site are also measured and the Leq is ~ 73 dB(A).

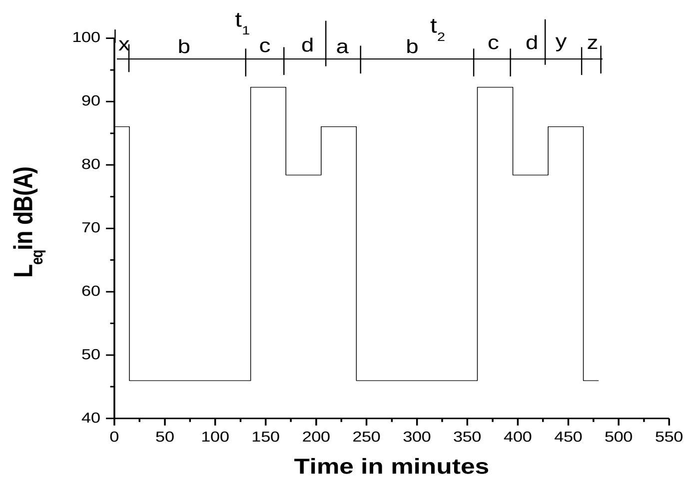


Figure 4.19 Exposure to noise in open truck

(x = Garage to collection point; b = Loading time at the collection point; c = collection point to Dhapa dump site in garbage loaded condition; d = Unloading time at Dhapa; a = Return from Dhapa to collection point for next trip; y = Return from Dhapa to garage; Rest period within garage; t_1 = 1st trip; t_2 = 2nd trip)

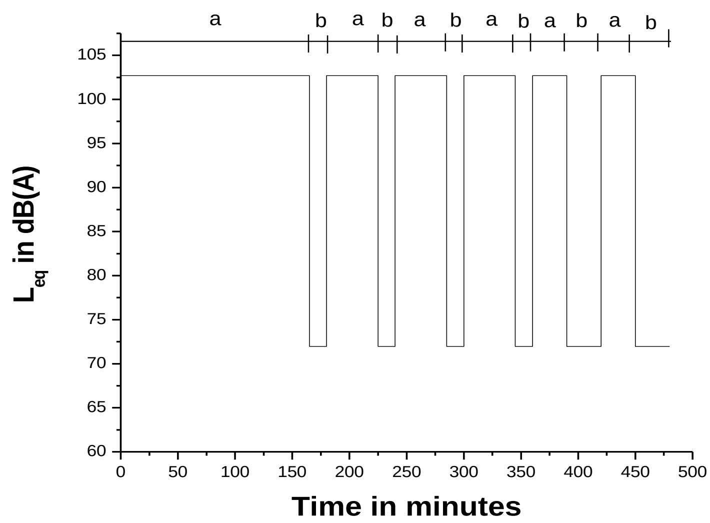


Figure 4.20 Exposure to noise in Bulldozer

(a = Operating mode of Bulldozer; b = Non operating mode of Bulldozer)

4.8.3 Observation on Result

Solid waste management is one of the largest essential service sectors and needs considerable manpower. Apart from noise affecting the workers, the noise pollution to the surrounding environments cannot be ignored. The present study reveals that the group of workers worst affected are the drivers and laborers of bulldozer; pay-loader fed tipper truck and manually loaded tipper truck.

Loading operation at storage points is limited within 1 to 2 hours except in certain cases (e.g. large vat points) it may go up to 4 hours. Payloader operated storage points are the noisiest (Leq 88.96 dB(A)) and the manually operated open vat points generate nominal noise to the surroundings. Conversion of manually operated open vat points to containerized system as required by the regulation would increase the noise level from ~46 dB(A) to ~83 dB(A).

All the waste carrying vehicles except new dumper placer are higher than the noise level limit of Motor Vehicles (89 dB(A)). It is alarming also from the health point of view. This violation calls for immediate attention by proactive maintenance and replacement of older vehicles. Replacement of an old dumper placer by a new one effectively reduces noise level by ~20% in dB(A) scale. Raised side walls of open trucks in order to carry more waste reduces fuel consumption per ton of waste hauled but adds to higher noise level in empty run. This needs alteration to minimize the noise possibly by properly bracing the raised side walls.

Eight-hour noise exposure study shows that the noise level in new dumper placers and open trucks are within the limit of personal noise level exposure. High Leq value of 95.15 dB(A) with L95 of 85 dB(A) in case of tipper truck is a health threat to the associated workers and needs to be addressed by use of appropriate protecting gears by the personnel as well as by better maintenance of the vehicles. The bulldozer operators being regularly exposed to a very high noise level (Leq 101 dB(A)) must use ear protection. Compulsory periodic check up to monitor their health needs to be built into the system.

Some of the preventive steps can be taken by the authorities are (a) strict enforcement to ban the use of air horns in and around the landfill site (b) proper traffic management at the dump site (c) widening of roads etc. to minimize noise impact (d) improvement and proper maintenance of road conditions which will smoothen the flow of traffic (e) there should be plenty of trees and bushes surrounding the landfill site to absorb the noise (f) there should be periodic noise inspection on the road (g) proper enforcement of already existing legislations for controlling of noise pollution (h) noise labeling in the SWM equipments specially vehicles and bulldozers would be effective step towards actual noise abatement (i) higher noise exposure is a major problem in SWM workers and should be tackled through awareness programme. Use of earplugs, earmuffs etc. can be encouraged for the vehicle and bulldozer operators.

4.9 LANDFILL GAS GENERATION AND ENERGY RECOVERY

4.9.1 Study Area of Solid Waste Disposal Site

Kolkata, capital of the state of West Bengal, is one of the four metropolitan cities in India. The city is centered on latitude 22^{o} 34' North and longitude 88^{o} 24' East. The city is approximately 30 km from the Bay of Bengal and river tides at Kolkata range over 4 m. Urbanization and industrialization influence the production of large quantity of city solid waste. Other cities in India, like Mumbai top the list with a population of 13.8 millions and daily MSW generation of

8000 t, Delhi 10 million and 6000 t, Chennai 5.8 million and 4000 t, Hyderabad 4.2 million and 2200 t (Chattopadhyay et al., 2007a).

Kolkata of about 187.33 sq.km Kolkata municipal corporation (KMC) area comprising of 15 boroughs and 141 electoral wards, has 9 million total population including floating population (Chattopadhyay et al., 2010a). The total MSW generation is about 3000 t d^{-1}. Census by the Institute of Local Government and Urban Studies, report the decennial growth of population of Kolkata city from 1981 to 1991 as 6.61% and from 1991 to 2001 as 4.00% (ILGUS, 2001). In case of floating population the increment considered is 2.15% per year. MSW acceptance from 2001 to 2011 is taken from computerized record of KMC and from 1987 to 2000 the same was calculated on the above basis. KMC operates two disposal sites, without having liner and leachate collection facilities that handle the city's MSW. The existing Dhapa landfill site owned and operated by KMC is a 21.4 ha fill site in ward 58 of Borough VII (Figure 4.1). The site has been divided into an eastern disposal area (8.1 ha) which receives waste from KMC's own vehicles, and a western disposal area (13.3 ha) which receives waste from KMC authorized private vehicles. Waste is deposited in an uncontrolled manner that has resulted in steep, unstable slopes, huge leachate accumulation within the waste mass and leachate runoff into nearby water bodies. Such conditions limit both LFG generation and the potential for efficient LFG extraction. This facility receives more than 98% of the city's MSW. A small disposal site in Garden reach receives less than 2% of the city's waste where there is also no gas recovery and leachate collection system (Chattopadhyay et al., 2009a); (Chattopadhyay et al., 2010b).

The physical and chemical compositions of garbage of MSW are shown in Table 4.1 and Table 4.2 (NEERI, 2005); (Chattopadhyay et al., 2007b). Biodegradable portion i.e., organic content is very high, recyclable portions are comparatively less and it has considerable quantity of inert materials which leads to overall low energy content (Chattopadhyay et al., 2009b). In the existing system, major portion of recyclable materials (~9.21% of the total garbage) are recovered by the informal sector of rag-pickers and the remaining portion is deposited in the landfill along with silt and rubbish. Deposited waste composition is considered for landfill gas generation. The composition of organic components (cellulose, proteins and lipids) affects the degradation of waste and as a result affects gas generation process.

Presence of easily degradable organic carbon sources generates higher CH_4. Cellulose-to-lignin ratio (CLR) has an effect on CH_4 production and it has also a negative relation with age of solid waste samples which indicate that the older samples are methanogenically active (Gurijala et al., 1997). Waste contains high amount of moisture which helps in higher rate of CH_4 production.

4.9.2 IPCC Model

The amount of methane generated at the landfill is estimated, using first order degradation (FOD) model in spreadsheet, presented in the IPCC guideline (IPCC, 2006). The estimation formula of FOD model is described below. FOD model calculates the amount of methane generated with assumption that the rate of generation is proportional to the amount of reactant remaining, in this case the mass of degradable organic carbon decomposable under anaerobic conditions. In FOD model, at the end of the year *T* at the landfill, the mass of organic carbon remaining and the mass of degradable organic carbon is worked out. In addition, the amounts of accumulation and decomposition of decomposable degradable organic carbon each year is calculated. Based on these, the decomposable degradable organic carbon (DDOC) entering the solid waste disposal site is calculated in accordance to each category of waste (e.g. food waste, paper/cardboard, park and garden waste and wood). The amount of methane generated from the decomposable degradable organic carbon is calculated by the following equation:

$CH_4 \ \ generated_T = DDOC_m \,.\, decomp_T \,.\, F \ .16/12$;

Where, $CH_4 \ \ generated_T =$ amount of CH_4 generated from $DDOC_m$ decomposed in year T ($DDOC_m \ decomp_T$), in Gg;

$F =$ fraction of CH_4 , by volume, in generated landfill gas;

$16/12 =$ molecular weight ratio CH_4 / C .

The CH_4 generated by each category of waste disposed is added to get total CH_4 generated in each year. Finally, emissions of CH_4 are calculated by subtracting first the CH_4 gas recovered from the disposal site, and then CH_4 oxidized to carbon dioxide in the cover layer.

$CH_4 \ \ emited_T = (\sum x \ CH_4 \ \ generated_{x,T} - R_T).(1 - OX_T)$;

where $CH_4 \ \ emited_T = CH_4$ emitted in year T , in Gg;

$x =$ waste type/material or waste category;

$R_T = CH_4$ recovered in year T , in Gg;

$OX_T =$ Oxidation factor in year T , (fraction).

4.9.2.1 Selection of Parameters

Since the mean annual temperature is above 20^0 C and mean annual precipitation is more than 1000 mm in Kolkata city, therefore, the parameters applicable to moist and wet tropical climate presented in the IPCC Guidelines are considered. In this case the fraction of degradable organic carbon is considered as food waste: 0.15; paper: 0.4; wood and straw: 0.43; textiles: 0.24 and the methane generation rate constant (k in y^{-1}) are set as food waste: 0.4; paper: 0.07; wood and straw: 0.035; textiles: 0.07. Methane content in landfill gas is assumed as 50%. Delay time 6 months, conversion factor, C to CH_4 1.33, and the fraction of methane gas oxidized to carbon dioxide are not taken into account due to absence of daily or intermediate cover. Input parameters and MSW activity values are shown in Table A-4.12 and Table A-4.13 of Annexure 4.4.

4.9.2.2 Results of Overall Gas Generation and CH_4 Recovery

As per IPCC method, the estimated methane generation from 1987 to 2021 is found 6,56,000 t; methane entrapment and recovery for the period 2012 to 2021 are 1,24,000 t and 62,000 t respectively as shown in Fig. 4.21. Results of methane generation from output model of IPCC is shown in Table A-4.14 of Annexure 4.4. GHG reduction will be 13,02,000 tCO_2-eq and for existing system total emission of CH_4 up to 2021 will be 1,24,74,000 tCO_2-eq.

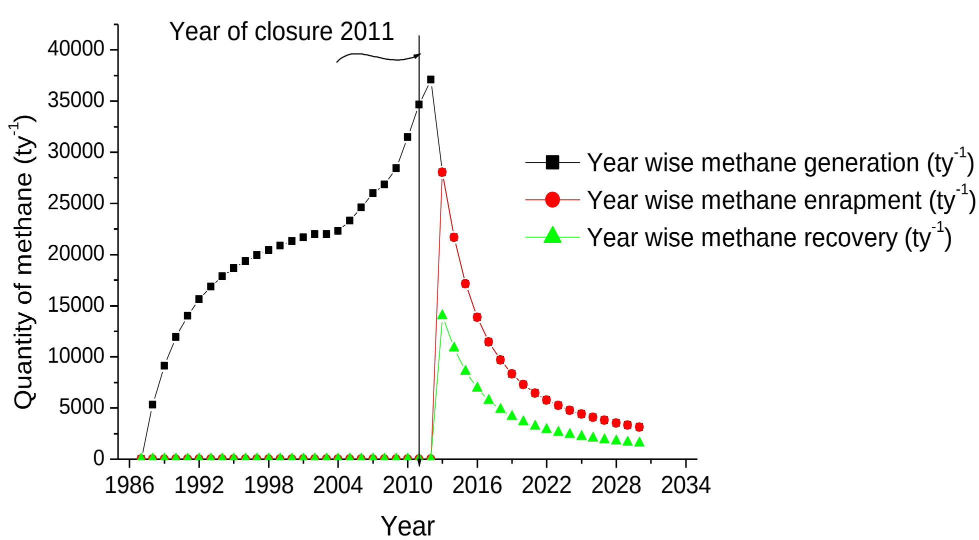


Figure 4.21 Year wise methane generation, entrapment and recovery from existing open dump site following IPCC mehod

4.9.2.3 Sensitivity Analysis

A sensitivity analysis is conducted by means of certain variations of degradable organic carbon (DOC) in respect of default values of DOC: 0.15 for food waste, DOC: 0.40 for paper and DOC: 0.43 for wood, to find out the effect of methane gas generation and recovery from individual waste category and to the total gas generation and recovery. If DOC for food waste is considered 0.08, methane generation and recovery of food waste reduces by ~47% and total methane generation and recovery reduces by ~27% and ~17% respectively with respect to the default value. For DOC value of 0.2, individual methane generation and recovery increases by ~34%, total methane generation and recovery increases by ~19% and ~12% respectively. So effect in totality is significant due to higher percentage of rapidly degradable food waste. In case of variation of DOC in paper at 0.36 and 0.45, individual methane generation and recovery reduces by ~10% for the earlier and increases by ~12.5% for the later. However, there are no significant changes of variation in total methane generation and recovery (± 0.3% to ± 0.6%) because of lesser of paper percentage in waste composition. For wood, if DOC value is taken at 0.39, individual methane generation and recovery decreases by ~9.3% and if it is 0.46 then the value increases to 7%. However, total methane generation and recovery differs with less than 2% but higher than paper as its degradation rate is slower than the paper.

A sensitivity analysis is also carried out by means of certain differences of methane generation rate constant (k) i.e. k = 0.17 y^{-1} (half life durations: 4 years); k = 0.7 y^{-1} (half life durations: 1 year) in respect to default value of k = 0.4 y^{-1} (half life durations: 1.75 years) for food waste, similarly k = 0.06 y^{-1} (half life durations: 12 years); k = 0.085 y^{-1} (half life durations: 8 years) in respect to default value of k = 0.07 y^{-1} (half life durations: 10 years) for paper, likewise k = 0.03 y^{-1} (half life durations: 25 years); k = 0.05 y^{-1} (half life durations: 15 years), in respect of default value of k = 0.035 y^{-1} (half life durations: 20 years) for wood to evaluate the outcome in individual and overall methane generation and recovery. Half life of the materials is related to the reaction rate (k) of the model through the equation $k = {t_{1/2}}^{-1} \ln 2$. According to the results, for methane generation rate constant variations of k = 0.17 y^{-1} and 0.7 y^{-1} for food waste, individual and total methane generation decreases by ~5.2% and ~3% for the first and increases by ~0.3% and ~0.2% for the later. But methane recovery from individual and total food waste significantly increases by ~77% and ~28% for the first along with decreased in recovery by ~46% (individual) and ~17% (total) with respect to the default value (*k* = 0.7 y^{-1}). Significant quantity of food waste is found in total waste. It is a rapidly biodegradable waste but if its half life increases i.e., degradation rate decreases, then remaining substantial amount of food waste in the landfill site are responsible for increased gas generation even after closure.

Regarding paper, individual and total methane generation decreases by ~7% and ~0.2% and recovery decreases by ~3% and ~0.2% for *k* = 0.06 y^{-1} with respect to the default value (*k* = 0.07 y^{-1}). Similarly for *k* = 0.09 y^{-1}, individual and total methane generation increases by ~10.5% and ~0.3% whereas recovery increases by ~2% and ~0.1%. The effect on methane recovery is very less as the amount of paper is small in comparison to the other materials. For *k* = 0.05 y^{-1} methane generation from wood only and total increases to 18.6% and 2.3% along with methane recovery increases by 13.2% (individual) and 3.2% (total) respectively. Shorter half life of wood, i.e. 15 years instead of 20 years, contributes more methane in 10 years recovery period. Similarly for *k* = 0.03 y^{-1}, methane generation decreases by 14.3% for wood with respect to default value and 1.73% in total, along with methane recovery decreases to 11.7% (individual) and 2.8% (total).

Sensitivity analysis is also done by means of certain variations (in %) in composition of food waste, wood, and paper as shown in Table 4.15.

Table 4.15 Effect of composition variation on methane generation and recovery

% variation w.r.t. total waste	Individual changes in methane generation and recovery	Changes in total methane generation	Changes in total methane recovery
Food waste (± 1%)	± 2.3%	± 1.4%	± 0.85%
Wood (± 1%)	± 15.9%	± 1.9%	± 3.9%
Paper (± 1%)	± 84.0%	± 2.7%	± 4.5%

In composition, food waste is too high (~50%) but it has low DOC (0.15). Due to its rapid biodegradability, methane generation is initially high for first five years from the deposition of waste but less amount of methane can be captured or recovered if the active period is more. Wood and paper are slowly biodegradable wastes with high DOC values (0.43) and (0.40), so, degradation rate is slow and significant methane generation will last for many years. Individual changes of methane generation and recovery is high because of higher percentage of carbon i.e., high DOC value but there is no major changes in total methane recovery as its quantity is very less in MSW.

4.9.3 LandGEM Model

USEPA landfill gas emission model (LandGEM) is widely used for the estimation of methane from degradation of solid wastes in the waste disposal site with time. LandGEM model can be used as screening tool with clean air act (CAA) default values to calculate expected minimum emissions for the purpose of determining the applicability of regulations to a landfill. The model is based on first-order decay reaction in waste biodegradation and methane generation as shown in equation

$$Q = L_0 R\left(e^{-kc} - e^{-kt}\right);$$

where $Q =$ methane generated in current year (m^3 y^{-1}),

$L_0 =$ methane generation potential (m^3 t^{-1} waste),

$R =$ average annual waste acceptance rate during active life (t y^{-1}),

$k =$ methane generation rate constant (y^{-1}),

$c =$ time since MSW landfill closure (y),

$t =$ time since MSW landfill opened (y) (USEPA, 2005).

4.9.3.1 Selection of Parameters

Methane generation potentials (L_o) of 103.7, 121.4 and 60.7 m^3 t^{-1} of waste were determined experimentally and used for Bangkok, other municipalities in case of landfill site and open dump site respectively (Towprayoon, 1994) as those were determined experimentally. The first-order decay rate constant k, 0.05 y^{-1} was recommended for developing countries (USEPA, 1998). The CAA default methane generation rate constant k value is 0.05 y^{-1} which corresponds to a half-life of about 14 years and default L_0 is 170 m^3 t^{-1}. However, the model can also be used with user-defined parameters based on site-specific data and waste composition (KEIP, 2007a). A higher k value (0.1 y^{-1} for 7 year half-life) is applicable for high moisture conditions and rapidly degradable materials such as food waste consistent with Kolkata conditions and MSW characteristics. The methane generation capacity (L_0 = 70 m^3 t^{-1}) should be reduced for Kolkata waste having high inert and moisture content and less wood and paper (KEIP, 2007a) (Chattopadhyay et al., 2010b). Input parameters and waste acceptance values are shown in Table A-4.15 of Annexure 4.4.

4.9.3.2 Results of Overall Gas Generation and CH_4 Recovery

As per LandGem model, estimated methane generation, entrapment, recovery and emission from existing open dump site, Dhapa are shown in Fig. 4.22. Considering k = 0.1 $y^{-1}$and L_0 = 70 m^3 t^{-1}, quantity of CH_4 generation (1987-2021); CH_4 entrapment and recovery for the period of 10 years (2012-2021) are estimated as 8,69,570 t; 2,51,537 t and 1,25,769 t respectively. Results of methane generation from output model of IPCC is shown in Table A-4.16 of Annexure 4.4. Compare to other models in LandGEM, CH_4 generation will continue for some more time after closure; however after 15 years of closure methane generation will have decreased. If recovery period is increased to 15 years, ~27% more methane recovery can be achieved. Quantity of GHG reduction would be 26,41,149 tCO_2-eq. For existing system 1,56,19,821 tCO_2-eq will be emitted from open dump site Dhapa and contribute to the climate warming.

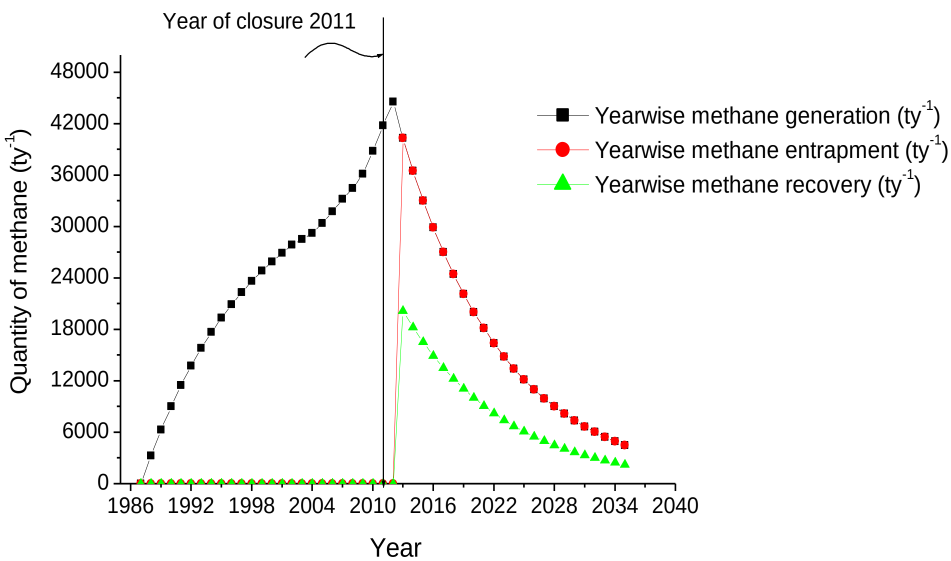


Figure 4.22 Year wise methane generation, entrapment and recovery from open dump site Dhapa following LandGEM mehod

4.9.3.3 Sensitivity Analysis

Keeping the same methane generation rate constant, if L_0 is varied from 68 to 72 m^3 t^{-1} then the amount of CH_4 generation and CH_4 recovery varies between 2% to 3%. If k = 0.05 y^{-1} and L_0 = 70 m^3 t^{-1} are taken for CH_4 estimation then its generation will be on an average ~26% less and also its recovery will be reduced by ~10% compared to assumed values (k = 0.1 y^{-1}; L_0 = 70 m^3 t^{-1}) due to lower degradation rate. A disadvantage of LandGEM is that it cannot differentiate the various types of organic matter as well as inert materials. Since the gas generation in LandGEM model is very much dependent on L_0 and k, therefore, these values should be considered based on the MSW characteristics and site conditions.

4.9.4 Triangular Model

In this model, organic materials present in MSW of Kolkata (Table 4.1) is divided into two parts (1) rapidly bio-degradable materials (RBW) [Table 4.16; Table 4.17] and (2) slowly bio-degradable materials (SBW) [Table 4.18; Table 4.19] (Chattopadhyay et al., 2008) [Table 4.16; Table 4.17]. The annual rates of degradation for fast and slowly biodegradable materials are based on a Triangular model. The degradation rate for RBW usually reaches the maximum within the first two years and continues for around 5 years whereas SBW reaches its peak within 7 to 8 years and continues up to 15 years (Tchobanoglous et al., 1993). The biogas production is assumed to begin at the end of the first complete year of the landfill operation. LFG release is estimated based on the combination of the triangular forms of RBW and SBW and the area under the release curve would represent the gas released over the period (Fig. 4.23).

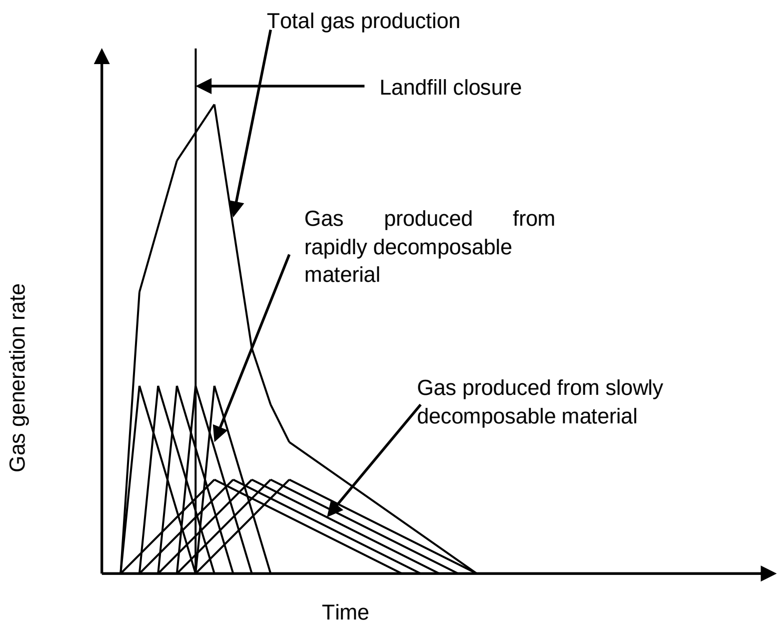


Fig. 4.23. Typical landfill gas generation rate from the rapidly and slowly decomposable organic materials

4.9.4.1 Analysis of Rapidly and Slowly Biodegradable Waste

Typical values of ultimate analysis (Tchobanoglous et al., 1993) for RBW are shown in Table 4.16. Table 4.17 shows chemical composition for the same.

Table 4.16 Typical values of ultimate analysis of RBW

Component	Percentage (%)					
	C	H	O	N	S	Ash
Food waste	48.6	6.4	37.6	2.0	0.4	5.0
Paper	43.5	6	44	0.3	0.2	6

Table 4.17 Analysis of weights and chemical composition of RBW (based on 100 kg Garbage)

Component	Moisture Content (%)	Weight (kg)		Composition (kg)					
		Wet	Dry	C	H	O	N	S	Ash
Food Waste	72.50	50.56	13.904	6.757	0.890	5.228	0.278	0.056	0.695
Paper	6.00	1.07	1.006	0.438	0.060	0.443	0.003	0.002	0.060
Total		51.63	14.91	7.195	0.95	5.671	0.281	0.058	0.755

Chemical formula for rapidly biodegradable waste (RBW) is $C_{29.95} H_{47.03} O_{17.72} N S_{0.09}$. Typical values of ultimate analysis and chemical composition of slowly biodegradable wastes (SBW) are shown in Table 4.18 and Table 4.19 respectively.

Table 4.18 Typical values of ultimate analysis of SBW

Component	Percentage (%)					
	C	H	O	N	S	Ash
Rubber and Leather	69	9	5.8	6	0.2	10
Wooden Matter	49.5	6	42.7	0.2	0.1	1.5
Coconut	49.6	6.1	43.2	0.1	0.1	0.9
Rags	55	6.6	31.2	4.6	0.15	2.5

Table 4.19 Analysis of weights and chemical composition of SBW

Component	Moisture Content (%)	Weight (kg)		Composition (kg)					
		Wet	Dry	C	H	O	N	S	Ash
Rubber and Leather	5.0	0.27	0.256	0.177	0.0230	0.015	0.015	0.000	0.026
Wooden Matter	25.0	1.15	0.862	0.427	0.051	0.368	0.002	0.001	0.013
Coconut	40.0	4.5	2.700	1.339	0.165	1.166	0.003	0.003	0.024
Rags	10	1.87	1.683	0.926	0.111	0.525	0.077	0.002	0.042
Total		7.79	5.501	2.869	0.350	2.074	0.097	0.006	0.105

Chemical formula for slowly biodegradable waste (SBW) is $C_{34.62} H_{50.22} O_{18.78} N S_{0.03}$.

4.9.4.2 Results of Overall Gas Generation and CH_4 Recovery

The estimated gas production for rapidly and slowly biodegradable organic materials is shown in Table 4.20. This is based on considering the 75% biodegradable portion of RBW and the rest are not at all degradable or very slowly degradable due to presence of non-biodegradable matter (lignin etc.). Due to the same reason, biodegradable portion for SBW is considered to be 50%. Detail analysis of gas production distribution over the five years period and fifteen years period is shown in Figure A-4.1, Table A-4.17, Figure A-4.2, Table A-4.18 of Annexure 4.4.4. At the end of 15 years, total gas generation will be 0.150 $m^3\,kg^{-1}$ of mixed waste (as discarded).

Table 4.20 Gas production rate of RBW and SBW

End of year	Gas production in $m^3\,kg^{-1}$ of dry weight in 1 year	
	RBW	SBW
0	0	0
1	0.214	0.0148
2	0.3745	0.0444
3	0.2675	0.074
4	0.1605	0.1036
5	0.0535	0.1332
6	0	0.1406
7	0	0.1258
8	0	0.1110
9	0	0.0962
10	0	0.0814
11	0	0.0666
12	0	0.0518
13	0	0.0370
14	0	0.0222
15	0	0.0074
Total	1.07	1.11

To estimate the total landfill gas production, waste deposited material from 1987 to 2011 is taken. Year 1987 is the landfill starting year and the landfill is assumed to be closed in 2011. One year is required to provide top cover and installation of gas extraction facilities so, gas entrapment starts from 2012. The effective extraction period for 10 years after the closure of the landfill is used in estimating methane generation and recovery. This is based on the fact that the majority of gas generation is in the first 10 years of total 15 years of effective gas production period. Same time period for waste deposition (1987-2011) and recovery (2012-2021) is considered for other models. Detailed analysis for methane generation, entrapment and recovery is shown in Annexure 4.4.4.4. From Fig. 4.24 it is observed that total CH_4 generation from 1987 to 2021 is 12,27,014 t and total methane entrapment will be 1,73,871 t. Considering 50% recovery for open dump site, total 86,936 t methane can be recovered up to 2021 i.e. 10 years after closure and amount of GHG reduction likely to be 18,25,656 tCO_2-eq.

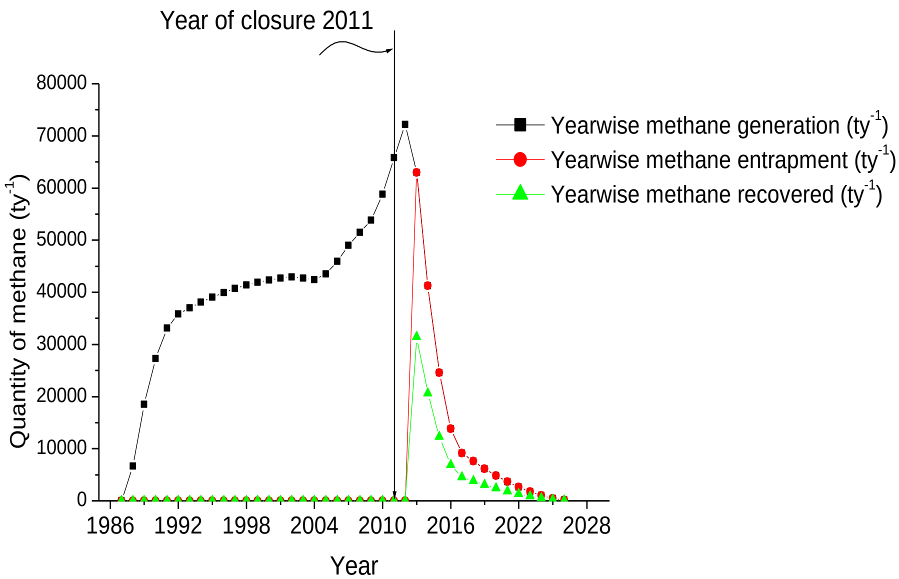


Figure 4.24 Year wise methane generation, entrapment and recovery from existing Dhapa landfill site following Triangular model

If methane recovery period is extended for another 5 years, only 3.3% increase in recovery is achievable, which is uneconomical for CDM benefit in respect of operation and maintenance cost of methane recovery system. So, 10 years after closure, is usually taken into account of gas recovery for CDM benefit. In the Triangular model, initial gas production is faster during active period but such initial higher rate gas generation cannot be captured from the active landfill site. Therefore for the existing open dump site at Dhapa, estimated methane recovery is less as major portion of the gas escapes when the active period is more. For existing system, total emission of CH_4 up to 2021 will be 2,39,41,638 tCO_2-eq.

4.9.4.3 Sensitivity Analysis

A sensitivity analysis is performed to estimate the total gas production by changes in biodegradable fraction in RBW and SBW. If 70% biodegradable waste in RBW and 40% biodegradable waste in SBW is considered, then the total gas generation for 15 years period is 0.135 m^3 kg^{-1} of mixed waste (as discarded). In case of 80% biodegradable in RBW and 60% biodegradable waste in SBW, the same generation will be 0.163 m^3 kg^{-1}.

4.9.5 Power Generation and CDM Benefit

Triangular, IPCC and LandGEM models are compared; average value of methane generation after closure from year 2012 to 2021 is found 1,83,136 t. It is observed that, methane generation in Triangular, IPCC and LandGEM model is 5.06% less, 32.29% less and 37.35% more from average value respectively. As Triangular model is considered based on site specific RBW and SBW composition of MSW, therefore it results close to the average value. IPCC is widely used model for methane generation for CDM benefit. As it is a conservative model to ensure the profit from CDM benefit it possibly predicts a lower value. LandGEM is also equally used for calculation of the gas generation but it is much sensitive to L_0 and k values. Absence of site specific L_0 value may lead to large gas generation deviation. So, the gas generation from MSW in the developing country like India, where bio-degradable and inert wastes are high, 40% weightage to Triangular model and 30% each for IPCC and LandGEM model is recommended. A summary of results of methane recovery from combined model is shown in Table A-4.19 of Annexure 4.4.5. Considering the said combination of the three models, estimate of total CH_4 generation (1987-2021), CH_4 entrapment (2012-2021) and CH_4 recovery (50% for open dump site) will be ~9,48,477 t; ~1,82,210 t; and ~91,105 t respectively and if it is flared then the certified emission reduction (CER) will be 19,13,205 tCO_2-eq.

4.9.5.1 Benefit from Existing Open Dump Site

Two technical options, power generation and flaring, are compared. Electrical power generation with IC engines or gas turbines is the most common practice for landfill gas-to-energy application. Projects are set up according to the perceived electrical power generation capacity and the number of generating units. If landfill gas production is insufficient to support at least one MW of power generation, it is generally deemed economically unsuitable. IC engines are typically used at sites capable of producing less than 3 MW (USEPA, 2008) and three to five engines are usually employed per project. However, one or two turbine units are preferred at landfills, where gas quantity can support more than 3 MW (Thorneloe, 1992). It is calculated, after scientific closure of the existing Dhapa disposal site, 5×10^9 MJ energy can be recovered and utilized within the specified period of 10 years. For calculation of power generation from existing system, energy content of methane as 55.7 kJg^{-1}, heat rate for IC engines as 12,000 BTU per kWh and 90% annual capacity factor are considered (USEPA, 2008). As methane generation from the waste disposal site could rapidly decrease, it is not appropriate to install a generator with large capacity; hence installed capacity will be limited to 3 MW (Fig. 4.25). Detail analysis of power generation is shown in Table A-4.19 of Annexure 4.4.5.

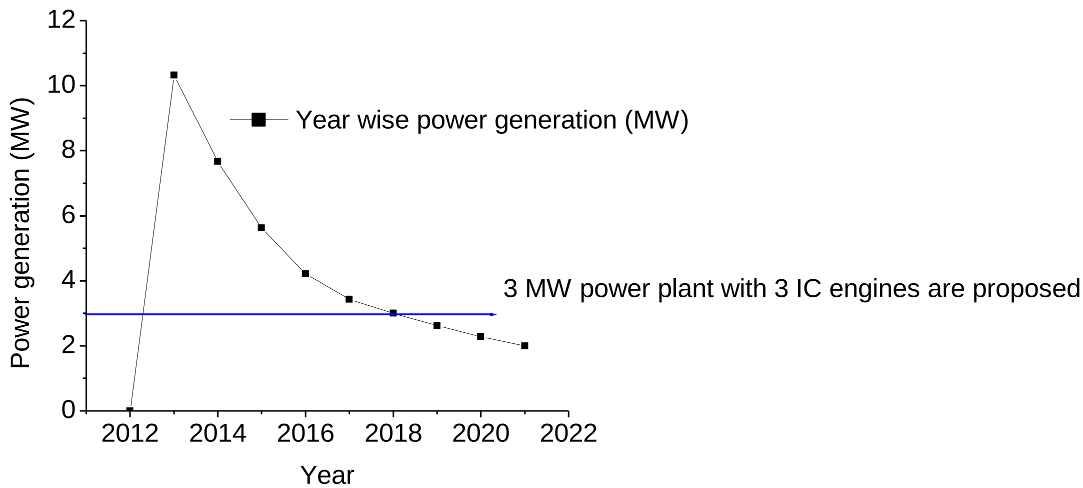


Figure 4.25 Proposed power generation from existing open dump site, Dhapa

In consideration of techno economical viability in Kolkata, earlier study (KEIP, 2007b) showed that cost of power generation in this range is not a profitable option. Therefore, as a CDM project, methane combustion by a flare system is preferred. In the case of flaring system, economic profits are summarized in Table 4.21 for the project crediting period of 10 years. The estimated engineering, procurement and construction (EPC) costs (assuming 20% escalation cost for 5 years on the estimated cost of 2007) (KEIP, 2007b) include (i) engineering, legal, commercial, accounting and professional services; (ii) well field installation cost; (iii) flare station installation etc.

Table 4.21 Summary of KMC profit for 10 years from existing site Dhapa

Project Income	Total CER (tCO_2-eq)	19,12,953
	Market price (INR/ tCO_2-eq)	364
	Total income	6,96,315
Project Expenditure	Capital cost (EPC cost + CDM set up cost)	2,26,842
	O&M cost	1,19,290
	Total expenditure	3,46,132
Project Profit	Profit before tax	3,50,183
	Tax (41.82%)	-1,46,447
	Profit after tax	2,03,736
KMC Income	Project profit 50%	1,01,868

Unit: in thousand INR except otherwise mentioned (1 US $=INR 52)

Estimated annual costs of operation, maintenance and monitoring (O&M cost) includes (i) well field maintenance @ 3% of well field cost; (ii) flare station maintenance @ 2% of flare station cost; (iii) electricity (0.02 kWh per cubic meter of landfill bio-gas); (iv) operating labor and security; (v) management and administration; (vi) testing and instrument maintenance and calibration; (vii) insurance, licenses and fees; (viii) professional services etc. (USEPA, 2007). Average market price of CER through the project period is assumed $7. Project profit of KMC is estimated according to its 50% investment of the EPC cost. The project profit of KMC, apart from environmental benefit, is around 10.2 crores for 10 years.

4.9.5.2 Benefit from Proposed ELF

For future case, it is considered that if the existing open dumping system with one phase is modified as an engineered landfill (ELF) site in two phases, of which first phase will be closed after first 10 years (2012-2021) and the second phase will be used for the next 10 years (2022-2031), then methane recovery percentage will increase compared to open dumping system. In case of proposed engineering landfill site, same combination of three models is also applied to estimate year wise generation, entrapment and recovery of methane as shown in Fig. 4.26. Total CH_4 generation for the years 2012 to 2041 is 23,89,785 MT; for 2022 to 2031 is 12,01,109.27 MT and for 2032 to 2041 is 5,44,115.23 MT. Total CH_4 entrapment for 2022 to 2031 is 3,15,838.51 MT and for 2032 to 2041 is 4,22,036.40 MT. Total CH_4 recovery for 2022 to 2031 is 2,36,880 MT and for 2032 to 2041 is 3,16,530 MT.

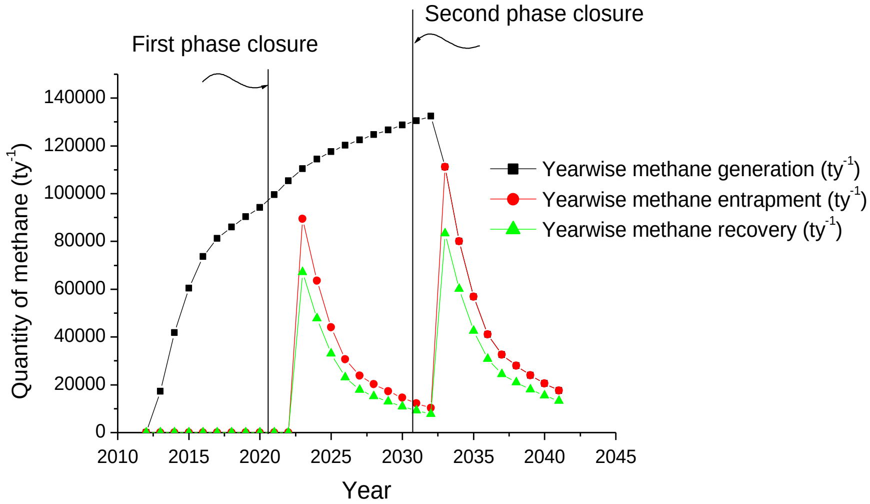


Figure 4.26 Year wise generation, entrapment and recovery of methane from proposed engineered landfill site

Year wise capture of gas in first ten years will be nil, then initiation of gas recovery will be started from first phase and continue. It will also be done from the second phase after closure, i.e. end of 20 years. Thereafter, it gradually diminishes with time elapsed. For the 1st 10 years (2022-2031) CH_4 recovery will be 2,36,880 t from the 1st phase and after closure of the 2nd phase recovery will be 3,16,530 t for the next 10 years (2032-2041). If phase wise system is not adopted then CH_4 recovery from the 1st phase will not be possible and additional 49,74,480 tCO_2-eq likely to be emitted in the environment which contributes to global warming. Since 75% gas recovery is considered for proposed ELF site, therefore, 5,53,410 t methane (year 2022 to 2041) can be captured and 3.5×10^{10} MJ energy would be available from it.

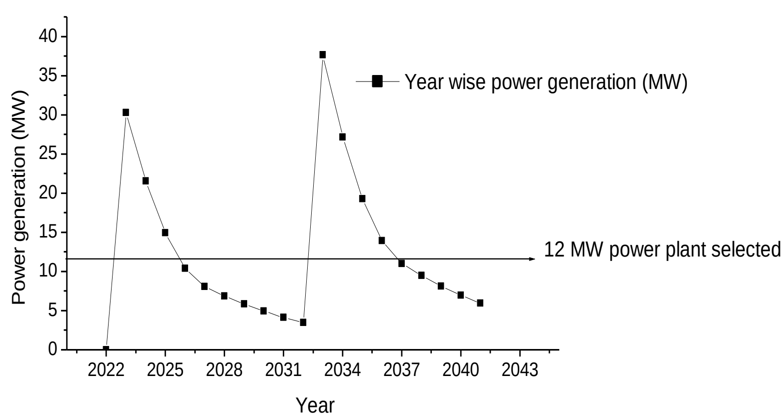


Figure 4.27 Power generation from proposed engineered landfill site

As this is a future project having phase wise closure facilities of engineered landfill site and greater methane capture rate achieves higher CER value (1,16,21,610 tCO_2-eq for 20 years) and higher energy generation. Average possible power generation for 20 years will be 12.5 MW (Figure 4.27), therefore considering its techno economic viability, 10 MW power can be recommended.

4.9.6 Observation on Results

Triangular, IPCC and LandGem, landfill gas emission models are used for the estimation of the landfill gas emission rates from existing open dump site, Dhapa and proposed ELF with phase wise closure facilities. The success of a LFG-to energy project is highly dependant to an accurate and timely estimation of the produced LFG, as an overestimation may lead to its failure. This estimation depends on the accuracy of the selected model, the quality of available data and the selection of correct coefficients. So for developing country like India, where organic and inert portion in MSW are high, appropriate combination of the three models is proposed for estimation of landfill gas. Sensitivity analysis is conducted to examine and specify the effect of the selected coefficients to be arrived at more representative assessed landfill gas generation. In Triangular model, 75% biodegradable portion of RBW and 50% biodegradable portion of SBW is recommended. In IPCC model, DOC and k value in food waste are highly sensitive in total methane generation and recovery due to its higher percentage. In LandGEM model, suggested values of k and L_0 are 0.1 y^{-1} and 70 $m^3\ t^{-1}$ respectively.

Site specific composition of MSW for Triangular model results close to the average value. As IPCC is a conservative model to ensure the profit from CDM benefit, it usually gives lower value. LandGEM is very much sensitive to L_0 and k values and compare to other models, CH_4 generation will continue for some more time after closure, which predicts higher recovery. So, the gas generation from MSW in the developing country like India, where bio-degradable and inert wastes are high, 40% weightage to Triangular model and 30% each for IPCC and LandGEM model is recommended.

For existing system, 5×10^9 MJ energy can be recovered for 10 years period after scientific closure of the existing open dump site, Dhapa, and installed plant capacity would be limited to 3 MW. So, flaring of methane is the suitable option because of its economic and commercial viability. From the CDM project profit of KMC, apart from environmental benefit, is around 10.2 crores for 10 years. Introduction of the engineered landfill with phase wise closure facilities for proposed project results 75% gas recovery efficiency and ~75% more methane recovery. If phase wise operation and closure is not adopted then additional 49,74,456 tCO_2-eq is likely to be emitted in the environment which contributes to global warming. From proposed ELF having CER value of 1,16,21,610 tCO_2-eq, 3.5×10^{10} MJ energy likely to be available and 10MW power plants could be supported for 20 years (year 2022 to 2041). Local benefits of this project include better managed landfill sites through reduced odors and explosion risks, employment opportunities and increased electricity supply, and reduced GHG emissions.

4.10 LANDFILL LEACHATE GENERATION

For providing appropriate cost effective leachate management options like liners, top covers, collection and treatment; quantitative and qualitative estimation of leachate are the key design parameters. The only method available for quantification of leachate, in case of existing landfills with no leachate collection system or future landfills, is modeling the site water balance. EPA's Hydrologic Evaluation of Landfill Performance (HELP) model is one of the best available well validated models for such purpose (Berger, 2002), (EPA, 2005), (Klink and Stuart, 1999). It predicts leachate generation with a good accuracy in annual basis (Shariatmadari et. al., 2010), (Tränkler et. al., 2001), (Katerina et. al., 2010), (Manandhar et. al., 2009). It can be used for selecting landfill final-cover systems (Agamuthu and Long, 2011). In India also HELP model has been employed for simulating the landfill hydrologic processes in an industrial area of Ankleshwar, Gujrat (Jose and Majumdar, 2003).

To find out the extent of contamination of ground water, conducting field test is costly and time consuming. Therefore use of validated models (Mohan and Muthukumaran, 2004), (Mirbagheri et. al., 2009), (Rouholahnejad and Sadrnejad, 2009) for this purpose is becoming a common practice. EPA's Composite Model for Leachate Migration and Transformation Products (EPACMTP) is one such validated model which has been used around the world (Sastry and Isukapalli, 1999), (Li and Benson, 2009), (Reinhart and McCreanor, 1999).

4.10.1 Study Area

Kolkata with 9 million populations generated 3000 MT/day of MSW as on 2006 analysis (Chattopadhyay et. al., 2007a) and at present waste generation has reached to ~ 4000 T/day. There is no source segregation arrangement, only 60% house-to-house collection and 50–55% open vats are used in the present collection system (Chattopadhyay et. al., 2009). Almost all of the waste generated is collected and transported to the disposal site but open dumping (without liners and without a leachate management facility) is carried out. The present dumping ground at Dhapa having 21.4 ha. area has been used for around 20 years and now has got exhausted (KEIP, 2005). The waste pile with no intermittent or top cover is almost a vertical structure with 20 m average height (Chattopadhyay et. al., 2007b). Currently some area adjacent to this site has been acquired by KMC and dumping is going on over there.

The physical composition of MSW of Kolkata is given in Table 4.3 (Chattopadhyay et. al., 2009b). For planning purposes, a density of 850 kg/m^3 has been adopted for biodegradable wastes (CPHEEO, 2000). The specific gravity, moisture content and total porosity of the waste is calculated as 1.58, 46 % and 0.694 (v/v) (Murthy, 1989) respectively. MSW of Kolkata is polluted with heavy metals like Hg (1 mg/kg), Cd (3 mg/kg), total Cr (43.9 mg/kg), Cu (54.4 mg/kg) and Pb (788 mg/kg) (KEIP, 2005).

Kolkata situated at 22.34^0 N latitude and longitude 88.24^0 E receives plenty of rainfall (1850 mm/year) and thus produces huge amount of leachate. A study conducted by CPCB in and around Dhapa landfill in Kolkata found that leachate is highly polluted with organic and inorganic pollutants (Saha et. al., 2003). Natural leachate collected around the old dumping grounds at Dhapa is found to have 0.43-0.85 mg/L Cr, 0.04-0.05 mg/L Cd, 0.002-0.009 mg/L Hg, 0.07-0.08 mg/L Pb and 0.06-0.28 mg/L Cu. Other than heavy metals natural leachate contains high BOD (375-425mg/L), COD (2455-2545 mg/L), Cl (3520-3943mg/L), TKN (228.6-585.5mg/L), TDS (9912-10186mg/L) and phenolic compounds < 1mg/L (KEIP, 2005).

The vadose zone below the ground surface generally contains 10 to 25m silty clay loam and its hydraulic conductivity varies between 10^{-8} to 10^{-5} cm/sec. Below this a fine sand bed is found which is the first shallow aquifer 10 to 20 m thick having hydraulic conductivity of around 10^{-3} cm/sec. Though the second aquifer at a depth of 80 - 90 m is the most potential and exploited aquifer of Kolkata, yet many parts of surrounding areas still use the shallow aquifer as drinking water source. The ground water flow in the Dhapa area is predominantly from east to west i.e. from landfill to city (KEIP, 2005), (Sengupta, 2009).

The analysis of water samples from the shallow aquifer around the Dhapa dumping ground clearly brings out the inherent poor chemical quality of the groundwater. The tube wells tapping deeper ground water have high concentrations of phenolic compounds at places, high Fe, Mn, high TDS (Ca, Mg and Cl content) and occasionally high Cr (KEIP, 2005).

4.10.2 Methodologies

4.10.2.1 HELP Model

The EPA-sponsored HELP model (Version 3.07) is a quasi-two-dimensional hydrologic model which uses water balance method to calculate daily water inflows and outflows and storage changes for a unit area of the system over a certain period of time. The basic water balance equation considers precipitation as the sum of runoff, evapotranspiration, leakage and change in water storage. The model uses daily climate data, landfill design data and soil data including waste characteristics for leachate estimation. The model is applicable to open, partially closed, and fully closed sites, and is a rapid and economical tool for screening landfill design alternatives (EPA, 1994a; EPA, 1994b). Detail analysis of estimation of leachate generation using HELP method is shown in Annexure 4.5.

4.10.2.2 Water Balance Method (WBM)

The potential for the formation of leachate can be assessed by preparing a water balance on the landfill. The principle sources include infiltration, i.e. precipitation minus runoff and evapotranspiration, the moisture in the solid waste, the moisture in the cover material. The principal sinks are the water leaving the landfill as part of the landfill gas (i.e., water used in the formation of the gas), as saturated water vapour in the landfill gas, and as leachate. The potential leachate quantity is the quantity of water in excess of the field capacity of the landfill material (Tchobanoglous, 1993). Detail analysis of estimation of leachate generation using WBM method is shown in Annexure 4.5.

4.10.2.3 EPACMTP Model

EPACMTP is simulates the fate and transport of dissolved contaminants from a point of release at the base of a different waste disposal unit (e.g. landfill), through the unsaturated zone and underlying groundwater, to a receptor well at an arbitrary downstream location in the aquifer. It takes into account various specific parameters of site, constituent, unsaturated and aquifer zone. Deterministic or Monte Carlo methodology can be used to model continuous or finite source. Detail analysis of estimation of leachate generation using EPACMTP model is shown in Annexure 4.5.

4.10.3 Considerations, Result and Discussions - HELP Model

4.10.3.1 Estimation of Leachate Generation from an Existing Open Dumping Ground at Dhapa, Kolkata using HELP Model

A study has been done with the HELP model to quantify the leachate generation from the existing open dumping ground at Dhapa, Kolkata. Two conditions have been modeled: filling (active) period and post filling (closure) period without any top cover. It is considered that during filling period waste is dumped at the rate of 1m lift per year for 20 years. The final moisture storage of each layer at the end of one year is set as the initial moisture content of those layers for the next year. Initial moisture storage of the topmost fresh waste layer is always set as 0.391(v/v) or 46 %. During post filling period the same 20 m waste layer without cover is simulated for the next 20 years.

(a) Input Data

Twenty years (1983 to 2002) daily precipitation, temperature and solar radiation data of Kolkata, obtained from weather monitoring station at Alipore of Indian Meteorological Department (IMD), have been used in the model. Daily solar radiation data for Kolkata is calculated from daily available sunshine hours considering the following equation.

Average daily radiation (Langley's/day) = $S_{min} + (S_{max} - S_{min}) \times$Sky clearance factor

Where, 1 Langley's is 0.042 $MJ/m^2/day$, sky clearance factor is the ratio of available and possible sunshine hours, S_{min} and S_{max} is minimum and maximum solar radiation (Sharma and

Gupta, 2005). Yearly average wind speed of 3.54 KPH and quarterly relative humidity of 67.12%, 71.0%, 77.65% and 73.83% has been used for Kolkata (NEERI, 2001).

Since waste is porous, it has been considered as a vertical percolation layer. MSW of Kolkata has a hydraulic conductivity of 10^{-3} cm/sec (KEIP, 2005) and porosity of 0.694 which is close to the default soil texture number 18 of HELP (Table 4.24) model having same hydraulic conductivity and 0.691 porosity (EPA, 1994b).

Evaporative Zone Depth is set to 45.7 cm (18 inches) since without vegetation capillary draw for clay approximately ranges between 12 to 60 inches (EPA, 1994a). Leaf Area Index (LAI) value of 0 has been considered i.e. bare ground is chosen as there is no vegetative cover on the top of the waste layer throughout the year. Considering total landfill area as 21.4 ha. (KEIP, 2005), percent of landfill area where runoff is possible is assumed as 80 %, surface slope as 1% and slope length as 100m.

The same 20 year weather data is repeated for simulation of filling and post filling period, keeping all other data same.

(b) Observation

Yearly average precipitation, runoff, evapotranspiration and leachate for filling and post filling period are shown in the Table 4.22 and Figure 4.28. During filling (active) period available evaporative zone water is more as fresh waste layer with 46% moisture is added each year. Therefore evapotranspiration is slightly more during filling process than post filling period when it has already percolated down. But on the other hand infiltrated water storage in the 20 m high porous waste pile is more than the water storage during filling period with slowly increasing (with) waste height. Subsequent release of this stored water resulted in slightly higher value of average leakage during post filling period.

Table 4.22 Yearly average precipitation, runoff, evapotranspiration and leachate both during filling (active) and post filling (closure) process

Average Values (L/m^2/year)	Filling (active) (20 year)	Post Filling (closure) (20 year)
Precipitation	1847.20	1847.20

Runoff	133.294	136.77
Evapotranspiration	883.657	723.49
Leachate	902.454	986.148

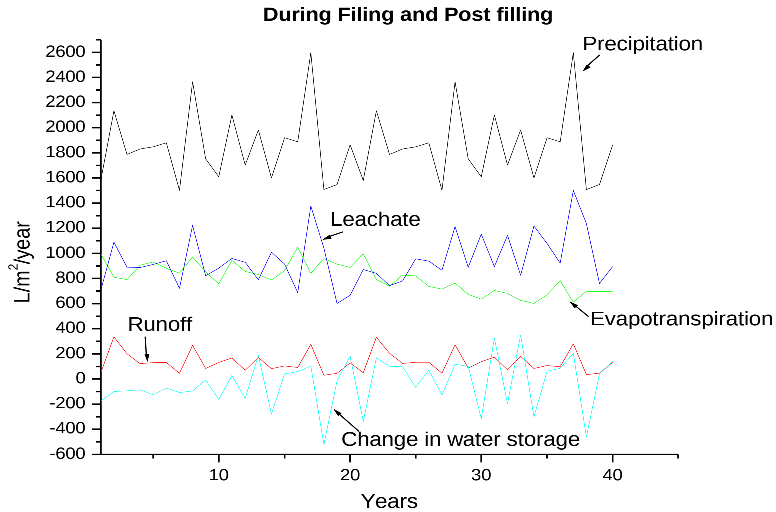


Figure 4.28 Graph showing yearly variations of precipitation, runoff, evapotranspiration and leachate both during filling (active) and post filling (post closure) process

It is observed lag period between precipitation and leachate generation due to the time it takes to travel the entire waste height. Figure 4.29 shows that lag period for leachate generation during filling period when waste pile of 5 m height is around one and a half month.

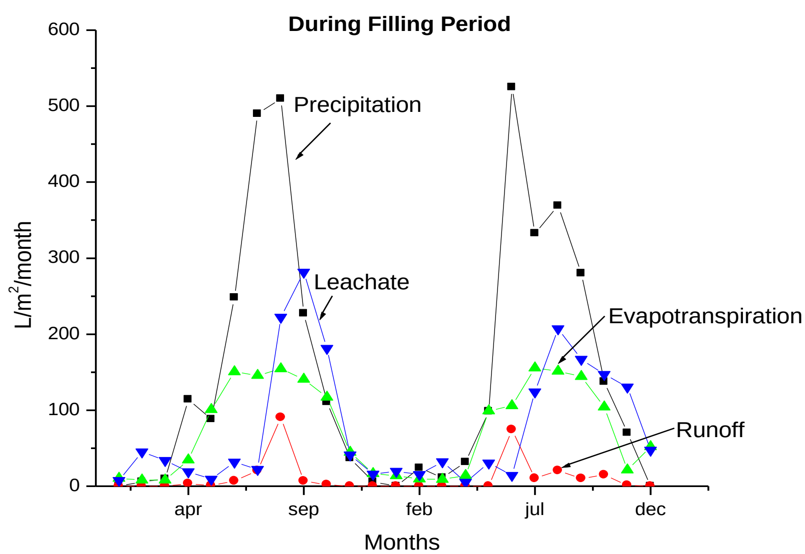


Figure 4.29 Graph showing monthly variations of leachate during filling process

For the same precipitation data during post filling lag period for leachate generation increased to five to six months (Figure 4.30). It is due to the higher leachate percolation time through 20 high waste pile.

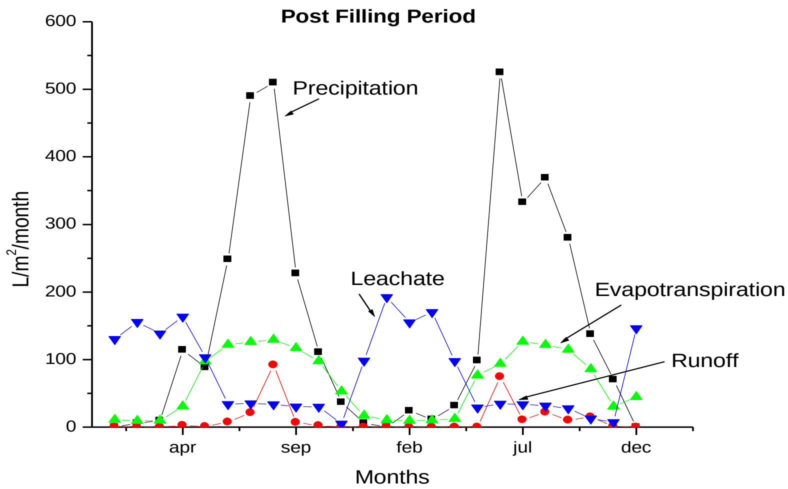


Figure 4.30 Graph showing monthly variations of leachate during post filling (closure) process.

Since, HELP model does not recognize chanelling effect which occurs due to non homogeneity of waste; retention of leachate considered by this program is higher than the reality. It is expected that the leachate will flow out faster in reality than the HELP model result (Shariatmadari, 2010), **(**Farquhar, 1988)**.**

The increase in moisture storage beyond the field capacity in case of uncovered waste can be due to the continuous downward percolation of huge amount of infiltrated rainfall and initial moisture content of waste from the above placed layers (Subramanya, 2009). Also due to lesser percolation rate of leachate into adjacent ground below the waste pile some water head may have developed. From data on final water storage of the waste layers at the end of filling period and 20 years after that shows that flow equilibrium have been reached and water storage does not change as the length of the model run increases (EPA, 2005).

Another point which should be considered that leachate from the solid waste dumpsites often gets stagnate in the surrounding area and can slowly finds its way into surface waters and ground water aquifers (ESG, 2011). Similar condition prevails around the Dhapa dumpsite also. To model this condition it is assumed that the bottommost waste layer acts as the lateral drainage layer through which infiltration percolating through the waste comes out from the side and gets stagnate beside the waste pile (Figure 4.31). Thus it is observed that lateral drainage is 894.58 L/m^2/year i.e. almost 90.7% of the infiltration. Only 37.37 L/m^2/year leachate (Table 4.23) reaches the shallow aquifer directly from the base of the landfill but stagnate leachate around the landfill can pollute surface and ground water aquifers.

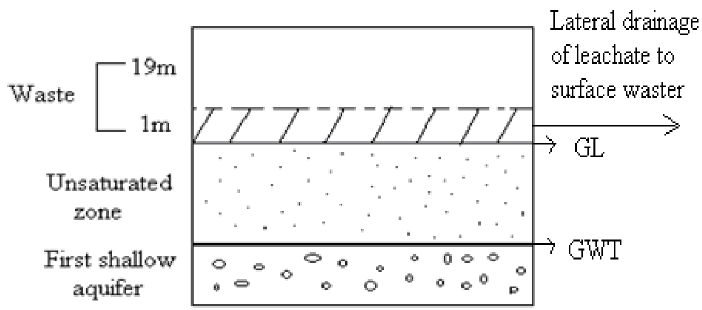


Figure 4.31 Cross-sectional view of existing open dumping at Dhapa considering lateral drainage through the last layer of waste

Table 4.23 Average yearly precipitation, runoff, evapotranspiration, lateral drainage from bottom waste layer, leachate into the shallow aquifer and head on top of the barrier soil

Precipitation	Runoff	Evapo - transpiration	Lateral drainage from bottom waste layer	Leachate into shallow aquifer	Head on top of the barrier soil layer
1849.85	136.77	723.49	894.58	37.37	3.7

*All values are in L/m^2/year except head which is in m.

4.10.3.2 Sensitivity Analysis of Different Input Parameters of HELP Model

(a) Variation of Slope of the Topmost Layer

As per Solid Waste Manual, 2000 top slope of landfill should vary from 3 to 5 % (CPHEEO, 2000). Keeping slope length constant at 100m, on increase of slope from 1 to 3 %, runoff increases by 4.92 % only and in case of 1 to 5 % increase of slope, runoff increases by 7.19 %. On the other hand decrease in leachate is observed only 0.6% and 1 % when slope increases from 1 to 3 % and 5 % respectively.

(b) Variation of Slope Length of the Topmost Layer

Keeping slope constant at 1 %, when slope length is decreased from 100m to 80m, increase in runoff is only 1.8 % and decrease in leachate generation is only 0.25 %. When slope length is increased from 100 m to 120 m, runoff is decreased by 2.6 % and leachate generation is increased by 0.28 % only. At a constant evaporative zone depth of 45 cm evapotranspiration does not change with such change in slope and slope length. The change in infiltration and hence the change in leachate generation is insignificant with change in slope length.

(c) Variation of Vegetation on Top Waste Layer

When some poor vegetative cover is considered on the top of the waste then most of the rain water gets trapped and run off decreases profoundly increasing infiltration. Runoff decreases almost by 58 % compared to bare waste ground. Therefore 31 % increase in evapotranspiration is observed as a result of predominant transpiration. Leachate on the other hand decreases by 14.4 % (Figure 4.32).

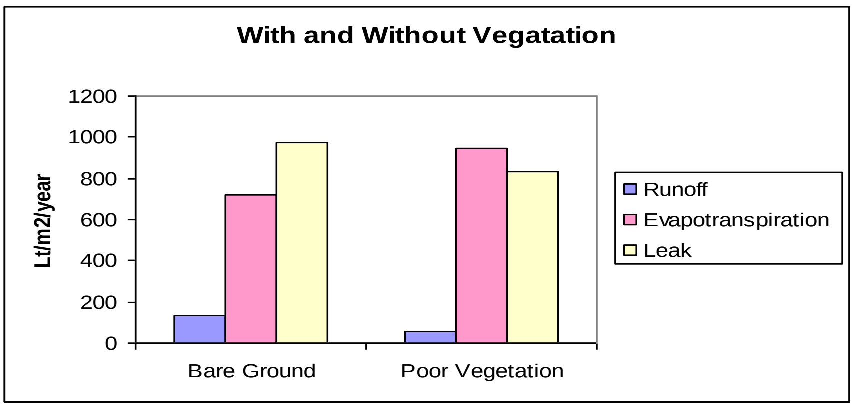


Figure 4.32 Variation of runoff, evapotranspiration and leachate with vegetation on top waste layer

(d) Variation of the Top Cover Layer

A good final cover system should be designed to reduce infiltration and ultimately leachate generation. Reduction of infiltration in a landfill is achieved by increasing runoff with minimal top cover erosion, transpiration, and restriction of percolation. The regulations require the final cover should be equal or better than the bottom liner system (Klink and Stuart, 1999). On the top of the waste pile, only a 60 cm vegetative soil cover (soil texture 12 of HELP model) is provided (CPHEEO, 2000) with 3% slope and 100m slope length and in another case 60 cm barrier soil cover (soil texture 16 of HELP model) (Table 4.24) is provided after the end of filling period. The initial moisture of the cover material is assumed to be same as their respective field capacity. Poor vegetation is considered on the top of both uncovered and covered waste.

Table 4.24 Soil and waste moisture retention parameters

Soil Texture No	Total Porosity (vol/vol)	Field Capacity (vol/vol)	Wilting Point (vol/vol)	Saturated Hydraulic Conductivity (cm/sec)
18	0.691	0.292	0.077	1.0×10^{-3}
12	0.471	0.342	0.210	4.2×10^{-5}
16	0.427	0.418	0.367	1.0×10^{-7}

It is observed that when a cover material is provided on the top of landfill infiltration decreases significantly and thus runoff increases (Table 4.25). When a soil cover is used runoff increases by 700.6 % and when a barrier soil is used it increases by 1411.8 % compared to uncovered condition. Leachate decreases by 45.37 % and 72.9 % when vegetative soil and barrier soil is used as cover material respectively instead of when waste is placed uncovered. Evapotranspiration on the other hand decreases only by 0.41% when silty clay is used and by 16.74 % when barrier soil is used (Table 4.25).

Table 4.25 Variation of runoff, evapotranspiration and leachate with on top layer

L/m^2/year	Uncovered waste	Vegetative soil cover	Barrier soil cover
Runoff	57.78	462.61	873.39
Evapotranspiration	947.18	943.29	788.6
Leachate	835.87	456.62	226.42

Decrease in infiltration is due to the reason that water holding capacity and saturated hydraulic conductivity of the cover material is less than the waste material (Table 4.24). Thus evaporation decreases but some of the infiltrated water gets lost by transpiration which was absent in case of uncovered waste. But overall evapotranspiration is less than uncovered waste case. Another reason of increased runoff is due to the increased slope and so overall leachate generation decreases to a great extent. When a barrier clay layer having lesser hydraulic conductivity is used, decrease in infiltration and leakage is much more than when silty clay soil is used.

(e) Variation of Intensity of Vegetation in the Vegetative Soil Covered Landfill

Variation of runoff, evapotranspiration and leachate with the intensity of vegetation on the 60 cm top soil cover with 3% slope and 100m slope length has been found out. It is observed that increasing vegetation increases leachate generation. Runoff decreases by ~ 40% when poor vegetation exists instead of bare ground and it further gets reduced by 60 % if a fair strand of grass is provided. Thus infiltration of the rainwater is more. On the other hand increase of evapotranspiration is significant, increased by 36.4 %, between bare ground and poor vegetative cover.

Thus it can be seen that minimum leakage (leachate) is obtained when the ground (cover) is bare and it increases with increasing vegetation. The maximum increase of leakage (leachate) rate between bare ground (cover) and excellent strand of grass is about 56.8 %. But bare soil cover will lead to its erosion, which in turn can expose the waste. It seems that poor vegetation will be optimum. Most landfills would tend to have at best a fair stand of grass and often only a poor stand of grass because landfills are not designed as ideal support systems for vegetative growth (HELP, 1994b). The climatic condition of Kolkata supports fair vegetation on silty clay cover. Therefore assuming fair strand of grass for engineered landfill and poor strand of grass in case on uncovered waste dumps is justifiable. The difference (increase) in leachate between poor and fair strand of grass is 12.69%.

If percent runoff area is increased from 80 to 90 % and to 100 % then leachate decreases by 10.65 % and 19.81 % respectively as runoff increases and infiltration decreases. Further it is observed that in this case as evaporative zone depth increases, evaporation increases and thus leachate decreases.

It is observed that depending on effectiveness of cover system post closer leachate generation can be reduced significantly. When minimum cover system as per the recommendation of CPCB was considered having 60 cm barrier clay on the top of the 20 m waste, then a 15 cm lateral drainage sand layer and finally a 45 cm top vegetative soil cover with runoff from 80% surface area, 3% slope, 100m slope length, 45 cm evaporative zone depth and fair strand of grass, then leachate quantity is significantly reduced to 43.01 L/m^2/year which is only ~ 2 % of precipitation. Thus leachate reduced by almost 95.6% compared to uncovered waste. This study is especially important for the existing dumpsites in order to minimize leachate generation at least after the end of its active life.

4.10.3.2 Estimation of Leachate Generation from Different Proposed Engineered Landfill Site using HELP Model

Leachate generation from different proposed engineered landfill site is estimated under the climatic condition of Kolkata using the HELP model.

(a) Phase-Wise Landfilling Operation

In this case it is assumed that total landfill area is divided into two halves and filling of waste is done in two phases. In the first phase waste is dumped in one half of the land at a rate of 2m/lift/year for 10 consecutive years. After completion of the first phase a 60 cm soil cover is placed with 1 % slope, 100m slope length and poor vegetative cover. Slope is not increased to account for the worst condition with minimum protection. Runoff is assumed to occur from 80% of the area. In the second phase, the other half of the landfill area is filled up for the next 10 years at the same rate and then covered. The phase-wise landfilling operation is described in the Figure 4.33.

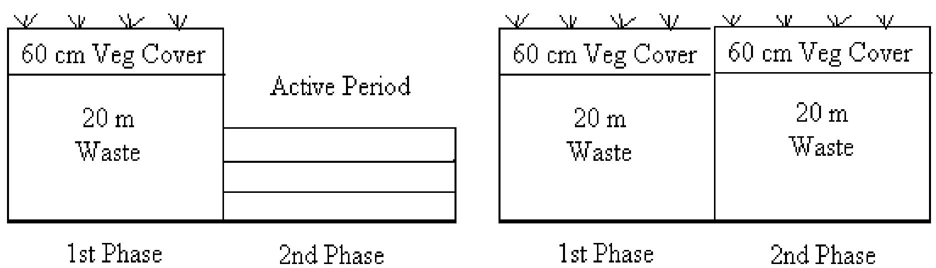


Figure 4.33 Phase-wise landfilling operation

Thus part I has a 10 year filling period and then it has been simulated for 30 year post filling period with cover. Similarly part 2 has a 10 year filling period and then it has been simulated for 20 year post filling period with cover in order to observe the leachate generation 20 year after the closer of the entire landfill operation. Thus this whole process can be divided into three phase. Therefore average leakage (leachate generation) through the entire landfill area in each of these three phases is as shown in Table 4.26.

Table 4.26 Average leachate generation from entire landfill area in phase-wise operation

Leachate generation(L/m^2/year)			
	From Part I	From Part II	From Total Area

			= (Part I + Part II)/2
Phase I (10 years)	949.65 (active)	0 (no activity)	474.83
Phase II (10-20 years)	474.3(covered)	1000.15(active)	737.23
Phase III (20-40 years)	442.96(covered)	460.54(covered)	454.75

It is observed that when phase-wise filling is done leachate generation decreased by 32.8 % during the active period of Phase II and by 54.2 % during the post closer period compared to the existing filling process in the Dhapa area i.e. dumping of waste over the entire area throughout the filling (active) period and without any top cover after end of the filling period. The importance of this process is that it reduces the leachate generation over the entire area even during the active period.

(b) A Semi-Engineered Landfill with Bottom Clay Liner, Leachate Collection System and a Top Soil Cover

Considering phase-wise filling operation, each phase of the landfill will consist of a bottom clay liner, leachate collection system and a top soil cover as shown in the Figure 4.34. This single liner system as described by CPCB (CPHEEO, 2000), is considered to observe the effect of cost minimization on leachate generation. The bottom lateral drainage layer is given a slope of 2% (CPHEEO, 2000) and slope length of 25 m. A system of perforated pipes and sumps are provided within the drainage layer.

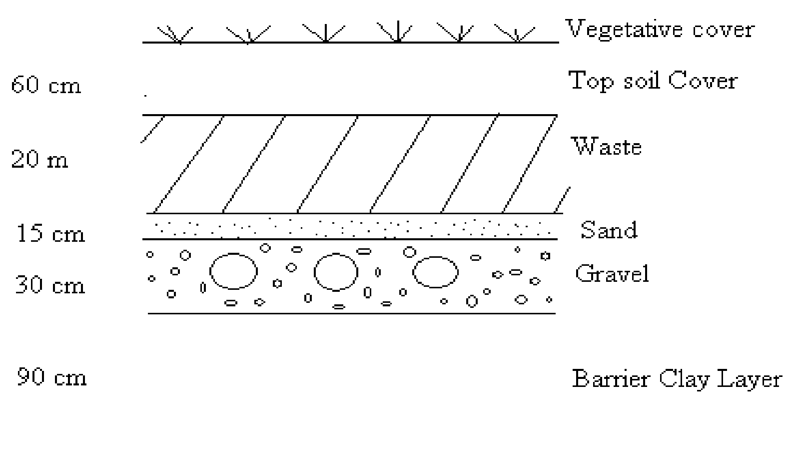


Figure 4.34 Cross-sectional view of the semi-engineered landfill

On the top of the liner system waste is dumped at a rate of 2m lift height/year for 10 years i.e. a total waste height of 20m. During the filling period top waste layer is given a minimum slope of 1%, and 100m slope length. After 10 years of filling, the waste is covered with 60 cm silty clay soil layer with 3 % slope and fair strand of grass. Evaporative zone depth is kept constant at 45 cm.

As stated this landfilling operation is also done in two phases so total average lateral drainage (leachate) which has to be collected and treated during first 10 year is 466.98 L/m^2/year, during next 10 year 720.88 L/m^2/year and post closer period 546.6 L/m^2/year. Average leak from bottommost layer during these periods is 14.9, 29.5 and 28.5 L/m^2/year respectively. Average head on the top of barrier clay liner during filling and post closer period is 6.13 mm and 3.50 mm respectively.

(c) A Complete Engineered Landfill

Considering phase-wise filling operation, each phase of the landfill will consist of the following layer arrangements as shown in Figure 4.35. The type of bottom liner system used is in accordance with the minimum requirement for all MSW landfills as recommended by CPCB (CPHEEO, 2000). 1.5 mm geo membrane has been considered with good placement and installation quality. In this case along with the minimum requirement, above the geo membrane a protective 5 mm geotextile filter is provided. It is also assumed that geo membranes have about 2 pinholes per hectare as manufacturing defects (EPA, 1994b). All other components were kept same as Case II i.e. waste is dumped at a rate of 2m lift height/year for ten years i.e. a total waste height of 20m.

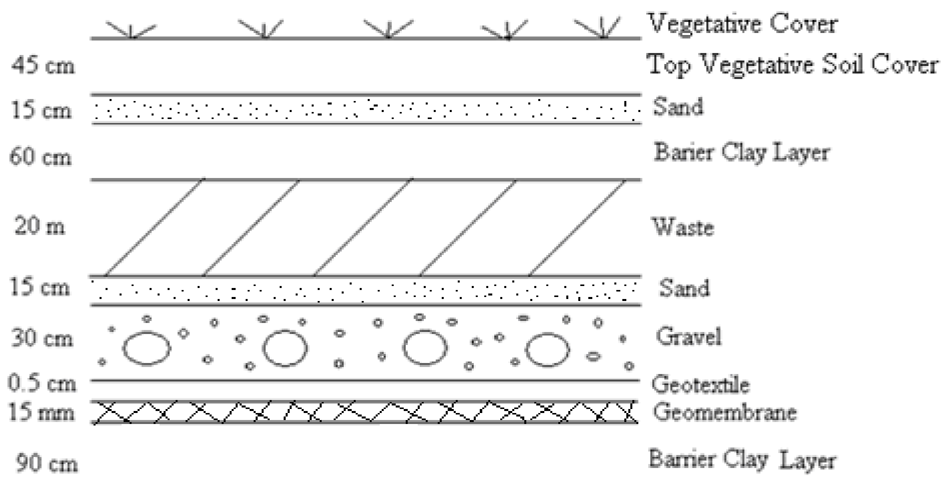


Figure 4.35 The cross-sectional view of a complete engineered landfill

During both filling and post closer period slope, slope length, top soil cover, evaporative zone depth and vegetation are kept same as semi engineered landfill. The top lateral drainage layer is given a slope of 1% and slope length of 100m.

During post closer period due to improved top cover system the infiltration is reduced from 44% to 8.5 % of precipitation. Average lateral drainage from the top of the waste is 73.2 % of the infiltration. Thus only 2.32% of the precipitations enter into the waste.

As stated this landfilling operation is also done in two phases so total average leachate generation which has to be collected and treated during first 10 year is 469.35 L/m^2/year, during next 10 year 503.6 L/m^2/year and post closer period only 42.4 L/m^2/year (Table 4.27). Average leak from bottommost layer during these periods is 0.0001, 0.00011 and 0.000024 L/m^2/year respectively i.e. almost nil. Thus chance of contamination of ground water during both filling (active) and post closer period gets highly reduced, as amount of leak through the geomembrane at the bottom is very low. And during post closer even if the quality of geomembrane deteriorates with time (Lee and Lee, 1993), still leak will be low as due to the top cover system infiltration into the waste itself is low.

Table 4.27 Total average leachate generation considering phase-wise landfill operation

Leachate generation from bottom (L/m^2/year) *			
	From Part I	From Part II	From Total Area = (Part I + Part II)/2
Phase I (10 year)	938.7 (active)	0 (no activity)	469.35
Phase II (10 year)	68.6 (covered)	938.7 (active)	503.6
PhaseIII(10 year)	42.4 (covered)	42.4 (covered)	42.4

*Leachate to be collected and treated

In complete engineered landfill the waste holds moisture equal to its field capacity and rest of it goes to the lateral drainage layer (Tränkler et. al., 2001). This is because of very low infiltration (~ 43 L/m^2/year) due to a good cover system.

Another study shows that if landfilling is done maintaining proper side slope (1:3) (CPHEEO, 2000) with earthen embankments and road width of 3 m then the increase in area requirement compared to straight vertical dumping as in case of Dhapa is 20%. Thus there can be an increase in leachate generation during the initial phase by maximum 20 %. But when one phase is complete the sides are covered for providing construction of roads thus there will be less infiltration as the process goes on. So on long term basis these two effects will average out each other.

4.10.4 Considerations, Result and Discussions - Water Balance Method (WBM)

Due to a limitation of HELP model it does not consider biodegradation of the solid waste and hence gas generation. Therefore WBM has been used to find out its effect on leachate generation from Dhapa dumping ground at Kolkata.

4.10.4.1 Considerations

Filling of waste has been done for 20 years at the rate of 1m lift height /year. In order to find the average infiltration into the waste HELP model was run with average annual rainfall 1850 mm (5.1 mm/d) for Kolkata keeping all other data same as used for existing case of Dhapa, Kolkata. HELP model gave runoff 0.36 mm/d or 7.08 % of rainfall. Co-efficient of run off for parks and undeveloped areas is generally considered as 10 to 20% (CPHEEO, 2000). As this is active dump site with much more void space and un-compacted loose solid waste so runoff co-efficient can be considered as 7%. Evaporation rate in dry season is generally 2.85 mm/d (7 months) and in wet season 1.96 mm/d (5 months) (ADB, 2005). So weighted average of evaporation rate is 2.48 mm/d. HELP model also predicted evapotranspiration rate as 2.55 mm/d. Therefore infiltration into the waste is 2.16 mm/d. Since in this case no final cover is considered even after the end of active period rainfall and infiltration value is kept constant for next 20 years also.

4.10.4.2 Observations

WBM calculated average leachate generation (during 20 year filling and 20 year post filling period) from an uncovered landfill as 944.3 L/m^2/year considering gas generation and 914.21 L/m^2/year without gas generation. Due to gas production during biodegradation of waste, the dry weight of waste get reduced which subsequently produce more leachate. But it is found that the effect of gas generation has negligible effect on leachate generation.

It is observed that HELP model over predicted leachate generation by only 2.63 % when compared to WBM considering gas generation and by 3.18 % when gas generation was not considered.

4.10.5 Considerations, Result and Discussions - EPACMTP Model

EPACMTP has been used to evaluate migration of waste constituents both metal and organics through the ground-water pathway from MSW landfill site at Dhapa Kolkata to down-gradient arbitrary drinking water wells situated in the shallow aquifer.

4.10.5.1 Considerations

Landfill without any cover or liner system is treated as a finite depleting source. Monte-Carlo method has been used to generate a probability distribution of well concentrations that reflects the variability in the various modeling parameters. Though Monte-Carlo analysis has been done yet site specific infiltration, recharge and soil characteristics has been given as constant value. Thus a combination of Monte Carlo and Deterministic analysis has been done by setting logical variable for Regional Site-based Analysis as false. Therefore Monte-Carlo method has been used with a combination of constant, derived and distribution of input variables to find the contaminant concentration at the receptor well. Figure 4.36 shows the different components of EPACMTP model. Detailed assumed data set used in EPACMTP model is given in Annexure 4.5.

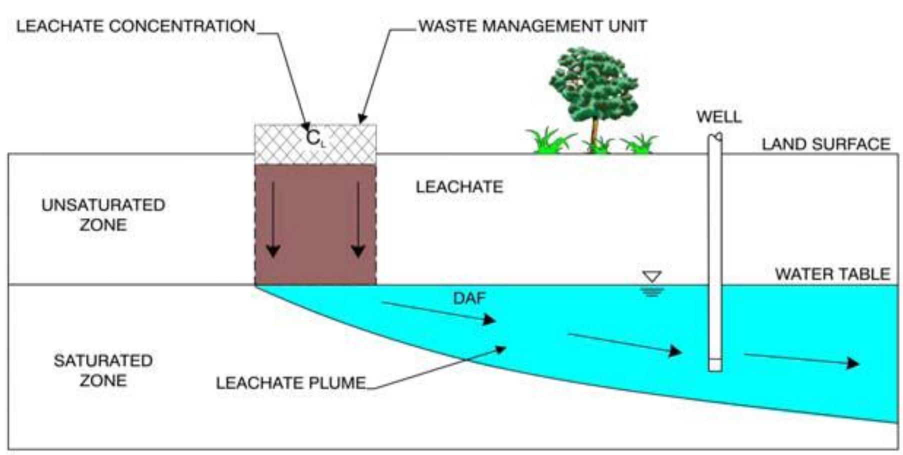


Figure 4.36 Different components of EPACMTP model

Since a finite source is being simulated, both the unsaturated and saturated zone transport modules are implemented in the transient mode and flow in steady state. Infiltration or leakage from 20m high landfill with 21.4 ha. area (at Kolkata's landfill site Dhapa) without any top cover or liner (KEIP, 2005) is estimated to be 986 L/m^2/year using HELP model. The recharge rate was determined for silty loam soil type as 456 L/m^2/year considering average annual rainfall of Kolkata to be 1850 L/m^2 using the HELP model. For Kolkata the aquifer saturated thickness is set as 10 m and the unsaturated zone (silty clay loam soil) thickness or depth to ground water table as 20 m considering the base of the landfill on the ground surface (KEIP, 2005). For conservative approach the aquifer hydraulic conductivity is set at 1890 m/year and the hydraulic gradient is assigned a value of 0.0057 **(**EPA, 2014). Since Kolkata region has sand and gravel aquifer (KEIP, 2005) non carbonate ground water type which represents unconsolidated sand and gravel aquifer with a natural pH of 7.4 has been used.

Depleting source is most appropriate for a landfill waste management scenario, where the waste accumulates during the active life of the unit, but leaching may continue for a long period of time after the unit is closed. Therefore considering depleting source metals have been modeled using linearized MINTEQA2 isotherm that calculates a single value of k_d (solid-liquid phase distribution coefficient) from a nonlinear isotherm (EPA, 2003b).

The hypothetical drinking water well is assumed to be located at a distance 500 m away from the edge of the waste unit because as per Solid Waste Management and Handling Rules in case of landfills no development buffer zone should be 500 m around the landfill (CPHEEO, 2000). Since the contaminant plume in the ground water follows a Gaussian plume pattern, highest concentration is always found along the plume centre line so well is considered at the plume centerline and at the midpoint of the saturated zone. Therefore assumed well is placed at a depth equal to unsaturated zone depth plus half of the saturated zone depth. The distance of the well has been varied to find concentration versus distance curve. Also the unsaturated zone depth has been varied to find its effect on concentration.

