SUSTAINABLE LANDFILL OPERATION BY COMBINING OPEN CELL AND WATER MANAGEMENT STRATEGIES

by

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Abstract

This study aims to investigate the open cell operation by combining with water management. Water management consisted of storage, evaporation and recirculation of leachate. The influence of leachate recirculation on open cell landfill was monitored. The application of Hydrologic Evaluation of Landfill Performance (HELP) model for water management was determined by comparing with the results of experiment.

Four landfill lysimeters located at AIT was adopted and operated in different simulation (open cell landfill, open cell landfill combine with leachate recirculation, open cell landfill of pre-sorted waste combine with leachate recirculation and conventional landfill). The leachate generation, leachate characteristics and settlement variation of MSW were monitored since July 2005. From December 2005, leachate recirculation mode was introduced due to reduced moisture content in lysimeters and reduced rainfall.

The open cell landfill operation by combining with leachate recirculation (Open Cell No.2 and 3) had lower COD and TKN concentration compared with the lysimeters without leachate recirculation (Open Cell No.1 and Conventional Landfill). The Open Cell No.3 which mainly contained the highly biodegradable organic fraction showed the highest cumulative leachate generation, specific cumulative COD load and settlement rate. The water management by storage, evaporation and recirculation of leachate lead to 30% reduction in volume of leachate for treatment compared with the lysimeters without leachate recirculation. The water balance evaluated by HELP model agreed with experimental results during the period where leachate recirculation was not introduced. The application of model for leachate recirculation mode was limited. Improving open cell operation in tropical climate by understanding water management was necessary. Leachate was recirculated to enhance the waste stabilization in landfill and to improve the quality of leachate. After eight months of operation, the COD concentration for Open Cell No. 1, 2, 3 and Conventional Landfill were 940, 875, 865 and 970 mg/L, respectively; the TKN concentration were 705, 665, 700 and 660, respectively. The waste volume reduction resulted in 21, 23, 29 and 16% of initial height of Open Cell No.1, 2, 3 and Conventional Landfill, respectively.

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List of Abbreviations

ASTM	American Society for Testing of Materials
AIT	Asian Institute of Technology
BOD	Biological Oxygen Demand
cm	centimeter
COD	Chemical Oxygen Demand
m^3	cubic meter
°C	degree Celsius
Ø	diameter
EEM	Environmental Engineering and Management program
FC	Field Capacity
HELP	Hydrologic Evaluation of Landfill Performance
SI	International System of Units
kg	kilogram
LFG	Landfill Gas
L	liter
MJ	Mega Joule
m	meter
µmhos/cm	micro mhos per centimeter
mS/cm	micro Seimen per centimeter
mg	milligram
mg/L	milligram per liter
mm	millimeter
MC	Moisture Content
MSW	Municipal Solid Waste
MSWM	Municipal Solid Waste Management
%	percent
PVC	Polyvinyl Chloride
lb	pound
m^2	square meter
TDS	Total Dissolved Solid
TKN	Total Kjeldahl Nitrogen
TOC	Total Organic Carbon
TS	Total Solid
TSS	Total Suspended Solid
TVA	Total Volatile Acid
USEPA	United States Environmental Protection Agency
VFA	Volatile Fatty Acid
VOA	Volatile Organic Acid
VS	Volatile Solid
v/v	volume per volume
WES	Waterway Experiment Station

Chapter 1

Introduction

1.1 Background

With the ever increasing population, rapid economic growth and urbanization in Asia, Municipal Solid Waste Management (MSWM) is one of the major concerns. The Municipal Solid Waste (MSW) generation rate has a strong correlation with the level of economic development. High income countries (e.g. Japan and Singapore) generate 1.5-2 kg/capita/day. Middle income countries (e.g. Indonesia, Malaysia, Thailand etc.) generate 0.75-1 kg/capita/day. While, low income countries (e.g. India, Philippines, etc.) generate 0.4-0.6 kg/capita/day. By 2025, several countries in this region, e.g. Bangladesh, Laos PDR, Myanmar, Nepal and Vietnam are predicted their urban waste quantities to be increased by about four to six times of the current amount (World Bank, 1999). Therefore, many cities are facing the accelerated problems of inadequate MSW collection, transportation including uncontrolled disposal sites.