4.10.5.2 Observations - Metal Simulation Results

(a) Chromium

Chromium concentration in MSW is taken as 43.9 mg/kg and in leachate as 0.5 mg/L as reported by KEIP for Dhapa, Kolkata (KEIP, 2005). Therefore ratio of chromium concentration in waste to leachate i.e. Nratio is 87.8 L/kg. EPA (USEPA, 2017) drinking water standard for chromium (MCL- Maximum Contaminant Level) is 0.1 mg/L and Indian Standards (IS 10500:2012) recommended maximum allowable concentration in drinking water for total chromium is 0.05mg/L.

The 90 percentile value is taken for the study as it assures that the ground water concentration will be less than this value for at least 90 percent time considering the range of variability associated with waste sites. Therefore it provides a large degree of confidence that the results are adequately protective of human health and the environment. The percentiles versus peak chromium concentration are plotted and are shown in the Figure 4.37.

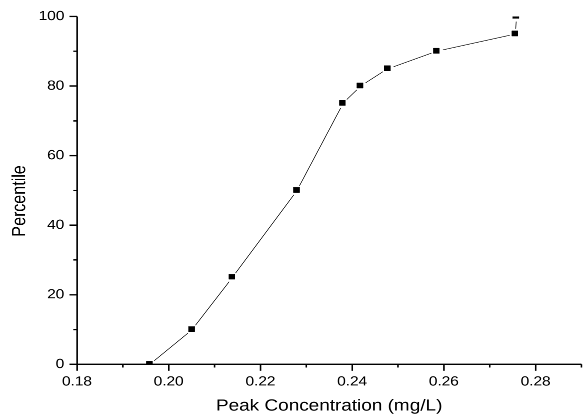


Figure 4.37 Graph showing percentile versus peak concentration (mg/L) curve

It is observed that peak chromium concentration appears in the receptor well after a certain period ~ 8 years as it takes some time to travel through the entire unsaturated zone and then through the aquifer before reaching the well. Therefore as the contaminated ground water plume reaches the well chromium concentration is observed and from then concentration starts increasing rapidly (Bhalla et. al., 2011). At around 9.5 years it crosses the maximum limit for DWS (Drinking water standard) and then reaches the highest concentration of 0.2585mg/L at around 30 years. Since EPACMTP gives the highest peak concentration within a time period it is observed that this highest peak concentration remains constant up to 1419 years and after that it decreases as shown in the Figure 4.38. The reason behind is that the landfill contains huge amount of chromium (high Nratio) which takes a long time to deplete. It takes almost 3485.6 years to exponentially reduce leachate concentration to 0.05 mg/L i.e DWS. Thus contaminants are contributed to the leachate for many years even after the site is closed (Farquhar, 1988). This time can be reduced only when total pollutant concentration in waste in the landfill is reduced by reducing Nratio, if all other variables are constant. If chromium concentration in the waste is taken as 140mg/kg i.e. the average concentration found in Chennai MSW (Esakku et. al., 2003) but in leachate it is kept at 0.5mg/L then the only difference in result will be that 0.2858 mg/L concentration will remain upto 4450 years and after that it will decrease. Therefore if only the contaminant concentration in the waste is increased, same peak concentration will remain in the receptor well but for longer period and vice-verse.

Peak, 30 year and 70 year average receptor well concentration of chromium with the passage of time is shown in Figure 4.39. At an early stage when the curve shows a sharp increase a substantial difference between peak and two average concentrations is obtained. As usual 30 year average is found to be more than a 70 year average as the exposure period is always selected to be centered about the time when peak receptor well concentration occurs. Since a flat curve remains for a long time during this period the steady state concentration, peak concentration and 30 year and 70 year average is found to be same.

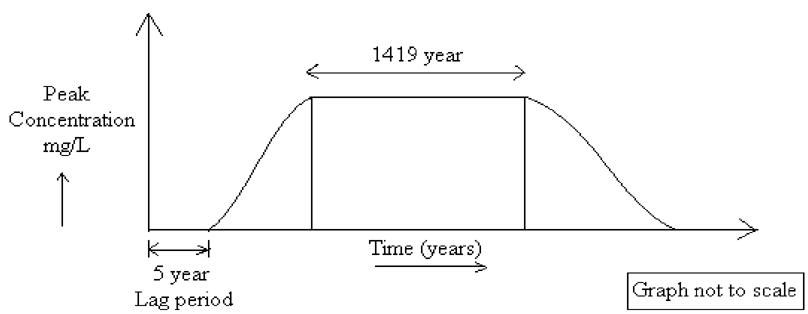


Figure 4.38 The concentration breakthrough curve for chromium

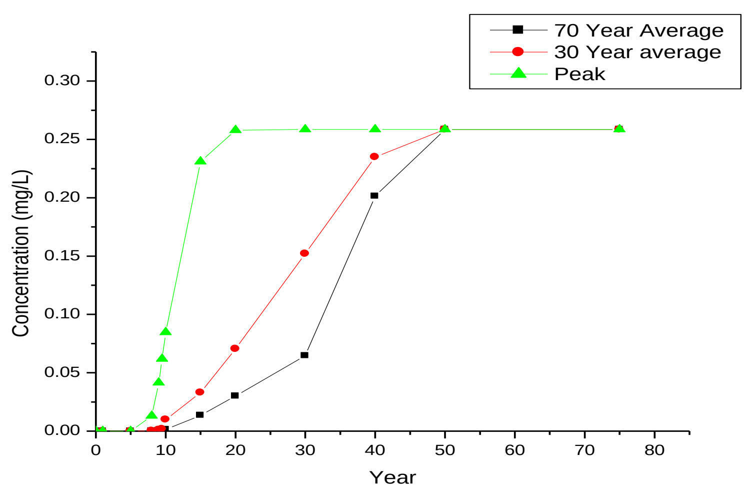


Figure 4.39 Peak, 30 year average and 70 year average chromium concentration variation with time

As the position of the receptor well is shifted away from the landfill the chromium concentration also decreases but even at 800 m distance away from the landfill it is above the DWS with a concentration of 0.1873 as shown in Table 4.28.

Table 4.28 Peak chromium concentration decreasing with distance

Distance (m)	50	100	300	500	700	800
Peak conc. (mg/L)	0.4771	0.4499	0.3458	0.2585	0.2104	0.1873

Variation of peak concentration of chromium at different distance with time is shown in Figure 4.40. Thus it is observed that contaminant concentration arrives at a receptor well earlier if it is near the landfill and stays there for lesser time than wells situated at far away distance.

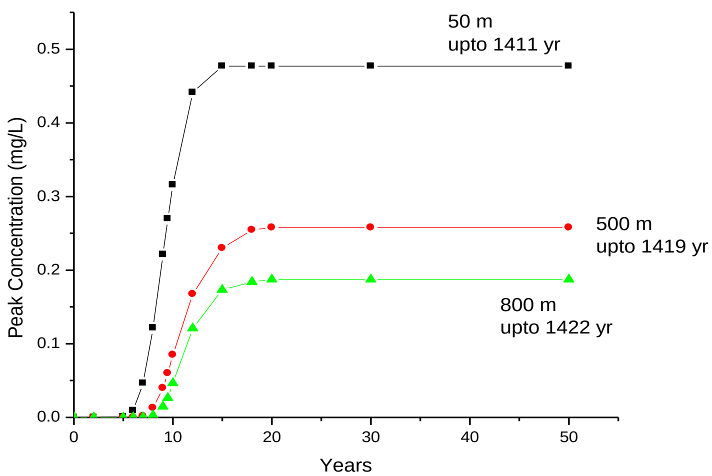


Figure 4.40 Variation of peak concentration of chromium at different distance with time

Depth to ground water affects the amount of dispersion and dilution that occurs between the base of the landfill and the well, and therefore impact concentrations at the monitoring well. Decrease in receptor well concentration with increasing depth to ground water is shown in Table 4.29.

Table 4.29 Variation of chromium concentration with unsaturated zone depth from ground level

Unsaturated zone depth (m)	11	15	20	40	80	100
Peak conc. (mg/L)	0.2758	0.2743	0.2585	0.2459	0.2456	0.2454

* Note: Concentrations are found at midpoint of aquifer having depth 10m.

At 500m distance away from the landfill and at 20 m unsaturated zone depth no concentration is found if saturated hydraulic conductivity of the aquifer is reduced to as low as 1×10^{-3} cm/sec, then slowly receptor well concentration increases as flow rate is increased and reaches a peak of 0.2847 mg/L at 1×10^{-2} cm/sec. After that it again starts decreasing probably due to a dilution effect caused by fast moving water at higher hydraulic conductivities (Rouholahnejad and Sadrnejad, 2009).

(b) Mercury

Mercury concentration in MSW is <1 mg/kg and in leachate is 0.0055 mg/L as reported by KEIP for Dhapa, Kolkata (KEIP, 2005). Mercury concentration in MSW is taken as 0.29 mg/kg which is the average concentration found in Chennai (Esakku et. al., 2003). EPA (EPA, 2017) drinking water standard for mercury (MCL) is 0.002 mg/L and Indian Standards (IS 10500:2012) recommended maximum allowable concentration in drinking water for mercury is 0.001mg/L. At around 12 years it crosses the maximum limit for DWS and then reaches the highest concentration of 0.002843 mg/L at around 30 years. After that the highest peak concentration i.e 0.002843 mg/L remains constant upto 876.8 years and then starts decreasing. It takes almost 1,558 years to reduce leachate concentration to 0.001 mg/L i.e DWS. As the position of the receptor well is shifted away from the landfill the mercury concentration also decreases but even at a distance of 800m receptor well concentration is 0.002058 mg/L which is above the DWS.

(c) Lead

Lead concentration in MSW is 788 mg/kg and in leachate as 0.075mg/L as reported by KEIP for Dhapa, Kolkata (KEIP, 2005). EPA (USEPA, 2017) recommended Maximum Contaminant Level (MCL) in drinking water is 0.015 mg/L but BIS (IS 10500:2012) recommended it as 0.01 mg/L. Lead appears in the receptor well after a very long, about 200 years, from the closer of the landfill. After 350 years peak concentration at the well crosses EPA standards. It reaches 0.0285 mg/L within 400 years but then concentration increases very slowly and reaches the steady state concentration of 0.03877mg/L at around 2000 year and remains constant up to 9600 year.

(d) Cadmium

Cadmium concentration in MSW is 3 mg/kg and in leachate is 0.045mg/L as reported by KEIP for Dhapa, Kolkata (KEIP, 2005). BIS (IS 10500:2012) recommended DWS is 0.003 mg/L but

EPA (USEPA, 2017) recommended MCL is 0.005 mg/L. Cadmium appears in the receptor well after 10 years from the closer of the landfill. At around 15 years it crosses the DWS for BIS and then increases rapidly and reaches 0.02202 mg/L within 40 years but then it concentration increases very slowly and reaches the steady state concentration of 0.02326 mg/L at around 100 year and remains constant up to 1140 years. It takes 3172 years to exponentially reduce leachate concentration to 0.003 mg/L.

(e) Copper

Copper concentration in MSW is 54.4 mg/kg and in leachate is 0.2 mg/L as reported by KEIP for Dhapa, Kolkata (KEIP, 2005). Thus as such copper concentration in leachate from Kolkata's dumping ground is within BIS (IS 10500:2012) maximum allowable standard in drinking water i.e 1.5mg/L and also well within EPA's (USEPA, 2017) MCL of 1.3 mg/L. EPACMTP has been run to check whether the ground water concentrations remains within the desirable limit of 0.05mg/L as set by BIS. Copper also appears in the receptor well after 80 years from the closer of the landfill. After 100 years it peak concentration at the well starts increasing rapidly and it crosses the desirable limit of 0.05 mg/L after 170 year. It reaches 0.0758 mg/L within 700 years but then it concentration increases very slowly and reaches the steady state concentration of 0.1034 mg/L at around 1300 year and remains constant up to 5114 year. Therefore it takes almost 6501.2 years to exponentially reduce leachate concentration to 0.05 mg/L. At a distance of 800 m receptor well concentration is 0.0749 mg/L which is above the desirable DWS of 0.05 mg/L.

4.10.5.2 Observations - Organics Simulation Results

Generally organic content of leachate is measured in terms of BOD_5 or COD. Exact concentration of particular organics in leachate or its proportion in solid waste is not available for Kolkata. Therefore EPACMTP has been used to find out maximum concentration of these compounds in leachate that results in safe ground water concentration. Time taken to decrease the leachate concentration below the DWS when Nratio is 0.1, 0.5, 1, 5 and 10 is around 25, 115, 200, 1000 and 2000 years respectively. Since gas generation occurs for around 15 years and BOD, COD of leachate gets highly reduced after 20 years and even xenobiotic organic compounds do not pose a major long-term problem (Kjeldsen, 2002), therefore Nratio of 1 is taken for all organic simulations. When simulation is done taking Nratio 1, peak concentration remains for approximately 25 years after the closer of the landfill. First order biodegradation rate constant of different organics in anaerobic groundwater condition as recommended for input into EPACMTP has been used. Same biodegradation rates have been used for both unsaturated and saturated zone. Table 4.30 summarizes the simulation results of organics. For all cases the receptor well is considered at a distance 500 m from the landfill and at 25 m depth.

Table 4.30 Receptor well concentrations of different organics

Organics	Biodegradation Rate (d^{-1}) (EPA, 1999)	Initial Leachate Concentration (mg/L)	Leak 986 L/m^2/year	
			Receptor Well Concentration (mg/L)	Dilution attenuation factor (DAF)
Phenol	0.0013	0.5	0.002	250
	0.032	28000	0	-
Chloroform	0	1300	0	-
Benzene	0	0.0097	0.005	1.94
	0.0033	410	0.00217	189027
Toluene	0.00099	800	1.008	794
	0.059*	1600	0	-
Vinyl Chloride	0.00033	0.015	0.00194	7.7
	0.0073*	100	0	-
Acetone	0.0037	11000	0.03892	282776

* Biodegradation rate are applied to unsaturated zone only

Organics concentration obtained in the receptor well is highly dependent on their biodegradation rate in the substrata. Benzene, phenol, toluene and vinyl chloride are somewhat persistent with low dilution attenuation factor (DAF). On the other hand chloroform due to high hydrolysis rate constants and acetone due to its high degradability is found to be safe. But though it is safe for drinking in terms of chloroform but its degradation products can be toxic so it should be studied further.

All the above results are obtained at 986 L/m^2/year leakage rate. If by providing the complete top cover system leachate is reduced to 43 L/m^2/year then at 500m distance away from the landfill and at 25 m depth below ground level then metal concentrations except cadmium are found to be safe in the receptor well. Even the high initial concentrations of toxic organic compounds in the leachate, as shown in table 4.31, do not have any trace in the receptor well if the leachate amount is 43 L/m^2/year.

Table 4.31 Safe peak rreceptor well concentration of different metal at 43 L/m^2/year leakage rate

Leakage Rate 43 L/m^2/year						
Metal				Organics		
	DWS (mg/L)	Safe Initial Leachate Concentration (mg/L)	Safe Peak Receptor Well Concentration (mg/L)	Organics	Bio-degradation Rate (d^{-1})	Safe Initial Leachate Concentration (mg/L)*
Chromium	0.05	0.5	0.048	Phenol	0.0013	28000
Mercury	0.001	0.0055	0.00053	Benzene	0.0033	410
Lead	0.01	0.075	0.005314	Toluene	0.00099	1600
Cadmium	0.003	0.045	0.0043	Vinyl Chloride	0.00033	100
Copper	0.05	0.2	0.2227×10^{-5}	Acetone	0.0037	11000
				Chloroform	0	1300

* Safe initial leachate concentrations (mg/L) at which no trace of these organics is found in the receptor well.

4.10.6 Observations on Results

Kolkata with sufficient precipitation especially during monsoon with unlined landfill sites is generating ~ (900-1000) L/m^2/year i.e. ~ 2.14×10^8 L/year leachate from Dhapa. A minimum of 60 cm vegetative soil cover or barrier clay cover reduces leachate generation by 54% and 73% respectively. But a complete top cover system is recommended as it reduces leachate by ~96%.

Phase-wise landfilling operation is recommended as it decreases leachate generation by 32.8 % even during active period.

From the output obtained from running EPACMTP model it is observed that metal concentration appears in the receptor well after a lag period and then increases rapidly and reaches the peak but remains for several hundred or thousand years. Peak concentration of organics on the other hand remains for around 25 years after the closer of the landfill and then starts decreasing, as by then the waste almost gets stabilized. Therefore during the active period providing leachate collection and treatment and using bottom liner system are necessity. However, several researchers have documented that liners eventually leak. Maximum life of liners is 50-100 years. Thus lined MSW landfills will postpone groundwater pollution only and remain a threat to groundwater quality forever from heavy metals point of view. If the leachate amount is reduced to 43 L/m^2/year by providing complete cover system then most of the metals and organics concentrations are found to be safe in ground water.

Thus for the future engineered landfills and for existing open dump sites throughout the country including the dumpsite at Dhapa, it is recommended that a complete cover system comprising 60cm barrier clay on the top of waste followed by 15 cm lateral drainage sand layer and 45 cm vegetative soil cover on top of it with fair vegetation should be provided as it reduces leachate generation by ~ 96% after the closer of the landfill in order to prevent contamination of precious groundwater due to solid waste disposal.

4.11 LAND POLLUTION

Land pollution, the deposition of solid or liquid waste materials on land or underground in a manner that can contaminate the soil and groundwater, threaten public health and cause unsightly conditions and nuisances. The permeability of soil formations underlying a waste disposal site is of great importance with regard to land pollution. The greater the permeability, the greater is the risks from land pollution. At present solid wastes are generally collected and placed on top of the ground in uncontrolled open dumps, which often become breeding grounds for rats, mosquitoes, flies and other disease carriers and are sources of unpleasant odours, windblown debris, and other nuisances.

4.11.1 Background

The East Kolkata Wetland (EKW) (22° 27′ N 88° 27′ E) comprises a large number of open land and water bodies distributed across the districts of South and North 24 Parganas. The multifunctional wetland ecosystem is spread over 12,500 hectares (IWMED, 2004). It has, along with the wetlands, 254 sewage-fed fisheries, agricultural and solid waste farms and some built up areas. Kolkata's only waste disposal landfill known as "Dhapa" also falls under this East Kolkata Wetland (EKW). In the year 2002 EKW was declared as a 'Ramsar site' (Ghosh, 2002; IWMED, 2004).

At western fringe of EKW area, Dhapa has been historically used for traditional waste dumping of MSW of Kolkata for many decades. The dumping sites are not water bodies. With the gradual development of the city towards the east, the waste dumping has moved away further eastwards from the city and the old dumping areas nearer to the main city are now used for farming (locally referred to as garbage farming). The current dumping area is spread over about 21.4 ha. It consists of two unlined dump sites (one part to the south with area of 13.3 ha and another part to the north with area of 8.1 ha), spaced around 500 m apart. The presence of Dhapa dump site will have an impact on the soil surrounding the dump site, mostly during the active phase and to some extent after closure. Soils in the Dhapa farming land also had high amount of waste materials such as papers, plastics, stones, glasses etc. which can be dangerous to farmers working at the field. The transport of waste to farm lands took place mainly during the active period however still some waste e.g. exposed by the pigs living on site, are transported to the nearby farmlands either as windblown litter or by surface water run-off (WBPCB et al., 2012).

4.11.2 Distribution of Soil Pollution

Very little natural terrestrial vegetation is encountered at and around the dumpsite. A large area to the west of the dumpsite is used for cultivating vegetables. The vegetable fields are situated on previous garbage dumping plots. Growing vegetables on organic matter from garbage has been practiced since the nineteenth century (Furedy and Ghosh 1984).

The landfill soils had significantly higher concentration of total iron, manganese, cadmium, lead, Zinc compared to those in the background soil. Surface soil quality, top soil around the dumpsite was taken under investigation. In all top soil samples some metals are above the allowable limits (Pb, Cd, Cr, Cu, Sn, and Zn). Thus at and around dump site there is contamination present in top soil due to heavy metals and PAH (Poly Aromatic Hydrocarbons) content. Significant variations existed in the metal concentrations among the landfill soils and were due to the heterogeneity in the waste materials dumped at the respective sites over the years (WBPCB et al., 2012).

The vegetable production is done by the surroduning fermers for their household sustenance and income. The vegetable fields are designed with alternate bands of garbage filled lands and long trench like ponds known as “jheels”, where sewage is detained for some time, and then used to irrigate vegetable fields. Some 150 tons of vegetables is harvested per day from the plots including brinjal (eggplant), spinach, cauliflower, cabbage and pumkin (WBPCB et al., 2012). Vegetables grown on the plots adjacent to Dhapa dumpsite may be accumulate heavy metals taken up via the roots from garbage mixed soil, sewage used for watering the crops and soil exposed to leachate from the dump site.

Atmospheric heavy metal pollution due to exhaust from cars, industries etc. may also be a source, especially for vegetables cultivated near trafficked highways which may be exposed to atmospheric pollution in the form of metal containing aerosols. These aerosols can be deposited on soil and are absorbed by vegetables, or alternatively deposited on leaves and fruits and then absorbed.

Human uptake of heavy metals via vegetables grown at the vegetable plots adjacent to Dhapa dumpsite has been of concern as this may pose a serious risk to human health. Levels of heavy metals in vegetables including brinjal, spinach, cauliflower, cabbage and pumpkins grown adjacent to the Dhapa dump site were also studied. Table 4.32 shows the mean concentration of cadmium, copper, lead and chromium in washed samples of vegetables and in soil at the vegetable plots adjacent to Dhapa dumpsite (Ray, 2010; WBPCB et al., 2012).

Table 4.32 Mean concentration of Pb, Cd, Cu and Cr in washed samples of vegetables and in soil at the vegetable plots adjacent to Dhapa dumpsite

Vegetable Samples	Lead (µg/g dry weight)	Cadmium (µg /g dry weight)	Copper (µg /g dry weight)	Chromium (µg /g dry weight)
Brinjal (eggplant)	14	0.51	11.75	1.2
Indian spinach	16.6	0.37	16.13	1.1
Red Indian spinach	57.9	0.94	17.14	0.69
Cauliflower	3.9	0.11	6.11	2.45
Cabbage	5.1	0.07	0.45	0.21
Pumpkin leaves	21.6	1.12	10.85	3.38
Soil sample	11.6	0.72	7.9	
Maximum allowable limits in vegetables for consumption (recommended by WHO/FAO)	0.3	0.2	40	2.3

Above study indicates that lead content of all vegetable samples exceed the maximum allowable limits in vegetables for consumption and cadmium content exceed the maximum allowable limits except for cauliflower and cabbage. Chromium concentrations exceed the maximum allowable limits only for cauliflower and pumpkin leaves and the mean concentrations of copper in all the samples were within the safe value recommended by FAO/WHO.

The sewage fed fisheries and garbage farms that grew out of waste disposal in the eastern wetlands, survive today and serve to process part of Kolkata's wastes. Productive shallow fish ponds act as oxidation ponds and are important for the city. There are about 1700 acres of farm land adjoining the Dhapa solid waste dump. Top soil is found to be contaminated with heavy metals and organics due to decades of dumping of garbage and waste water disposal but there is not any significant bio-magnification of hazardous substances noted. The study on fish shows clearly that minimal toxic concentration and fish can be used for safe human consumption as the accumulated level of these toxic metals in human through fish consumption remains always far below the standards set by the WHO (EKWMA, 2010).

4.12 INFERENCE

From the foregoing study it is clear that existing municipal solid waste management system generates heavy pollution load which has a vast environmental impact. Air pollutants generation from MSWM transport sector can be reduced if optimized routs are used; higher fuel efficient new vehicle is used and increasing better maintenance and operation of vehicles. Noise pollution can be reduced by phase wise replacement of old vehicles and better maintenance and monitoring.

At present around 90% of the total mixed waste is being disposed in the dumping ground. High organic content of the waste generating huge quantity of landfill gases, majority of them are greenhouse gases, which are responsible for global warming and others are highly toxic organic gases, which has enormous health effects especially on the landfill workers. In the integrated MSW management system only inert will be disposed in the engineered landfill. So there will be no landfill gas generation. From existing MSW management to immediate switching to effective integrated MSW management is extremely difficult. In developing countries as money and social awareness are constraints, there will be a substantial amount of transition period between these two extreme phases. In the transition period, while developing the source segregation and other waste treatment facilities for integrated system, mixed waste will be disposed in the newly built engineered landfill, where along with leachate collection and treatment facilities, gas collection facilities will also be there. From the study it reveals that from phase wise landfilling of mixed waste, ~6 times more methane will be captured i.e. ~6 times more certified emission reduction (CER) in terms of CO_2-eq. will be possible than the existing system. It also reveals from phase wise landfilling of mixed waste in the transition period that 10 MW of power generation will be possible for 20 years rather than only 3 MW of power generation for 10 years in the existing system.

Around 900 to 1000 L/m^2 leachate with heavy pollution load is being generated every year from the existing landfill site and polluting the surrounding water bodies and the precious ground water beneath it. Unless proper top cover is used during post-closure, heavy metal pollution is going to persists in ground water for prolonged period of time. Phase wise landfilling during transition period will reduce the leachate generation by ~33% during active period and ~54% during post closure period. Use of a complete top cover system at post closure will reduce the leachate generation by ~96%.

In the integrated MSW management system only inert will go to engineered landfill after segregation and treatment. It will reduce the landfill amount i.e. landfill area, so leachate quantity will reduce drastically with a much better quality. All these study indicates that integrated MSW management system might be a much better option than the existing system. So study of an integrated MSW management system considering its different components and socio-economic conditions merits investigation.

4.13 PROPOSED INTEGRATED MSW MANAGEMENT SYSTEM WITH PROPER SEGREGATION AND TREATMENT

The integrated waste management philosophy is to endeavor to treat all wastes as resource material, some suitable for recycling, others for conversion to either compost and or waste-to-energy etc. Integrated waste management evolved from the realization that one activity (e.g. recycling or recovery of products) alone would not achieve the objective of minimizing risks associated with waste. Several inter-related activities are necessary to achieve a significant risk reduction. The combination of activities is selected in a manner suitable to handle targeted portions of the waste stream. The integration of programs for waste reduction and reuse at the source, recycling and treatment/recovery of products are aimed at reducing the amount of waste disposed of in landfills.

Kolkata generates two types of waste (i) garbage (~90% of the total waste), whose composition is given in Table 4.3 (ii) silt or rubbish (~10% of the total waste), which is inert material. Silt or rubbish, as it is inert and collected separately by the hired vehicle only, will be disposed in the landfill site directly without any treatment. Primary collection of the garbage will be done by the department from house to house and other places to the containers, which is having almost fixed nature of cost. 5% of the recyclables will be sorted at source and conveyed to material recycling facility. Rest 95% of the garbage will be conveyed by both the departmental and privet (hired) vehicles from the container points to the sorter. Observing the characteristics of the garbage it is assumed that, at the sorting stations 10% of the inert present in the garbage will be identified easily due to improved sorting at source and sent to the engineered landfill site. After sorting, other components of the wastes will go to the thermal processing or biological processing according to their characteristics. In both the treatment facilities pre-sorting will be provided to improve the feed quality and hence to increase the processing efficiency.

Fig. 4.41 shows the flow chart for proposed integrated MSW management system showing the pathways of garbage processing considering 100 MT of its generation. The flow chart shows material recovery, compost production, waste volume reduction due to incineration, reduced landfilling etc. The basic considerations of proposed integration system are as follows: (1) Proper segregation done at source by providing two bins – one for biodegradable waste and the other for non-biodegradable waste. (2) In no case solid waste should not touch the ground. (3) For biodegradable waste, frequency of waste collection will be daily and for non- biodegradable waste, frequency of waste collection will be twice or thrice a week. (4) Central or intermediate sorting facility to be provided from where recyclable material will be sent for recycling. (5) Treatment and disposal of waste will be done as per its characteristics - like high calorific value of waste may go for incineration and biodegradable organic waste for composting. In all treatment facilities, pre-sorting facilities will be there for segregating the inert and recyclable from the pretreated waste. Inert and residues from treatment plant will go for engineered landfill.

From data presented in Table 4.3 the amount of total recyclable materials taken out from garbage in proposed integrated system is shown in table 4.33.

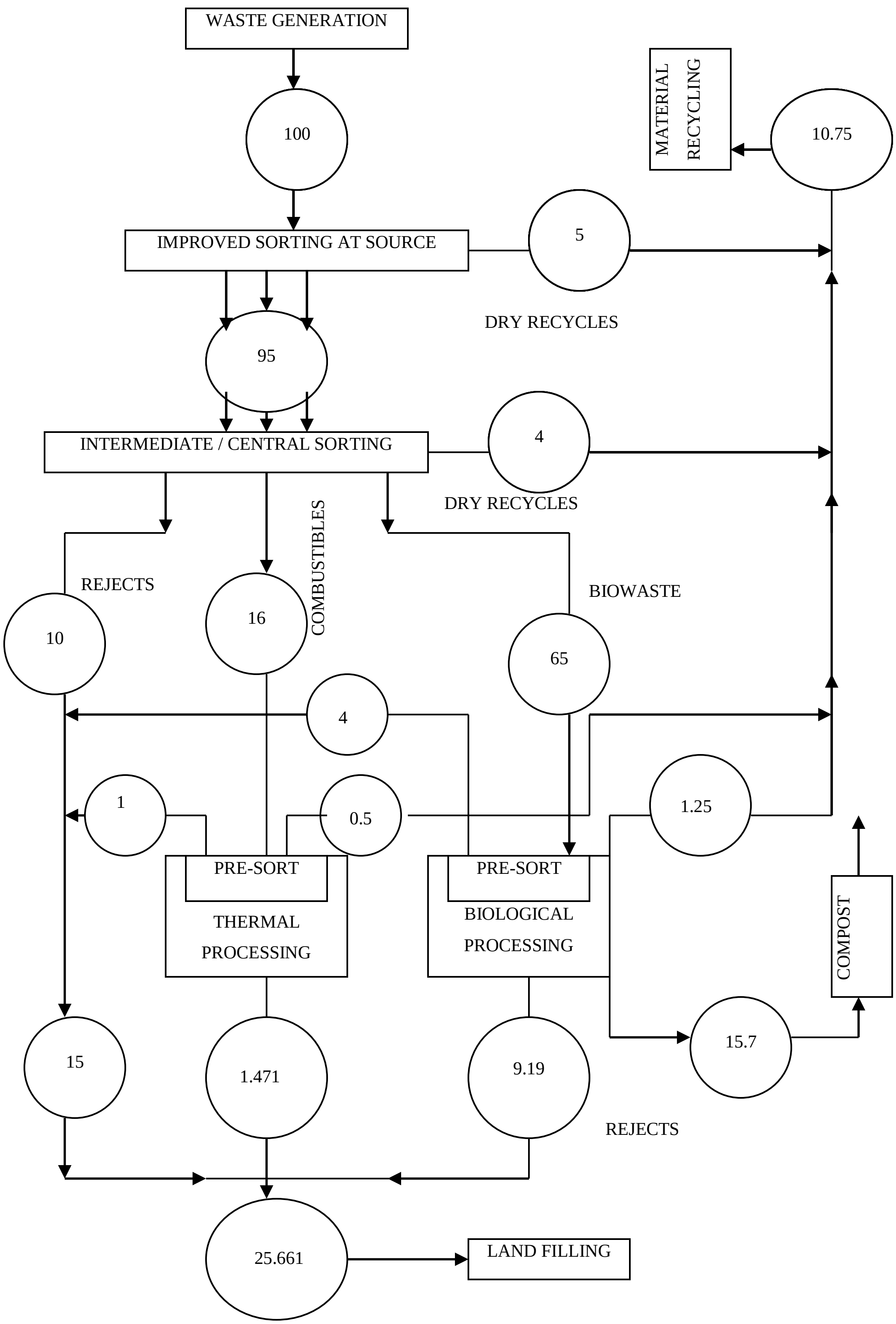


Figure 4.41 Materials flow chart of garbage

This recyclable amount (10.75 MT) is higher than the existing system (9.21 MT) because of proposed improved source segregation and sorting, but not too much as total amount of recyclable present in the garbage is less.

Table 4.33 Total recyclable components taken out from garbage in the proposed integrated system

	Waste components					Total recyclable
	Paper	Rubber & leather	Plastic	Glass	Metal	
Quantity (T)	5*	0.34	4.88@	0.34	0.19	10.75

*Out of this 5T Paper, 0.5T is the paper recycled out of pre-sorter in thermal treatment
@Out of this 4.88T Plastic, 1.25T is the plastic recycled out of pre-sorter in composting plant

From physical and chemical composition of solid waste it is clear that amount of high calorific value materials in the garbage is not more after sorting of recyclable materials especially paper and plastics. Total input material composition for the incinerator is given in table 4.34. Some amount of inert and compostable materials are assumed to be mixed with remaining high calorific value materials as incinerator feed due to expected inefficiency in sorting. Some amount of inert (1 MT) and recyclable (0.5 MT) will be separated out from the incinerator pre-sorter. As the amount of high quality incinerator feed is not much, power generation option is not considered in the proposed integrated system. Through mass burn incineration substantial volume reduction is possible which reduces the landfill area requirement. Incinerator generates high amount of air pollutants, so air pollution control equipment will have to be considered to minimize the air pollution.

Table 4.34 Input material composition for thermal processing in the proposed integrated system

	Waste components										Total Combustible
	Incineration feed after pre-sorter								Recyclable Materials from Pre-Sorter		
	Paper	Rubber & Leather	Rags	Wooden Matter	Coconut shells	Bones	IIF@	CPIF#	Inert	Recyclable Materials$	
Quantity (T)	1.07	0.34	1.87	1.15	4.5	0.16	2.41	3	1	0.5	**16**

@ Inert in incineration feed [IIF] (due to inefficiency of central sorter)
#Compostable portion in incineration feed [CPIF] (due to inefficiency of central sorter)
$Paper recycled out of pre-sorter in thermal treatment

Amount of organic material along with food waste is more in MSW in developing countries like India. Windrow composting is considered as biological processing rather than bio-methanation. Compost plant needs less capital cost and unskilled supervision. Compost enhances the natural fertilizing capacity of soil which is required in the developing countries having vast agricultural land. Table 4.35 shows total breakup of the input for composting plant. After sorted out of recyclable (1.25 MT) and inert (4 MT) by the compost plant pre-sorter and inert process reject (9.19 MT) from compost process, remaining 50.56 MT (47.56 + 3) will be converted to compost. Out of this, 30% (Flintoff, 1984) of compostable i.e, (47.56×0.3) MT along with 3 MT inert materials, 17.27 MT of compost product will be produced.

Table 4.35 Composition of composting plant feed in proposed integrated system

Components of compos plant feed					Total
Compostable	Recyclable	Inert			
(50.56−3*) = 47.56	1.25**	3.0#	4.0$	9.19&	65

*3 tons of compostable material enters as incineration feed due to inefficiency of central sorter
** Plastic recycled out of composting pre-sorter
#3 tons of inert present in composting product i.e. compost
$4 tons of inert rejects at composting pre-sorter
&9.19 tons of inert rejects during composting process

Similar calculations for amount of recyclable materials sorted out from different processing techniques in a disposal site are shown in Table 4.36. Table 4.37 shows material balance of inert, originally present in the garbage.

Table 4.36 Amount of recyclable materials sorted out from different operations in proposed integrated system

	Operations				Total Recycled
	Improved sorting at source (house-hold level)	Intermediate central sorting	Presorting in Thermal Processing	Presorting in Composting	
Recycled quantity (Tons)	5@	4#	0.5$	1.25*	**10.75**

@Out of this 5T, 3.5T is paper, 0.15T is metal and 1.35T is plastic
#Out of this 4T, 1T is paper, 0.04T is metal, 2.28T is plastic, 0.34T is glass and 0.34T rubber and leather
$This 0.5T is the paper recycled out of pre-sorter in thermal treatment
*This 1.25T is the plastic recycled out of the composting plant

Table 4.37 Material balance of inert materials originally present in garbage from different operations

	Operations						Total
	Rejects from intermediate sorting	Pre-sorting from thermal processing	Pre-sorting from composting / biological processing	In combustion	Residue from composting / biological processing	In composted material	
Quantity (Tons)	10	1	4	2.41	9.19	3	29.6

In integrated MSW management system engineered landfill is considered i.e. proper bottom liner with leachate collection system. Leachate will be collected and treated during active period as well as post closure period of landfill. A complete final cover will be provided after closure to minimize leachate generation i.e. to minimize ground water pollution. In this system silt or rubbish which is ~10% of the total waste and 25.661% inert (15% inert + 1.471 incinerator ash + 9.19 inorganic process reject from compost plant) from garbage, which is ~90% of the total waste, will be disposed in the engineered landfill. So, in this system (10 + 25.661 × 0.9) % i.e. ~33% of the inert material of the total waste will be disposed in the engineered landfill. On the contrary at present in the existing MSW system 9.21% recyclable materials is taken out by the informal rag pickers and only around 5 to 6% of the garbage is converted to compost. So 85.79% of garbage i.e, (85.79×0.9) % of the total waste and silt or rubbish (10% of the total waste) i.e, (10 + 85.79 × 0.9) % or ~87 to 90% mixed waste (organic + inorganic) is being disposed.

Based on the above a generic MSW management linear programming (LP) model will be developed considering its different components and economics. A specific existing MSW management LP model will be prepared with the data of Kolkata and will be validated and studied. In the next step the proposed integrated MSW management LP model will be prepared and studied. These two systems will be compared to achieve optimized cost effective sustainable solution methodology of MSW management system for developing countries like India.

Chapter 5

5 DEVELOPMENT OF A SOLID WASTE MANAGEMENT OPTIMISATION MODEL

5.1 BACKGROUND

The conventional system deals with the storage, collection, transportation and disposal of wastes designated as the responsibility of the municipal authorities. Recycling, re-use, waste minimization, engineered landfill, waste to energy etc do not receive much attention. In many cities, the municipal or contracted system only handles a minor fraction of the potential waste generated by residential, commercial, industrial, institutions etc. In many cities more wastes are taken care of outside the municipal garbage system, informally than by the local authorities (Furedy, 1994) leading to illegal dumping and open burning. This approach shows some disabilities which can be traced back to a few factors: inability of the local authorities to pick up all the waste, lack of proper data, lack of financial resources, lack of skill, increasing thrown away mentalities, improper disposal facilities etc.

It can be inferred from the literature that no single methodology can solve the problem of waste management (Freduah, 2007). There is a need to combine different methods and stakeholders in such a way so as to minimize environmental and social costs associated with waste management. The present study is an attempt to integrate the best feasible methods of different components of waste management along with socio-economic condition in Kolkata considering systems approach. The integrated approach to SWM was a response to failure of the conventional approach in developed countries. ISWM includes preventing waste, minimizing the initial generation of materials through source reduction, reusing and recycling and composting to reduce the volume of materials being sent to landfills or incineration.

The purpose of the model is to assist in selecting strategies that minimize the cost of waste collection, storage, transportation, operation of recycling, treatment and disposal subject to physical constraints. It also helps to reduce the adverse environmental impact of the SWM. The proposed model includes the revenues produced by the sale of recyclable materials, sale of composting materials generated by the facility. The optimized model is driven by the minimization of secondary collection and transportation, operation of treatment and disposal, the revenues from recycling and composting. The constraints include those linking waste flows and its mass balance, recycle amount, processing plants operation and capacity, landfill operation and capacity, transport vehicle operation and capacity, number of trips, etc. The linear programming model integrating different functional elements was solved by LINDO optimization software (Schrage, 1984) and various possible waste management options were considered during sensitivity analysis. Sensitivity analysis is also done as model includes many types of economic factors; hence a small change of those factors shows change in marginal cost and its impact in operation. The model is validated with the existing datasets of SWM system of Kolkata city of 2007 and further the model is extended for the proposed integrated waste management system to explore its effect on cost and various operational parameters. This will help to predict the outcome of ISWM which facilitates for environmental policy making in future SWM.

5.2 MODEL DEVELOPMENT

5.2.1 Assumptions

Integrated Solid Waste Management (ISWM) is considered for an Indian city with proper segregation and treatment along with the following basic assumptions:

- The municipality uses departmental and hired vehicles to transport wastes. Departmental vehicles carry garbage only while hired vehicles carry both garbage and silt/rubbish. Silt/rubbish and garbage are collected separately. There are different types of departmental vehicles but only one type of hired vehicle.
- For a particular Borough calculating the waste transportation distance borough centres have been assumed as the waste generation points.
- The city is divided into zones for each disposal site.
- Minimum and maximum number of trips of departmental vehicles as well as for hired vehicles is fixed for each zone.
- The departmental vehicles will have to undertake certain minimum number of trips per day as they are salaried staff of municipality.
- The drivers and helpers of departmental vehicles will be paid incentives if they carry out more than minimum number of trips. Hired vehicles will be paid on the basis of tonnage of waste transportation to the different destination.
- Average waste generation data of the boroughs of the concerned municipality is considered for running the model

- To make the model flexible and more realistic, borough-wise minimum and maximum garbage carrying range (in fraction) for both departmental and hired vehicles is considered based on variation of actual waste carried by different types of vehicles from different boroughs.
- In integrated solid waste management segregation at source is considered. Two bin systems - one for biodegradable waste and the other for non-biodegradable waste is assumed.
- Garbage enters central/intermediate sorter and subsequently to the different processing plants, while silt/rubbish goes straight to landfill without sorting or processing.
- Intermediate or central sorting facility is considered for sorting the recyclable, biodegradable, combustible and inert from garbage.
- Recyclable should be sent to the common recycling facilities and revenue will be generated by selling the recyclables.
- High calorific value of waste may go for incineration and biodegradable waste for composting. To improve the thermal and bio processing feed, pre-sorting facilities are provided for further segregating the inert and recyclable. Inert, process rejects and residues from treatment plant will go to engineered landfill with extra transportation charges.
- The operational cost of the incinerator includes the operation (including pre-sorter) and maintenance cost of incinerator and the transportation cost of combustible waste from the sorting facility to the incinerator.
- The operational cost of the composting plant includes cost of operation (including pre-sorter) and maintenance of composting plant and transportation cost from the central sorting facility to composting plant.
- Environmental costs of the processing plants and landfilling has not been taken into account.
- The model excludes the cost of primary collection as it is more or less fixed cost within a time frame.

Considering the above assumptions, a material flow chart (Figure 4.13) with a intake of 100 ton has been developed. It is assumed that 5 MT of waste is segregated and recycled at household level and storage points which is managed by NGOs. Remaining 95 MT of the recyclable materials along with garbage generate from household, shops, markets and other sources like institutions, road sweeping goes to the central sorting facility of an engineered landfill site and is subjected to different processing techniques present within that engineered landfill site. It is assumed that the city has different engineered landfill sites. Since western site of Kolkata is extended upto river Ganga and on the other bank Howrah city is located with their solid waste management system so no solid waste disposal facilities at western side is considered. Each disposal site has one intermediate central sorting facility, one incineration facility and one composting facility and one engineered landfill. From the intermediate central sorting (ICS) facility, recyclable waste materials go to recycling facility, while high calorific waste materials send to incinerator, biodegradable waste materials go to composting plant, and inert waste sent to engineered landfill as shown in the Figure 4.13. To improve the efficiency of treatment processes waste materials from ICS are delivered to the pre-sorting units of the incinerator and composting plants and the inert fraction are taken directly to the engineered landfill.

5.2.2 Parameter Definition

Indices

BR	Total number of boroughs. For KMC's case, BR = 15
DS	Total number of disposal sites. For KMC's case, DS = 1 for existing; 3 for proposed. [in the applied model it is mentioned as D for existing and D, N, S for proposed]
DV	Total number of types of departmental vehicles. For KMC's case, DV = 4. [in the applied model it is mentioned as D1, D2, D3 and D4]
HV	Total number of types of hired vehicles. There is only one type of hired vehicle in KMC i.e. HV = 1. [in the applied model it is mentioned as HH]
ZN	Total number of zones associated with each disposal site *ds*. In KMC's case, ZN = 2.
br	Index for boroughs (1..BR)
ds	Index for disposal site (1..DS)
dv	Index for departmental vehicle (1..DV)
hv	Index for hired vehicle (1..HV)
zn	Index for zones associated with a particular disposal site *ds* (1..ZN)

Input data in the form of matrices

br_wg_{br}	Amount of garbage generated in borough *br*, MT. (BR × 1) matrix.
br_ws_{br}	Amount of silt generated in borough *br*, MT. (BR × 1) matrix.
$br\_fgdvmx_{br,dv}$	Maximum fraction of garbage can be transported by *dv* type departmental vehicles from borough *br* center. (BR × DV) matrix.
$br\_fgdvmn_{br,dv}$	Minimum fraction of garbage can be transported by *dv* type departmental vehicles from borough *br* center. (BR × DV) matrix.
br_fghvmx_{br}	Maximum fraction of garbage can be transported by hired vehicles *hv* from borough *br* center. (BR × HV) matrix. Here HV = 1.
br_fghvmn_{br}	Minimum fraction of garbage can be transported by hired vehicles *hv* from borough *br* center. (BR × HV) matrix. Here HV = 1.
ss_rf_{ds}	Recyclable fraction of solid waste coming out from central sorting station (sorter) at disposal site *ds*. (DS × 1) matrix.
ss_ddf_{ds}	Direct disposable fraction of solid waste coming out from sorter at disposal site *ds*. (DS × 1) matrix.
$ss\_mxincif_{ds}$	Maximum incinerable fraction of solid waste coming out from sorter at disposal site *ds*. (DS × 1) matrix.
$ss\_mxcompf_{ds}$	Maximum compostable fraction of solid waste coming out from sorter at disposal site *ds*. (DS × 1) matrix.
ip_rf_{ds}	Recyclable fraction of waste coming out from incinerator pre-sorter at *ds*. (DS × 1) matrix.
ip_irf_{ds}	Incineration inorganic reject fraction coming out from incinerator pre-sorter at disposal site *ds*. (DS × 1) matrix.
ip_arf_{ds}	Incineration ash reject fraction (incineration product) coming out from the incinerator at disposal site *ds*. (DS × 1) matrix.
cp_rf_{ds}	Recyclable fraction of waste coming out from composting plant pre-sorter at *ds*. (DS × 1) matrix.
cp_irf_{d}	Composting inorganic reject fraction coming out from the composting plant pre-sorter, at disposal site *ds*. (D × 1) matrix.
cp_prf_{ds}	Compost plant process rejects fraction coming out from the composting plant at disposal site *ds*. (DS × 1) matrix.

cp_pfr_{ds}	Composting product (compost) fraction coming out from the composting plant at disposal site *ds*. (DS × 1) matrix.
ss_mncap_{ds}	Minimum capacity of the sorter at a disposal site *ds*, MT. (DS × 1) matrix.
ss_mxcap_{ds}	Maximum capacity of the sorter at a disposal site *ds*, MT. (DS × 1) matrix.
ip_mncap_{ds}	Minimum capacity of the incinerator at a disposal site *ds*, MT. (DS × 1) matrix.
ip_mxcap_{ds}	Maximum capacity of the incinerator at a disposal site *ds*, MT. (DS × 1) matrix.
cp_mncap_{ds}	Minimum capacity of the composting plant at a disposal site *ds*, MT. (DS × 1) matrix.
cp_mxcap_{ds}	Maximum capacity of the composting plant at a disposal site *ds*, MT. (DS × 1) matrix.
lf_mxcap_{ds}	Maximum capacity of the landfill at disposal site *ds*, MT. (DS × 1) matrix.
dv_cap_{dv}	Average waste carrying capacity of a *dv* type of departmental vehicle, MT. (DV × 1) matrix.
hv_gcap_{hv}	Average garbage carrying capacity for hired vehicle *hv*, MT. (HV× 1) matrix.
hv_scap_{hv}	Average silt carrying capacity for hired vehicle *hv*, MT. (HV × 1) matrix.
dv_nr_{dv}	Total number of *dv* type departmental vehicles running. (DV × 1) matrix.
$zn\_mxtrip_{dv,ds,zn}$	Maximum number of trips that a *dv* type departmental vehicle is allowed to undertake in zone *zn* of disposal site *ds*. (DV × DS × ZN) matrix.
$mxzn\_mxtrip_{dv}$	Maximum value of $zz\_mxtrip_{dv,ds,zn}$ for a particular *dv* type vehicle, considering all disposal sites *ds* for all zone *zn*. (DV × 1) matrix.
$zn\_mntrip_{dv,ds,zn}$	Minimum number of trips that a *dv* type departmental vehicle has to undertake in zone *zn* of disposal site *ds*. (DV × DS × ZN) matrix.
$mnzn\_mntrip_{dv}$	Minimum value of $zn\_mntrip_{dv,ds,zn}$ for a particular *dv* type vehicle,

	considering all disposal sites *ds* for all zone *zn*. (DV × 1) matrix.
lf_cost_{ds}	Landfilling cost in Rs/MT of solid waste for the landfilling site associated with a disposal site *ds*. It includes cost of liner, cover material, leachate collection and treatment cost. (DS × 1) matrix.
$ss\_cost\_sort_{ds}$	Operational cost of sorting per ton of solid waste for the central sorting station (sorter) associated with the disposal site *ds*, Rs/MT. (DS × 1) matrix.
$ss\_cost\_r_{ds}$	Cost of transporting recyclable material segregated from the sorter at disposal site *ds* to recycling facility, Rs/MT. (DS × 1) matrix.
$ss\_cost\_ad_{ds}$	Cost of additional dumping from sorter to landfill at disposal site *ds*, Rs/MT. (DS × 1) matrix.
$ip\_cost\_op_{ds}$	Operational cost of the incinerator at disposal site *ds*, Rs/MT. (DS × 1) matrix.
$ip\_cost\_r_{ds}$	Transportation cost of the recyclables from the incinerator pre-sorter attached to the disposal site *ds*, to the recycling facility, Rs/MT. (DS × 1) matrix.
$ip\_cost\_ar_{ds}$	Transportation cost of the incinerator ash reject from the incinerator pre-sorter to landfill for a particular disposal site *ds*, Rs/MT. (DS × 1) matrix.
$ip\_cost\_ir_{ds}$	Transportation cost of transferring inorganic rejects from the incinerator pre-sorter to landfill attached to disposal site *ds*, Rs/MT. (DS × 1) matrix.
$cp\_cost\_op_{ds}$	Operational cost of the composting plant at disposal site *ds*, Rs/MT. (DS × 1) matrix.
$cp\_cost\_r_{ds}$	Transportation cost of the recyclables from composting plant pre-sorter attached to the disposal site *ds* to the recycling facility, Rs/MT. (DS × 1) matrix.
$cp\_cost\_ir_{ds}$	Transportation cost of inorganic rejects from the composting pre-sorter to landfill at *ds*, Rs/MT. (DS × 1) matrix.
$cp\_cost\_pr_{ds}$	Transportation cost of composting process rejects from the composting plant pre-sorter to the landfill at disposal site *ds*, Rs/MT. (DS × 1) matrix.

$ss\_rev\_r_{ds}$ Revenue earned by selling per ton of recyclable materials generated from the central sorting station attached to disposal site *ds*, Rs/MT. (DS × 1) matrix.

$ip\_rev\_r_{ds}$ Revenues earned from selling recyclable materials sorted out from incinerator pre-sorter at a disposal site *ds*, Rs/MT. (DS × 1) matrix.

$cp\_rev\_r_{ds}$ Revenues earned from selling recyclable materials sorted out from composting pre-sorter at a disposal site *ds*, Rs/MT. (DS × 1) matrix.

$cp\_sp\_c_{ds}$ Selling price of the compost, Rs/ ton for a disposal site *ds*. (DS × 1) matrix.

$br\_cost\_hg_{br,ds}$ Transportation cost of garbage from the borough *br* center to disposal site *ds* for a hired vehicle, Rs./MT. (BR × DS) matrix.

$br\_cost\_hs_{br,ds}$ Transportation cost of silt from the borough *br* center to disposal site *ds* for a hired vehicle, Rs./MT. (BR × DS) matrix.

$br\_cost\_fl_{br,ds,dv}$ Average fuel cost for transporting per ton waste from borough *br* to disposal site *ds* by a *dv* type departmental vehicle, Rs/MT. (BR × DS × DV) matrix.

dv_no_{dv} Total number of *dv* type departmental vehicles in KMC fleet. (DV × 1) matrix.

$dv\_cost\_fxr_{dv}$ Fixed running cost for each *dv* type departmental vehicle, Rs. (DV × 1) matrix

$dv\_cost\_fxi_{dv}$ Fixed idle cost for each *dv* type departmental vehicle, Rs. (DV × 1) matrix.

r_inc_{dv} Rate of incentive (per extra ton basis) to be paid to the driver and helper of a *dv* type vehicle for transporting waste over and above the minimum trips, Rs/MT. (DV × 1) matrix.

Variables:

COSTTRN Total cost of transportation of waste to all the disposal sites *ds*, in Rs.

COSTINC Total incentive payable to KMC departmental vehicle drivers and helpers if they run trips more than their minimum requisite number of trips, Rs.

COSTSS — Total cost for sorting operation at central sorters associated with the disposal site *ds*, in Rs.

COSTIP — Total cost of incineration process, in Rs.

COSTCP — Total cost of composting process, in Rs.

COSTLF — Total landfilling cost for all the disposal sites *ds*, in Rs.

REVR — Total revenue generated by selling recyclable materials from the recycling facility, in Rs.

REVC — Total revenue generated by selling compost (product), in Rs.

$QGDV_{br,ds,dv}$ — Quantity of garbage transported from a particular borough *br* centre to disposal site *ds* by *dv* type departmental vehicle, in MT.

$QGHV_{br,ds,hv}$ — Quantity of garbage transported from a particular borough *br* center to a disposal site *ds* by a hired vehicle *hv*, in MT.

$QSHV_{br,ds.hv}$ — Quantity of silt transported from a particular borough center *br* to a disposal site *ds* by a hired vehicle *hv*, in MT.

SSF_{ds} — Feed to central sorting station associated with disposal site *ds*, in MT.

SSR_{ds} — Amount of recyclable material segregated from the solid waste feed at the central sorting station associated with disposal site *ds*, in MT.

$SSDD_{ds}$ — Direct disposable portion of waste stream (consisting of inert) that is directly taken to landfill bypassing central sorter, for a disposal site *ds*, in MT.

$SSAD_{ds}$ — Additional disposable amount of waste to be transferred directly from the central sorting facility (after sorting but without any processing) to the landfill in case of emergency, for a disposal site *ds*, in MT. This value was equated to zero under normal circumstances.

$SSIPF_{ds}$ — Feed from sorter to the incinerator at a disposal site *ds*, in MT.

$SSCPF_{ds}$ — Feed from sorter to the composting plant at a disposal site *ds*, in MT.

IPR_{ds} — Recyclable portion sorted out from the incinerator pre-sorter at a disposal site *ds* and transferred to the recycling facility, in MT.

$IPIR_{ds}$ Inorganic reject portion separated from the incinerator pre-sorter and sent to the landfill at a disposal site *ds*, in MT.

$IPAR_{ds}$ Amount of incinerator ash transported from the incinerator to the landfill at a disposal site *ds*, in MT.

CPR_{ds} Recyclable portion sorted out from the composting plant pre-sorter at a disposal site *ds* and transferred to the recycling facility, in MT.

$CPIR_{ds}$ Inorganic reject portion separated from the composting plant pre-sorter and sent to the landfill at a disposal site *ds*, in MT.

$CPPR_{ds}$ Composting process reject portion separated from the composting process and sent to the landfill at a disposal site *ds*, in MT.

$CPPROD_{ds}$ Compost (product) produced in the composting plant at the disposal site *ds*, in MT.

LFW_{ds} Amount of waste being disposed off in the landfill associated with a disposal site *ds*, in MT.

LFS_{ds} Amount of silt transported to landfill at a disposal site *ds*, in MT.

LFG_{ds} Amount of garbage transported to landfill at a disposal site *ds*, in MT.

$LFRJ_{ds}$ Quantity of rejects from different processing units like incineration inorganic reject, incineration ash, composting inorganic reject and composting process reject transferred to associated landfill at disposal site *ds*, in MT.

$ACTRPDV_{dv,ds,zn}$ Actual number of trips made by *dv* type departmental vehicle in a zone *zn* of a disposal site *ds* for transportation of garbage.

$ACTRPHVG_{hv,ds,zn}$ Actual number of trips made by hired vehicles *hv* in a zone *zn* of a disposal site *ds* for transportation of garbage.

$ACTRPHVS_{hv,ds,zn}$ Actual number of trips made by hired vehicles *hv* in a zone *zn* of a disposal site *ds* for transportation of silt.

$GDV_{dv,ds,zn}$ Amount of garbage transported by *dv* type departmental vehicle to a disposal site *ds* from zone *zn* of that *ds*, in MT.

$GHV_{hv,ds,zn}$ Amount of garbage transported by hired vehicle *hv* to a disposal site *ds* from zone *zn* of that *ds*, in MT.

$SHV_{hv.ds,zn}$	Amount of silt transported by hired vehicle *hv* to a disposal site *ds* from zone *zn* of that *ds*, in MT.
$COSTTRHV_{hv}$	Total cost of transportation of solid waste (garbage and silt/rubbish) by hired vehicles *hv*, in Rs.
$COSTTRHVG_{hv}$	Total garbage transportation cost by hired vehicles *hv* from borough centers *br* to disposal sites *ds*, in Rs.
$COSTTRHVS_{hv}$	Total silt transportation cost by hired vehicles *hv* from borough centers *br* to disposal sites *ds*, in Rs.
$COSTTRDV_{dv}$	Garbage transportation cost by *dv* type departmental vehicles, in Rs.
$COSTFLDV_{dv}$	Total cost of fuel incurred by the *dv* type departmental vehicles for garbage transportation, in Rs.
$COSTFXR_{dv}$	Total fixed cost for running *dv* type departmental vehicles, in Rs.
$COSTFXI_{dv}$	Total fixed cost for idle *dv* type departmental vehicles, in Rs.
$CINC_{dv}$	Total amount of incentive to be paid to the driver and helpers of *dv*-type departmental vehicle for transporting garbage more than the minimum stipulated number of trips, in Rs.

5.2.3 Model

It is required to minimize the total cost of solid waste management. The objective function, taken as the total cost of solid waste management, may be expressed as:

Objective function = Cost of transportation + Incentive cost + Sorting cost + Incineration cost + Composting cost + Landfilling cost − Revenue earned from recycling − Revenue earned from composting

$$\begin{aligned} Objective\ function = {} & COSTTRN + COSTINC + COSTSS + COSTIP + COSTCP + COSTLF \\ & - REVR - REVC \end{aligned} \tag{1}$$

COSTTRN is the total cost of transportation of solid waste to all the disposal sites *ds*. *COSTINC* is the total incentive cost payable to the departmental vehicle drivers and helpers if trips are more than their allotted minimum number of trips. Mode of payment is based on per ton of waste transported to the disposal sites in excess of the minimum allotted trips. *COSTSS*, *COSTIP*, *COSTCP*, *COSTLF* are the total sorting cost, incineration cost, composting cost and landfilling cost for all disposal sites *ds*; *REVR* is the total revenue generated by selling recyclable materials from recycling facility for all disposal sites *ds*. *REVC* is the revenue generated by selling compost from composting plants for all disposal sites *ds*.

Borough-wise minimum and maximum garbage carrying range (in fraction) for both departmental and hired vehicles has to be considered based on average waste carried by different types of vehicles from different boroughs. This makes the model flexible and more realistic as it indicates the optimum garbage carrying trend by different vehicles. The data is being used to set the following waste transportation constraints.

Garbage balance at a particular borough *br*:

$$\sum_{ds=1}^{DS}\sum_{dv=1}^{DV} QGDV_{br,ds,dv} + \sum_{ds=1}^{DV} QGHV_{br,ds,hv} = br\_wg_{br} \qquad \forall br = 1,2,\dots,BR \tag{2}$$

$QGDV_{br,ds,dv}$ is the quantity of garbage transported from borough *br* centre to disposal site *ds* by *dv* type departmental vehicles. $QGHV_{br,ds,hv}$ is the quantity of garbage transported from a particular borough *br* center to a disposal site *ds* by only one type of hired vehicle. br_wg_{br} is the amount of garbage generated in borough *br*.

Silt or Rubbish balance at a particular borough *br*:

$$\sum_{ds=1}^{DS} QSHV_{br,ds,hv} = br\_ws_{br} \qquad \forall\ br = 1,2,\dots,BR \tag{3}$$

$QSHV_{br,ds,hv}$ is the quantity of silt transported by only one type of hired vehicle from a particular borough *br* center to a disposal site *ds*. br_ws_{br} is the amount of silt generated at a borough *br*.

Maximum amount of garbage can be transported from borough *br* centre by *dv* type departmental vehicle:

$$\sum_{ds=1}^{DS} QGDV_{br,ds,dv} \leq br\_wg_{br} \times br\_fgdvmx_{br,dv} \quad \forall br = 1,2,\ldots,BR, \quad \forall dv = 1,2,\ldots,DV \tag{4}$$

$br\_fgdvmx_{br,dv}$ is the maximum fraction of garbage can be transported from borough *br* center by *dv* type departmental vehicles.

Maximum amount of garbage can be transported from borough *br* centre by only one type of hired vehicle *hv*:

$$\sum_{ds=1}^{DS} QGHV_{br,ds,hv} \leq br\_wg_{br} \times br\_fghvmx_{br} \qquad \forall br = 1,2,\ldots,BR \tag{5}$$

br_fghvmx_{br} is the maximum fraction of garbage can be transported from borough *br* centre by only one type of hired vehicle *hv*.

Minimum amount of garbage can be transported from borough *br* centre by *dv* type departmental vehicle:

$$\sum_{ds=1}^{DS} QGDV_{br,ds,dv} \geq br\_wg_{br} \times br\_fgdvmn_{br,dv} \qquad \forall br = 1,2,\ldots,BR, \forall dv = 1,2,\ldots,DV \tag{6}$$

$br\_fgdvmn_{br,dv}$ is the minimum fraction of garbage can be transported from borough *br* centre by *dv* type departmental vehicle.

Minimum amount of garbage can be transported from borough *br* center by only one type of hired vehicle *hv*:

$$\sum_{ds=1}^{DS} QGHV_{br,ds,hv} \geq br\_wg_{br} \times br\_fghvmn_{br} \quad \forall br = 1,2,\ldots,BR \tag{7}$$

br_fghvmn_{br} is the minimum fraction of garbage can be transported from borough *br* centre by only one type of hired vehicle *hv*.

Equating feed to central sorter located at a disposal site *ds*:

$$SSF_{ds} - \sum_{br=1}^{BR}\sum_{dv=1}^{DV} QGDV_{br,ds,dv} - \sum_{br=1}^{BR} QGHV_{br,ds,hv} = 0 \qquad \forall ds = 1,2,\dots,DS \tag{8}$$

SSF_{ds} is the feed to the central sorting station associated with a disposal site *ds*.

Input and output streams balancing for the central sorting facility located at a disposal site *ds*:

$$SSF_{ds} - SSR_{ds} - SSDD_{ds} - SSAD_{ds} - SSIPF_{ds} - SSCPF_{ds} = 0 \qquad \forall ds = 1,2,\dots,DS \tag{9}$$

SSR_{ds} is the amount of recyclable material separated from the waste stream at the central sorting station associated with a disposal site *ds*, in MT. $SSDD_{ds}$ is the direct disposable inert portion of solid waste which is directly discharged to landfill without sorting after visual inspection, in MT. $SSAD_{ds}$ is the additional amount of waste can be transferred directly from the sorting facility (after sorting but without any processing) to the landfill in case of emergency, in MT. $SSIPF_{ds}$ is the high calorific waste feed from sorter to incinerator associated with a disposal site *ds*, in MT. $SSCPF_{ds}$ is the biodegradable waste feed entering the composting plant from sorter at a disposal site *ds*, in MT.

Maximum amount recycled from sorter at disposal site *ds*:

$$SSR_{ds} - SSF_{ds} \times ss\_rf_{ds} \leq 0 \qquad \forall ds = 1,2,\dots,DS \tag{10}$$

ss_rf_{ds} is the recyclable fraction of solid waste coming out from sorter at a disposal site *ds*.

Maximum inert amount visually sorted for direct disposing in the landfill at a disposal site *ds*:

$$SSDD_{ds} - SSF_{ds} \times ss\_ddf_{ds} \leq 0 \qquad \forall ds = 1,2,\dots,DS \tag{11}$$

ss_ddf_{ds} is the direct disposable inert fraction of solid waste coming out from sorter at disposal site *ds*.

Maximum amount of sorted feed to incinerator plant at a disposal site *ds*:

$$SSIPF_{ds} - SSF_{ds} \times ss\_mxincif_{ds} \leq 0 \qquad \forall ds = 1,2, \dots, DS \tag{12}$$

$ss\_mxincif_{ds}$ is the maximum incinerable fraction of solid waste coming out from sorter at a disposal site *ds*.

Maximum amount of sorted feed to composting plant at a disposal site *ds*:

$$SSCPF_{ds} - SSF_{ds} \times ss\_\mathrm{mxcompf}_{ds} \leq 0 \qquad \forall ds = 1,2, \dots, DS \tag{13}$$

$ss\_mxcompf_{ds}$ is the maximum compostable fraction of solid waste coming out from sorter at a disposal site *ds*.

Balance of incinerator recyclables at a disposal site *ds*:

$$IPR_{ds} - SSIPF_{ds} \times ip\_rf_{ds} = 0 \qquad \forall ds = 1,2, \dots, DS \tag{14}$$

IPR_{ds} is the recyclable portion which is sorted out from incinerator pre-sorter and transported to the recycling facility, in MT, at a transportation cost of *ip_cost_rds* per MT. ip_rf_{ds} is the recyclable fraction of waste coming out from incinerator pre-sorter at a disposal site *ds*. The incinerator pre-sorter is responsible for enhancing incinerator feed by segregating out the recyclable fraction further.

Balance of incinerator inorganic rejects at a disposal site *ds*:

$$IPIR_{ds} - SSIPF_{ds} \times ip\_irf_{ds} = 0 \qquad \forall ds = 1,2, \dots, DS \tag{15}$$

$IPIR_{ds}$ is the inorganic reject portion separated from the incinerator pre-sorter and sent directly to landfill at a transportation cost of $ip\_cost\_ir_{ds}$ per MT. ip_irf_{ds} is the incineration inorganic reject fraction coming out from the incinerator pre-sorter, at a disposal site *ds*.

Balance of incinerator process ash rejects at a disposal site *ds*:

$$IPAR_{ds} - SSIPF_{ds} \times ip\_arf_{ds} = 0 \qquad \forall ds = 1,2,\ldots,DS \tag{16}$$

$IPAR_{ds}$ is the incinerator ash which is transported from the incinerator to the landfill site at a transportation cost of $ip\_cost\_ar_{ds}$ per MT, for a particular disposal site *ds*. ip_arf_{ds} is the incineration ash reject fraction generated from the incinerator feed ($SSIPF_{ds}$) after incineration at a disposal site *ds*.

Balance of composting plant recyclables at a disposal site *ds*:

$$CPR_{ds} - SSCPF_{ds} \times cp\_rf_{ds} = 0 \qquad \forall ds = 1,2,\ldots,DS \tag{17}$$

CPR_{ds} is the amount of waste recycled from the composting plant pre-sorter to the recycling facility, in MT, at transportation cost of *cp_cost_rds* per MT. cp_rf_{ds} is the recyclable fraction of waste coming out from composting plant pre-sorter at a disposal site *ds*. The composting plant pre-sorter is responsible for enhancing compostable feed by segregating out this portion.

Balance of composting inorganic rejects at disposal site *ds*:

$$CPIR_{ds} - SSCPF_{ds} \times cp\_irf_{ds} = 0 \qquad \forall ds = 1,2,\ldots,DS \tag{18}$$

$CPIR_{ds}$ is the inorganic reject amount transported from composting pre-sorter to the landfill, in MT, at a transportation cost of $cp\_cost\_ir_{ds}$ per MT. cp_irf_{ds} is the composting inorganic reject fraction coming out from the composting plant at a disposal site *ds*. The inorganic reject portion of waste is sorted out by the composting plant pre-sorter and transported directly to landfill.

Balance of composting process rejects at a disposal site *ds*:

$$CPPR_{ds} - SSCPF_{ds} \times cp\_prf_{ds} = 0 \qquad \forall ds = 1,2,\ldots,DS \tag{19}$$

$CPPR_{ds}$ is the composting process reject amount for a disposal site *ds*, in MT. The process rejects are transferred directly to the landfill at a cost of $cp\_cost\_pr_{ds}$ per MT. cp_prf_{ds} is the compost plant process rejects fraction coming out from the composting plant, at disposal site *ds*.

Balance of composting plant product at a disposal site *ds*:

$$CPPROD_{ds} - SSCPF_{ds} \times cp\_pfr_{ds} = 0 \qquad \forall ds = 1,2,\ldots,DS \tag{20}$$

$CPPROD_{ds}$ is the finished compost produced in the composting plant associated at a disposal site *ds*, in MT. cp_pfr_{ds} is the composting product i.e. compost fraction generated from composting plant feed, $SSCPF_{ds}$ at a disposal site *ds*.

Balancing landfill amount at a disposal site *ds*:

$$LFW_{ds} - LFS_{ds} - LFG_{ds} - LFRJ_{ds} = 0 \qquad \forall ds = 1,2,\ldots,DS \tag{21}$$

LFW_{ds} is the amount of solid waste being disposed off in the landfill associated with the disposal site *ds*, in MT. LFS_{ds} and LFG_{ds} are the total amounts of silt and garbage transported to the landfill at a disposal site *ds*. $LFRJ_{ds}$ are the rejects from different processing methods like incineration and composting transferred to the associated landfill at a disposal site *ds*.

Balance of silt in the landfill associated with a disposal site *ds*:

$$LFS_{ds} - \sum_{br=1}^{BR} QSHV_{br,ds,hv} = 0 \qquad \forall ds = 1,2,\ldots,DS \tag{22}$$

Balance of direct disposable and additional disposable amount at the landfill at a disposal site *ds*:

$$LFG_{ds} - SSDD_{ds} - SSAD_{ds} = 0 \qquad \forall ds = 1,2,\ldots,DS \tag{23}$$

Balancing all process rejects to the landfill at a disposal site *ds*:

$$LFRJ_{ds} - IPIR_{ds} - CPIR_{ds} - IPAR_{ds} - CPPR_{ds} = 0 \qquad \forall ds = 1,2,\ldots,DS \tag{24}$$

Maximum and minimum capacity limits of central sorter associated with a disposal site *ds*:

$$SSF_{ds} \le ss\_mxcap_{ds} \qquad \forall ds = 1, 2, ..., DS \qquad (25)$$

$$SSF_{ds} \ge ss\_nmcap_{ds} \qquad \forall ds = 1, 2, ..., DS \qquad (26)$$

ss_mncap_{ds} and ss_mxcap_{ds} are the minimum and maximum capacity of the central sorting facility associated with a disposal site *ds*.

Maximum and minimum capacity limits of incinerator associated with a disposal site *ds*:

$$SSIPF_{ds} \le ip\_mxcap_{ds} \qquad \forall ds = 1, 2, ..., DS \qquad (27)$$

$$SSIPF_{ds} \ge ip\_mncap_{ds} \qquad \forall ds = 1, 2, ..., DS \qquad (28)$$

ip_mncap_{ds} and ip_mxcap_{ds} are the minimum and maximum capacity of the incinerator associated with a disposal site *ds*.

Maximum and minimum capacity limits of composting plant associated with a disposal site *ds*:

$$SSCPF_{ds} \le cp\_mxcap_{ds} \qquad \forall ds = 1, 2, ..., DS \qquad (29)$$

$$SSCPF_{ds} \ge cp\_mncap_{ds} \qquad \forall ds = 1, 2, ..., DS \qquad (30)$$

cp_mncap_{ds} and cp_mxcap_{ds} are the minimum and maximum capacity of the composting plant associated with a disposal site *ds*.

Constraints for maximum capacity of landfill associated with a disposal site *ds*:

$$LFW_{ds} \le lf\_mxcap_{ds} \qquad \forall ds = 1, 2, ..., DS \qquad (31)$$

lf_mxcap_{ds} is the maximum capacity of the landfill associated with a disposal site *ds*. Minimum capacity of the landfill has not been fixed.

The municipal area is divided into *zn* number of zones for each disposal site *ds*. The divisions of zones are made based on their closeness to the disposal site *ds*. The maximum trip limits ($zn\_mxtrip_{dv,ds,zn}$) and minimum trip limits ($zn\_mntrip_{dv,ds,zn}$) for each zone *zn* of a disposal site *ds* for a *dv*-type departmental vehicle has been fixed by the municipal authority. The drivers and the helpers are paid incentives if they do trips beyond the minimum trip limits, stipulated for a particular zone *zn*. Similarly, the hired vehicles *hv* are paid per ton of waste basis according to the zone *zn* (of a disposal site *ds*). Constraints based on the number of trips made by departmental or hired vehicles in a zone *zn* of a disposal site *ds* are given below.

Number of trips made by a departmental vehicle *dv* in a zone *zn* of a disposal site *ds*:

$$ACTRPDV_{dv,ds,zn} \times dv\_cap_{dv} - \sum_{br=1}^{BR} QGDV_{br,ds,dv} = 0 \qquad (32)$$
$$\forall dv = 1,2,...,DV, \quad \forall ds = 1,2,...,DS, \quad \forall zn = 1,2,..,ZN$$

$ACTRPDV_{dv,ds,zn}$ is the actual number of trips made by *dv* type departmental vehicle to a zone *zn* of a disposal site *ds*. dv_cap_{dv} is the average waste carrying capacity of a *dv* type departmental vehicle. In calculating $\sum QGDV_{br,ds,dv}$, only those *br* boroughs are considered which belong to the zone *zn* of the disposal site *ds*.

Actual number of trips made by hired vehicles *hv* (which is only one type) in a zone *zn* of a disposal site *ds* for collection of garbage:

$$ACTRPHVG_{hv,ds,zn} \times hv\_gcap_{hv} - \sum_{br=1}^{BR} QGHV_{br,ds,hv} = 0 \qquad (33)$$
$$\forall ds = 1,2,...,DS, \quad \forall zn = 1,2,...,ZN$$

$ACTRPHVG_{hv,ds,zn}$ is the actual number of trips made by hired vehicles *hv* in a zone *zn* of a disposal site *ds* for collection of garbage. hv_gcap_{hv} is the average garbage carrying capacity for a hired vehicle *hv*. In calculating $\sum QGHV_{br,ds,hv}$, only those *br* boroughs are considered which belong to the zone *zn* of the disposal site *ds*.

Actual number of trips made by hired vehicles *hv* in a zone *zn* of a disposal site *ds* for collection of silt:

$$ACTRPHVS_{hv,ds,zn} \times hv\_scap_{hv} - \sum_{br=1}^{BR} QSHV_{br,ds,hv} = 0 \quad \forall ds = 1,2,\ldots,DS, \quad \forall zn = 1,2,\ldots,ZN \tag{34}$$

$ACTRPHVS_{hv,ds,zn}$ is the actual number of trips made by hired vehicles *hv* (which is only one type) in a zone *zn* of a disposal site *ds* for collection of silt. hv_scap_{hv} is the average silt carrying capacity for a hired vehicle *hv*. In calculating $\sum QSHV_{br,ds,hv}$, only those *br* boroughs are considered which belong to the zone *zn* of the disposal site *ds*.

Maximum possible trip limit of *dv* type departmental vehicle in zone *zn* of *ds*:

$$ACTRPDV_{dv,ds,zn} \le dv\_nr_{dv} \times zn\_mxtrip_{dv,ds,zn} \quad \forall dv = 1,2,\ldots,DV, \quad \forall ds = 1,2,\ldots,DS, \quad \forall zn = 1,2,\ldots,ZN \tag{35}$$

$zn\_mxtrip_{dv,ds,zn}$ is the maximum number of trips that a *dv* type departmental vehicle is allowed to undertake in zone *zn* of disposal site *ds*. dv_nr_{dv} is the total number of *dv* type departmental vehicles running.

Maximum possible trip limit by *dv* type departmental vehicle in all disposal site *ds*, all zone *zn*:

$$\sum_{ds=1}^{DS} \sum_{zn=1}^{ZN} ACTRPDV_{dv,ds,zn} \le dv\_nr_{dv} \times mxzn\_mxtrip_{dv} \qquad \forall dv = 1,2,\ldots,DV \tag{36}$$

For a particular *dv* type vehicle, considering all disposal sites *ds*, the maximum value of $zn\_mxtrip_{dv,ds,zn}$ is taken as $mxzn\_mxtrip_{dv}$.

Minimum possible trip limit by *dv* type departmental vehicle in all disposal site *ds*, all zone *zn*:

$$\sum_{ds=1}^{DS}\sum_{zn=1}^{ZN} ACTRPDV_{dv,ds,zn} \geq dv\_nr_{dv} \times mnzn\_mntrip_{dv} \qquad \forall dv = 1,2,...,DV \tag{37}$$

$zn\_mntrip_{dv,ds,zn}$ is the minimum number of trips that a *dv* type departmental vehicle has to undertake in zone *zn* of disposal site *ds*. For a particular *dv* type vehicle, considering all disposal sites *ds*, the minimum value of $zn\_mntrip_{dv,ds,zn}$ is taken as $mnzn\_mntrip_{dv}$.

Balancing amount of garbage transported by *dv* type departmental vehicle to disposal site *ds* from zone *zn* of that *ds*:

$$GDV_{dv,ds,zn} - \sum_{br=1}^{BR} QGDV_{br,ds,dv} = 0 \qquad \forall zn = 1,2,...,ZN,\ \forall ds = 1,2,...,DS,\ \forall dv = 1,2,...,DV \tag{38}$$

$GDV_{dv,ds,zn}$ is the amount of garbage transported by *dv* type departmental vehicle to a disposal site *ds* from zone *zn* of that *ds*. $\sum QGDV_{br,ds,dv}$ is the total amount of garbage taken by *dv* type vehicle to disposal site *ds* from all those *br* boroughs which belong to zone *zn* of that *ds*.

Balancing amount of garbage transported by hired vehicle *hv* to disposal site *ds* from zone *zn* of that *ds*:

$$GHV_{hv,ds,zn} - \sum_{br=1}^{BR} QGHV_{br,ds,hv} = 0 \qquad \forall zn = 1,2,...,ZN,\ \forall ds = 1,2,...,DS \tag{39}$$

$GHV_{hv,ds,zn}$ is the amount of garbage transported by hired vehicle *hv* to disposal site *ds* from zone *zn* of that *ds*. $\sum QGHV_{br,ds,hv}$ is the total amount of garbage taken by hired vehicle *hv* to disposal site *ds* from all those *br* boroughs which belong to zone *zn* of that *ds*.

Balancing amount of silt transported by hired vehicle *hv* to disposal site *ds* from zone *zn* of that *ds*:

$$SHV_{hv,ds,zn} - \sum_{br=1}^{BR} QSHV_{br,ds,\text{hv}} = 0 \qquad \forall zn = 1,2,...,ZN, \;\; \forall ds = 1,2,...,DS \qquad (40)$$

$SHV_{hv,ds,zn}$ is the amount of silt transported by hired vehicle *hv* to disposal site *ds* from zone *zn* of *ds*. $\sum QSHV_{br,ds,hv}$ is the total amount of silt taken by hired vehicle *hv* to disposal site *ds* from all those *br* boroughs which belong to zone *zn* of *ds*.

Total cost of sorting associated with all disposal sites *ds*:

$$\begin{aligned} COSTSS &- \sum_{ds=1}^{DS}\left[SSF_{ds} \times ss\_cost\_sort_{ds}\right] \\ &- \sum_{ds=1}^{DS}\left[SSR_{ds} \times ss\_cost\_r_{ds} + SSAD_{ds} \times ss\_cost\_ad_{ds}\right] = 0 \end{aligned} \qquad (41)$$

$ss\_cost\_sort_{ds}$ is the sorting cost per ton of solid waste feed for the central sorting station associated with the disposal site *ds*. $ss\_cost\_r_{ds}$ is the cost of transporting recyclable material from the sorter associated with disposal site *ds* to the recycling facility, Rs/MT. Per ton cost of additional dumping in associated *ds* is $ss\_cost\_ad_{ds}$, Rs/MT.

Total cost of incineration associated with all disposal sites *ds*:

$$COSTIP - \sum_{ds=1}^{DS}\begin{bmatrix} SSIPF_{ds} \times ip\_cost\_op_{ds} + IPR_{ds} \times ip\_cost\_r_{ds} \\ +IPAR_{ds} \times ip\_cost\_ar_{ds} + IPIR_{ds} \times ip\_cost\_ir_{ds} \end{bmatrix} = 0 \qquad (42)$$

$ip\_cost\_op_{ds}$ is the operational cost of the incinerator at disposal site *ds*, Rs/MT of incinerator feed. It includes the construction and operational cost of incinerator and also the transportation cost from the associated sorting facility to the incinerator. $ip\_cost\_r_{ds}$ is the transportation cost of the recyclables (Rs/MT) from the incinerator pre-sorter attached to the disposal site *ds* to the recycling facility. $IPAR_{ds}$ is the incinerator ash product and it is transported from the incinerator to the associated landfill site at a transportation cost of $ip\_cost\_ar_{ds}$ (Rs/MT) for a particular disposal site *ds*. $IPIR_{ds}$ is the inorganic reject portion, separated from the incinerator pre-sorter, and is sent to landfill associated with a particular disposal site *ds* at a transportation cost of $ip\_cost\_ir_{ds}$ (Rs/MT).

Total cost of composting associated with all disposal sites *ds*:

$$COSTCP-\sum_{ds=1}^{DS}\begin{bmatrix} SSCPF_{ds}\times cp\_cost\_op_{ds}+CPR_{ds}\times cp\_cost\_r_{ds} \\ +CPIR_{ds}\times cp\_cost\_ir_{ds}+CPPR_{ds}\times cp\_cost\_pr_{ds} \end{bmatrix}=0 \tag{43}$$

$cp\_cost\_op_{ds}$ is the operational cost of the composting plant including cost of construction and operation of composting plant and transportation cost of compost plant feed from the central sorting facility to composting plant, Rs/MT. $cp\_cost\_r_{ds}$ is the transportation cost (Rs/MT) of recyclables from composting pre-sorter for a particular disposal site *ds* to the recycling facility. $CPIR_{ds}$ is the inorganic reject amount transported from composting pre-sorter to the associated landfill at a transportation cost of $cp\_cost\_ir_{ds}$ (Rs/MT). The composting process rejects for a disposal site *ds*, $CPPR_{ds}$, are transported to the associated landfill at a cost of $cp\_cost\_pr_{ds}$ (Rs/MT).

Total cost of landfilling associated with all disposal sites *ds*:

$$COSTLF-\sum_{ds=1}^{DS}LFW_{ds}\times lf\_cost_{ds}=0 \tag{44}$$

lf_cost_{ds} is the landfilling cost in Rs/MT for the landfilling site associated with the disposal site *ds*. It includes the cost of land, cost of liner, leachate management, final cover, etc.

Total revenue generated by selling recyclable materials sorted out from all the disposal site *ds*:

$$REVR-\sum_{ds=1}^{DS}\left[SSR_{ds}\times ss\_rev\_r_{ds}+IPR_{ds}\times ip\_rev\_r_{ds}+CPR_{ds}\times cp\_rev\_r_{ds}\right]=0 \tag{45}$$

$ss\_rev\_r_{ds}$ is the revenue earned from selling of recyclable materials generated from the sorting station associated with the disposal site *ds,* Rs/MT. $ip\_rev\_r_{ds}$ and $cp\_rev\_r_{ds}$ are the revenues earned from selling of recyclable materials sorted out from incinerator pre-sorter and composting pre-sorter respectively, associated with the disposal site *ds*, Rs/MT.

Total revenue earned by selling all compost produced from compost plants associated with all disposal sites *ds*:

$$REVC - \sum_{ds=1}^{DS} \left[CPPROD_{ds} \times cp\_sp\_c_{ds} \right] = 0 \tag{46}$$

$cp\_sp\_c_{ds}$ is the selling price of the compost, Rs/MT.

Total cost of transportation of waste to all the disposal sites:

$$COSTTRN - COSTTRHV_{hv} - \sum_{dv=1}^{DV} COSTTRDV_{dv} = 0 \tag{47}$$

Total cost of transportation of solid waste to all the disposal sites *ds* includes the transportation cost for hired vehicles *hv* as well as the cost of transportation incurred by the departmental vehicles *dv*. $COSTTRHV_{hv}$ is the total cost of transportation of waste by hired vehicles. $COSTTRDV_{dv}$ is waste transportation cost by *dv* type departmental vehicles. Incidentally, hired vehicles collect and transport both garbage and silt, while departmental vehicles transport only garbage. There is only one type of hired vehicle. Haulage capacities of garbage and silt/rubbish for hired vehicle are considered different. Rates for garbage and silt transportations are different. Also, garbage and silt transportation charges by hired vehicles are paid to them on the basis of different zones (associated with different disposal sites *ds*) from which the wastes are being transported. All liabilities of hired vehicles are the responsibility of the respective private agencies.

Total cost of waste transportation by hired vehicles from borough *br* centers to disposal sites *ds*:

$$COSTTRHV_{hv} - COSTTRHVG_{hv} - COSTTRHVS_{hv} = 0 \tag{48}$$

Total cost of transportation by hired vehicles is the summation of garbage transportation cost by hired vehicles from borough *br* centers to disposal sites *ds*, $COSTTRHVG_{hv}$, and the silt transportation cost by hired vehicles from borough *br* centers to disposal sites *ds*, $COSTTRHVS_{hv}$.

Total cost of garbage transportation by hired vehicles from borough *br* centers to disposal sites *ds*:

$$COSTTRHVG_{hv} - \sum_{br=1}^{BR} \sum_{ds=1}^{DS} \left[QGHV_{br,ds,hv} \times br\_cost\_hg_{br,ds} \right] = 0 \quad (49)$$

$br\_cost\_hg_{br,ds}$ is the per ton transportation cost of garbage from borough *br* center to disposal site *ds* for a hired vehicle *hv*, Rs./MT.