The most municipal solid waste disposal practices in developing countries are open dumping. In Thailand and India, for example, 70-90% of final disposal sites are open dumps (Visvanathan et al., 2003). Environmental impacts from open dump are the leachate contamination to surface and ground water, potential global worming due to greenhouse gas emissions, the breeding of disease vectors, nuisance etc.

Sanitary landfill, composting and incineration are technologies suggested for reduction of these environmental problems. Sanitary landfills are popular because of the most economical and environmentally acceptable method for the disposal of solid wastes throughout the world. Furthermore, sanitary landfills are ultimate disposal of residue. The main important facilities of sanitary landfill are covers, landfill lining, leachate collection and treatment system and landfill gas controlling.

However, moderate or low income countries like most Asian countries do not have enough funds for investment and operation that modern disposal system. The lack of financial support, proper planning of MSWM, technical knowledge and human resources result in limiting landfill construction, operation and maintenance at minimum standards of sanitary practice (Ranaweera and Tränkler, 2001). Although, many open dump sites are being improve by operating with at least compacting MSW, provide daily covers for reducing nuisance and final cover when areas are full (Ashford et al., 2000). Leachate and landfill gas emissions still are problems that need a proper treatment.

The open cell approach can be a suitable approach for developing countries because it does not differ too much from current operational mode. Improving the open dump practices related to the real conditions of tropical climate and capability operations of MSW in Asian countries could be achieved by understanding of the water management (Manandhar and Tränkler, 2000; Tränkler et al., 2005). Leachate recirculation system is one option of landfills which is well known as bioreactor landfill. Leachate recirculation enhances moisture content for accelerated biodegradation in landfill lead to rapid stabilization of waste. The other advantages are accelerating landfill gas production that be used for energy source, waste volume reduction, reducing amount of leachate to treatment and reducing burden of monitoring and cost saving of aftercare (Reinhart and Al-Yousfi, 1996).

The purpose of this study is to investigate the open cell landfill operation combining with water management. The Hydrologic Evaluation of Landfill Performance (HELP) model was used to simulate water balance of lysimeter study.

1.2 Objectives of Study

The objectives of study could be summarized as follows;

1) To determine the influence of leachate recirculation on open cell landfill simulations in terms of leachate generation, leachate characteristics and settlement variation of MSW.
2) To determine water management and water balance of open cell landfill lysimeters by experiment and HELP model application.
3) To recommend an appropriate open cell landfill and leachate management option for sustainable landfill in correlation with the Asian tropical climate.

1.3 Scope of Study

The study was based on experimental research and model application. The lysimeters were used for simulating conditions. The scopes of the study have been stated as follows;

1) Four landfill lysimeters at Environmental Research Station of AIT were adopted for operating open cell landfill and leachate management in different simulation (open cell landfill, open cell landfill combine with leachate recirculation, open cell landfill of pre-sorted waste combine with leachate recirculation and conventional landfill).
2) Monitoring the open cell landfill lysimeters in terms of leachate generation, leachate characteristics and settlement variation of MSW. Comparing this data to investigate the effects of leachate recirculation on MSW degradation rate and leaching of pollutant.
3) Determining water management for open cell landfill lysimeters by considering moisture content of MSW, leachate recirculation experiments including reviewing on HELP model and its application.
4) Determining the necessity of leachate pre-treatment before recirculation to protect clogging of leachate collection and recirculation system.

Chapter 2

Literature Review

2.1 Municipal Solid Waste Management in Asia

The management of Municipal Solid Waste (MSW) is becoming a major social and environmental issue in Asia. Municipal solid waste includes all community wastes with the exception of industrial process wastes and agricultural wastes. Nowadays, the quantity of MSW has increased significantly. It caused by the increasing population, urbanization and industrialization in this region. In 1999, World Bank reported that the cities in Asia generated approximately 0.76 million tons per day of MSW. This rate will jump to about 1.8 million tons per day by 2025 (World Bank, 1999). The generation of MSW differs in each country. For instance, the generation of MSW in China ranges from 0.6-0.9 kg/capita/day, India from 0.3-0.6 kg/capita/day, Sri Lanka from 0.4-0.8 kg/capita/day and Thailand from 0.5-1.0 kg/capita/day (Visvanathan et al., 2004).