Total cost of silt transportation by hired vehicles from borough *br* centers to disposal sites *ds*:

$$COSTTRHVS_{hv} - \sum_{br=1}^{BR} \sum_{ds=1}^{DS} \left[QSHV_{br,ds,hv} \times br\_cost\_hs_{br,ds} \right] = 0 \quad (50)$$

$br\_cost\_hs_{br,ds}$ is the per ton transportation cost of silt from borough *br* center to disposal site *ds* for a hired vehicle *hv*, Rs./MT.

Total cost of garbage transportation (without incentives) by *dv* type departmental vehicles is the summation of fuel cost, fixed cost of running vehicles and fixed cost of idle vehicles.

Waste transportation cost by *dv* type departmental vehicle from borough *br* centre to disposal sites *ds*:

$$COSTTRDV_{dv} - COSTFLDV_{dv} - COSTFXR_{dv} - COSTFXI_{dv} = 0 \qquad \forall\ dv = 1,2,...,DV \quad (51)$$

$COSTFLDV_{dv}$ is the cost of fuel incurred by *dv* type departmental vehicles for waste transportation. $COSTFXR_{dv}$ and $COSTFXI_{dv}$ are the total fixed cost for running and the total fixed cost for idle *dv* type departmental vehicles. The fixed costs include annualized capital cost of vehicles, maintenance cost and driver and helper cost. Everyday approximately 50 to 80% of the departmental vehicles run; other remain in idle or standby condition.

The cost of fuel incurred by *dv* type departmental vehicle:

$$COSTFLDV_{dv} - \sum_{ds=1}^{DS}\sum_{br=1}^{BR}\left[QGDV_{br,ds,dv} \times br\_cost\_fl_{br,ds,dv}\right] = 0 \qquad \forall dv = 1,2,...,DV \qquad (52)$$

$br\_cost\_fl_{br,ds,dv}$ is the average fuel cost for transporting per ton waste from borough *br* center to disposal site *ds* by a *dv* type vehicle.

Total fixed cost for running *dv* type departmental vehicle:

$$COSTFXR_{dv} - dv\_nr_{dv} \times dv\_cost\_fxr_{dv} = 0 \qquad \forall dv = 1,2,...,DV \qquad (53)$$

$dv\_cost\_fxr_{dv}$ is the fixed cost for running each *dv* type departmental vehicle.

Total fixed cost for idle *dv* type departmental vehicle:

$$COSTFXI_{dv} - (dv\_no_{dv} - dv\_nr_{dv}) \times dv\_cost\_fxi_{dv} = 0 \qquad \forall dv = 1,2,\ldots,DV \qquad (54)$$

dv_no_{dv} is the total number of *dv* type of departmental vehicles available in the municipality's fleet. $dv\_cost\_fxi_{dv}$ is the fixed idle cost for each *dv* type vehicle.

Total amount of incentives to be paid to *dv* type departmental vehicle drivers and helpers can be approximated by:

$$COSTINC - \sum_{dv=1}^{DV} CINC_{dv} = 0 \qquad (55)$$

$$\begin{aligned} CINC_{dv} - \left[\sum_{ds=1}^{DS}\sum_{zn=1}^{ZN} GDV_{dv,ds,zn} \times r\_inc_{dv}\right] \\ + dv\_nr_{dv} \times mnzn\_mntrip_{dv} \times dv\_cap_{dv} \times r\_inc_{dv} = 0 \qquad \forall dv = 1,2,...,DV \end{aligned} \qquad (56)$$

$CINC_{dv}$ is the amount of incentive (in Rs.) to be paid to a *dv* type vehicle for transporting waste more than the minimum stipulated number of trips. r_inc_{dv} is the rate of incentive (per extra ton basis) to be paid to the driver and helper of a *dv* type vehicle for transporting waste over and above the minimum trips.

5.3. GENERATION AND SOLVING THE MODEL

A program is written in MATLAB v 7.1 to read the input data items in a specific tabular format. The output of the program is the LP formulation in the IBM MPSX LP input file format readable by the commercially available LP solver 'LINDO' (Schrage, 1984). LINDO is a software tool for utilising the power of linear optimisation to formulate large problems concisely, solve them, and analyze the solution (LINDO Systems Inc., 2004). Solved the model it generates the results in the form of a solution report. After interpreting the solution report, relevant data tables were generated. A flow chart of the entire process is given below:

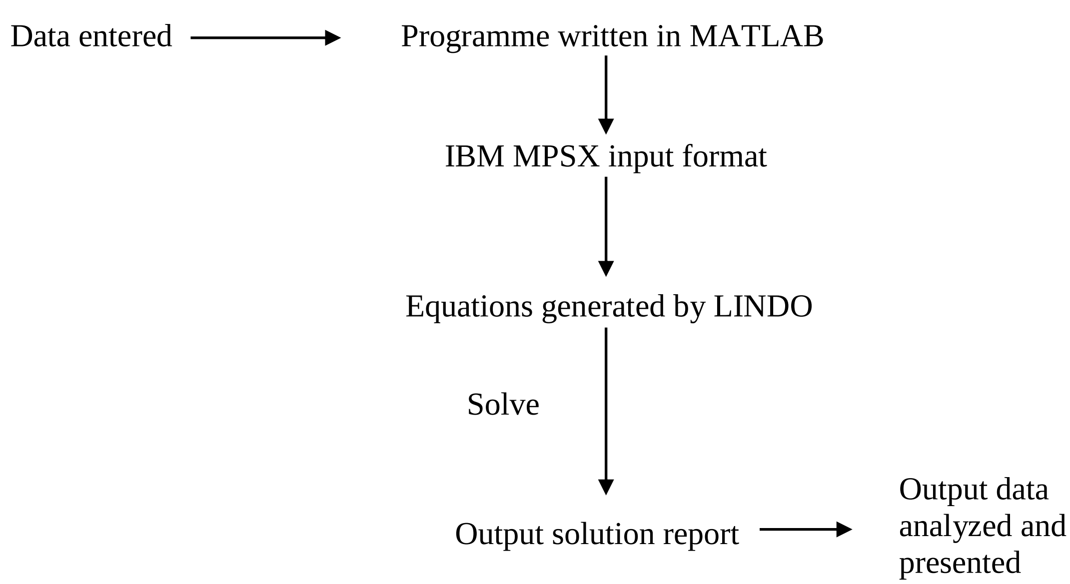


Figure 5.1 Flowchart detailing steps for running the model in LINDO

Due to the limitation of the length of the variable in LINDO, while applying the model using LINDO variable manes have to be shortened and it is provided in the Annexure 6.17, 6.18, 6.19 and 6.20 in Annexure 6.

6. VALIDATION AND ANALYSIS OF A SOLID WASTE MANAGEMENT OPTIMISATION MODEL

6.1 APPLICATION OF MODEL IN EXISTING SOLID WASTE MANAGEMENT OF KOLKATA AND ITS OPTIMIZATION

6.1.1 Basic Assumptions and Input of the Model Considering Existing Situation

6.1.1.1 General Description

In the existing MSW management system open dumping of waste without any liner and gas collection system is practiced. Borough wise (borough I to borough XV) 15 regions are selected and only one landfill site at the eastern fringe of Kolkata, Dhapa is considered along with composting facility. As the existing dumping ground, Dhapa is about 10 KM distance from the center of the city so at present department (KMC) does not have any transfer station.

The waste is broadly classified in two categories (i) garbage which is ~90% of the total waste and its characteristics is given in table 4.1 (ii) silt or rubbish, which is ~10% of the total waste and it is basically inert material. No effective source segregation of waste is practiced. Around 5% recyclables of the garbage is taken out by the informal rag pickers at the household, container and vat point level. All the collected garbed is transported directly to the dumping ground at Dhapa by both departmental (KMC) vehicles (four types) and private own vehicles (one type). Minor part of the garbage (5 to 6%) is converted to compost at the adjacent to the Dhapa dumping ground and KMC gets some royalty out of it. Silt or rubbish is transported to the dumping ground by privet vehicles (hired) only. After reaching rest of the garbage to the dumping ground, Dhapa informal rag pickers further segregated out around 4.21% recyclable. So total recovered recyclable is around 9.21% of the garbage and no revenue is earned by the KMC. Rest ~90% of mixed waste is disposed in Dhapa dumping ground.

6.1.1.2 Borough Wise Garbage and Silt or Rubbish Generation

Average daily garbage and silt or rubbish generation in each of 15 boroughs are shown in (Table 6.1).

Table 6.1 Borough wise average daily garbage and silt / rubbish generation

Boro.	Total Garbage (tpd)			Total Silt+Rubbish (tpd)			Total Waste (tpd)		
	Max	Min	Avg.	Max	Min	Avg.	Max	Min	Avg.
Br.1	193.460	176.928	178.44	30.790	11.723	20.11	215.261	178.532	198.55
Br.2	187.999	167.631	175.12	31.253	3.007	12.03	219.252	186.466	187.150
Br.3	203.261	163.989	179.48	31.475	9.398	20.09	232.025	173.388	199.57
Br.4	204.805	134.960	156.23	24.490	7.300	12.72	224.673	142.252	168.95
Br.5	208.776	185.853	188.48	27.654	8.697	17.14	236.431	204.439	205.62
Br.6	258.256	204.648	234.22	61.668	15.182	35.14	318.065	227.586	269.36
Br.7	276.742	206.717	241.52	88.196	44.059	62.55	352.873	259.363	304.07
Br.8	172.660	147.754	160.39	72.744	19.044	40.08	241.312	166.300	200.47
Br.9	290.705	240.975	266.00	43.199	12.665	25.92	341.712	249.579	291.92
Br.10	387.740	281.185	336.92	76.347	10.781	30.92	428.905	302.093	367.84
Br.11	101.225	90.897	95.46	3.464	0.677	1.8	103.698	92.277	97.26
Br.12	90.726	77.641	83.54	6.379	0.205	2.25	95.909	79.670	85.79
Br.13	179.524	146.612	157.04	13.941	0.909	3.94	182.088	149.563	160.98
Br.14	149.191	111.811	129.27	19.366	4.141	9.37	153.332	117.955	138.64
Br.15	25.022	21.723	22.183	0.416	0.278	0.058	25.022	25.344	22.241

6.1.1.3 Maximum and Minimum Limit (in Fraction) of Garbage Quantity Carried by Different Vehicles

Borough wise garbage disposal is analyzed considering maximum and minimum fraction of waste carried by four types departmental vehicles D1, D2, D3, D4 and one type hired vehicle HH. Number of available vehicles of different types is shown in Table 4.6. To make the model flexible and more realistic, borough-wise minimum and maximum garbage carrying range (in fraction) for both departmental and hired vehicles is considered. From existing data it reveals that garbage carried by of different vehicles varies by ± 5% (KMC,2007). Accordingly maximum and minimum limit of garbage carrying capacity by both departmental and hired vehicles are varied by around same percentage (Table 6.2).

Table 6.2 Borough wise minimum and maximum garbage carrying quantity range (in fraction) for departmental and hired vehicles

Borough	D1		D2		D3		D4		HH	
	Min fraction	Max fraction	Min fraction	Max fraction	Min fraction	Max fraction	Min fraction	Max fraction	Min fraction	Max fraction
Br.1	0.00	0.01	0.14	0.24	0.18	0.28	0.06	0.16	0.41	0.51
Br.2	-	-	0.15	0.25	0.12	0.22	-	-	0.57	0.67
Br.3	0.00	0.04	0.22	0.32	0.19	0.29	-	-	0.42	0.52
Br.4	-	-	0.10	0.20	0.00	0.11	0.21	0.31	0.48	0.58
Br.5	-	-	0.00	0.08	0.00	0.07	0.29	0.39	0.53	0.63
Br.6	-	-	0.00	0.11	0.00	0.04	0.13	0.23	0.70	0.80
Br.7	-	-	0.10	0.20	0.00	0.08	0.05	0.18	0.67	0.77
Br.8	-	-	0.15	0.25	0.18	0.28	-	-	0.53	0.63
Br.9	-	-	0.12	0.22	0.15	0.25	-	-	0.58	0.68
Br.10	-	-	0.13	0.23	-	-	-	-	0.77	0.87
Br.11	0.15	0.25	-	-	0.15	0.25	-	-	0.55	0.65
Br.12	0.20	0.30	-	-	0.20	0.30	-	-	0.45	0.55
Br.13	0.10	0.20	-	-	0.25	0.35	-	-	0.50	0.60
Br.14	0.05	0.15	-	-	0.25	0.35	-	-	0.65	0.75
Br.15	-	-	-	-	0.00	0.02	-	-	0.95	1.00

Note: "–" indicates vehicle types are not allotted

6.1.1.4 Maximum and Minimum Trip Limits of Departmental Vehicles

Primarily based on the distance between borough to disposal site Dhapa, concentration of waste generation points and accessibility of vehicles to the collection points, the KMC area are divided into two zones, zone 1 and zone 2. Borough 2 to borough 8 and borough 12 fall under zone1 and Borough 1, borough 9 to borough 11 and borough 13 to borough 15 fall under zone 2. Borough wise distance and their zones are mentioned in Table 6.3.

Table 6.3 Borough wise distance and their zones for disposal site Dhapa

Boroughs under zone 1	Borough distance from Dhapa disposal site (KM)	Boroughs under zone 2	Borough distance from Dhapa disposal site (KM)
Br.2	7.5	Br.1	9.0
Br.3	5.0	Br.9	9.5
Br.4	7.5	Br.10	7.0
Br.5	7.0	Br.11	8.0
Br.6	7.0	Br.13	10.0
Br.7	3.5	Br.14	11.5
Br.8	6.5	Br.15	13.5
Br.12	3.0		

For departmental vehicles maximum and minimum trip limits are considered. Maximum and minimum trip limits of departmental vehicles are derived based on past few years of KMC data on availability of vehicles in different garages, use of vehicles in different boroughs, the number of trips by different vehicles, and amount of waste transportation. Each running departmental vehicles has to make minimum trips. Incentives are given to the drivers and helpers for carrying wastes more than the minimum trip but up to the maximum trip limit. In case of D1, D2 (hydraulically operated) and D4 (payloader loaded) type vehicles 1 driver and 1 helper and for D3 (manually loaded) type vehicle 1 driver and 5 helpers are allowed. Maximum and minimum trip limits and incentive of departmental vehicles are shown in Table 6.4. Detail calculation of average weight carried by departmental vehicles is shown in Table A-6.1 of Annexure 6.1. Sample calculation of incentive rate per ton of departmental vehicles is shown in Annexure 6.2.

Table 6.4 Maximum and minimum trip limits of departmental vehicles for different zones and their incentive

Type of departmental vehicles	Zone 1		Zone 2		Average wt. carried (MT)	Incentive rate per ton (Rs / MT)		
	Maxm. trips	Minm. trips	Maxm. trips	Minm. trips		Driver	Helper	Total
D1 (1 driver and 1 helper)	6	3	6	2	1.75	10	5	15
D2 (1 driver and 1 helper)	8	3	6	2	2	7	3.5	10.5
D3 (1 driver and 5 helpers)	8	3	4	2	3	10	5	35
D4 (1 driver and 1 helper)	8	3	4	2	7	5	2.5	7.5

Note: Total incentive rate (Rs / MT) = (Incentive rate of Driver, Rs / MT) + (Incentive rate of Helper, Rs / MT) × No. of Helper

6.1.1.5 Cost of Transportation

Cost of waste transportation includes transportation cost for departmental and hired vehicles from storage points i.e. container points or vat points to the treatment and disposal site. Transportation cost of departmental vehicles is the summation of fuel cost, fixed cost of running vehicle and fixed cost of idle vehicle. KMC is responsible for procurement, operation and maintenance of its departmental vehicles. Fuel is issued from different departmental garages to the departmental vehicles and fuel consumption for four different types of departmental vehicles is considered on the basis of loaded run condition and empty run condition. Number of total, running and idle vehicles of different types are shown in Table 6.7. Fixed running cost of departmental vehicles is calculated on the basis of depreciation, interest, and all wages for different types of running vehicles. Similarly for idle vehicles i.e. vehicles under maintenance, the fixed costs of different departmental vehicles are estimated on the basis of depreciation, interest, and maintenance wages only.

Garbage and silt transportation costs (Rs /MT) by hired vehicles are paid on the basis of different zones. All other costs like capital, depreciation, fuel, maintenance and wages are included in the mutually approved zone wise rates for garbage and silt. All liabilities of hired vehicles are the responsibility of the respective private agencies.

(a) Cost of transportation for departmental vehicles

D1, D2, D3 and D4 are four types of departmental vehicles with their different (i) load carrying capacities (ii) fuel consumptions in loaded run and empty run conditions and (iii) number of driver and helpers (iv) capital and maintenance costs. So fuel cost for transporting per ton of garbage and fixed costs vary for different departmental vehicles.

(i) Fuel cost for departmental vehicles

Up and down (i.e. loaded trip and unloaded trip) distance for each trip is considered same for each borough as the distances are calculated from center of borough to Dhapa disposal site (Table 6.3). Average waste carrying capacity, varying fuel consumption for loaded and empty run condition i.e. different fuel costs in loaded and empty run conditions for different vehicles are shown in Table 6.5. Basis for calculation of fuel consumption in loaded and empty run condition (KM/lit) is shown in Table A-6.2. Sample calculation of fuel cost/KM in loaded and in empty run condition is shown in Annexure 6.1. Fuel cost per ton for different type of vehicles for different boroughs is estimated based on the above and shown in Table 6.6. Detail calculation of fuel per ton for departmental vehicle is shown in Table A-6.3, Table A-6.3, Table A-6.4, Table A-6.5, Table A-6.6 and Table A-6.7 of Annexure 6.3. Sample calculation of D1, D2, D3 and D4 vehicle in Borough1 is shown in Annexure 6.3.

Table 6.5 Average load carrying capacity, fuel consumption and cost in loaded and empty run condition for departmental vehicles

Type of vehicles	Avg. wt carried (MT/day)	Fuel consumption in loaded run condition (KM /Lit)	Fuel consumption in empty run condition (KM /Lit)	Fuel cost / KM in loaded run condition (Rs/KM)	Fuel cost / KM in empty run condition (Rs/KM)
D1	1.75	4.25	5.5	8.00	6.18
D2	2.0	3.5	4.5	9.71	7.56
D3	3.0	3.35	4.35	10.15	7.82
D4	7.0	1.67	2.33	20.36	14.59

Note: Fuel consumption cost in loaded run condition (Rs/KM) = Fuel cost (Rs/Lit) / Fuel consumption in loaded run condition (KM/Lit). Fuel cost is taken Rs. 34 per liter (KMC, 2007).

Table 6.6 Fuel cost per ton for departmental vehicles

Borough	Fuel cost (Rs/MT) for D1 vehicle	Fuel cost (Rs/MT) for D2 vehicle	Fuel cost (Rs/MT) for D3 vehicle	Fuel cost (Rs/MT) for D4 vehicle
Br. 1	72.93	77.72	53.91	44.94
Br. 2	60.77	64.77	44.93	37.45
Br. 3	40.51	43.18	29.95	24.96
Br. 4	60.77	64.77	44.93	37.45
Br. 5	56.72	60.45	41.93	34.95
Br. 6	56.72	60.45	41.93	34.95
Br. 7	28.36	30.23	20.97	17.48
Br. 8	52.67	56.13	38.94	32.45
Br. 9	76.98	82.04	56.91	47.43
Br. 10	56.72	60.45	41.93	34.95
Br. 11	64.82	69.08	47.92	39.94
Br. 12	24.31	25.91	17.97	14.98
Br. 13	81.03	86.35	59.9	49.93
Br. 14	93.18	99.31	68.89	57.42
Br. 15	109.39	116.58	80.87	67.40

Note: Fuel cost for each borough (Rs/MT) = [Cost of average fuel consumptions for loaded and empty run (Rs/KM) × Up and down distance (KM)] / Average waste carrying capacity (MT).

(ii) Fixed costs for departmental vehicles

Fixed cost of running departmental vehicles D1, D2, D3 and D4 are calculated on the basis of depreciation (assuming scrap value 10% of capital cost, life of vehicle as 10 years), interest (10% on reducing loan), wages of driver and helper [Basic, Dearness Allowances (D.A.), Medical Allowances (M.A), House Rent Allowances (H.R.A) including 30% overtime allowances), wages of garage staff including administration and managerial, annual operational and maintenance costs (10% of capital cost). For the calculation of fixed cost of idle departmental vehicles, wages of driver and helper are not considered as optimized numbers of drivers and helpers are available which is almost used regularly by the running vehicles. Detailed analysis of fixed and idle costs is shown in Annexure 6.4. Different types of number of running and idle vehicles and their fixed and idle costs are shown in Table 6.7. Calculation for percentage of running and idle vehicles is shown in Table A-6.8 of Annexure 6.5.

Table 6.7 Different types of total number departmental vehicles and their fixed running and idle costs

Type of vehicles	Total number of vehicles	Running vehicle (%)	Fixed cost / vehicle / day	
			Running cost (Rs) / vehicle / day	Idle cost (Rs)/ vehicle / day
D1	16	56.25	2029.19	1388.10
D2	73	46.58	2167.69	1526.59
D3	82	67.07	2625.39	1214.99
D4	28	42.86	3180.18	2282.64

(b) Cost of transportation for hired vehicles

Hired vehicles carry garbage and silt or rubbish separately so, transportation cost (Rs/MT) for hired vehicles are considered for silt or rubbish and garbage separately for different zones and shown in Table 6.8 (KMC, 2007c). Carrying capacities of garbage and silt or rubbish for hired vehicle are considered as 7 MT/trip and 9 MT/trip respectively.

Table 6.8 Garbage and silt or rubbish carrying cost of hired vehicles

Borough	Garbage carrying cost (Rs / MT)	Silt or rubbish carrying cost (Rs / MT)
1	153	143
2	144	134
3	133.50	123.50
4	142	132
5	140	130
6	132.50	122.50
7	147.75	137.75
8	140	130
9	156.70	146.70
10	148.30	138.30
11	157.80	147.80
12	154.30	144.30
13	159.40	149.40
14	160.0	150.0
15	160.0	150.0

6.1.1.6 Sorting and Recycling

Recyclable materials generated in Kolkata are currently recovered exclusively through an informal, market driven, recycling collection and processing system. In the informal system, high value, good quality materials and items such as rigid plastics, metals, glasses, newsprints, furniture etc. are typically purchased directly from waste generators by traders. These materials do not enter the KMC waste stream. Scavengers recover a portion of the recyclable materials by picking through loads of waste which is temporarily stored at secondary collection points located throughout the city (vats), as well as picking through waste disposed at Dhapa landfill site and this recyclable amount is estimated as 5%.

At the Dhapa landfill site, a group of rag pickers sorted out the recyclable materials in a regular basis which is estimated as ~4.21%. So, in the existing system 9.21% of recyclable materials are recycled by rag pickers through this informal system of scavenging at vats and at the disposal site. All these recycling systems are done in informal system. For this reason no revenue is earned by the management authority. The management authority direct gains only ~9.21% reduction of waste (Figure 4.2).

6.1.1.7 Composting

(a) Biological conversion of MSW through composting and cost of compost

Compost plant exists at Dhapa disposal site and their maximum and minimum capacities are 500 tpd and 150 tpd respectively. In most of the time compost plant runs with 150 tpd. So, from model validation for the existing system, compost processing is considered as 150 tpd. Since compost plant is run through PPP model so no cost of compost production is borne by KMC that means total cost of compost production is considered as zero.

(b) Revenue from compost

Total revenue from compost is considered as 2.5% of sale price where sale price of compost per ton is Rs. 3500. Compost plant is run under PPP model. Amount of compost is considered as 26.57% of the feed. Inorganic rejects and process rejects etc. from composting goes to landfill site with an extra transportation cost.

(c) Operational and maintenance (O&M) cost of compost

Operational and maintenance cost of composts is calculated on the basis of (i) cost of labour and establishment (General, skilled, administration / management, miscellaneous, contingency) (ii) capital and maintenance cost (structures, fixed equipment, mobile equipment, miscellaneous, contingency) (iii) cost of utilities (power, water, sanitary, miscellaneous, contingency). O&M cost of compost is considered as Rs. 507.88/- per ton. O&M cost break up for composting is shown in Table A-6.9 of Annexure 6.6.

6.1.1.8 Incineration

For existing system no incineration is considered.

6.1.1.9 Landfilling

Apart from the recyclables and compost remaining mixed MSW along with rejects from compost goes to landfill site. Landfilling is basically open dumping without any liner system, leachate and gas collection facilities.

Operational and maintenance cost of open dumping system is calculated on the basis of (i) labour and establishment cost (general, skilled, administration/management, miscellaneous, contingency) (ii) capital and maintenance cost (fixed equipment, mobile equipment, spare parts for bull dozers, fuel, supply of trip tokens, ribbons etc), (iii) cost of utilities (power and utilities, miscellaneous, contingency). Amount of O&M cost of open dumping system is considered as Rs. 95/- per MT. O&M cost break up of open disposal site is shown in Table A-6.10 of Annexure 6.7.

6.1.2 Model Validation of Existing MSW Management System

Existing SWM system of Kolkata is not optimized. So for model validation, costs, availability of vehicles, waste transported by different vehicles and other parameters of existing MSW management system are compared with the model results of the existing MSW management situation without optimization of vehicle requirement.

For this model assumptions are same as above. In case of composting processed quantity is ~150 MT/day considered. Minimum capacity of landfill is zero and maximum capacity of landfill is unlimited. Major output after model (Annexure 6.17) run is shown in Table A-6.18.

6.1.2.1 Analysis of Model Output

(a) Waste quantities shared by individual vehicles in different boroughs

Waste quantities shared by different types of vehicles in 15 boroughs are explained in the following manner.

For borough 1 the fuel cost and incentive cost for departmental vehicles along with disposal cost of HH type vehicle are compared as other transportation costs of departmental vehicles are fixed costs (fixed running cost and fixed idle cost). Minimum cost is found for D4 vehicle and then the increased order of cost maintained by the other vehicle types are D1, D2, D3 and HH. After allotment of minimum amount of waste to all the vehicles, rest of the wastes are distributed to fulfill the maximum limit of waste in the order of D4, D1, D2, D3 and HH. Sample calculation for waste distribution of departmental and private vehicle is shown in Table A-6.11 of Annexure 6.8. So for Br.1, D4 is reaching its maximum limit first then for fulfilling the maximum amount for D1 and D2 the balance amount is exhausted.

For the rest of the boroughs according to the maximum and minimum limits of waste carrying capacities along with allotment of the vehicles (Table 6.2), the respective fuel costs (Table 6.6) and incentive costs (Table 6.4) of departmental vehicles and disposal cost of hire vehicles (Table 6.8), preferential order of vehicle types for waste disposal is chosen by the model. Amount of waste disposal for different boroughs by the different type of vehicles is shown in Figure 6.1.

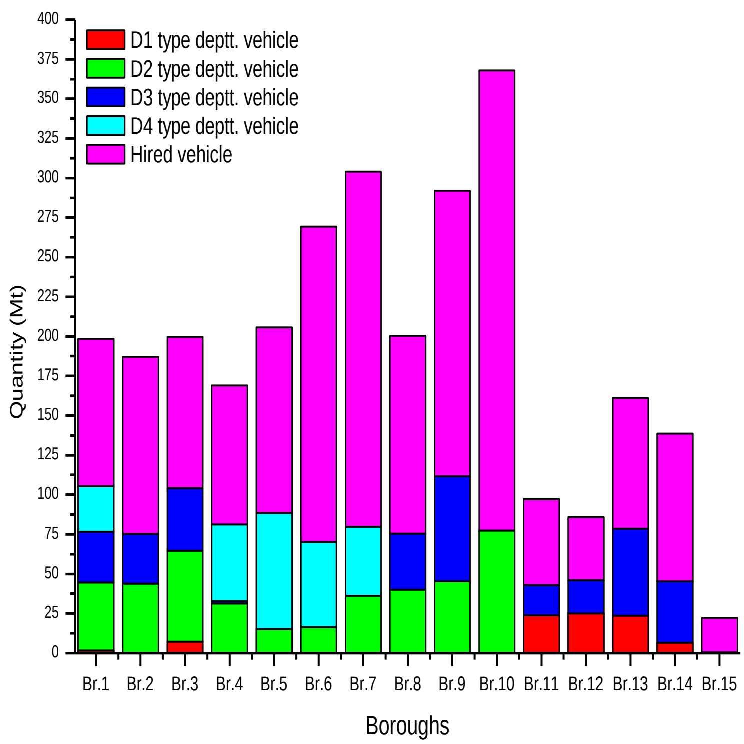


Fig.6.1 Waste shared quantity by individual vehicles in different boroughs

(b) Borough wise waste quantity carried by departmental and hired vehicles

Quantity of garbage and silt or rubbish carried by departmental vehicles and hired vehicles for different boroughs is shown in figure 6.2. According to the existing waste carrying limit and waste carrying costs, departmental vehicles carry more wastes in borough 1, borough 3 and borough 12 where as in other boroughs hired vehicles transport more than the departmental vehicles. In borough 6 and borough 7, department carries only ~26%, and in case of borough 10 and borough 15 departmental vehicle transports only ~21% and ~2.00% respectively. On an average in other boroughs departmental vehicles carry waste in between 42% to 55%.

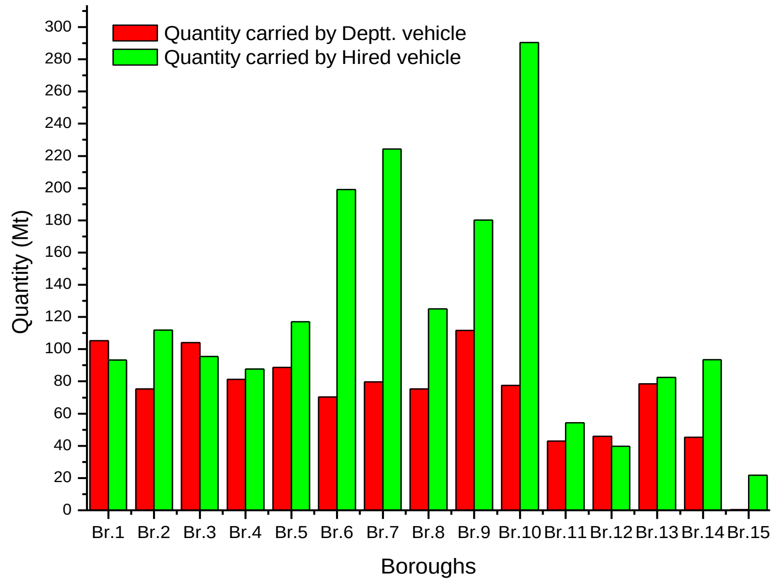


Fig.6.2 Borough wise waste quantity shared by departmental and hired vehicles

(c) Total waste quantity carried by departmental and hired vehicles

Percentage share of the total transportation of waste by different type of departmental vehicles (like D1, D2, D3, D4) and hired vehicles (HH) are 3.03%, 14.00%, 11.8%, 8.55% and 62.7% (figure 6.3).

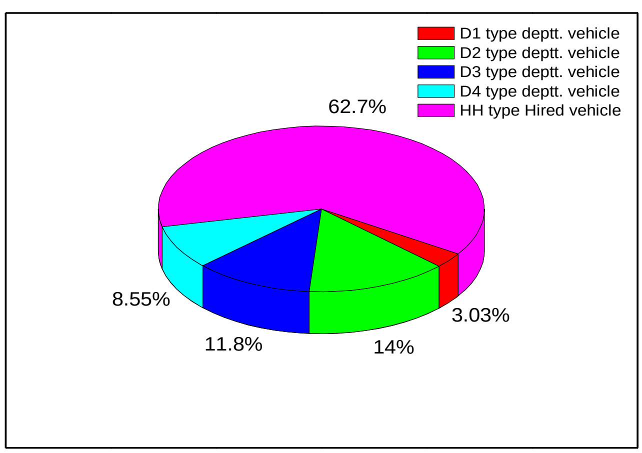


Fig.6.3 Shared quantity of waste (in percentage) by departmental and hired vehicles

In existing practice ratio of total quantity of waste i.e. garbage and silt or rubbish transported by departmental vehicles and hired vehicles is 33:67. But from model the ratio is found ~ 37:63. In existing practice if it is compared only with garbage disposal, then the ratio is found as 37:63 and in model 42:58 (figure 6.4). From existing practice model prefers 5% excess waste carried by departmental vehicles as their variable portion (fuel plus incentive costs) of the disposal costs is less than the disposal cost of hire vehicles.

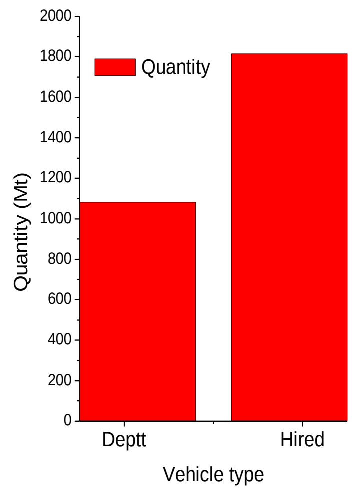


Fig.6.4 Waste quantity carried by departmental and hired vehicles

Departmental vehicles carry only garbage and hired vehicles i.e. open trucks carry both garbage and silt or rubbish and their sharing is shown in figure 6.5.

Fig.6.5 Quantity of garbage and silt or rubbish removed by hired vehicles

(d) Total transportation and O&M cost of departmental and hired vehicles

Total cost of departmental vehicles includes fixed running cost, fixed idle cost, incentive cost and fuel cost.

(i) Fixed running cost and fixed idle cost of departmental vehicles

Fixed running cost for D4 type vehicle is highest (Ref Table 6.7) if compared each type of vehicles individually but in totality fixed running cost for D3 vehicle is maximum as highest number (55 numbers) of D3 vehicles are in running condition (Table 4.6). Percentage of idle vehicles for D1, D2, D3, D4 are 43.75%, 53.42%, 32.93% and 57.14% respectively. Fixed idle cost for D4 type vehicle is least if compared individually but in totality fixed idle cost for D2 vehicle is maximum as highest number (39 numbers) of D2 vehicles are in idle condition (Table 4.6) in garages (figure 6.8).

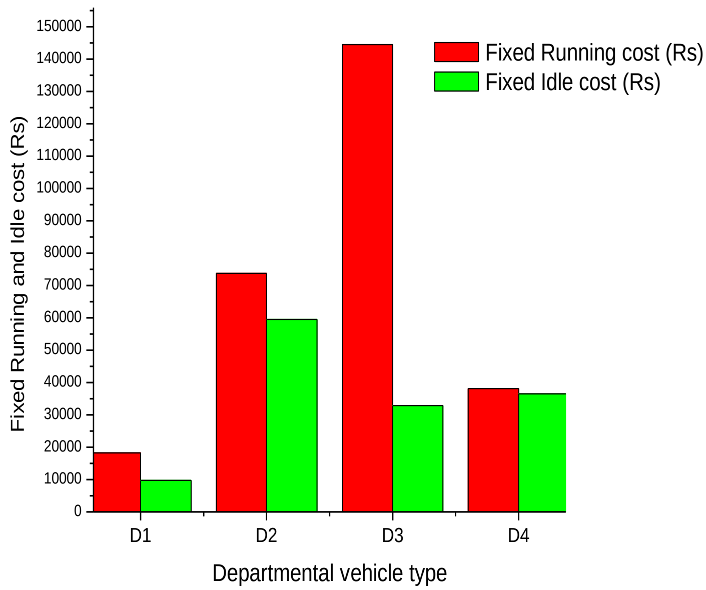


Fig.6.8 Total fixed running and fixed idle cost of different types of departmental vehicles

(ii) Incentive cost

Variation of total incentive cost (Rs.) required per day for departmental vehicles are shown in figure 6.9. Incentive rate per ton (Rs/ton) is maximum for D3 vehicle (Table 6.4) so model minimizes the total incentive amount of D3 vehicles. Though D4 has the minimum incentive rate, as the number of D4 vehicle is less it does not affect much on its total incentive value. D4 having the 2nd lowest incentive value and higher number of running vehicles results highest incentive amount.

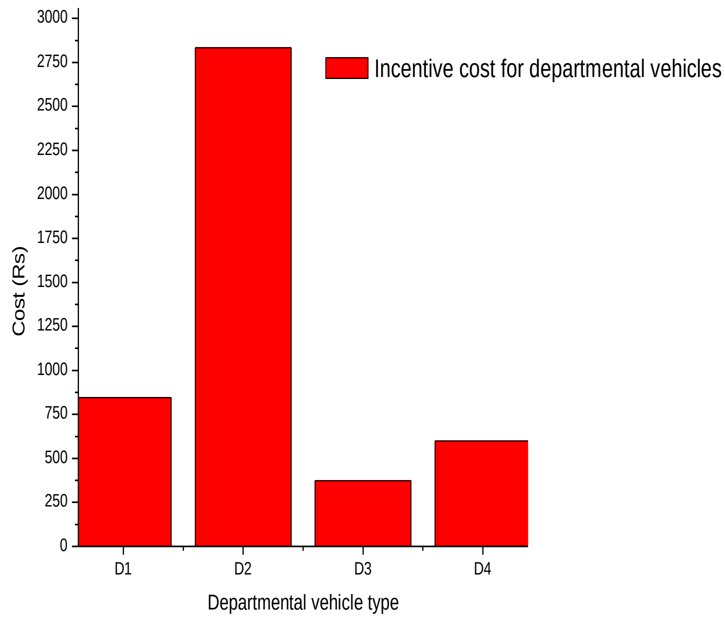


Fig.6.9 Incentive cost of departmental vehicles per day

(iii) Fuel cost

Fuel cost for departmental vehicles in different boroughs is shown in figure 6.10. In borough 9 the departmental fuel cost is highest, because cost of fuel for D2 and D3 (Rs. 82.04/t and Rs. 56.91/t) are high (table 6.6) and maximum amount of garbage (111.72 t) is carried by these two departmental vehicles. Departmental fuel cost in borough 1 is also in higher side due to higher fuel cost and higher amount garbage disposal by departmental vehicle. Even if fuel cost per ton of departmental vehicle is maximum (table 6.6) but total fuel cost is minimum for borough 15 because only D3 type of vehicle carries small quantity of waste. Though borough 7 carries more waste than borough 6, borough 8 and borough 10 but cost of fuel for departmental vehicle in borough 7 is less compared to these boroughs as fuel cost per ton is less due to its proximity to Dhapa disposal ground. Quantity of waste transported by departmental vehicles from borough 13, borough 7 and borough 4 is almost same (~80 MT/d) but borough wise departmental fuel cost in borough 13 and borough 4 are higher i.e. ~2.8 times and 1.3 times the cost of borough 7 due to higher fuel cost per ton of departmental vehicles.

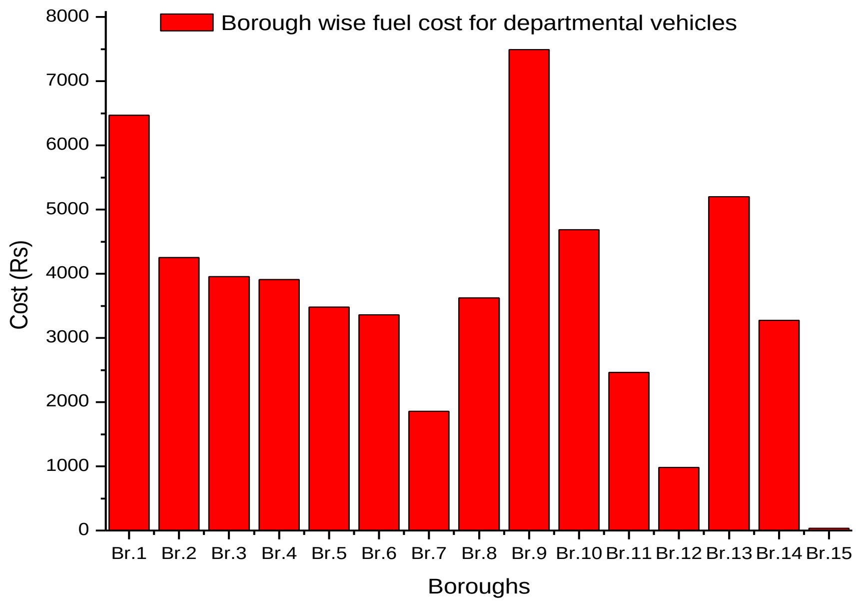


Fig.6.10 Borough wise fuel cost of departmental vehicles

Comparison of fuel cost, fixed running cost, fixed idle cost, incentive cost and total transportation cost for D1, D2, D3 and D4 type vehicle are shown in figure 6.11. D1, D2, D3 and D4 carries ~8.1%, ~37.5%, ~31.5% and ~22.9% of total quantity of waste carried by departmental vehicles and variation of their respective total cost are ~ 7.2%, ~34%, 41% and 17.8% respectively (table 6.9). D3 vehicle carries less quantity of waste than D2 vehicles but total transportation cost of D3 is more than D2 due to more number of vehicles in operation and engagement of higher number of helpers for D3 type manually loaded vehicle (table 6.7). In case of payloader loaded D4 type vehicles though the fixed cost is high yet less number of operating vehicles and higher carrying capacity results comparatively lesser total transportation cost than D2 and D3 type vehicles.

Table 6.9 Waste quantity carried and its costs for different departmental vehicles

Departmental vehicle type	Quantity (TPD)	Cost (Rs)
D1	87.9101	33067.65
D2	405.7969	157546.90
D3	340.6421	194050.46
D4	247.8331	83477.53

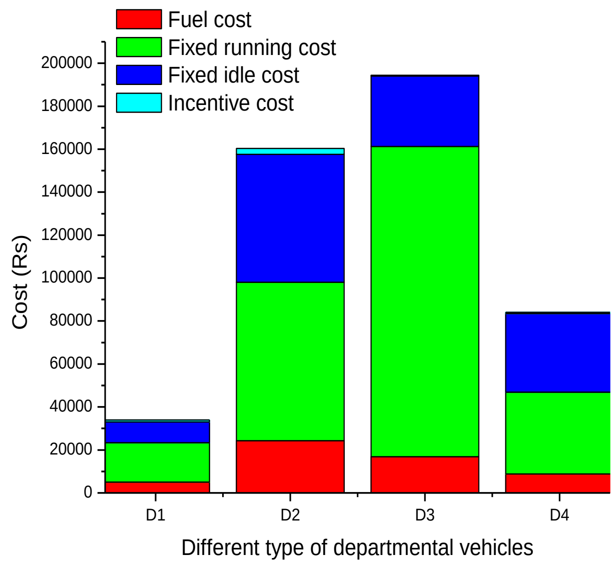


Fig.6.11 Different components of waste transportation costs for different types of departmental vehicles

Borough wise transportation cost of hired vehicles is shown in figure 6.12. Cost of garbage transportation by hired vehicles in Borough 10 is highest in comparison to other boroughs as ~79% (259.43 MT) (Table 6.1) of generated waste in this borough is transported by hired vehicles.

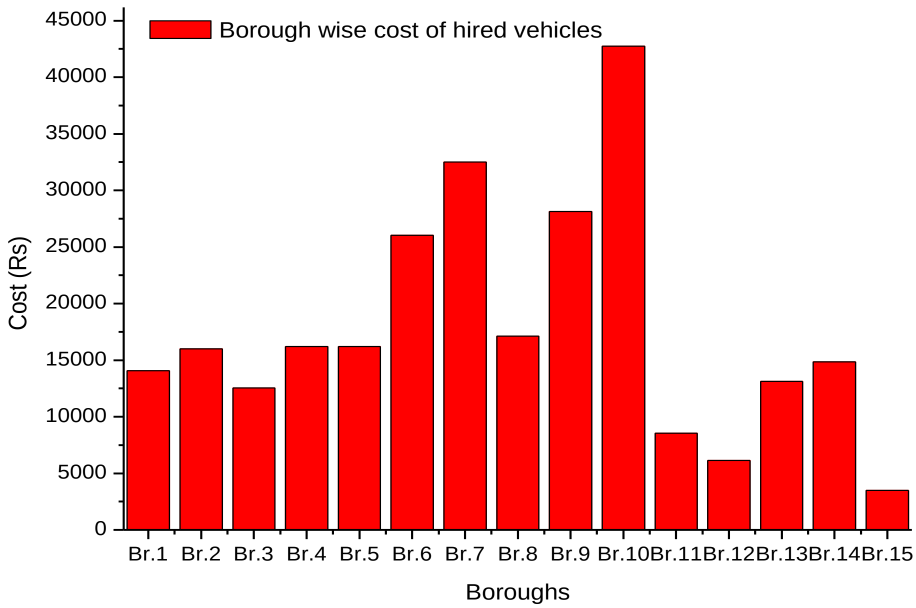


Fig.6.12 Borough wise transportation costs of hired vehicles

Cost of borough 15 is least as waste generation quantity (22.183 MT) (table 6.1) is less in comparison to other boroughs. Removal cost of garbage, silt or rubbish and total waste for hire vehicles is shown in figure 6.13. 85% cost (of total waste carrying cost of hired vehicles) is incurred to remove 84% garbage quantities and 15% cost is incurred to remove 16% silt or rubbish.

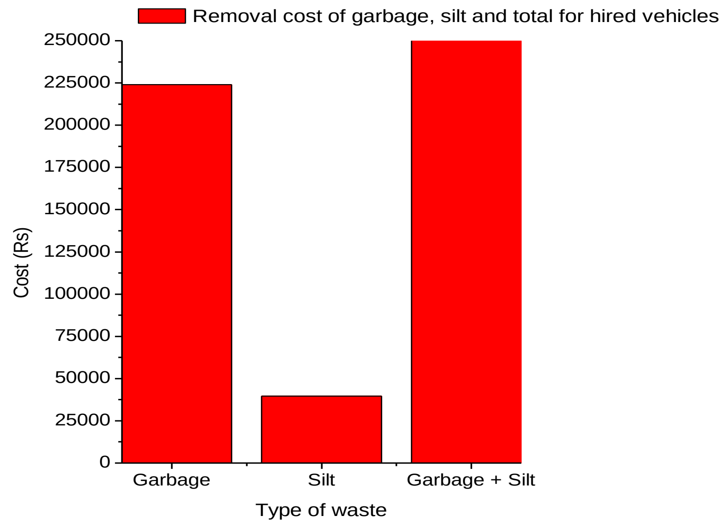


Fig.6.13 Transportation costs of hired vehicles carrying garbage and silt or rubbish

Figure 6.14 shows that ~ 64.2% of the total transportation cost is incurred for departmental vehicles to remove ~ 37% of total waste quantities where as for hired vehicles ~ 35.8% cost is incurred to remove ~ 63% of total waste quantities.

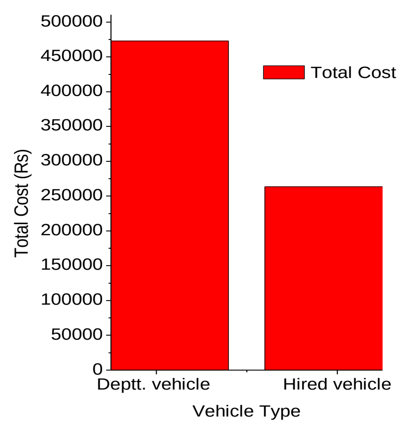


Fig.6.14 Total transportation cost comparison for departmental and hired vehicles

Considering all expenditure, cost per ton of waste removal by hire vehicles is less compared to departmental vehicles having higher fixed cost and incentive cost.

6.1.2.2 Analysis of Solid Waste Management Cost for Existing Situation and its Validation

Different types of cost components are as follows:

(a) Total transportation cost

Total transportation cost including incentive incurred for the departmental and hired vehicles for the existing MSW management system is calculated from KMC budget which is around ~ Rs.

815 thousand/day. Model analysis for the existing system shows 10.7% lower value than the actual scenario. In the model analysis for existing scenario gives the optimized value so there is an opportunity for the existing MSW management system to minimize its transportation cost at around 10%.

Further analysis of individual fuel cost of departmental vehicles shows that in the model the total fuel cost for D1, D2, D3 and D4 type vehicles is reduced by ~2.5 times, ~2.3 times, ~2.3 times and ~1.4 times respectively than the actual cost.

Total actual fuel cost incurred for departmental vehicles is around Rs. 120 thousand/day (KMC, 2007c) which is 2.17 times higher than the model analysis (~ Rs. 55 thousand/day). This increased fuel cost is 8.82% of the total transportation cost given by the model. So there is a possibility to minimize the departmental fuel consumption through routing optimization which is done by the model. There is other reason for higher fuel cost in existing practice. Kilometer wise fuel consumption cannot be monitored in existing practice as kilometer-reading meters of most of the vehicles are damaged and the amount of fuel issued on trip basis is high. This mismanagement leads to unusual higher fuel consumption and subsequently fuel costs.

The fixed costs for the departmental vehicles are practically same for both the cases as these values will be unchanged for same numbers of running and idle vehicles engaged in waste removal.

For hired vehicles model analysis for existing situation shows 5% lesser amount of garbage transportation than the actual. Silt transportation is done by hired vehicle only. So there is no effect on cost variation. Model result of garbage transportation cost (~Rs. 224 thousand/day) by hired vehicle is ~ 5.1% lower than the actual cost (~Rs. 236 thousand/day) (KMC, 2007c). The higher value of garbage transportation by hired vehicle is mainly due to higher amount of garbage transportation on regular basis and sometimes accidental services served for urgent removal of solid waste.

Model generated total incentive cost (Rs. 4650/day) for departmental vehicles is ~30% less than the actual cost (Rs. 6600/day). The difference may occur due to mismanagement of the monitoring system and in some cases the department renders night service during emergency services. As the incentive cost is less in comparison to the total transportation cost so the difference in incentive cost is 0.24% of the total transportation cost.

(b) Cost of compost

As the compost plant operated through PPP model total production cost of compost is considered zero for both the existing MSW management system and model analysis.

(c) Revenue from compost

Total revenue from existing compost management system is same as the model analysis since same existing revenue system from compost (2.5% of compost sale price) is considered for the model. Model takes the maximum capacity of compost plant (~151MT/d) as it always tries to (i) maximize the revenue earning from compost; (ii) minimize the landfill cost by minimizing the landfill amount i.e. maximize the compost production having zero production cost.

(d) Cost of landfill

Cost of landfill at dumpsite 'D' includes (i) establishment cost i.e. regular salaries of the employees (ii) capital and maintenance cost (iii) fuel cost for dozers (iv) maintenance of dozers (v) overtime allowances for dozer repairing staffs, conservancy mazdoors, overseers, dozer operators, Sub Assistant Engineers etc. (vi) supply of trip tokens, ribbons etc. (vii) salary of driver and fuel cost for the vehicles dedicated for the maintenance staff of the landfill. The landfill cost from model analysis shows only 0.64% less value than that of the existing MSW management system. It indicates that the existing landfill management system is almost optimized.

Cost comparison of model analysis for existing MSW management and actual cost incurred for existing solid waste management system is shown in table 6.10. Sample detail calculation of cost of landfill in practical situation is shown in Annexure 6.9.

Table 6.10 Comparison of costs between model analysis of existing MSW management and actual cost incurred

Individual items	Cost (in model) (in Rs.)	Cost (in practical situation) (in Rs.)	Cost variation (%) in model compared to actual situation
Cost of transportation including incentives	7,36,443.25/-	Rs. 8,15,225.07/- 8,02,848.37/-	8.27% (decreased)
Cost of compost	0	0	0%
Revenue from compost	Rs. 3,510.56/-	Rs. 3,510.56/-	0%
Cost of landfill	Rs. 2,53,498.80/-	Rs. 2,55,153.42/-	0.65% (decreased)
Total expenditure	Rs. 9,86,431.49/-	Rs. 10,61,512.35/-	7.07% (decreased)

Total expenditure = Cost of transportation + Cost of compost + Cost of landfill amount -Revenue from compost

The above validation of the existing model shows very good results and also indicates ~7% cost minimization is possible in the existing scenario. So, the basic model can be used for further analysis.

6.1.3 Optimization of Existing Validated Model by Minimizing Number of Vehicles

Existing validated model is an optimized model. Validated optimized model generates optimum amount of waste carried by different type of departmental and hired vehicles to minimize the cost. Vehicle routine is also optimized for different boroughs in different zones to minimize the transportation cost of waste. But in this model numbers of vehicles are kept as it is in the existing system. These are excessive in numbers and more fixed cost is required to maintain the vehicles. In the next study keeping all other conditions like waste carrying limit for individual departmental and hired vehicles in different boroughs in zone 1 and zone 2, running efficiency of D1 (56.25%), D2 (46.58%), D3 (67.07%) and D4 (42.86%) departmental vehicles, composting and land filling processes etc. the same, fixed cost due to the excess number of departmental vehicles and total cost are minimized by reducing the excess number of vehicles to its minimum requirement.

6.1.3.1 Comparison of Existing Optimized Validated Model without Minimization of Vehicles and with Optimization of Vehicles

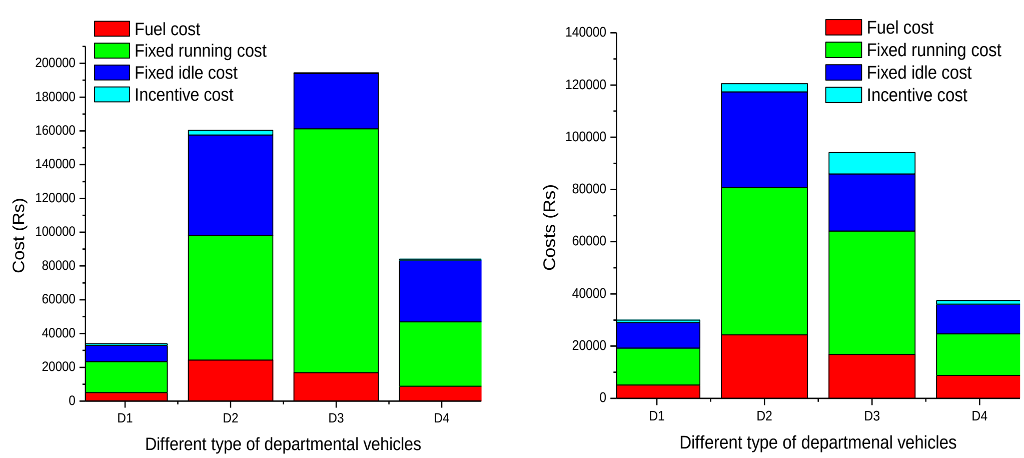
Validated model for the existing situation is optimized by reducing the excess number of vehicles to its minimum requirement. Output summary of cost of existing optimized model is shown in Table 6.11.

Table 6.11 Output summary of cost of existing optimized model

Item	Cost (Rs/day)
Total SWM Cost	7,95,647.80
Total transportation cost	5,32,063.3
Incentive cost	1,3596.24
Landfilling cost	253498.80
Sorting cost	39679.67
Incineration cost	0
Composting cost	0
Revenue earned from recyclables	0
Revenue earned from composting	3510.56

Model result shows that D1 type vehicle can be minimized upto ~22% for which fixed running cost and fixed idle cost are reduced by ~Rs 4,060/day (~22%) and ~Rs 2,800/day (~29%). Similarly, D2 vehicle can be minimized upto ~24% and on such reduction fixed running cost and fixed idle cost are reduced by ~Rs 17,350/day (~24%) and ~Rs 13,740/day (~23%). Similarly D3 and D4 vehicles are minimized by ~67% and ~58% respectively. If optimum number of D3 vehicle are used, fixed running cost and fixed idle cost can be reduced by ~Rs 97,140/day (~67%) and ~Rs 21,870/day. For optimum number of D4 vehicles, fixed running cost and fixed idle cost can be reduced by ~Rs 22,261/day (~58%) and ~Rs 20,545/day (~56%). So cost reduction in total departmental transportation cost is ~43% and total transportation cost is ~27%.

Model analysis for the optimized condition shows that total incentive cost increases by 3 times of the result of validated model without reduction of vehicles in existing condition as individual incentive cost for D3 and D4 increases by 22 times and 2.2 times respectively. But there will be no change in fuel cost since total quantity is shared by the optimized vehicles by performing more number of trips as well as utilized their maximum carrying capacity. The model shows very good results and also indicates ~19% of total cost minimization is possible in the existing scenario only by reducing the excess number of vehicles to its minimum requirement (figure 6.15(a), figure 6.15(b)). So, the basic model can be used for further analysis.



(a) (b)

Fig.6.15 Comparison of costs in (a) model without reduction of vehicles and (b) model with optimization of vehicles in existing situation

6.1.3.2 Optimized Operations with Different Cases of Running Efficiencies

In earlier section validated model for the existing situation has been optimized by reducing the excess number of vehicles to its minimum requirement keeping the running efficiency of departmental vehicle as per existing efficiency. In this study model is optimized considering different cases of varying running efficiencies (30% to 80%) of all departmental vehicles to observe its effect on operation and cost. Model result shows that the optimized cost considering 50% running efficiencies of all the departmental vehicles is almost same (variation ~0.005% only) with the existing optimized model. It indicates existing optimized model with varying running efficiencies of departmental vehicles (reference section 2.7) is equivalent to 50% running efficiency operation of departmental vehicles.

Cost analysis of optimized model with varying running efficiencies of all departmental vehicles from 30% to 80% are shown in figure 6.16 (b). With the change of running efficiency of vehicles only the number of idle vehicles are varying for different cases keeping the optimized running vehicles same for all the cases. If running efficiency decreases or increases there will be no change in fuel cost [D1 (Rs 5,088/day) (ref. figure 6.16 (a)); D2 (Rs 24,308/day); D3 (Rs 16,849/day) and D4 (Rs 8,793/day)] (figure 6.16), fixed running cost [D1 (Rs 14,204/day); D2 (Rs 56,360/day); D3 (Rs 47,257/day) and D4 (Rs 15,901/day)] (figure 6.16), and incentive cost [D1 (Rs 9,51/day); D2 (Rs 3,169/day); D3 (Rs 8,142/day) and D4 (Rs 1,334/day)] (ref. figure 6.16 (b)) due to number of running vehicles remain same in all cases.

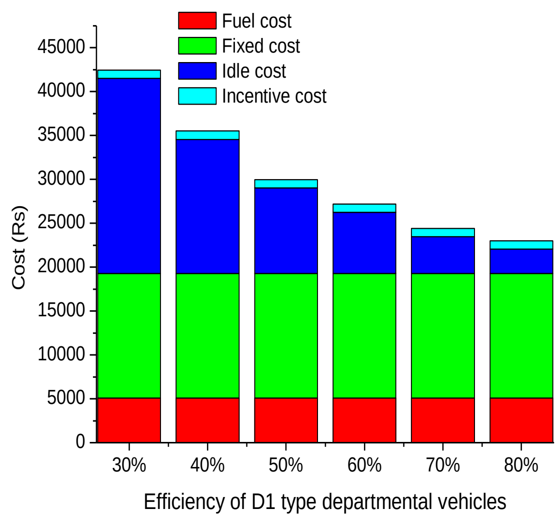


Fig.6.16 (a) Comparison of transportation costs components in different running efficiency for D1 vehicle

Since the number of idle vehicle varies due to change in efficiencies, fixed idle cost increases when running efficiency decreases and vice versa. Running efficiency 50% is on lower side in case of well managed solid waste management system and it should be ~70% (Reference) by which ~ (56%) savings (~Rs. 44,500/- per day) in fixed idle cost and ~5.6% overall cost savings can be achieved. However due to poor work culture, inadequate infrastructure for developing countries, 60% efficiency may be considered by which ~3.2% overall cost savings (~Rs. 25,370/- per day) should be achievable.

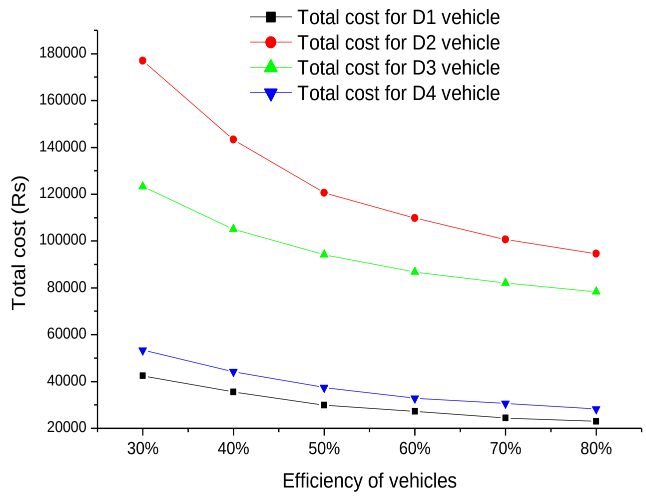


Fig.6.16 (b) Comparison of total transportation costs in different running efficiency for different departmental vehicles

Number of running as well as corresponding idle vehicles of D2 and D3 are more as they carry more waste than other departmental vehicles. Therefore, the impact of efficiency for D2 and D3 vehicles are more on fixed idle cost. If efficiency increases from 50% to 80% then total optimum cost decreases upto 7.3% and if efficiency decreases from 50% to 30%, total optimum cost increases upto 14.33%.

6.1.4 Optimized Operating Plans for Different Percentage of Weight Sharing of Garbage by Departmental and Hired Vehicles

Presently garbage carried by departmental vehicles is ~42%. Because of higher fixed and idle cost, overall transportation cost (considering fuel and fixed cost) of per ton of waste by departmental vehicles is higher (table 6.6 and 6.7) than the hired vehicles (table 6.8). So, reduction of the garbage sharing by departmental vehicles will definitely reduce the overall transportation cost. In this study model is optimized to observe the effect on cost and operation for different percentage of garbage sharing by departmental vehicles (from maximum 60% to minimum 15%). Different models having different percentage of garbage sharing are prepared by shifting the average garbage transportation capacity with an interval of ± 5% i.e if average transportation capacity of the hired vehicles is reduced by 5% then the same for departmental vehicles is increased by 5%. For all the cases 50% operational efficiency is considered for departmental vehicles. Variation of the range of the carrying limit is given in Table A-6.12 and Table A-6.13 of Annexure 6.10.

For different cases of weight sharing of garbage - minimum number of running vehicles, fuel costs, fixed running and idle cost, incentive cost of departmental vehicles and optimum total costs are observed. In existing situation to remove 42% of garbage, 110 numbers of total departmental vehicles are required. In case of garbage carrying percentage by departmental vehicles reduces to 35%, 30%, 25%, 20% and 15%, total numbers of departmental vehicles are reduced by 18%, 32%, 41%, 50% and 63% compared to existing optimized result. Similarly, if the garbage carrying percentage by departmental vehicles increases to 45%, 50%, 55% and 60%, total numbers of departmental vehicles are increased by 11%, 20%, 30% and 38% (figure 6.17). Variation of garbage percentage has major impact on the numbers of D2 and D3 vehicles as in departmental vehicles most of the waste are carried by these vehicles. For reduction of garbage carrying percentage from 42% to 15%, reduction in numbers in D2 and D3 vehicles are 69% and 61%. The numbers in D2 and D3 vehicles are increased by 31% and 50% due to increase in garbage carrying percentage from 42% to 60%.

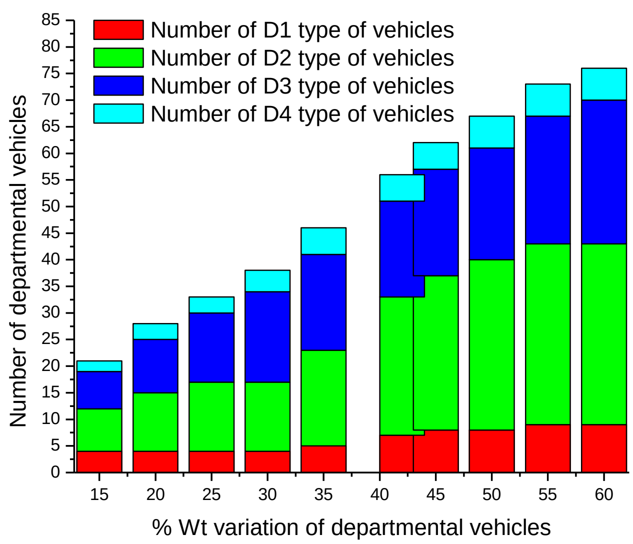


Fig.6.17 Optimum number of different departmental vehicles required for variation of different percentage of garbage transportation sharing

Variation of fuel, fixed running, fixed idle and incentive cost with changes of different percentage of garbage sharing by departmental vehicles are shown in figure 6.18. If the waste removal percentage reduces from 42% to initially 35% to finally 15% with 5% interval, fuel cost for departmental vehicles can be reduced from ~19% to ~66%; fixed running cost from ~16% to ~62%; fixed idle cost from ~15% to ~61%; incentive cost from ~1.1 times to ~3 times and total cost reduced from ~3% to ~9% (figure 6.18). When garbage removal percentage increases from 42% to initially 45% to finally 60% with same % interval, fuel cost increased from ~9% to ~44%; fixed running cost from ~10% to ~36%; fixed idle cost from ~14% to ~39%; incentive cost from ~1.1 times to ~1.6 times and total cost also increased from ~2% to ~5% (figure 6.19).

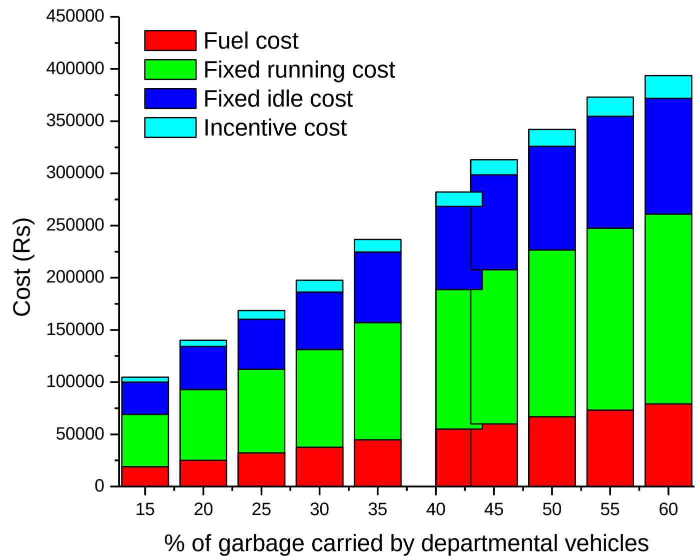


Fig.6.18 Variation of transportation cost components of departmental vehicles for variation of different percentage of garbage sharing

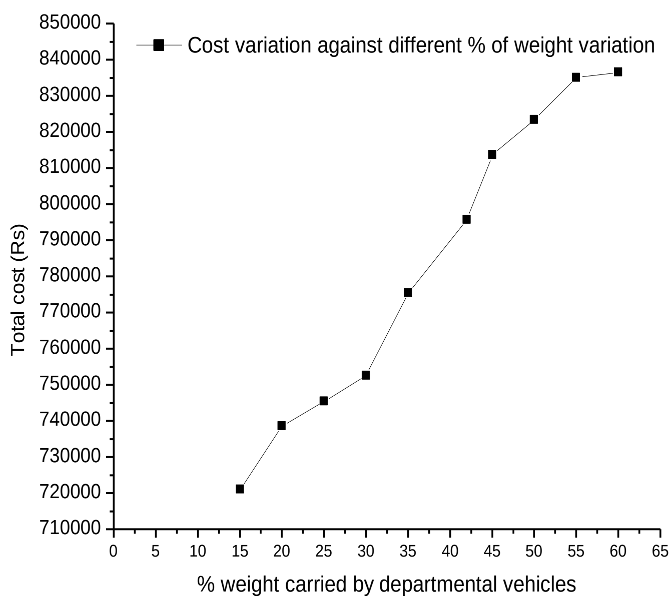


Fig.6.19 Variation of optimum total cost for different percentage of garbage sharing by departmental vehicles

6.1.5 Sensitivity Analysis for Existing MSW Management System

6.1.5.1 Incentive Cost Variation

In optimized existing validated model incentive cost for departmental vehicle (Rs. 13596/- per day) is only ~1.7% of the total optimized cost and ~5% of the transportation cost of departmental vehicle. Due to incentive cost variation, cost effects on others are negligible. If incentive cost increases by 10%, cost increase of incentive is ~7.5%, transportation cost of departmental vehicle is ~0.16% and total SWM cost is ~0.18%. If incentive cost decreases by 10%, cost decrease of incentive is ~12.4%, transportation cost of departmental vehicle is ~0.04% and for total cost is ~0.22% (figure 6.20). Incentive is important for cleaning of garbage by the optimum number of departmental vehicles. But its rate increment has negligible effect on total cost. Garbage clearance efficiency by departmental vehicle can be increased by increasing incentive.

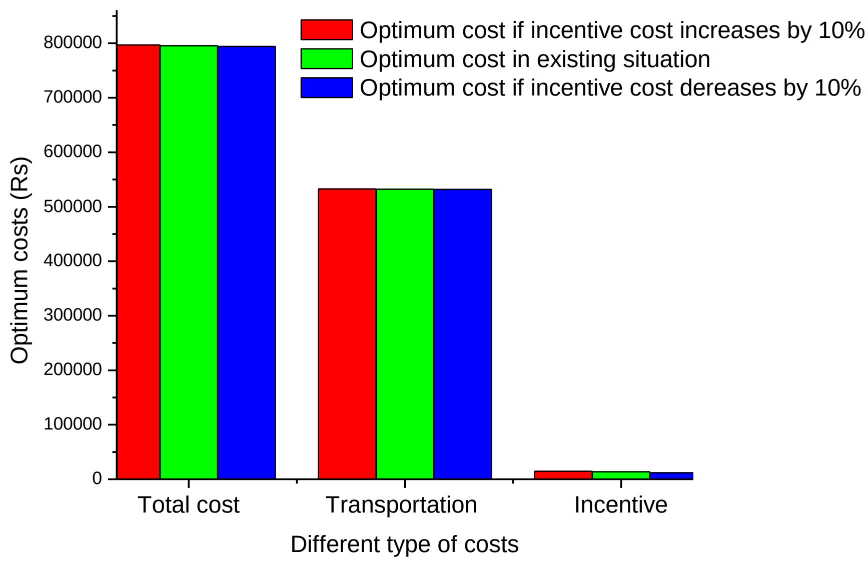


Fig.6.20 Effects of incentive cost variation

6.1.5.2 Variation of Fixed Running Cost

In optimized existing validated model fixed running cost for departmental vehicle (Rs. 1,33,722/- per day) is ~17% of the total optimized cost and ~50% of the transportation cost by departmental vehicle. Cost effects on others are negligible due to variation of fixed running cost. If fixed running cost increases by 10%, increase of transportation cost by departmental vehicle is ~5% and for total cost is ~1.7%. If fixed running cost decreases by 10%, decrease of transportation cost by departmental vehicle is ~5% and for total cost is ~1.7% (figure 6.21). So, fixed running cost has significant effect on transportation cost of departmental vehicles and it also affects the total optimized cost moderately. Selection of vehicle operators should be done judiciously and careful maintenance of vehicle is also suggested.

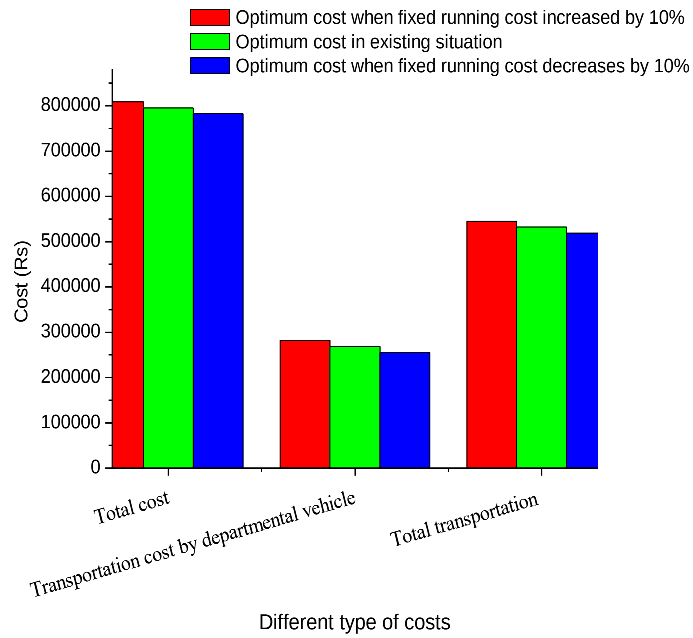


Fig.6.21 Effects of fixed running cost variation

6.1.5.3 Variation of Fixed Idle Cost

In optimized existing validated model fixed idle cost of departmental vehicle (Rs. 79652/- per day) is ~10.0% of the total optimized cost and ~30% of the transportation cost by departmental vehicle. Variation of fixed idle cost has negligible effects on others costs. If fixed idle cost increases by 10%, increase of transportation cost by departmental vehicle is ~3% and for total cost is ~1%. If fixed idle cost decreases by 10%, decrease of transportation cost by departmental vehicle ~3% and for total cost is ~1% (figure 6.22). Reduction of idle vehicles increases efficiency but its rate decline has negligible effect on total cost. As fixed idle cost of departmental vehicle has significant effect on transportation cost of departmental vehicles, so vehicle maintenance staff should be selected judiciously for careful maintenance of the departmental vehicles.

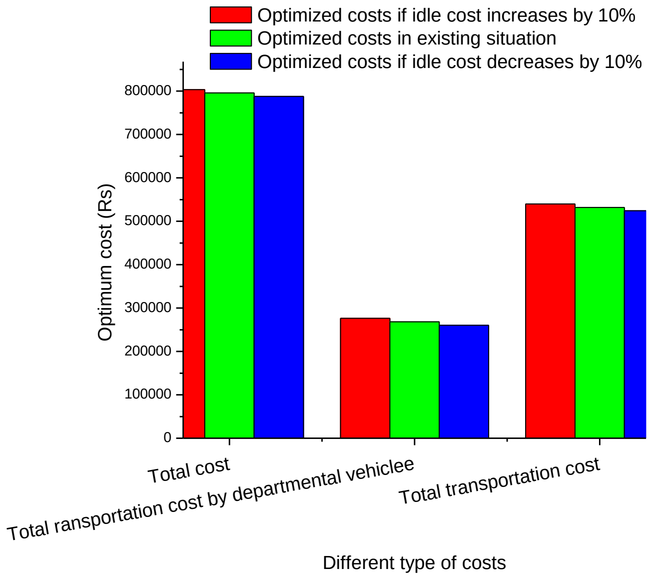


Fig.6.22 Effects of fixed idle cost variation

6.1.5.4 Variation of Fuel Cost

In optimized existing validated model fuel cost for departmental vehicle (Rs. 55039/- per day) is ~7% of the total optimized cost and ~21% of the transportation cost by departmental vehicle. Cost effects on others are negligible due to variation of fuel cost. If fuel cost increases by 5%, increase of transportation cost by departmental vehicle is ~1% and for total cost is < 0.4%. If fuel cost decreases by 5%, decrease of transportation cost by departmental vehicle is ~1% and for total cost is < 0.4% (figure 6.23). If optimum number of departmental vehicles is used for cleaning of garbage, fuel cost variation has less effect on total cost.

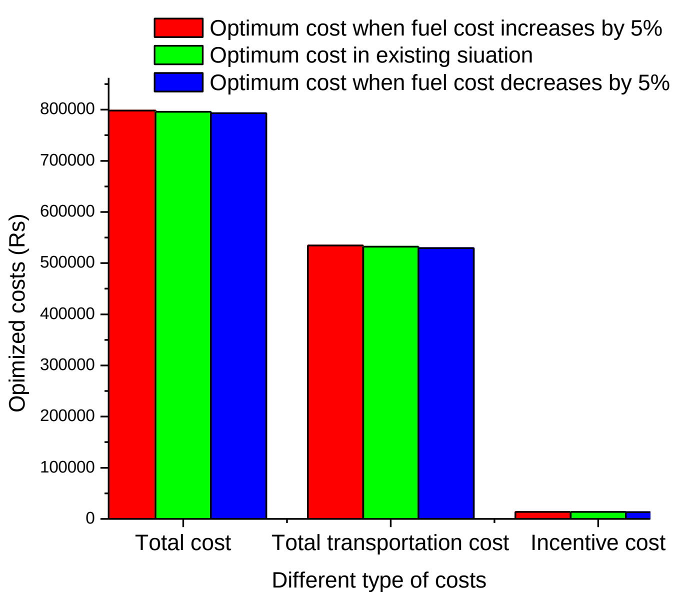


Fig.6.23 Effects of fuel cost variation

6.1.5.5 Variation of Transportation Cost of Hired Vehicles

In optimized existing validated model transportation cost for hired vehicle (Rs. 263651/- per day) is ~33% of the total optimized cost and ~50% of the total transportation cost. Variation of the transportation cost of hired vehicles has negligible effects on others costs. If the transportation cost of hired vehicles increases by 5%, increase of total transportation cost is ~2.5% and for total cost is ~1.7%. If the transportation cost of hired vehicles decreases by 5%, decrease of total transportation cost is ~2.5% and for total cost is ~1.7% (figure 6.24). The transportation cost of hired vehicles has significant cost effect in total transportation cost as well as total SWM cost. So, proper attention should be paid for fixing and reviewing of zone wise transportation cost of silt and garbage.

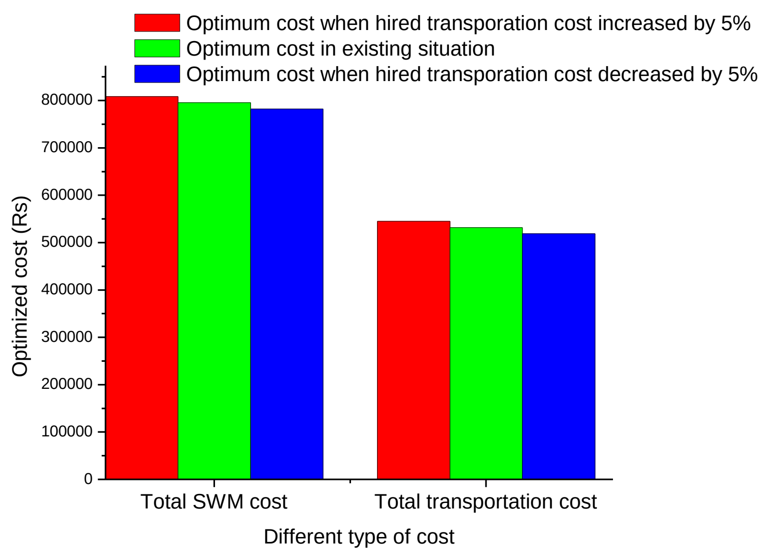


Fig.6.24 Effects of variation of transportation cost of hired vehicle

6.1.5.6 Variation of Revenue Cost i.e. Royalty from Compost

In optimized existing validated model revenue cost from the royalty of compost (Rs. 3511/- per day) is ~0.5% of the total optimized cost of SWM. Variation of royalty from compost has negligible effects on other costs. If revenue cost increases by 5%, total SWM cost decreases by ~0.02% and vice versa (figure 6.25). So its rate increment of royalty has negligible effect on total SWM cost.

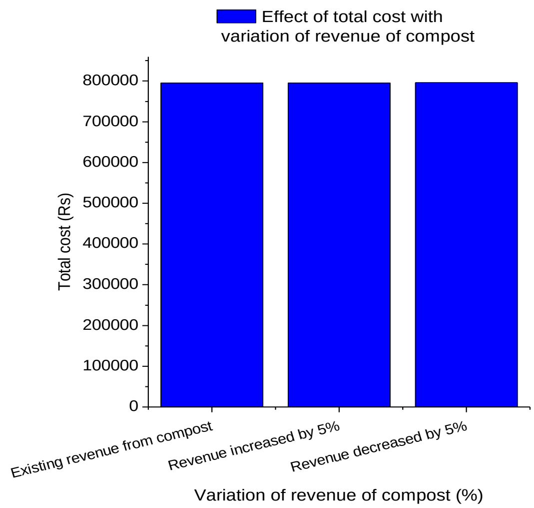


Fig.6.25 Effect of variation of revenue cost of compost on total cost

6.1.5.7 Variation of Operational and Maintenance Cost of Landfilling

In optimized existing validated model landfilling cost (Rs. 253499/- per day) is ~32% of the total optimized cost. Cost effects of variation of operational and maintenance cost of landfilling on others are negligible. If landfilling cost increases by 5%, total SWM cost increases by ~1.6% and vice versa (figure 6.26). So its rate increment in operational and maintenance has significant effect on total cost.

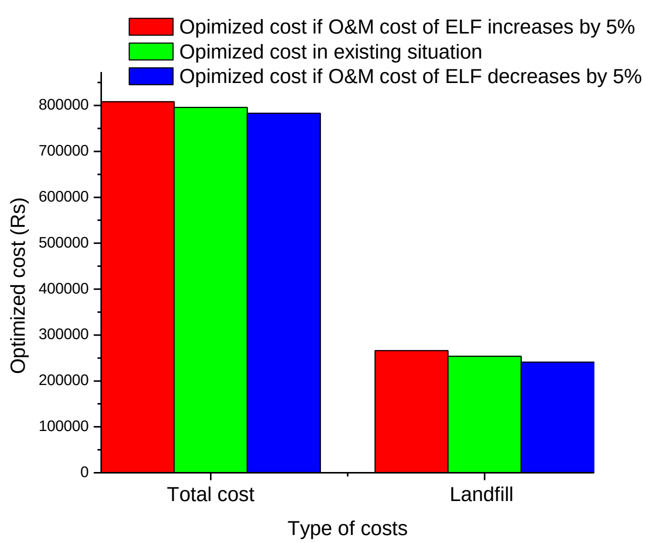


Fig.6.26 Effects of variation of O&M cost of ELF

6.1.5.8 Variation of Waste Generation

In optimized existing validated model if waste generation increases by 5% then total transportation cost, incentive cost, landfilling cost and total SWM cost increases by ~3%, ~8%, ~5% and ~4% respectively and vice versa (figure 6.27). As variation of waste generation has major effects on the costs of solid waste management, proper estimation of waste generation is very important for future planning.

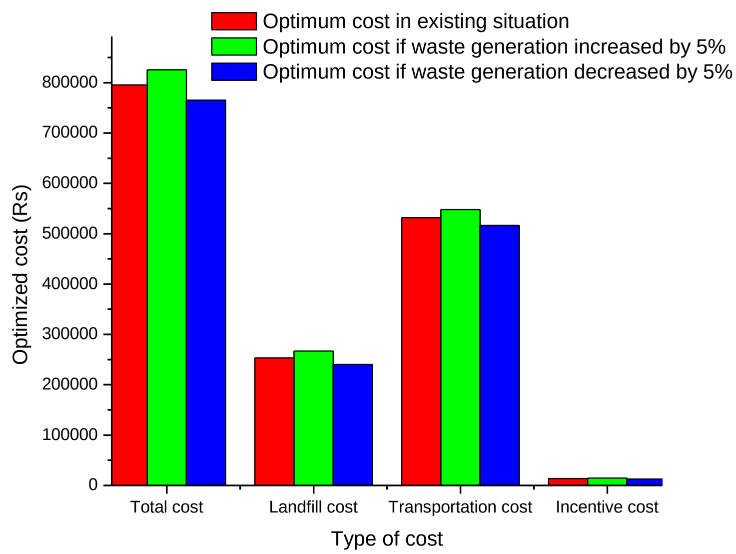


Fig.6.27 Effects of variation of waste generation

6.1.6 Observation on Result of Existing Model

The MSW management LP model is applied to the specific existing system with the data of Kolkata and also validated the applied the model and studied. Major output after model (Annexure 6.17) run 'is shown in Table A-6.18. Ratio of total quantity of waste i.e. garbage and silt or rubbish actually transported by departmental vehicles and hired vehicles is 33:67 where as from model it is found ~ 37:63. In respect of only garbage disposal, in present practice the ratio is found as 37:63 where as in the model it is 42:58. In existing model departmental vehicles prefers to carry 5% excess waste than the existing practice.

Percentage of idle vehicles for D1, D2, D3, D4 are 43.75%, 53.42%, 32.93% and 57.14% and these vehicles carry ~8.1%, ~37.5%, ~31.5% and ~22.9% of total quantity of waste carried by departmental vehicles. Total cost variations are ~7.2%, ~34%, ~41% and ~17.8% respectively. So, average departmental vehicle running efficiency is only 50%.

85% cost (of total waste carrying cost of hired vehicles) is incurred to remove 84% garbage quantities and 15% cost is incurred to remove 16% silt or rubbish. ~64.2% of the total transportation cost is incurred for departmental vehicles to remove only ~37% of total waste quantities whereas for hired vehicles ~35.8% cost is incurred to remove ~63% of total waste quantities. So, hired vehicle is more cost effective.

In the LP model, analysis for existing scenario gives the optimized value and results indicate that there is an opportunity to minimize its total transportation cost at around 10% for the existing MSW management system. The validation of the LP model for existing scenario with actual data shows very good results and it indicates ~8% cost minimization is possible in the existing scenario. So variation of model validation result is within ±10% and it can be used for further analysis.

This basic model is used further to optimize the number of departmental vehicle than the existing. Analysis shows that the reduction of D1 type vehicle is possible up to ~22%, D2 vehicle up to ~24%, D3 vehicles up to ~67% and D4 vehicles up to ~58%. So reducing the redundant departmental vehicles, ~43% cost reduction in total departmental transportation cost and ~27% cost reduction in total transportation cost can be achieved. The model shows very encouraging results which indicates ~19% of total cost minimization is possible in the existing scenario only by reducing the excess number of departmental vehicles to its minimum requirement.

Since the number of idle vehicle varies due to change in vehicle running efficiencies, fixed idle cost increases when running efficiency decreases and vice versa. Running efficiency 50% is on lower side in case of well managed solid waste management system and it should be ~70% (Chalmin and Gaillochet, 2009) by which ~56% savings in fixed idle cost and ~5.6% overall cost savings can be achieved. However due to poor work culture, inadequate infrastructure for developing countries, 60% efficiency may be considered by which ~3.2% overall cost savings is possible. If vehicle running efficiency increases from 50% to 80% then total optimum cost decreases up to 7.3%. If the same decreases from 50% to 30%, total optimum cost increases up to 14.33%.

In existing situation 42% of garbage is carried by departmental vehicle. If the garbage carrying percentage by departmental vehicles reduces from 35% to 15%, total numbers of departmental vehicles are reduced from 18% to 63%, fuel cost reduced from ~19% to ~66% and total cost reduced from ~3% to ~9% compared to existing optimized result. Similarly, if the garbage carrying percentage by departmental vehicles increases from 45% to 60%, total number of departmental vehicles are increased from 11% to 38%, fuel cost increased from ~9% to ~44% and total cost also increased from ~2% to ~5% w.r.t. existing optimized result.

Rate increment in incentive has negligible effect on total cost. However, garbage clearance efficiency by departmental vehicle can be increased by increasing incentive.

Fixed running cost has significant effect on transportation cost of departmental vehicles. If it increases by 10%, transportation cost by departmental vehicle and total cost are increased by ~5% and ~1.7%. Variation of fixed idle cost has negligible effects on others costs. If fixed idle cost increases by 10%, increase of transportation cost by departmental vehicle is ~3% and for total cost is ~1%. As fixed idle cost of departmental vehicle has significant effect on transportation cost of departmental vehicles, so vehicle maintenance staff should be selected judiciously for careful maintenance of the departmental vehicles.

If optimum number of departmental vehicles is used for cleaning of garbage, fuel cost variation has less effect on total cost.

If the transportation cost of hired vehicles increases by 5%, total transportation cost is increased by ~2.5% and for total cost increment is ~1.7% which are significant. So, proper attention should be paid for fixing and reviewing of zone wise transportation cost of silt and garbage for hired vehicle.

Operational and maintenance cost landfilling has significant effect on total cost. If landfilling cost increases by 5%, total SWM cost increases by ~1.6% and vice versa.

If waste generation is increased by 5% then total transportation cost, incentive cost, landfilling cost and total SWM cost are increased by ~3%, ~8%, ~5% and ~4% respectively and vice versa. It indicates variation of waste generation has major effects on the costs of solid waste management. So, proper estimation of waste generation is very important for effective management and future planning of MSW.

6.2 APPLICATION OF MODEL IN PROPOSED INTEGRATED SOLID WASTE MANAGEMENT OF KOLKATA AND ITS OPTIMIZATION

6.2.1 Basic Assumptions and Input of the Model Considering Integrated Systems Approach

6.2.1.1 General Description

In case of proposed model also same waste type, composition and generation are considered in 15 boroughs as in existing model. Silt or rubbish (~10% of total waste) will be disposed by private vehicles directly to landfill and garbage (~90% of total waste) will be transported by departmental vehicles. Three engineered landfill (ELF) sites associated with three material sorting facilities, incineration facilities and composting facilities are considered. These three ELF sites are considered at eastern site named as “D”, northern site named as “N” and southern site named as “S”. As western side of Kolkata is extended up to river Ganges and on the other bank Howrah district is located with their own solid waste management system, no solid waste disposal facilities at western site is considered. Proper source segregation of waste will be done at by providing two bins – one for biodegradable waste and the other for non-biodegradable waste. After separating out 5% recyclable at source rest amount of garbage will be transported to central sorting facilities attached with each ELF for further separating out of recyclable materials. Revenue will be earned by the KMC from selling of recyclables. Then treatment and disposal of garbage will be done as per its characteristics. High calorific value of garbage fraction will go for thermal processing and biodegradable fraction for biological processing. For thermal processing mass burn incineration facilities will be provided along with air pollution control equipment. For biological processing windrow composting will be done. In all treatment facilities, pre-sorting facilities will be provided for segregating out the inert and recyclable from the pre-processed garbage to increase efficiency of the treatment processes (Figure 4. 41). Inert and residues from treatment plant will go for engineered landfills having proper bottom liner with leachate collection system. Leachate will be collected and treated during active period as well as post closure period of landfill. A complete final cover will be provided after closure to minimize leachate generation.

6.2.1.2 Borough Wise Garbage and Silt or Rubbish Generation

Garbage and silt or rubbish generation is considered same as existing, to compare between the existing and proposed integrated management system (Table 6.1).

6.2.1.3 Maximum and Minimum Limit (in Fraction) of Garbage Quantity Carried by Different Vehicles

Maximum and minimum limit of garbage quantities carried by different departmental and hired vehicles are same as existing (Ref. para 6.1.1.3 and table 6.2).

6.2.1.4 Maximum and Minimum Trip Limits of Departmental vehicles

Three ELF sites are considered, at eastern site named as "D", northern site named as "N" and southern site named as "S". For each ELF site 15 boroughs are divided into 2 zones. For eastern ELF site "D" zones and their respective distances for boroughs are considered same as Dhapa ELF site "D" (reference para. 6.1.1.4 and table 6.3). Borough wise distance and their zones for northern ELF site "N" and southern ELF site "S" are given in table 6.12 and table 6.13.

Table 6.12 Borough wise distance and their zones for northern ELF site "N"

Boroughs under zone 1	Borough distance from northern disposal site (Km)	Boroughs under zone 2	Borough distance from northern disposal site (Km)
Br.1	3.5	Br.9	17.85
Br.2	5.25	Br.10	16.80
Br.3	9.66	Br.11	19.95
Br.4	6.65	Br.12	19.60
Br.5	9.45	Br.13	17.85
Br.6	10.5	Br.14	22.75
Br.7	14.7	Br.15	23.80
Br.8	12.95		

Table 6.13 Borough wise distance and their zones southern ELF site "S"

Boroughs under zone 1	Borough distance from southern disposal site (Km)	Boroughs under zone 2	Borough distance from southern disposal site (Km)
Br.6	8.4	Br.1	16.45
Br.7	13.3	Br.2	15.75
Br.8	10.5	Br.3	15.05
Br.9	4.9	Br.4	13.65
Br.10	10.15	Br.5	10.15
Br.13	6.3	Br.11	13.65
Br.14	10.85	Br.12	17.15
Br.15	1.75		

In integrated management system daily operational time (especially vehicle running time) of SWM should be reduced and started as early as possible in the morning so that city will be cleaned early. It will also avoid any congestion and pollution during peak traffic hours. As operational time is reduced, number of maximum possible trips by the departmental vehicles assumed to be reduced and given in table 6.14. This will help to increase the operational efficiency as the operational time and numbers of trips are reduced. So, running efficiency of the vehicle will increase and assumed to be as ~ 60%.

Table 6.14 Maximum and minimum trip limits of departmental vehicles for different zones and their incentive

Type of departmental vehicles	Zone 1		Zone 2		Avg. wt. carried (Mt)	Incentive rate / ton (Rs / Mt)		
	Maxm. trips	Minm. trips	Maxm. trips	Minm. trips		Driver	Helper	Total
D1 (1 driver and 1 helper)	6	2	4	2	1.75	10	5	15
D2 (1 driver and 1 helper)	6	2	4	2	2	7	3.5	10.5
D3 (1 driver and 5 helper)	4	2	3	2	3	10	5	35
D4 (1 driver and 1 helper)	4	2	3	2	7	5	2.5	7.5

Note: Total incentive rate (Rs / MT) = (Incentive rate of Driver, Rs / MT) + (Incentive rate of Helper, Rs / MT) × No. of Helper

Incentives of different vehicles for all ELF sites are considered same as for existing disposal site Dhapa “D” (table 6.14).

6.2.1.5 Cost of Transportation

Total available vehicles are considered same as existing. Number of total, running and idle vehicles of different types are shown in Table 6.7.

(a) Cost of transportation for departmental vehicles

Basic consideration for calculation of fuel cost of departmental vehicles is same as existing model (Table 6.5). Only cost of fuel is considered 1.5 times higher in the proposed model than the old fuel cost (Rs. 34 per liter) in the existing model.

(i) Fuel cost for departmental vehicles

This proposed model will be used for future planning. So in this model present enhanced cost is considered rather than the year of 2007 cost which was used to explain the existing model. Fuel cost has changed substantially from the year 2007 (1.5 times higher).

Fuel cost per ton of departmental vehicles for ELF site “D”, “N” and “S” are given in table 6.15, table 6.16 and table 6.17.

Table 6.15 Fuel cost per ton for departmental vehicles for ELF site “D”

Borough	Fuel cost (Rs/Mt) for D1 vehicle	Fuel cost (Rs/Mt) for D2 vehicle	Fuel cost (Rs/Mt) for D3 vehicle	Fuel cost (Rs/Mt) for D4 vehicle
Br. 1	108.85	116.00	80.46	67.07
Br. 2	90.70	96.67	67.06	55.90
Br. 3	60.46	64.45	44.70	37.25
Br. 4	90.70	96.67	67.06	55.90
Br. 5	84.66	90.22	62.58	52.16
Br. 6	84.66	90.22	62.58	52.16
Br. 7	42.33	45.12	31.30	26.09
Br. 8	78.61	83.78	58.12	48.43
Br. 9	114.90	122.45	84.94	70.79
Br. 10	84.66	90.22	62.58	52.16
Br. 11	96.75	103.10	71.52	59.61
Br. 12	36.28	38.67	26.82	22.36
Br. 13	120.94	128.88	89.40	74.52
Br. 14	139.07	148.22	102.82	85.70
Br. 15	163.27	174.00	120.70	100.60

Table 6.16 Fuel cost per ton for departmental vehicles for ELF site “N”

Borough	Fuel cost (Rs/Mt) for D1 vehicle	Fuel cost (Rs/Mt) for D2 vehicle	Fuel cost (Rs/Mt) for D3 vehicle	Fuel cost (Rs/Mt) for D4 vehicle
Br. 1	42.33	45.11	31.29	26.08
Br. 2	63.49	67.66	46.94	39.12
Br. 3	116.83	124.50	86.36	71.99
Br. 4	80.43	85.71	59.46	49.55
Br. 5	114.29	121.80	84.49	70.42
Br. 6	126.99	135.33	93.87	78.25
Br. 7	177.81	189.45	131.42	109.54
Br. 8	156.61	166.90	115.78	96.50
Br. 9	215.89	230.05	159.58	133.02
Br. 10	203.18	216.52	150.20	125.19
Br. 11	241.27	257.12	178.36	148.67
Br. 12	237.04	252.61	175.23	146.06
Br. 13	214.98	230.05	159.58	133.02
Br. 14	275.16	293.20	203.39	169.54
Br. 15	287.85	306.74	212.78	177.36

Table 6.17 Fuel cost per ton for departmental vehicles for ELF site "S"

Borough	Fuel cost (Rs/Mt) for D1 vehicle	Fuel cost (Rs/Mt) for D2 vehicle	Fuel cost (Rs/Mt) for D3 vehicle	Fuel cost (Rs/Mt) for D4 vehicle
Br. 1	198.94	212.01	147.05	122.59
Br. 2	190.48	203.00	140.80	117.37
Br. 3	182.01	193.97	134.53	112.15
Br. 4	165.08	175.93	122.02	101.72
Br. 5	122.75	130.83	90.73	75.64
Br. 6	101.59	108.26	75.08	62.60
Br. 7	160.85	171.41	118.89	99.12
Br. 8	126.99	135.33	93.87	78.25
Br. 9	59.26	63.15	43.80	36.52
Br. 10	122.75	130.83	90.73	75.64
Br. 11	165.08	175.93	122.03	101.72
Br. 12	207.41	221.03	153.31	127.81
Br. 13	76.19	81.20	56.32	46.96
Br. 14	131.22	139.84	97.00	80.85
Br. 15	21.17	22.55	15.64	13.04

Note: Fuel cost for each borough (Rs/MT) = [Cost of average fuel consumptions for loaded and empty run (Rs/KM) × Up and down distance (KM)] / Average waste carrying capacity (MT)

(ii) Fixed cost for departmental vehicles

Fixed running cost and fixed idle cost for departmental vehicles have been changed from the existing as capital cost of vehicles and wages of driver, helper, garage staff including managerial and administrative are increased. The multiplication factors with respect to the old costs (Table 6.7) are mentioned in table 6.18.

Table 6.18 Multiplication factor of running and idle departmental vehicles for the proposed model with respect to the old costs

Type of vehicles	Multiplication factor of Fixed cost / vehicle / day	
	Running cost (Rs) / vehicle / day	Idle cost (Rs)/ vehicle / day
D1	2.5	2.4
D2	2.5	2.4
D3	2.8	2.5
D4	2.7	2.0

(b) Cost of transportation for hired vehicles

As fuel, capital and maintenance cost of vehicle have increased, enhanced transportation cost rate for carrying garbage and silt or rubbish by hired vehicles are given in table 6.19 (a) & table 6.19(b).

Table 6.19 (a) Transportation cost per ton of garbage for hired vehicles for ELF site "D", "N" and "S"

Borough	Transportation cost per ton of garbage (Rs/Mt) for hired vehicle (ELF site "D")	Transportation cost per ton of garbage (Rs/Mt) for hired vehicle (ELF site "N")	Transportation cost per ton of garbage (Rs/Mt) for hired vehicle (ELF site "S")
Br. 1	355.81	302.33	372.09
Br. 2	334.88	302.33	372.09
Br. 3	310.47	372.09	372.09
Br. 4	330.23	325.58	372.09
Br. 5	325.58	372.09	372.09
Br. 6	308.14	372.09	348.84
Br. 7	343.60	372.09	372.09
Br. 8	325.58	372.09	372.09
Br. 9	364.42	372.09	302.33
Br. 10	344.88	372.09	372.09
Br. 11	366.98	372.09	372.09
Br. 12	358.84	372.09	372.09
Br. 13	370.70	372.09	325.58
Br. 14	372.09	372.09	372.09
Br. 15	372.09	372.09	302.33

Table 6.19 (b) Transportation costs per ton of silt or rubbish for hired vehicles for ELF site "D", "N" and "S"

Borough	Transportation cost per ton of silt or rubbish (Rs/Mt) for hired vehicle (ELF site "D")	Transportation cost per ton of silt or rubbish (Rs/Mt) for hired vehicle (ELF site "N")	Transportation cost per ton of silt or rubbish (Rs/Mt) for hired vehicle (ELF site "S")
Br. 1	357.5	300.0	375.0
Br. 2	335.0	300.0	375.0
Br. 3	308.75	375.0	375.0
Br. 4	330.0	325.0	375.0
Br. 5	325.0	375.0	375.0
Br. 6	306.25	375.0	350.0
Br. 7	344.38	375.0	375.0
Br. 8	325.0	375.0	375.0
Br. 9	366.75	375.0	300.0
Br. 10	345.75	375.0	375.0
Br. 11	369.5	375.0	375.0
Br. 12	360.75	375.0	375.0
Br. 13	373.50	375.0	325.0
Br. 14	375.0	375.0	375.0
Br. 15	375.0	375.0	300.0

6.2.1.6 Sorting and Recycling

(a) Material balance

In the integrated solid waste management system three ELF sites are considered in eastern site (D), northern site (N) and southern site (S) of Kolkata. In each ELF sites central sorting system, composting and incineration facilities are considered. In integrated system two bin system – one for bio-degradable waste and other for non bio-degradable waste is considered. NGOs will manage the non bio-degradable i.e. recyclable portions at source, which is ~5% of the total waste generation. Costing of NGOs will be compensated by selling these recyclable portions. As revenue from this 5% of recyclable portions and cost of NGOs are compensated by each other, so it is not considered in this model. Rest 95% garbage as recorded by KMC reaches to the municipal authority for further management. The same quantity i.e. 95% garbage reaches to the central sorting system (ICS).

Due to the improved sorting system of bio-degradable and non bio-degradable waste at source, out of ~ 30% inert materials, 10% is considered as finely sorted inert materials at source. After inspection at the ICS, it (10%) goes directly to the ELF site without unloading at ICS, as direct dumpable inert portion from the garbage. 95% of the garbage reaches to the ICS and input/output stream at ICS is shown in Figure 6.28.

Transportation costs of incineration feed and compost feed from ICS to incineration and compost plant are considered within the operating costs of these two units. Cost for transportation of recyclable materials from ICS to material recycling unit and additional dumpable quantities from ICS to ELF are considered. Extra transportation cost for direct dumpable quantities is not required as it goes directly to the ELF sites after inspection at the ICS unit.

(b) Operational and maintenance (O&M) cost of sorter

Operational and maintenance cost of sorter is calculated on the basis of (i) labour and establishment cost (ii) capital and maintenance cost - structures, fixed equipment, mobile equipment, miscellaneous, contingency (iii) cost of utilities - power, water, sanitary, miscellaneous, contingency. O&M cost of sorter is considered as Rs. 0.50/- per MT. Break up of this cost is shown in Table A-6.14 of Annexure 6.12.

(c) Revenue from recyclable materials

Apart from 5% (of the total garbage) recyclable portions separated at source and managed by the authorized NGOs, recyclables are also separated out from sorter (4% of the total garbage), pre-sorter of the incinerator (0.5% of the total garbage) and pre-sorter of the compost (1.25% of the total garbage). These 5.75% (of the total garbage) recyclables are transported to the recycling facility and revenue @ Rs. 2000/- per MT is earned by the municipal authority.

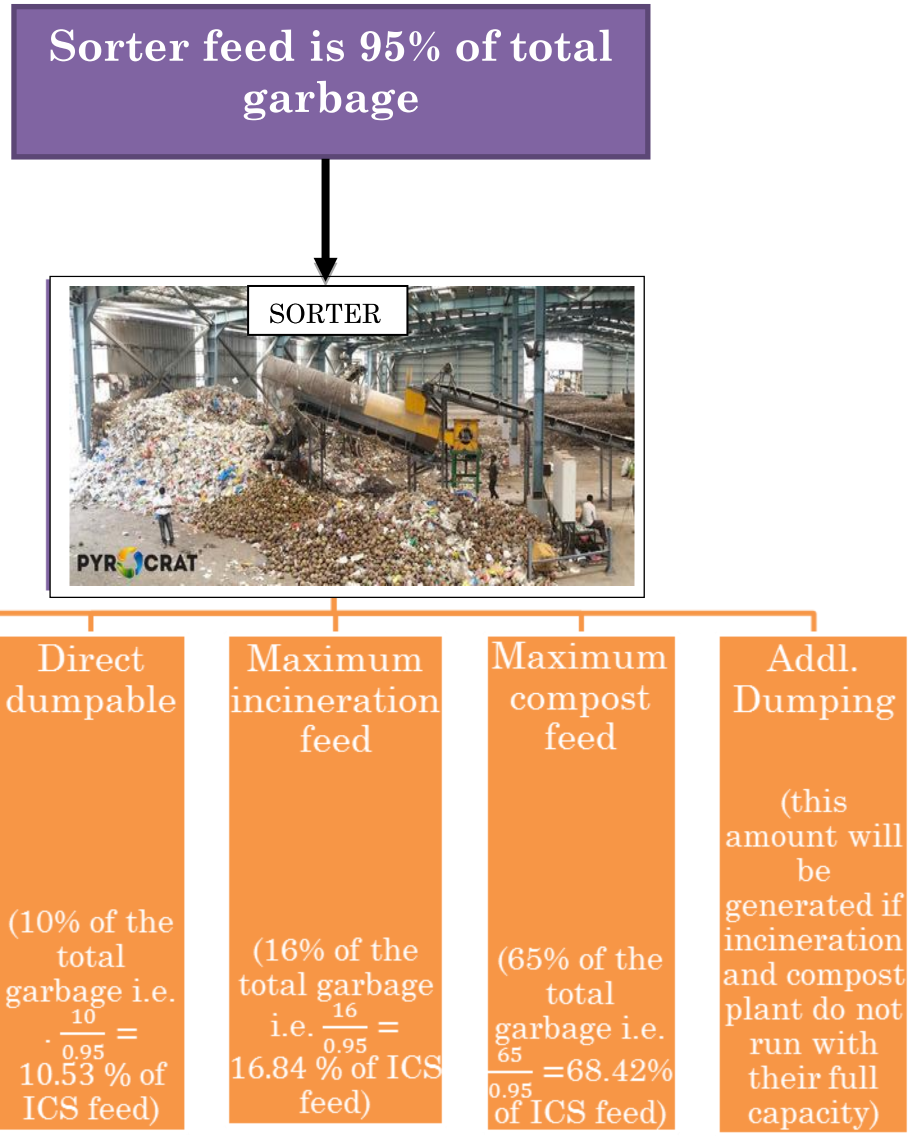


Fig.6.28 Sorter (ICS) balance

6.2.1.7 Incineration

(a) Material balance

Three mass burn incineration plants are considered at three ELF sites along with pollution control and other facilities. Maximum incineration feed is 16.84% of respective ICS feed of that

ELF site only. Composition of incineration feed is shown in earlier chapter (Table 4.34). Input and output streams of the incineration plans are given in figure 6.29.

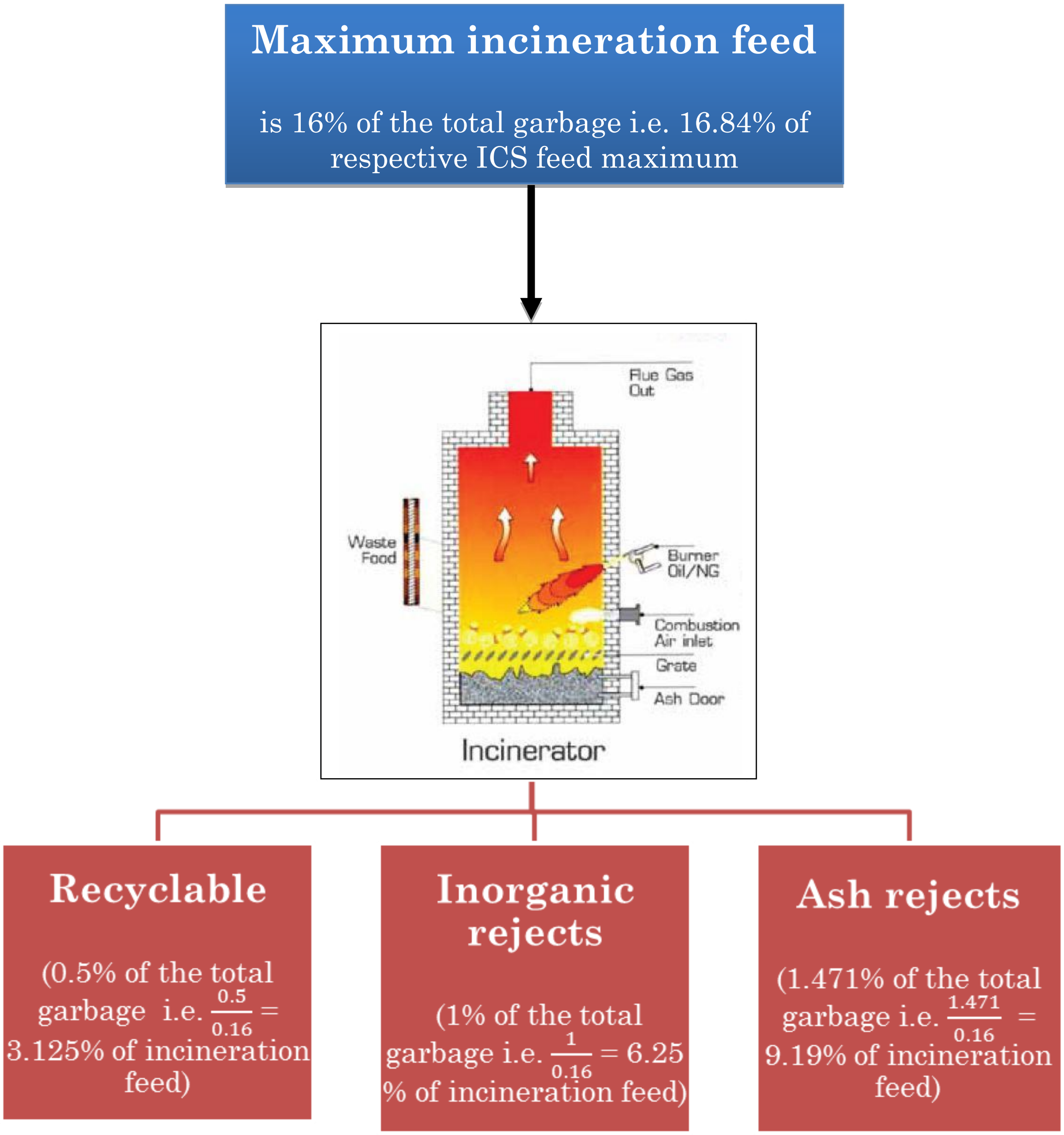


Fig.6.29 Incineration balance

(b) Operational and maintenance cost (O&M) of incinerator

Operational and maintenance cost of incinerator is calculated on the basis of (i) cost of labour and establishment (General, skilled, administration or management, miscellaneous, contingency) (ii) capital and maintenance cost (structures, fixed equipment, mobile equipment, miscellaneous, contingency) (iii) cost of utilities (power, water, sanitary, miscellaneous, contingency). O&M

cost of incinerator is considered as Rs. 1726/- per MT. Break up of this cost is shown in Table A-6.15 Annexure 6.13.

Apart from operation and maintenance cost of incineration, extra cost of transportation of recyclables from incineration to recycling facilities; inorganic rejects from incineration plant to respective ELF sites and ash rejects to the respective ELF sites is considered as Rs. 50/MT.

6.2.1.8 Composting

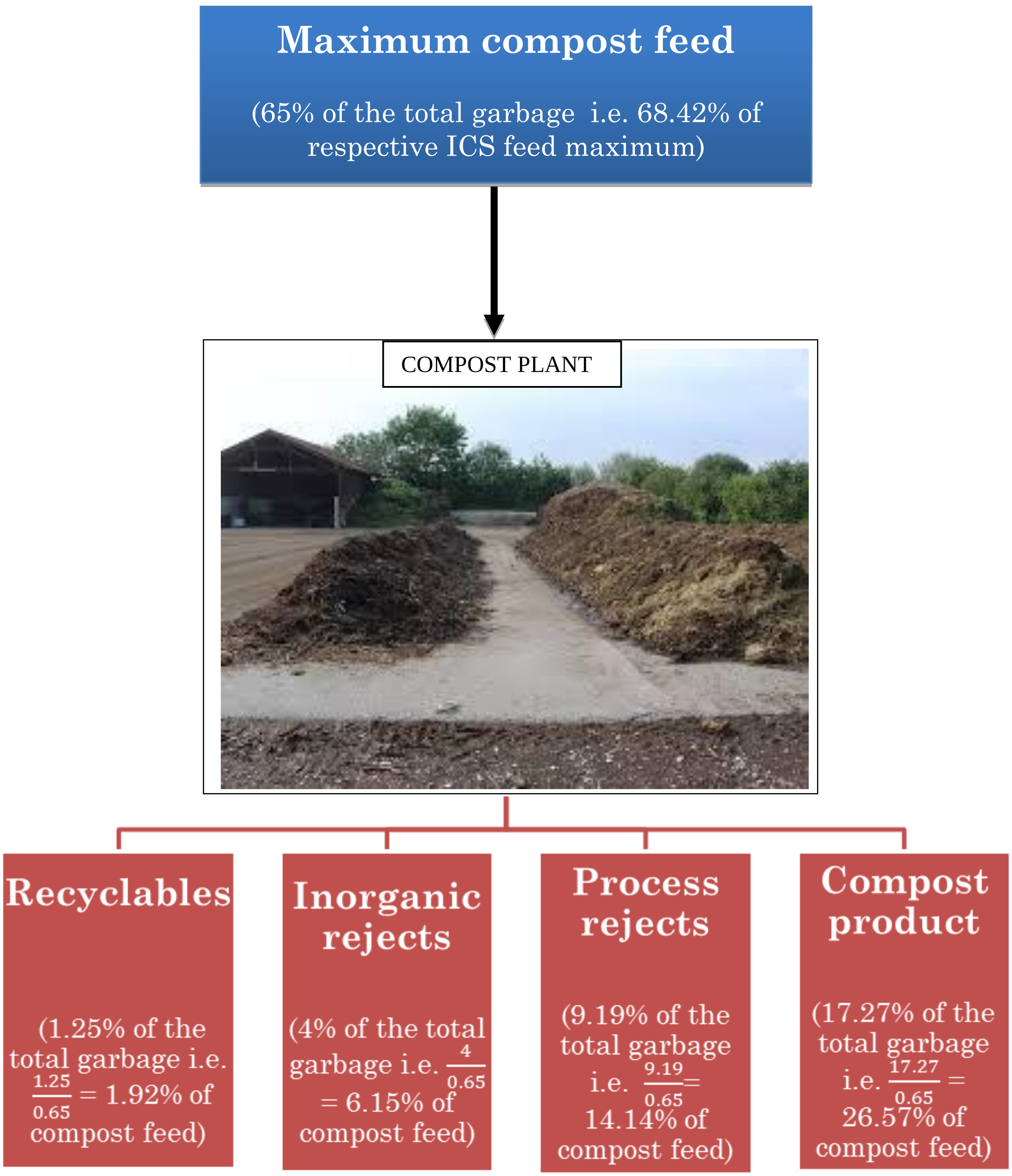


Fig.6.30 Compost balance

(a) Material balance

Three compost plants are considered adjacent to three ELF sites along with other facilities. Semi mechanized windrow composting is considered and the composition of composting feed is given in Table 4.35. Maximum compost feed is 68.42% of the respective ICS feed of that ELF site only. Input and output streams of compost plants are given in Figure 6.30. In the compost feed 47.56 units out of 65 units of total garbage is compostable. So, 30% of compostable (Flintoff, 1984) along with three units inert materials i.e. [(47.56 x 0.3) + 3] = 17.27 units of compost is produced out of 65 unit of compostable materials.

(b) Operational and maintenance (O&M) cost of compost plant

Operational and maintenance cost of compost plant is considered same as in existing model i.e. Rs. 507.88/- per ton.

Apart from operation and maintenance cost of compost plant, extra cost of transportation of recyclables from compost plant to recycling unit; inorganic and process rejects to respective ELF sites is considered as Rs 50/MT.

(c) Revenue from compost

Revenue from compost product is considered as Rs 3500/- per MT of compost product.

6.2.1.9 Landfilling

In the proposed integrated model three ELF sites are considered in eastern site (D), northern site (N) and southern site (S) of Kolkata. In each ELF sites central sorting system, composting and incineration facilities are considered. All silt or rubbish, direct dumpable (inert) from sorter, inorganic rejects and ash rejects from incinerator, inorganic rejects and process rejects from compost plant are disposed in their respective engineered landfill (ELF) site. In rare cases (occasional shutdown or accidental breakdown of incinerator and compost plant) organic wastes may go to landfill. As the disposable wastes mostly inorganic in nature, only liner and leachate collection and treatment system are considered without any gas collection system.

Operational and maintenance cost of ELF system is calculated on the basis of (i) labour and establishment cost (general, skilled, administration/management, miscellaneous, contingency) (ii) capital and maintenance cost (fixed equipment, mobile equipment, spare parts for bull dozers, fuel, supply of trip tokens, ribbons etc), (iii) cost of liner, (iv) cost of leachate collection and treatment system, (v) cost of utilities (power and utilities, miscellaneous, contingency). O&M cost of ELF is considered as Rs 200/- per MT compared to open dumping cost of Rs 95/- per MT in existing model. Break up of this cost is shown in Table A-6.16 of Annexure 6.14.

6.2.2 Proposed Model with Same Cost Configuration of Existing Model to Compare with Optimized Existing Model

The proposed integrated model is run considering the three ELF sites along with running of ICS; incineration; and composting at their full capacity at the respective ELF sites. Running efficiency of the departmental vehicles is considered as 50%. Operation and maintenance cost of ELF cost is considered as Rs 200/- per MT compared to open dumping cost of Rs 95/- per MT in existing model.

Total optimum cost for SWM for this condition of proposed model is Rs 4,31,461/- per day (Table 6.20), which is ~46% lower than the existing optimized model (optimum vehicle with 50% vehicle efficiency and total SWM cost – Rs. 7,95,687/-).

Table 6.20 Output summary of cost for proposed model with same cost configuration of existing model

Item	Cost (Rs/day)	Cost (Rs/day)
Total SWM Cost	7,95,687.30	431460.6
Total transportation cost	532102.8	497363.20
Incentive cost	1,3596.24	14144.86
Landfilling cost	253498.80	199520.6
Sorting cost	0	6784.184
Incineration cost	0	761043.80
Composting cost	0	924757.20
Revenue earned from recyclables	0	315115.0
Revenue earned from composting	3510.56	1657038.0

In the existing optimized model quantity of solid waste disposal is 2668.40 MT and its disposal cost (open dumping) is Rs 2,53,499/- @ Rs 95/- per ton of disposal.

In the proposed model landfill quantity includes inert, process rejects and ash at ELF site “D” 606.01 MT/day; at ELF site “N” 191.94 MT/day and ELF site “S” 199.65 MT/day because of different location of disposal sites. So, total landfill amount is 997.6 MT; ELF cost is Rs

1,99,520.60/- @ Rs 200/- per MT. Though the ELF cost is high because of lesser amount of land filling, total ELF cost is ~ 21% less.

In the proposed model fuel cost of departmental vehicle is reduced by ~21% (from Rs 55039/- to Rs 43612/-) and total transportation of hired vehicle is reduced by ~4% (from Rs 263651/- to Rs 252699/-). Transportation cost for existing model is Rs 5,32,102.8/- as total distance covered by the vehicles for management of solid waste is more as single dump site is available. In the proposed model as three ELF sites are considered, solid waste is transported to the nearest ELF sites depending upon the distance between waste generation point and disposal sites. Because of optimized distances covered by the vehicles, total transportation cost is Rs 4,97,363.20/- i.e. ~6.5% less than the existing.

Incentive in the proposed model is ~ 4% higher as because of higher no. of trips of the same vehicle. But compare to total cost the amount of incentive cost is very less. So, increasing the incentive cost, waste carrying efficiency of departmental vehicles can be enhanced.

Total sorter feed in the proposed model is 2604.29 MT/day and sorting cost including transportation cost of sorted recyclable (@ Rs. 50/- per MT) is Rs 6784.18/-.

Total recyclable materials generated from sorter, composting and incineration facilities is ~158 MT/Day and revenue out of it is Rs 3,15,115/- @ Rs 2000/- per MT. which is substantial amount compared to sorting.

Total incinerable quantity is 438.56 MT/Day and total incineration cost is Rs 7,61,043.80/- including O&M cost @ Rs 1726/- per MT and transportation cost of rejected materials to the nearby ELF site @ Rs 50/- per MT. Cost of incineration is substantially high but because of obligation of integrated solid waste management, cost of incineration has to be borne by the authority.

In the existing model less amount i.e. 151 MT garbage is composted by the private entrepreneur and 2.5% revenue, i.e Rs. 3510/- pre day, is earned by municipal authority from the selling price of compost.

In the proposed model total amount of compost is 473.44 MT/day and revenue generation from selling of compost product is Rs 16, 57,038/- @ Rs 3500/- per MT of compost. Total expenditure i.e. total cost of composting is Rs 9,24,757.20/- including O&M cost @ Rs 507.88/- per MT and transportation cost of recyclable amount and rejects @ Rs 50/- per MT. So, compost is one of the most profitable units of integrated MSW system.

So far in integrated SWM, though the O&M cost of incineration and compost plant is high but revenue earning for recyclable and compost reduces the cost of solid waste management by 46% than existing model. Composting facility and sorting facility must be operated.

As the incineration cost is high, same model is run without considering incineration to observe its effect on integrated solid waste management. In this case, rather than expenditure of Rs 4,31,460.60/- per day it generates earning of Rs 2,06,075.10/- per day. So, integrated solid waste management without incineration is profitable as incineration cost is high. This system generates more amount of landfill, and it has some adverse impact on landfill life i.e. cost of land and leachate generation. Landfill cost is increased by ~ 27% as landfill quantity is increased by same percentage due to closure of incineration. Cost of central sorting has increased from Rs 6784.18/- to Rs 28712.33/- due to transportation cost of additional dumpable quantity to ELF which is allocated for incineration. Revenue from recyclable is reduced by ~ 9.5% because of no recyclable amount is coming from incineration pre-sorter. Other components like transportation cost and incentive; O&M cost for composting and revenue from composting are unchanged.

6.2.3 Proposed Model, Considering Present Enhanced Cost, Running at Full Capacity of Incineration and Composting with 60% Running Vehicle Efficiency

This proposed integrated solid waste management model is run with full capacity of incineration and composting facility to minimize environmental hazards, to reduce landfill area requirement etc. In this model present enhanced cost is considered and the running efficiency of the vehicle is assumed as ~60%. Revenue from compost is considered as @ Rs 3500/- per MT of compost to achieve safe estimated waste management cost. Major output after model run is shown in Table A-6.20 of Annexure 6.20.

Total optimum cost of this model is Rs 12,96,051/- and other costs after model run are shown in Table 6.21. This cost increment from the proposed model with old cost (optimum cost Rs. 4,31,461/-) is mainly due to increase of waste carrying cost (from Rs. 4,97,363.20/- to Rs. 9,33,330.1/-) and increase of fixed running and idle cost of departmental vehicle (from Rs. 2,75,067.43/- to Rs. 7,06,922.42/-).

Table 6.21 Output summary of cost for proposed model considering enhanced cost, running at full capacity of incineration & composting with 60% running efficiency

Item	**Cost (Rs/day)**
Total SWM Cost	1296051.00
Total transportation cost	1365185.00
Incentive cost	10913.36
Landfilling cost	199520.60
Sorting cost	6784.184
Incineration cost	761043.80
Composting cost	924757.20
Revenue earned from recyclables	315115.00
Revenue earned from composting	1657038.00

Quantity of sorter feed for garbage sorting at engineered landfill sites of ‘D’, ‘N’ and ‘S’ are 1467.14 MT/day (56.34%), 592.82 MT/day (22.76%) and 544.34 MT/day (20.9%) respectively. Since ‘D’ ELF site is nearer to most of the boroughs, major portion goes to this site to minimize the transportation cost. Due to the same reason quantity of waste from boroughs in north mostly goes to their nearest ELF site ‘N’ and boroughs in south mostly goes to southern ELF site ‘S’.

Compost plants adjacent to ‘D’, ‘N’ and ‘S’ take 1003.82 MT/day, 405.6 MT/day and 372.44 MT/day. As composting is profitable, model takes the maximum possible compost amount. Net earnings from compost is Rs.7,32,281/- per day, which is a substantial profit for solid waste management.

Incineration is basically considered as a direct expenditure in the solid waste management though it has substantial positive impact on land resource because of high volume reduction of waste. This model is forced to take the maximum incineration feed and it takes 247.07 MT/day, 99.83 MT/day and 91.67 MT/day for ‘D’, ‘N’ and ‘S’ respectively. Expenditure for incineration is Rs. 7,61,044/- per day. From the Figure 6.31 it is clear that the revenue earnings in compost and sorter are higher than the expenditure.

Amount of silt and rubbish, inert materials (direct dumpable) and process rejects deposited in different ELFs are given in Table 6.22. Landfill site ‘D’ receives maximum amount of waste i.e. 615.65 MT/day (61.7% of total landfill amount) due to its advantageous location. Silt is only carried by hired vehicles. Major portion of silt [219.34 MT/day (74.58%)] is taken by ELF site ‘D’ due to its location and favorable zone wise silt carrying rate of the hired vehicles.

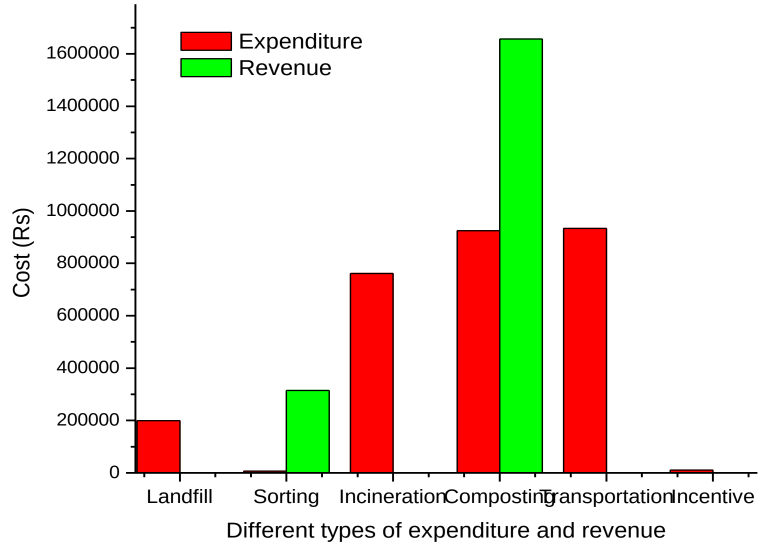


Fig. 6.31 Status of expenditure and revenue for the different components of SWM

Table **6.22** Total landfill amount and their different components for different ELF

ELF sites	Total landfill quantity at ELF sites	Silt quantity	Direct dumpable quantity	Process rejects and ash quantity
D	615.65 MT/day (100%)	219.34 MT/day (35.63%)	154.49 MT/day (25.09%)	241.82 MT/day (39.28%)
N	204.99 MT/day (100%)	44.86 MT/day (21.88%)	62.42 MT/day (30.45%)	97.71 MT/day (47.67%)
S	176.96 MT/day (100%)	29.92 MT/day (16.91%)	57.32 MT/day (32.39%)	89.72 MT/day (50.7%)

From the above analysis it is clear that when the integrated SWM system operates along with fully functional three integrated facilities, the capacity of sorter should be ~57 to 62% at ‘D’, ~22 to 27% at ‘N’ and ~21 to 26% at ‘S’ of the total sorter feed amount. Incineration capacity at ‘D’, ‘N’ and ‘S’ should be 10-15%, 4-8% and 4-8% of the total sorter feed amount. Composting capacity at ‘D’, ‘N’ and ‘S’ should be 39-44%, 16-21% and 15-20% of the total sorter feed amount.

Capacity of the landfill at ‘D’, ‘N’ and ‘S’ should be ~20 to 25%, 7 to 12% and 6 to 10% of the total waste generation considering certain flexibility.

6.2.4 Effects on Optimized Proposed Model for Variation of Incineration Capacity

Capital as well as operation and maintenance cost of incineration is high without any direct revenue earning, though it reduces considerable amount of waste volume, increases life of landfill and improves the quality of leachate. Because of these advantages, incineration is considered as a part of the modern integrated solid waste management system.

Incineration unit can be operated between 100% to 50% effectively and the shutdown point is considered as 50% of its maximum capacity. In this study effect of reduction of incineration amount @ 10% i.e. from 100% to 50% on MSW operation is observed. Whenever incineration quantity decreases, left over quantity will go to the engineered landfill as additional dumpable quantity.

Incineration cost per day has been reduced from Rs. 7,61,044/- to Rs. 3,81,769/- because of the reduction of incinerable amount from 438.59 MT (100%) to 220 MT (50%) per day. Revenue earning from recyclable is reduced from Rs 3,15,115/- per day to Rs 3,01,455/- per day i.e. ~ Rs 14,00/- per day only due to reduction of pre-incineration recyclable amount from 13.69 MT to 6.88 MT per day. As incinerable amount is reduced, additional dumpable quantity is increased accordingly from 0 MT to 218.56 MT per day (figure 6.32).

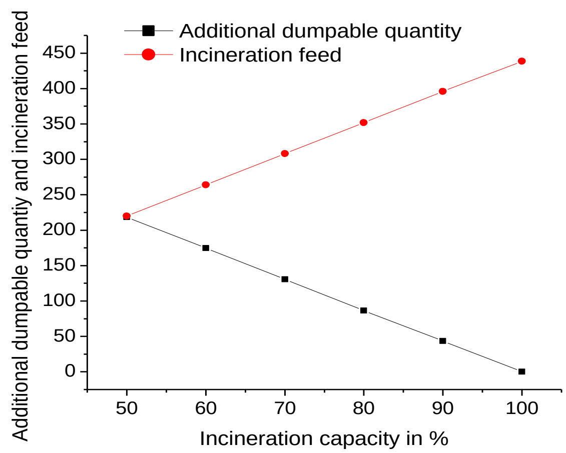


Fig.6.32 Variation of additional dumpable and incineration feed quantities with the variation of incineration capacity

Transportation cost (@Rs 50/- per ton) of additional dumpable quantity from sorting facility to engineered landfill (ELF) is considered in the sorting operation. As a result, sorting cost is increased from Rs. 6,784/- per day to Rs. 17,712/- per day. Since additional amount goes to ELF, therefore, cost of ELF is increased from Rs 1,99,521/- per day to Rs 2,36,484/- per day. No changes are found in composting, transportation and incentive cost as vehicle numbers are unaltered with the variation of incineration capacity. Due to combine effect of the above facts total cost of SWM is decreased from Rs. 12,96,051/- per day to Rs. 9,78,328/- (~25%) as shown in figure 6.33.

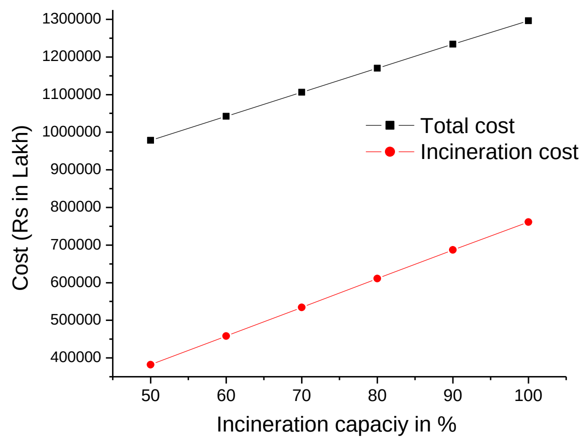


Fig.6.33 Change of incineration cost and total cost with the variation of incineration capacities

6.2.5 Effects on Optimized Proposed Model for Variation of Composting Capacity

Major portion of the MSW is biodegradable. So biotransformation of the MSW i.e. composting is an important component in the integrated SWM especially in developing countries. Composting is a very useful process for reducing the amount of waste and producing compost as a soil conditioner. It is also the major revenue earning process in the SWM system.

In this study composting unit can be operated between 100% to 50% effectively and the shutdown point is also considered as 50% of its maximum capacity. Effect of reduction of composting amount @ 10% i.e. from 100% to 50% on MSW operation is observed. Whenever composting quantity decreases, left over quantity will go to the engineered landfill as additional dumpable quantity.

Composting cost per day has been reduced from Rs 9,24,757/- to Rs 4,62,416/- because of the reduction of compostable amount from 1781.86 MT(100%) to 891.00 MT (50%) per day. Revenue from compost decreases from Rs 16,57,038/- per day to Rs 8,28,585/- per day as compost amount decreases from 473.44 MT to 236.74 MT per day. Revenue earning from recyclable is reduced from Rs 3,15,115/- to Rs 2,80,906/- per day due to reduction of pre compost recyclable amount from 34.21 MT to 17.11 MT per day. As compostable amount is reduced, additional dumpable quantity is increased from 0 MT to 890.85 MT per day (figure 6.34).

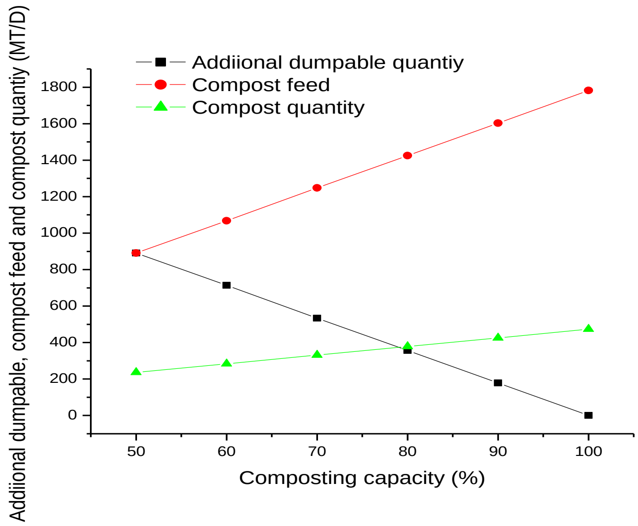


Fig.6.34 Quantity of additional dumpable and compostable feed with variation of composting capacities

Transportation cost (@Rs 50/- per ton) of additional dumpable quantity from sorting facility to engineered landfill (ELF) is considered in the sorting operation. As a result, sorting cost is increased from Rs. 6,784/- to Rs. 51,327/- per day. Since additional amount goes to ELF, therefore, cost of ELF is increased (~71%) from Rs. 1,99,521/- to Rs. 3,41,541/- per day. No changes are found in incineration, transportation and incentive cost as vehicle numbers are unaltered with the variation of composting capacity. Due to combine effect of the above facts total cost of SWM is substantially increased (~45%) from Rs. 12,96,051/- to Rs. 18,82,935/- per day as shown in figure 6.35.

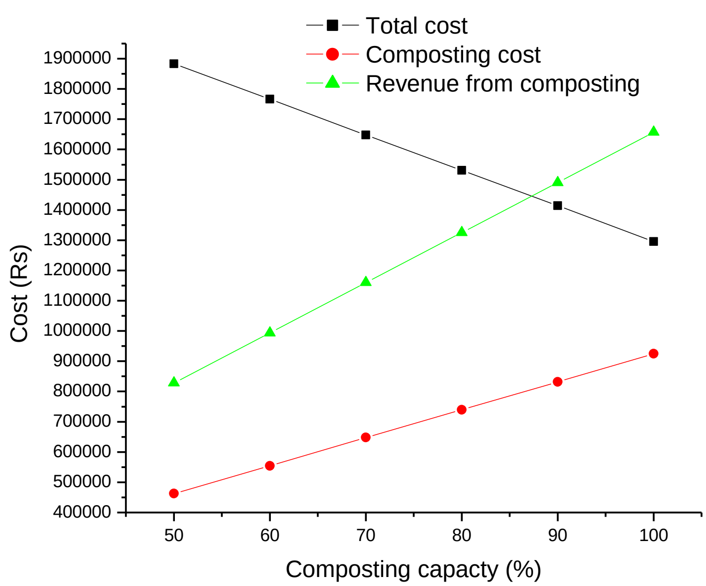


Fig.6.35 Change of composting cost and total cost with variation of composting capacities

6.2.6 Optimized Proposed Model with Full Incineration and Without Composting

Effect of SWM system having full capacity of incineration but without composting facility, on its operation is observed. The composting cost of the SWM system with full capacity of incineration and composting facility is Rs. 9,24,757/- per day, which is reduced to Rs. 0/- in case of without composting facility and the reduction of compostable amount is from 1781.86 MT to 0 MT/day. A summary of total SWM and other costs after model run is shown in Table 6.23.

Table 6.23 Output summary of cost for optimized proposed model with full incineration and without composting

Item	Cost (Rs/day)
Total SWM Cost	2469912.00
Total transportation cost	1365185.00
Incentive cost	10913.36
Landfilling cost	483584.30
Sorting cost	95877.05
Incineration cost	761043.80
Composting cost	0
Revenue earned from recyclables	246691.70
Revenue earned from composting	0

Compost amount is reduced from 473.44 MT to 0 MT/day and subsequently the revenue from compost selling (@Rs 3,500/- per MT) is reduced from Rs. 16,57,038/- to Rs. 0/- per day. Revenue earning from total recyclable is reduced from Rs. 3,15,115/- per day to Rs. 2,46,692/- per day (Table 6.23) due to reduction in pre-composting recyclable amount from 34.21 MT to 0 MT/day which is a substantial amount.

As composting has been stopped, 1781.85 MT/day compostable waste is converted to additional dumpable waste. 1781.85 MT/day of additional dumpable quantity is transported from sorting facility to engineered landfill (ELF) @Rs 50/- per MT and its cost is considered in the sorting operation. As a result, sorting cost is increased from Rs. 6,784/- per day to Rs. 95,877/- per day.

Landfill quantity at ELF site ‘D’ is increased from 615.65 MT/day to 1415 MT/day (30% increment), and same for ELF site ‘N’ and ‘S’ are increased from 205MT/day to 528.3 MT/day (158% increment) and 177 MT/day to 474.64 MT/day (168% increment) respectively. It shows that elimination of composting facility reduces substantial amount of landfill life and increases its daily operation.

Since additional amount goes to ELF, therefore, total operation cost of ELF is increased from Rs. 1,99,521/- per day to Rs. 4,83,584/- per day. Because of the above facts as well as major revenue loss from composting, total cost is increased per day from Rs. 12,96,051/- to Rs. 24,69,912/- (Table 6.23) as shown in figure 6.36.

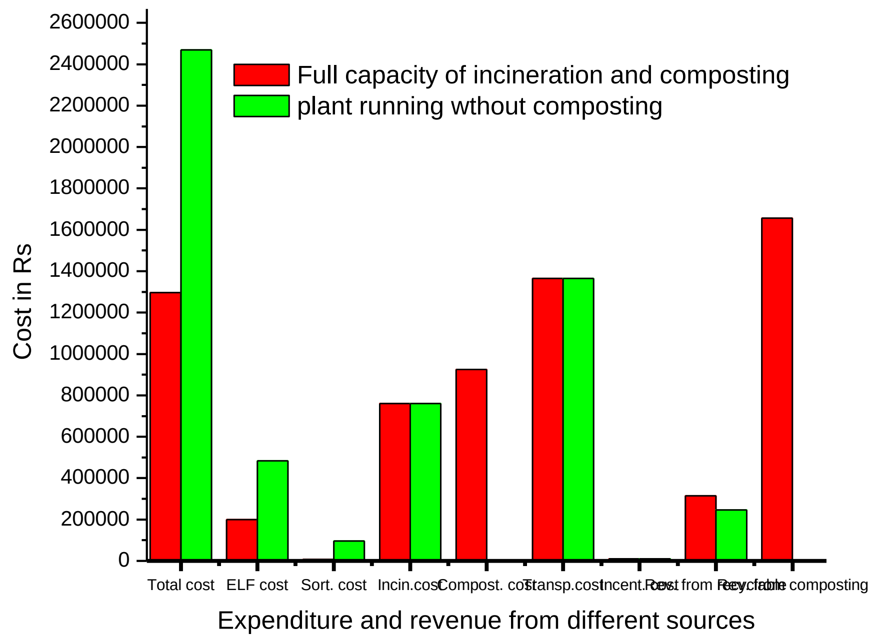


Fig.6.36 Comparison of different expenditure and revenue when (i) both compost plant and incineration in operation and (ii) without compost plant operation

6.2.7 Effects of Closure of One ELF on other ELF Sites

One of the three ELF sites may have to close for certain period of time due to major maintenance, accidental failure, and some inadvertent situations like labour strike, natural calamities etc. The effects of closure of one ELF site on the other two ELF site is observed.

When ELF site "D" is closed and "N" and "S" are in operation then the waste are almost equally shared. Sorter feed, compost feed and incineration feed are shared by ~53% and ~47% and landfill amount is shared by ~46% and ~54% by "N" and "S" ELF sites depending on their location and cost of transportation. Their individual capacity of all units is increased by more than 100% to process the total waste quantity (Table 6.24).

For both the operations when only "N" closed and only "S" closed then "D" ELF site takes the major load (~80%) of the waste processing and landfill load (~80%). It indicates that location of ELF site "D' is much favorable than other two ELF sites (Table 6.24).

As the position of ELF site D is most suitable, therefore, closure of ELF site D along with each processing units has its maximum impact on cost especially the transportation cost. The transportation cost is increased by % ~5% and total cost is increased by ~5%. All the cases incentive cost is increased by ~1 to 2% (Table 6.25) which is very nominal amount. Apart from the existing ELF site “D”, amount of increased cost in transportation and incentive indicates appropriate choice of future landfill site “N” and “S”.

Table 6.24 Sharing of quantities for different processing facilities for closure of ELF site

ELF sites	Sorter Feed quantity (MT/D)			Compostable quantity (MT/D)			Incinerable Quantity (MT/D)			Landfill Quantity (MT/D)		
	D	N	S	D	N	S	D	N	S	D	N	S
“D”, “N” and “S” are in operation	1467.14 (56.34%)	592.82 (22.76%)	544.34 (20.9%)	1003.82 (56.34%)	405.60 (22.76%)	372.44 (20.9%)	247.07 (56.34%)	99.83 (22.76%)	91.67 (20.9%)	615.65 (61.71%)	204.99 (20.55%)	176.96 (17.74%)
“D” closed, “N” and “S” are in operation	0	1384.01 (53.14%)	1220.29 (46.86%)	0	946.94 (53.14%)	834.92 (46.86%)	0	233.07 (53.14%)	205.50 (46.86%)	0	454.95 (45.6%)	542.65 (54.4%)
“N” closed, “D” and “S” are in operation	2058.96 (79.06%)	0	545.34 (20.94%)	1408.74 (79.06%)	0	373.12 (20.94%)	346.73 (79.06%)	0	91.84 (20.94%)	811.00 (81.30%)	0	186.60 (18.7%)
“S” closed, “D” and “N” are in operation	2094.51 (80.42%)	509.79 (19.58%)	0	1433.06 (80.42%)	348.8 (19.58%)	0	352.71 (80.42%)	85.86 (19.58%)	0	805.61 (80.75%)	191.99 (19.25%)	0

Table 6.25 Sharing of different costs for different processing facilities for closure of one ELF site

ELF sites	Total optimum cost	Total Transportation cost	Total incentive cost
"D", "N" and "S" are in operation	Rs 12,96,051/-	Rs 13,65,185/-	Rs 10,913/-
"D" closed, "N" and "S" are in operation	Rs 13,60,120/-	Rs 14,29,119/-	Rs 11,048/-
"N" closed, "D" and "S" are in operation	Rs 13,12,625/-	Rs 13,81,507/-	Rs 11,165/-
"S" closed, "D" and "N" are in operation	Rs 13,21,386/-	Rs 13,90,361/-	Rs 11,072/-

6.2.8 Effects of Changes of Garbage Carrying Ratio of Departmental Vehicle to Hired Vehicle on SWM Operation and Economics

In this study, effects of changes of garbage carrying ratio of departmental vehicle to hired vehicle on SWM operation and economics is observed. The model is run for different percentage of garbage sharing by departmental vehicles i.e. from maximum 60% to minimum 15% and rest by hired vehicle. Different models having different percentage of garbage sharing are prepared by reallocating the average garbage transportation capacity with a flexibility of ~ ±5% i.e. if average transportation capacity of the hired vehicles is reduced by 5% then the same for departmental vehicles is increased by 5%. For all the cases 60% operational efficiency of departmental vehicles is considered. Variation of the range of the garbage carrying limit for different weight ratios are given in Annexure 6.15 and Annexure 6.16.

The major impacts of variation of garbage sharing by departmental vehicles and hired vehicles are on total transportation cost of departmental vehicles which includes fuel costs, fixed running and idle cost of vehicles, incentive cost; transportation cost of hired vehicles and consequently total cost of SWM.

For the optimized operation, garbage sharing of the departmental vehicles is 42% and rest by hired vehicles. Total silt amount is taken by hired vehicles only. In this case total SWM cost is Rs 12,96,051/- per day. The variation of garbage sharing by departmental vehicles is done from 15% to 60% @ 5% increment. Daily transportation cost of departmental vehicles including incentive is increased from Rs. 2,77,836/- for 15% of garbage sharing to Rs. 11,44,708/- for 60% of garbage sharing by departmental vehicles. This change is ~27% to ~76% of their respective total SWM cost. Transportation cost of hired vehicles is decreased from Rs. 7,27,365/- per day for 85% of garbage sharing to Rs 3,41,765/- per day for 40% of garbage sharing by hired vehicles. This change is ~71% to ~23% of their respective total SWM cost. There is no cost impact on silt as it is carried by hired vehicles only (figure 6.37). Total cost is increased (~16%) by Rs. 2,06,007/- per day w.r.t variation of 42% to 60% and reduced (~21%) by Rs 2,75,265/- per day w.r.t variation of 42% to 15%. Sample calculation of borough wise maximum and minimum garbage carrying quantity range (in fraction) for departmental and hired vehicle is shown in Table A-6.17 of Annexure 6.15.

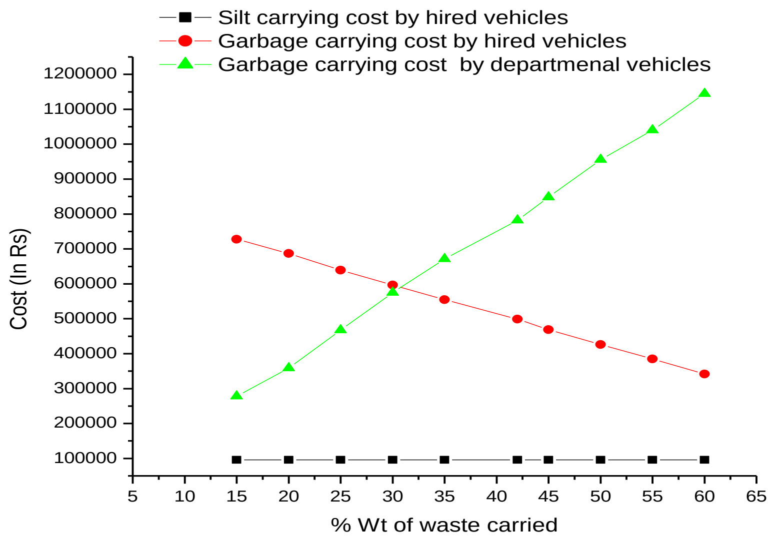


Fig.6.37 Garbage and silt carrying costs by departmental and hired vehicles with variation of different percentage of garbage weight carried by departmental vehicle

Variation of total SWM cost and its major sub component of transportation cost of departmental vehicles i.e. cost of fuel, fixed running cost, fixed idle cost and incentive with changes of different percentage of garbage sharing by departmental vehicles are shown in figure 6.38. If the garbage removal percentage reduces from 42% to 15%, with respect to the optimized operation cost, reduction of fuel cost for departmental vehicles is by ~67%; fixed running cost by ~65%; fixed idle cost by ~62% and incentive cost is by ~66%. Similarly, when the garbage removal percentage increases from 42% (optimized operation) to 60%, increment of the same of fuel cost for departmental vehicles is by ~46%; fixed running cost by ~48%; fixed idle cost by ~43% and incentive cost is by ~53%.

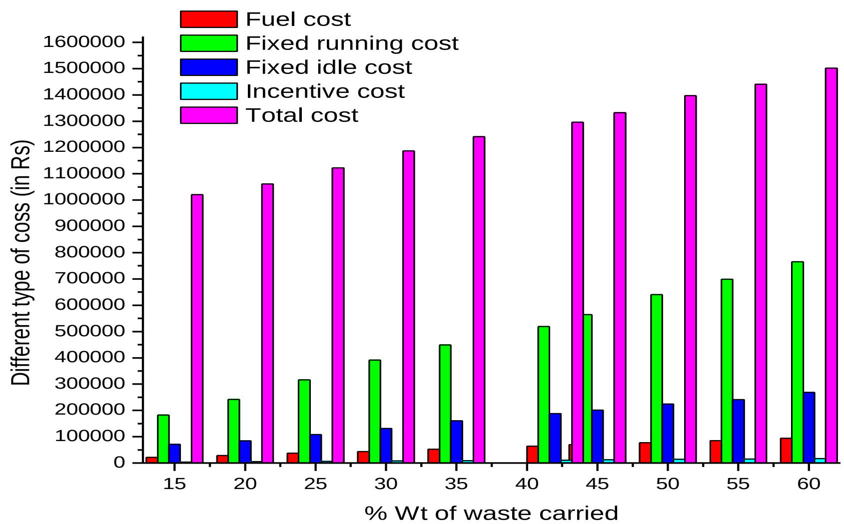


Fig.6.38 Effects on total, fuel, fixed and incentive costs for variation of different percentage of garbage weight carried by departmental vehicle

For the change of garbage sharing %, the amount of garbage taken by the different departmental vehicles and hired vehicles are shown in Figure 6.39. Since D2 and D3 vehicle takes the maximum load of the departmental garbage shared so impact on their weight sharing is maximum.

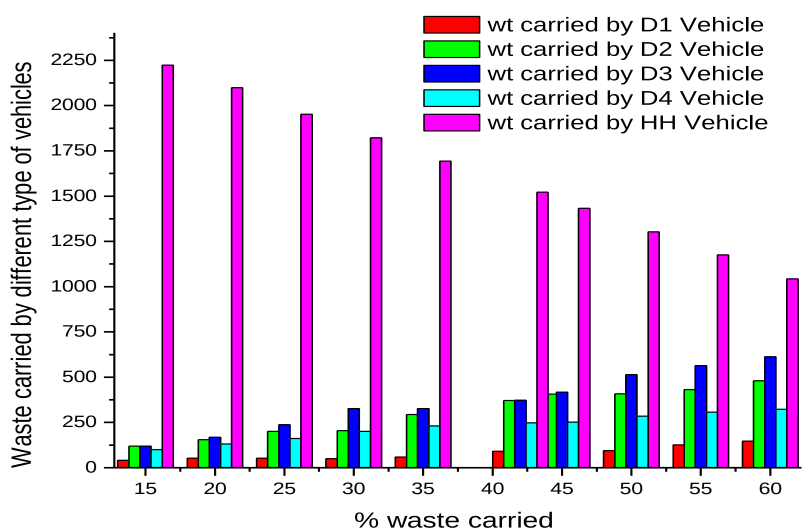


Fig.6.39 Weight shared by different vehicles for variation of different percentage of garbage weight carried by departmental vehicle

In optimized operation i,e, 42% of garbage sharing of departmental vehicles, 80 numbers of total departmental vehicles are required. In case of garbage carrying percentage by departmental vehicles reduces to 35%, 30%, 25%, 20% and 15%, total numbers of departmental vehicles are reduced by 15%, ~28%, 40%, ~54% and 65% compared to proposed optimized operation. Similarly, if the garbage carrying percentage by departmental vehicles increases to 45%, 50%, 55% and 60%, total numbers of departmental vehicles are increased by ~9%, ~21%, ~33% and

~46% (figure 6.40). Variation of garbage percentage has major impact on the numbers of D2 and D3 vehicles as in departmental vehicles most of the waste are carried by these vehicles. For reduction of garbage carrying percentage from 42% to 15%, reduction in numbers in D2 and D3 vehicles are ~68% and ~68%. The numbers of D1 and D3 vehicles are increased by ~56% and ~65% due to increase in garbage carrying percentage from 42% to 60%.

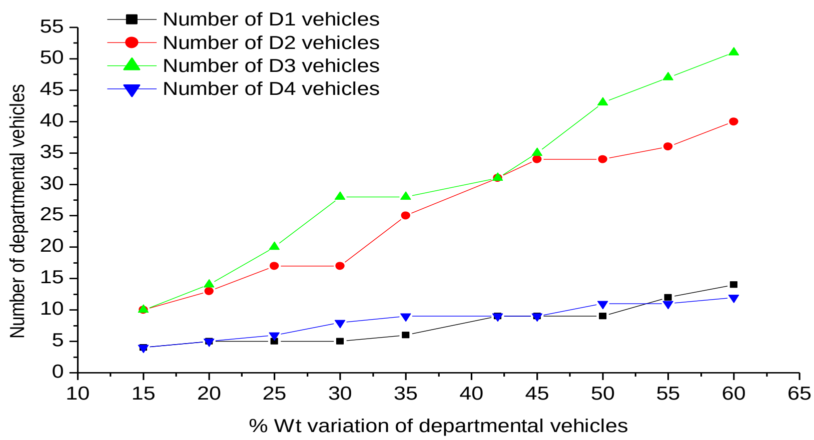


Fig.6.40 Effects on departmental vehicles number for variation of different percentage of garbage weight carried by them

6.2.9 Sensitivity Analysis of the Proposed MSW Management System

6.2.9.1 Effect of Variation of Waste Generation

In proposed optimized model if waste generation increases or decreases by 5% then cost impacts are shown in table 6.26. If waste generation is increased by 5%, then transportation cost by hired vehicles is increased by ~7.5% and increment in transportation cost by departmental vehicles is negligible. As the number of running vehicles is same as optimized condition so amount of increase of waste transportation by departmental vehicles is less (~0.8%) compared to hired vehicles (~8%). When waste generation is reduced by 5%, waste transported by departmental vehicles is reduced by ~5% and its impact on incentive is ~9% but its impact on transportation cost by departmental vehicles is only ~0.4% because of unchanged fixed and running cost of the departmental vehicles. Impact of reduced waste generation on waste transportation by hired vehicles is ~5% reduction and on cost of waste transportation by hired vehicles is also ~5% reduction. As cost impact on other cost component of SWM like sorting cost to revenue from compost is proportional to waste generation, so, impact of ±5% waste generation is also same (Figure 6.41).

Impact of ±5% waste generation on the capacities of the western waste management processing and disposal sites ‘D’ varies from +5.5% to -5%; for northern site ‘N’ varies from +5.2% to -

18% and for southern site 'S' varies from +3.7% to +9.7% because of the rate of the waste transportation cost of the hired vehicles for different zones for different processing and disposal sites.

Table 6.26 Effects of variation of waste generation on cost components in percentage

Cost parameter	Cost impacts for +5% waste generation with respect to optimized model	Cost impacts for -5% waste generation with respect to optimized model
Total cost	~3% (+Ve)	~2.5% (-Ve)
Total transportation cost	~3% (+Ve)	~2.4% (-Ve)
Total departmental transportation cost	~0%	~0.4% (-Ve)
Total hired transportation cost	~7.5% (+Ve)	~5.0% (-Ve)
Incentive cost for departmental vehicles	~0.8% (+Ve)	~9.0% (-Ve)
Sorting cost	~5% (+Ve)	~5.0% (-Ve)
Incineration cost	~5% (+Ve)	~5.0% (-Ve)
Composting cost	~5% (+Ve)	~5.0% (-Ve)
Engineered Landfill cost	~5% (+Ve)	~5.0% (-Ve)
Revenue from recyclable	~5% (+Ve)	~5.0% (-Ve)
Revenue from compost	~5% (+Ve)	~5.0% (-Ve)

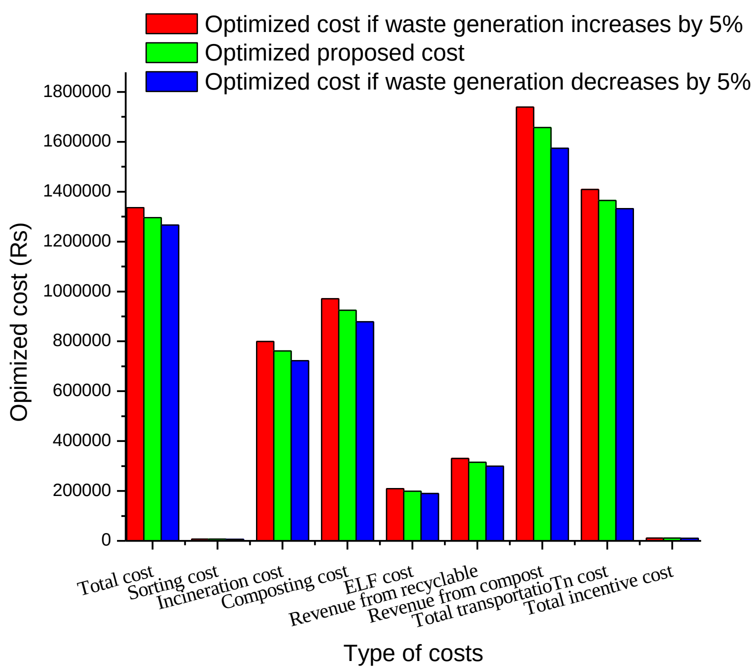


Fig. 6.41Effects of variation of waste generation on cost components

6.2.9.2 Effects of Variation of Recyclable Amount in the Waste

Study of the impact of the variation of recyclable quantity is done by assuming these variations are balanced only by the inert material i.e. direct dumpable quantity. Effects of ±1% variation of recyclable quantity on revenue from recyclable is ±17.4% and on total cost –4.5% to +4.5%. As the impact of recyclable quantity on total SWM cost is substantial so due attention must be paid for the recovery of maximum quantity of recyclable. Impact of landfill cost is –2.7% to +2.7% as more the recyclable amount less the landfill quantity. Operating cost of sorting varies ±5% for ±1% recyclable quantity variation because of the increment of transportation cost of sorted recyclable materials (Figure 6.42).

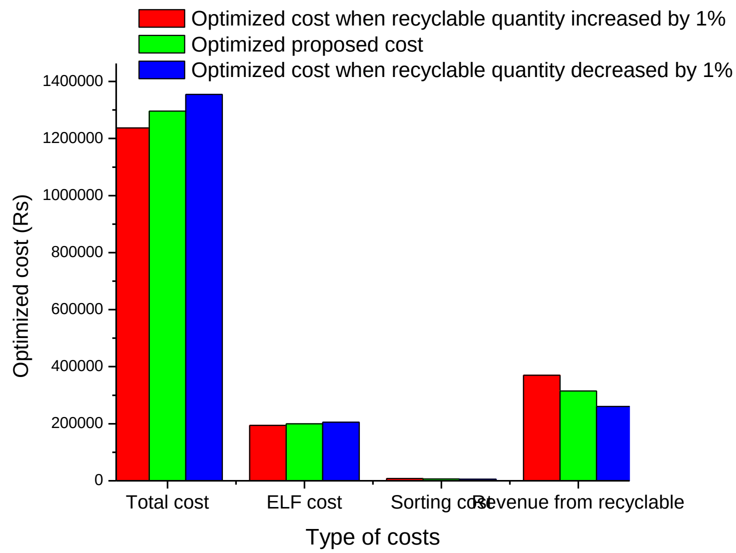


Fig. 6.42 Effects of variation of recyclable amount in the waste on different cost components

6.2.9.3 Effects of Variation of Compostable Amount in the Waste

Study of the impact of the variation of compostable quantity is done by assuming these variations are balanced only by the inert material i.e. direct dumpable quantity. Effects of ±1% variation of compostable quantity on revenue from compost is ±1.5% because compost quantity increases with increase of the compostable amount and total cost is –1.3% to +1.3% as revenue earning increasing because of increase of compostable quantity. Revenue cost variation is due to generation of more amounts of recyclable materials from more amounts of compostable materials.

As the impact of compostable quantity on total SWM cost is substantial (Figure 6.43) so due attention must be paid for the recovery of maximum quantity of compost. Impact on landfill cost is – 2.2% to +2.2% as more the compostable amount less the direct dumpable quantity i.e. less the landfill quantity. Operating cost of composting varies ±5% for ±1% compostable quantity variation because of the increment of compostable amount increases the processing and transportation of the process rejects and recyclable amount.

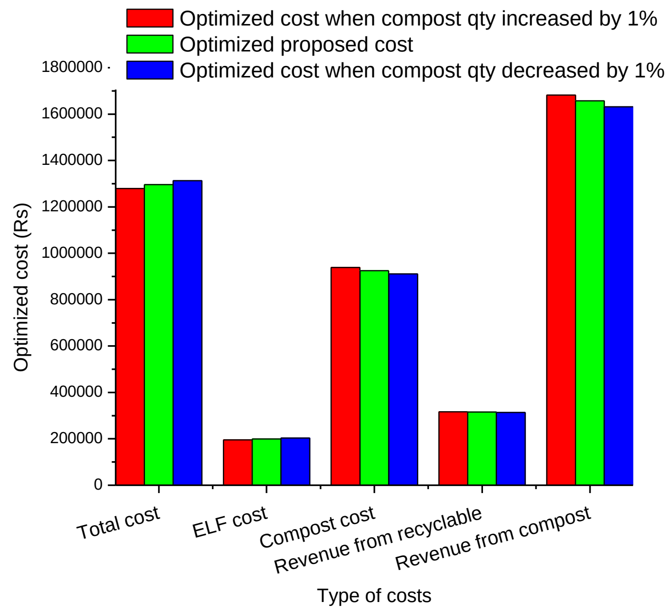


Fig. 6.43 Effects on different cost components for variation of compostable amount in the waste

6.2.9.4 Effects of Variation of Incinerable Amount in the Waste

In the study of the impact of the variation of incinerable quantity is done based on same assumption as in the case of compostable quantity, i.e. these variations are balanced only by the inert material. Effects of ±1% variation of incinerable amount, incineration cost and total cost varies ±6.2% and ±3.2% respectively (Figure 6.44). This impact is high on both the cost components because of the higher operation and maintenance cost of incineration unit. Impact on engineered landfill cost is –2.3% to +2.3% as more the incinerable amount less the direct dumpable quantity i.e. less the landfill quantity. Small variation (±0.5%) of revenue cost is due to generation of more amounts of recyclable materials from more amounts of incinerable materials.

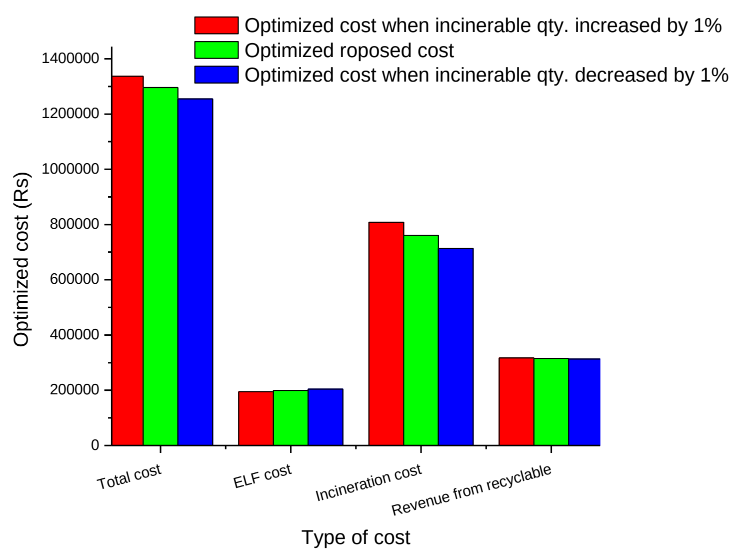


Fig. 6.44 Effects on different cost components for variation of incinerable amount in the waste

6.2.9.5 Effects on Variation of Fuel Cost

If fuel cost varies, it will affect departmental transportation cost but the transportation cost of hired vehicle will be unchanged, as payment of hired vehicle is done by rate contract including fuel.

If fuel cost increases by 5%, transportation cost by departmental vehicle increases by ~0.4% and vice versa (figure 6.45). Incentive costs are unchanged and however the total SWM cost changes only by ±0.25% due to the effect of total departmental transportation cost.

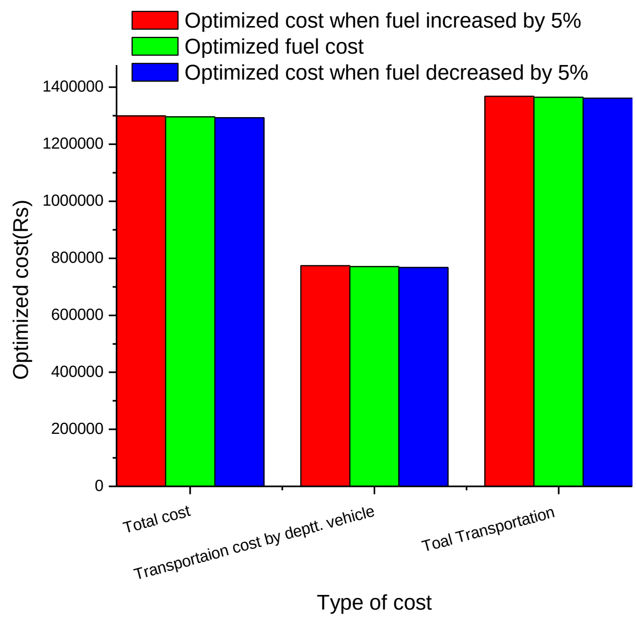


Fig.6.45 Effects on cost of fuel cost variation

6.2.9.6 Effects on Variation of Fixed Running Cost

If fixed running cost increases by 10%, increase of transportation cost by departmental vehicle is ~6.7% and for total SWM cost is ~4% and vice versa (Figure 6.46). So, fixed running cost has significant effect on transportation cost of departmental vehicles and it also affects the total optimized cost moderately. Selection of vehicle operators should be done judiciously and careful maintenance of vehicle is also suggested.

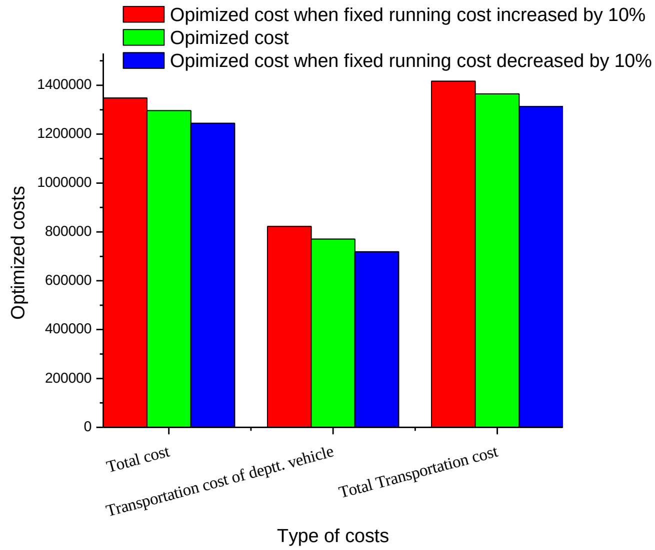


Fig.6.46 Effects on cost for fixed running cost variation

6.2.9.7 Effects on Variation of Fixed Idle Cost

If fixed idle cost increases by 10%, increase of transportation cost by departmental vehicle is ~2.5% and for total SWM cost is ~1.5% and vice versa (Figure 6.47). The effect of fixed idle cost has moderate effect on transportation cost by departmental vehicle, so efficient departmental vehicle maintenance staff should be chosen judiciously to minimize this cost.

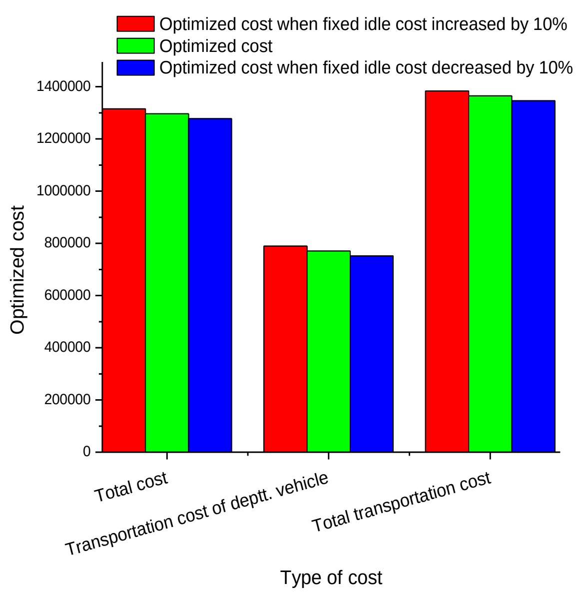


Fig.6.47 Effects on cost for fixed idle cost variation

6.2.9.8 Effects on Incentive Cost Variation

Incentive is given to the drivers and helpers of departmental vehicles to boost them for regular and timely clearance of solid waste from primary collection points. Variation of incentive rates by ±10%, it is observed that total SWM cost varies ±0.08%. Though incentive plays an important role in SWM yet it has negligible effect on total cost of SWM. So authority can achieve efficient SWM by increasing the incentive rates to satisfy the demands of the drivers and helpers of the departmental vehicles.

6.2.9.9 Effects on Variation of Transportation Cost of Hired Vehicles

If the transportation cost of hired vehicles increases by 5%, increase of total transportation cost is ~2.2% and for total SWM cost is ~2.3% and vice versa. The transportation cost of hired vehicles has significant cost effect in total transportation cost as well as total SWM cost (Figure 6.48). So, proper attention should be paid for reviewing and fixing the distance wise zones and their respective transportation cost of silt and garbage.

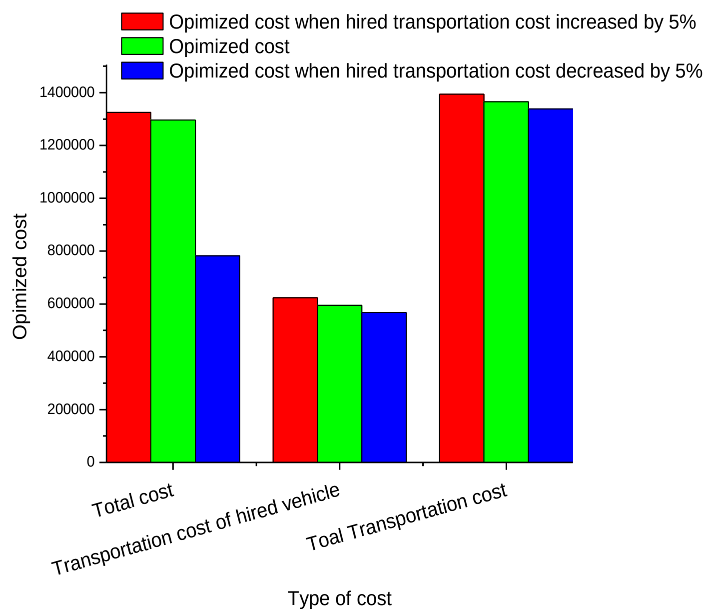


Fig.6.48 Effects on cost for variation of transportation cost of hired vehicles

6.2.9.10 Effects of Variation of Revenue Cost

Cost of compost is one of the major revenue earning components of SWM. Revenue cost of compost if increases by 5%, total expenditure i.e, total SWM cost decreases by ~6.4% and vice versa. As selling price of compost has major effect on total SWM cost, so proper attention should be paid for quality, timely production and marketing of the compost.

6.2.9.11 Effects of Variation of Operational and Maintenance Cost of Compost

Composting is a major processing unit and 65% of the garbage quantity i.e, ~1700 MT of garbage is processed daily with an O&M cost @ Rs 508/- per MT for producing compost. If operation and maintenance cost of compost plant increases by 5%, total SWM cost increases by

~3.5% and vice versa. As operation and maintenance cost of compost processing unit has a major impact on total SWM cost therefore, proper selection of the equipment and its careful maintenance should be done to minimize the operation and maintenance cost of compost processing.

6.2.9.12 Effects of Variation of Operational and Maintenance Cost of Incineration

In incineration unit 16% of the garbage quantity i.e, ~417MT is processed with a high operation and maintenance cost @ Rs. 1726/- per MT. If operation and maintenance cost of incineration increases by 5%, total SWM cost increases by ~2.9% and vice versa. Proper selection of the equipment of incineration plant and its maintenance should be done carefully to minimize the O&M cost as it has a major impact on total SWM cost.

6.2.9.13 Effects on Variation of Operational and Maintenance Cost of Landfilling

Landfilling is an essential component of SWM as it receives the inert and the other residues like process rejects and ashes from compost and incineration units. The annualized capital cost (excluding land cost) and O&M is ~Rs 200/- per MT for ELF. If this cost of ELF increases by 5%, total SWM cost increases by ~0.8% only and vice versa. However, it has no effects on other costs. The ELF should be properly constructed and operated to minimize the environmental impact.

6.2.10 Observation on Result of Proposed Integrated SWM model

In this step proposed integrated MSW management LP model is successfully prepared and analyzed. These two systems are compared to achieve optimized cost effective sustainable solution methodology of MSW management system for developing countries like India.

Total optimum cost for proposed integrated SWM model with same cost configuration is Rs 4,31,461/- per day, which is ~46% lower than the total SWM cost (Rs. 7,95,687/-) in existing optimized model.

Quantity of solid waste disposal in optimized model is 2668.40 MT and its disposal cost (open dumping) is Rs 2,53,499/- @ Rs 95/- per ton. In the proposed model having three landfill sites with treatment and disposal facilities at “D”, “N” and “S”, total landfill amount is 997.6 MT; ELF cost is Rs 1,99,520.60/- @ Rs 200/- per MT. Though the ELF rate is high but total ELF cost is ~21% less because of lesser amount of land filling.

In proposed model fuel cost of departmental vehicle is reduced by ~21% (from Rs 55039/- to Rs 43612/-) and total transportation of hired vehicle is reduced by ~4% (from Rs 263651/- to Rs 252699/-). Total transportation cost is ~6.5% less than the existing model because of lesser distances covered by the vehicles to transport waste to the nearest of three ELF sites in proposed model.

Total recyclable materials generated from sorter, composting and incineration facilities is ~158 MT/Day which generates a substantial amount of revenue [Rs 3,15,115/- (@ Rs 2000/- per MT)].

In the existing model less amount i.e. 151 MT garbage is composted by the private entrepreneur and @ 2.5% royalty, revenue amount is only Rs. 3510/- per day. In the proposed model total amount of compost is 473.44 MT/day and revenue generation from selling of compost product is Rs 16, 57,038/- @ Rs 3500/- per MT of compost. On the contrary total expenditure of composting is Rs 9,24,757.20/-. So, composting is highly profitable component in the proposed system.

Total incinerable quantity is 438.56 MT/Day and total incineration cost is Rs 7,61,043.80/- which is quite high. As the incineration cost is high, same model is run without considering incineration to observe its effect on integrated solid waste management. In this case, rather than expenditure of Rs 4,31,460.60/- per day it generates earning of Rs 2,06,075.10/- per day. Since incineration cost is high therefore integrated solid waste management without incineration is apparently profitable. But without incineration generates more amount of landfill, and has some adverse impact on landfill life i.e. cost of land. As landfill quantity is increased due to closure of incineration so landfill cost is also increased by ~27%. Higher amount of landfill generates more amount of leachate i.e. chances of water pollution is more. So, considering sustainability, it is suggested that, higher calorific value materials should be incinerated with proper air pollution equipment.

So far in integrated SWM, though the O&M cost of incineration and compost plant is high but revenue earning for recyclable and compost reduces the cost of solid waste management by 46% than the existing model. Composting facility and sorting facility must be operated.

If proposed integrated model is run with full capacity of incineration and composting, 60% running vehicular efficiency and enhanced cost, quantity of sorter feed for garbage sorting at engineered landfill sites of ‘D’, ‘N’ and ‘S’ are 1467.14 MT/day (56.34%), 592.82 MT/day

(22.76%) and 544.34 MT/day (20.9%) respectively. Since ‘D’ ELF site is nearer to most of the boroughs, major portion goes to this site to minimize the transportation cost. Due to the same reason quantity of waste from boroughs in north mostly goes to their nearest ELF site ‘N’ and boroughs in south mostly goes to southern ELF site ‘S’. Compost plants adjacent to ‘D’, ‘N’ and ‘S’ take 1003.82 MT/day, 405.6 MT/day and 372.44 MT/day. This model is forced to take the maximum incineration feed and it takes 247.07 MT/day, 99.83 MT/day and 91.67 MT/day for ‘D’, ‘N’ and ‘S’.

When the integrated SWM system operates along with fully functional three integrated facilities, the capacity of sorter should be ~57 to 62% at ‘D’, ~22 to 27% at ‘N’ and ~21 to 26% at ‘S’ of the total sorter feed amount. Incineration capacity at ‘D’, ‘N’ and ‘S’ should be 10-15%, 4-8% and 4-8% of the total sorter feed amount. Composting capacity at ‘D’, ‘N’ and ‘S’ should be 39 - 44%, 16 - 21% and 15 - 20% of the total sorter feed amount. Capacity of the landfill at ‘D’, ‘N’ and ‘S’ should be ~20 to 25%, 7 to 12% and 6 to 10% of the total waste generation considering certain flexibility. So, with this methodology capacity of different units of integrated MSW management for proposed plan can be set successfully.

If incineration amount is reduced @ 10% i.e. from 100% to 50% then incineration cost per day has been reduced by ~50% (from Rs. 7,61,044/- to Rs. 3,81,769/-) because of the reduction of incinerable amount from 438.59 MT (100%) to 220 MT (50%) per day and cost of ELF is increased by ~19% (from Rs 1,99,521/- per day to Rs 2,36,484/- per day) as the unburnt incinerable amount goes to landfill as additional dumpable quantity. Due to these combine effects total cost of SWM is decreased by ~25% (from Rs. 12,96,051/- per day to Rs. 9,78,328/-).

If composting amount is reduced @ 10% i.e. from 100% to 50% then composting cost per day has been reduced by ~50% (from Rs 9,24,757/- to Rs 4,62,416/-) because of the reduction of compostable amount from 1781.86 MT (100%) to 891.00 MT (50%) per day. Revenue from compost decreases by ~50% (from Rs 16,57,038/- per day to Rs 8,28,585/- per day). Therefore, cost of ELF is increased by ~71% (from Rs. 1,99,521/- to Rs. 3,41,541/- per day) due to additional dumpable quantity to ELF. No changes are found in incineration, transportation and incentive cost. Due to these combine effects total cost of SWM is substantially increased by ~45% (from Rs. 12,96,051/- to Rs. 18,82,935/- per day). So, attention should be paid for proper running of compost plants.

In case SWM system runs with full capacity of incineration but without composting facility the revenue from compost selling (@Rs 3,500/- per MT) is reduced from Rs. 16,57,038/- to Rs. 0/- per day. Revenue earning from total recyclable is reduced by ~22% (from Rs. 3,15,115/- per day to Rs. 2,46,692/- per day). Since additional amount goes to ELF, therefore, total operational cost of ELF is increased by ~2.5 times (from Rs. 1,99,521/- per day to Rs. 4,83,584/- per day). Because of the above facts as well as major revenue loss from composting, total cost is increased by ~2 times (per day from Rs. 12,96,051/- to Rs. 24,69,912/-). So, generation of compost should not be interrupted and market should be well developed for regular selling of the entire compost product.

One of the three ELF sites may have to be closed for certain period of time due to major maintenance, accidental failure, and some inadvertent situations like labour strike, natural calamities etc. If "D" is closed and "N" and "S" are in operation sorter feed, compost feed and incineration feed are shared by ~53% and ~47% and landfill amount is shared by ~46% and ~54% by "N" and "S" ELF sites depending on their location and cost of transportation. Total optimum cost will be 4.9% more than the normal situation.

For both the operations when only "N" is closed and only "S" is closed then "D" ELF site takes the major load (~80%) of the waste processing and landfill load (~80%). It indicates that location of ELF site "D' is in much favorable location than other two ELF sites. For these two cases total optimum cost will vary from 1.2% to 1.9% more than the normal situation.

In the optimized operation of proposed integrated MSW management system, 42% garbage is shared by the departmental vehicles and rest by hired vehicles. In this case total SWM cost is Rs 12,96,051/- per day.

When garbage carrying ratio of departmental vehicles changes from maximum 60% to minimum 15% and rest by hired vehicles, daily transportation cost of departmental vehicles including incentive is increased from Rs. 2,77,836/- for 15% of garbage sharing to Rs. 11,44,708/- for 60% of garbage sharing by departmental vehicles. This change is ~27% to ~76% of their respective total SWM cost.

For change of garbage sharing by departmental vehicles from 42% to 60%, total SWM cost is increased by ~16% (Rs. 2,06,007/- per day) and from 42% to 15%, total SWM cost is reduced by ~21% (Rs. 2,75,265/- per day).

If waste generation is increased by 5%, total SWM cost is increased by ~3% and if its generation is reduced by 5%, total SWM cost is reduced by ~2.5%. So, proper attention should be paid for estimation of waste generation.

An Effect of ±1% variation of recyclable quantity on revenue from recyclable is ±17.4% and on total cost –4.5% to +4.5%. Impact of recyclable quantity on total SWM cost is substantial for the recovery of maximum quantity of recyclable.

An effect of ±1% variation of compostable quantity, revenue from compost is ±1.5% and total cost is –1.3% to +1.3% as revenue earning increases because of increase of compostable quantity. Effects of ±1% variation of incinerable amount, incineration cost and total cost varies ±6.2% and ±3.2% respectively. This impact is high on both the cost components because of the higher operation and maintenance cost of incineration unit.

An effect of ±5% variation of fuel cost, Total optimum cost changes only by ±0.25%. If fixed running cost increases by 10% then total optimum cost is increased by ~4% and vice versa. Fixed running cost has significant effect on transportation cost of departmental vehicles. If fixed idle cost increases by 10%, then total optimum cost is increased by ~1.5% and vice versa and observed moderate effect on transportation cost. For variation of incentive rates by ±10%, total SWM cost varies ±0.08%. Though it has negligible effect on total cost of SWM yet incentive plays an important role to increase garbage removal efficiency. An effect of variation (±5%) of transportation cost of hired vehicles, total transportation cost varies ±2.2% and total optimum cost varies ±2.3% which is significant.

If revenue cost of compost is increased by 5%, total SWM cost decreases by ~6.4% and vice versa. Operation and maintenance cost of compost plant if increases by 5%, total SWM cost is increased by ~3.5% and vice versa. Both revenue and O & M cost of compost processing unit have major impacts on total SWM cost. If operation and maintenance cost of incineration plant is increased by 5%, then total optimum cost is increased by ~2.9% and vice versa which is significant. An effect of ±5% variation of O & M cost of ELF total SWM cost varies ±0.8%. However, it has no effects on other costs.

6.3 POLLUTION MINIMIZATION POTENTIAL OF INTEGRATED MSW MANAGEMENT

6.3.1 Air Pollution Reduction from Transport Sector

From the study it is found that in the proposed integrated MSW management model (reference 6.2.2) cost of fuel used by the departmental vehicle is 21% less than the existing MSW management model. Cost of fuel in the existing MSW management model is Rs. 55,039/- per day and in the proposed integrated MSW management model is Rs. 43,612/-per day, which is ~21% less. This is due to less distance travel by the departmental vehicles to dispose the garbage at the nearest of the three ELF from different boroughs. The consumption of fuel is proportional to the cost of fuel and the emission of air pollutants is proportional to the fuel combusted. So in the proposed integrated MSW management system from departmental vehicles ~21% less air pollutants will be emitted.

Cost of transportation by the private (hired) vehicles in the existing MSW management model is Rs.2,63,651/- per day and the same in the proposed integrated MSW management model is Rs. 2,52,699/- per day, which is ~4% less. It indicates that in the proposed integrated MSW management system ~25% of air pollution reduction possibility is there from the waste transportation sector (by departmental and private vehicles) than the existing MSW management system. Total optimum cost for SWM in the proposed integrated MSW management system is also ~46% lower than the existing MSW management system.

In integrated MSW management system additional 15 to 20% more air pollution reduction is possible by introduction of better fuel efficient higher stage vehicle (e.g. Bharat stage VI) and improved vehicle maintenance (ICCT Policy Update, 2016; Bishop, 2000).

6.3.2 Air Pollution Reduction from Landfill

In the existing MSW management system after sorted out 9.21% recyclable from garbage (90% of total waste) and converting 5 to 6% of the garbage to compost, the rest 85.79% of garbage i.e. (85.79× 0.9) % of the total waste and silt or rubbish (10% of the total waste) i.e. total (10 + 85.79 × 0.9) % or ~87 to 90% of mixed waste (organic + inorganic) is being disposed to Dhapa dumping ground without any liner, leachate collection and proper top cover system (reference 4.13).Height of the landfill is around 20 m. Due to anaerobic action huge quantity of landfill gas, mainly methane (47.7%) and carbon dioxide (47%) are being generated. These are major greenhouse gases which are responsible for global warming. Apart from these some amount hydrogen sulfide (0.01%) and small amount of highly toxic VOCs are also generated, which are highly detrimental to the health of landfill workers. In the existing system total estimated methane emission is ~9,48,477 MT i.e. 1,99,18,017 MT CO_2-eq (ref. 4.9.5).

If gas is collected from existing dumping ground, 3 MW power generations is possible for 10 years (reference section 4.9.5). During this 20 years active period amount of methane emitted in the atmosphere is about [9,48,477 (generated) - 1,82,210 (entrapped)] MT i.e. 7,66,267 MT i.e. 1,60,91,607 MT CO_2-eq (19% reduction). Possible methane recovery is 91,105 MT and if it is flared then the certified emission reduction (CER) will be 19,13,205 tCO_2-eq.

In transition period, between existing and integrated waste management system, when phase wise (10 years + 10 years) garbage disposal will be done in the ELF, then [23,89,785 (generation) – 7,37,874 (entrapment)] MT i.e. 31% methane emission reduction will be possible which is equivalent to 1,54,95,354 MT CO_2-eq. 5,53,410 MT of methane will be captured which will support 10 MW of power plant for 20 years and CER value will be 1,16,21,610 tCO_2-eq (Ref. 4.9.5.2).

In the integrated MSW management system only inert will go to engineered landfill after segregation and treatment. In this system ~33% of the inert material of the total waste will be disposed in the engineered landfill. So there will be no gas generation from ELF (Ref. section 4.12).

6.3.3 Comparison of Gaseous Emission from MSW between Existing MSW Management System and Proposed Integrated MSW Management System (Except Transport Sector)

At present the disposal of MSW in developing countries and in some of the developed countries is heavy reliant on landfills. Open uncontrolled dumping is the most common method of waste disposal in the developing countries and is slowly changing towards engineered landfill. Other waste treatment and disposal technologies (i.e. material recycling, incineration, composting etc.) have not been widely used in the developing world.

In Kolkata garbage is 90% of the total MSW and the rest 10% is the inert silt or rubbish. In existing system 9.21% of recyclable is sorted out from garbage. Ignoring the small amount of compost production and its consequent gas generation, rest (100 – 9.21) % i.e. 90.79 % of garbage is disposed in Dhapa dumping ground. So, out of 100 MT of garbage 90.79 MT is producing gaseous pollutants like CH_4 (47.7%), CO_2 (47%), H_2S (0.01%) $^{v}/_{v}$ and small amount of toxic VOCs.

In the proposed integrated MSW management system out of 100 MT of garbage 14.5 MT is incinerated (reference table 4.34 of section 4.13) and 50.56 MT is converted to compost (reference table 4.35 of section 4.13). Major gases from incinerator are CO_2, NO_2 and SO_2 and from compost process are CO_2, CH_4, NO_2 and NH_3. So, comparison of gas generation between two systems is required for proper evaluation of the systems.

6.3.3.1 Gas Generation from 100MT of Garbage in the Existing MSW Management System

From section 4.9 it is clear that Triangular gas production model is almost same as mean value of all methods and it gives total amount of gas generation considering specific garbage composition. As per triangular method considering the specific garbage total landfill gas generation is $150m^3$/ton (reference section 4.9.4.2).

Amount of CH_4 generation from 1MT of garbage is $(150 \times 47.7/100) = 71.55\ m^3$.
Volume of 16 g of CH_4 at 25ºC = $(0.0224 / 273) \times 298 = 0.02445\ m^3$
So, $71.55\ m^3$ of CH_4 at 25ºC = $[(16/24.45) \times 71.55]$ kg = 46.82 kg of CH_4/ MT of garbage

Amount of CO_2 generation from 1MT of garbage is $(150 \times 47/100) = 70.50\ m^3$.
Volume of 44 g of CO_2 at 25ºC = $(0.0224 / 273) \times 298 = 0.02445\ m^3$
So, $70.50\ m^3$ of CO_2 at 25ºC = $[(44/24.45) \times 70.50]$ kg = 126.87 kg of CO_2/ MT of garbage

Amount of H_2S generation from 1MT of garbage is $(150 \times 0.01/100) = 0.015\ m^3$.
Volume of 34 g of H_2S at 25ºC = $(0.0224 / 273) \times 298 = 0.02445\ m^3$
So, $0.015\ m^3$ of H_2S at 25ºC = $[(34/24.45) \times 0.015]$ kg = 0.021 kg of H_2S/ MT of garbage

So, from 100 MT of garbage generation ≡ 90.79 MT garbage in landfill, the amount of gas generations are:
Amount of CH_4 generation from 90.79 MT of garbage is $(46.82 \times 90.79/1000)$ MT = 4.25 MT
Amount of CO_2 generation from 90.79 MT of garbage is $(126.87 \times 90.79/1000)$ MT = 11.52 MT
Amount of H_2S generation from 90.79 MT of garbage is $(0.021 \times 90.79/1000)$ MT = 0.002 MT

6.3.3.2 Gas Generation from 100MT of Garbage in the Proposed Integrated MSW Management System

(a) Gas generation from incineration

Out of 100 MT of garbage, 14.5 MT is incinerated directly after pre-sorting (reference table 4.34 of section 4.13).

Material balance, physical and chemical compositions of incinerated waste (after pre-sorting) are given in table 6.27.

Table 6.27 Physical and chemical composition for incinerated waste (Tchobanoglous et.al., 1993)

Composition for Thermal Processing after presorting		Typical ultimate analysis % dry basis					
		C	H	O	N	S	Ash
Paper	1.07	43.5	6	44	0.3	0.2	6***
Rubber & Leather	0.34	69	9	5.8	6	0.2	10
Rags	1.87	55	6.6	31.2	4.6	0.15	2.5
Wooden Matter	1.15	49.5	6	42.7	0.2	0.1	1.5
*Coconut	4.5	49.6	6.1	43.2	0.1	0.1	0.9
**Bones	0.16	60	8	11.6	10	0.4	10
Compostable	3	48.6	6.4	37.6	2	0.4	5
Inert	2.41	26.3	3	2	0.5	0.2	68
TOTAL	14.5						

** ultimate analysis same as hard wood* *** ultimate analysis same as leather* **** ultimate analysis average of rubber & leather*

The analysis of chemical composition of incinerated waste based on dry weight and ultimate analysis is given in table 6.28.

Table 6.28 Analysis of chemical composition for incinerated waste

Component	Moist Mass (ton)	Moisture Content (*w*%)	Dry Mass (ton)	Chemical Components (ton)					
				C	H	O	N	S	Ash
Paper	1.07	6	1.01	0.440	0.062	0.440	0.003	0.002	0.063
Rubber & Leather	0.34	5	0.32	0.220	0.029	0.019	0.019	0.001	0.032
Rags	1.87	10	0.19	0.101	0.014	0.060	0.009	0.000	0.006
Wooden Matter	1.15	25	0.86	0.426	0.052	0.366	0.002	0.001	0.013
Coconut	4.5	40	2.7	1.340	0.165	1.166	0.003	0.003	0.023
Bones	0.16	5	0.15	0.090	0.012	0.017	0.015	0.001	0.015
Compostable	3	72.5	0.825	0.401	0.053	0.310	0.017	0.003	0.041
Inert	2.41	22	1.88	0.494	0.056	0.038	0.010	0.004	1.278
TOTAL	14.5		7.935	3.512	0.443	2.416	0.078	0.015	1.471

Amount of moisture = (moist mass - dry mass) = 6.565 ton
Hydrogen component from water = 0.729 ton
Oxygen from water = 5.836 ton

After availability of values of chemical components the approximate chemical formula can be determined and shown in Table 6.29.

Table 6.29 Determination of approximate chemical formula for incinerated waste

Component	Mass (ton)	M.W.	Moles	Mole Ratio (S = 1)
Carbon	3.512	12.011	0.292	584
Hydrogen	1.172	1.0079	1.163	2326
Oxygen	8.252	15.9994	0.516	1032
Nitrogen	0.078	14.0067	0.006	12
Sulfur	0.015	32.066	0.0005	1

$C_{584}H_{2326}O_{1032}N_{12}S$

Apart from major gases like CO_2, NO_2, and SO_2, incinerators burning MSW can also produce a number of pollutants in the flue gas in varying concentration like carbon monoxide, particulate matter containing heavy metal compounds and dioxins due to incomplete or partial combustion. So, complete combustion along with air pollution control equipment is necessary. Major gas generations, considering complete combustion, during incineration are shown below.

Amount of CO_2 generation from complete combustion is [(44/12) ×3.512] MT= 12.88 MT;
Amount of NO_2 generation from complete combustion is [(46/14) × 0.078] MT= 0.256 MT;
Amount of SO_2 generation from complete combustion is [(64/32) × 0.015] MT = 0.03 MT.

(b) Gas generation from composting process

Out of 100 MT of garbage, 50.56 MT is converted to compost directly after pre-sorting and rejecting the compost process rejects (reference table 4.35 of section 4.13).

Researchers show that major gases generated from windrow composting are CO_2, CH_4, N_2O and NH_3. N_2O after oxidation is converted to NO_2.

Following are the generation rate of gases from windrow composting of MSW (Clemens and Cuhls, 2003).

CO_2 generation rate ranges from 0.63 to 413 kg/MT of waste. So, average CO_2 generation rate is 206.82 kg/MT of waste.

CH_4 generation rate ranges from 6 to 12 kg/MT of waste. So, average CH_4generation rate is 9 kg/MT of waste.

NH_3 generation rate ranges from 0.018 to 0.115 kg/MT of waste. So, average NH_3 generation rate is 0.0665 kg/MT of waste.

N_2O generation rate ranges from 0.00144 to 0.378 kg/MT of waste. So, average N_2O generation rate is 0.19 kg/MT of waste.

After oxidation N_2O converted to NO_2 [$N_2O \rightarrow 2NO_2$]. So from 44 g of N_2O, 92 g of NO_2 is produced. So, average NO_2generation rate is [0.19 × (92/44)] i.e. 0.4 kg/MT of waste.

So, from 50.56 MT of compostable material amount of major gases from windrow composting are given below.

Amount of CO_2 emission from windrow composting is [(206.82 × 50.56)/1000] MT = 10.46 MT;

Amount of CH_4 emission from windrow composting is [(9 × 50.56)/1000] MT = 0.46 MT;

Amount of NO_2 emission from windrow composting is [(0.4 × 50.56)/1000] MT = 0.02 MT;

Amount of NH_3 emission from windrow composting is [(0.0665 × 50.56)/1000] MT = 0.0034 MT.

6.3.3.3 Comparison

Comparison of major gaseous emissions from MSW between existing MSW management system and proposed integrated MSW management system is shown in Table 6.30.

Table 6.30 Comparison of major gaseous emissions from MSW between existing and proposed integrated MSW management system

Major gases	Gaseous emission from existing MSW management system (in MT)	Gaseous emission from proposed integrated MSW management system (in MT)	Remarks
CH_4	4.25	0.46	89% (reduction from existing)
CO_2	11.52	(12.88+10.46) = 23.34	103% (increase from existing)
H_2S	0.002	-	
SO_2	-	0.03	
NO_2	-	(0.256+0.02) = 0.276	
NH_3	-	0.0034	
Total	15.772	24.11	53% (increase from existing)

Overall gaseous emission in the proposed integrated MSW management system is increased by 53% (table 4.12) from the existing because of higher CO_2 emission (103% increases from existing) both from incineration and composting. CH_4emission, one of the potential GHGs, is reduced by 89% from the existing system, which is a substantial amount. CH_4 is 21 times more potential as greenhouse gas than CO_2.

So, certified GHG emissions CO_2 equivalent from 100 MT of garbage for existing MSW management system is (4.25 × 21 + 11.52) MT = 100.77 MT

Certified GHG emission as CO_2 equivalent from 100 MT of garbage for proposed integrated MSW management system = (0.46 × 21 + 23.34) = 33 MT

GHG emission reduction in proposed integrated MSW management system than existing is [(100.77 MT – 33 MT) / 100.77] × 100 = 67.3%, which is a substantial amount.

6.3.4 Water Pollution Reduction from Landfill

At present in the existing MSW management system, after sorted out some amount of recyclable (9.21% of garbage) and converting 5 to 6% of the garbage to compost, rest garbage and silt i.e. ~87 to 90% mixed waste is being disposed to Dhapa dumping ground without any liner, and gas collection system (reference 4.13). At present around 900 to 1000 L/$m^2$of leachate is being generated every year from the existing landfill site. It contains high organic and inorganic materials (reference 4.10.3). This leachate, having heavy pollution load,is polluting the surrounding water bodies and the precious ground water in and around the landfill siteDhapa. Unless proper top cover is used during post-closure, heavy metal pollution is going to persists in ground water for prolonged period of time (reference 4.10.5).

Phase wise (two phase, each having 10 years) landfilling during transition period will reduce the leachate generation by ~33% during active period and ~54% during post closure period (reference 4.10.3.2 a). Use of a complete top cover system, i.e. use of vegetative cover, top vegetation soil cover (45 cm) to support vegetation, sand layer (15 cm) for drainage and barrier clay layer (60 cm), at post closure will reduce the leachate generation by ~96% (reference 4.10.3.2 c) i.e. ~43 L/m^2/year. At this level of leachate generation EPACMTP shows most of the metals and organics concentrations will be within the safe limit in ground water (reference 4.10.5.2).

In integrated MSW management system engineered landfill will proper bottom liner with leachate collection system will be provided. Leachate will be collected and treated during active period as well as post closure period of landfill. A complete final cover will be provided after closure to minimize leachate generation i.e. to minimize ground water pollution. In this system only ~33% of the inert material of the total waste will go to engineered landfill after segregation and treatment (reference 4.13).So in the integrated system direct reduction of leachate generation is [{(87- 33)/87}× 100] % i.e. ~62%. Phase wise disposal will further reduce the leachate generation about 33% on the remaining 38% during active period. So during active period over all leachate generation will be around (38 × 0.67)% i.e. ~25.5%. It indicates around 75% leachate generation reduction will be possible during active period from the existing MSW management system. During post closure period in the proposed integrated system, complete top cover system will further reduce the leachate generation by ~96% on the remaining 38%, i.e.leachate generation will be (38 × 0.04) % i.e. ~1.5%. So during post closure period of integrated system, around 98.5% leachate generation reduction will be possible than the existing system.

As only inert will be disposed in the landfill during proposed integrated system, compare to mixed waste in the existing system, leachate quality will also improve substantially. Though leachate treatment facilities will be there, yet pollutant transport study indicates all the metals and organic pollutants will be well within the safe limit in the surrounding water resources.

6.3.5 Land Pollution Reduction Possibilities

In the existing MSW management system 87% mixed waste is being disposed in the Dhapa dumping ground without any liner, leachate collection and treatment and gas collection system. It is polluting the disposal ground and surroundings. More amount of valuable land resource is being utilized for waste management and the land itself becomes a source of pollutants for the surroundings. Since long farmers of the cultivated land around the disposal ground are utilizing unofficially a portion of untreated garbage directly as a soil enhancer. It increases the chances of heavy metal pollution in the food chain and consequent bio-magnification.

6.3.5.1 Land Area Requirement for the Existing MSW Management System

From the existing MSW management system if garbage generation quantity is 1000 TPD, minimum amount of mixed waste disposed for landfill is considered as 870 TPD.

[In the existing MSW system 9.21% recyclable materials is taken out by the informal rag pickers and only around 5 to 6% of the garbage is converted to compost. So 85.79% of garbage i.e, (85.79×0.9) % of the total waste and silt or rubbish (10% of the total waste) i.e, (10 + 85.79 × 0.9) % or ~87.2% mixed waste (organic + inorganic) is being disposed.**]**

For 1000 TPD capacity ELF facility, area requirement is 67 ha. Detail land area calculation is shown in Annexure 6.21.1.

So, land area requirement for 870 TPD capacity is [(67/1000) × 870] = 58.29 ha

So, from the existing MSW management system if garbage generation quantity is 1000 TPD, land requirement is 58.29 ha.

6.3.5.2 Land Area Requirement for the Proposed Integrated MSW Management System

In the proposed integrated MSW management system for 1000 TPD garbage generation total capacity of the central sorter will be 950 TPD, total capacity of incinerator will be 160 TPD and total capacity of windrow compost plant will be 650 TPD (reference section 4.13 and fig 4.41). In this system 33% of inert material i.e. 330 TPD will be the inert landfill amount for ELF if generation of garbage is 1000TPD.

[In the proposed integrated MSW management system, silt or rubbish which is ~10% of the total waste and 25.661% inert (15% inert + 1.471 incinerator ash + 9.19 inorganic process reject from compost plant) from garbage (which is ~90% of the total waste), will be disposed in the engineered landfill. So, in this system (10 + 25.661 × 0.9) % i.e. ~33% of the inert material of the total waste will be disposed in the engineered landfill (reference section 4.13 and fig 4.41).]

So, in the proposed integrated MSW management system total land area requirement have to be calculated considering sorter, incinerator, compost plant along with engineered landfill.

(a) Sorter

For 1000 TPD capacity material sorting facility, area requirement is ~2.5 ha. Detail analysis is shown in Annexure 6.21.3.

So, land area requirement for 950 TPD capacity sorter plant is [(2.5/1000)×950] = 2.38 ha.say 2.5 ha.

(b) Incinerator

Total land area required for 600 TPD capacity incineration plant is 2.4 ha (KMC, 2017)

So, land area requirement for 160 TPD capacity incineration plant is [(2.4/600) × 160] = 0.64 ha say 1 ha.

(c) Compost plant

For 1000 TPD capacity windrow compost plant land area requirement is ~14 ha. Detail analysis is shown in Annexure 6.21.2.

So, land area requirement for 650 TPD capacity windrow compost plant is [(14/1000) × 650] = 9.1 ha. say 10 ha.

(d) Engineered landfill

For 1000 TPD capacity ELF facility, area requirement is 67 ha. Detailed calculation is shown in Annexure 6.21.1. So, land area requirement for 330 TPD capacity is [(67/1000) × 330] = 22.11 ha. Say 23 ha.

6.3.5.3Land Area Reduction for Proposed Integrated MSW Management System

Total land area requirement for proposed integrated MSW management facilities (sorter, incineration, composting and engineered landfill) will be (2.5+1+10+23) ha. i.e. 36.5 ha. when garbage generation will be 1000 TPD

Area reduction is [(58.29 – 36.5) / 58.29] × 100% i.e. 37%

So, in the proposed integrated MSW management system reduction in total land area requirement will be 37% which will be a substantial amount cost and valuable land resource saving. In this ELF only inert will be disposed. So, leachate quantity will be reduced and quality will be improved and furthermore it will be collected and treated before discharge. It will reduce the possibility of pollution from leachate substantially. As good quality of compost will be produced and will be used also by local farmer for enhancing the fertility of surrounding agricultural land so, there will be no chance of heavy metal pollution in the soil and food chain.

Above studies indicates substantial amount of pollution reduction possibilities are there in the proposed integrated MSW management system than the existing system. So, integrated MSW management system not only provides cost effective management but also offer less polluted solution. The study conclusively delivers a methodology to achieve a sustainable solution of MSW management system in developing countries like India.

Chapter 7

7. CONCLUSIONS

7.1 CONCLUSIONS

The huge generation of MSWand its improper management, especially in developing countries, has become a life-threaten issue for the society as the urban local bodies, though committed to their services, are finding it difficult to manage properly due to higher generation, lack of awareness and socio-economic constraints.Improper management and crude dumping of MSW leads to high emission of GHGs like CH_4, CO_2 and other toxic gases, huge generation of highly polluted leachate and degradation of natural resources like air, water and land. It has been realized gradually that existing conventional MSW management is unable to satisfy the goal of sustainable development. Integrated MSW management system is a need of the hour to achieve this goal, and there is a concerned effort to develop a methodology to find optimized path to shift towards integrated MSW management approach. In a developing country like India, a major metropolitan city Kolkata is considered for developing this methodology.

In existing MSW management system of Kolkata no source segregation, 60% house-to-house collection, 50-55% open vats, 50% operational efficiency of KMC transport system with 30-35% old vehicles, 80% old hired vehicles, informal recycling system,uncontrolled land disposalwithout having liner and leachate management facility are the most pressing problems of the city today which causes a number of environmental and human health hazards.With a target of source segregation, 100% collection, transportation, treatment and disposal, municipal authority would need to prepare a macro plan which identifies the broad strategy to be adopted to manage the MSW management system sustainably.

In developing countries as money and social awareness are constraints, immediate switching to effective integrated MSW management is extremely difficult. There will be a substantial amount of transition period between these two extreme phases. In the transition period, while developing the source segregation and other waste treatment facilities for integrated system, mixed waste will be disposed in the newly built engineered landfill, where along with leachate collection and treatment facilities, gas collection facilities will also be there.

A significant amount (3106 MT/year) of air pollutants is generated from existing MSW transportation sector of Kolkata. A major greenhouse gas CO_2 emission is the largest (97.84%) then NOx emission is the second largest (1.17%) and other major air pollutants are CO (0.66%), HC (0.19%), PM (0.12%) and SOx (0.02%).

Solid waste management is one of the largest essential service sectors and needs considerable manpower. The noise pollution study on existing situation reveals that the group of workers worst affected are the drivers and laborers of bulldozer; pay-loader fed tipper truck and manually loaded tipper truck. All the waste carrying vehicles except new dumper placer are higher than the permissible noise level and replacement of an old dumper placer by a new one effectively reduces noise level by ~20% in dB(A) scale.

For estimation of landfill gas in Triangular model, 75% biodegradable portion of RBW and 50% biodegradable portion of SBW are recommended. In IPCC model, DOC and *k* value in food waste are highly sensitive in total methane generation and recovery due to its higher percentage in the garbage. In LandGEM model, suggested values of *k*and L_0 are 0.1 y^{-1} and 70 m^3 t^{-1} respectively.

Site specific composition of MSW for Triangular model results close to the average value of CH_4 recovery. As IPCC is a conservative model to ensure the profit from CDM benefit, it usually gives lower value. LandGEM is very much sensitive to $L_0$and *k* values and compare to other models, CH_4 generation will continue for some more time after closure, which predicts higher recovery. So, the gas generation from MSW in the developing country like India, where bio-degradable and inert wastes are high, 40% weightage to Triangular model and 30% each for IPCC and LandGEM model is recommended.

For existing system, 5×10^9 MJ energy can be recovered for 10 years period after scientific closure of the existing open dump site, Dhapa, and installed plant capacity would be limited to only 3 MW. So, flaring of methane is the suitable option considering economic and commercial non-viability of power generation.From the CDM project profit of KMC, apart from environmental benefit, is around 10.2 crores for 10 years.

During transition period introduction of the engineered landfill with phase wise closure facilities,with 75% gas recovery efficiency, results reduction of additional 49,74,456 tCO_2-eq.

From proposed ELF having CER value of 1,16,21,610 tCO_2-eq, 3.5×10^{10} MJ energy likely to be available and 10MW commercially viablepower plants could be supported for 20 years.

HELP model analysis for Kolkata with sufficient precipitation especially during monsoon with unlined landfill sites is generating ~ (900-1000) L/m^2/year i.e. ~ 2.14×10^8 L/year leachate from Dhapa. A minimum of 60 cm vegetative soil cover or barrier clay cover reduces leachate generation by 54% and 73% respectively. Use of a complete top cover system, i.e. use of vegetative cover, top vegetation soil cover (45 cm) to support vegetation, sand layer (15 cm) for lateral drainage and barrier clay layer (60 cm), at post closure reduces the leachate generation by ~96% i.e. only ~43 L/m^2/year generation.

Phase-wise landfilling operation is recommended during transition period as it decreases leachate generation by ~33 % even during active period.

EPACMTP model analysis shows that metal concentration appears in the receptor well after a lag period and then increases rapidly to its peak and remains for several hundred or thousand years. Peak concentration of organics on the other hand remains for around 25 years after the closer of the landfill and then starts decreasing, as by then the waste almost gets stabilized. Therefore during the active period use of bottom liner, leachate collection and treatment are necessity. Maximum life of liners is 50-100 years. After that landfill will remain a threat to groundwater quality for long period from heavy metals point of view. So, in the post filling period, complete cover system is recommended for reduction of leachate generation by ~96% to prevent contamination of precious groundwater due to solid waste disposal.

A generic MSW management linear programming (LP) model is developed considering its different components and economics. Then it is applied to the existing MSW management system and validated. In the next step it is applied for the proposed integrated MSW management system. These two systems are compared to achieve optimized cost effective sustainable solution methodology of MSW management system for developing countries like India.

The MSW management LP model is applied to the specific existing system with the data of Kolkata. Ratio of total quantity of waste i.e. garbage and silt or rubbish actually transported by departmental vehicles and hired vehicles is 33:67 whereas from model it is found ~ 37:63. In respect of only garbage disposal, in present practice the ratio is found as 37:63 where as in the model it is 42:58. In existing model departmental vehicles prefers to carry 5% excess waste than the existing practice. Average departmental vehicle running efficiency is only 50% and it should be improved to minimize cost.

Hired vehicles need ~35.8% of the total transportation cost to remove ~63% of total waste quantities. Though hired vehicles are more cost effective yet departmental vehicles are also needed to meet local constraints and better control over the MSW management system.

The validation of the LP model for existing scenario with actual data shows very good results (± 10%) and it indicates ~7% cost minimization is possible in the existing scenario.

Further optimization of number of departmental vehicle shows~27% cost reduction in total transportation cost and ~19% of total cost minimization is possible in the existing scenario only by reducing the excess number of departmental vehicles to its minimum requirement.

Since the number of idle vehicle varies due to change in vehicle running efficiencies, fixed idle cost increases when running efficiency decreases and vice versa. As the 50% departmental vehicle running efficiency is on lower side, considering work culture and inadequate infrastructure for developing countries, 60% vehicle running efficiency may be considered by which ~3.2% overall cost savings is possible.

Running of departmental vehicle is costly and in existing situation 42% of garbage is carried by departmental vehicle. If the garbage carrying percentage by departmental vehicles reduces from 35% to 15%, total cost is reduced from ~3% to ~9% compared to existing optimized result. Similarly, if the garbage carrying percentage by departmental vehicles increases from 45% to 60%, total cost is increased from ~2% to ~5% w.r.t. existing optimized result.

Rate increment in incentive has negligible effect on total cost. However, garbage clearance efficiency by departmental vehicle can be increased by increasing incentive.Fixed running cost and idle cost of departmental vehicles have significant effect on transportation cost of departmental vehicles, so vehicle maintenance staff should be selected judiciously for careful maintenance of the departmental vehicles.The transportation cost of hired vehicles has also significant effect on total SWM cost.So, proper attention should be paid for fixing and reviewing of zone wise transportation cost of silt and garbage for hired vehicle.

If waste generation is increased by 5%, total SWM cost is increased by ~4% and vice versa. It indicates variation of waste generation has major effects on the costs of solid waste management.

So, proper estimation of waste generation is very important for effective management and future planning of MSW.

In the next step proposed integrated MSW management LP model is successfully prepared and analyzed. These two systems are compared to achieve optimized cost effective sustainable solution methodology of MSW management system.

Total optimum cost for proposed integrated SWM model with same cost configuration is ~46% lower than the total SWM cost in existing optimized model.

In this system ~33% of the inert material of the total waste will be disposed in the engineered landfill.Though the ELF operation rate is high but total ELF running cost is ~21% less because of lesser amount of land filling.

In proposed model fuel cost of departmental vehicle is reduced by ~21% and transportation of hired vehicle is reduced by ~4%. Total transportation cost is ~6.5% less than the existing model because of lesser distances covered by the vehicles to transport waste to the nearest of three ELF sites in proposed model.

Total recyclable materials generate a substantial amount of revenue, so attention should be paid for source segregation and running of sorting facility for recovery of recyclables. Revenue from compost is ~1.8 times higher than its production cost, socomposting is a highly profitable component in the proposed system.So far in integrated SWM, though the O&M cost of incineration and compost plant is high but revenue earning for recyclable and compost reduces the cost of solid waste management by 46% than the existing model. So, generation of compost should not be interrupted and market should be well developed for regular selling of the entire compost productfor successful running of integrated MSW management system.

If incineration amount is reduced from 100% to 50% then due to reduction of incineration cost and increase of landfill cost, total cost of SWM is decreased by ~25%.If composting amount is reduced from 100% to 50% then due to decrease in revenue and O&M cost from compost plant and increase in landfill cost, total cost of SWM is substantially increased by ~45%.

Since incineration cost is high therefore integrated solid waste management without incineration is apparently profitable. But without incineration generates more amount of landfill quantity. As landfill quantity is increased due to closure of incineration so landfill cost is also increased by

~27%. Higher amount of landfill generates more amount of leachate i.e. chances of water pollution is more. So, considering sustainability, it is suggested that, higher calorific value materials should be incinerated with proper air pollution equipment.

Since ‘D’ ELF site is nearer to most of the boroughs, major portion goes to this site to minimize the transportation cost.When the integrated SWM system operates along with fully functional three integrated facilities, the capacity of sorter should be ~57 to 62% at ‘D’, ~22 to 27% at ‘N’ and ~21 to 26% at ‘S’ of the total sorter feed amount. Incineration capacity at ‘D’, ‘N’ and ‘S’ should be 10-15%, 4-8% and 4-8% of the total sorter feed amount. Composting capacity at ‘D’, ‘N’ and ‘S’ should be 39 - 44%, 16 - 21% and 15 - 20% of the total sorter feed amount. Capacity of the landfill at ‘D’, ‘N’ and ‘S’ should be ~20 to 25%, 7 to 12% and 6 to 10% of the total waste generation considering certain flexibility. So, with this methodology capacity of different units of integrated MSW management for proposed plan can be set successfully.

In the optimized operation of proposed integrated MSW management system, 42% garbage is shared by the departmental vehicles and rest by hired vehicles. For change of garbage sharing by departmental vehicles from 42% to 60%, total SWM cost is increased by ~16% and from 42% to 15%, total SWM cost is reduced by ~21%.

Like existing situation variation of waste generation; recyclable, compostable and incinerable quantity; fixed running and idle costs of departmental vehicles and waste transportation cost of hired vehicles have significant impact in the total integrated MSW management cost.

Apart from management and economic gain, pollution minimization potential study of proposed integrated MSW management system also shows encouraging result.

Departmental and private vehicles generate substantial air pollutants during waste transportation. In the proposed integrated MSW management system ~25% of air pollution reduction possibility is there from the waste transportation sector than the same forexisting MSW management system. Total optimum cost for SWM in the proposed integrated MSW management system is also ~46% lower than the existing MSW management system.

In the existing MSW management system ~87 to 90% of mixed waste is being disposed to Dhapa dumping ground without any liner, leachate collection and proper top cover system.Due to anaerobic action huge quantity of landfill gas, mainly methane (47.7%) and carbon dioxide (47%) are being generated along with some amount of hydrogen sulfide (0.01%) and small amount of highly toxic VOCs. Methane and carbon dioxide are major GHGs. In the existing system total estimated methane emission is ~9,48,477 MT i.e. 1,99,18,017 MT CO_2-eq .In transition period, between existing and integrated waste management system, when phase wise garbage disposal will be done in the ELF, then 31% methane emission reduction will be possible.In the integrated MSW management system only inert will go to engineered landfill after segregation and treatment. In this system ~33% of the inert material of the total waste will be disposed in the engineered landfill. So there will be no gas generation from ELF.

Apart from transport sector in existing system landfill generates huge amount of gases and in integrated MSW management system rather than landfill substantial amount of gases are generated from incineration and composting process. Comparison study shows that overall gaseous emission in the proposed integrated MSW management system is increased by 53% from the existing because of higher CO_2 emission (103% increases from existing) both from incineration and composting. On the contrary CH_4emissionis reduced by 89% from the existing system, which is a substantial amount. As CH_4 is 21 times more potential as greenhouse gas than CO_2, substantial amount overall GHG emission reduction (67.3%) can be achieved in proposed integrated MSW management system.

In the existing MSW management system~87 to 90% mixed waste is being disposed to Dhapa dumping ground from which~900 to 1000 L/$m^2$of leachate is being generated every year containing high organic and inorganic materials. This leachateis polluting the surrounding water bodies and the precious ground water in and around the landfill siteDhapa. Unless proper top cover is used during post-closure, heavy metal pollution is going to persists in ground water for prolonged period of time. Phase wise (two phase, each having 10 years) landfilling during transition period can reduce the leachate generation by ~33% during active period and ~54% during post closure period. Use of a complete top cover system at post closure will reduce the leachate generation by ~96% i.e. only ~43 L/m^2/year generation. At this level of leachate generation, EPACMTP shows that most of the metals and organics concentrations will be within the safe limit in ground water.

In integrated MSW management system engineered landfill will proper bottom liner with leachate collection system will be provided. Leachate will be collected and treated during active period as well as post closure period of landfill. A complete final cover will be provided after closure to minimize leachate generation i.e. to minimize ground water pollution. In this system only ~33% of the inert material of the total waste will go to engineered landfill after segregation and treatment. So in the integrated system direct reduction of leachate generation is ~62%. Adoptingphase wise disposal during active period over all leachate generation will be ~25.5%. It indicates around 75% leachate generation reduction will be possible during active period. During post closure period with complete top cover leachate generation will be ~1.5%. So during post closure period of integrated system, around 98.5% leachate generation reduction will be possible than the existing system. Because of only inert material present in the landfill, leachatequality will also improve substantially. Though leachate treatment facilities will be there, yet pollutant transport study using EPACMTP indicates all the metals and organic pollutants will be well within the safe limit in the surrounding water resources.

In the proposed integrated MSW management system reduction in total land area requirement will be 37% which will be a substantial amount cost and valuable land resource saving. Leachate quantity will be reduced and quality will be improved and furthermore it will be collected and treated before discharge. It will reduce the possibility of pollution from leachate substantially. As good quality of compost will be produced and will be used also by the local farmer for enhancing the fertility of surrounding agricultural land so, there will be no chance of heavy metal pollution in the soil and food chain.

Above studies indicates substantial amount of pollution reduction possibilities are there in the proposed integrated MSW management system than the existing system. So, integrated MSW management system not only provides cost effective management but also offer less polluted solution.

In this study existing MSW management system has been thoroughly analyzed for Kolkata, a metropolitan city of a developing country, India. A genericMSW management LP model has been developed considering its different components and socio-economic condition. Then it has been successfully applied, validated and studied in the existing situation and proposed integrated system. Results have been analyzed systematically to achieve optimized solution. The study conclusively has delivered a methodology to achieve a sustainable solution of MSW management system in developing countries like India.

7.2 FUTURE SCOPE OF WORK

Based on the scope and findings of the present investigation, the following suggestions are made for future studies.

1. The study can be extended using geographic information system (GIS) based management information system (MIS) for municipal solid waste management.

2. Potential environmental impact of all pollutants emitted from MSW management system can be estimated by Life Cycle Impact Assessment (LCIA) methodology or Waste Reduction Algorithm (WAR) methodology and compare between existing and proposed system.

3. Multi-objective optimization model considering competing objectives like SWM cost, pollutants emission etc. may be adopted in the future study.

4. Social and environmental cost benefit analysis of MSW management can be done in future study.

5. In future Life Cycle Assessment study of MSW management can be used as an important tool for future sustainable planning.

6. At present some compacters are introduced in the MSW management system of KMC area. It can be incorporated in the future study.

7. In the future study energy generation potential from thermal processing and bio-processing can be incorporated in the model.

8. In the present model primary collection is considered as a fixed cost and waste transportation is considered from borough centers. In future model ward level primary collection optimization and then borough level optimization can be connected for the study.

9. Industrial and bio-medical waste management can also be incorporated in future along with MSW management.

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Annexure 4.1:

Table A-4.1 Population of the Boroughs (upto 2035)

Year	Cluster I - Borough I to IX	Cluster II - Borough X to XV	Total (Borough I to XV)
2001	2927122	1653422	4580544
2003	2925748	1695905	4621653
2005	2924370	1738385	4662755
2007	2920377	1783058	4703435
2009	2916387	1827730	4744117
2011	2912394	1872403	4784797
2013	2907765	1917068	4824833
2015	2903133	1961729	4864862
2017	2899166	2005886	4905052
2019	2895200	2050042	4945242
2021	2891233	2094199	4985432
2023	2887555	2138119	5025674
2025	2883873	2182035	5065908
2027	2880538	2225762	5106300
2029	2877204	2269489	5146693
2031	2873869	2313216	5187085
2033	2870918	2356781	5227699
2035	2867963	2400341	5268304

Annexure 4.2:

4.2 SAMPLE CALCULATION OF BOROUGH WISE EMISSION STATUS FROM DUMPER PLACER BIG (7m^3) DEPARTMENTAL VEHICLE:

Total waste carried by departmental vehicle i.e., DP (big), DP (small), Hand load & Pay loaded vehicles is 124.17 MT/Day (Table 4.10). DP (Big) vehicle carries 33.47% of total waste carried by departmental vehicle i.e. [(33.47/100) × 124.17] = 41.56 MT/Day.

Average weight carrying capacity of DP (big) vehicle is 2.8 MT/Trip (Table 4.9). But actual weight carried by DP (Big) vehicle is 2 MT/Trip. So, no of trips per day = (41.56 MT/Day / 2 MT/Trip) = 20.78 Trips/Day (Table 4.10).

Total distance covered by DP (Big) vehicle = no of trips/day × distance from borough to disposal site Dhapa × 2 = 20.78 ×9 × 2 = 374.04 KM/Day (Table 4.10).

4.2.1 Sample calculation of PM from Dumper Placer Big ($7m^3$) departmental vehicle) in Borough 1:

Total distance covered by DP (Big) vehicle = no of trips/day × distance from borough to disposal site Dhapa × 2 = 20.78 × 9 × 2 = 374.04 KM/Day (Table 4.10).

Weighted average of emission factor (EF) of pollutants PM = 0.29 g/KM (Table 4.12).

So, PM emission by DP (Big) vehicle in Borough 1 = Total distance in KM × EF of PM = 374.04 KM/Day × 0.29 gm/KM = 108.4716 gm/day.

4.2.2 Sample calculation of CO from Dumper Placer Big ($7m^3$) departmental vehicle in Borough 1:

Total distance covered by DP (Big) vehicle = no of trips/day × distance from borough to disposal site Dhapa × 2 = 20.78 ×9 × 2 = 374.04 KM/Day (Table 4.10). Emission factor of CO = 3.566 gm/KM.

So, CO emission by DP (Big) vehicle in Borough 1 = (374.04 KM/Day × 3.566 gm/KM) = 1333.827 gm/day.

4.2.3 Sample calculation of CO_2 from Dumper Placer Big ($7m^3$) departmental vehicle in Borough 1:

Average fuel consumption = 4 KM/Lit. (Table 4.9).

Total fuel consumption = Total distance covered (KM/Day) (Table 4.10) / (Average fuel consumption × 1000) = 374.04 / (4 × 1000) = 0.09351 m^3 / Day

Density of the fuel = 820 Kg / m^3

Total weight of fuel = 0.09351 m^3 / Day × 820 KG / m3 = 76.6782 Kg / Day

% of Carbon by weight = 87%

Total Carbon amount = 76.6782 Kg / Day × 0.87 = 66.710034 Kg / Day

Total CO amount = 1.333 Kg / Day (Table 4.13)

Carbon in CO amount = [Total CO × (12/28)] = [1.3338 Kg / Day × (12/28)] = 0.5716 Kg / Day [Molecular weight of CO = (12 + 16) = 28]

Remaining CO from CO_2 generated = Total Carbon amount – Carbon in CO = 66.710034 Kg / Day – 0.5716 Kg / Day = 66.1389 Kg / Day

So, total CO_2 generation = 66.1389 KG / Day × (44/12) = 242.507 Kg / Day

4.2.4 Sample calculation of SO_2 from Dumper Placer Big ($7M^3$) departmental vehicle in Borough 1:

Total distance covered by DP (Big) vehicle = no of trips/day × distance from borough to disposal site Dhapa × 2 = 20.78 ×9 × 2 = 374.04 KM/Day (Table 4.10).

Average fuel consumption = 4 KM / Lit (Table 4.9)

Total fuel consumption = 374.04 / (4 × 1000) = 0.09351m^3 / Day

Density of the fuel = 820 Kg / m^3

Total weight of fuel = 0.09351 m^3 / Day × 820 KG / m3 = 76.6782 Kg / Day

% of S by weight = 0.035 Kg/m^3

Total S amount = Total weight of fuel × (0.035/100) = 0.02683737 Kg/Day

Total SO2 emission from DP (Big) vehicle in borough 1 = [0.02683737 Kg/Day × (64/32)] = 53.68 gm/day.

4.2.5 Sample calculation of NO_x from Dumper Placer Big ($7m^3$) departmental vehicle in Borough 1:

Total distance covered by DP (Big) vehicle = no of trips/day × distance from borough to disposal site Dhapa × 2 = (20.78 ×9 × 2) = 374.04 KM/Day (Table 4.10). Emission factor of NO_x = 6.277 gm/KM (Table 4.12).

So, NO_x emission by DP (Big) vehicle in Borough 1 = (374.04 KM/Day × 6.277 gm/KM) = 2347.849 gm/day.

4.2.6 Sample calculation of HC from Dumper Placer Big ($7m^3$) departmental vehicle in Borough 1:

Total distance covered by DP (Big) vehicle = no of trips/day × distance from borough to disposal site Dhapa × 2 = 20.78 ×9 × 2 = 374.04 KM/Day (Table 4.10). Emission factor of HC = 0.921 gm/KM (Table 4.12).

So, HC emission by DP (Big) vehicle in Borough 1 = (374.04 KM/Day × 0.0921 gm/KM) = 344.4808 gm/day.

4.2.7 Sample calculation of Benzene from Dumper Placer Big (7m^3) departmental vehicle in Borough 1:

Total distance covered by DP (Big) vehicle = no of trips/day × distance from borough to disposal site Dhapa × 2 = 20.78 ×9 × 2 = 374.04 KM/Day (Table 4.10). Emission factor of Benzene = 0.004 gm/KM (Table 4.12).

So, Benzene emission by DP (Big) vehicle in Borough 1 = (374.04 KM/Day × 0.004 gm/KM) = 1.0 gm/day.

4.2.8 Sample calculation of Butadiene from Dumper Placer Big (7M^3) departmental vehicle) in Borough 1:

Total distance covered by DP (Big) vehicle = no of trips/day × distance from borough to disposal site Dhapa × 2 = (20.78 × 9 × 2) KM/day = 374.04 KM/day (Table 4.10). Emission factor of Butadiene = 0.0008 gm/KM (Table 4.12).

So, Butadiene emission by DP (Big) vehicle in Borough 1 = (374.04 KM/day × 0.0008 gm/KM) = 0.30 gm/day.

Annexure 4.3:

4.3 NOISE CALCULATION

Measurement of the noise is done in Dhapa landfill site. All the corresponding values of sound in decibel (dB) are taken with the help of sound level meter. One sample calculation shown in 4.3.1 and other field data along with their results are shown in different Tables A-4.2 to Table A-4.11.

4.3.1 Location: Vivekananda Park Collection Point (Container collection point)

$$L_{eq} = 10 \log \sum_{i=1}^{i=n} 10^{Li/10} \times t_i$$

$$\sum_{1}^{60} 10^{Li/10} \times t_i$$

= [$(10)^{60.3/10}$ + $(10)^{60.2/10}$ + $(10)^{60.9/10}$ + $(10)^{60.5/10}$ + $(10)^{60.2/10}$ + $(10)^{60.9/10}$ + $(10)^{60.7/10}$ + $(10)^{60.6/10}$ + $(10)^{61.3/10}$ + $(10)^{61.1/10}$ + $(10)^{61.5/10}$ + $(10)^{61.5/10}$ + $(10)^{61.9/10}$ + $(10)^{61.1/10}$ + $(10)^{61/10}$ + $(10)^{61/10}$ + $(10)^{61/10}$ + $(10)^{61.3/10}$ + $(10)^{61.2/10}$ + $(10)^{61.9/10}$ + $(10)^{61.8/10}$ + $(10)^{62.8/10}$ + $(10)^{62.5/10}$ + $(10)^{62.3/10}$ + $(10)^{62.5/10}$ + $(10)^{62.3/10}$ + $(10)^{62.8/10}$ + $(10)^{62.6/10}$ + $(10)^{62.5/10}$ + $(10)^{62.7/10}$ + $(10)^{62.9/10}$ + $(10)^{62.9/10}$ + $(10)^{62.8/10}$ + $(10)^{62.5/10}$ + $(10)^{62.6/10}$ + $(10)^{62.9/10}$ + $(10)^{62.8/10}$ + $(10)^{62.7/10}$ + $(10)^{63.2/10}$ + $(10)^{63.9/10}$ + $(10)^{63.5/10}$ + $(10)^{63.7/10}$ + $(10)^{63.7/10}$ + $(10)^{63.8/10}$ + $(10)^{63.4/10}$ + $(10)^{63.3/10}$ + $(10)^{63.2/10}$ + $(10)^{63.9/10}$ + $(10)^{64.6/10}$ + $(10)^{64.5/10}$ + $(10)^{64.6/10}$ + $(10)^{64.1/10}$ + $(10)^{64.3/10}$ + $(10)^{64.2/10}$ + $(10)^{64.6/10}$ + $(10)^{64.5/10}$ + $(10)^{64.3/10}$ + $(10)^{64.1/10}$ + $(10)^{64.9/10}$ + $(10)^{64.6/10}$]x 10/600

= [1071519.305 + 1047128.548 + 1230268.771 + 1122018.454 + 1047128.548 + 1230268.771 + 1174897.555 + 1148153.621 + 1348962.883 + 1288249.552 + 1412537.545 + 1412537.545 + 1548816.619 + 1288249.552 + 1258925.412 + 1258925.412 + 1258925.412 + 1348962.883 + 1318256.739 + 1548816.619 + 1513561.248 + 1905460.718 + 1778279.41 + 1698243.652 + 1778279.41 + 1698243.652 + 1905460.718 + 1819700.859 + 1778279.41 + 1862087.137 + 1949844.6 + 1949844.6 + 1905460.718 + 1778279.41 + 1819700.859 + 1949844.6 + 1905460.718 + 1862087.137 + 2089296.131 + 2454708.916 + 2238721.139 + 2344228.815 + 2344228.815 + 2398832.919 + 2187761.624 + 2137962.09 + 2089296.131 + 2454708.916 + 2884031.503 + 2818382.931 + 2884031.503 + 2570395.783 + 2691534.804 + 2630267.992 + 2884031.503 + 2818382.931 + 2691534.804 + 2570395.783 + 3090295.433 + 2884031.503]x 10/600

= [114378730.6] x 1/60

= 1906312.176

$$L_{eq} = 10 \log \sum 10^{Li/10} \times t_i$$

= 10 log 1906312.176

= 10 x 6.280194022

= 62.80194022 dB

= 62.80 dB

Table A-2 Noise calculation at collection point Ballygunge Circular road (while tipper truck operating & non operating position).

<table>
<tr><th>Decibel (dB)</th><th>Operating</th><th>Non-Operating</th><th>dB Values Non Operating</th><th>dB Values Operating</th></tr>
<tr><td>62-64</td><td>0</td><td>0</td><td rowspan="18">64.5, 65.4, 65.1, 64.3, 64.7, 65.3, 65.1, 67.6, 66.6, 67.2, 66.3, 66.6, 67.5, 68.5, 69.8, 69.2, 68.8, 69.1, 68.3, 69.9, 69.5, 71.1, 70.5, 70.6, 70.0, 70.5, 70.6, 70.1, 71.2, 70.3, 72.5, 73.5, 73.6, 72.1, 72.6, 72.3, 72.7, 72.9, 73.3, 74.4, 75.8, 75.3, 75.3, 74.5, 75.3, 74.3, 76.2, 76.9, 77.3, 76.9, 76.5, 78.2, 79.3, 79.2, 78.2, 78.5, 86.3, 86.3, 86.5, 87.2</td><td rowspan="18">75.4, 74.9, 75.3, 74.9, 76.8, 76.2, 77.3, 76.4, 79.5, 79.8, 79.2, 78.5, 78.8, 82.1, 82.1, 82.8, 83.4, 82.1, 82.3, 82.1, 83.3, 83.2, 84.7, 85.3, 85.5, 85.6, 84.1, 85.3, 85.1, 84.3, 84.9, 84.9, 86.8, 87.8, 86.5, 86.2, 87.8, 86.2, 86.3, 87.1, 87.3, 91.7, 90.2, 91.8, 90.2, 90.6, 91.3, 92.1, 92.1, 93.1, 92.4, 92.1, 92.9, 92.3, 92.1, 93.3, 95.4, 94.2, 95.6, 95.9</td></tr>
<tr><td>64-66</td><td>0</td><td>7</td></tr>
<tr><td>66-68</td><td>0</td><td>6</td></tr>
<tr><td>68-70</td><td>0</td><td>8</td></tr>
<tr><td>70-72</td><td>0</td><td>9</td></tr>
<tr><td>72-74</td><td>0</td><td>9</td></tr>
<tr><td>74-76</td><td>4</td><td>7</td></tr>
<tr><td>76-78</td><td>4</td><td>5</td></tr>
<tr><td>78-80</td><td>5</td><td>5</td></tr>
<tr><td>80-82</td><td>0</td><td>0</td></tr>
<tr><td>82-84</td><td>9</td><td>0</td></tr>
<tr><td>84-86</td><td>10</td><td>0</td></tr>
<tr><td>86-88</td><td>9</td><td>4</td></tr>
<tr><td>88-90</td><td>0</td><td>0</td></tr>
<tr><td>90-92</td><td>6</td><td>0</td></tr>
<tr><td>92-94</td><td>9</td><td>0</td></tr>
<tr><td>94-96</td><td>4</td><td>0</td></tr>
<tr><td>Leq</td><td>88.961 dB</td><td>77.062 dB</td></tr>
</table>

Table A-4.3 Noise calculation on Dumper Placer ($7m^3$)

Decibel (dB)	Loaded	Unloaded	dB Values (Loaded)	dB Values (Unloaded)
68-70	0	0	71.1, 70.6, 71.1, 70.2, 71.3, 73.1, 72.0, 73.6, 72.3, 72.3, 72.9, 75.1, 74.1, 75.2, 74.3, 75.5, 76.2, 76.1, 77.3, 79.1, 79.2, 78.2, 79.5, 78.6, 79.2, 79.5, 81.7, 80.3, 80.6, 80.9, 80.1, 80.0, 80.3, 80.5, 80.6, 80.3, 80.1, 80.6, 81.5, 83.8, 83.2, 83.2, 82.1, 82.9, 83.5, 84.4, 84.2, 85.5, 84.1, 85.6, 84.3, 85.2, 87.1, 86.2, 87.2, 88.2, 88.2, 88.5, 88.6, 89.2	70.2, 71.6, 73.2, 73.1, 72.3, 72.9, 73.1, 73.5, 75.2, 75.1, 75.1, 75.5, 75.6, 75.9, 74.9, 75.2, 77.2, 76.3, 76.8, 77, 76.9, 76.2, 77.3, 77.5, 78.1, 79.6, 78.1, 78.5, 79.2, 79.1, 79.3, 79.9, 80.3, 80.5, 81.1, 80.7, 81.2, 80, 81.1, 81.9, 80.2, 80.4, 81.2, 80.5, 81.9, 82.3, 82.5, 83.3, 84.1, 84.2, 84.6, 84, 85.5, 85.9, 86.2, 86.9, 86.2, 86.7, 87.7, 87.5
70-72	5	2		
72-74	6	6		
74-76	5	8		
76-78	3	8		
78-80	7	8		
80-82	13	13		
82-84	6	3		
84-86	7	6		
86-88	3	6		
88-90	5	0		
90-92	0	0		
Leq	82.599 dB	81.436 dB		

Table A-4.4 Noise Calculation Inside the Tipper Truck (11m^3)

Decibel (dB)	Loaded	Unloaded	dB Values (Loaded)	dB Values (Unloaded)
68-70	0	0	85.5, 84.6, 85.2, 89.1, 88.5, 89.6, 88.7, 88, 89.7, 88.5, 88.8, 91.7, 91.6, 90.1, 92.9, 93.8, 93.8, 93.8, 92.7, 93.4, 94.4, 94.7, 94.3, 94.2, 95.5, 97.2, 96.2, 96.9, 97.1, 96.0, 96.2, 96.2, 98.2, 99.6, 99.0, 98.1, 98.9, 98.2, 99.5, 99.9, 100.5,101.3, 101.9, 101, 101.5,100.9,103.4,102.4, 103.5,102.6,102.3,103.4, 103.9,102.3,104.1,104.3, 104, 106.7, 106.5, 107.2	71.2, 70.5, 70.3, 71.9, 71.8, 72.5, 74.3, 75.2, 76.1, 76, 83.4, 83.2, 82.2, 82.3, 83.5, 83.8, 85.2, 85.3, 84.3, 85, 85.2, 85.2, 84.3, 84.9, 87.4, 86.3, 87.6, 87.2, 86, 87, 86.1, 86.2, 86.9, 86.6, 87.5, 88.2, 88.5, 88.7, 88.3, 88.2, 89.1, 89, 90.6, 90.1, 90.2, 90.6, 90.2, 91.1, 91.6, 92.1, 92.7, 92.6, 92.2, 93.5, 95.4, 94.3, 94.3, 95.1, 95.5, 95
70-72	0	5		
72-74	0	1		
74-76	0	2		
76-78	0	2		
78-80	0	0		
80-82	0	0		
82-84	0	6		
84-86	3	8		
86-88	0	11		
88-90	8	7		
90-92	3	7		
92-94	6	5		
94-96	5	6		
96-98	7	0		
98-100	8	0		
100-102	6	0		
102-104	8	0		
104-106	3	0		
106-108	3	0		
108-110	0	0		
Leq	99.963 dB	89.248 dB		

Table A-4.5 Noise calculation inside the Tipper Truck (7m[3])

<table>
<tr><th>Decibel (dB)</th><th>Loaded</th><th>Unloaded</th><th>dB Values (Loaded)</th><th>dB Values (Unloaded)</th></tr>
<tr><td>70-72</td><td>0</td><td>5</td><td rowspan="17">79.9, 79.5, 78.3, 79.2, 83.4, 83.7, 83.2, 82.9, 82.8, 84.5, 85.8, 84.1, 85.8, 84.3, 85.2, 85.0, 89.1, 88.1, 88.8, 89.7, 89.7, 88.9, 89.8, 88.7, 88.8, 89.2, 89.1, 90.4, 91.2, 90.5, 90.1, 91.5, 91.8, 90.7, 90.3, 94.4, 95.5, 95.2, 94.6, 94.8, 95.1, 96.6, 97.7, 97.1, 96.5, 97.7, 96.2, 96.7, 97.4, 98.8, 98, 99.1, 98.7, 99.9, 99.2, 98.7, 99.6, 99.0, 101.3, 100.8</td><td rowspan="17">70.7, 70.6, 70.5, 71.9, 71.7, 72.1, 72.3, 75.6, 74.5, 75.1, 75.6, 76.2, 81.4, 81.1, 81.6, 80.2, 81.5, 80.5, 82.5, 83.9, 83.6, 82.2, 83.2, 83, 85.8, 85.5, 85.4, 84.9, 84.8, 85.5, 84.2, 84.1, 85.3, 84.5, 87.6, 87.9, 86.3, 87.2, 86.9, 87.3, 88.8, 88.7, 88.8, 89.7, 89, 89.3, 90.3, 90.6, 91.1, 90.4, 91.2, 91.6, 90.7, 91.1, 92.5, 92.3, 93.1, 92.2, 94.2, 95.6</td></tr>
<tr><td>72-74</td><td>0</td><td>2</td></tr>
<tr><td>74-76</td><td>0</td><td>4</td></tr>
<tr><td>76-78</td><td>0</td><td>1</td></tr>
<tr><td>78-80</td><td>4</td><td>0</td></tr>
<tr><td>80-82</td><td>0</td><td>6</td></tr>
<tr><td>82-84</td><td>5</td><td>6</td></tr>
<tr><td>84-86</td><td>7</td><td>10</td></tr>
<tr><td>86-88</td><td>0</td><td>6</td></tr>
<tr><td>88-90</td><td>11</td><td>6</td></tr>
<tr><td>90-92</td><td>8</td><td>8</td></tr>
<tr><td>92-94</td><td>0</td><td>4</td></tr>
<tr><td>94-96</td><td>6</td><td>2</td></tr>
<tr><td>96-88</td><td>8</td><td>0</td></tr>
<tr><td>98-100</td><td>9</td><td>0</td></tr>
<tr><td>100-102</td><td>2</td><td>0</td></tr>
<tr><td>Leq</td><td>94.743 dB</td><td>87.869 dB</td></tr>
</table>

Table A-4.6 Noise calculation on Hired Vehicle

Decibel (dB)	Loaded	Unloaded	dB Values (Loaded)	dB Values (Unloaded)
74-76	0	0	78.5, 79.6, 78.7, 80, 81.1, 81.7, 81.1, 83.9, 82.8, 82.8, 82.9, 83.7, 82.5, 82.2, 82.6, 83.9, 82.2, 83.9, 82.3, 84.1, 84.3, 84.4, 84.3, 85.7, 85.8, 84.4, 85.2, 87.2, 87.8, 86.6, 87.7, 86.1, 87.3, 87.1, 89.2, 88.1, 88.1, 88.5, 89.6, 89.9, 89.2, 91.8, 90.7, 91.2, 90.8, 91.4, 90.6, 90.9, 90.6, 90.5, 93.2, 92.1, 92.3, 98.4, 99.2, 99.9, 101.1, 100.1,100.2, 100.5	77.2, 76.3, 77.1, 79.3, 78.9, 78.1, 78.9, 80.3, 81.2, 81.5, 80.9, 81.2, 81.9, 82.6, 83.5, 83.6, 82.1, 82.7, 83.6, 83.7, 83.8, 83.6, 82.1, 83.7, 83.6, 83.2, 82.5, 84.8, 84.4, 85.7, 85.8, 84.0, 85.6, 85.4, 85.2, 85.6, 84.3, 86, 87.8, 86, 86.1, 86.4, 87.8, 86.2, 86.1, 87.2, 89.5, 88.2, 88.2, 89.8, 88.8, 89.1, 89.2, 88.6, 88.3, 90, 90.4, 90.1, 90.5, 91.2
76-78	0	3		
78-80	3	4		
80-82	4	6		
82-84	12	14		
84-86	8	10		
86-88	7	9		
88-90	7	9		
90-92	9	5		
92-94	3	0		
94-96	0	0		
96-98	0	0		
98-100	3	0		
100-102	4	0		
Leq	92.271 dB	86.047 dB		

Table A-4.7 Noise calculation for Bull dozer in running condition

Decibel (dB)	Occurrence	dB Values
84-86	5	84.5, 84.2, 85.1, 85.8, 85, 86.9, 87, 86.7, 87.1, 89.7, 89, 89.3, 89.1, 90, 91, 91.5, 91.5, 90.3, 90, 90, 92.3, 92, 93.1, 93, 93.7, 93.9, 93.2, 93.3, 92.5, 94.9, 94.3, 94.5, 95, 95.2, 95.7, 94, 96, 97.5, 97.9, 96.2, 96.8, 98.2, 99.1, 99, 99.7, 98.7, 98.5, 99.3, 99, 99.9, 99.9, 99.8, 100.1, 100.5, 100.9, 101.3, 101, 101.3, 100.4, 100.3, 103.3, 103.5, 103.8, 103.9, 103.5, 104.1, 104, 104.3, 105.2, 105.5, 105.6, 105.9, 106.8, 107, 107.3, 106.5, 106, 106, 107.2, 107.7, 107.1, 108, 108.3, 108, 108.1, 108.1, 108.9, 108.9, 109.1, 109
86-88	4	
88-90	4	
90-92	7	
92-94	9	
94-96	7	
96-88	5	
98-100	11	
100-102	8	
102-104	5	
104-106	7	
106-108	9	
108-110	7	
110-112	2	
Leq	102.711 dB	

Table A-4.8 Noise calculation at Garage (outside & inside)

Decibel (dB)	Outside	Inside	dB Values (Outside)	dB Values (Inside)
52-54	1	0	52.3, 54.3, 54.3, 54.8, 56.1, 56.7, 56.0, 56.8, 56.9, 57.6, 58.9, 59.3, 59.0, 59.0, 60.5, 60.5, 60.1, 60.2, 64.9, 64.9, 66.2, 66.1, 67.1, 67.2, 70.6, 70.6, 70.2, 71.1, 71.8, 70.9, 71.4, 72.6, 73.9, 73.2, 73.6, 74.5, 75.0, 75.1, 76.9, 77.2, 76.6, 76.2, 76.2, 77.3, 77.8, 78.3, 78.2, 78.8, 79.1, 78.3, 80.7, 80.2, 81.9, 80.0, 86.7, 87.3, 88.3, 88.5, 90.7, 91.2	62.9, 63, 64, 65, 65.2, 65.1, 64.9, 66.2, 66.7, 69.5, 68.6, 68.1, 68.9, 68.9, 71.4, 71.3, 71.4, 72.8, 73.8, 73.9, 73.2, 73.8, 73.9, 75.2, 75.6, 74.1, 74.6, 76.1, 77.0, 77.2, 76.8, 76.9, 79.2, 78.9, 78.5, 79.0, 79.1, 79.3, 80.5, 80.2, 80.5, 80.6, 82.9, 82.4, 83.2, 83.2, 82.6, 82.3, 82, 85.1, 85.8, 85.6, 86.7, 86.2, 87.9, 87.5, 87.5, 88.2, 91.2, 90.8
54-56	3	0		
56-58	6	0		
58-60	4	0		
60-62	4	0		
62-64	0	2		
64-66	2	5		
66-68	4	3		
68-70	0	5		
70-72	7	3		
72-74	4	6		
74-76	3	4		
76-78	7	5		
78-80	5	6		
80-82	4	4		
82-84	0	7		
84-86	0	3		
86-88	2	5		
88-90	2	1		
90-92	2	2		
Leq	80.256 dB	82.087 dB		

Table A-4.9 Noise calculation at departmental dumpsite

<table>
<tr><th>Decibel (dB)</th><th>Noisy</th><th>Background</th><th>dB Values (Noisy)</th><th>dB Values (Background)</th></tr>
<tr><td>46-48</td><td>0</td><td>4</td><td rowspan="20">48, 49.5, 51.7, 52.7, 53.8, 53, 52, 55.3, 55, 55.8, 55, 55, 55, 55, 56.5, 57.8, 56.5, 56, 56, 56, 56, 58, 59, 58, 59, 61, 60.3, 61, 60.2, 63, 63.8, 63.3, 63.8, 63, 62, 65.1, 64.5, 64.2, 65, 64.8, 65.8, 67, 66.7, 66.2, 66.9, 68, 68.5, 69.8, 69.8, 69.8, 68.9, 68.5, 69.2, 70, 70.1, 71, 71, 70.8, 70.5, 70.9, 70, 71.6, 70.2, 70.2, 70.9, 72.8, 72.8, 72.8, 73, 72.6, 73.5, 75.1, 74.2, 74.3, 74, 75.4, 75.9, 75.8, 74.7, 75.4, 74.5, 74.1, 74.4, 75.9, 77, 76.7, 76.1, 80, 81.5, 83.8</td><td rowspan="20">44.3, 45.2, 45.9, 44.1, 44.3, 45.2, 45, 46.2, 46.9, 47.3, 47.5, 48.3, 48.5, 49.2, 49.2, 49, 48, 48.3, 48.8, 50.1, 50.3, 50.5, 51.1, 51.9, 51.8, 51, 51.9, 50, 50.3, 50.5, 50.6, 52.3, 52.1, 52.9, 53.1, 53, 54.3, 54.5, 54.1, 54.6, 55.5, 55.6, 55, 56.2, 56.6, 65.5, 57.3, 57.9, 57, 56.2, 56.9, 57.7, 57, 58.3, 58.5, 59.2, 59.9, 58.9, 58.3, 58.3</td></tr>
<tr><td>48-50</td><td>2</td><td>8</td></tr>
<tr><td>50-52</td><td>1</td><td>12</td></tr>
<tr><td>52-54</td><td>4</td><td>5</td></tr>
<tr><td>54-56</td><td>7</td><td>7</td></tr>
<tr><td>56-58</td><td>7</td><td>10</td></tr>
<tr><td>58-60</td><td>4</td><td>7</td></tr>
<tr><td>60-62</td><td>4</td><td>0</td></tr>
<tr><td>62-64</td><td>6</td><td>0</td></tr>
<tr><td>64-66</td><td>6</td><td>0</td></tr>
<tr><td>66-68</td><td>4</td><td>0</td></tr>
<tr><td>68-70</td><td>8</td><td>0</td></tr>
<tr><td>70-72</td><td>12</td><td>0</td></tr>
<tr><td>72-74</td><td>6</td><td>0</td></tr>
<tr><td>74-76</td><td>13</td><td>0</td></tr>
<tr><td>76-78</td><td>3</td><td>0</td></tr>
<tr><td>78-80</td><td>0</td><td>0</td></tr>
<tr><td>80-82</td><td>2</td><td>0</td></tr>
<tr><td>82-84</td><td>1</td><td>0</td></tr>
<tr><td>Leq</td><td>71.95 dB</td><td>54.99 dB</td></tr>
</table>

Table A-4.10 Noise calculation on approach road towards disposal site

Decibel (dB)	Noisy	Background	dB Values (Noisy)	dB Value (Background)
40-41	0	5	49.6, 48.8, 48.3, 49.1, 49.3, 50.2, 51.7, 55.4, 55.6, 54.9, 54.7, 55.2, 59.6, 59.5, 59.2, 58.9, 58.3, 63.2, 62.8, 62.8, 63.1, 63, 63.7, 62.9, 67.8, 67.7, 66.5, 66.9, 67.1, 66.5, 66.2, 67.3, 67.9, 69.6, 68.3, 69.2, 69, 68.8, 68.3, 74.5, 74.8, 75.2, 75.8, 75, 77.5, 77.3, 76.9, 76.8, 77.8, 80, 80.2, 80.8, 81.3, 81, 84.1, 84.2, 84, 84.2, 84.8, 85.6	40.1, 40.3, 40.3, 40.5, 40.3, 41.3, 41.2, 41.5, 41.5, 42.1, 42.3, 42.3, 42.5, 42.9, 42.9, 42.3, 42.9, 42.8, 43.2, 43.1, 43.5, 43.3, 43.2, 44.1, 44.3, 44.1, 44, 44.8, 44, 44.3, 45.3, 45.2, 45.1, 45.2, 46.3, 46.9, 46.2, 46, 46.3, 46.1, 46.5, 47.2, 47.8, 47.3, 47.3, 47.1, 48.2, 48.1, 48.5, 49.1, 49.6, 49.7, 49.3, 49.5, 49, 50.2, 50.6, 50.5, 50.3, 50.2
41-42	0	4		
42-43	0	9		
43-44	0	5		
44-45	0	7		
45-46	0	4		
46-47	0	7		
47-48	0	5		
48-50	5	3		
50-52	2	6		
52-54	0	5		
54-56	5	0		
56-58	0	0		
58-60	5	0		
60-62	0	0		
62-64	7	0		
64-66	0	0		
66-68	9	0		
68-70	6	0		
70-72	0	0		
72-74	0	0		
74-76	5	0		
76-78	5	0		
78-80	0	0		
80-82	5	0		
82-84	0	0		
84-86	6	0		
Leq	76.732 dB	46.254 dB		

Table A-4.11 Noise calculation at weigh bridge (background & noisy)

Decibel (dB)	Noisy	Background	dB Values (Noisy)	dB Values (Background)
44-46	0	3	60.2, 62.6, 62.4, 63.4, 64.7, 65.4, 65.9, 65.3, 66, 66.6, 66.8, 66.5, 67.2, 66.7, 66.5, 66.8, 68.2, 68, 67.9, 68.7, 68.4, 69.7, 71.5, 71.2, 71.4, 70.8, 71.5, 71.8, 70.5, 70.2, 71.2, 70.2, 70.9, 70.4, 71.5, 70.1, 71.5, 70.8, 70.8, 71, 71.6, 70.9, 71.5, 73.8, 72.5, 73.5, 73.5, 73.8, 73.2, 73.4, 72.2, 71.8, 73.3, 72.6, 73, 75.8, 75.7, 75.5, 74.4, 75.4, 75.6, 74.9, 75.9, 74.5, 74.6, 74.4, 75.6, 74.9, 76.1, 76, 77.9, 76.1, 76.2, 76.4, 77.4, 76.2, 77.8, 78.4, 79.4, 78, 78.3, 78.5, 80.6, 80.2, 80.5, 82.3, 83.5, 84.4, 84.5, 87.2	44.6, 44.9, 45.2, 46.1, 46.7, 46.7, 46.0, 46.2, 47.3, 47.7, 46.9, 48.3, 48.5, 49.2, 48.6, 50.7, 50.2, 50.3, 50.8, 51.3, 51.1, 50.6, 51.7, 51.0, 52.2, 52.3, 52.7, 53.1, 53.8, 53.0, 52.2, 53.9, 52.7, 53.6, 53.5, 53.3, 54.9, 54.3, 54.4, 55.6, 55.0, 54.3, 54.9, 54.7, 55.2, 54.3, 56.6, 57.2, 56.1, 57.1, 57.0, 57.5, 56.5, 56.4, 58.5, 58.9, 59.9, 59.2, 58.3, 59.9
46-48	0	8		
48-50	0	4		
50-52	0	9		
52-54	0	12		
54-56	0	10		
56-58	0	8		
58-60	0	6		
60-62	1	0		
62-64	3	0		
64-66	4	0		
66-68	8	0		
68-70	6	0		
70-72	21	0		
72-74	12	0		
74-76	13	0		
76-78	9	0		
78-80	5	0		
80-82	3	0		
82-84	2	0		
84-86	2	0		
86-88	1	0		
Leq	76.06 dB	54.286 dB		

Annexure 4.4:

4.4 Detail Calculation of Gas Generation from IPCC, LandGEM and TRIANGULAR Model

4.4.1 Amount of Waste Generated

According to records on waste received at the Dhapa disposal site, around 3000 MT of waste are daily deposited and disposed. With the population of Kolkata city are approximately 4.6 million, the calculation of an annual amount of waste generation per head from the figure averages ranged from 206 kg/cap/yr to 214 kg/cap/yr which represents a good coherence to the basic unit default of the amount of waste generated per head per annual, as described in IPCC Guideline Asia South Central.

For an appropriate estimation of the amount of LFG (methane) generated from the landfill, it is necessary to get a good grasp of the amounts of waste deposition going back to from 5 to

10 years before, but the data on these past amounts of waste generated were estimated, based on the population of Kolkata city and the basic unit of the amount of waste generation. Accordingly to the census of India, the data revealed that the population of Kolkata city in 1999 and 2001 was 4399,819 and 4,580,544, respectively. Based on these a population between 1987, the year of the commence of the Dhapa landfill, and 2000 was set as approximately 4.4 million, while a population between 2001 and 2011, the year of planned site closure, as approximately 4.6 million. In addition, assuming a basic unit of the annual amount of waste generated per head was 210 kg/cap/yr, the amount of waste generated was calculated.

4.4.2 Waste Composition

Following the categories on the IPCC Guide line (2006 IPCC Guidelines for National Greenhouse Gas Inventories), Degradable Organic Carbon (DOC) and Default value for Dhapa landfill site of Kolkata is mentioned in Table A-4.12.

4.4.3 Parameters of First Order Decay (FOD) Model

Input parameters are shown in Table A-4.12.

Table A-4.12 Parameters for IPCC model

Country Asia: South-central

Region

Please enter parameters in the yellow cells. If no national data are available, copy the IPCC default value.
Help on parameter selection can be found in the 2006 IPCC guidelines

	IPCC default value		Country-specific parameters	
			Value	Reference and remarks
Starting year		1950	1950	
	Waste by composition			
DOC (Degradable organic carbon)				
(weight fraction, wet basis)	**Range**	**Default**		
Food waste	0.08-0.20	0.15	0.15	
Garden	0.18-0.22	0.2	0.2	
Paper	0.36-0.45	0.4	0.4	
Wood and straw	0.39-0.46	0.43	0.43	
Textiles	0.20-0.40	0.24	0.24	
Disposable nappies	0.18-0.32	0.24	0.24	
Sewage sludge	0.04-0.05	0.05	0.05	
Industrial waste	0-0.54	0.15	0.15	
DOCf (fraction of DOC dissimilated)		0.5	0.5	
	Moist and wet tropical			
Methane generation rate constant (k)				
(years^{-1})	**Range**	**Default**		
Food waste	0.17–0.7	0.4	0.4	

Garden	0.15–0.2	0.17	0.17	
Paper	0.06–0.085	0.07	0.07	
Wood and straw	0.03–0.05	0.035	0.035	
Textiles	0.06–0.085	0.07	0.07	
Disposable nappies	0.15–0.2	0.17	0.17	
Sewage sludge	0.17–0.7	0.4	0.4	
Industrial waste	0.15–0.2	0.17	0	
Delay time (months)		6	6	
Fraction of methane (F) in developed gas		0.5	0.5	
Conversion factor, C to CH_4		1.33	1.33	
Oxidation factor (OX)		0	0	
Parameters for carbon storage				
% paper in industrial waste		0%	0%	
% wood in industrial waste		0%	0%	

Table A- 4.13 MSW activity data
for IPCC model

Enter population, waste per capita and MSW waste composition into the yellow cells.
Help and default regional values are given in the 2006 IPCC Guidelines.
Industrial waste activity data must be entered separately starting in Column Q.

IPCC Regional defaults

		210		74%	40%	0%	11%	8%	3%	0%	38%	100%
					Composition of waste going to solid waste disposal sites							
Year	**Population**	**Waste per capita**	**Total MSW**	**% to SWDS**	**Food**	**Garden**	**Paper**	**Wood**	**Textile**	**Nappies**	**Plastics, other inert**	**Total**
	millions	kg/cap/yr	Gg	%	%	%	%	%	%	%	%	(=100%)
1987	6.1	163.6	997.96	74%	43%	14%	1%	6%	2%	0%	34%	100%
1988	6.2	161.5	1001.3	74%	43%	14%	1%	6%	2%	0%	34%	100%
1989	6.4	157.1	1005.44	74%	43%	14%	1%	6%	2%	0%	34%	100%
1990	6.5	155.2	1008.8	74%	43%	14%	1%	6%	2%	0%	34%	100%
1991	6.6	153.6	1013.76	74%	43%	14%	1%	6%	2%	0%	34%	100%
1992	6.8	149.6	1017.28	74%	43%	14%	1%	6%	2%	0%	34%	100%
1993	6.9	148	1021.2	74%	43%	14%	1%	6%	2%	0%	34%	100%
1994	7	146.6	1026.2	74%	43%	14%	1%	6%	2%	0%	34%	100%
1995	7.1	145.1	1030.21	74%	43%	14%	1%	6%	2%	0%	34%	100%
1996	7.3	141.7	1034.41	74%	43%	14%	1%	6%	2%	0%	34%	100%
1997	7.4	140.2	1037.48	74%	43%	14%	1%	6%	2%	0%	34%	100%
1998	7.5	138.9	1041.75	74%	43%	14%	1%	6%	2%	0%	34%	100%
1999	7.6	137.7	1046.52	74%	43%	14%	1%	6%	2%	0%	34%	100%
2000	7.8	134.6	1049.88	74%	43%	14%	1%	6%	2%	0%	34%	100%
2001	7.9	133.5	1054.65	74%	43%	14%	1%	6%	2%	0%	34%	100%

2002	8.1	123.2	997.92	74%	43%	14%	1%	6%	2%	0%	34%	100%
2003	8.2	127.9	1048.78	74%	43%	14%	1%	6%	2%	0%	34%	100%
2004	8.3	142.8	1185.24	74%	43%	14%	1%	6%	2%	0%	34%	100%
2005	8.5	150.6	1280.1	74%	43%	14%	1%	6%	2%	0%	34%	100%
2006	8.6	159.2	1369.12	74%	43%	14%	1%	6%	2%	0%	34%	100%
2007	8.7	152.6	1327.62	74%	43%	14%	1%	6%	2%	0%	34%	100%
2008	8.9	168.9	1503.21	74%	43%	14%	1%	6%	2%	0%	34%	100%
2009	9	205.5	1849.5	74%	43%	14%	1%	6%	2%	0%	34%	100%
2010	9.1	222	2020.2	74%	43%	14%	1%	6%	2%	0%	34%	100%
2011	9.2	222	2042.4	74%	43%	14%	1%	6%	2%	0%	34%	100%
2012	0	0	0	74%	43%	14%	1%	6%	2%	0%	34%	100%
2013	0	0	0	74%	43%	14%	1%	6%	2%	0%	34%	100%
2014	0	0	0	74%	43%	14%	1%	6%	2%	0%	34%	100%
2015	0	0	0	74%	43%	14%	1%	6%	2%	0%	34%	100%
2016	0	0	0	74%	43%	14%	1%	6%	2%	0%	34%	100%
2017	0	0	0	74%	43%	14%	1%	6%	2%	0%	34%	100%
2018	0	0	0	74%	43%	14%	1%	6%	2%	0%	34%	100%
2019	0	0	0	74%	43%	14%	1%	6%	2%	0%	34%	100%
2020	0	0	0	74%	43%	14%	1%	6%	2%	0%	34%	100%
2021	0	0	0	74%	43%	14%	1%	6%	2%	0%	34%	100%
2022	0	0	0	74%	43%	14%	1%	6%	2%	0%	34%	100%
2023	0	0	0	74%	43%	14%	1%	6%	2%	0%	34%	100%
2024	0	0	0	74%	43%	14%	1%	6%	2%	0%	34%	100%
2025	0	0	0	74%	43%	14%	1%	6%	2%	0%	34%	100%
2026	0	0	0	74%	43%	14%	1%	6%	2%	0%	34%	100%
2027	0	0	0	74%	43%	14%	1%	6%	2%	0%	34%	100%
2028	0	0	0	74%	43%	14%	1%	6%	2%	0%	34%	100%
2029	0	0	0	74%	43%	14%	1%	6%	2%	0%	34%	100%
2030	0	0	0	74%	43%	14%	1%	6%	2%	0%	34%	100%

Table A-4.14 Results of methane generation from IPCC model

Country

India

Enter starting year, industrial waste disposal data and methane recovery into the yellow cells.
MSW activity data is entered on MSW sheet

	Methane generated												
Year	**Food**	**Garden**	**Paper**	**Wood**	**Textile**	**Nappies**	**Sludge**	**MSW**	**Industrial**	**Total**	**Methane recovery**		**Methane emission**
	A	B	C	D	E	F	G	H	J	K	L		M = (K-L)*(1-OX)
	Gg	Gg	Gg	Gg	Gg	Gg	Gg	Gg	Gg	Gg	Gg		Gg
1987	0	0	0	0	0	0	0		0	0	0		0
1988	4	1	0	0	0	0	0		0	5	1		4
1989	7	2	0	0	0	0	0		0	9	2		7
1990	9	2	0	1	0	0	0		0	12	3		9
1991	10	3	0	1	0	0	0		0	14	4		10
1992	11	3	0	1	0	0	0		0	16	4		11
1993	12	4	0	1	0	0	0		0	17	5		12
1994	12	4	0	1	0	0	0		0	18	5		12
1995	12	4	0	1	0	0	0		0	19	6		13
1996	13	4	0	1	0	0	0		0	19	6		13
1997	13	5	0	2	1	0	0		0	20	7		13
1998	13	5	1	2	1	0	0		0	20	7		14
1999	13	5	1	2	1	0	0		0	21	7		14
2000	13	5	1	2	1	0	0		0	21	7		14
2001	13	5	1	2	1	0	0		0	22	8		14

2002	13	5	1	2	1	0	0		0	22	8	14
2003	13	5	1	2	1	0	0		0	22	8	14
2004	13	5	1	2	1	0	0		0	22	8	14
2005	14	6	1	3	1	0	0		0	23	8	15
2006	14	6	1	3	1	0	0		0	25	9	16
2007	15	6	1	3	1	0	0		0	26	9	17
2008	16	6	1	3	1	0	0		0	27	10	17
2009	17	7	1	3	1	0	0		0	28	10	18
2010	19	7	1	3	1	0	0		0	31	11	21
2011	21	8	1	4	1	0	0		0	35	9	25
2012	23	8	1	4	1	0	0		0	37	8	29
2013	15	7	1	4	1	0	0		0	28	7	21
2014	10	6	1	4	1	0	0		0	22	6	15
2015	7	5	1	4	1	0	0		0	17	6	11
2016	5	4	1	3	1	0	0		0	14	5	9
2017	3	4	1	3	1	0	0		0	11	5	7
2018	2	3	1	3	1	0	0		0	10	4	6
2019	1	3	1	3	1	0	0		0	8	4	5
2020	1	2	1	3	1	0	0		0	7	3	4
2021	1	2	1	3	1	0	0		0	6	3	3
2022	0	2	1	3	1	0	0		0	6	3	3
2023	0	1	0	3	1	0	0		0	5	3	3
2024	0	1	0	3	0	0	0		0	5	2	2
2025	0	1	0	2	0	0	0		0	4	2	2
2026	0	1	0	2	0	0	0		0	4	2	2
2027	0	1	0	2	0	0	0		0	4	2	2
2028	0	1	0	2	0	0	0		0	4	2	2
2029	0	0	0	2	0	0	0		0	3	2	2
2030	0	0	0	2	0	0	0		0	3	1	2

Table A-4.15 User input in LandGEM model

USER INPUTS

Landfill Name or Identifier: Dhapa disposal site, Kolkata

Clear ALL Non-Parameter Inputs/Selections

1: PROVIDE LANDFILL CHARACTERISTICS

Landfill Open Year	1987
Landfill Closure Year	2011
Have Model Calculate Closure Year?	◯ Yes ◉ No FALSE
Waste Design Capacity	megagrams

Restore Default Model Parameters

2: DETERMINE MODEL PARAMETERS

Methane Generation Rate, k (*year*$^{-1}$)

User-specified -1

User-specified k value should be based on site-specific data and determined by EPA Method 2E.

User-specified value: 0.100

Potential Methane Generation Capacity, L_o (*m^3/Mg*)

User-specified -1

User-specified Lo value should be based on site-specific data and determined by waste type and composition.

User-specified value: 70

NMOC Concentration (*ppmv as hexane*)

CAA - 4,000 4000

Methane Content (*% by volume*)

4: ENTER WASTE ACCEPTANCE RATES

Input Units: Mg/year

Year	Input Units (*Mg/year*)	Calculated Units (*short tons/year*)
1987	738,076	811,884
1988	741,028	815,131
1989	743,991	818,390
1990	746,968	821,665
1991	749,956	824,952
1992	752,955	828,251
1993	755,967	831,564
1994	748,990	823,889
1995	762,026	838,229
1996	765,075	841,583
1997	768,135	844,949

CAA - 50% by volume

50

3: SELECT GASES/POLLUTANTS

Gas / Pollutant #1 **Default pollutant parameters are currently being used by model.**

Total landfill gas

Total landfill gas

Gas / Pollutant #2

Methane

Methane

Gas / Pollutant #3

Carbon dioxide

Carbon dioxide

Gas / Pollutant #4

NMOC

NMOC

Edit Existing or Add New Pollutant Parameters

Restore Default Pollutant Parameters

1998	771,207	848,328
1999	774,293	851,722
2000	777,389	855,128
2001	780,499	858,549
2002	738,765	812,642
2003	776,301	853,931
2004	877,050	964,755
2005	947,132	1,041,845
2006	1,012,769	1,114,046
2007	982,729	1,081,002
2008	1,112,807	1,224,088
2009	1,368,752	1,505,627
2010	1,494,948	1,644,443
2011	1,511,376	1,662,514

Table A-4.16 Results of total landfill gas and methane generation from LandGEM model

Landfill Name or Identifier: Dhapa disposal site, Kolkata

Closure Year (with 80-year limit) = 2011

Methane = *50% by volume*

Please choose a third unit of measure to represent all of the emission rates below.

User-specified Unit: *av ft^3/min*

av ft

Year	Waste Accepted		Waste-In-Place		Total landfill gas			Methane		
	(Mg / year)	*(short tons/year)*	*(Mg)*	*(short tons)*	*(Mg/year)*	*(m^3/year)*	*(av ft^3/min)*	*(Mg/year)*	*(m^3/year)*	*(av ft^3/min)*
1987	738,076	811,884	0	0	0	0	0	0	0	0
1988	741,028	815,131	738,076	811,884	1.234E+04	9.882E+06	6.640E+02	3.297E+03	4.941E+06	3.320E+02
1989	743,991	818,390	1,479,104	1,627,014	2.356E+04	1.886E+07	1.267E+03	6.293E+03	9.432E+06	6.337E+02
1990	746,968	821,665	2,223,095	2,445,405	3.376E+04	2.703E+07	1.816E+03	9.017E+03	1.352E+07	9.081E+02
1991	749,956	824,952	2,970,063	3,267,069	4.303E+04	3.446E+07	2.315E+03	1.149E+04	1.723E+07	1.158E+03
1992	752,955	828,251	3,720,019	4,092,021	5.148E+04	4.122E+07	2.770E+03	1.375E+04	2.061E+07	1.385E+03
1993	755,967	831,564	4,472,974	4,920,271	5.917E+04	4.738E+07	3.184E+03	1.581E+04	2.369E+07	1.592E+03
1994	748,990	823,889	5,228,941	5,751,835	6.618E+04	5.299E+07	3.561E+03	1.768E+04	2.650E+07	1.780E+03
1995	762,026	838,229	5,977,931	6,575,724	7.241E+04	5.798E+07	3.896E+03	1.934E+04	2.899E+07	1.948E+03
1996	765,075	841,583	6,739,957	7,413,953	7.826E+04	6.267E+07	4.210E+03	2.090E+04	3.133E+07	2.105E+03
1997	768,135	844,949	7,505,032	8,255,535	8.360E+04	6.695E+07	4.498E+03	2.233E+04	3.347E+07	2.249E+03

1998	771,207	848,328	8,273,167	9,100,484	8.849E+04	7.086E+07	4.761E+03	2.364E+04	3.543E+07	2.381E+03
1999	774,293	851,722	9,044,374	9,948,811	9.297E+04	7.444E+07	5.002E+03	2.483E+04	3.722E+07	2.501E+03
2000	777,389	855,128	9,818,667	10,800,534	9.707E+04	7.773E+07	5.222E+03	2.593E+04	3.886E+07	2.611E+03
2001	780,499	858,549	10,596,056	11,655,662	1.008E+05	8.074E+07	5.425E+03	2.693E+04	4.037E+07	2.712E+03
2002	738,765	812,642	11,376,555	12,514,211	1.043E+05	8.351E+07	5.611E+03	2.786E+04	4.175E+07	2.805E+03
2003	776,301	853,931	12,115,320	13,326,852	1.067E+05	8.545E+07	5.741E+03	2.850E+04	4.273E+07	2.871E+03
2004	877,050	964,755	12,891,621	14,180,783	1.095E+05	8.771E+07	5.893E+03	2.926E+04	4.386E+07	2.947E+03
2005	947,132	1,041,845	13,768,671	15,145,538	1.138E+05	9.111E+07	6.122E+03	3.039E+04	4.555E+07	3.061E+03
2006	1,012,769	1,114,046	14,715,803	16,187,383	1.188E+05	9.512E+07	6.391E+03	3.173E+04	4.756E+07	3.196E+03
2007	982,729	1,081,002	15,728,572	17,301,429	1.244E+05	9.963E+07	6.694E+03	3.323E+04	4.981E+07	3.347E+03
2008	1,112,807	1,224,088	16,711,301	18,382,431	1.290E+05	1.033E+08	6.941E+03	3.446E+04	5.165E+07	3.471E+03
2009	1,368,752	1,505,627	17,824,108	19,606,519	1.353E+05	1.084E+08	7.282E+03	3.615E+04	5.419E+07	3.641E+03
2010	1,494,948	1,644,443	19,192,860	21,112,146	1.453E+05	1.164E+08	7.820E+03	3.882E+04	5.819E+07	3.910E+03
2011	1,511,376	1,662,514	20,687,808	22,756,589	1.565E+05	1.253E+08	8.421E+03	4.181E+04	6.266E+07	4.210E+03
2012	0	0	22,199,184	24,419,102	1.669E+05	1.336E+08	8.979E+03	4.458E+04	6.682E+07	4.490E+03
2013	0	0	22,199,184	24,419,102	1.510E+05	1.209E+08	8.125E+03	4.034E+04	6.046E+07	4.062E+03
2014	0	0	22,199,184	24,419,102	1.366E+05	1.094E+08	7.352E+03	3.650E+04	5.471E+07	3.676E+03
2015	0	0	22,199,184	24,419,102	1.236E+05	9.900E+07	6.652E+03	3.302E+04	4.950E+07	3.326E+03
2016	0	0	22,199,184	24,419,102	1.119E+05	8.958E+07	6.019E+03	2.988E+04	4.479E+07	3.009E+03
2017	0	0	22,199,184	24,419,102	1.012E+05	8.106E+07	5.446E+03	2.704E+04	4.053E+07	2.723E+03
2018	0	0	22,199,184	24,419,102	9.159E+04	7.334E+07	4.928E+03	2.447E+04	3.667E+07	2.464E+03
2019	0	0	22,199,184	24,419,102	8.288E+04	6.636E+07	4.459E+03	2.214E+04	3.318E+07	2.229E+03
2020	0	0	22,199,184	24,419,102	7.499E+04	6.005E+07	4.035E+03	2.003E+04	3.002E+07	2.017E+03
2021	0	0	22,199,184	24,419,102	6.785E+04	5.433E+07	3.651E+03	1.812E+04	2.717E+07	1.825E+03
2022	0	0	22,199,184	24,419,102	6.140E+04	4.916E+07	3.303E+03	1.640E+04	2.458E+07	1.652E+03
2023	0	0	22,199,184	24,419,102	5.555E+04	4.448E+07	2.989E+03	1.484E+04	2.224E+07	1.494E+03
2024	0	0	22,199,184	24,419,102	5.027E+04	4.025E+07	2.704E+03	1.343E+04	2.013E+07	1.352E+03

2025	0	0	22,199,184	24,419,102	4.548E+04	3.642E+07	2.447E+03	1.215E+04	1.821E+07	1.224E+03
2026	0	0	22,199,184	24,419,102	4.116E+04	3.296E+07	2.214E+03	1.099E+04	1.648E+07	1.107E+03
2027	0	0	22,199,184	24,419,102	3.724E+04	2.982E+07	2.004E+03	9.947E+03	1.491E+07	1.002E+03
2028	0	0	22,199,184	24,419,102	3.369E+04	2.698E+07	1.813E+03	9.000E+03	1.349E+07	9.064E+02
2029	0	0	22,199,184	24,419,102	3.049E+04	2.441E+07	1.640E+03	8.144E+03	1.221E+07	8.202E+02
2030	0	0	22,199,184	24,419,102	2.759E+04	2.209E+07	1.484E+03	7.369E+03	1.105E+07	7.421E+02
2031	0	0	22,199,184	24,419,102	2.496E+04	1.999E+07	1.343E+03	6.668E+03	9.994E+06	6.715E+02
2032	0	0	22,199,184	24,419,102	2.259E+04	1.809E+07	1.215E+03	6.033E+03	9.043E+06	6.076E+02
2033	0	0	22,199,184	24,419,102	2.044E+04	1.637E+07	1.100E+03	5.459E+03	8.183E+06	5.498E+02
2034	0	0	22,199,184	24,419,102	1.849E+04	1.481E+07	9.949E+02	4.939E+03	7.404E+06	4.975E+02
2035	0	0	22,199,184	24,419,102	1.673E+04	1.340E+07	9.002E+02	4.469E+03	6.699E+06	4.501E+02
2036	0	0	22,199,184	24,419,102	1.514E+04	1.212E+07	8.146E+02	4.044E+03	6.062E+06	4.073E+02
2037	0	0	22,199,184	24,419,102	1.370E+04	1.097E+07	7.371E+02	3.659E+03	5.485E+06	3.685E+02
2038	0	0	22,199,184	24,419,102	1.240E+04	9.926E+06	6.669E+02	3.311E+03	4.963E+06	3.335E+02
2039	0	0	22,199,184	24,419,102	1.122E+04	8.981E+06	6.035E+02	2.996E+03	4.491E+06	3.017E+02
2040	0	0	22,199,184	24,419,102	1.015E+04	8.127E+06	5.460E+02	2.711E+03	4.063E+06	2.730E+02
2041	0	0	22,199,184	24,419,102	9.183E+03	7.353E+06	4.941E+02	2.453E+03	3.677E+06	2.470E+02

4.4.4 Sample Calculation of Gas Generation from Triangular Production Model

4.4.4.1 Determination of Amount of Gas at the End of Each Year from 1 kg of Bio Degradable Waste

4.4.4.2. For Rapidly Bio-degradable Waste (RBW):

Let us consider a decomposition period of 5 years for rapidly biodegradable solid waste. Figure A-4.1 shows gas production over five year period from RBW.

Let $h^{/}$ be the height of the triangle.

Volume of gas per kg dry weight of RBW = 1.07 m^3/kg of dry weight of RBW

$1/2 \times 5 \times h^{/} = 1.07$

$h^{/} = 0.428\ m^3/kg/yr$

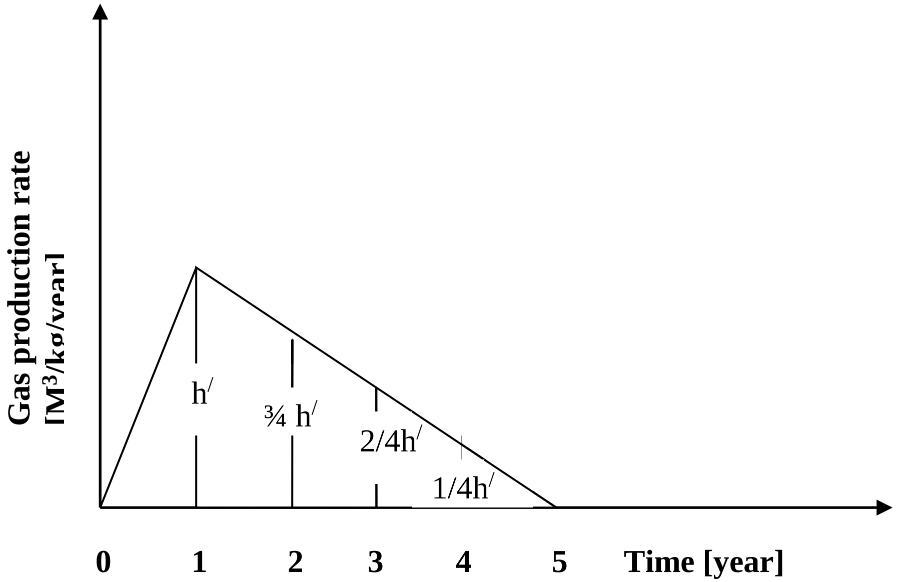

Figure A-4.1 Gas production over five year period from RBW

Table A-4.17 Gas production distribution over the five years period

End of year	Rate of gas production(m^3/yr/kg of dry weight of RBW)	Gas production (m^3/kg of dry weight of SBW)
0	0	0
1	0.428	0.214
2	0.321	0.3745
3	0.214	0.2675
4	0.107	0.1605
5	0	0.0535
Total	1.07	1.07

4.4.4.3 For Slowly Bio-degradable Waste [SBW]:

Let us consider a decomposition period of 15 years for slowly biodegradable solid waste. Let $h^{//}$ be the height of the triangle.

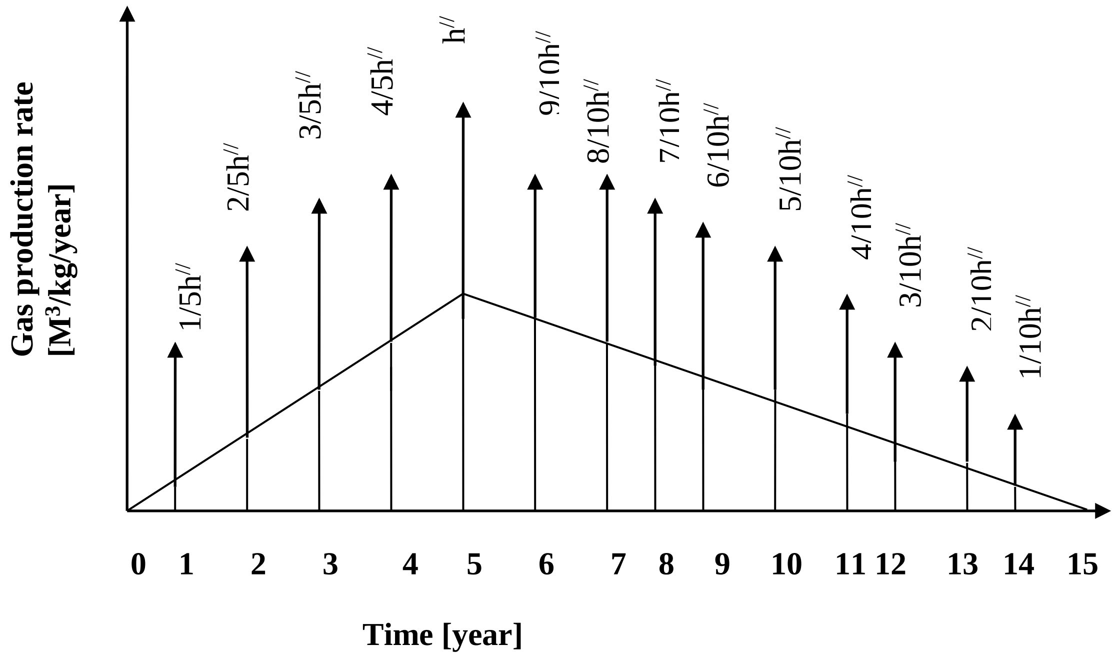

Figure A-4.2 Gas production over fifteen year period from SBW

Volume of gas per kg dry weight of RBW = 1.11 m^3/kg of dry weight of_SBW

$1/2 \times 15 \times h^{//} = 1.11$

$h^{/} = 0.148$ m^3/kg/yr

Table A-4.18 Gas production distribution over the fifteen years period

End of yr	**Rate of gas production(m^3/yr/kg of dry weight of RBW)**	**Gas Production (m^3/kg of dry weight of SBW)**
0	0	0
1	0.0296	0.0148
2	0.0592	0.0444
3	0.0888	0.074
4	0.1184	0.1036
5	0.148	0.1332
6	0.1332	0.1406
7	0.1184	0.1258
8	0.1036	0.1110
9	0.0888	0.0962
10	0.0740	0.0814
11	0.0592	0.0666
12	0.0444	0.0518
13	0.0296	0.0370
14	0.0148	0.0222
15	0	0.0074
Total	1.11	1.11

4.4.4.4 Calculation of Yearly Gas Production

(a) Calculation of biodegradability factors

Let us assume that percentage of biodegradable portion for Rapidly Biodegradable Solid Waste and Slowly Biodegradable Solid Waste are 75% and 50% respectively.

Fraction of waste that is rapidly biodegradable= [14.91/100] × 0.75=0.112 kg of dry weight of RBW /kg of total waste [Dry weight of RBW component = 14.91 Kg (Table 4.14)]

Fraction of waste that is slowly biodegradable= [5.501/100] ×0.50 =0.027 kg of dry weight of SBW/kg of total waste [Dry weight of SBW component = 5.501 Kg (Table 4.16)]:

i) Total amount of gas produced per kg of rapidly biodegradable waste = Gas_{RBW} = 0.112 m^3 /kg of total waste

ii) Total amount of gas produced per kg of slowly biodegradable waste = Gas_{SBW} = 0.027 m^3 /kg of total waste

Table A-4.19a Yearly gas production for solid waste with 75% and 50% bio-degradability factor of RBW & SBW

End of Year	Gas generation from rapidly bio-degradable waste (m^3/kg of total waste)	Gas generation from rapidly bio-degradable waste (m^3/kg of total waste)	Total Gas generation (m^3/ kg of total waste)
0			
	0	0	0
1			
	0.023968	0.0004	0.024368
2			
	0.041944	0.001199	0.043143
3			
	0.029960	0.001998	0.031958
4			
	0.017976	0.002797	0.020773

5			
	0.006499	0.003596	0.009588
6			
		0.003796	0.003796
7			
		0.003397	0.003397
8			
		0.002997	0.002997
9			
		0.002597	0.002597
10			
		0.002198	0.002198
11			
		0.001798	0.001798
12			
		0.001399	0.001399
13			
		0.000999	0.000999
14			
		0.000599	0.000599
15			
		0.000200	0.000200
16			
Total			0.14981

4.4.4.5 Sample Calculation for Gas Collection for the Year 1988

Total Gas generation rate in the year 1988 = 0.024368 m^3/ kg of total waste

Total Gas generation in the year 1988 = 8.23 $\times 10^5$ MT

Total gas generation in the year 1988 = (8.23×10^{8} kg × 0.024368 m^3/ kg) = 20054864 m^3

Total methane generation = (20054864 m^3 × 0.5) = 10027432 m^3/year

1 m^3/year = 6.67148×10^{-4} MT/year

Total methane generation in the year 1988 = ($10027432 \times 6.67148 \times 10^{-4}$) = 6664.59 MT/year

So, total methane generation from the year 1987 to 2011 = 12,27,014 MT,

Total methane entrapment from the year 1987 to 2011 = 1,73.871 MT

Considering 50% recovery for open disposal site total 86,936 MT can be recovered upto year 2021 i.e 10 years after closure.

4.4.5 Calculation of Power Generation Potential from Existing Disposal Site, Dhapa

4.4.5.1 Sample Calculation of Power Generation for the Year 2013

Gas generation from MSW in the developing country like India, where biodegradable and inert wastes are high, 40% weightage to Triangular model and 30% each for IPCC and LandGEM model is recommended.
So, quantity of methane recovery in 2013 is 22848.79 MT;

1 m^3/year = 6.67148×10^{-4} MT/year;

So, methane recovery for the year 2013 = [(22848.79115 x 1000)/6.67148] = 34248459.33 m^3/year.

Methane recovery for the year 2013 = [34248459.33 x 0.0968] cf/day

Energy content = 500 Btu/cf.

Heat rate for IC engine = 12000 Btu/kWh;

Gross power generation potential for the year 2013 = [3315250.863 cf/day x 500 Btu/cf x (1/12000)] / 24 = 5755.64386 KW = 5.76 MW

Table A-4.19b Gross power generation potential from existing disposal site Dhapa

Year	**Recovery (50%) in MT/year (30% IPCC; 30% Landgem; 40% Triangular model**	**Recovery (50%) in m^3/year**	**Recovery (50%) in cf/day**	**Energy content(Btu/cf)**	**1/Heat rate(kWh/Btu)**	**Gross Power generation potential(kW)**
2012	0	0	0	500	8.33333E-05	0
2013	22848.79115	34248459.33	3315250.863	500	8.33333E-05	5755.64386
2014	16974.37838	25443197.58	2462901.525	500	8.33333E-05	4275.870704
2015	12444.57243	18653390.89	1805648.238	500	8.33333E-05	3134.805969
2016	9321.350814	13971938.48	1352483.645	500	8.33333E-05	2348.061884
2017	7598.922768	11390160.46	1102567.532	500	8.33333E-05	1914.179743
2018	6635.355798	9945852.791	962758.5501	500	8.33333E-05	1671.455816
2019	5795.589203	8687111.71	840912.4135	500	8.33333E-05	1459.917385
2020	5059.69183	7584062.052	734137.2067	500	8.33333E-05	1274.543762
2021	4414.185311	6616500.853	640477.2825	500	8.33333E-05	1111.939727

As methane recovery from the waste disposal site decreases (Table A-4.19b) therefore, installed power generation capacity will be limited to 3 MW.

Annexure 4.5

4.5 LEACHATE GENERATION

4.5.1 Geological Information of Kolkata

Geologically Kolkata belongs to the lower deltaic plain of the Ganga-Padma river system. KEIP studied the soil profile around the periphery of the existing landfill at Dhapa by drilling boreholes at Bantala, Chowbhaga Additional Pump House. The following soil strata were found as shown in Table A-4.20.

Table A-4.20 Soil profile around the existing landfill at Dhapa

Stratum	Soil Type	Thickness (m)	Sat. Hydraulic Conductivity (cm/sec)
I	Fill material (old MSW)	1-4	$3\text{-}6 \times 10^{-6}$
II	Soft brownish grey silty clay	4-6	1×10^{-7}
III	Soft grey silty clay	4-6	1×10^{-7}
IV	Stiff bluish grey silty clay with kankar	4-6	1×10^{-8}
V	Stiff to very stiff bluish grey sandy silty clay with *kankar*	3-4.5	1×10^{-5}
VI	Dense brown silty sand	5-10	1×10^{-3}

The first or uppermost aquifer is about 10 to 20 m thick on an average but yield little water. Below this level another clay, dark brown to grayish brown in colour occur up to a depth of 60 to 100-metre below ground level. From this depth another sand zone occur which comprises of fine, medium and coarse sand and extends up to a depth of 120 to 180 m below ground level. Below this sand zone gravel bed occurs. Tertiary black and sticky clay occurs at the bottom of the sand and gravel zone. Thus the second aquifer occurs between a depth of 80 - 90 m and this aquifer is about 30-50 m thick. This is the most potential and most exploited aquifer of Kolkata. The ground water flow in the Dhapa area is predominantly from east to west (KEIP, 2005), (Sengupta, 2009).

4.5.2 Estimation of Landfill Leachate Generation Using HELP Model

(a) For Running the Model Following Data are to be Provided

4.5.2.1 Weather Data and Evapotranspiration Data

Unit – All the input data are given in Metric unit

City – Kolkata

State – West Bengal

Latitude – 22.34 ^{0} N (KEIP, 2005)

(a) Evaporative zone depth – is the maximum depth from which water may be removed by evapotranspiration. The value specified influences the storage of water near the surface and therefore directly affects the computations for evapotranspiration and runoff. It is assumed as 45.7 cm [Because without vegetation capillary draw for clay approximately ranges between 12 to 60 inches. In humid area (like Kolkata), considering fair vegetation rooting depth can vary from 6 to 24 inches. So, approximately 18 inches (45.7 cm) is considered as evaporative zone depth (EPA, 1994a).

(b) Maximum leaf area index (LAI) – is defined as the dimensionless ratio of the leaf area of actively transpiring vegetation to the nominal surface area of the land on which the vegetation is growing. Table A-4.21 lists the LAI values for different conditions of vegetation (EPA, 1994a). LAI value of 0 has been considered i.e. bare ground is chosen because during filling there is no vegetative cover on the top of the waste layer.

Table A-4.21 LAI values for different conditions of vegetation

Bare	**Poor Stand of Grass**	**Fair Stand of Grass**	**Good Stand of Grass**	**Excellent Stand of Grass**
0.0	1.0	2.0	3.5	5.0

(c) Growing season start day and end day – 0. There is no vegetation throughout the year so starting and ending day for the growth of vegetation has been taken as zero.

(d) Average wind speed – 3.54 KPH. Yearly average wind speed of Kolkata is obtained from Daily Meteorological Data during monitoring period (March 2001 – February 2002) for the city of Kolkata (NEERI, 2001).

(e) Quarterly relative humidity data for Kolkata are as follows (NEERI, 2001).

First quarter relative humidity – 67.12 %

Second quarter relative humidity – 71.0 %

Third quarter relative humidity – 77.65 %

Fourth quarter relative humidity – 73.83 %

4.5.2.2 Precipitation, Temperation and Solar Radiation

The Create/Edit option has been used to enter daily weather data. As per the model's requirement daily precipitation (in mm), temperature(in degree Celsius) and solar radiation data (in $MJ/m^2/day$) of Kolkata for 20 years has been obtained for the years 1983 to 2002 from weather monitoring station at Alipore, Kolkata of Indian Meteorological Department (IMD). Daily solar radiation data for Kolkata is calculated from daily available sunshine hours as follows

Average daily radiation (Langley's/day) = $S_{min} + (S_{max} – S_{min})$ * Sky clearance factor

Where, 1 Langley's = 1 $cal/cm^2/day$ = 0.042 $MJ/m^2/day$, Sky clearance factor = available sunshine hours / possible sunshine hours, S_{min} and S_{max} is minimum and maximum solar radiation (in Langley's/day) (Sharma and Gupta, 2005).

Daily available sunshine duration in hours and approximate duration of possible sunshine hours on horizontal surfaces for 22^{nd} Dec, 21^{st} Mar, 22^{nd} June and 23^{rd} Sep is available for Kolkata. These four values are used for four quarters of the year respectively. Solar radiation is probable average values of solar insolation – direct and diffuse – on a horizontal surface at sea level in Langley's/day, and is available for different latitudes. Data is available for 22^0 N and 24^0 N and since Kolkata is situated in between these two latitudes, value at 22.34 ^{0} N is obtained by interpolation method. Average monthly value is used throughout the month.

Example:

Average daily radiation for day 1 = S_{min} + ($S_{max} – S_{min}$) × Sky clearance factor

= 292.2 + (474.3 - 292.2) × 5.8/10.73

= 292.2 + 182.1 × 0.5405

= 390.644 Langley's

= 0.042 × 390.644

= 16.41 $MJ/m^2/day$

4.5.2.3 Soil and Design Data

(a) Landfill general inforation

Landfill Area – 21.4 hectare (KEIP, 2005)

Percent of landfill area where runoff is possible – 80 % (Physical observation)

Method of initialization of moisture storage – User specified

Initial Snow water storage – No (Not applicable in this case)

(b) Layer data

Layer Type – 1 [Waste is porous and so considered as Vertical Percolation Layer]

Layer Thickness – 100 cm, considering 1m lift height per year

Soil Texture – 18 which represents municipal solid waste (900 pcy) having porosity = 0.691(v/v),

field capacity = 0.292 (v/v), wilting point = 0.077 (v/v) and saturated hydraulic conductivity = 0.001 cm/sec. 900 pcy (pound per cubic yard) = 533.95 kg/m^3 (EPA, 1994b).

4.5.2.4 Characteristic of MSW of Kolkata

Density of MSW = 850 kg/m^3. The density of waste varies on account of large variations in waste composition, degree of compaction and state of decomposition. Densities may range as low as 400 kg/m^3 to 1250 kg/m^3. For planning purposes, a density of 850 kg/m^3 may be adopted for biodegradable wastes and with higher values typically 1100 kg/m^3 for inert waste (CPHEEO, 2000).

The physical composition of MSW of Kolkata is given in Table A-4.22 (Chattopadhyay et al., 2009). The MSW has a specific gravity 1.5 and moisture content 46%.

Table A-4.22 The physical composition of MSW of Kolkata

No.	Components	Wet Weight %	Wet Weight Kg	Moisture content%	Dry Weight	Sp. Gravity *	SG * Dry Weight
1	Compostable	50.56	429.76	72.5	118.184	1.1	130.0024
2	Paper	6.07	51.595	6	48.4993	0.9	43.64937
3	Plastic	4.88	41.48	2	40.6504	1.1	44.71544
4	Glass	0.34	2.89	2	2.8322	2.4	6.79728
5	Metal	0.19	1.615	2	1.5827	6	9.4962
6	Inert	29.6	251.6	22	196.248	2	392.496
7	Rubber & leather	0.68	5.78	5	5.491	0.95	5.21645
8	Rags	1.87	15.895	10	14.3055	1.2	17.1666
9	Wood	1.15	9.775	25	7.33125	0.7	5.131875
10	Coconut	4.5	38.25	40	22.95	1.2	27.54
11	Bones	0.16	1.36	5	1.292	0.015	0.01938
	Total	100	850		459.37		682.23

* (The Engineering ToolBox, 2010)

$$\text{Moisture content} = \frac{(\text{Total Wet Weight} - \text{Total Dry Weight}) \times 100}{\text{Total Wet Weight}}$$

$$= \frac{(850 - 459.37)}{850} = 45.96 = 46\ \%$$

$$\text{Total Sp. Gravity} = G = \frac{\sum (\text{Dry Weight} \times \text{Sp. Gravity})}{\text{Total Dry Weight}} = \frac{682.23}{459.37} = 1.485 = 1.5$$

(a) Calculation of total porosity **(Murthy, 1989)**

If γ_d = Dry density of solid waste, γ_w = Density of Water, e = void ratio of the solid waste and n = porosity of solid waste.

Then $\gamma_d = (\underline{G \times \gamma_w}) / (1+e) = 459.37/1000 = 1.5 \times 1 / (1+e)$

$\therefore$ e = 2.265 and n = $e / (1+e)$ = 0.694

From an empirical formula field capacity and wilting point of soil can be calculated roughly though these formulas are not verified for solid waste (EPA, 1994a). Assuming 0 % clay and sand in the solid waste field capacity and wilting point are calculated as follows

Field Capacity = 0.1535 - (0.0018) (% Sand) + (0.0039) (% Clay)
+ (0.1943) (Total Porosity)
= 0.1535 - (0.0018) (0) + (0.0039) (0) + (0.1943) (0.694)
= 0.288

Wilting Point = 0.0370 - (0.0004) (% Sand) + (0.0044) (% Clay)
+ (0.0482) (Total Porosity)
= 0.0370 - (0.0004) (0) + (0.0044) (0) + (0.0482) (0.694)
= 0.070

If a solid waste is compacted its density increases and porosity decreases. Specific gravity and moisture content of waste remaining constant variation of porosity with density is shown below in Table A-4.23

Table A-4.23 Variation of porosity with density of solid waste

Density (kg/m^3)	534	850	1000	1250
Total Porosity	0.81	0.694	0.6	0.55

Keeping density same, porosity of waste can vary with varying moisture content and sp. gravity of waste which in turn depends on the composition of waste. Some combination of sp gravity and moisture content of waste material with a specified density (900 pcy) and same porosity is shown below in Table A-4.24. Therefore from this study it is observed that two different types of waste with different composition (specific gravity and moisture content) can have same porosity.

Table A-4.24 Different combination of specific gravity and moisture that give sane density and total porosity

Density(kg/m^3)	**Sp. Gravity**	**Moisture Content %**	**Total Porosity**
534	0.92	43	0.671
534	1.2	26	0.671
534	1.5	8	0.671

Generally total porosity of MSW varies between 0.4 and 0.67 depending on composition and compaction (Eusuf et al., 2007). MSW of Kolkata has a porosity of 0.694 with sp. gravity 1.5 and 46 % which is close to the default soil texture no 18 of HELP model having porosity 0.691. Saturated hydraulic conductivity of MSW of Kolkata is in the order of 10^{-3} cm/sec (KEIP, 2005).So soil texture 18 has been used throughout the study.

***(b) Initial volumetric soil water content* –** 0.391 (v/v) [Initial moisture content of municipal solid waste in Kolkata is approximately 46% .Moisture content =0.46 x 850 = 391 kg/m^3 of solid waste. Density of water = 1000 kg/m^3. Therefore Volume of water = 391/1000 = 0.391 m^3/ m^3 of solid waste = 0.391 (v/v).

4.5.2.5 Runoff Curve Number Information

Curve number is computed by HELP program based on the following information:

Slope – 1%. Since in this case practically as such no slope is provided but due to program constraints some whole number value has to be provided so 1% is chosen.

Slope Length – 100m (Physical observation)

Soil Texture – 18. Since no cover material is provided during both filling and post filling so topmost layer is always the waste layer i.e. soil texture number -18.

Vegetation – 1. Since there is no vegetative cover during both filling and post filling so as per model specification for bare ground it is 1.

4.5.2.6 Procedure Used to Run the Model

(a) During filling (Active period)

The first simulation is done with the above said data for one year. After one year simulation it gave daily, monthly and yearly average precipitation, runoff, evapotranspiration, leachate through the waste layer. It also gave final moisture content of the first layer as 0.2276 (v/v). Next year above this layer another 100 cm municipal solid waste layer is placed whose initial moisture content is 0.391 (v/v) and the initial moisture content of the previous layer is changed to 0.2276 (v/v). All other data is kept unchanged.

At the end of the 2nd year simulation it gave final moisture content of both the layers which is used as the initial moisture content of those two existing layers respectively in the 3rd year and again a 100 cm fresh waste layer (moisture content 0.391(v/v)) is placed on the top for the 3rd year simulation. This process is repeated for 20 years until the waste height reached to 20 m.

(b) Post filling (Post closure period)

The same 20 m waste layer is simulated for another 20 years with initial moisture content of the layers same as the final moisture content of the layers at the end of active period. The same weather data (1983-2002) is repeated for simulation during post filling, keeping all other data same.

4.5.2.7 Calculation of Area Requirement for Landfill

Basic Data Requirements

Average waste deposited per day	**=** 3000T/d
No of working day per year	=364 (except DOLJATRA)
Total waste deposited per year	=364 × 3000 = 1092000 T/d
Average rate of increase of waste generation	=1 %
Proposed life of landfill	=20 year
Total quantity of waste which has to landfilled in 20 years	=22.02 × 1092000 = 24045840 T
Average density of waste	=0.85 T/d
Average total volume of waste	=24045840/0.85 = 28.29×10^6 m^3

Case a

If the existing condition of the waste dump in Dhapa is considered, then height of the waste pile is 20m and it is almost a vertical structure. Therefore, the required area = 28.29×10^6 m^3/ 20 m = 1.4145 $\times10^6$ m^2 = 1.4145 km^2. If a square area is considered then L×B = (1.18 × 1.18) km^2.

Case b

In this case landfilling is done using the area method maintaining proper side slope with earth embankments. The side slope of the waste pile is taken as 1:3 (CPHEEO, 2000) and road width as 3 m. Thus the waste volume takes the shape of an inverted frustum as shown in Figure A-4.3. The total height is fixed at 20m so it is considered that waste in dumped in four phases in 20 year. In each phase waste is dumped upto 5m. Total volume of waste is same as case a i.e. 28.29×10^6 m^3. The total calculated area comes to be 1.67 km^2. If a square area is considered then L×B = (1.29 × 1.29) km^2. Figure 4.25 shows the pictorial representation of both case (a) and case (b).

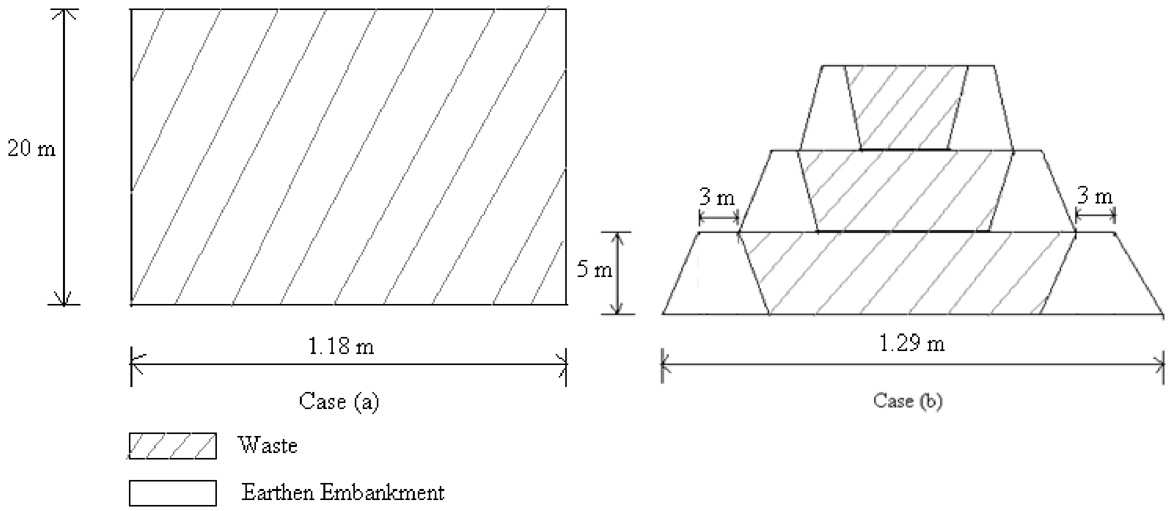

Figure A-4.3 A pictorial representation of case (a) and case (b)

4.5.3 Estimation of Leachate Quantity Using Water Balance Method (WBM)

4.5.3.1 Basic Data

(a) Waste quantities

Waste deposited per day - 3000 Tones

Number of operating days - 364 (except DOLJATRA)

Waste deposited per year - 1092,000 Tones

(b) Waste characteristics

Compacted specific weight of the waste - 0.85 T/m^3 (CPHEEO, 2000)

Initial moisture content of the waste - 46% by mass (ref. section 4.2)

(c) Landfill characteristics

General

Filling of waste has been done for 20 years at the rate of 1m lift height /year.

i. **Lift height** - 1 m

ii. **Waste cover ratio** - Nil, as landfill is uncovered

iii. **Number of lifts** - 20 (one corresponding to each year)

Final Cover material - No cover material is used

Gas production

i. The year wise total rate of gas production from a landfill from 100 MT waste is taken from as shown in Table 4.31

ii. Water consumed in the formation of landfill gas - 0.16 kg/$m^3$of gas produced (Tchobanoglous et. al., 1993)

iii. Water present as water vapour in landfill gas - 0.016 kg/m^3 of gas produced (Tchobanoglous et. al., 1993)

iv. Density of landfill gas - 1.34 kg/m^3

4.5.3.2 Rainfall Quantities

Unlike HELP model here only an average infiltration rate has to be provided. Infiltration is calculated from average annual rainfall minus the sum total of average runoff and evapotranspiration. Average annual rainfall of Kolkata as calculated from daily precipitation data from 1983 to 2002 is 1850 mm/year (IMD, Kolkata). In order to find the average runoff and evapotranspiration percentage HELP model was run with 1987 daily weather data as on that year average annual rainfall was 1850mm. All other data and simulation process was same as done in estimating leachate generation from the open dumping ground at Dhapa, Kolkata using HELP model. The results of these simulations are as follows:

i. Rainfall = 1850 mm/yr = 5.1 mm/day

ii. Runoff = 130.968 mm/yr = 0.36 mm/day = 7.08 % of rainfall

Co-efficient of run off for parks and undeveloped areas is considered as 10 to 20%. As this is active dump site with much more void space and un-compacted loose solid waste so run off co-efficient is considered as 7% (CPHEEO, 2000).

iii.Evapotranspiration rate = 931.206 mm/yr = 2.55 mm/day = 50.34 % of rainfall.

Evaporation rate in dry season is 2.85 mm per day and in wet season 1.96 mm per day. For Kolkata, wet season is considered for 5 months (June to October) and dry season is considered for rest of the seven months. Therefore average evaporation rate can be taken as 2.48 mm/day (ADB, 2005).

Therefore, rainfall that infiltrates the into the waste during the active period i.e first 20 years of operation = Rainfall – (Runoff + Evapotranspiration)

= 1850 – (130.968 + 931.206)

= 787.826 mm/year = 0.789 m/yr = 2.16 mm/d

Therefore infiltration is 42.59 % of rainfall approximately. Since in this case no final cover is considered even after the end of active period rainfall and infiltration value is kept constant for next 20years also.

4.5.4 Determination of Ground Water Concentration of Metal and Organics With the Help of EPACMTP Model

The EPACMTP model has been used to evaluate migration of waste constituents through the ground-water pathway from Kolkata's MSW landfill to down-gradient arbitrary drinking water wells and establish protective levels in waste. Landfill without any cover or liner system is treated as a finite depleting source. Since a finite source is being simulated, both the unsaturated and saturated zone transport modules are implemented in the transient mode and flow in steady state. Monte-Carlo method is used with a combination of constant, derived and distribution of variables to find the contaminant concentration at the receptor well. Both toxic metal and organics has been simulated.

4.5.4.1 Data Requirements

(a) Control parameters

Assumed values of the EPACMTP control parameters, Monte Carlo control parameters, Deterministic control parameters and Finite source specific data are give in Table A-4.25, Table A-4.26, Table A-4.27 and Table A-4.28 respectively.

Table A-4.25 EPACMTP control parameters

Variable	Description	Assumed Value	Comments
**	Stands for comment records for any line	**	
GRPCOD	Record identifier; must be 'GP' always	GP	
MC	Monte Carlo control parameter = T (True) for Monte Carlo run (Default) = F (False) for deterministic run	T	
IVADS	Control parameter for unsaturated zone simulation = 0 if no unsaturated zone modeling is required = 1 if unsaturated zone modeling is required (Default)	1	
ISTMD	Control parameter for saturated zone simulation = 0 if no saturated zone modeling is required = 1 if saturated zone modeling is required (Default).	1	
NSPC	Number of contaminant component species in the system (Default)	1	
KFDM	Simulation method = 0 finite element (leachate concentration is constant over a prescribed period of time and then goes to zero). = 1 finite difference (the leachate concentration diminishes gradually to reflect depletion of the contaminant mass in the waste unit).	1	Finite depleting source option is a physically best justified assumption for landfills.
KFS	Control parameter for selecting continuous (infinite) source or finite source = 0 for continuous source option = 2 for landfill finite source option.	2	
FULL3D	Logical control parameter for selecting fully 3D or quasi3D saturate zone modeling option = T(True) for fully 3D simulation (for single iteration purpose) = F(False) for quasi-3D simulation (Multi number of iteration from 100 to 1000). Note: FULL3D = F(False) should be used for Monte Carlo simulation	F	
METL	Logical control parameter for metals	T	For simulating

	simulation = T(True)for metals modeling = F(False)for non metals modeling		organics 'False' option is chosen
KDVL	Integer control parameter for selecting the scheme for determining the metals sorption isotherm = 1 Use the method of Loux for calculating k_d from pH = 2 Use linearized MINTEQA2 isotherm = 3 Use nonlinear MINTEQA2 isotherm = 0 (if METAL = False or 0).	2	The depleting source landfills cannot be used to model metals that have non-linear sorption isotherms, so linearized isotherm is used.
Tchk	Logical variable to check minimum transmissivity = F (False) if no transmission can occur in the time of vertical transport of pollutant = T (True) if yes (default) vertical as well as horizontal transmission occur in the time of pollutant transport	T	
RGNL	Logical variable for Regional Site-based Analysis = F (False) for (Nationwide Analysis deterministic analysis) = T (True) if yes (default Mote Carlo analysis)	F	Though Monte-Carlo analysis has been done yet site specific infiltration, recharge and soil characteristics has been given as a constant value, so False option is chosen to do a semi deterministic analysis
STYP	Control parameter for selecting the type of waste source = 0 for Landfill = 1 for SI = 2 for WP = 3 for LAU	0	
ILNR	Control parameter for landfill liner condition = 0 for landfill with no liner = 1 for landfill with clay liner = 2 for landfill with composite liner	0	The difference between these 3 options is based on amount of leakage.

Table A-4.26 Monte Carlo control parameters

Variable	Description	Assumed Value	Comments
NRUN	Number of iterations in both Monte Carlo and deterministic run. (Recommended value is 1000 or greater for Monte -Carlo run).	10,000	
ECHO	Logical variable for creating output 'IVAR' files = F(alse) ; IVAR files should not be created (Default), = T(rue) ; IVAR files should be created	T	
CHEK	Logical variable indicating if generated random variables are restricted to lie within specified upper and lower bounds = F(False) if no limit of the variable is used = T(True) if maximum and minimum limit of variable is used	T	
CORR	Logical variable indicating if statistical correlation is to be used in generating unsaturated zone parameters, = F(alse) if no co-relation is used for indicating variable = T(rue) if co-relation is used for indicating variable	F	
LDRV	Logical variable indicating if derived Monte Carlo variables are constrained to lie within specified upper and lower bound = F(False) if no bounds for the variable is present = T(True) if bounds for the variable is present	T	
LYCH	Logical variable indicating if observation well is constrained to lie within the approximate areal extent of the plume = F(False) if no = T(True) if yes	F	
LZCH	Logical variable indicating if observation well depth is constrained to lie within the approximate vertical plume depth = F(False) if no, = T(True) if yes	F	
SBND	Logical variable indicating if the '.BND' output file is to be created = F(False) if no (Default), = T(True) if yes	T	
ALLRUN	Logical option control parameter to set aggregation =T(True) to automatically aggregate Monte Carlo results overall soil and cover types = F(False) to perform run only for the selected soil and	F	

	cover type.		
TCUTOFF	Value of the upper time limit, in years, for determining the receptor well maximum concentration in finite source modeling. Note: Maximum of 10,000 years can be used	10,000	This is varied to find the concentration breakthrough curve
VERBOSE	Character varible , used in EPA CMTP =F(False) always for land landfill with no liner	F	

Table A-4.27 Deterministic control parameters

Variable	Description	Assumed Value	Comments
ISBC	Contaminant source boundary condition = 0 if contaminant flux(mg/kg of waste concentration) is given = 1 if contaminant concentration (mg/l of leachate concentration) is given	1	
IBAT	Control parameter for decaying source boundary condition, = 0 if no (continuous source or non-degrader infinite source) = 1 Biochemical decay (hydrolysis) = 2 Physical decay due to leaching (source depletion) = 3 Combine 1+2	2	
IUST	Control parameter indicating whether transport in the unsaturated zone is steady- state or transient, = 0 for transient (if KFS=1 or 2), continuing only for short time = 1 for steady-state (if KFS=0).	0	Blank if IVDS = 0 or no unsaturated zone modeling is required
ISST	Control parameter indicating whether transport in the saturated zone is steady- state or transient, = 0 for transient (if KFS=1 or 2), continuing only for short time = 1 for steady-state (if KFS=0). Note: Blank if ISTMD = 0 or no saturated zone modeling is required	0	
NTOB	Number of time values at which concentration at the water table is to be computed. Note: Blank if ISTMD = 1,	1	

	and/or IUST=1, and/or MC=T(True).		
NTS	Number of time values at which receptor well concentrations in the saturated zone are to be computed Note: NTS = -1 or 0 to run finite source option in Monte-Carlo mode. Bank if ISTMD=0, or ISST=1	1	
NWELLS	Number of receptor wells in the saturated zone. Note: Blank if ISTMOD = 0 or no unsaturated zone modeling is required.	1	
QRMAX	Maximum groundwater vertical flux ratio for saturated zone contaminant transport solution. Recommended value is 0.02. Note: Blank if ISTMD = 0.	0.02	
NRATIO	Number of ratios of CW/CL to be used for finite source scenario (KFS=2). Note: Value should be 1 (Default) to 8. Blank for a continuous source analysis (KFS=0) or a finite source analysis with a constant	1	
ICRW	Control parameter indicating the time-dependent receptor well concentration to be computed for the finite source analysis = 0 compute peak receptor well concentration (Default) = 1 compute temporally averaged receptor well concentration Note: When ICRW=1 is used, the averaging period for each of the species must be specified in variable CARC, in the chemical specific data records.	1	Since both 30 and 70 year average concentration are required ICRW is set as 2
IWLOC	Control parameter for ground water type (GWT) =F(False) no specified ground water type (Default) =T (True) for specified ground water type	T	Noncarbonate GWT has been used in all cases

Table A-4.28 Finite Source specific data

Variable	Description	Assumed Value	Comments
FS	Finite Source Specific data records Sequential values (in increasing order) of the ratios C_W/C_L(Nratio) to be used in the finite Source Monte Carlo analysis	Variable	Different C_W/C_L ratio has been used for different metal and organics

(b) Source-specific parameters

(i) Waste unit area and depth

Dhapa landfill area = 21.4 Ha (KEIP, 2005).

Considering square unit EPACMTP computes landfill length and breadth. Thus these two parameters are kept as derived parameters. Depth of Dhapa Landfill = 20m.

(ii) Initial leachate concentrations (C_{zero})

In our case we have considered landfill as a finite depleting source and we have provided the initial leachate concentration for each metal or organics we have simulated.

(iii) Infiltration and recharge rates

Infiltration rate is the rate of leakage from the bottom of the landfill. Infiltration or leakage from 20m high landfill (at Kolkata's landfill site Dhapa) without any top cover or liner is estimated to be 986 L/m^2/year. This infiltration rate is kept constant.

The recharge rate is the net rate of vertical downward percolation through the unsaturated zone to the water table in the surrounding area of the landfill and was determined for silty loam soil type considering average annual rainfall of Kolkata to be 1850 L/m^2 using the HELP model. Poor strand of grass has been considered on the top of 60 cm soil layer to determine recharge rate. The recharge rate was estimated as 446.0L/m^2/year. Also giving the same 60 cm top soil cover on the top of 19m waste pile estimated leakage is around 456.62 L/m^2/year (ref. Table 4.14). So a recharge rate of approximately 450 L/m^2/year is used. This recharge rate is kept constant.

The source infiltration rate can be different from the recharge rate for a variety of reasons, including engineering design of the waste site, topography, land use, and vegetation. In the case of landfills, if the cover type and soil type underneath the unit are the same, the infiltration rate will be the same as the regional recharge rate for that soil type as shown above.

(iv) Source leaching duration

The length of the pulse duration, in the case of landfills, is determined by the code based upon the initial amount of contaminant in the landfill, infiltration rate, landfill dimensions, waste and leachate concentration and waste density. In the case of landfills, the waste is left in place after closure of the site, and may continue to leach over a long period of time. The landfill scenario is therefore best handled as follows (EPA, 2003b):

In the Monte Carlo analysis, the pulse duration, t_p, is treated as a derived parameter and can be set in one of two ways. Specifically, the amount of contaminant leached over the time period t_p must be equal to the amount of contaminant initially present in the landfill.

Method 1, Equation 4.4.1 below assumes that source contamination, C_L, is constant until an amount of mass equal to the initial mass is depleted.

$$t_p = \frac{d \cdot F_h \cdot P_{hw}}{I} \cdot \frac{C_w}{C_L}$$

…….Eqn (4.4.1)

Where, d = Depth of waste unit (m)

F_h = Volume fraction of waste unit that contains waste of concern

P_{hw} = Density of the waste (g/cm3)

I = Areal infiltration rate (m/y)

C_L = Leaching concentration of constituent (mg/L)

C_w = Total leachable waste concentration of the constituent (mg/kg)

Alternatively, Method 2, Eqn. 4.4.2 below, calculates tp from a more rigorous analysis that considers the decrease in the source concentration, C_L, due to leaching from the waste. In this case, the leachate concentration decreases exponentially, with time:

$$C_L = C_L^0 e^{-\left(\frac{I}{d\ F_h\ P_{hw}\ \frac{C_w}{C_L^0}}\right)t}$$

……..Eqn (4.4.2)

Where, C_L^0 = Initial leachate concentration (mg/L) and t = Time (yrs)

In our case we have considered landfill as a finite depleting source and so Method 2 has been followed by the model.

(v) Waste density

Density of MSW of Kolkata has been 0.85g/cm^3 (CPHEEO, 2000).

(vi) Hazardous fraction of waste

The input values for waste density and fraction of the waste unit that is occupied by the waste, are required only for the landfill scenario. In our case it is taken as 1 since we have considered that 21.4 Ha of the landfill is entirely filled up with the waste.

(vii) Source transformation rates

The model has the capability to account for first-order type chain decay reactions inside the waste source. By default, however, the source transformation rate is set to zero, i.e., it is assumed that the contaminant does not degrade inside the waste unit.

(viii) Depth below ground surface

The depth below grade is defined as the depth of the bottom of the landfill below the surrounding ground surface. If a non-zero value is entered for this input, then the thickness of the unsaturated zone beneath the landfill is adjusted accordingly. In our case this value is zero as the base of the landfill is on the ground surface.

(ix) ICLR, ISTYPE and IGWR (EPA, 2003a)

ICLR, ISTYPE and IGWR are climate center index, soil type index and hydrogeologic environment index respectively. These indexes are assigned to each 102 climate centers, to three soil type and to each of 13 hydrogeologic environments respectively. During a Monte-Carlo run these indexes helps to specify which infiltration and recharge rates, soil type (unsaturated zone soil characteristics) and hydrogeologic environment (aquifer characteristics) should be used to model a given WMU. EPACMTP characterizes an aquifer by four parameter – aquifer thickness, aquifer hydraulic conductivity, aquifer hydraulic gradient and depth to ground water. If the subsurface hydrogeological environment is unknown, or it is different from any of the twelve main types used in EPACMTP, the subsurface environment Type 13 can be used which provides US's national average values.

Infiltration equal to 986L/m^2/year and recharge rate 450 L/m^2/year for Kolkata was kept constant. To match Kolkata's soil profile, only silty clay loam was used for the unsaturated zone (KEIP, 2005). Mean aquifer characteristics like aquifer hydraulic conductivity of 1890m/year and aquifer hydraulic gradient of 0.0057 m/m was used. In Kolkata the first aquifer is found at a depth of 10 m and has a thickness of 10 m (KEIP, 2005). Since as all these parameters are kept at constant values, ICLR, ISTYPE and IGWR was not used.

(c) Chemical specific parameters

(i) For all constituents

Molecular diffusion coefficient (Di)

Molecular diffusion coefficient values for some common organic constituents has been provided by EPA(EPA, 2003a). If data are not available for the modeled constituent, this parameter should be set to zero, which will be a conservative approach. Otherwise hydrodynamic dispersion and molecular diffusion are used to calculate the dispersion coefficient, one of the variables in the transport equation.

Constituent drinking water standards

If a finite source simulation is being performed the applicable drinking water standard (DWS) for each constituent in the waste must be provided. The drinking water standard (mg/L) is the level assumed to be protective. The DWS is used in finite source scenarios when the depleting landfill source option is invoked to determine the duration of the exponentially decaying concentration boundary condition (t_p). Leaching is assumed to continue until the constituent concentration in the leachate has dropped below the drinking water standard. The leaching duration, t_p, is determined by setting Equation 4.4.2 equal to the DWS and solving for t (time).

Exposer period

If a finite source simulation is being performed the exposure averaging period is used in the risk calculations for determining the drinking water standard. Usual values of the latter parameter are 70 years (lifetime exposure) or 30 years (average residence time).

Molecular weight (MW)

MW has been provided for each metal and organics simulated.

(ii) Organic constituents

Organic carbon partition coefficient (k_{oc})

This parameter is applicable to organic constituent which tend to sorb onto the organic matter in soil or in an aquifer. The organic carbon partition coefficient is a constituent-specific input parameter; values for some common organic constituents are included in the model documents (EPA, 2003a). If constituent-specific data for the organic to be modeled are not available, this input value can be set to zero – a value that means the constituent's ground-water concentration will not be decreased due to adsorption.

Chemical hydrolysis rates

Dissolved phase and sorbed phase decay rates can be specified directly, or they can be derived based on chemical specific hydrolysis rate constants and the ground-water temperature and pH. In the latter case, the hydrolysis rate constants for each constituent has been be obtained from EPA reference documents (EPA, 2003a)

Dissolved phase hydrolysis decay rate (λ_1)

The dissolved phase hydrolysis decay rate has been internally derived by the model. The acid-catalyzed, base-catalyzed, and neutral hydrolysis rate constants were combined to yield a composite first order hydrolysis rate in the dissolved phase:

$$\lambda_1 = K_a^T [H^+] + K_n^T + K_b^T [OH^-]$$

…….Eqn (4.4.3)

Where, λ_1 = First-order decay rate for dissolved phase (1/yr)

K_a^T, K_n^T, K_b^T = Hydrolysis rate constants

[$H+$] = Hydrogen ion concentration (mole/L)

[$OH-$] = Hydroxyl ion concentration (mole/L)

[$H+$] and [$OH-$] are computed from the pH of the soil or aquifer using

$[H+]=10^{-pH}$, $[OH-]=10^{-(14-pH)}$

Sorbed phase hydrolysis decay rate (λ_2)

The sorbed phase hydrolysis decay rate has been internally derived by the model. For the case of sorbed phase hydrolysis, evidence suggests that base-neutralized hydrolysis can be neglected and that the acid-neutralized hydrolysis rate is enhanced by a factor of α. Thus, the effective sorbed phase decay rate can be expressed as:

$$\lambda_2 = \alpha K_a^T [H^+] + K_n^T$$

……..Eqn (4.4.4)

where α = acid-catalyzed hydrolysis rate enhancement factor for sorbed phase with a typical value of 10.0, and λ_2 = decay constant for the sorbed phase [1/yr]. K_a^T and K_n^T are acid and neutral catalyzed hydrolysis rate constant respectively (1/mole/yr).[$H+$] = Hydrogen ion concentration (computed from the pH of the soil or aquifer using $[H+] = 10^{-pH}$).

Hydrolysis rate constant

The acid-catalyzed, K_a^{Tr} (1/mol-yr), neutral rate constant, K_n^{Tr} (1/yr) and base-catalyzed rate constant, K_b^{Tr} (1/mol-yr) is used to quantify how the rate of the hydrolysis reaction is affected by the pH of the subsurface i.e in acidic, neutral and alkaline conditions. The values of the rate constants for some common organic constituents are included in the model document (EPA, 2003a). If constituent-specific data for the organic to be modeled are not available, this input value can be set to zero – a conservative value that means the constituent’s ground-water concentration will not be decreased due to chemical hydrolysis.

Reference temperature

The chemical-specific hydrolysis rate constants are measured at a constant reference temperature of 25^0 C. The reference temperature is used in the Arrhenius equation to convert the input hydrolysis rate constants to the actual temperature of the subsurface.

(d) Metal specific parameters

In modeling metals transport in the unsaturated zone, EPACMTP uses the complete, nonlinear sorption isotherms and for saturated zone, EPACMTP uses linearized MINTEQA2 isotherms, based on the assumption that after dilution of the leachate plume in ground water, concentration values of metals will typically be in a range where the isotherm is approximately linear. This assumption may not be valid when metals concentrations in the leachate are high.

Since the depleting source scenario is most appropriate for a landfill waste management scenario, where the waste accumulates during the active life of the unit, but leaching may continue for a long period of time after the unit is closed, therefore in our case all metals have been modeled using linearized isotherm that calculates a single value of K_d from a nonlinear isotherm (EPA, 2003b).

The following sections describe the available options and the input parameters required to perform ground-water fate and transport modeling of metal constituents.

(i) Metal identification number (ID)

The metal identification number is simply an arbitrary number assigned to each metal, which is used by the EPACMTP model to identify which supplemental input file contains the appropriate non-linear isotherm data.

(ii) Soil and aquifer pH

The pH distribution obtained from nearly 25,000 field analysis has been provided by EPA (EPA, 2003a). The data are represented by an empirical distribution with low and high values of 3.2 and 9.7, respectively and a median value of 6.8. For modeling purposes it is assumed that the unsaturated zone and the saturated zone have the same pH value.

(iii) Fraction iron-hydroxide adsorbent

Iron hydroxide represents one of the dominant adsorbents for metal sorption in environmental systems, and is an important in determining the extent to which a constituent's transport through the ground-water pathway is retarded due to adsorption. Limited available data on iron hydroxide content is used to define a uniform distribution which results in a low value of 0.0126 and a high value of 1.115 percent iron hydroxide by weight.

(vi) Leachate organic matter

Many organic acids found in leachate have significant metal-complexing capacity that may influence metal mobility. The model uses a uniform distribution for the concentration of anthropogenic dissolved organic carbon (DOC) in the leachate. The distribution has a low value of 0.001173 mg/L, and a high value of 0.00878 mg/L.

(v) Percent organic matter

When modeling a metal using the MINTEQA2-derived isotherms, the default distribution for percent organic matter in the unsaturated zone is based on the default distribution for percent organic matter for the silty loam soil type. The default distribution type has a minimum value is 0.0 and the maximum value is 8.51. Conversely, when modeling a metal using the MINTEQA2-derived isotherms, the default distribution for fraction organic carbon in the saturated zone is based on the default distribution for percent organic matter for the sandy loam soil type with mean and standard deviation of $4.32\ 10^{-4}$ and 0.0456, respectively, and an upper bound of 0.0638.

(vi) Ground-water type (IGWT)

The ground-water type is simply an arbitrary number assigned to provide a simple means of specifying which set of isotherms should be used (there is one set for carbonate ground water and another set for non-carbonate ground water). Since Kolkata region has sand and gravel aquifer (KEIP, 2005) non carbonate ground water type which represents unconsolidated sand and gravel aquifer with a natural pH of 7.4 has been used.

4.5.4.2 Unsaturated Zone

(a) Thickness of the unsaturated zone

The unsaturated zone thickness, or depth to the water table for each waste site is taken as 20m since generally water table or the first aquifer in Kolkata is found at this depth (KEIP, 2005).

(b) Soil hydraulic characteristics

Kolkata generally has silty clay loam soil type ((KEIP, 2005) so specific values for this soil characteristic are set to available constant value (EPA, 2003a). These are used as an input to the unsaturated zone flow module and are used to calculate the moisture content in the soil under a given rate of leachate infiltration from the WMU.

(c) Longitudinal dispersivity

The longitudinal dispersivity of the soil was set as derived variable and is computed as a linear function of the total depth of the unsaturated zone by the model.

(d) Freundlich sorption coefficient and Freundlich isotherm exponent

For organic compounds, the two isotherm parameters required are the Freundlich sorption coefficient and the Freundlich exponent. When the isotherm is linear, the leading Freundlich coefficient is known as the solid-liquid phase distribution coefficient (k_d) which is set as a derived variable. Since isotherm is linear for organics and linearized MINTEQA2 Adsorption Isotherm is used for metals, Freundlich exponent is set to 1.

(e) Chemical and biological transformation coefficients

By default the first order biodegradation rate constant is set to zero but wherever available, specific value has been given as input. On the other-hand chemical degradation rate is a derived parameter.

4.5.4.3 Saturated-Zone Simulation

(a) Particle diameter

For Monte Carlo analyses, porosity and bulk density are determined from the mean particle diameter. The mean particle diameter distribution is a frequency distribution based on analysis of 11,000 samples of US soil by EPA. The particle sizes ranges from a lower bound of 4×10^{-4} cm to an upper bound of 0.8 cm (EPA, 2003a).

(b) Porosity

Total Porosity is set as a derived parameter and is calculated from the particle diameter by the model.

(c) Bulk density

The aquifer bulk density (g/cm3) directly influences the retardation of solutes. It is set as a derived parameter and computed from aquifer porosity.

(d) Aquifer characteristic

The hydrogeological databases for 13 hydrogeologic environments (EPA, 2003a) were collected by independent investigators for approximately 400 hazardous waste sites throughout the United States. The aquifer characteristics included the following data:

For Kolkata the aquifer saturated thickness is set as 10 m and depth to ground water table as 20m (KEIP, 2005). The aquifer hydraulic conductivity is set at 1890 m/year and the hydraulic gradient is assigned a value of 0.0057. These two values have been taken from the unknown hydrogeologic environment database.

(e) Seepage velocity

The seepage velocity is related to the aquifer properties through Darcy's law. It is set as a derived parameter and calculated from hydraulic conductivity, hydraulic gradient and effective porosity.

(f) Retardation factor

The retardation factor (R) is a derived variable and is computed from k_d, bulk density and porosity. When the sorption isotherm is nonlinear, R is no longer constant as in case of linear adsorption isotherm but depends on k_d-concentration relation.

(g) Dispersion coefficients

The model computes the longitudinal, lateral, and vertical dispersion coefficients as the product of the seepage velocity and longitudinal (D_L), transverse (D_T) and vertical (D_V) dispersivities.

(h) Temperature

A distribution of groundwater temperature has been used with a mean value of 14.4^0C.

(i) Ground water pH

Since we have chosen non carbonate ground water type, ground water pH is set at 7.4.

(j) Fractional organic carbon content

The default distribution for fractional organic carbon content has a mean and standard deviation of 4.32×10^{-4} and 0.0456, respectively and upper and lower limits of 0.064 and 0.0, respectively.

(k) Chemical & biological transformation coefficients

The saturated zone derivation of the overall decay is calculated the same way as for the unsaturated zone. Although the temperature and pH values are assumed not to vary between the saturated and unsaturated zones, the porosity and bulk density values may differ, leading to a difference in the decay coefficients for the two zones.

(l) Freundlich sorption coefficient and freundlich isotherm exponent

For the saturated zone, these two parameter are used in the same way as for the unsaturated zone.

(m) Anisotropy

In EPACMTP, the horizontal transverse hydraulic conductivity is always set equal to the horizontal longitudinal conductivity, i.e., K_y=K_x. The default value is 1, which indicates an isotropic system.

(n) Receptor well location

A receptor well is a hypothetical drinking water well that is located downgradient of the waste management unit in consideration. A receptor well can be located anywhere down-gradient of the waste management unit and at any depth within the saturated zone. In our case the location of the receptor well is fixed by assigning the following:

1. x, distance from the edge of the waste unit = 500 m [As per Solid Waste Management and Handling Rules in case of landfills no development buffer zone should be 500m around the landfill (CPHEEO, 2000).

2. y, distance from the plume centerline = 0 m [Since the contaminant plume in the ground water follows a Gaussian plume pattern, highest concentration is always found along the plume centre line so this value is kept constant at zero]

3. z, well depth within the saturated zone = 0.5 [ZWELL should be given as a fraction of the saturated zone thickness. Therefore 0.5 means half the thickness of the saturated zone, thus the well position has been fixed at a constant depth i.e midpoint of the saturated zone.

Note 1: The distance of the well has been varied to find concentration versus distance curve. Also the depth has been varied to find its effect on concentration.

Concentrations are found at midpoint of aquifer having depth 10m.Therefore depth below ground level = (unsaturated zone depth +5).

Annexure 6.1:

Table A-6.1 Calculation of average weight carrying of departmental vehicles

Garages	D1 (DP small)	D2 (DP big)	D3 (Hand load)	D4 (Pay Load)
Dist I garage	Trip*: 69	Trip: 1181	Trip: 819	Trip: 36
	Weight**: 96.94	Weight: 2886.13	Weight: 4580.75	Weight: 223.46
Dist II garage	Trip: 0	Trip: 1062	Trip: 459	Trip: 0
	Weight: 0	Weight: 1597.74	Weight: 1724.72	Weight: 0
Dist III garage	Trip: 0	Trip: 1299	Trip: 452	Trip: 159
	Weight: 0	Weight: 2851.42	Weight: 1176.32	Weight: 902.03
Dist IV garage	Trip: 0	Trip: 1188	Trip: 454	Trip: 0
	Weight: 0	Weight: 1977.60	Weight: 1329.44	Weight: 0
Dhapa garage	Trip: 1	Trip: 389	Trip: 185	Trip: 10.36
	Weight: 1.7	Weight: 773.28	Weight: 490.08	Weight: 6478.605
Jadavpur unit	Trip: 554	Trip: 0	Trip: 56	Trip: 0
	Weight: 906.34	Weight: 0	Weight: 113.39	Weight: 0
Behala	Trip: 541	Trip: 0	Trip: 191	Trip: 0
	Weight:1007.18	Weight: 0	Weight: 428.07	Weight: 0
Garden reach unit	Trip: 0	Trip: 0	Trip: 22	Trip: 0
	Weight: 0	Weight: 0	Weight: 85.14	Weight: 0
*Above trips are expressed in number / month; ** Above weights are expressed in MT / month				
Total Trips (numbers/day	37.58	165.13	95.09	35.71
Vehicle wise weight (Mt/day)	64.9	325.36	320.26	245.29
Total weight (Mt/day)	(64.9 + 325.36 + 320.26 + 245.29) = 955.81			
Average capacity (Mt)	(64.9/37.58) = 1.73 (~ 1.75)	(325.36/165.13) = 1.97 (~2.00)	(320.26/95.09) = 3.36 (~3.00)	(245.29/35.71) = 6.86(~7.00)

Table A-6.2 Calculation of fuel consumption (ADB, 2005)

Vehicle Type	Loaded in KM/Litre	Unloaded in KM/Litre	Fuel consumption in KM/Litre
4,5 m^3 Dumper Placer	4.25	5.5	Av. => 5 km/lit (ADB Master Plan) In our case (4.25 + 5.5) = 4.875 km/lit
7 m^3 Dumper Placer	3.5	4.5	Av.=> 4 km/lit (ADB Master Plan) In our case (3.5 + 4.5) = 4 km/lit
8 m^3 Tipper Truck	3.35	4.35	Av.=> 4 km/lit (ADB Master Plan) In our case (3.35 + 4.35) = 3.8 km/lit
11 m^3 Open Truck	1.67 (2.5/1.5)	2.33 (3.5/1.5)	ADB Data (1.5 Km/Lit is considered for Pay Loader. In our case (1.67 + 2.33) = 2.0 km/lit
Open Truck (Hired)	3.25	4.25	(3.25 + 4.25) = 3.75 Km/lit

So, fuel charge in loaded run condition for D1 vehicle (4.5 m^3) = (Rs 34 / lit) × (lit / 4.25 km) = Rs 8/- per km (Table 6.5).

Fuel charge in unloaded run condition for D1 vehicle (4.5 m^3) = (Rs 34 / lit) × (lit / 5.5 km) = Rs 6.18/- per km (Table 6.5).

Annexure 6.2:

6.2 SAMPLE CALCULATION OF INCENTIVE RATE OF HAND LOADED TIPPER TRUCK ($8m^3$) AS 'D3' (DEPARTMENTAL VEHICLE):

Total incentive rate (Rs / ton) = (Incentive rate of driver, Rs / ton) + (incentive rate of helper. Rs / ton) × No of helper = Rs (10 + 5 × 5) / ton = Rs 35 / ton (Table 6.4).

Annexure 6.3:

6.3 SAMPLE CALCULATION OF FUEL COST PER TON OF DEPARTMENTAL VEHICLES D1, D2, D3 AND D4 IN BOROUGH 1

Fuel cost per ton for departmental vehicles are shown in Table A-6.3, Table A-6.4, Table A-6.5. Table A-6.6 and Table A-6.7 of Annexure 6.4.

(a) Sample calculation of fuel cost per ton of departmental vehicle D1 in Borough1 is shown below:

Fuel cost of D1 vehicle in Borough 1 (Rs / MT) = [Cost of average fuel consumptions for loaded and empty run (Rs / KM) (Table 6.2) × up and down distance (KM)] (Table 4.7) / Average waste carrying capacity (MT) (Table A-6.1) = [(8+6.18) × 9] /1.75 = Rs 72.93 / MT (Table A-6.3 of Annexure 6.4) & Table 6.6.

(b) Sample calculation of fuel cost per ton of departmental vehicle D2 in Borough1 is shown below:

Fuel cost of D2 vehicle in Borough 1 (Rs / MT) = [Cost of average fuel consumptions for loaded and empty run (Rs / KM) (Table 6.2) × up and down distance (KM)] (Table 4.7) / Average waste carrying capacity (MT) (Table A-6.1) = [(9.71+7.56) × 9] /2.0 = Rs 77.72 / MT (Table A-6.3 of Annexure 6.4) & Table 6.6.

(c) Sample calculation of fuel cost per ton of departmental vehicle D3 in Borough1 is shown below:

Fuel cost of D3 vehicle in Borough 1 (Rs / MT) = [Cost of average fuel consumptions for loaded and empty run (Rs / KM) (Table 6.2) × up and down distance (KM)] (Table 4.7) / Average waste carrying capacity (MT) (Table A-6.1) = [(10.15+7.82) × 9] /3.0 = Rs 53.91 / MT (Table A-6.3 of Annexure 6.4) & Table 6.6.

(d) Sample calculation of fuel cost per ton of departmental vehicle D4 in Borough1 is shown below:

Fuel cost of D4 vehicle in Borough 1 (Rs / MT) = [Cost of average fuel consumptions for loaded and empty run (Rs / KM) (Table 6.2) × up and down distance (KM)] (Table 4.7) / Average waste carrying capacity (MT) (Table A-6.1) = [(20.36 + 14.59) × 9] / 7.0 = Rs 44.94 / MT (Table A-6.3 of Annexure 6.4) & Table 6.6.

Table A-6.3 Fuel cost per ton for departmental vehicles in Borough 1, Borough 2 and Borough 3

Deptt.Vehicle	**Fuel charge (Rs/km)**		**Borough-1**			**Borough-2**			**Borough-3**		
	Loaded (Rs/Km)	**Unloaded (Rs/Km)**	**Distance (km)**	**Cost (Rs)**	**Cost/ton (in Rs.)**	**Distance (km)**	**Cost (Rs)**	**Cost/ton (in Rs.)**	**Distance (km)**	**Cost (Rs)**	**Cost/ton (in Rs.)**
4.5 m^3 Dumper Placer	8	6.18	9	127.62	72.92571	7.5	106.35	60.77143	5	70.9	40.51429
7.0 m^3 Dumper Placer	9.71	7.56	9	155.43	77.715	7.5	129.53	64.765	5	86.35	43.175
8.0 m^3 Tipper Truck	10.15	7.82	9	161.73	53.91	7.5	134.78	44.92667	5	89.85	29.95
11.0 m^3 Tipper Truck	20.36	14.59	9	314.55	44.93571	7.5	262.13	37.44714	5	174.75	24.96429

Table A-6.4 Fuel cost per ton for departmental vehicles in Borough 4, Borough 5 and Borough 6

Deptt.Vehicle	Fuel charge (Rs/km)		Borough-4			Borough-5			Borough-6		
	Loaded (Rs/Km)	Unloaded (Rs/Km)	Distance (km)	Cost (Rs)	Cost/ton (in Rs.)	Distance (km)	Cost (Rs)	Cost/ton (in Rs.)	Distance (km)	Cost (Rs)	Cost/ton (in Rs.)
4.5 m^3 Dumper Placer	8	6.18	7.5	106.35	60.77143	7	99.26	56.72	7	99.26	56.72
7.0 m^3 Dumper Placer	9.71	7.56	7.5	129.53	64.765	7	120.89	60.445	7	120.89	60.445
8.0 m^3 Tipper Truck	10.15	7.82	7.5	134.78	44.92667	7	125.79	41.93	7	125.79	41.93
11.0 m^3 Tipper Truck	20.36	14.59	7.5	262.13	37.44714	7	244.65	34.95	7	244.65	34.95

Table A-6.5 Fuel cost per ton for departmental vehicles in Borough 7, Borough 8 and Borough 9

Deptt.Vehicle	Fuel charge (Rs/km)		Borough-7			Borough-8			Borough-9		
	Loaded (Rs/Km)	Unloaded (Rs/Km)	Distance (km)	Cost (Rs)	Cost/ton (in Rs.)	Distance (km)	Cost (Rs)	Cost/ton (in Rs.)	Distance (km)	Cost (Rs)	Cost/ton (in Rs.)
4.5 m^3 Dumper Placer	8	6.18	3.5	49.63	28.36	6.5	92.17	52.66857	9.5	134.71	76.97714
7.0 m^3 Dumper Placer	9.71	7.56	3.5	60.45	30.225	6.5	112.26	56.13	9.5	164.07	82.035
8.0 m^3 Tipper Truck	10.15	7.82	3.5	62.9	20.96667	6.5	116.81	38.93667	9.5	170.72	56.90667
11.0 m^3 Tipper Truck	20.36	14.59	3.5	122.33	17.47571	6.5	227.18	32.45429	9.5	332.03	47.43286

Table A-6.6 Fuel cost per ton for departmental vehicles in Borough 10, Borough 11 and Borough 12

Deptt.Vehicle	Fuel charge (Rs/km)		Borough-10			Borough-11			Borough-12		
	Loaded (Rs/Km)	Unloaded (Rs/Km)	Distance (km)	Cost (Rs)	Cost/ton (in Rs.)	Distance (km)	Cost (Rs)	Cost/ton (in Rs.)	Distance (km)	Cost (Rs)	Cost/ton (in Rs.)
4.5 m^3 Dumper Placer	8	6.18	7	99.26	56.72	8	113.44	64.82286	3	42.54	24.30857
7.0 m^3 Dumper Placer	9.71	7.56	7	120.89	60.445	8	138.16	69.08	3	51.81	25.905
8.0 m^3 Tipper Truck	10.15	7.82	7	125.79	41.93	8	143.76	47.92	3	53.91	17.97
11.0 m^3 Tipper Truck	20.36	14.59	7	244.65	34.95	8	279.6	39.94286	3	104.85	14.97857

Table A-6.7 Fuel cost per ton for departmental vehicles in Borough 13, Borough 14 and Borough 15

Deptt.Vehicle	Fuel charge (Rs/km)		Borough-13			Borough-14			Borough-15		
	Loaded (Rs/Km)	Unloaded (Rs/Km)	Distance (km)	Cost (Rs)	Cost/ton (in Rs.)	Distance (km)	Cost (Rs)	Cost/ton (in Rs.)	Distance (km)	Cost (Rs)	Cost/ton (in Rs.)
4.5 m^3 Dumper Placer	8	6.18	10	141.8	81.02857	11.5	163.07	93.18286	13.5	191.43	109.3886
7.0 m^3 Dumper Placer	9.71	7.56	10	172.7	86.35	11.5	198.61	99.305	13.5	233.15	116.575
8.0 m^3 Tipper Truck	10.15	7.82	10	179.7	59.9	11.5	206.67	68.89	13.5	242.6	80.86667
11.0 m^3 Tipper Truck	20.36	14.59	10	349.5	49.92857	11.5	401.93	57.41857	13.5	471.83	67.40429

Annexure 6.4:

6.4 SAMPLE CALCULATION OF FIXED RUNNING AND FIXED IDLE COST OF DEPARTMENTAL VEHICLES

6.4.1 Fixed Cost (for running condition) Per Ton For 4.5 m^3 Dumper Placer:

(i) Depreciation (Assume scrap value 10% of capital cost) = Rs (11,50,000 – 1,15,000)/10 = Rs 1,03,500/- [Life of vehicle is considered as 10 years].

(ii) Interest @ 10% on reducing loan = (11,50,000 x 0.1) / $[(1 + 0.1)^{10}-1]$ = Rs 72,157.20/-

(iii) Wages of 1 driver and 1 helper = 1.3 x (9000 + 6000) x 12 = Rs 2,34,000/- [Multiplication factor 1.3 means 30% overtime allowances] [Working time (6.00 A.m to 4.00 P.M); regular duty 8 hrs + 2 to 2.5 hrs extra i.e. 30% overtime]

(iv) Wages of garage staff including managerial and administrative = 2 (numbers per vehicle) x Rs 9000 x 12 = Rs 2,16,000/- [Manager and administrative garage staff + standby drivers for departmental vehicles (MSW) are considered 2 numbers per vehicle (All vehicles). Total vehicles (Running + Idle) are considered for calculating the above staffs;]

(v) Annual operational and maintenance (O&M) cost = 10% of capital cost = Rs 1,15,000/- [Rs 11,50,000 x 0.1]

(vi) Total cost per annum (including depreciation and interest) per running vehicle = (i) + (ii) + (iii) + (iv) + (v) = Rs 7,40,657.2/-

(vii) Total cost per day per running vehicle = Rs (7,40,657.2 / 365) = Rs 2029.19/- (Table 6.7)

6.4.2 Fixed Cost (for idle condition) per ton for 4.5 m^3 Dumper Placer:

(i) Depreciation (Assume scrap value 10% of capital cost) = Rs (11,50,000 – 1,15,000)/10 = Rs 1,03,500/- [Life of vehicle is considered as 10 years].

(ii) Interest @ 10% on reducing loan = (11,50,000 x 0.1) / $[(1 + 0.1)^{10}-1]$ = Rs 72,157.20/-

(iii) Wages of 1 driver and 1 helper = 1.3 x (9000 + 6000) x 12 = Rs 2,34,000/- [Multiplication factor 1.3 means 30% overtime allowances] [Working time (6.00 A.m to 4.00 P.M); regular duty 8 hrs + 2 to 2.5 hrs extra i.e. 30% overtime].

(iv) Wages of garage staff including managerial and administrative = 2 (numbers per vehicle) x Rs 9000 x 12 = Rs 2,16,000/- [Manager and administrative garage staff + standby drivers for departmental vehicles (MSW) are considered 2 numbers per vehicle (All vehicles). Total vehicles (Running + Idle) are considered for calculating the above staffs].

(v) Annual operational and maintenance (O&M) cost = 10% of capital cost = Rs 1,15,000/- [Rs 11,50,000 x 0.1].

(vi) Total cost per annum (including depreciation and interest) per idle vehicle = (i) + (ii) + (iii) + (iv) + (v) – (iii) = Rs (7,40,657.2 – 2,34,000) = Rs 5,06,657.2/-.

(vii) Total fixed cost per day per idle vehicle = Rs (5,06,657.2 / 365) = Rs 1388.1/- (Table 6.7)

6.4.3 Fixed Cost (for running condition) per ton for 7 m^3 Dumper Placer:

(i) Depreciation (Assume scrap value 10% of capital cost) = Rs (13,50,000 – 1,35,000)/10 = Rs 1,21,500/- [Life of vehicle is considered as 10 years].

(ii) Interest @ 10% on reducing loan = (13,50,000 x 0.1) / $[(1 + 0.1)^{10}-1]$ = Rs 84,706.28/-

(iii) Wages of 1 driver and 1 helper = 1.3 x (9000 + 6000) x 12 = Rs 2,34,000/- [Multiplication factor 1.3 means 30% overtime allowances] [Working time (6.00 A.m to 4.00 P.M); regular duty 8 hrs + 2 to 2.5 hrs extra i.e. 30% overtime]

(iv) Wages of garage staff including managerial and administrative = 2 (numbers per vehicle) x Rs 9000 x 12 = Rs 2,16,000/- [Manager and administrative garage staff + standby drivers for departmental vehicles (MSW) are considered 2 numbers per vehicle (All vehicles). Total vehicles (Running + Idle) are considered for calculating the above staffs;]

(v) Annual operational and maintenance (O&M) cost = 10% of capital cost = Rs 1,15,000/- [Rs 11,50,000 x 0.1]

(vi) Total cost per annum (including depreciation and interest) per running vehicle = (i) + (ii) + (iii) + (iv) + (v) = Rs 7,91,206.28/-

(viii) Total cost per day per running vehicle = Rs (7,91,206.28 / 365) = Rs 2167.69/- (Table 6.7)

6.4.4 Fixed Cost (for idle condition) per ton for 7 m^3 Dumper Placer:

(i) Depreciation (Assume scrap value 10% of capital cost) = Rs (13,50,000 – 1,35,000)/10 = Rs 1,21,500/= [Life of vehicle is considered as 10 years].

(ii) Interest @ 10% on reducing loan = (13,50,000 x 0.1) / [(1 + 0.1)^{10}-1] = Rs 84,706.28/=

(iii) Wages of 1 driver and 1 helper = 1.3 x (9000 + 6000) x 12 = Rs 2,34,000/= [Multiplication factor 1.3 means 30% overtime allowances] [Working time (6.00 A.m to 4.00 P.M); regular duty 8 hrs + 2 to 2.5 hrs extra i.e. 30% overtime]

(iv) Wages of garage staff including managerial and administrative = 2 (numbers per vehicle) x Rs 9000 x 12 = Rs 2,16,000/= [Manager and administrative garage staff + standby drivers for departmental vehicles (MSW) are considered 2 numbers per vehicle (All vehicles). Total vehicles (Running + Idle) are considered for calculating the above staffs;]

(v) Annual operational and maintenance (O&M) cost = 10% of capital cost = Rs 1,15,000/= [Rs 11,50,000 x 0.1]

(vi) Total cost per annum (including depreciation and interest) per idle vehicle = (i) + (ii) + (iii) + (iv) + (v) – (iii) = Rs (7,91,206.28 – 2,34,000) = Rs 5,57,206.28/=

(ix) Total fixed cost per day per idle vehicle = Rs (5,57,206.28 / 365) = Rs 1526.59/= (Table 6.7)

6.4.5 Fixed Cost (for running condition) per ton for 8 m^3 Tipper Truck:

(i) Depreciation (Assume scrap value 10% of capital cost) = Rs (9,00,000 – 90,000)/10 = Rs 81,000/= [Life of vehicle is considered as 10 years].

(ii) Interest @ 10% on reducing loan = (9,00,000 x 0.1) / [(1 + 0.1)^{10}-1] = Rs 56,470.85/=

(iii) Wages of 1 driver and 4 helper = 1.3 x (9000 + 6000 x 4) x 12 = Rs 5,14,800/= [Multiplication factor 1.3 means 30% overtime allowances] [Working time (6.00 A.m to 4.00 P.M); regular duty 8 hrs + 2 to 2.5 hrs extra i.e. 30% overtime]

(iv) Wages of garage staff including managerial and administrative = 2 (numbers per vehicle) x Rs 9000 x 12 = Rs 2,16,000/= [Manager and administrative garage staff + standby drivers for departmental vehicles (MSW) are considered 2 numbers per vehicle (All vehicles). Total vehicles (Running + Idle) are considered for calculating the above staffs;]

(v) Annual operational and maintenance (O&M) cost = 10% of capital cost = Rs 90,000/= [Rs 9,00,000 x 0.1]

(vi) Total cost per annum (including depreciation and interest) per running vehicle = (i) + (ii) + (iii) + (iv) + (v) = Rs 9,58,270.85/=

(x) Total cost per day per running vehicle = Rs (9,58,270.85 / 365) = Rs 2625.39/=(Table 6.7)

6.4.6 Fixed Cost (for idle condition) per ton for 8 m^3 Tipper Truck:

(i) Depreciation (Assume scrap value 10% of capital cost) = Rs (9,00,000 – 90,000)/10 = Rs 81,000/= [Life of vehicle is considered as 10 years].

(ii) Interest @ 10% on reducing loan = (9,00,000 x 0.1) / [(1 + 0.1)^{10}-1] = Rs 56,470.85/=

(iii) Wages of 1 driver and 4 helper = 1.3 x (9000 + 6000 x 4) x 12 = Rs 5,14,800/= [Multiplication factor 1.3 means 30% overtime allowances] [Working time (6.00 A.m to 4.00 P.M); regular duty 8 hrs + 2 to 2.5 hrs extra i.e. 30% overtime]

(iv) Wages of garage staff including managerial and administrative = 2 (numbers per vehicle) x Rs 9000 x 12 = Rs 2,16,000/= [Manager and administrative garage staff + standby drivers for departmental vehicles (MSW) are considered 2 numbers per vehicle (All vehicles). Total vehicles (Running + Idle) are considered for calculating the above staffs;]

(v) Annual operational and maintenance (O&M) cost = 10% of capital cost = Rs 90,000/= [Rs 9,00,000 x 0.1]

(vi) Total cost per annum (including depreciation and interest) per idle vehicle = (i) + (ii) + (iii) + (iv) + (v) – (iii) = Rs 4,43,470.85/=

(xi) Total cost per day per idle vehicle = Rs (4,43,470.85 / 365) = Rs 1214.99/= (Table 6.7)

6.4.7 Fixed Cost (for running condition) per ton for 11 m^3 Tipper Truck:

Total number of 11 m^3 Tipper truck = 28
Vehicle in operation = 12
Total number of Pay loader = 10
Ratio of Pay loader and Tipper truck = 10:28 i.e. (10/28) = 0.35
Assume per Tipper Truck 0.4 number of Pay loader is used

(i) Depreciation (Assume scrap value 10% of capital cost) = Rs [(11,00,000 – 1,10,000) + 0.4 (25,00,000 – 2,50,000)] / 10 = Rs 1,89,000/= [Life of vehicle is considered as 10 years].

(ii) Interest @ 10% on reducing loan = [(11,00,000 x 0.1) / $(1 + 0.1)^{10}$-1] + [(25,00,000 x 0.1 x 0.4) / $(1 + 0.1)^{10}$-1] = Rs 1,31,765.32/=

(iii) Wages of 1.4 driver and 1.4 helper (40% from Pay load) = 1.3 x {(9000 + 6000) + 0.4 (9000 + 6000)} x 12 = Rs 3,27,600/= [Multiplication factor 1.3 means 30% overtime allowances] [Working time (6.00 A.m to 4.00 P.M); regular duty 8 hrs + 2 to 2.5 hrs extra i.e. 30% overtime]

(iv) Wages of garage staff including managerial and administrative = 2 (numbers per vehicle) x 1.4 (40% increase due to Pay load) x Rs 9000 x 12 = Rs 3,02,400/= [Manager and administrative garage staff + standby drivers for departmental vehicles (MSW) are considered 2 numbers per vehicle (All vehicles). Total vehicles (Running + Idle) are considered for calculating the above staffs;]

(v) Annual operational and maintenance (O&M) cost = 10% of capital cost = Rs 2,10,000/= [Rs (11,00,000 + 25,00,000 x 0.4) x 0.1] [40% due to Pay load]

(vi) Total cost per annum (including depreciation and interest) per running vehicle = (i) + (ii) + (iii) + (iv) + (v) = Rs 11,60,765.32/=

(xii) Total cost per day per running vehicle = Rs (11,60,765.32 / 365) = Rs 3180.18/=(Table 6.7)

6.4.8 Fixed Cost (for idle condition) per ton for 11 m^3 Tipper Truck:

Total number of 11 m^3 Tipper truck = 28
Vehicle in operation = 12
Total number of Pay loader = 10
Ratio of Pay loader and Tipper truck = 10:28 i.e. (10/28) = 0.35
Assume per Tipper Truck 0.4 number of Pay loader is used

(i) Depreciation (Assume scrap value 10% of capital cost) = Rs [(11,00,000 – 1,10,000) + 0.4 (25,00,000 – 2,50,000)] / 10 = Rs 1,89,000/= [Life of vehicle is considered as 10 years].

(ii) Interest @ 10% on reducing loan = [(11,00,000 x 0.1) / $(1 + 0.1)^{10}$-1] + [(25,00,000 x 0.1 x 0.4) / $(1 + 0.1)^{10}$-1] = Rs 1,31,765.32/=

(iii) Wages of 1.4 driver and 1.4 helper (40% from Pay load) = 1.3 x {(9000 + 6000) + 0.4 (9000 + 6000)} x 12 = Rs 3,27,600/= [Multiplication factor 1.3 means 30% overtime allowances] [Working time (6.00 A.M to 4.00 P.M); regular duty 8 hrs + 2 to 2.5 hrs extra i.e. 30% overtime]

(iv) Wages of garage staff including managerial and administrative = 2 (numbers per vehicle) x 1.4 (40% increase due to Pay load) x Rs 9000 x 12 = Rs 3,02,400/= [Manager and administrative garage staff + standby drivers for departmental vehicles (MSW) are considered 2 numbers per vehicle (All vehicles). Total vehicles (Running + Idle) are considered for calculating the above staffs;]

(v) Annual operational and maintenance (O&M) cost = 10% of capital cost = Rs 2,10,000/= [Rs (11,00,000 + 25,00,000 x 0.4) x 0.1] [40% due to Pay load]

(vi) Total cost per annum (including depreciation and interest) per idle vehicle = (i) + (ii) + (iii) + (iv) + (v) – (iii) = Rs (11,60,765.32 – 3,27,600) = Rs 8,33,165.32/-.

(vii) Total cost per day per idle vehicle = Rs (8,33,165.32 / 365) = Rs 2282.64/= (Table 6.7)

ANNEXURE 6.5

Table A-6.8 Calculation of fixed running and idle cost of departmental vehicles per day

Type of vehicles	Garages (Operating)	Total No. of vehicles	Vehicles in operation	Idle vehicle	Fixed cost for running vehicle / day	Fixed cost for idle vehhicle / day
4.5 m^3 Dumper Placer	Dist. 1 Dist 7 Dist 8	1 7 8 } 16	1 4 4 } 9	16 - 9 = 7 43.75%	@Rs. 2029.19 x 9 = Rs. 18262.71	@Rs. 1388.10x 7 = Rs. 9716.70
7.0 m^3 Dumper Placer	Dist. 1 Dist. 2 Dist. 3 Dist. 4 Dist. 5	20 13 17 18 5 } 73	8 6 8 9 3 } 34	73 - 34 = 39 53.42%	@Rs.2167.69 x 34 =Rs. 73701.46	@Rs. 1526.59 x 39 =Rs. 59537.01
8.0 m^3 Tipper Truck	Dist. 1 Dist. 2 Dist. 3 Dist. 4 Dist. 5 Dist. 6 Dist. 7 Dist. 8	18 17 12 17 5 5 4 4 } 82	10 10 10 11 5 2 4 3 } 55	82 - 55 = 27 32.93%	@Rs. 2625.39 x 55 = Rs. 144396.45	@Rs. 1214.99 x 55 =Rs. 66824.45
11.0 m^3 Tipper Truck	Dist. 1 Dist 3 Dist 5	1 1 26 } 28	1 1 10 } 12	28 - 12 = 16 57.14%	@Rs. 3180.18 x 12 =Rs. 38162.16	@Rs. 2282.64 x 16 = Rs. 36522.24

ANNEXURE 6.6

Table A-6.9 Compost facility (500 MT capacities) operating cost estimate

		Unit	Unit Cost (Rs)	Quantum	Total (Rs)	% of total
Labour						
	General labour	Per capita	75,600	120	90,72,000	
	Skilled labour	Per capita	1,26,000	40	50,40,000	
	Administration	Per capita	1,60,000	20	32,00,000	
	Miscellaneous	%	0	0%		
	Contingency	%	0	0%		
	Sum of labour	0	0	0	1,73,12,000	10%
O&M						
	Structures	% of Capx	1443750000	3%	4,33,12,500	
	Fixed equipment	% of Capx	1443750000	5%	7,21,87,500	
	Mobile equipment	% of Capx	58000000	5%	29,00,000	
	Miscellaneous	%	0	5%	59,20,000	
	Contingency	%	0	25%	3,10,80,000	
	Sum of O&M		0	0	15,54,00,000	87%
Utilities						
	Power	LS	-	-	40,00,000	
	Water	LS	-	-	-	
	Sanitary	LS	-	-	-	
	Miscellaneous	%	0	5%	2,00,000	
	Contingency	%	0	25%	10,50,000	
	Sum of utilities	0	0	0	52,50,000	3%
Sum of Compost Opx Iems		**0**	**0**	**0**	**17,79,62,000**	

So, annual O&M cost of composting facility per ton per day = (Rs 17,79,62,000.00)/(300 MT × 365 days) = Rs 507.88 per ton per day (6.1.1.7 (c) of chapter 6).

ANNEXURE 6.7

Table A-6.10 Operation and maintenance of open disposal facility (90 MT capacities)

Description	**Cost in Rs, Crore**
Capital cost	
Landfill and infrastructure	6.00
Site infrastructure (includes roads, water drainage, electricity	0.95
Equipment (JCB, Compactors, Bulldozers, tractors, weighbridges)	1.10
Contingency (Assumed as 5%)	0.40
Total cost	8.45
Annual O&M expenses	
Operation and maintenance cost for landfill operations	0.31

Operation and maintenance cost of engineered landfill (ELF) per MT = Rs [31,00,000/(90 x 365)] = ~ Rs. 95 per MT (6.1.1.9 of chapter 6)

ANNEXURE 6.8

Sample calculation of waste quantity shared by individual vehicle is shown in Table A-6.10

Table A-6.11 Waste distribution of departmental and private vehicles in Borough 1

BOROUGH – I				
Vehicle type	**Fuel cost (Rs/MT)**	**Incentive cost (Rs/MT)**	**Total cost (Rs/MT)**	**Rank wise cost**
D1	63.81 x (2/1.75) = 72.93	15.0	87.93	2
D2	55.51 x (2.8/2) = 77.71	10.5	88.21	3
D3	40.43 x (4/3) = 53.91	35.0	88.91	4
D4	44.93	7.5	52.43	1
HH	-	-	130	5

Vehicle type	**Minm. wt. (MT)**	**Maxm. Wt. (MT)**	**Actual wt. taken (MT)**	**Reasons for taking actual wt. (MT) by the vehicles**
D4 (1st least cost)	10.7064	28.5504	28.5504	10.7064 (Minm wt) + 17.844 (balanced wt)
D1(2nd least cost)	0	1.7844	1.7844	0 (Minm wt) + 1.7844 (balanced wt
D2 (3rd least cost)	24.9816	42.8256	42.8256	24.9816 (Minm wt) + 17.844 (balanced wt
D3 (4th least cost)	32.1196	49.9632	32.1196	32.1196 (Minm w)
HH(5th least cost)	73.16	91.00	73.16	73.16 (Minm wt)
Total	**140.9676**	**214.1236**	**178.44**	

Note:

Step 1: Difference of Actual and Minm wt. = (178.44 – 140.9676) = 37.4724 MT; So, the remaining wt will be balanced in a following manner

Step 2: Initially all vehicles will take their minimum wt (MT) and then accept the balanced weight to achieve their maximum wt; so, D4 according to the least cost will take Minimum wt (10.7064 MT) + balanced wt. 17.844 MT (Difference of Maximum and Minimum) = to achieve maximum wt (28.5504 MT) of D4.

Step 3: Now, remaining balance of wt: (37.4724 MT – 17.844 MT) = 19.6284 MT > Difference of maximum and minimum wt of D1 vehicle (1.7844 MT). So, D1 vehicle will take their minimum wt (0 MT) + balanced wt. (1.7844 MT) = 1.7844 MT to achieve their maximum wt (1.7844 MT)

Step 4: Now, remaining balance of wt: (19.6284 MT – 1.7844 MT) = 17.844 MT = Difference of maximum and minimum wt of D2 vehicle (17.844 MT). So, D2 as 3rd least cost vehicle will take their minimum wt (24.9816 MT) + balanced wt 17.844 MT = 42.8256 MT.

Step 5: D3 as 4th least cost will take minimum wt. 32.1196 MT since no balance is left.

Step 6: HH vehicle will also take their minimum wt i.e. 73.16 MT.

Annexure 6.9:

6.9 (A) SAMPLE CALCULATION OF COST OF TRANSPORTATION IN PRACTICAL SITUATION

Total transportation cost = Transportation cost of departmental vehicle D1 + Transportation cost of departmental vehicle D2 + Transportation cost of departmental vehicle D3 + Transportation cost of departmental vehicle D4 + Transportation cost of hired vehicle HH + Total incentive cost of departmental vehicles (D1 + D2 + D3 + D4)

6.9.1 Transportation cost of departmental vehicle D1 = Fuel cost of departmental vehicle D1 + Fixed running cost of D1 vehicle + Fixed idle cost of vehicle D1

(a) Fuel cost of departmental vehicle D1

Total number of average trips = 50.23

Fuel issued = 8 lit/trip

Total fuel issued = 8 lit × 50.23 = 401.84 lit

Cost of fuel = Rs 34/lit

Total fuel cost = 401.84 lit × Rs 34/lit = Rs 13662.56/-

(b) Fixed running cost of departmental vehicle D1 = No of vehicle/day × Fixed running cost/vehicle/day = 9 × Rs 2029.19/- = Rs 18262.71/-

(c) Fixed idle cost of departmental vehicle D1 = No of vehicle/day × Fixed idle cost/vehicle/day = 7 × Rs 1388.10/- = Rs 9716.70/-

Transportation cost of departmental vehicle D1 = Rs (13662.56/- +18262.71/- +9716.70/-) = Rs 41641.97/-

6.9.2 Transportation cost of departmental vehicle D2 = Fuel cost of departmental vehicle D2 + Fixed running cost of D2 vehicle + Fixed idle cost of vehicle D2

(a) Fuel cost of departmental vehicle D2

Total number of average trips = 202.9

Fuel issued = 8 lit/trip

Total fuel issued = 8 lit × 202.9 = 1623.2 lit

Cost of fuel = Rs 34/lit

Total fuel cost = 1623.2 lit × Rs 34/lit = Rs 55188.8/-

(b) Fixed running cost of departmental vehicle D1 = No of vehicle/day × Fixed running cost/vehicle/day = 34 × Rs 2167.69/- = Rs 73701.46/-

(c) Fixed idle cost of departmental vehicle D1 = No of vehicle/day × Fixed idle cost/vehicle/day = 39 × Rs 1526.59/- = Rs 59537.01/-

Transportation cost of departmental vehicle D2 = Rs (55188.8/- + 73701.46/- + 59537.01/-) = Rs 188427.27/-

6.9.3 Transportation cost of departmental vehicle D3 = Fuel cost of departmental vehicle D3+ Fixed running cost of D3 vehicle + Fixed idle cost of vehicle D3

(a) Fuel cost of departmental vehicle D3

Total number of average trips = 113.54

Fuel issued = 10 lit/trip

Total fuel issued = 10 lit × 113.54 = 1135.4 lit

Cost of fuel = Rs 34/lit

Total fuel cost = 1135.4 lit × Rs 34/lit = Rs 38603.6/-

(b) Fixed running cost of departmental vehicle D3 = No of vehicle/day × Fixed running cost/vehicle/day = 55 × Rs 2625.39/- = Rs 144396.5/-

(c) Fixed idle cost of departmental vehicle D3 = No of vehicle/day × Fixed idle cost/vehicle/day = 27 × Rs 1214.99/- = Rs 32804.73/-

Transportation cost of departmental vehicle D3 = Rs (38603.6/- + 144396.5/- + 32804.73/-) = Rs 215804.83/-

6.9.4 Transportation cost of departmental vehicle D4 = Fuel cost of departmental vehicle D4+ Fixed running cost of D4 vehicle + Fixed idle cost of vehicle D4

(a) Fuel cost of departmental vehicle D4

Total number of average trips = 35.41

Fuel issued = 10 lit/trip

Total fuel issued = 10 lit × 35.41 = 354.1 lit

Cost of fuel = Rs 34/lit

Total fuel cost = 354.1 lit × Rs 34/lit = Rs 12039.4/-

(b) Fixed running cost of departmental vehicle D4 = No of vehicle/day × Fixed running cost/vehicle/day = 12 × Rs 3180.18/- = Rs 38162.16/-

(c) Fixed idle cost of departmental vehicle D4 = No of vehicle/day × Fixed idle cost/vehicle/day = 16 × Rs 2282.64/- = Rs 36522.24/-

Transportation cost of departmental vehicle D4 = Rs (12039.4/- + 38162.16/- + 36522.24/-) = Rs 86723.80/-

6.9.5 Transportation cost of hired vehicle HH = Rs 263650.5/-

6.9.6 Total incentive cost of departmental vehicles (D1+D2+D3+D4) = Rs 263650.5/-

Total transportation cost = (Rs 41641.97/- + Rs 188427.27/- + Rs 215804.83/- + Rs 86723.80/- + Rs 263650.5/- + Rs 6600/-) = Rs 802848.37/-

6.9 (B) SAMPLE CALCULATION OF COST OF LANDFILL AT DISPOSAL SITE 'D' IN PRACTICAL SITUATION

(a) Establishment cost: Rs 131.90 Lakhs (KMC Schedule of Establishment for the year 2007-2008)

(b) Capital and maintenance cost: Rs 684.31 Lakhs (KMC Schedule of Establishment for the year 2007-2008)

(c) Fuel cost for Bull Dozers: (600 lit/day × 364 days × Rs 34/ lit = Rs 74.26 Lakh

(d) Maintenance of Bull Dozers: Rs 20 lakhs

(e) Overtime allowances for Bull Dozer repairing staffs, conservancy mazdoors, overseers, Bull Dozer operators, Engineers: Rs 13 Lakhs

(f) Supply of trip tokens, ribbons etc: Rs 3 Lakhs

(g) Salary of driver and fuel for jeep: Rs 4.84 Lakhs

Total landfill cost: Rs 93131000/- per year

Total landfill cost: (Rs 93131000.00 / 365) = Rs 255153.42/- per day (Table 6.10).

Annexure 6.10:

Table A-6.12 Borough wise minimum and maximum garbage carrying quantity range (in fraction) for departmental and hired vehicles (15:85)

Borough	D1		D2		D3		D4		HH	
	Min fraction	Max fraction	Min fraction	Max fraction	Min fraction	Max fraction	Min fraction	Max fraction	Min fraction	Max fraction
Br.1	0.00	0.01	0.04	0.14	0.05	0.15	0.02	0.12	0.74	0.79
Br.2	-	-	0.04	0.14	0.01	0.11	-	-	0.86	0.91
Br.3	0.00	0.04	0.06	0.16	0.06	0.16	-	-	0.77	0.82
Br.4	-	-	0.04	0.14	0.00	0.11	0.04	0.14	0.77	0.82
Br.5	-	-	0.00	0.08	0.00	0.07	0.04	0.14	0.84	0.89
Br.6	-	-	0.00	0.10	0.00	0.04	0.00	0.10	0.88	0.93
Br.7	-	-	0.00	0.10	0.00	0.08	0.00	0.10	0.86	0.91
Br.8	-	-	0.03	0.13	0.03	0.13	-	-	0.85	0.90
Br.9	-	-	0.02	0.12	0.02	0.12	-	-	0.87	0.92
Br.10	-	-	0.00	0.10	0.00	-	-	-	0.95	1.00
Br.11	0.02	0.12	-	-	0.00	0.10	-	-	0.88	0.93
Br.12	0.07	0.17	-	-	0.04	0.14	-	-	0.80	0.85
Br.13	0.03	0.13	-	-	0.04	0.14	-	-	0.84	0.89
Br.14	0.00	0.10	-	-	0.00	0.10	-	-	0.90	0.95
Br.15	-	-	-	-	0.00	0.02	-	-	0.95	1.00

Table A-6.13 Borough wise minimum and maximum garbage carrying quantity range (in fraction) for departmental and hired vehicles (60:40)

Borough	D1		D2		D3		D4		HH	
	Min fraction	Max fraction	Min fraction	Max fraction	Min fraction	Max fraction	Min fraction	Max fraction	Min fraction	Max fraction
Br.1	0.00	0.03	0.20	0.30	0.23	0.33	0.11	0.21	0.25	0.35
Br.2	-	-	0.24	0.34	0.21	0.31	-	-	0.41	0.51
Br.3	0.03	0.05	0.30	0.40	0.28	0.38	-	-	0.25	0.35
Br.4	-	-	0.18	0.28	0.03	0.13	0.29	0.39	0.31	0.41
Br.5	-	-	0.02	0.12	0.02	0.12	0.40	0.50	0.36	0.46
Br.6	-	-	0.06	0.16	0.04	0.14	0.21	0.31	0.50	0.60
Br.7	-	-	0.16	0.26	0.03	0.13	0.14	0.24	0.47	0.57
Br.8	-	-	0.24	0.34	0.27	0.37	-	-	0.35	0.45
Br.9	-	-	0.21	0.31	0.24	0.34	-	-	0.41	0.51
Br.10	-	-	0.31	0.41	0.00	-	-	-	0.60	0.70
Br.11	0.30	0.34	-	-	0.24	0.34	-	-	0.37	0.47
Br.12	0.34	0.39	-	-	0.29	0.39	-	-	0.28	0.38
Br.13	0.23	0.28	-	-	0.35	0.45	-	-	0.33	0.43
Br.14	0.18	0.23	-	-	0.35	0.45	-	-	0.38	0.48
Br.15	-	-	-	-	0.16	0.26	-	-	0.75	0.85

Annexure 6.11:

6.11 SAMPLE CALCULATION OF FUEL COST PER TON OF DEPARTMENTAL VEHICLES D1 IN BOROUGH 1 FOR PROPOSED DISPOSAL SITE 'D' 'N' AND 'S'

In earlier existing model fuel cost was considered Rs 34/- per lit. In proposed integrated model fuel cost is considered Rs 51/- per lit. But the same procedure is followed for calculation of fuel cost per ton for D1, D2, D3 and D4 vehicles for all boroughs in proposed disposal site 'D', 'N' and 'S' (Table 6.15, Table 6.16 and Table 6.17).

Annexure 6.12:

Table A-6.14 O&M cost for material sorting facility (3000 MT capacities)

		Unit	Unit Cost (Rs)	Quantum	Total (Rs)
Labour (staff)					
	Manager	Per capita	96000	1	96000
	Mechanics Helper	Per capita	84000	1	84000
	Equipment operator	Per capita	66000	1	66000
	Sorters	Per capita	48000	7	336000
	Sum of staffs	0			582000
O&M					
	Structures	2 % of Capx	20000	1	20000
	Fixed equipment	3 % of Capx	15000	1	15000
	Mobile equipment	15 % of Capx	10000	1	10000
	Sum of O&M		0	0	45000
Utilities					
	General utilities	LS	8000	1	8000
Sum of MRF Opx Iems		**0**	**0**	**0**	**635000**

O&M cost of material sorter facility = [Rs 635000/- / (365 days×3000 MT/day)] = Rs 0.50/- per MT

Annexure 6.13:

Table A-6.15 O&M cost for incineration facility (1250 MT capacities)

Description	Cost in Rs	Cost in US$	Comments
Capital cost	Rs 15750000000	$ 30000000	Based on $800 per tonne of annual installed capacity
Annual capital cost	Rs 1265000000	$ 28100000	Amortized over 20 years at 5%
Annual operating cost	Rs 787500000	$ 17500000	5% capital cost is a typical annual operating cost

Capital cost includes land plot, infrastructure (e.g. roads, buildings, and air pollution control systems), services and equipment (e.g. grate, boiler, ash handling etc).

O&M cost of incineration per MT = [Rs 787500000/- / (365 days×1250 MT/day)] = Rs 1726/- per MT

Annexure 6.14:

Table A-6.16 O&M cost of engineered landfill facility (ELF) (90 MT capacities)

Description	Cost in Rs, Crore
Capital cost	
Landfill and infrastructure	14.58
Site infrastructure (includes roads, water drainage, electricity	1.78
Equipment (JCB, Compactors, Bulldozers, tractors, weighbridges)	1.42
Contingency (Assumed as 5%)	0.89
Total cost	18.67
Annual O&M expenses	
Operation and maintenance cost for landfill operations	0.65

Operation and maintenance cost of Engineered landfill per MT = Rs 6500000/(90x365) = Rs. 200 per MT

Annexure 6.15:

Table A-6.17 Borough wise minimum and maximum garbage carrying quantity range (in fraction) for departmental and hired vehicles (15:85)

Borough	D1		D2		D3		D4		HH	
	Min fraction	Max fraction	Min fraction	Max fraction	Min fraction	Max fraction	Min fraction	Max fraction	Min fraction	Max fraction
Br.1	0.00	0.01	0.02	0.12	0.05	0.15	0.03	0.13	0.73	0.78
Br.2	-	-	0.02	0.12	0.02	0.12	-	-	0.84	0.89
Br.3	0.00	0.02	0.07	0.17	0.07	0.17	-	-	0.73	0.78
Br.4	-	-	0.01	0.11	0.00	0.06	0.08	0.18	0.76	0.81
Br.5	-	-	0.00	0.02	0.00	0.02	0.10	0.20	0.81	0.86
Br.6	-	-	0.00	0.02	0.00	0.02	0.00	0.02	0.97	1.00
Br.7	-	-	0.00	0.03	0.00	0.02	0.00	0.03	0.94	0.99
Br.8	-	-	0.04	0.14	0.03	0.13	-	-	0.81	0.86
Br.9	-	-	0.01	0.11	0.01	0.11	-	-	0.86	0.91
Br.10	-	-	0.00	0.02	0.00	0.00	-	-	0.99	1.00
Br.11	0.01	0.11	-	-	0.03	0.13	-	-	0.84	0.89
Br.12	0.06	0.16	-	-	0.06	0.16	-	-	0.76	0.81
Br.13	0.01	0.11	-	-	0.09	0.19	-	-	0.78	0.83
Br.14	0.00	0.04	-	-	0.00	0.08	-	-	0.92	0.97
Br.15	-	-	-	-	0.00	0.00	-	-	1.00	1.00

Annexure 6.16:

Table A-6.18 Borough wise minimum and maximum garbage carrying quantity range (in fraction) for departmental and hired vehicles (60:40)

Borough	D1		D2		D3		D4		HH	
	Min fraction	Max fraction	Min fraction	Max fraction	Min fraction	Max fraction	Min fraction	Max fraction	Min fraction	Max fraction
Br.1	0.00	0.04	0.20	0.30	0.23	0.33	0.11	0.21	0.25	0.35
Br.2	-	-	0.24	0.34	0.21	0.31	-	-	0.41	0.51
Br.3	0.00	0.05	0.30	0.40	0.28	0.38	-	-	0.24	0.34
Br.4	-	-	0.18	0.28	0.03	0.13	0.29	0.39	0.30	0.40
Br.5	-	-	0.02	0.12	0.02	0.12	0.40	0.50	0.36	0.46
Br.6	-	-	0.06	0.16	0.04	0.14	0.21	0.31	0.50	0.60
Br.7	-	-	0.16	0.26	0.03	0.13	0.14	0.24	0.47	0.57
Br.8	-	-	0.24	0.34	0.27	0.37	-	-	0.34	0.44
Br.9	-	-	0.21	0.31	0.24	0.34	-	-	0.41	0.51
Br.10	-	-	0.31	0.41	-	-	-	-	0.60	0.70
Br.11	0.24	0.34	-	-	0.24	0.34	-	-	0.37	0.47
Br.12	0.29	0.39	-	-	0.29	0.39	-	-	0.28	0.38
Br.13	0.18	0.28	-	-	0.35	0.45	-	-	0.32	0.42
Br.14	0.13	0.23	-	-	0.35	0.45	-	-	0.37	0.47
Br.15	-	-	-	-	0.16	0.26	-	-	0.74	0.84

Annexure 6.17

6.17 MATHEMATICAL MODEL FOR EXISTING SOLID WASTE MANAGEMENT OF KOLKATA AND ITS OPTIMIZATION

MIN CTCX + CTCI - CTREVC + CTRANSP + CINCT

SUBJECT TO

BS01) Q01DHHS + Q01NHHS + Q01SHHS = 20.11
BG01) Q01DD1G + Q01DD2G + Q01DD3G + Q01DD4G + Q01ND1G + Q01ND2G + Q01ND3G + Q01ND4G + Q01SD1G + Q01SD2G + Q01SD3G + Q01SD4G + Q01DHHG + Q01NHHG + Q01SHHG
= 178.44
BS02) Q02DHHS + Q02NHHS + Q02SHHS = 12.03
BG02) Q02DD1G + Q02DD2G + Q02DD3G + Q02DD4G + Q02ND1G + Q02ND2G
+ Q02ND3G + Q02ND4G + Q02SD1G + Q02SD2G + Q02SD3G + Q02SD4G + Q02DHHG
+ Q02NHHG + Q02SHHG = 175.12
BS03) Q03DHHS + Q03NHHS + Q03SHHS = 20.09
BG03) Q03DD1G + Q03DD2G + Q03DD3G + Q03DD4G + Q03ND1G + Q03ND2G + Q03ND3G + Q03ND4G + Q03SD1G + Q03SD2G + Q03SD3G + Q03SD4G + Q03DHHG + Q03NHHG + Q03SHHG
= 179.48
BS04) Q04DHHS + Q04NHHS + Q04SHHS = 12.72
BG04) Q04DD1G + Q04DD2G + Q04DD3G + Q04DD4G + Q04ND1G + Q04ND2G
+ Q04ND3G + Q04ND4G + Q04SD1G + Q04SD2G + Q04SD3G + Q04SD4G + Q04DHHG
+ Q04NHHG + Q04SHHG = 156.23
BS05) Q05DHHS + Q05NHHS + Q05SHHS = 17.14
BG05) Q05DD1G + Q05DD2G + Q05DD3G + Q05DD4G + Q05ND1G + Q05ND2G
+ Q05ND3G + Q05ND4G + Q05SD1G + Q05SD2G + Q05SD3G + Q05SD4G + Q05DHHG
+ Q05NHHG + Q05SHHG = 188.48
BS06) Q06DHHS + Q06NHHS + Q06SHHS = 35.14
BG06) Q06DD1G + Q06DD2G + Q06DD3G + Q06DD4G + Q06ND1G + Q06ND2G
+ Q06ND3G + Q06ND4G + Q06SD1G + Q06SD2G + Q06SD3G + Q06SD4G + Q06DHHG
+ Q06NHHG + Q06SHHG = 234.22
BS07) Q07DHHS + Q07NHHS + Q07SHHS = 62.55
BG07) Q07DD1G + Q07DD2G + Q07DD3G + Q07DD4G + Q07ND1G + Q07ND2G
+ Q07ND3G + Q07ND4G + Q07SD1G + Q07SD2G + Q07SD3G + Q07SD4G + Q07DHHG
+ Q07NHHG + Q07SHHG = 241.52
BS08) Q08DHHS + Q08NHHS + Q08SHHS = 40.08
BG08) Q08DD1G + Q08DD2G + Q08DD3G + Q08DD4G + Q08ND1G + Q08ND2G
+ Q08ND3G + Q08ND4G + Q08SD1G + Q08SD2G + Q08SD3G + Q08SD4G + Q08DHHG
+ Q08NHHG + Q08SHHG = 160.39
BS09) Q09DHHS + Q09NHHS + Q09SHHS = 25.92
BG09) Q09DD1G + Q09DD2G + Q09DD3G + Q09DD4G + Q09ND1G + Q09ND2G
+ Q09ND3G + Q09ND4G + Q09SD1G + Q09SD2G + Q09SD3G + Q09SD4G + Q09DHHG
+ Q09NHHG + Q09SHHG = 266
BS10) Q10DHHS + Q10NHHS + Q10SHHS = 30.92
BG10) Q10DD1G + Q10DD2G + Q10DD3G + Q10DD4G + Q10ND1G + Q10ND2G
+ Q10ND3G + Q10ND4G + Q10SD1G + Q10SD2G + Q10SD3G + Q10SD4G + Q10DHHG
+ Q10NHHG + Q10SHHG = 336.92001
BS11) Q11DHHS + Q11NHHS + Q11SHHS = 1.8
BG11) Q11DD1G + Q11DD2G + Q11DD3G + Q11DD4G + Q11ND1G + Q11ND2G
+ Q11ND3G + Q11ND4G + Q11SD1G + Q11SD2G + Q11SD3G + Q11SD4G + Q11DHHG
+ Q11NHHG + Q11SHHG = 95.46
BS12) Q12DHHS + Q12NHHS + Q12SHHS = 2.25
BG12) Q12DD1G + Q12DD2G + Q12DD3G + Q12DD4G + Q12ND1G + Q12ND2G
+ Q12ND3G + Q12ND4G + Q12SD1G + Q12SD2G + Q12SD3G + Q12SD4G + Q12DHHG
+ Q12NHHG + Q12SHHG = 83.54
BS13) Q13DHHS + Q13NHHS + Q13SHHS = 3.94
BG13) Q13DD1G + Q13DD2G + Q13DD3G + Q13DD4G + Q13ND1G + Q13ND2G

+ Q13ND3G + Q13ND4G + Q13SD1G + Q13SD2G + Q13SD3G + Q13SD4G + Q13DHHG
+ Q13NHHG + Q13SHHG = 157.03999
BS14) Q14DHHS + Q14NHHS + Q14SHHS = 9.37
BG14) Q14DD1G + Q14DD2G + Q14DD3G + Q14DD4G + Q14ND1G + Q14ND2G
+ Q14ND3G + Q14ND4G + Q14SD1G + Q14SD2G + Q14SD3G + Q14SD4G + Q14DHHG
+ Q14NHHG + Q14SHHG = 129.27
BS15) Q15DHHS + Q15NHHS + Q15SHHS = 0.058
BG15) Q15DD1G + Q15DD2G + Q15DD3G + Q15DD4G + Q15ND1G + Q15ND2G
+ Q15ND3G + Q15ND4G + Q15SD1G + Q15SD2G + Q15SD3G + Q15SD4G + Q15DHHG
+ Q15NHHG + Q15SHHG = 22.183
MXG01D1) Q01DD1G + Q01ND1G + Q01SD1G <= 1.7844
MNG01D1) Q01DD1G + Q01ND1G + Q01SD1G >= 0
MXG01D2) Q01DD2G + Q01ND2G + Q01SD2G <= 42.8256
MNG01D2) Q01DD2G + Q01ND2G + Q01SD2G >= 24.9816
MXG01D3) Q01DD3G + Q01ND3G + Q01SD3G <= 49.9632
MNG01D3) Q01DD3G + Q01ND3G + Q01SD3G >= 32.1192
MXG01D4) Q01DD4G + Q01ND4G + Q01SD4G <= 28.5504
MNG01D4) Q01DD4G + Q01ND4G + Q01SD4G >= 10.7064
MXG02D1) Q02DD1G + Q02ND1G + Q02SD1G <= 0
MNG02D1) Q02DD1G + Q02ND1G + Q02SD1G >= 0
MXG02D2) Q02DD2G + Q02ND2G + Q02SD2G <= 43.7800
MNG02D2) Q02DD2G + Q02ND2G + Q02SD2G >= 26.2680
MXG02D3) Q02DD3G + Q02ND3G + Q02SD3G <= 38.5264
MNG02D3) Q02DD3G + Q02ND3G + Q02SD3G >= 21.0144
MXG02D4) Q02DD4G + Q02ND4G + Q02SD4G <= 0
MNG02D4) Q02DD4G + Q02ND4G + Q02SD4G >= 0
MXG03D1) Q03DD1G + Q03ND1G + Q03SD1G <= 7.1792
MNG03D1) Q03DD1G + Q03ND1G + Q03SD1G >= 0
MXG03D2) Q03DD2G + Q03ND2G + Q03SD2G <= 57.4336
MNG03D2) Q03DD2G + Q03ND2G + Q03SD2G >= 39.4856
MXG03D3) Q03DD3G + Q03ND3G + Q03SD3G <= 52.0492
MNG03D3) Q03DD3G + Q03ND3G + Q03SD3G >= 34.1012
MXG03D4) Q03DD4G + Q03ND4G + Q03SD4G <= 0
MNG03D4) Q03DD4G + Q03ND4G + Q03SD4G >= 0
MXG04D1) Q04DD1G + Q04ND1G + Q04SD1G <= 0
MNG04D1) Q04DD1G + Q04ND1G + Q04SD1G >= 0
MXG04D2) Q04DD2G + Q04ND2G + Q04SD2G <= 31.2460
MNG04D2) Q04DD2G + Q04ND2G + Q04SD2G >= 15.6230
MXG04D3) Q04DD3G + Q04ND3G + Q04SD3G <= 17.1853
MNG04D3) Q04DD3G + Q04ND3G + Q04SD3G >= 0
MXG04D4) Q04DD4G + Q04ND4G + Q04SD4G <= 48.4313
MNG04D4) Q04DD4G + Q04ND4G + Q04SD4G >= 32.8083
MXG05D1) Q05DD1G + Q05ND1G + Q05SD1G <= 0
MNG05D1) Q05DD1G + Q05ND1G + Q05SD1G >= 0
MXG05D2) Q05DD2G + Q05ND2G + Q05SD2G <= 15.0784
MNG05D2) Q05DD2G + Q05ND2G + Q05SD2G >= 0
MXG05D3) Q05DD3G + Q05ND3G + Q05SD3G <= 13.1936
MNG05D3) Q05DD3G + Q05ND3G + Q05SD3G >= 0
MXG05D4) Q05DD4G + Q05ND4G + Q05SD4G <= 73.5072
MNG05D4) Q05DD4G + Q05ND4G + Q05SD4G >= 54.6592
MXG06D1) Q06DD1G + Q06ND1G + Q06SD1G <= 0
MNG06D1) Q06DD1G + Q06ND1G + Q06SD1G >= 0
MXG06D2) Q06DD2G + Q06ND2G + Q06SD2G <= 25.7642
MNG06D2) Q06DD2G + Q06ND2G + Q06SD2G >= 0
MXG06D3) Q06DD3G + Q06ND3G + Q06SD3G <= 9.3688
MNG06D3) Q06DD3G + Q06ND3G + Q06SD3G >= 0
MXG06D4) Q06DD4G + Q06ND4G + Q06SD4G <= 53.8706
MNG06D4) Q06DD4G + Q06ND4G + Q06SD4G >= 30.4486
MXG07D1) Q07DD1G + Q07ND1G + Q07SD1G <= 0
MNG07D1) Q07DD1G + Q07ND1G + Q07SD1G >= 0
MXG07D2) Q07DD2G + Q07ND2G + Q07SD2G <= 48.304
MNG07D2) Q07DD2G + Q07ND2G + Q07SD2G >= 24.152
MXG07D3) Q07DD3G + Q07ND3G + Q07SD3G <= 19.3216

MNG07D3) Q07DD3G + Q07ND3G + Q07SD3G >= 0
MXG07D4) Q07DD4G + Q07ND4G + Q07SD4G <= 43.4736
MNG07D4) Q07DD4G + Q07ND4G + Q07SD4G >= 12.076
MXG08D1) Q08DD1G + Q08ND1G + Q08SD1G <= 0
MNG08D1) Q08DD1G + Q08ND1G + Q08SD1G >= 0
MXG08D2) Q08DD2G + Q08ND2G + Q08SD2G <= 40.0975
MNG08D2) Q08DD2G + Q08ND2G + Q08SD2G >= 24.0585
MXG08D3) Q08DD3G + Q08ND3G + Q08SD3G <= 44.9092
MNG08D3) Q08DD3G + Q08ND3G + Q08SD3G >= 28.8702
MXG08D4) Q08DD4G + Q08ND4G + Q08SD4G <= 0
MNG08D4) Q08DD4G + Q08ND4G + Q08SD4G >= 0
MXG09D1) Q09DD1G + Q09ND1G + Q09SD1G <= 0
MNG09D1) Q09DD1G + Q09ND1G + Q09SD1G >= 0
MXG09D2) Q09DD2G + Q09ND2G + Q09SD2G <= 58.52
MNG09D2) Q09DD2G + Q09ND2G + Q09SD2G >= 31.92
MXG09D3) Q09DD3G + Q09ND3G + Q09SD3G <= 66.50
MNG09D3) Q09DD3G + Q09ND3G + Q09SD3G >= 39.90
MXG09D4) Q09DD4G + Q09ND4G + Q09SD4G <= 0
MNG09D4) Q09DD4G + Q09ND4G + Q09SD4G >= 0
MXG10D1) Q10DD1G + Q10ND1G + Q10SD1G <= 0
MNG10D1) Q10DD1G + Q10ND1G + Q10SD1G >= 0
MXG10D2) Q10DD2G + Q10ND2G + Q10SD2G <= 77.4916
MNG10D2) Q10DD2G + Q10ND2G + Q10SD2G >= 43.7996
MXG10D3) Q10DD3G + Q10ND3G + Q10SD3G <= 0
MNG10D3) Q10DD3G + Q10ND3G + Q10SD3G >= 0
MXG10D4) Q10DD4G + Q10ND4G + Q10SD4G <= 0
MNG10D4) Q10DD4G + Q10ND4G + Q10SD4G >= 0
MXG11D1) Q11DD1G + Q11ND1G + Q11SD1G <= 23.865
MNG11D1) Q11DD1G + Q11ND1G + Q11SD1G >= 14.319
MXG11D2) Q11DD2G + Q11ND2G + Q11SD2G <= 0
MNG11D2) Q11DD2G + Q11ND2G + Q11SD2G >= 0
MXG11D3) Q11DD3G + Q11ND3G + Q11SD3G <= 23.865
MNG11D3) Q11DD3G + Q11ND3G + Q11SD3G >= 14.319
MXG11D4) Q11DD4G + Q11ND4G + Q11SD4G <= 0
MNG11D4) Q11DD4G + Q11ND4G + Q11SD4G >= 0
MXG12D1) Q12DD1G + Q12ND1G + Q12SD1G <= 25.062
MNG12D1) Q12DD1G + Q12ND1G + Q12SD1G >= 16.708
MXG12D2) Q12DD2G + Q12ND2G + Q12SD2G <= 0
MNG12D2) Q12DD2G + Q12ND2G + Q12SD2G >= 0
MXG12D3) Q12DD3G + Q12ND3G + Q12SD3G <= 25.062
MNG12D3) Q12DD3G + Q12ND3G + Q12SD3G >= 16.708
MXG12D4) Q12DD4G + Q12ND4G + Q12SD4G <= 0
MNG12D4) Q12DD4G + Q12ND4G + Q12SD4G >= 0
MXG13D1) Q13DD1G + Q13ND1G + Q13SD1G <= 31.408
MNG13D1) Q13DD1G + Q13ND1G + Q13SD1G >= 15.704
MXG13D2) Q13DD2G + Q13ND2G + Q13SD2G <= 0
MNG13D2) Q13DD2G + Q13ND2G + Q13SD2G >= 0
MXG13D3) Q13DD3G + Q13ND3G + Q13SD3G <= 54.964
MNG13D3) Q13DD3G + Q13ND3G + Q13SD3G >= 39.26
MXG13D4) Q13DD4G + Q13ND4G + Q13SD4G <= 0
MNG13D4) Q13DD4G + Q13ND4G + Q13SD4G >= 0
MXG14D1) Q14DD1G + Q14ND1G + Q14SD1G <= 19.3905
MNG14D1) Q14DD1G + Q14ND1G + Q14SD1G >= 6.4635
MXG14D2) Q14DD2G + Q14ND2G + Q14SD2G <= 0
MNG14D2) Q14DD2G + Q14ND2G + Q14SD2G >= 0
MXG14D3) Q14DD3G + Q14ND3G + Q14SD3G <= 45.2445
MNG14D3) Q14DD3G + Q14ND3G + Q14SD3G >= 32.3175
MXG14D4) Q14DD4G + Q14ND4G + Q14SD4G <= 0
MNG14D4) Q14DD4G + Q14ND4G + Q14SD4G >= 0
MXG15D1) Q15DD1G + Q15ND1G + Q15SD1G <= 0
MNG15D1) Q15DD1G + Q15ND1G + Q15SD1G >= 0
MXG15D2) Q15DD2G + Q15ND2G + Q15SD2G <= 0
MNG15D2) Q15DD2G + Q15ND2G + Q15SD2G >= 0

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MXG15D3)   Q15DD3G + Q15ND3G + Q15SD3G <=   0.44366
MNG15D3)   Q15DD3G + Q15ND3G + Q15SD3G >=   0
MXG15D4)   Q15DD4G + Q15ND4G + Q15SD4G <=   0
MNG15D4)   Q15DD4G + Q15ND4G + Q15SD4G >=   0
MXTD1D1)   ATD1D1 <=   54
MXTD1D2)   ATD1D2 <=   54
MXTD1N1)   ATD1N1 <=   0
MXTD1N2)   ATD1N2 <=   0
MXTD1S1)   ATD1S1 <=   0
MXTD1S2)   ATD1S2 <=   0
MXTD2D1)   ATD2D1 <=   272
MXTD2D2)   ATD2D2 <=   204
MXTD2N1)   ATD2N1 <=   0
MXTD2N2)   ATD2N2 <=   0
MXTD2S1)   ATD2S1 <=   0
MXTD2S2)   ATD2S2 <=   0
MXTD3D1)   ATD3D1 <=   440
MXTD3D2)   ATD3D2 <=   220
MXTD3N1)   ATD3N1 <=   0
MXTD3N2)   ATD3N2 <=   0
MXTD3S1)   ATD3S1 <=   0
MXTD3S2)   ATD3S2 <=   0
MXTD4D1)   ATD4D1 <=   96
MXTD4D2)   ATD4D2 <=   48
MXTD4N1)   ATD4N1 <=   0
MXTD4N2)   ATD4N2 <=   0
MXTD4S1)   ATD4S1 <=   0
MXTD4S2)   ATD4S2 <=   0
  MXTD1)   ATD1D1 + ATD1D2 + ATD1N1 + ATD1N2 + ATD1S1 + ATD1S2 <=   54
  MXTD2)   ATD2D1 + ATD2D2 + ATD2N1 + ATD2N2 + ATD2S1 + ATD2S2 <=   272
  MXTD3)   ATD3D1 + ATD3D2 + ATD3N1 + ATD3N2 + ATD3S1 + ATD3S2 <=   440
  MXTD4)   ATD4D1 + ATD4D2 + ATD4N1 + ATD4N2 + ATD4S1 + ATD4S2 <=   96
  MNTD1)   ATD1D1 + ATD1D2 + ATD1N1 + ATD1N2 + ATD1S1 + ATD1S2 >=   18
  MNTD2)   ATD2D1 + ATD2D2 + ATD2N1 + ATD2N2 + ATD2S1 + ATD2S2 >=   68
  MNTD3)   ATD3D1 + ATD3D2 + ATD3N1 + ATD3N2 + ATD3S1 + ATD3S2 >=   110
  MNTD4)   ATD4D1 + ATD4D2 + ATD4N1 + ATD4N2 + ATD4S1 + ATD4S2 >=   24
 DGHHD1) - Q02DHHG - Q03DHHG - Q04DHHG - Q05DHHG - Q06DHHG - Q07DHHG
   - Q08DHHG - Q12DHHG + DGHHD1 =    0
 DGHHD2) - Q01DHHG - Q09DHHG - Q10DHHG - Q11DHHG - Q13DHHG - Q14DHHG
   - Q15DHHG + DGHHD2 =    0
 DGHHN1) - Q01NHHG - Q02NHHG - Q03NHHG - Q04NHHG - Q05NHHG - Q06NHHG
   - Q07NHHG - Q08NHHG + DGHHN1 =    0
 DGHHN2) - Q09NHHG - Q10NHHG - Q11NHHG - Q12NHHG - Q13NHHG - Q14NHHG
   - Q15NHHG + DGHHN2 =    0
 DGHHS1) - Q06SHHG - Q07SHHG - Q08SHHG - Q09SHHG - Q10SHHG - Q13SHHG
   - Q14SHHG - Q15SHHG + DGHHS1 =    0
 DGHHS2) - Q01SHHG - Q02SHHG - Q03SHHG - Q04SHHG - Q05SHHG - Q11SHHG
   - Q12SHHG + DGHHS2 =    0
 DGD1D1) - Q02DD1G - Q03DD1G - Q04DD1G - Q05DD1G - Q06DD1G - Q07DD1G
   - Q08DD1G - Q12DD1G + DGD1D1 =    0
 DGD1D2) - Q01DD1G - Q09DD1G - Q10DD1G - Q11DD1G - Q13DD1G - Q14DD1G
   - Q15DD1G + DGD1D2 =    0
 DGD1N1) - Q01ND1G - Q02ND1G - Q03ND1G - Q04ND1G - Q05ND1G - Q06ND1G
   - Q07ND1G - Q08ND1G + DGD1N1 =    0
 DGD1N2) - Q09ND1G - Q10ND1G - Q11ND1G - Q12ND1G - Q13ND1G - Q14ND1G
   - Q15ND1G + DGD1N2 =    0
 DGD1S1) - Q06SD1G - Q07SD1G - Q08SD1G - Q09SD1G - Q10SD1G - Q13SD1G
   - Q14SD1G - Q15SD1G + DGD1S1 =    0
 DGD1S2) - Q01SD1G - Q02SD1G - Q03SD1G - Q04SD1G - Q05SD1G - Q11SD1G
   - Q12SD1G + DGD1S2 =    0
 DGD2D1) - Q02DD2G - Q03DD2G - Q04DD2G - Q05DD2G - Q06DD2G - Q07DD2G
   - Q08DD2G - Q12DD2G + DGD2D1 =    0
 DGD2D2) - Q01DD2G - Q09DD2G - Q10DD2G - Q11DD2G - Q13DD2G - Q14DD2G
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- Q15DD2G + DGD2D2 = 0
DGD2N1) - Q01ND2G - Q02ND2G - Q03ND2G - Q04ND2G - Q05ND2G - Q06ND2G
- Q07ND2G - Q08ND2G + DGD2N1 = 0
DGD2N2) - Q09ND2G - Q10ND2G - Q11ND2G - Q12ND2G - Q13ND2G - Q14ND2G
- Q15ND2G + DGD2N2 = 0
DGD2S1) - Q06SD2G - Q07SD2G - Q08SD2G - Q09SD2G - Q10SD2G - Q13SD2G
- Q14SD2G - Q15SD2G + DGD2S1 = 0
DGD2S2) - Q01SD2G - Q02SD2G - Q03SD2G - Q04SD2G - Q05SD2G - Q11SD2G
- Q12SD2G + DGD2S2 = 0
DGD3D1) - Q02DD3G - Q03DD3G - Q04DD3G - Q05DD3G - Q06DD3G - Q07DD3G
- Q08DD3G - Q12DD3G + DGD3D1 = 0
DGD3D2) - Q01DD3G - Q09DD3G - Q10DD3G - Q11DD3G - Q13DD3G - Q14DD3G
- Q15DD3G + DGD3D2 = 0
DGD3N1) - Q01ND3G - Q02ND3G - Q03ND3G - Q04ND3G - Q05ND3G - Q06ND3G
- Q07ND3G - Q08ND3G + DGD3N1 = 0
DGD3N2) - Q09ND3G - Q10ND3G - Q11ND3G - Q12ND3G - Q13ND3G - Q14ND3G
- Q15ND3G + DGD3N2 = 0
DGD3S1) - Q06SD3G - Q07SD3G - Q08SD3G - Q09SD3G - Q10SD3G - Q13SD3G
- Q14SD3G - Q15SD3G + DGD3S1 = 0
DGD3S2) - Q01SD3G - Q02SD3G - Q03SD3G - Q04SD3G - Q05SD3G - Q11SD3G
- Q12SD3G + DGD3S2 = 0
DGD4D1) - Q02DD4G - Q03DD4G - Q04DD4G - Q05DD4G - Q06DD4G - Q07DD4G
- Q08DD4G - Q12DD4G + DGD4D1 = 0
DGD4D2) - Q01DD4G - Q09DD4G - Q10DD4G - Q11DD4G - Q13DD4G - Q14DD4G
- Q15DD4G + DGD4D2 = 0
DGD4N1) - Q01ND4G - Q02ND4G - Q03ND4G - Q04ND4G - Q05ND4G - Q06ND4G
- Q07ND4G - Q08ND4G + DGD4N1 = 0
DGD4N2) - Q09ND4G - Q10ND4G - Q11ND4G - Q12ND4G - Q13ND4G - Q14ND4G
- Q15ND4G + DGD4N2 = 0
DGD4S1) - Q06SD4G - Q07SD4G - Q08SD4G - Q09SD4G - Q10SD4G - Q13SD4G
- Q14SD4G - Q15SD4G + DGD4S1 = 0
DGD4S2) - Q01SD4G - Q02SD4G - Q03SD4G - Q04SD4G - Q05SD4G - Q11SD4G
- Q12SD4G + DGD4S2 = 0
DSHHD1) - Q02DHHS - Q03DHHS - Q04DHHS - Q05DHHS - Q06DHHS - Q07DHHS
- Q08DHHS - Q12DHHS + DSHHD1 = 0
DSHHD2) - Q01DHHS - Q09DHHS - Q10DHHS - Q11DHHS - Q13DHHS - Q14DHHS
- Q15DHHS + DSHHD2 = 0
DSHHN1) - Q01NHHS - Q02NHHS - Q03NHHS - Q04NHHS - Q05NHHS - Q06NHHS
- Q07NHHS - Q08NHHS + DSHHN1 = 0
DSHHN2) - Q09NHHS - Q10NHHS - Q11NHHS - Q12NHHS - Q13NHHS - Q14NHHS
- Q15NHHS + DSHHN2 = 0
DSHHS1) - Q06SHHS - Q07SHHS - Q08SHHS - Q09SHHS - Q10SHHS - Q13SHHS
- Q14SHHS - Q15SHHS + DSHHS1 = 0
DSHHS2) - Q01SHHS - Q02SHHS - Q03SHHS - Q04SHHS - Q05SHHS - Q11SHHS
- Q12SHHS + DSHHS2 = 0
ATD1D1) - Q02DD1G - Q03DD1G - Q04DD1G - Q05DD1G - Q06DD1G - Q07DD1G
- Q08DD1G - Q12DD1G + 1.75 ATD1D1 = 0
ATD1D2) - Q01DD1G - Q09DD1G - Q10DD1G - Q11DD1G - Q13DD1G - Q14DD1G
- Q15DD1G + 1.75 ATD1D2 = 0
ATD1N1) - Q01ND1G - Q02ND1G - Q03ND1G - Q04ND1G - Q05ND1G - Q06ND1G
- Q07ND1G - Q08ND1G + 1.75 ATD1N1 = 0
ATD1N2) - Q09ND1G - Q10ND1G - Q11ND1G - Q12ND1G - Q13ND1G - Q14ND1G
- Q15ND1G + 1.75 ATD1N2 = 0
ATD1S1) - Q06SD1G - Q07SD1G - Q08SD1G - Q09SD1G - Q10SD1G - Q13SD1G
- Q14SD1G - Q15SD1G + 1.75 ATD1S1 = 0
ATD1S2) - Q01SD1G - Q02SD1G - Q03SD1G - Q04SD1G - Q05SD1G - Q11SD1G
- Q12SD1G + 1.75 ATD1S2 = 0
ATD2D1) - Q02DD2G - Q03DD2G - Q04DD2G - Q05DD2G - Q06DD2G - Q07DD2G
- Q08DD2G - Q12DD2G + 2 ATD2D1 = 0
ATD2D2) - Q01DD2G - Q09DD2G - Q10DD2G - Q11DD2G - Q13DD2G - Q14DD2G
- Q15DD2G + 2 ATD2D2 = 0
ATD2N1) - Q01ND2G - Q02ND2G - Q03ND2G - Q04ND2G - Q05ND2G - Q06ND2G
- Q07ND2G - Q08ND2G + 2 ATD2N1 = 0

ATD2N2) - Q09ND2G - Q10ND2G - Q11ND2G - Q12ND2G - Q13ND2G - Q14ND2G - Q15ND2G + 2 ATD2N2 = 0
ATD2S1) - Q06SD2G - Q07SD2G - Q08SD2G - Q09SD2G - Q10SD2G - Q13SD2G - Q14SD2G - Q15SD2G + 2 ATD2S1 = 0
ATD2S2) - Q01SD2G - Q02SD2G - Q03SD2G - Q04SD2G - Q05SD2G - Q11SD2G - Q12SD2G + 2 ATD2S2 = 0
ATD3D1) - Q02DD3G - Q03DD3G - Q04DD3G - Q05DD3G - Q06DD3G - Q07DD3G - Q08DD3G - Q12DD3G + 3 ATD3D1 = 0
ATD3D2) - Q01DD3G - Q09DD3G - Q10DD3G - Q11DD3G - Q13DD3G - Q14DD3G - Q15DD3G + 3 ATD3D2 = 0
ATD3N1) - Q01ND3G - Q02ND3G - Q03ND3G - Q04ND3G - Q05ND3G - Q06ND3G - Q07ND3G - Q08ND3G + 3 ATD3N1 = 0
ATD3N2) - Q09ND3G - Q10ND3G - Q11ND3G - Q12ND3G - Q13ND3G - Q14ND3G - Q15ND3G + 3 ATD3N2 = 0
ATD3S1) - Q06SD3G - Q07SD3G - Q08SD3G - Q09SD3G - Q10SD3G - Q13SD3G - Q14SD3G - Q15SD3G + 3 ATD3S1 = 0
ATD3S2) - Q01SD3G - Q02SD3G - Q03SD3G - Q04SD3G - Q05SD3G - Q11SD3G - Q12SD3G + 3 ATD3S2 = 0
ATD4D1) - Q02DD4G - Q03DD4G - Q04DD4G - Q05DD4G - Q06DD4G - Q07DD4G - Q08DD4G - Q12DD4G + 7 ATD4D1 = 0
ATD4D2) - Q01DD4G - Q09DD4G - Q10DD4G - Q11DD4G - Q13DD4G - Q14DD4G - Q15DD4G + 7 ATD4D2 = 0
ATD4N1) - Q01ND4G - Q02ND4G - Q03ND4G - Q04ND4G - Q05ND4G - Q06ND4G - Q07ND4G - Q08ND4G + 7 ATD4N1 = 0
ATD4N2) - Q09ND4G - Q10ND4G - Q11ND4G - Q12ND4G - Q13ND4G - Q14ND4G - Q15ND4G + 7 ATD4N2 = 0
ATD4S1) - Q06SD4G - Q07SD4G - Q08SD4G - Q09SD4G - Q10SD4G - Q13SD4G - Q14SD4G - Q15SD4G + 7 ATD4S1 = 0
ATD4S2) - Q01SD4G - Q02SD4G - Q03SD4G - Q04SD4G - Q05SD4G - Q11SD4G - Q12SD4G + 7 ATD4S2 = 0
ATHHGD1) - Q02DHHG - Q03DHHG - Q04DHHG - Q05DHHG - Q06DHHG - Q07DHHG - Q08DHHG - Q12DHHG + 7 ATHHGD1 = 0
ATHHGD2) - Q01DHHG - Q09DHHG - Q10DHHG - Q11DHHG - Q13DHHG - Q14DHHG - Q15DHHG + 7 ATHHGD2 = 0
ATHHGN1) - Q01NHHG - Q02NHHG - Q03NHHG - Q04NHHG - Q05NHHG - Q06NHHG - Q07NHHG - Q08NHHG + 7 ATHHGN1 = 0
ATHHGN2) - Q09NHHG - Q10NHHG - Q11NHHG - Q12NHHG - Q13NHHG - Q14NHHG - Q15NHHG + 7 ATHHGN2 = 0
ATHHGS1) - Q06SHHG - Q07SHHG - Q08SHHG - Q09SHHG - Q10SHHG - Q13SHHG - Q14SHHG - Q15SHHG + 7 ATHHGS1 = 0
ATHHGS2) - Q01SHHG - Q02SHHG - Q03SHHG - Q04SHHG - Q05SHHG - Q11SHHG - Q12SHHG + 7 ATHHGS2 = 0
ATHHSD1) - Q02DHHS - Q03DHHS - Q04DHHS - Q05DHHS - Q06DHHS - Q07DHHS - Q08DHHS - Q12DHHS + 9 ATHHSD1 = 0
ATHHSD2) - Q01DHHS - Q09DHHS - Q10DHHS - Q11DHHS - Q13DHHS - Q14DHHS - Q15DHHS + 9 ATHHSD2 = 0
ATHHSN1) - Q01NHHS - Q02NHHS - Q03NHHS - Q04NHHS - Q05NHHS - Q06NHHS - Q07NHHS - Q08NHHS + 9 ATHHSN1 = 0
ATHHSN2) - Q09NHHS - Q10NHHS - Q11NHHS - Q12NHHS - Q13NHHS - Q14NHHS - Q15NHHS + 9 ATHHSN2 = 0
ATHHSS1) - Q06SHHS - Q07SHHS - Q08SHHS - Q09SHHS - Q10SHHS - Q13SHHS - Q14SHHS - Q15SHHS + 9 ATHHSS1 = 0
ATHHSS2) - Q01SHHS - Q02SHHS - Q03SHHS - Q04SHHS - Q05SHHS - Q11SHHS - Q12SHHS + 9 ATHHSS2 = 0
MXG01HH) Q01DHHG + Q01NHHG + Q01SHHG <= 91.00
MXG02HH) Q02DHHG + Q02NHHG + Q02SHHG <= 117.33
MXG03HH) Q03DHHG + Q03NHHG + Q03SHHG <= 93.33
MXG04HH) Q04DHHG + Q04NHHG + Q04SHHG <= 90.61
MXG05HH) Q05DHHG + Q05NHHG + Q05SHHG <= 118.74
MXG06HH) Q06DHHG + Q06NHHG + Q06SHHG <= 187.37
MXG07HH) Q07DHHG + Q07NHHG + Q07SHHG <= 185.97
MXG08HH) Q08DHHG + Q08NHHG + Q08SHHG <= 101.05
MXG09HH) Q09DHHG + Q09NHHG + Q09SHHG <= 180.88

MXG10HH) Q10DHHG + Q10NHHG + Q10SHHG <= 293.12
MXG11HH) Q11DHHG + Q11NHHG + Q11SHHG <= 62.049
MXG12HH) Q12DHHG + Q12NHHG + Q12SHHG <= 45.947
MXG13HH) Q13DHHG + Q13NHHG + Q13SHHG <= 94.224
MXG14HH) Q14DHHG + Q14NHHG + Q14SHHG <= 96.9525
MXG15HH) Q15DHHG + Q15NHHG + Q15SHHG <= 22.183
MNG01HH) Q01DHHG + Q01NHHG + Q01SHHG >= 73.16
MNG02HH) Q02DHHG + Q02NHHG + Q02SHHG >= 99.82
MNG03HH) Q03DHHG + Q03NHHG + Q03SHHG >= 75.38
MNG04HH) Q04DHHG + Q04NHHG + Q04SHHG >= 74.99
MNG05HH) Q05DHHG + Q05NHHG + Q05SHHG >= 99.89
MNG06HH) Q06DHHG + Q06NHHG + Q06SHHG >= 163.95
MNG07HH) Q07DHHG + Q07NHHG + Q07SHHG >= 161.82
MNG08HH) Q08DHHG + Q08NHHG + Q08SHHG >= 85.01
MNG09HH) Q09DHHG + Q09NHHG + Q09SHHG >= 154.28
MNG10HH) Q10DHHG + Q10NHHG + Q10SHHG >= 259.43
MNG11HH) Q11DHHG + Q11NHHG + Q11SHHG >= 52.503
MNG12HH) Q12DHHG + Q12NHHG + Q12SHHG >= 37.593
MNG13HH) Q13DHHG + Q13NHHG + Q13SHHG >= 78.52
MNG14HH) Q14DHHG + Q14NHHG + Q14SHHG >= 84.0255
MNG15HH) Q15DHHG + Q15NHHG + Q15SHHG >= 21.07
SGFD) Q01DD1G + Q01DD2G + Q01DD3G + Q01DD4G + Q02DD1G + Q02DD2G
+ Q02DD3G + Q02DD4G + Q03DD1G + Q03DD2G + Q03DD3G + Q03DD4G + Q04DD1G
+ Q04DD2G + Q04DD3G + Q04DD4G + Q05DD1G + Q05DD2G + Q05DD3G + Q05DD4G
+ Q06DD1G + Q06DD2G + Q06DD3G + Q06DD4G + Q07DD1G + Q07DD2G + Q07DD3G
+ Q07DD4G + Q08DD1G + Q08DD2G + Q08DD3G + Q08DD4G + Q09DD1G + Q09DD2G
+ Q09DD3G + Q09DD4G + Q10DD1G + Q10DD2G + Q10DD3G + Q10DD4G + Q11DD1G
+ Q11DD2G + Q11DD3G + Q11DD4G + Q12DD1G + Q12DD2G + Q12DD3G + Q12DD4G
+ Q13DD1G + Q13DD2G + Q13DD3G + Q13DD4G + Q14DD1G + Q14DD2G + Q14DD3G
+ Q14DD4G + Q15DD1G + Q15DD2G + Q15DD3G + Q15DD4G + Q01DHHG + Q02DHHG
+ Q03DHHG + Q04DHHG + Q05DHHG + Q06DHHG + Q07DHHG + Q08DHHG + Q09DHHG
+ Q10DHHG + Q11DHHG + Q12DHHG + Q13DHHG + Q14DHHG + Q15DHHG - SGFD
= 0
SGFN) Q01ND1G + Q01ND2G + Q01ND3G + Q01ND4G + Q02ND1G + Q02ND2G
+ Q02ND3G + Q02ND4G + Q03ND1G + Q03ND2G + Q03ND3G + Q03ND4G + Q04ND1G
+ Q04ND2G + Q04ND3G + Q04ND4G + Q05ND1G + Q05ND2G + Q05ND3G + Q05ND4G
+ Q06ND1G + Q06ND2G + Q06ND3G + Q06ND4G + Q07ND1G + Q07ND2G + Q07ND3G
+ Q07ND4G + Q08ND1G + Q08ND2G + Q08ND3G + Q08ND4G + Q09ND1G + Q09ND2G
+ Q09ND3G + Q09ND4G + Q10ND1G + Q10ND2G + Q10ND3G + Q10ND4G + Q11ND1G
+ Q11ND2G + Q11ND3G + Q11ND4G + Q12ND1G + Q12ND2G + Q12ND3G + Q12ND4G
+ Q13ND1G + Q13ND2G + Q13ND3G + Q13ND4G + Q14ND1G + Q14ND2G + Q14ND3G
+ Q14ND4G + Q15ND1G + Q15ND2G + Q15ND3G + Q15ND4G + Q01NHHG + Q02NHHG
+ Q03NHHG + Q04NHHG + Q05NHHG + Q06NHHG + Q07NHHG + Q08NHHG + Q09NHHG
+ Q10NHHG + Q11NHHG + Q12NHHG + Q13NHHG + Q14NHHG + Q15NHHG - SGFN
= 0
SGFS) Q01SD1G + Q01SD2G + Q01SD3G + Q01SD4G + Q02SD1G + Q02SD2G
+ Q02SD3G + Q02SD4G + Q03SD1G + Q03SD2G + Q03SD3G + Q03SD4G + Q04SD1G
+ Q04SD2G + Q04SD3G + Q04SD4G + Q05SD1G + Q05SD2G + Q05SD3G + Q05SD4G
+ Q06SD1G + Q06SD2G + Q06SD3G + Q06SD4G + Q07SD1G + Q07SD2G + Q07SD3G
+ Q07SD4G + Q08SD1G + Q08SD2G + Q08SD3G + Q08SD4G + Q09SD1G + Q09SD2G
+ Q09SD3G + Q09SD4G + Q10SD1G + Q10SD2G + Q10SD3G + Q10SD4G + Q11SD1G
+ Q11SD2G + Q11SD3G + Q11SD4G + Q12SD1G + Q12SD2G + Q12SD3G + Q12SD4G
+ Q13SD1G + Q13SD2G + Q13SD3G + Q13SD4G + Q14SD1G + Q14SD2G + Q14SD3G
+ Q14SD4G + Q15SD1G + Q15SD2G + Q15SD3G + Q15SD4G + Q01SHHG + Q02SHHG
+ Q03SHHG + Q04SHHG + Q05SHHG + Q06SHHG + Q07SHHG + Q08SHHG + Q09SHHG
+ Q10SHHG + Q11SHHG + Q12SHHG + Q13SHHG + Q14SHHG + Q15SHHG - SGFS
= 0
BSGFD) SGFD - SRD - SDDD - SADD - SIFD - SCFD = 0
BSGFN) SGFN - SRN - SDDN - SADN - SIFN - SCFN = 0
BSGFS) SGFS - SRS - SDDS - SADS - SIFS - SCFS = 0
MXSRD) - 0.0421 SGFD + SRD <= 0
MXSRN) - 0.0421 SGFN + SRN <= 0
MXSRS) - 0.0421 SGFS + SRS <= 0

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MXSDDD) - 0.1053 SGFD + SDDD <=   0
MXSDDN) - 0.1053 SGFN + SDDN <=   0
MXSDDS) - 0.1053 SGFS + SDDS <=   0
MXSIFD) - 0.1684 SGFD + SIFD <=   0
MXSIFN) - 0.1684 SGFN + SIFN <=   0
MXSIFS) - 0.1684 SGFS + SIFS <=   0
MXSCFD) - 0.6842 SGFD + SCFD <=   0
MXSCFN) - 0.6842 SGFN + SCFN <=   0
MXSCFS) - 0.6842 SGFS + SCFS <=   0
  BIRD) - 0.03125 SIFD + IRD =    0
  BIRN) - 0.03125 SIFN + IRN =    0
  BIRS) - 0.03125 SIFS + IRS =    0
 BIIRD) - 0.0625 SIFD + IIRD =    0
 BIIRN) - 0.0625 SIFN + IIRN =    0
 BIIRS) - 0.0625 SIFS + IIRS =    0
 BIARD) - 0.0919 SIFD + IARD =    0
 BIARN) - 0.0919 SIFN + IARN =    0
 BIARS) - 0.0919 SIFS + IARS =    0
  BCRD) - 0.0192 SCFD + CRD =    0
  BCRN) - 0.0192 SCFN + CRN =    0
  BCRS) - 0.0192 SCFS + CRS =    0
 BCIRD) - 0.0615 SCFD + CIRD =    0
 BCIRN) - 0.0615 SCFN + CIRN =    0
 BCIRS) - 0.0615 SCFS + CIRS =    0
 BCPRD) - 0.1414 SCFD + CPRD =    0
 BCPRN) - 0.1414 SCFN + CPRN =    0
 BCPRS) - 0.1414 SCFS + CPRS =    0
 BCPDD) - 0.2657 SCFD + CPD =    0
 BCPDN) - 0.2657 SCFN + CPN =    0
 BCPDS) - 0.2657 SCFS + CPS =    0
   XFD)   XFD - XSILTD - XFGD - XFRJD =    0
   XFN)   XFN - XSILTN - XFGN - XFRJN =    0
   XFS)   XFS - XSILTS - XFGS - XFRJS =    0
  BXSD) - Q01DHHS - Q02DHHS - Q03DHHS - Q04DHHS - Q05DHHS - Q06DHHS
   - Q07DHHS - Q08DHHS - Q09DHHS - Q10DHHS - Q11DHHS - Q12DHHS - Q13DHHS
   - Q14DHHS - Q15DHHS + XSILTD =    0
  BXSN) - Q01NHHS - Q02NHHS - Q03NHHS - Q04NHHS - Q05NHHS - Q06NHHS
   - Q07NHHS - Q08NHHS - Q09NHHS - Q10NHHS - Q11NHHS - Q12NHHS - Q13NHHS
   - Q14NHHS - Q15NHHS + XSILTN =    0
  BXSS) - Q01SHHS - Q02SHHS - Q03SHHS - Q04SHHS - Q05SHHS - Q06SHHS
   - Q07SHHS - Q08SHHS - Q09SHHS - Q10SHHS - Q11SHHS - Q12SHHS - Q13SHHS
   - Q14SHHS - Q15SHHS + XSILTS =    0
 BXFGD) - SDDD - SADD + XFGD =    0
 BXFGN) - SDDN - SADN + XFGN =    0
 BXFGS) - SDDS - SADS + XFGS =    0
BXFRJD) - IIRD - IARD - CIRD - CPRD + XFRJD =    0
BXFRJN) - IIRN - IARN - CIRN - CPRN + XFRJN =    0
BXFRJS) - IIRS - IARS - CIRS - CPRS + XFRJS =    0
SCAPXD)   SGFD <=   5000
SCAPXN)   SGFN <=   0
SCAPXS)   SGFS <=   0
SCAPND)   SGFD >=   0
SCAPNN)   SGFN >=   0
SCAPNS)   SGFS >=   0
ICAPXD)   SIFD <=   0
ICAPXN)   SIFN <=   0
ICAPXS)   SIFS <=   0
ICAPND)   SIFD >=   0
ICAPNN)   SIFN >=   0
ICAPNS)   SIFS >=   0
CCAPXD)   SCFD <=   151
CCAPXN)   SCFN <=   0
CCAPXS)   SCFS <=   0
```

CCAPND) SCFD >= 150
CCAPNN) SCFN >= 0
CCAPNS) SCFS >= 0
XCAPXD) XFD <= 5000
XCAPXN) XFN <= 0
XCAPXS) XFS <= 0
CTCX) - 95 XFD - 95 XFN - 95 XFS + CTCX = 0
CTCI) - 1726.03003 SIFD - 1726.03003 SIFN - 1726.03003 SIFS - 50 IRD
- 50 IRN - 50 IRS - 50 IIRD - 50 IIRN - 50 IIRS - 50 IARD - 50 IARN
- 50 IARS + CTCI = 0
CTREVC) - 87.5 CPD - 87.5 CPN - 87.5 CPS + CTREVC = 0
CTRANSP) CTRANSP - CTCHH - CTCD1 - CTCD2 - CTCD3 - CTCD4 = 0
CTCHH) - CTCHH + CTCGHH + CTCSHH = 0
CTCGHH) - 153 Q01DHHG - 130 Q01NHHG - 160 Q01SHHG - 144 Q02DHHG
- 130 Q02NHHG - 160 Q02SHHG - 133.5 Q03DHHG - 160 Q03NHHG
- 160 Q03SHHG - 142 Q04DHHG - 140 Q04NHHG - 160 Q04SHHG - 140 Q05DHHG
- 160 Q05NHHG - 160 Q05SHHG - 132.5 Q06DHHG - 160 Q06NHHG
- 150 Q06SHHG - 147.75 Q07DHHG - 160 Q07NHHG - 160 Q07SHHG
- 140 Q08DHHG - 160 Q08NHHG - 160 Q08SHHG - 156.7 Q09DHHG
- 160 Q09NHHG - 130 Q09SHHG - 148.3 Q10DHHG - 160 Q10NHHG
- 160 Q10SHHG - 157.8 Q11DHHG - 160 Q11NHHG - 160 Q11SHHG
- 154.3 Q12DHHG - 160 Q12NHHG - 160 Q12SHHG - 159.39999 Q13DHHG
- 160 Q13NHHG - 140 Q13SHHG - 160 Q14DHHG - 160 Q14NHHG - 160 Q14SHHG
- 160 Q15DHHG - 160 Q15NHHG - 130 Q15SHHG + CTCGHH = 0
CTCSHH) - 143 Q01DHHS - 120 Q01NHHS - 150 Q01SHHS - 134 Q02DHHS
- 120 Q02NHHS - 150 Q02SHHS - 123.5 Q03DHHS - 150 Q03NHHS
- 150 Q03SHHS - 132 Q04DHHS - 130 Q04NHHS - 150 Q04SHHS - 130 Q05DHHS
- 150 Q05NHHS - 150 Q05SHHS - 122.5 Q06DHHS - 150 Q06NHHS
- 140 Q06SHHS - 137.75 Q07DHHS - 150 Q07NHHS - 150 Q07SHHS
- 130 Q08DHHS - 150 Q08NHHS - 150 Q08SHHS - 146.7 Q09DHHS
- 150 Q09NHHS - 120 Q09SHHS - 138.3 Q10DHHS - 150 Q10NHHS
- 150 Q10SHHS - 147.8 Q11DHHS - 150 Q11NHHS - 150 Q11SHHS
- 144.3 Q12DHHS - 150 Q12NHHS - 150 Q12SHHS - 149.39999 Q13DHHS
- 150 Q13NHHS - 130 Q13SHHS - 150 Q14DHHS - 150 Q14NHHS - 150 Q14SHHS
- 150 Q15DHHS - 150 Q15NHHS - 120 Q15SHHS + CTCSHH = 0
CTCD1) CTCD1 - CFUELD1 - CFXDRD1 - CFXDID1 = 0
CTCD2) CTCD2 - CFUELD2 - CFXDRD2 - CFXDID2 = 0
CTCD3) CTCD3 - CFUELD3 - CFXDRD3 - CFXDID3 = 0
CTCD4) CTCD4 - CFUELD4 - CFXDRD4 - CFXDID4 = 0
CFUELD1) 63.81 Q01DD1G + 24.815 Q01ND1G + 116.631 Q01SD1G + 53.18 Q02DD1G
+ 37.226 Q02ND1G + 111.67 Q02SD1G + 35.45 Q03DD1G + 68.49 Q03ND1G
+ 106.705 Q03SD1G + 53.18 Q04DD1G + 47.153 Q04ND1G + 96.78 Q04SD1G
+ 49.63 Q05DD1G + 67 Q05ND1G + 71.964 Q05SD1G + 49.63 Q06DD1G
+ 74.45 Q06ND1G + 59.556 Q06SD1G + 24.82 Q07DD1G + 104.244 Q07ND1G
+ 94.297 Q07SD1G + 46.09 Q08DD1G + 91.82 Q08ND1G + 74.445 Q08SD1G
+ 67.36 Q09DD1G + 126.566 Q09ND1G + 34.741 Q09SD1G + 49.63 Q10DD1G
+ 119.112 Q10ND1G + 71.964 Q10SD1G + 56.72 Q11DD1G + 141.45 Q11ND1G
+ 96.779 Q11SD1G + 21.27 Q12DD1G + 138.964 Q12ND1G + 121.594 Q12SD1G
+ 70.9 Q13DD1G + 126.56 Q13ND1G + 44.667 Q13SD1G + 81.54 Q14DD1G
+ 161.31 Q14ND1G + 76.927 Q14SD1G + 95.72 Q15DD1G + 168.75101 Q15ND1G
+ 12.408 Q15SD1G - 0.875 CFUELD1 = 0
CFUELD2) 55.51 Q01DD2G + 21.59 Q01ND2G + 101.464 Q01SD2G + 46.26 Q02DD2G
+ 32.382 Q02ND2G + 97.15 Q02SD2G + 30.84 Q03DD2G + 59.583 Q03ND2G
+ 92.83 Q03SD2G + 46.26 Q04DD2G + 41.02 Q04ND2G + 84.193 Q04SD2G
+ 43.18 Q05DD2G + 58.288 Q05ND2G + 62.61 Q05SD2G + 43.18 Q06DD2G
+ 64.764 Q06ND2G + 51.811 Q06SD2G + 21.59 Q07DD2G + 90.67 Q07ND2G
+ 82.03 Q07SD2G + 40.09 Q08DD2G + 79.88 Q08ND2G + 64.764 Q08SD2G
+ 58.59 Q09DD2G + 110.1 Q09ND2G + 30.22 Q09SD2G + 43.18 Q10DD2G
+ 103.62 Q10ND2G + 62.61 Q10SD2G + 49.32 Q11DD2G + 123.05 Q11ND2G
+ 84.193 Q11SD2G + 18.5 Q12DD2G + 120.89 Q12ND2G + 105.78 Q12SD2G
+ 61.68 Q13DD2G + 110.1 Q13ND2G + 38.86 Q13SD2G + 70.93 Q14DD2G
+ 140.32001 Q14ND2G + 66.923 Q14SD2G + 83.27 Q15DD2G + 146.8 Q15ND2G
+ 10.794 Q15SD2G - 0.7143 CFUELD2 = 0

```
  CFUELD3)   40.43 Q01DD3G + 15.73 Q01ND3G + 73.893 Q01SD3G + 33.7 Q02DD3G
     + 23.59 Q02ND3G + 70.75 Q02SD3G + 22.46 Q03DD3G + 43.4 Q03ND3G
     + 67.6 Q03SD3G + 33.7 Q04DD3G + 29.88 Q04ND3G + 61.316 Q04SD3G
     + 31.45 Q05DD3G + 42.46 Q05ND3G + 45.594 Q05SD3G + 31.45 Q06DD3G
     + 47.18 Q06ND3G + 37.73 Q06SD3G + 15.72 Q07DD3G + 66.05 Q07ND3G
     + 59.74 Q07SD3G + 29.2 Q08DD3G + 58.18 Q08ND3G + 47.17 Q08SD3G
     + 42.68 Q09DD3G + 80.2 Q09ND3G + 22.01 Q09SD3G + 31.45 Q10DD3G
     + 75.48 Q10ND3G + 45.594 Q10SD3G + 35.94 Q11DD3G + 89.64 Q11ND3G
     + 61.32 Q11SD3G + 13.48 Q12DD3G + 88.06 Q12ND3G + 77.04 Q12SD3G
     + 44.93 Q13DD3G + 80.2 Q13ND3G + 28.3 Q13SD3G + 51.67 Q14DD3G
     + 102.22 Q14ND3G + 48.74 Q14SD3G + 60.65 Q15DD3G + 106.93 Q15ND3G
     + 7.861 Q15SD3G - 0.75 CFUELD3 =    0
  CFUELD4)   44.93 Q01DD4G + 17.48 Q01ND4G + 82.135 Q01SD4G + 37.45 Q02DD4G
     + 26.21 Q02ND4G + 78.64 Q02SD4G + 24.96 Q03DD4G + 48.23 Q03ND4G
     + 75.14 Q03SD4G + 37.45 Q04DD4G + 33.2 Q04ND4G + 68.15 Q04SD4G
     + 34.95 Q05DD4G + 47.18 Q05ND4G + 50.68 Q05SD4G + 43.95 Q06DD4G
     + 52.43 Q06ND4G + 41.94 Q06SD4G + 17.48 Q07DD4G + 73.4 Q07ND4G
     + 66.41 Q07SD4G + 32.45 Q08DD4G + 64.66 Q08ND4G + 52.43 Q08SD4G
     + 47.43 Q09DD4G + 89.13 Q09ND4G + 24.47 Q09SD4G + 34.95 Q10DD4G
     + 83.88 Q10ND4G + 50.68 Q10SD4G + 39.94 Q11DD4G + 99.61 Q11ND4G
     + 68.15 Q11SD4G + 14.98 Q12DD4G + 97.863 Q12ND4G + 85.63 Q12SD4G
     + 49.93 Q13DD4G + 89.13 Q13ND4G + 31.46 Q13SD4G + 57.41 Q14DD4G
     + 113.591 Q14ND4G + 54.17 Q14SD4G + 67.4 Q15DD4G + 118.83 Q15ND4G
     + 8.74 Q15SD4G - CFUELD4 =    0
  CFXDRD1)   CFXDRD1 =    18262.71094
  CFXDRD2)   CFXDRD2 =    73701.46094
  CFXDRD3)   CFXDRD3 =    144396.45313
  CFXDRD4)   CFXDRD4 =    38162.16016
  CFXDID1)   CFXDID1 =    9716.7
  CFXDID2)   CFXDID2 =    59537.01
  CFXDID3)   CFXDID3 =    32804.73
  CFXDID4)   CFXDID4 =    36522.24
  CINCD1)   15 DGD1D1 + 15 DGD1D2 + 15 DGD1N1 + 15 DGD1N2 + 15 DGD1S1
      + 15 DGD1S2 - CINCD1 =    472.5
  CINCD2)   10.5 DGD2D1 + 10.5 DGD2D2 + 10.5 DGD2N1 + 10.5 DGD2N2
      + 10.5 DGD2S1 + 10.5 DGD2S2 - CINCD2 =    1428
  CINCD3)   35 DGD3D1 + 35 DGD3D2 + 35 DGD3N1 + 35 DGD3N2 + 35 DGD3S1
      + 35 DGD3S2 - CINCD3 =    11550
  CINCD4)   7.5 DGD4D1 + 7.5 DGD4D2 + 7.5 DGD4N1 + 7.5 DGD4N2
      + 7.5 DGD4S1 + 7.5 DGD4S2 - CINCD4 =    1260
  CINCT)   CINCT - CINCD1 - CINCD2 - CINCD3 - CINCD4 =    0
END
```

Annexure 6.18

6.18 MODEL OUTPUT FOR EXISTING SOLID WASTE MANAGEMENT OF KOLKATA AND ITS OPTIMIZATION

Table A-6.19 Output results from existing solid waste management model

Total cost	Total solid waste management cost in Rs.	986431.40
CTCX	Total landfilling cost in Rs.	253498.80
CTCI	Total incineration cost in Rs.	0
CTREVC	Total revenue (royalty) from compost in Rs.	3510.56
CTRANSP	Total transportation cost in Rs.	731793
CINCT	Total incentive cost in Rs.	4650.24
DGHHD1	Garbage carried by hired vehicle from Zone 1 in MT	798.45
DGHHD2	Garbage carried by hired vehicle from Zone 2 in MT	723.66
DGD1D1	Garbage carried by D1 vehicle from Zone 1 in MT	32.24
DGD1D2	Garbage carried by D1 vehicle from Zone 2 in MT	55.67
DGD2D1	Garbage carried by D2 vehicle from Zone 1 in MT	240.26
DGD2D2	Garbage carried by D2 vehicle from Zone 2 in MT	165.54
DGD3D1	Garbage carried by D3 vehicle from Zone 1 in MT	128.74
DGD3D2	Garbage carried by D3 vehicle from Zone 2 in MT	211.90
DGD4D1	Garbage carried by D4 vehicle from Zone 1 in MT	219.28
DGD4D2	Garbage carried by D4 vehicle from Zone 1 in MT	28.55
DSHHD1	Silt carried by hired vehicle from Zone 1 in MT	202
DSHHD2	Silt carried by hired vehicle from Zone 2 in MT	92.12
SRD	Recyclables from landfill in MT	109.64
SCFD	Compost plant feed in MT	151
CRD	Recyclables from compost plant in MT	2.90
CIRD	Inorganic rejects from compost plant in MT	9.29
CPRD	Process rejects from compost plant in MT	21.35
CPD	Compost product in MT	40.12
XFD	Total landfill amount in MT	2668.41
XSILTD	Total silt amount in landfill in MT	294.12
XFGD	Total garbage amount in landfill in MT	2343.65

XFRJD	Total rejects amount in landfill in MT	30.64
CTCHH	Total transportation cost by hired vehicle in Rs.	263650.50
CTCD1	Total transportation cost by D1 vehicle in Rs.	33067.65
CTCD2	Total transportation cost by D2 vehicle in Rs.	157546.90
CTCD3	Total transportation cost by D3 vehicle in Rs.	194050.40
CTCD4	Total transportation cost by D4 vehicle in Rs.	83477.53
CTCGHH	Total garbage transportation cost by hired vehicle in Rs.	223970.80
CTCSHH	Total silt transportation cost by hired vehicle in Rs.	39679.67
CFUELD1	Total fuel cost by D1 vehicle in Rs.	5088.24
CFXDRD1	Total fixed running cost by D1 vehicle in Rs.	18262.71
CFXDID1	Total fixed idle cost by D1 vehicle in Rs.	9716.70
CFUELD2	Total fuel cost by D2 vehicle in Rs.	24308.43
CFXDRD2	Total fixed running cost by D2 vehicle in Rs.	73701.46
CFXDID2	Total fixed idle cost by D2 vehicle in Rs.	59537.01
CFUELD3	Total fuel cost by D3 vehicle in Rs.	16849.23
CFXDRD3	Total fixed running cost by D3 vehicle in Rs.	144396.50
CFXDID3	Total fixed idle cost by D3 vehicle in Rs.	32804.73
CFUELD4	Total fuel cost by D4 vehicle in Rs.	8793.13
CFXDRD4	Total fixed running cost by D4 vehicle in Rs.	38162.16
CFXDID4	Total fixed idle cost by D4 vehicle in Rs.	36522.24
CINCD1	Total incentive cost by D1 vehicle in Rs.	846.15
CINCD2	Total incentive cost by D2 vehicle in Rs.	2832.87
CINCD3	Total incentive cost by D3 vehicle in Rs.	372.47
CINCD4	Total incentive cost by D4 vehicle in Rs.	598.75

Annexure 6.19

6.19 MATHEMATICAL MODEL FOR PROPOSED INTEGRATED SOLID WASTE MANAGEMENT OF KOLKATA AND ITS OPTIMIZATION

MIN CTCX + CTCS + CTCI + CTCC - CTREVR - CTREVC + CTRANSP + CINCT

SUBJECT TO

BS01) Q01DHHS + Q01NHHS + Q01SHHS = 20.11
BG01) Q01DD1G + Q01DD2G + Q01DD3G + Q01DD4G + Q01ND1G + Q01ND2G
+ Q01ND3G + Q01ND4G + Q01SD1G + Q01SD2G + Q01SD3G + Q01SD4G + Q01DHHG
+ Q01NHHG + Q01SHHG = 178.44
BS02) Q02DHHS + Q02NHHS + Q02SHHS = 12.03
BG02) Q02DD1G + Q02DD2G + Q02DD3G + Q02DD4G + Q02ND1G + Q02ND2G
+ Q02ND3G + Q02ND4G + Q02SD1G + Q02SD2G + Q02SD3G + Q02SD4G + Q02DHHG
+ Q02NHHG + Q02SHHG = 175.12
BS03) Q03DHHS + Q03NHHS + Q03SHHS = 20.09
BG03) Q03DD1G + Q03DD2G + Q03DD3G + Q03DD4G + Q03ND1G + Q03ND2G
+ Q03ND3G + Q03ND4G + Q03SD1G + Q03SD2G + Q03SD3G + Q03SD4G + Q03DHHG
+ Q03NHHG + Q03SHHG = 179.48
BS04) Q04DHHS + Q04NHHS + Q04SHHS = 12.72
BG04) Q04DD1G + Q04DD2G + Q04DD3G + Q04DD4G + Q04ND1G + Q04ND2G
+ Q04ND3G + Q04ND4G + Q04SD1G + Q04SD2G + Q04SD3G + Q04SD4G + Q04DHHG
+ Q04NHHG + Q04SHHG = 156.23
BS05) Q05DHHS + Q05NHHS + Q05SHHS = 17.14
BG05) Q05DD1G + Q05DD2G + Q05DD3G + Q05DD4G + Q05ND1G + Q05ND2G
+ Q05ND3G + Q05ND4G + Q05SD1G + Q05SD2G + Q05SD3G + Q05SD4G + Q05DHHG
+ Q05NHHG + Q05SHHG = 188.48
BS06) Q06DHHS + Q06NHHS + Q06SHHS = 35.14
BG06) Q06DD1G + Q06DD2G + Q06DD3G + Q06DD4G + Q06ND1G + Q06ND2G
+ Q06ND3G + Q06ND4G + Q06SD1G + Q06SD2G + Q06SD3G + Q06SD4G + Q06DHHG
+ Q06NHHG + Q06SHHG = 234.22
BS07) Q07DHHS + Q07NHHS + Q07SHHS = 62.55
BG07) Q07DD1G + Q07DD2G + Q07DD3G + Q07DD4G + Q07ND1G + Q07ND2G
+ Q07ND3G + Q07ND4G + Q07SD1G + Q07SD2G + Q07SD3G + Q07SD4G + Q07DHHG
+ Q07NHHG + Q07SHHG = 241.52
BS08) Q08DHHS + Q08NHHS + Q08SHHS = 40.08
BG08) Q08DD1G + Q08DD2G + Q08DD3G + Q08DD4G + Q08ND1G + Q08ND2G
+ Q08ND3G + Q08ND4G + Q08SD1G + Q08SD2G + Q08SD3G + Q08SD4G + Q08DHHG
+ Q08NHHG + Q08SHHG = 160.39
BS09) Q09DHHS + Q09NHHS + Q09SHHS = 25.92
BG09) Q09DD1G + Q09DD2G + Q09DD3G + Q09DD4G + Q09ND1G + Q09ND2G
+ Q09ND3G + Q09ND4G + Q09SD1G + Q09SD2G + Q09SD3G + Q09SD4G + Q09DHHG
+ Q09NHHG + Q09SHHG = 266
BS10) Q10DHHS + Q10NHHS + Q10SHHS = 30.92
BG10) Q10DD1G + Q10DD2G + Q10DD3G + Q10DD4G + Q10ND1G + Q10ND2G
+ Q10ND3G + Q10ND4G + Q10SD1G + Q10SD2G + Q10SD3G + Q10SD4G + Q10DHHG
+ Q10NHHG + Q10SHHG = 336.92001
BS11) Q11DHHS + Q11NHHS + Q11SHHS = 1.8
BG11) Q11DD1G + Q11DD2G + Q11DD3G + Q11DD4G + Q11ND1G + Q11ND2G
+ Q11ND3G + Q11ND4G + Q11SD1G + Q11SD2G + Q11SD3G + Q11SD4G + Q11DHHG
+ Q11NHHG + Q11SHHG = 95.46
BS12) Q12DHHS + Q12NHHS + Q12SHHS = 2.25
BG12) Q12DD1G + Q12DD2G + Q12DD3G + Q12DD4G + Q12ND1G + Q12ND2G
+ Q12ND3G + Q12ND4G + Q12SD1G + Q12SD2G + Q12SD3G + Q12SD4G + Q12DHHG
+ Q12NHHG + Q12SHHG = 83.54
BS13) Q13DHHS + Q13NHHS + Q13SHHS = 3.94
BG13) Q13DD1G + Q13DD2G + Q13DD3G + Q13DD4G + Q13ND1G + Q13ND2G
+ Q13ND3G + Q13ND4G + Q13SD1G + Q13SD2G + Q13SD3G + Q13SD4G + Q13DHHG
+ Q13NHHG + Q13SHHG = 157.03999
BS14) Q14DHHS + Q14NHHS + Q14SHHS = 9.37

BG14) Q14DD1G + Q14DD2G + Q14DD3G + Q14DD4G + Q14ND1G + Q14ND2G
+ Q14ND3G + Q14ND4G + Q14SD1G + Q14SD2G + Q14SD3G + Q14SD4G + Q14DHHG
+ Q14NHHG + Q14SHHG = 129.27
BS15) Q15DHHS + Q15NHHS + Q15SHHS = 0.058
BG15) Q15DD1G + Q15DD2G + Q15DD3G + Q15DD4G + Q15ND1G + Q15ND2G
+ Q15ND3G + Q15ND4G + Q15SD1G + Q15SD2G + Q15SD3G + Q15SD4G + Q15DHHG
+ Q15NHHG + Q15SHHG = 22.183
MXG01D1) Q01DD1G + Q01ND1G + Q01SD1G <= 1.7844
MNG01D1) Q01DD1G + Q01ND1G + Q01SD1G >= 0
MXG01D2) Q01DD2G + Q01ND2G + Q01SD2G <= 42.8256
MNG01D2) Q01DD2G + Q01ND2G + Q01SD2G >= 24.9816
MXG01D3) Q01DD3G + Q01ND3G + Q01SD3G <= 49.9632
MNG01D3) Q01DD3G + Q01ND3G + Q01SD3G >= 32.1192
MXG01D4) Q01DD4G + Q01ND4G + Q01SD4G <= 28.5504
MNG01D4) Q01DD4G + Q01ND4G + Q01SD4G >= 10.7064
MXG02D1) Q02DD1G + Q02ND1G + Q02SD1G <= 0
MNG02D1) Q02DD1G + Q02ND1G + Q02SD1G >= 0
MXG02D2) Q02DD2G + Q02ND2G + Q02SD2G <= 43.7800
MNG02D2) Q02DD2G + Q02ND2G + Q02SD2G >= 26.2680
MXG02D3) Q02DD3G + Q02ND3G + Q02SD3G <= 38.5264
MNG02D3) Q02DD3G + Q02ND3G + Q02SD3G >= 21.0144
MXG02D4) Q02DD4G + Q02ND4G + Q02SD4G <= 0
MNG02D4) Q02DD4G + Q02ND4G + Q02SD4G >= 0
MXG03D1) Q03DD1G + Q03ND1G + Q03SD1G <= 7.1792
MNG03D1) Q03DD1G + Q03ND1G + Q03SD1G >= 0
MXG03D2) Q03DD2G + Q03ND2G + Q03SD2G <= 57.4336
MNG03D2) Q03DD2G + Q03ND2G + Q03SD2G >= 39.4856
MXG03D3) Q03DD3G + Q03ND3G + Q03SD3G <= 52.0492
MNG03D3) Q03DD3G + Q03ND3G + Q03SD3G >= 34.1012
MXG03D4) Q03DD4G + Q03ND4G + Q03SD4G <= 0
MNG03D4) Q03DD4G + Q03ND4G + Q03SD4G >= 0
MXG04D1) Q04DD1G + Q04ND1G + Q04SD1G <= 0
MNG04D1) Q04DD1G + Q04ND1G + Q04SD1G >= 0
MXG04D2) Q04DD2G + Q04ND2G + Q04SD2G <= 31.2460
MNG04D2) Q04DD2G + Q04ND2G + Q04SD2G >= 15.6230
MXG04D3) Q04DD3G + Q04ND3G + Q04SD3G <= 17.1853
MNG04D3) Q04DD3G + Q04ND3G + Q04SD3G >= 0
MXG04D4) Q04DD4G + Q04ND4G + Q04SD4G <= 48.4313
MNG04D4) Q04DD4G + Q04ND4G + Q04SD4G >= 32.8083
MXG05D1) Q05DD1G + Q05ND1G + Q05SD1G <= 0
MNG05D1) Q05DD1G + Q05ND1G + Q05SD1G >= 0
MXG05D2) Q05DD2G + Q05ND2G + Q05SD2G <= 15.0784
MNG05D2) Q05DD2G + Q05ND2G + Q05SD2G >= 0
MXG05D3) Q05DD3G + Q05ND3G + Q05SD3G <= 13.1936
MNG05D3) Q05DD3G + Q05ND3G + Q05SD3G >= 0
MXG05D4) Q05DD4G + Q05ND4G + Q05SD4G <= 73.5072
MNG05D4) Q05DD4G + Q05ND4G + Q05SD4G >= 54.6592
MXG06D1) Q06DD1G + Q06ND1G + Q06SD1G <= 0
MNG06D1) Q06DD1G + Q06ND1G + Q06SD1G >= 0
MXG06D2) Q06DD2G + Q06ND2G + Q06SD2G <= 25.7642
MNG06D2) Q06DD2G + Q06ND2G + Q06SD2G >= 0
MXG06D3) Q06DD3G + Q06ND3G + Q06SD3G <= 9.3688
MNG06D3) Q06DD3G + Q06ND3G + Q06SD3G >= 0
MXG06D4) Q06DD4G + Q06ND4G + Q06SD4G <= 53.8706
MNG06D4) Q06DD4G + Q06ND4G + Q06SD4G >= 30.4486
MXG07D1) Q07DD1G + Q07ND1G + Q07SD1G <= 0
MNG07D1) Q07DD1G + Q07ND1G + Q07SD1G >= 0
MXG07D2) Q07DD2G + Q07ND2G + Q07SD2G <= 48.304
MNG07D2) Q07DD2G + Q07ND2G + Q07SD2G >= 24.152
MXG07D3) Q07DD3G + Q07ND3G + Q07SD3G <= 19.3216
MNG07D3) Q07DD3G + Q07ND3G + Q07SD3G >= 0
MXG07D4) Q07DD4G + Q07ND4G + Q07SD4G <= 43.4736
MNG07D4) Q07DD4G + Q07ND4G + Q07SD4G >= 12.076

MXG08D1) Q08DD1G + Q08ND1G + Q08SD1G <= 0
MNG08D1) Q08DD1G + Q08ND1G + Q08SD1G >= 0
MXG08D2) Q08DD2G + Q08ND2G + Q08SD2G <= 40.0975
MNG08D2) Q08DD2G + Q08ND2G + Q08SD2G >= 24.0585
MXG08D3) Q08DD3G + Q08ND3G + Q08SD3G <= 44.9092
MNG08D3) Q08DD3G + Q08ND3G + Q08SD3G >= 28.8702
MXG08D4) Q08DD4G + Q08ND4G + Q08SD4G <= 0
MNG08D4) Q08DD4G + Q08ND4G + Q08SD4G >= 0
MXG09D1) Q09DD1G + Q09ND1G + Q09SD1G <= 0
MNG09D1) Q09DD1G + Q09ND1G + Q09SD1G >= 0
MXG09D2) Q09DD2G + Q09ND2G + Q09SD2G <= 58.52
MNG09D2) Q09DD2G + Q09ND2G + Q09SD2G >= 31.92
MXG09D3) Q09DD3G + Q09ND3G + Q09SD3G <= 66.50
MNG09D3) Q09DD3G + Q09ND3G + Q09SD3G >= 39.90
MXG09D4) Q09DD4G + Q09ND4G + Q09SD4G <= 0
MNG09D4) Q09DD4G + Q09ND4G + Q09SD4G >= 0
MXG10D1) Q10DD1G + Q10ND1G + Q10SD1G <= 0
MNG10D1) Q10DD1G + Q10ND1G + Q10SD1G >= 0
MXG10D2) Q10DD2G + Q10ND2G + Q10SD2G <= 77.4916
MNG10D2) Q10DD2G + Q10ND2G + Q10SD2G >= 43.7996
MXG10D3) Q10DD3G + Q10ND3G + Q10SD3G <= 0
MNG10D3) Q10DD3G + Q10ND3G + Q10SD3G >= 0
MXG10D4) Q10DD4G + Q10ND4G + Q10SD4G <= 0
MNG10D4) Q10DD4G + Q10ND4G + Q10SD4G >= 0
MXG11D1) Q11DD1G + Q11ND1G + Q11SD1G <= 23.865
MNG11D1) Q11DD1G + Q11ND1G + Q11SD1G >= 14.319
MXG11D2) Q11DD2G + Q11ND2G + Q11SD2G <= 0
MNG11D2) Q11DD2G + Q11ND2G + Q11SD2G >= 0
MXG11D3) Q11DD3G + Q11ND3G + Q11SD3G <= 23.865
MNG11D3) Q11DD3G + Q11ND3G + Q11SD3G >= 14.319
MXG11D4) Q11DD4G + Q11ND4G + Q11SD4G <= 0
MNG11D4) Q11DD4G + Q11ND4G + Q11SD4G >= 0
MXG12D1) Q12DD1G + Q12ND1G + Q12SD1G <= 25.062
MNG12D1) Q12DD1G + Q12ND1G + Q12SD1G >= 16.708
MXG12D2) Q12DD2G + Q12ND2G + Q12SD2G <= 0
MNG12D2) Q12DD2G + Q12ND2G + Q12SD2G >= 0
MXG12D3) Q12DD3G + Q12ND3G + Q12SD3G <= 25.062
MNG12D3) Q12DD3G + Q12ND3G + Q12SD3G >= 16.708
MXG12D4) Q12DD4G + Q12ND4G + Q12SD4G <= 0
MNG12D4) Q12DD4G + Q12ND4G + Q12SD4G >= 0
MXG13D1) Q13DD1G + Q13ND1G + Q13SD1G <= 31.408
MNG13D1) Q13DD1G + Q13ND1G + Q13SD1G >= 15.704
MXG13D2) Q13DD2G + Q13ND2G + Q13SD2G <= 0
MNG13D2) Q13DD2G + Q13ND2G + Q13SD2G >= 0
MXG13D3) Q13DD3G + Q13ND3G + Q13SD3G <= 54.964
MNG13D3) Q13DD3G + Q13ND3G + Q13SD3G >= 39.26
MXG13D4) Q13DD4G + Q13ND4G + Q13SD4G <= 0
MNG13D4) Q13DD4G + Q13ND4G + Q13SD4G >= 0
MXG14D1) Q14DD1G + Q14ND1G + Q14SD1G <= 19.3905
MNG14D1) Q14DD1G + Q14ND1G + Q14SD1G >= 6.4635
MXG14D2) Q14DD2G + Q14ND2G + Q14SD2G <= 0
MNG14D2) Q14DD2G + Q14ND2G + Q14SD2G >= 0
MXG14D3) Q14DD3G + Q14ND3G + Q14SD3G <= 45.2445
MNG14D3) Q14DD3G + Q14ND3G + Q14SD3G >= 32.3175
MXG14D4) Q14DD4G + Q14ND4G + Q14SD4G <= 0
MNG14D4) Q14DD4G + Q14ND4G + Q14SD4G >= 0
MXG15D1) Q15DD1G + Q15ND1G + Q15SD1G <= 0
MNG15D1) Q15DD1G + Q15ND1G + Q15SD1G >= 0
MXG15D2) Q15DD2G + Q15ND2G + Q15SD2G <= 0
MNG15D2) Q15DD2G + Q15ND2G + Q15SD2G >= 0
MXG15D3) Q15DD3G + Q15ND3G + Q15SD3G <= 0.44366
MNG15D3) Q15DD3G + Q15ND3G + Q15SD3G >= 0
MXG15D4) Q15DD4G + Q15ND4G + Q15SD4G <= 0

MNG15D4) Q15DD4G + Q15ND4G + Q15SD4G >= 0
MXTD1D1) ATD1D1 <= 54
MXTD1D2) ATD1D2 <= 36
MXTD1N1) ATD1N1 <= 54
MXTD1N2) ATD1N2 <= 36
MXTD1S1) ATD1S1 <= 54
MXTD1S2) ATD1S2 <= 36
MXTD2D1) ATD2D1 <= 186
MXTD2D2) ATD2D2 <= 124
MXTD2N1) ATD2N1 <= 186
MXTD2N2) ATD2N2 <= 124
MXTD2S1) ATD2S1 <= 186
MXTD2S2) ATD2S2 <= 124
MXTD3D1) ATD3D1 <= 124
MXTD3D2) ATD3D2 <= 93
MXTD3N1) ATD3N1 <= 124
MXTD3N2) ATD3N2 <= 93
MXTD3S1) ATD3S1 <= 124
MXTD3S2) ATD3S2 <= 93
MXTD4D1) ATD4D1 <= 36
MXTD4D2) ATD4D2 <= 27
MXTD4N1) ATD4N1 <= 36
MXTD4N2) ATD4N2 <= 27
MXTD4S1) ATD4S1 <= 36
MXTD4S2) ATD4S2 <= 27
MXTD1) ATD1D1 + ATD1D2 + ATD1N1 + ATD1N2 + ATD1S1 + ATD1S2 <= 54
MXTD2) ATD2D1 + ATD2D2 + ATD2N1 + ATD2N2 + ATD2S1 + ATD2S2 <= 186
MXTD3) ATD3D1 + ATD3D2 + ATD3N1 + ATD3N2 + ATD3S1 + ATD3S2 <= 124
MXTD4) ATD4D1 + ATD4D2 + ATD4N1 + ATD4N2 + ATD4S1 + ATD4S2 <= 36
MNTD1) ATD1D1 + ATD1D2 + ATD1N1 + ATD1N2 + ATD1S1 + ATD1S2 >= 18
MNTD2) ATD2D1 + ATD2D2 + ATD2N1 + ATD2N2 + ATD2S1 + ATD2S2 >= 62
MNTD3) ATD3D1 + ATD3D2 + ATD3N1 + ATD3N2 + ATD3S1 + ATD3S2 >= 62
MNTD4) ATD4D1 + ATD4D2 + ATD4N1 + ATD4N2 + ATD4S1 + ATD4S2 >= 18
DGHHD1) - Q02DHHG - Q03DHHG - Q04DHHG - Q05DHHG - Q06DHHG - Q07DHHG - Q08DHHG - Q12DHHG + DGHHD1 = 0
DGHHD2) - Q01DHHG - Q09DHHG - Q10DHHG - Q11DHHG - Q13DHHG - Q14DHHG - Q15DHHG + DGHHD2 = 0
DGHHN1) - Q01NHHG - Q02NHHG - Q03NHHG - Q04NHHG - Q05NHHG - Q06NHHG - Q07NHHG - Q08NHHG + DGHHN1 = 0
DGHHN2) - Q09NHHG - Q10NHHG - Q11NHHG - Q12NHHG - Q13NHHG - Q14NHHG - Q15NHHG + DGHHN2 = 0
DGHHS1) - Q06SHHG - Q07SHHG - Q08SHHG - Q09SHHG - Q10SHHG - Q13SHHG - Q14SHHG - Q15SHHG + DGHHS1 = 0
DGHHS2) - Q01SHHG - Q02SHHG - Q03SHHG - Q04SHHG - Q05SHHG - Q11SHHG - Q12SHHG + DGHHS2 = 0
DGD1D1) - Q02DD1G - Q03DD1G - Q04DD1G - Q05DD1G - Q06DD1G - Q07DD1G - Q08DD1G - Q12DD1G + DGD1D1 = 0
DGD1D2) - Q01DD1G - Q09DD1G - Q10DD1G - Q11DD1G - Q13DD1G - Q14DD1G - Q15DD1G + DGD1D2 = 0
DGD1N1) - Q01ND1G - Q02ND1G - Q03ND1G - Q04ND1G - Q05ND1G - Q06ND1G - Q07ND1G - Q08ND1G + DGD1N1 = 0
DGD1N2) - Q09ND1G - Q10ND1G - Q11ND1G - Q12ND1G - Q13ND1G - Q14ND1G - Q15ND1G + DGD1N2 = 0
DGD1S1) - Q06SD1G - Q07SD1G - Q08SD1G - Q09SD1G - Q10SD1G - Q13SD1G - Q14SD1G - Q15SD1G + DGD1S1 = 0
DGD1S2) - Q01SD1G - Q02SD1G - Q03SD1G - Q04SD1G - Q05SD1G - Q11SD1G - Q12SD1G + DGD1S2 = 0
DGD2D1) - Q02DD2G - Q03DD2G - Q04DD2G - Q05DD2G - Q06DD2G - Q07DD2G - Q08DD2G - Q12DD2G + DGD2D1 = 0
DGD2D2) - Q01DD2G - Q09DD2G - Q10DD2G - Q11DD2G - Q13DD2G - Q14DD2G - Q15DD2G + DGD2D2 = 0
DGD2N1) - Q01ND2G - Q02ND2G - Q03ND2G - Q04ND2G - Q05ND2G - Q06ND2G - Q07ND2G - Q08ND2G + DGD2N1 = 0

DGD2N2) - Q09ND2G - Q10ND2G - Q11ND2G - Q12ND2G - Q13ND2G - Q14ND2G
- Q15ND2G + DGD2N2 = 0
DGD2S1) - Q06SD2G - Q07SD2G - Q08SD2G - Q09SD2G - Q10SD2G - Q13SD2G
- Q14SD2G - Q15SD2G + DGD2S1 = 0
DGD2S2) - Q01SD2G - Q02SD2G - Q03SD2G - Q04SD2G - Q05SD2G - Q11SD2G
- Q12SD2G + DGD2S2 = 0
DGD3D1) - Q02DD3G - Q03DD3G - Q04DD3G - Q05DD3G - Q06DD3G - Q07DD3G
- Q08DD3G - Q12DD3G + DGD3D1 = 0
DGD3D2) - Q01DD3G - Q09DD3G - Q10DD3G - Q11DD3G - Q13DD3G - Q14DD3G
- Q15DD3G + DGD3D2 = 0
DGD3N1) - Q01ND3G - Q02ND3G - Q03ND3G - Q04ND3G - Q05ND3G - Q06ND3G
- Q07ND3G - Q08ND3G + DGD3N1 = 0
DGD3N2) - Q09ND3G - Q10ND3G - Q11ND3G - Q12ND3G - Q13ND3G - Q14ND3G
- Q15ND3G + DGD3N2 = 0
DGD3S1) - Q06SD3G - Q07SD3G - Q08SD3G - Q09SD3G - Q10SD3G - Q13SD3G
- Q14SD3G - Q15SD3G + DGD3S1 = 0
DGD3S2) - Q01SD3G - Q02SD3G - Q03SD3G - Q04SD3G - Q05SD3G - Q11SD3G
- Q12SD3G + DGD3S2 = 0
DGD4D1) - Q02DD4G - Q03DD4G - Q04DD4G - Q05DD4G - Q06DD4G - Q07DD4G
- Q08DD4G - Q12DD4G + DGD4D1 = 0
DGD4D2) - Q01DD4G - Q09DD4G - Q10DD4G - Q11DD4G - Q13DD4G - Q14DD4G
- Q15DD4G + DGD4D2 = 0
DGD4N1) - Q01ND4G - Q02ND4G - Q03ND4G - Q04ND4G - Q05ND4G - Q06ND4G
- Q07ND4G - Q08ND4G + DGD4N1 = 0
DGD4N2) - Q09ND4G - Q10ND4G - Q11ND4G - Q12ND4G - Q13ND4G - Q14ND4G
- Q15ND4G + DGD4N2 = 0
DGD4S1) - Q06SD4G - Q07SD4G - Q08SD4G - Q09SD4G - Q10SD4G - Q13SD4G
- Q14SD4G - Q15SD4G + DGD4S1 = 0
DGD4S2) - Q01SD4G - Q02SD4G - Q03SD4G - Q04SD4G - Q05SD4G - Q11SD4G
- Q12SD4G + DGD4S2 = 0
DSHHD1) - Q02DHHS - Q03DHHS - Q04DHHS - Q05DHHS - Q06DHHS - Q07DHHS
- Q08DHHS - Q12DHHS + DSHHD1 = 0
DSHHD2) - Q01DHHS - Q09DHHS - Q10DHHS - Q11DHHS - Q13DHHS - Q14DHHS
- Q15DHHS + DSHHD2 = 0
DSHHN1) - Q01NHHS - Q02NHHS - Q03NHHS - Q04NHHS - Q05NHHS - Q06NHHS
- Q07NHHS - Q08NHHS + DSHHN1 = 0
DSHHN2) - Q09NHHS - Q10NHHS - Q11NHHS - Q12NHHS - Q13NHHS - Q14NHHS
- Q15NHHS + DSHHN2 = 0
DSHHS1) - Q06SHHS - Q07SHHS - Q08SHHS - Q09SHHS - Q10SHHS - Q13SHHS
- Q14SHHS - Q15SHHS + DSHHS1 = 0
DSHHS2) - Q01SHHS - Q02SHHS - Q03SHHS - Q04SHHS - Q05SHHS - Q11SHHS
- Q12SHHS + DSHHS2 = 0
ATD1D1) - Q02DD1G - Q03DD1G - Q04DD1G - Q05DD1G - Q06DD1G - Q07DD1G
- Q08DD1G - Q12DD1G + 1.75 ATD1D1 = 0
ATD1D2) - Q01DD1G - Q09DD1G - Q10DD1G - Q11DD1G - Q13DD1G - Q14DD1G
- Q15DD1G + 1.75 ATD1D2 = 0
ATD1N1) - Q01ND1G - Q02ND1G - Q03ND1G - Q04ND1G - Q05ND1G - Q06ND1G
- Q07ND1G - Q08ND1G + 1.75 ATD1N1 = 0
ATD1N2) - Q09ND1G - Q10ND1G - Q11ND1G - Q12ND1G - Q13ND1G - Q14ND1G
- Q15ND1G + 1.75 ATD1N2 = 0
ATD1S1) - Q06SD1G - Q07SD1G - Q08SD1G - Q09SD1G - Q10SD1G - Q13SD1G
- Q14SD1G - Q15SD1G + 1.75 ATD1S1 = 0
ATD1S2) - Q01SD1G - Q02SD1G - Q03SD1G - Q04SD1G - Q05SD1G - Q11SD1G
- Q12SD1G + 1.75 ATD1S2 = 0
ATD2D1) - Q02DD2G - Q03DD2G - Q04DD2G - Q05DD2G - Q06DD2G - Q07DD2G
- Q08DD2G - Q12DD2G + 2 ATD2D1 = 0
ATD2D2) - Q01DD2G - Q09DD2G - Q10DD2G - Q11DD2G - Q13DD2G - Q14DD2G
- Q15DD2G + 2 ATD2D2 = 0
ATD2N1) - Q01ND2G - Q02ND2G - Q03ND2G - Q04ND2G - Q05ND2G - Q06ND2G
- Q07ND2G - Q08ND2G + 2 ATD2N1 = 0
ATD2N2) - Q09ND2G - Q10ND2G - Q11ND2G - Q12ND2G - Q13ND2G - Q14ND2G
- Q15ND2G + 2 ATD2N2 = 0
ATD2S1) - Q06SD2G - Q07SD2G - Q08SD2G - Q09SD2G - Q10SD2G - Q13SD2G

- Q14SD2G - Q15SD2G + 2 ATD2S1 = 0
ATD2S2) - Q01SD2G - Q02SD2G - Q03SD2G - Q04SD2G - Q05SD2G - Q11SD2G
- Q12SD2G + 2 ATD2S2 = 0
ATD3D1) - Q02DD3G - Q03DD3G - Q04DD3G - Q05DD3G - Q06DD3G - Q07DD3G
- Q08DD3G - Q12DD3G + 3 ATD3D1 = 0
ATD3D2) - Q01DD3G - Q09DD3G - Q10DD3G - Q11DD3G - Q13DD3G - Q14DD3G
- Q15DD3G + 3 ATD3D2 = 0
ATD3N1) - Q01ND3G - Q02ND3G - Q03ND3G - Q04ND3G - Q05ND3G - Q06ND3G
- Q07ND3G - Q08ND3G + 3 ATD3N1 = 0
ATD3N2) - Q09ND3G - Q10ND3G - Q11ND3G - Q12ND3G - Q13ND3G - Q14ND3G
- Q15ND3G + 3 ATD3N2 = 0
ATD3S1) - Q06SD3G - Q07SD3G - Q08SD3G - Q09SD3G - Q10SD3G - Q13SD3G
- Q14SD3G - Q15SD3G + 3 ATD3S1 = 0
ATD3S2) - Q01SD3G - Q02SD3G - Q03SD3G - Q04SD3G - Q05SD3G - Q11SD3G
- Q12SD3G + 3 ATD3S2 = 0
ATD4D1) - Q02DD4G - Q03DD4G - Q04DD4G - Q05DD4G - Q06DD4G - Q07DD4G
- Q08DD4G - Q12DD4G + 7 ATD4D1 = 0
ATD4D2) - Q01DD4G - Q09DD4G - Q10DD4G - Q11DD4G - Q13DD4G - Q14DD4G
- Q15DD4G + 7 ATD4D2 = 0
ATD4N1) - Q01ND4G - Q02ND4G - Q03ND4G - Q04ND4G - Q05ND4G - Q06ND4G
- Q07ND4G - Q08ND4G + 7 ATD4N1 = 0
ATD4N2) - Q09ND4G - Q10ND4G - Q11ND4G - Q12ND4G - Q13ND4G - Q14ND4G
- Q15ND4G + 7 ATD4N2 = 0
ATD4S1) - Q06SD4G - Q07SD4G - Q08SD4G - Q09SD4G - Q10SD4G - Q13SD4G
- Q14SD4G - Q15SD4G + 7 ATD4S1 = 0
ATD4S2) - Q01SD4G - Q02SD4G - Q03SD4G - Q04SD4G - Q05SD4G - Q11SD4G
- Q12SD4G + 7 ATD4S2 = 0
ATHHGD1) - Q02DHHG - Q03DHHG - Q04DHHG - Q05DHHG - Q06DHHG - Q07DHHG
- Q08DHHG - Q12DHHG + 7 ATHHGD1 = 0
ATHHGD2) - Q01DHHG - Q09DHHG - Q10DHHG - Q11DHHG - Q13DHHG - Q14DHHG
- Q15DHHG + 7 ATHHGD2 = 0
ATHHGN1) - Q01NHHG - Q02NHHG - Q03NHHG - Q04NHHG - Q05NHHG - Q06NHHG
- Q07NHHG - Q08NHHG + 7 ATHHGN1 = 0
ATHHGN2) - Q09NHHG - Q10NHHG - Q11NHHG - Q12NHHG - Q13NHHG - Q14NHHG
- Q15NHHG + 7 ATHHGN2 = 0
ATHHGS1) - Q06SHHG - Q07SHHG - Q08SHHG - Q09SHHG - Q10SHHG - Q13SHHG
- Q14SHHG - Q15SHHG + 7 ATHHGS1 = 0
ATHHGS2) - Q01SHHG - Q02SHHG - Q03SHHG - Q04SHHG - Q05SHHG - Q11SHHG
- Q12SHHG + 7 ATHHGS2 = 0
ATHHSD1) - Q02DHHS - Q03DHHS - Q04DHHS - Q05DHHS - Q06DHHS - Q07DHHS
- Q08DHHS - Q12DHHS + 9 ATHHSD1 = 0
ATHHSD2) - Q01DHHS - Q09DHHS - Q10DHHS - Q11DHHS - Q13DHHS - Q14DHHS
- Q15DHHS + 9 ATHHSD2 = 0
ATHHSN1) - Q01NHHS - Q02NHHS - Q03NHHS - Q04NHHS - Q05NHHS - Q06NHHS
- Q07NHHS - Q08NHHS + 9 ATHHSN1 = 0
ATHHSN2) - Q09NHHS - Q10NHHS - Q11NHHS - Q12NHHS - Q13NHHS - Q14NHHS
- Q15NHHS + 9 ATHHSN2 = 0
ATHHSS1) - Q06SHHS - Q07SHHS - Q08SHHS - Q09SHHS - Q10SHHS - Q13SHHS
- Q14SHHS - Q15SHHS + 9 ATHHSS1 = 0
ATHHSS2) - Q01SHHS - Q02SHHS - Q03SHHS - Q04SHHS - Q05SHHS - Q11SHHS
- Q12SHHS + 9 ATHHSS2 = 0
MXG01HH) Q01DHHG + Q01NHHG + Q01SHHG <= 91.00
MXG02HH) Q02DHHG + Q02NHHG + Q02SHHG <= 117.33
MXG03HH) Q03DHHG + Q03NHHG + Q03SHHG <= 93.33
MXG04HH) Q04DHHG + Q04NHHG + Q04SHHG <= 90.61
MXG05HH) Q05DHHG + Q05NHHG + Q05SHHG <= 118.74
MXG06HH) Q06DHHG + Q06NHHG + Q06SHHG <= 187.37
MXG07HH) Q07DHHG + Q07NHHG + Q07SHHG <= 185.97
MXG08HH) Q08DHHG + Q08NHHG + Q08SHHG <= 101.05
MXG09HH) Q09DHHG + Q09NHHG + Q09SHHG <= 180.88
MXG10HH) Q10DHHG + Q10NHHG + Q10SHHG <= 293.12
MXG11HH) Q11DHHG + Q11NHHG + Q11SHHG <= 62.049
MXG12HH) Q12DHHG + Q12NHHG + Q12SHHG <= 45.947

MXG13HH) Q13DHHG + Q13NHHG + Q13SHHG <= 94.224
MXG14HH) Q14DHHG + Q14NHHG + Q14SHHG <= 96.9525
MXG15HH) Q15DHHG + Q15NHHG + Q15SHHG <= 22.183
MNG01HH) Q01DHHG + Q01NHHG + Q01SHHG >= 73.16
MNG02HH) Q02DHHG + Q02NHHG + Q02SHHG >= 99.82
MNG03HH) Q03DHHG + Q03NHHG + Q03SHHG >= 75.38
MNG04HH) Q04DHHG + Q04NHHG + Q04SHHG >= 74.99
MNG05HH) Q05DHHG + Q05NHHG + Q05SHHG >= 99.89
MNG06HH) Q06DHHG + Q06NHHG + Q06SHHG >= 163.95
MNG07HH) Q07DHHG + Q07NHHG + Q07SHHG >= 161.82
MNG08HH) Q08DHHG + Q08NHHG + Q08SHHG >= 85.01
MNG09HH) Q09DHHG + Q09NHHG + Q09SHHG >= 154.28
MNG10HH) Q10DHHG + Q10NHHG + Q10SHHG >= 259.43
MNG11HH) Q11DHHG + Q11NHHG + Q11SHHG >= 52.503
MNG12HH) Q12DHHG + Q12NHHG + Q12SHHG >= 37.593
MNG13HH) Q13DHHG + Q13NHHG + Q13SHHG >= 78.52
MNG14HH) Q14DHHG + Q14NHHG + Q14SHHG >= 84.0255
MNG15HH) Q15DHHG + Q15NHHG + Q15SHHG >= 21.07
SGFD) Q01DD1G + Q01DD2G + Q01DD3G + Q01DD4G + Q02DD1G + Q02DD2G
+ Q02DD3G + Q02DD4G + Q03DD1G + Q03DD2G + Q03DD3G + Q03DD4G + Q04DD1G
+ Q04DD2G + Q04DD3G + Q04DD4G + Q05DD1G + Q05DD2G + Q05DD3G + Q05DD4G
+ Q06DD1G + Q06DD2G + Q06DD3G + Q06DD4G + Q07DD1G + Q07DD2G + Q07DD3G
+ Q07DD4G + Q08DD1G + Q08DD2G + Q08DD3G + Q08DD4G + Q09DD1G + Q09DD2G
+ Q09DD3G + Q09DD4G + Q10DD1G + Q10DD2G + Q10DD3G + Q10DD4G + Q11DD1G
+ Q11DD2G + Q11DD3G + Q11DD4G + Q12DD1G + Q12DD2G + Q12DD3G + Q12DD4G
+ Q13DD1G + Q13DD2G + Q13DD3G + Q13DD4G + Q14DD1G + Q14DD2G + Q14DD3G
+ Q14DD4G + Q15DD1G + Q15DD2G + Q15DD3G + Q15DD4G + Q01DHHG + Q02DHHG
+ Q03DHHG + Q04DHHG + Q05DHHG + Q06DHHG + Q07DHHG + Q08DHHG + Q09DHHG
+ Q10DHHG + Q11DHHG + Q12DHHG + Q13DHHG + Q14DHHG + Q15DHHG - SGFD
= 0
SGFN) Q01ND1G + Q01ND2G + Q01ND3G + Q01ND4G + Q02ND1G + Q02ND2G
+ Q02ND3G + Q02ND4G + Q03ND1G + Q03ND2G + Q03ND3G + Q03ND4G + Q04ND1G
+ Q04ND2G + Q04ND3G + Q04ND4G + Q05ND1G + Q05ND2G + Q05ND3G + Q05ND4G
+ Q06ND1G + Q06ND2G + Q06ND3G + Q06ND4G + Q07ND1G + Q07ND2G + Q07ND3G
+ Q07ND4G + Q08ND1G + Q08ND2G + Q08ND3G + Q08ND4G + Q09ND1G + Q09ND2G
+ Q09ND3G + Q09ND4G + Q10ND1G + Q10ND2G + Q10ND3G + Q10ND4G + Q11ND1G
+ Q11ND2G + Q11ND3G + Q11ND4G + Q12ND1G + Q12ND2G + Q12ND3G + Q12ND4G
+ Q13ND1G + Q13ND2G + Q13ND3G + Q13ND4G + Q14ND1G + Q14ND2G + Q14ND3G
+ Q14ND4G + Q15ND1G + Q15ND2G + Q15ND3G + Q15ND4G + Q01NHHG + Q02NHHG
+ Q03NHHG + Q04NHHG + Q05NHHG + Q06NHHG + Q07NHHG + Q08NHHG + Q09NHHG
+ Q10NHHG + Q11NHHG + Q12NHHG + Q13NHHG + Q14NHHG + Q15NHHG - SGFN
= 0
SGFS) Q01SD1G + Q01SD2G + Q01SD3G + Q01SD4G + Q02SD1G + Q02SD2G
+ Q02SD3G + Q02SD4G + Q03SD1G + Q03SD2G + Q03SD3G + Q03SD4G + Q04SD1G
+ Q04SD2G + Q04SD3G + Q04SD4G + Q05SD1G + Q05SD2G + Q05SD3G + Q05SD4G
+ Q06SD1G + Q06SD2G + Q06SD3G + Q06SD4G + Q07SD1G + Q07SD2G + Q07SD3G
+ Q07SD4G + Q08SD1G + Q08SD2G + Q08SD3G + Q08SD4G + Q09SD1G + Q09SD2G
+ Q09SD3G + Q09SD4G + Q10SD1G + Q10SD2G + Q10SD3G + Q10SD4G + Q11SD1G
+ Q11SD2G + Q11SD3G + Q11SD4G + Q12SD1G + Q12SD2G + Q12SD3G + Q12SD4G
+ Q13SD1G + Q13SD2G + Q13SD3G + Q13SD4G + Q14SD1G + Q14SD2G + Q14SD3G
+ Q14SD4G + Q15SD1G + Q15SD2G + Q15SD3G + Q15SD4G + Q01SHHG + Q02SHHG
+ Q03SHHG + Q04SHHG + Q05SHHG + Q06SHHG + Q07SHHG + Q08SHHG + Q09SHHG
+ Q10SHHG + Q11SHHG + Q12SHHG + Q13SHHG + Q14SHHG + Q15SHHG - SGFS
= 0
BSGFD) SGFD - SRD - SDDD - SADD - SIFD - SCFD = 0
BSGFN) SGFN - SRN - SDDN - SADN - SIFN - SCFN = 0
BSGFS) SGFS - SRS - SDDS - SADS - SIFS - SCFS = 0
MXSRD) - 0.0421 SGFD + SRD <= 0
MXSRN) - 0.0421 SGFN + SRN <= 0
MXSRS) - 0.0421 SGFS + SRS <= 0
MXSDDD) - 0.1053 SGFD + SDDD = 0
MXSDDN) - 0.1053 SGFN + SDDN = 0
MXSDDS) - 0.1053 SGFS + SDDS = 0

MXSIFD) - 0.1684 SGFD + SIFD = 0
MXSIFN) - 0.1684 SGFN + SIFN = 0
MXSIFS) - 0.1684 SGFS + SIFS = 0
MXSCFD) - 0.6842 SGFD + SCFD <= 0
MXSCFN) - 0.6842 SGFN + SCFN <= 0
MXSCFS) - 0.6842 SGFS + SCFS <= 0
BIRD) - 0.03125 SIFD + IRD = 0
BIRN) - 0.03125 SIFN + IRN = 0
BIRS) - 0.03125 SIFS + IRS = 0
BIIRD) - 0.0625 SIFD + IIRD = 0
BIIRN) - 0.0625 SIFN + IIRN = 0
BIIRS) - 0.0625 SIFS + IIRS = 0
BIARD) - 0.0919 SIFD + IARD = 0
BIARN) - 0.0919 SIFN + IARN = 0
BIARS) - 0.0919 SIFS + IARS = 0
BCRD) - 0.0192 SCFD + CRD = 0
BCRN) - 0.0192 SCFN + CRN = 0
BCRS) - 0.0192 SCFS + CRS = 0
BCIRD) - 0.0615 SCFD + CIRD = 0
BCIRN) - 0.0615 SCFN + CIRN = 0
BCIRS) - 0.0615 SCFS + CIRS = 0
BCPRD) - 0.1414 SCFD + CPRD = 0
BCPRN) - 0.1414 SCFN + CPRN = 0
BCPRS) - 0.1414 SCFS + CPRS = 0
BCPDD) - 0.2657 SCFD + CPD = 0
BCPDN) - 0.2657 SCFN + CPN = 0
BCPDS) - 0.2657 SCFS + CPS = 0
XFD) XFD - XSILTD - XFGD - XFRJD = 0
XFN) XFN - XSILTN - XFGN - XFRJN = 0
XFS) XFS - XSILTS - XFGS - XFRJS = 0
BXSD) - Q01DHHS - Q02DHHS - Q03DHHS - Q04DHHS - Q05DHHS - Q06DHHS
- Q07DHHS - Q08DHHS - Q09DHHS - Q10DHHS - Q11DHHS - Q12DHHS - Q13DHHS
- Q14DHHS - Q15DHHS + XSILTD = 0
BXSN) - Q01NHHS - Q02NHHS - Q03NHHS - Q04NHHS - Q05NHHS - Q06NHHS
- Q07NHHS - Q08NHHS - Q09NHHS - Q10NHHS - Q11NHHS - Q12NHHS - Q13NHHS
- Q14NHHS - Q15NHHS + XSILTN = 0
BXSS) - Q01SHHS - Q02SHHS - Q03SHHS - Q04SHHS - Q05SHHS - Q06SHHS
- Q07SHHS - Q08SHHS - Q09SHHS - Q10SHHS - Q11SHHS - Q12SHHS - Q13SHHS
- Q14SHHS - Q15SHHS + XSILTS = 0
BXFGD) - SDDD - SADD + XFGD = 0
BXFGN) - SDDN - SADN + XFGN = 0
BXFGS) - SDDS - SADS + XFGS = 0
BXFRJD) - IIRD - IARD - CIRD - CPRD + XFRJD = 0
BXFRJN) - IIRN - IARN - CIRN - CPRN + XFRJN = 0
BXFRJS) - IIRS - IARS - CIRS - CPRS + XFRJS = 0
SCAPXD) SGFD <= 5000
SCAPXN) SGFN <= 5000
SCAPXS) SGFS <= 5000
SCAPND) SGFD >= 0
SCAPNN) SGFN >= 0
SCAPNS) SGFS >= 0
ICAPXD) SIFD <= 2000
ICAPXN) SIFN <= 2000
ICAPXS) SIFS <= 2000
ICAPND) SIFD >= 0
ICAPNN) SIFN >= 0
ICAPNS) SIFS >= 0
CCAPXD) SCFD <= 2000
CCAPXN) SCFN <= 2000
CCAPXS) SCFS <= 2000
CCAPND) SCFD >= 0
CCAPNN) SCFN >= 0
CCAPNS) SCFS >= 0

XCAPXD) XFD <= 5000
XCAPXN) XFN <= 5000
XCAPXS) XFS <= 5000
CTCX) - 200 XFD - 200 XFN - 200 XFS + CTCX = 0
CTCS) - 0.5 SGFD - 0.5 SGFN - 0.5 SGFS - 50 SRD
- 50 SRN - 50 SRS - 50 SADD - 50 SADN - 50 SADS + CTCS = 0
CTCI) - 1726.03003 SIFD - 1726.03003 SIFN - 1726.03003 SIFS - 50 IRD
- 50 IRN - 50 IRS - 50 IIRD - 50 IIRN - 50 IIRS - 50 IARD - 50 IARN
- 50 IARS + CTCI = 0
CTCC) - 507.88 SCFD - 507.88 SCFN - 507.88 SCFS - 50 CRD
- 50 CRN - 50 CRS - 50 CIRD - 50 CIRN - 50 CIRS - 50 CPRD - 50 CPRN
- 50 CPRS + CTCC = 0
CTREVR) - 2000 SRD - 2000 SRN - 2000 SRS - 2000 IRD - 2000 IRN
- 2000 IRS - 2000 CRD - 2000 CRN - 2000 CRS + CTREVR = 0
CTREVC) - 3500 CPD - 3500 CPN - 3500 CPS + CTREVC = 0
CTRANSP) CTRANSP - CTCHH - CTCD1 - CTCD2 - CTCD3 - CTCD4 = 0
CTCHH) - CTCHH + CTCGHH + CTCSHH = 0
CTCGHH) - 153 Q01DHHG - 130 Q01NHHG - 160 Q01SHHG - 144 Q02DHHG
- 130 Q02NHHG - 160 Q02SHHG - 133.5 Q03DHHG - 160 Q03NHHG
- 160 Q03SHHG - 142 Q04DHHG - 140 Q04NHHG - 160 Q04SHHG - 140 Q05DHHG
- 160 Q05NHHG - 160 Q05SHHG - 132.5 Q06DHHG - 160 Q06NHHG
- 150 Q06SHHG - 147.75 Q07DHHG - 160 Q07NHHG - 160 Q07SHHG
- 140 Q08DHHG - 160 Q08NHHG - 160 Q08SHHG - 156.7 Q09DHHG
- 160 Q09NHHG - 130 Q09SHHG - 148.3 Q10DHHG - 160 Q10NHHG
- 160 Q10SHHG - 157.8 Q11DHHG - 160 Q11NHHG - 160 Q11SHHG
- 154.3 Q12DHHG - 160 Q12NHHG - 160 Q12SHHG - 159.39999 Q13DHHG
- 160 Q13NHHG - 140 Q13SHHG - 160 Q14DHHG - 160 Q14NHHG - 160 Q14SHHG
- 160 Q15DHHG - 160 Q15NHHG - 130 Q15SHHG + 0.43 CTCGHH = 0
CTCSHH) - 143 Q01DHHS - 120 Q01NHHS - 150 Q01SHHS - 134 Q02DHHS
- 120 Q02NHHS - 150 Q02SHHS - 123.5 Q03DHHS - 150 Q03NHHS
- 150 Q03SHHS - 132 Q04DHHS - 130 Q04NHHS - 150 Q04SHHS - 130 Q05DHHS
- 150 Q05NHHS - 150 Q05SHHS - 122.5 Q06DHHS - 150 Q06NHHS
- 140 Q06SHHS - 137.75 Q07DHHS - 150 Q07NHHS - 150 Q07SHHS
- 130 Q08DHHS - 150 Q08NHHS - 150 Q08SHHS - 146.7 Q09DHHS
- 150 Q09NHHS - 120 Q09SHHS - 138.3 Q10DHHS - 150 Q10NHHS
- 150 Q10SHHS - 147.8 Q11DHHS - 150 Q11NHHS - 150 Q11SHHS
- 144.3 Q12DHHS - 150 Q12NHHS - 150 Q12SHHS - 149.39999 Q13DHHS
- 150 Q13NHHS - 130 Q13SHHS - 150 Q14DHHS - 150 Q14NHHS - 150 Q14SHHS
- 150 Q15DHHS - 150 Q15NHHS - 120 Q15SHHS + 0.40 CTCSHH = 0
CTCD1) CTCD1 - CFUELD1 - CFXDRD1 - CFXDID1 = 0
CTCD2) CTCD2 - CFUELD2 - CFXDRD2 - CFXDID2 = 0
CTCD3) CTCD3 - CFUELD3 - CFXDRD3 - CFXDID3 = 0
CTCD4) CTCD4 - CFUELD4 - CFXDRD4 - CFXDID4 = 0
CFUELD1) 63.81 Q01DD1G + 24.815 Q01ND1G + 116.631 Q01SD1G + 53.18 Q02DD1G
+ 37.226 Q02ND1G + 111.67 Q02SD1G + 35.45 Q03DD1G + 68.49 Q03ND1G
+ 106.705 Q03SD1G + 53.18 Q04DD1G + 47.153 Q04ND1G + 96.78 Q04SD1G
+ 49.63 Q05DD1G + 67 Q05ND1G + 71.964 Q05SD1G + 49.63 Q06DD1G
+ 74.45 Q06ND1G + 59.556 Q06SD1G + 24.82 Q07DD1G + 104.244 Q07ND1G
+ 94.297 Q07SD1G + 46.09 Q08DD1G + 91.82 Q08ND1G + 74.445 Q08SD1G
+ 67.36 Q09DD1G + 126.566 Q09ND1G + 34.741 Q09SD1G + 49.63 Q10DD1G
+ 119.112 Q10ND1G + 71.964 Q10SD1G + 56.72 Q11DD1G + 141.45 Q11ND1G
+ 96.779 Q11SD1G + 21.27 Q12DD1G + 138.964 Q12ND1G + 121.594 Q12SD1G
+ 70.9 Q13DD1G + 126.56 Q13ND1G + 44.667 Q13SD1G + 81.54 Q14DD1G
+ 161.31 Q14ND1G + 76.927 Q14SD1G + 95.72 Q15DD1G + 168.75101 Q15ND1G
+ 12.408 Q15SD1G - 0.5863 CFUELD1 = 0
CFUELD2) 55.51 Q01DD2G + 21.59 Q01ND2G + 101.464 Q01SD2G + 46.26 Q02DD2G
+ 32.382 Q02ND2G + 97.15 Q02SD2G + 30.84 Q03DD2G + 59.583 Q03ND2G
+ 92.83 Q03SD2G + 46.26 Q04DD2G + 41.02 Q04ND2G + 84.193 Q04SD2G
+ 43.18 Q05DD2G + 58.288 Q05ND2G + 62.61 Q05SD2G + 43.18 Q06DD2G
+ 64.764 Q06ND2G + 51.811 Q06SD2G + 21.59 Q07DD2G + 90.67 Q07ND2G
+ 82.03 Q07SD2G + 40.09 Q08DD2G + 79.88 Q08ND2G + 64.764 Q08SD2G
+ 58.59 Q09DD2G + 110.1 Q09ND2G + 30.22 Q09SD2G + 43.18 Q10DD2G
+ 103.62 Q10ND2G + 62.61 Q10SD2G + 49.32 Q11DD2G + 123.05 Q11ND2G

+ 84.193 Q11SD2G + 18.5 Q12DD2G + 120.89 Q12ND2G + 105.78 Q12SD2G
+ 61.68 Q13DD2G + 110.1 Q13ND2G + 38.86 Q13SD2G + 70.93 Q14DD2G
+ 140.32001 Q14ND2G + 66.923 Q14SD2G + 83.27 Q15DD2G + 146.8 Q15ND2G
+ 10.794 Q15SD2G - 0.4786 CFUELD2 = 0
CFUELD3) 40.43 Q01DD3G + 15.73 Q01ND3G + 73.893 Q01SD3G + 33.7 Q02DD3G
+ 23.59 Q02ND3G + 70.75 Q02SD3G + 22.46 Q03DD3G + 43.4 Q03ND3G
+ 67.6 Q03SD3G + 33.7 Q04DD3G + 29.88 Q04ND3G + 61.316 Q04SD3G
+ 31.45 Q05DD3G + 42.46 Q05ND3G + 45.594 Q05SD3G + 31.45 Q06DD3G
+ 47.18 Q06ND3G + 37.73 Q06SD3G + 15.72 Q07DD3G + 66.05 Q07ND3G
+ 59.74 Q07SD3G + 29.2 Q08DD3G + 58.18 Q08ND3G + 47.17 Q08SD3G
+ 42.68 Q09DD3G + 80.2 Q09ND3G + 22.01 Q09SD3G + 31.45 Q10DD3G
+ 75.48 Q10ND3G + 45.594 Q10SD3G + 35.94 Q11DD3G + 89.64 Q11ND3G
+ 61.32 Q11SD3G + 13.48 Q12DD3G + 88.06 Q12ND3G + 77.04 Q12SD3G
+ 44.93 Q13DD3G + 80.2 Q13ND3G + 28.3 Q13SD3G + 51.67 Q14DD3G
+ 102.22 Q14ND3G + 48.74 Q14SD3G + 60.65 Q15DD3G + 106.93 Q15ND3G
+ 7.861 Q15SD3G - 0.5025 CFUELD3 = 0
CFUELD4) 44.93 Q01DD4G + 17.48 Q01ND4G + 82.135 Q01SD4G + 37.45 Q02DD4G
+ 26.21 Q02ND4G + 78.64 Q02SD4G + 24.96 Q03DD4G + 48.23 Q03ND4G
+ 75.14 Q03SD4G + 37.45 Q04DD4G + 33.2 Q04ND4G + 68.15 Q04SD4G
+ 34.95 Q05DD4G + 47.18 Q05ND4G + 50.68 Q05SD4G + 43.95 Q06DD4G
+ 52.43 Q06ND4G + 41.94 Q06SD4G + 17.48 Q07DD4G + 73.4 Q07ND4G
+ 66.41 Q07SD4G + 32.45 Q08DD4G + 64.66 Q08ND4G + 52.43 Q08SD4G
+ 47.43 Q09DD4G + 89.13 Q09ND4G + 24.47 Q09SD4G + 34.95 Q10DD4G
+ 83.88 Q10ND4G + 50.68 Q10SD4G + 39.94 Q11DD4G + 99.61 Q11ND4G
+ 68.15 Q11SD4G + 14.98 Q12DD4G + 97.863 Q12ND4G + 85.63 Q12SD4G
+ 49.93 Q13DD4G + 89.13 Q13ND4G + 31.46 Q13SD4G + 57.41 Q14DD4G
+ 113.591 Q14ND4G + 54.17 Q14SD4G + 67.4 Q15DD4G + 118.83 Q15ND4G
+ 8.74 Q15SD4G - 0.67 CFUELD4 = 0
CFXDRD1) CFXDRD1 = 45656.78
CFXDRD2) CFXDRD2 = 167995.98
CFXDRD3) CFXDRD3 = 227883.85
CFXDRD4) CFXDRD4 = 77278.37
CFXDID1) CFXDID1 = 19988.64
CFXDID2) CFXDID2 = 76940.14
CFXDID3) CFXDID3 = 63786.98
CFXDID4) CFXDID4 = 27391.68
CINCD1) 15 DGD1D1 + 15 DGD1D2 + 15 DGD1N1 + 15 DGD1N2 + 15 DGD1S1
+ 15 DGD1S2 - CINCD1 = 472.5
CINCD2) 10.5 DGD2D1 + 10.5 DGD2D2 + 10.5 DGD2N1 + 10.5 DGD2N2
+ 10.5 DGD2S1 + 10.5 DGD2S2 - CINCD2 = 1302
CINCD3) 35 DGD3D1 + 35 DGD3D2 + 35 DGD3N1 + 35 DGD3N2 + 35 DGD3S1
+ 35 DGD3S2 - CINCD3 = 6510
CINCD4) 7.5 DGD4D1 + 7.5 DGD4D2 + 7.5 DGD4N1 + 7.5 DGD4N2
+ 7.5 DGD4S1 + 7.5 DGD4S2 - CINCD4 = 945
CINCT) CINCT - CINCD1 - CINCD2 - CINCD3 - CINCD4 = 0
DGHHD15) DGHHD1 >= 622.643
DGHHD15) DGHHD1 <= 624.643
DGHHD25) DGHHD2 >= 310.933
DGHHD25) DGHHD2 <= 312.933
DGHHN15) DGHHN1 >= 246.97
DGHHN15) DGHHN1 <= 248.97
DGHHN25) DGHHN2 >= 83.0255
DGHHN25) DGHHN2 <= 85.0255
DGHHS15) DGHHS1 >= 253.5393
DGHHS15) DGHHS1 <= 255.5393
DGHHS25) DGHHS2 >= .00000
DGHHS25) DGHHS2 <= .00000
DGD1D15) DGD1D1 >= 31.2412
DGD1D15) DGD1D1 <= 33.2412
DGD1D25) DGD1D2 >= 18.092
DGD1D25) DGD1D2 <= 20.092
DGD1N15) DGD1N1 >= 0.7844
DGD1N15) DGD1N1 <= 2.7844

```
  DGD1N25)   DGD1N2 >=    .0000
  DGD1N25)   DGD1N2 <=    .0000
  DGD1S15)   DGD1S1 >=    36.8715
  DGD1S15)   DGD1S1 <=    38.8715
  DGD1S25)   DGD1S2 >=    .0000
  DGD1S25)   DGD1S2 <=    .0000
  DGD2D15)   DGD2D1 >=    132.0506
  DGD2D15)   DGD2D1 <=    134.0506
  DGD2D25)   DGD2D2 >=    76.49002
  DGD2D25)   DGD2D2 <=    78.49002
  DGD2N15)   DGD2N1 >=    101.229
  DGD2N15)   DGD2N1 <=    103.229
  DGD2N25)   DGD2N2 >=    0.0000
  DGD2N25)   DGD2N2 <=    0.0000
  DGD2S15)   DGD2S1 >=    57.52
  DGD2S15)   DGD2S1 <=    59.52
  DGD2S25)   DGD2S2 >=    .000
  DGD2S25)   DGD2S2 <=    .000
  DGD3D15)   DGD3D1 >=    126.8438
  DGD3D15)   DGD3D1 <=    128.8438
  DGD3D25)   DGD3D2 >=    22.865
  DGD3D25)   DGD3D2 <=    24.865
  DGD3N15)   DGD3N1 >=    79.8249
  DGD3N15)   DGD3N1 <=    81.8249
  DGD3N25)   DGD3N2 >=    .000
  DGD3N25)   DGD3N2 <=    .000
  DGD3S15)   DGD3S1 >=    138.5367
  DGD3S15)   DGD3S1 <=    140.5367
  DGD3S25)   DGD3S2 >=    .00
  DGD3S25)   DGD3S2 <=    .00
  DGD4D15)   DGD4D1 >=    115.9808
  DGD4D15)   DGD4D1 <=    117.9808
  DGD4D25)   DGD4D2 >=    .0000
  DGD4D25)   DGD4D2 <=    .0000
  DGD4N15)   DGD4N1 >=    75.9817
  DGD4N15)   DGD4N1 <=    77.9817
  DGD4N25)   DGD4N2 >=    .00
  DGD4N25)   DGD4N2 <=    .00
  DGD4S15)   DGD4S1 >=    52.8706
  DGD4S15)   DGD4S1 <=    54.8706
  DGD4S25)   DGD4S2 >=    .0000
  DGD4S25)   DGD4S2 <=    .0000
  DSHHD15)   DSHHD1 >=    176.25
  DSHHD15)   DSHHD1 <=    178.25
  DSHHD25)   DSHHD2 >=    41.09
  DSHHD25)   DSHHD2 <=    43.09
  DSHHN15)   DSHHN1 >=    43.86
  DSHHN15)   DSHHN1 <=    45.86
  DSHHN25)   DSHHN2 >=    0.00
  DSHHN25)   DSHHN2 <=    0.00
  DSHHS15)   DSHHS1 >=    28.918
  DSHHS15)   DSHHS1 <=    30.918
  DSHHS25)   DSHHS2 >=    .00
  DSHHS25)   DSHHS2 <=    .00
END
```

Annexure 6.20

6.20 MODEL OUTPUT FOR PROPOSED INTEGRATED SOLID WASTE MANAGEMENT OF KOLKATA AND ITS OPTIMIZATION

Table A-6.20 Output results from proposed integrated solid waste management model

OBJ Value	Total solid waste management cost in Rs.	1296051.00
CTCX	Total landfilling cost in Rs.	199520.60
CTCS	Total sorting cost in Rs.	6784.18
CTCI	Total O&M cost of incineration plant in Rs.	761043.80
CTCC	Total O&M cost of compost plant in Rs.	924757.20
CTREVR	Total revenue from recyclables in Rs.	315115.00
CTREVC	Total revenue from compost in Rs.	1657038.00
CTRANSP	Total transportation cost in Rs.	1365185.00
CINCT	Total incentive cost in Rs.	10913.36
DGHHD1	Garbage carried by hired vehicle from Zone 1 of D in MT	623.64
DGHHD2	Garbage carried by hired vehicle from Zone 2 of D in MT	312.93
DGHHN1	Garbage carried by hired vehicle from Zone 1 of N in MT	247.97
DGHHN2	Garbage carried by hired vehicle from Zone 2 of N in MT	83.03
DGHHS1	Garbage carried by hired vehicle from Zone 1 of S in MT	254.54
DGHHS2	Garbage carried by hired vehicle from Zone 2 of S in MT	0
DGD1D1	Garbage carried by D1 vehicle from Zone 1 of D in MT	32.24
DGD1D2	Garbage carried by D1 vehicle from Zone 2 of D in MT	19.09
DGD1N1	Garbage carried by D1 vehicle from Zone 1 of N in MT	1.78
DGD1N2	Garbage carried by D1 vehicle from Zone 2 of N in MT	0
DGD1S1	Garbage carried by D1 vehicle from Zone 1 of S in MT	37.87
DGD1S2	Garbage carried by D1 vehicle from Zone 2 of S in MT	0
DGD2D1	Garbage carried by D2 vehicle from Zone 1 of D in MT	133.12
DGD2D2	Garbage carried by D2 vehicle from Zone 2 of D in MT	77.49
DGD2N1	Garbage carried by D2 vehicle from Zone 1 of N in MT	102.23
DGD2N2	Garbage carried by D2 vehicle from Zone 2 of N in MT	0
DGD2S1	Garbage carried by D2 vehicle from Zone 1 of S in MT	58.52
DGD2S2	Garbage carried by D2 vehicle from Zone 2 of S in MT	0
DGD3D1	Garbage carried by D3 vehicle from Zone 1 of D in MT	127.77

DGD3D2	Garbage carried by D3 vehicle from Zone 2 of D in MT	23.87
DGD3N1	Garbage carried by D3 vehicle from Zone 1 of N in MT	80.82
DGD3N2	Garbage carried by D3 vehicle from Zone 2 of N in MT	0
DGD3S1	Garbage carried by D3 vehicle from Zone 1 of S in MT	139.54
DGD3S2	Garbage carried by D3 vehicle from Zone 2 of S in MT	0
DGD4D1	Garbage carried by D4 vehicle from Zone 1 of D in MT	116.98
DGD4D2	Garbage carried by D4 vehicle from Zone 2 of D in MT	0
DGD4N1	Garbage carried by D4 vehicle from Zone 1 of N in MT	76.98
DGD4N2	Garbage carried by D4 vehicle from Zone 2 of N in MT	0
DGD4S1	Garbage carried by D4 vehicle from Zone 1 of S in MT	53.87
DGD4S2	Garbage carried by D4 vehicle from Zone 2 of S in MT	0
DSHHD1	Silt carried by hired vehicle from Zone 1 of D in MT	177.25
DSHHD2	Silt carried by hired vehicle from Zone 2 of D in MT	42.09
DSHHN1	Silt carried by hired vehicle from Zone 1 of N in MT	44.86
DSHHN2	Silt carried by hired vehicle from Zone 2 of N in MT	0
DSHHS1	Silt carried by hired vehicle from Zone 1 of S in MT	29.92
DSHHS2	Silt carried by hired vehicle from Zone 2 of S in MT	0
SGFD	Sorter feed at D disposal site in MT	1467.14
SGFN	Sorter feed at N disposal site in MT	592.82
SGFS	Sorter feed at S disposal site in MT	544.34
SRD	Recyclables from sorter at D disposal site in MT	61.77
SDDD	Direct dumpable at D disposal site in MT	154.49
SADD	Additional dumpable at D disposal site in MT	0
SIFD	Incinerator feed at D disposal site in MT	247.07
SCFD	Compost plant feed at D disposal site in MT	1003.82
SRN	Recyclables from sorter at N disposal site in MT	24.96
SDDN	Direct dumpable at N disposal site in MT	62.42
SADN	Additional dumpable at N disposal site in MT	0
SIFN	Incinerator feed at N disposal site in MT	99.83
SCFN	Compost plant feed at N disposal site in MT	405.60
SRS	Recyclables from sorter at S disposal site in MT	22.92
SDDS	Direct dumpable at S disposal site in MT	57.32

SADS	Additional dumpable at S disposal site in MT	0
SIFS	Incinerator feed at S disposal site in MT	91.67
SCFS	Compost plant feed at S disposal site in MT	372.44
IRD	Recyclable from incinerator at D site in MT	7.72
IRN	Recyclable from incinerator at N site in MT	3.12
IRS	Recyclable from incinerator at S site in MT	2.86
IIRD	Inorganic rejects from incinerator at D site in MT	15.44
IIRN	Inorganic rejects from incinerator at N site in MT	6.24
IIRS	Inorganic rejects from incinerator at S site in MT	5.73
IARD	Incineration ash from incinerator at D site in MT	22.71
IARN	Incineration ash from incinerator at N site in MT	9.17
IARS	Incineration ash from incinerator at S site in MT	8.42
CRD	Recyclable from compost plant at D site in MT	19.27
CRN	Recyclable from compost plant at N site in MT	7.79
CRS	Recyclable from compost plant at S site in MT	7.15
CIRD	Inorganic rejects from compost plant at D site in MT	61.73
CIRN	Inorganic rejects from compost plant at N site in MT	24.94
CIRS	Inorganic rejects from compost plant at S site in MT	22.90
CPRD	Process rejects from compost plant at D site in MT	141.94
CPRN	Process rejects from compost plant at N site in MT	57.35
CPRS	Process rejects from compost plant at S site in MT	52.66
CPD	Compost product from compost plant at D site in MT	266.71
CPN	Compost product from compost plant at N site in MT	107.77
CPS	Compost product from compost plant at S site in MT	98.96
XFD	Total landfill amount at D disposal site in MT	615.65
XSILTD	Total silt amount at D disposal site in MT	219.34
XFGD	Total garbage amount at D disposal site in MT	154.45
XFRJD	Total rejects amount at D disposal site in MT	241.82
XFN	Total landfill amount at N disposal site in MT	204.99
XSILTN	Total silt amount at N disposal site in MT	44.86
XFGN	Total garbage amount at N disposal site in MT	62.42
XFRJN	Total rejects amount at N disposal site in MT	97.71

XFS	Total landfill amount at S disposal site in MT	176.96
XSILTS	Total silt amount at S disposal site in MT	29.92
XFGS	Total garbage amount at S disposal site in MT	57.32
XFRJS	Total rejects amount at S disposal site in MT	89.72
CTCHH	Total transportation cost by hired vehicle in Rs.	594344.10
CTCD1	Total transportation cost by D1 vehicle in Rs.	72152.10
CTCD2	Total transportation cost by D2 vehicle in Rs.	270553.70
CTCD3	Total transportation cost by D3 vehicle in Rs.	311979.60
CTCD4	Total transportation cost by D4 vehicle in Rs.	116155.60
CTCGHH	Total garbage transportation cost by hired vehicle in Rs.	498711.50
CTCSHH	Total silt transportation cost by hired vehicle in Rs.	95632.59
CFUELD1	Total fuel cost by D1 vehicle in Rs.	6506.68
CFXDRD1	Total fixed running cost by D1 vehicle in Rs.	45656.78
CFXDID1	Total fixed idle cost by D1 vehicle in Rs.	19988.64
CFUELD2	Total fuel cost by D2 vehicle in Rs.	25617.61
CFXDRD2	Total fixed running cost by D2 vehicle in Rs.	167996.00
CFXDID2	Total fixed idle cost by D2 vehicle in Rs.	76940.14
CFUELD3	Total fuel cost by D3 vehicle in Rs.	20308.80
CFXDRD3	Total fixed running cost by D3 vehicle in Rs.	227883.80
CFXDID3	Total fixed idle cost by D3 vehicle in Rs.	63786.98
CFUELD4	Total fuel cost by D4 vehicle in Rs.	11485.54
CFXDRD4	Total fixed running cost by D4 vehicle in Rs.	77278.37
CFXDID4	Total fixed idle cost by D4 vehicle in Rs.	27391.68
CINCD1	Total incentive cost by D1 vehicle in Rs.	892.34
CINCD2	Total incentive cost by D2 vehicle in Rs.	2597.28
CINCD3	Total incentive cost by D3 vehicle in Rs.	6510.00
CINCD4	Total incentive cost by D4 vehicle in Rs.	913.75

Annexure 6.21

6.21 LAND REQUIREMENT FOR DIFFERENT TREATMENT AND DISPOSAL FACILITIES

6.21.1 Land requirement for Engineered Landfill site (CPHEEO, 2016):

1. Current waste generation: 1000 TPD
2. Estimated waste generation after 16 years: 1700 TPD
3. Total waste generation in 16 years: 0.5[1000+1700]×365×16 = 7×10^6tonnes
4. Total waste volume (assumed density 0.85 tonnes/m^3): $[7\times10^6]/0.85 = 8.25\times10^6 m^3$
5. Volume of daily cover: $0.1\times0.825\times10^6 m^3 = 0.825\times10^6 m^3$
6. Volume of liner and cover systems: $0.125\times8.25\times10^6 m^3 = 1.03\times10^6 m^3$
7. Estimate of landfill volume: $[8.25+0.825+1{,}03-0.825]\times10^6 m^3 = 9.28\times10^6 m^3$
8. Likely shape of a landfill: Rectangular in plan (length : width = 2:1)
9. Area restrictions: Nil
10. Possible maximum landfill height: 20 m
11. Area required: $[19.28\times10^6]/20 = 4.15\times10^5\ m^2$ = 41.5 hectares
12. Additional land is required around the landfill to place infrastructure facilities (site fencing, weighbridges, administrative office, site control office, washing bay, leachate treatment plant other facilities etc: 26.5 hectares

Total land area required for engineered landfill: (41.5 ha + 26.5 ha) = 67 ha
So for 1000 TPD ELF facility, area requirement will be 67 ha.

6.21.2 Land requirement for 500 TPD capacities Compost Plant (CPHEEO, 2016)

1. Pre processing area (covered): 120 m^2
2. Pre processing area (uncovered): 2000 m^2
3. Compost pad (covered 30%): 8300 m^2
4. Compost pad (uncovered 70%): 19400 m^2
5. Machine shed: 500m^2
6. Curing area: 1400 m^2
7. Finished product godown: 1500m^2
8. Surface area with impermeable structure having load bearing capacity of 40 MT/m^2: 30700 m^2
9. Surface area with impermeable structure having load bearing capacity of 20-30 MT/m^2: 3520m^2

10. Office laboratory and other amenities: 300 m^2
11. Green belt: 8000 m^2
12. Buffer area for future expansion: 8000m^2
13. Free space for demonstrations and parking vehicles etc,: 3000m^2
14. Roads (all weather conditions): 3 KM

Total land area required for compost plant: 55220 m^2 say ~6 ha
So for 1000 TPD composting facility, area requirement will be 14 ha.

6.21.3 Land requirement for 150 TPH capacities Material Sorting Plant:

1. Processing facility including tipping floor, processing equipment, residue transfer area and storage: 16000 m^2
2. Scales, truck queuing and outdoor vehicle maneuvering space: 9700 m^2
3. Parking for rolling stock: 24,800 m^2
4. Employee parking: 3200 m^2
5. Site buffer allowances: 14,700 m^2

Total land area required for material sorting plant: [68400 m^2/(16 x 150)] say 28.5 m^2/TPD
Since siting requirement varies from 5.9 m^2 to 40 m^2 /TPD, therefore in this semi mechanized plant, land area for material sorting facility is considered as 25 m^2.
So for 1000 TPD material sorting facility, area requirement will be 2.5 ha.

6.21.4 Land requirement for 600 TPD capacities incineration Plant:

Total land area required for incineration plant: 2.4 ha (KMC, 2017)
So for 1000 TPD incineration facility, area requirement will be 4.1 ha.