The individual components of MSW can be divided in types of biodegradable waste (e.g. food waste, yard waste, paper, etc.) and non-biodegradable waste (e.g. glass, tin cans, aluminum cans, other metal, etc). Identification of MSW composition is important in management. MSW composition varies dependending on locality, season, socio-economic condition and live style. The major portion of the MSW generated in Asia is mainly composed of easily biodegradable organic material with high moisture content. The moisture content is in range 60-70% (Hogland et al., 2005). Resentlys, increasing plastic portion restricts the compaction of MSW to solely 400-500 kg/m^3 (Ranaweera and Tränkler, 2001). Table 2.1 shows the compositions of urban solid waste in Asian countries (World Bank, 1999). Generally, all low and high income countries have a high percentage of compostable organic matter in urban waste stream. China and India traditionally use coal as a household fuel source. Therefore, ash is produced very high. It is included in "others" category and makes up 45% and 54% of India and China's waste composition, respectively.

Table 2.1 Compositions of urban solid waste in Asian countries

Country	Compostables	Paper	Plastic	Glass	Metal	Others
Bangladesh	84	6	2	3	3	2
Myanmar	80	4	2	0	0	14
Loa PDR	54	3	8	9	4	23
India	42	6	4	2	2	45
Sri Lanka	76	11	6	1	1	5
China	36	4	4	2	0	54
Indonesia	70	11	9	2	2	6
Thailand	49	15	14	5	4	14
Singapore	44	28	12	4	5	7
Japan	26	46	9	7	8	12

Source: World Bank (1999).

In most developing countries, local organizations or municipalities are responsible for the collection, transportation and the disposal of MSW. Daily collection is common practices in big cities. In Asia, on an average about 70% of the solid waste is collected (EISA and

Visvanathan, 2002). Inadequate staff, funds and equipment are main reasons of solid waste uncollected. These lead to solid waste littering, dumping or burning in backyard and open spaces.

2.1.1 Open Dump Approach

Open dump is a traditional and common MSW disposal practice in most Asian countries because of its simplicity such as no need investment for engineering designs, facilities construction and technical operation. It needs only land area for dumping MSW and then allow solid wastes degradation under natural condition. Table 2.2 illustrates the disposal methods in some selected countries of the Asia. Environmental impacts from open dump are contamination to surface and ground water from leachate, landfill gas emission (e.g. CH_4 and CO_2) and breeding of disease vectors. Furthermore, some open dump sites burning is prevalent to reduce amount of MSW to save land area, recover valuable materials for sale, reduce odor from MSW decomposition. Open burning causes air pollution problems. Therefore, open burning and scavenging are also common practices at dump site in this region (Hogland, 2005).

Table 2.2 Disposal methods of MSW in selected countries of the Asia

Country/territory	Disposal methods (%)				
	Open dumping	Composting	Land filling	Incineration	Others*
Bangladesh	95	0	0	0	5
Japan	0	10	15	75	0
Indonesia	60	15	10	2	13
Malaysia	50	10	30	5	5
Nepal	70	5	10	0	15
Philippine	75	10	10	0	5
Republic of Korea	20	5	60	5	10
Singapore	0	0	30	70	0
Sri Lanka	85	5	0	0	10
Thailand	65	10	5	5	15
Vietnam	70	10	0	0	20

* Animal feeding, dumping in water bodies, ploughing into soil and open burning
Source: United Nations (2000).

Presently, open dumping is being phase out in many countries. The closure or upgrading of existing dump sites to engineering landfills is the important steps.

2.1.2 Landfill Technology

Landfills are the physical facilities used for solid waste disposal in the surface soil of the earth. Sanitary landfill is considered as the most cost-effective and reliable methods of MSW disposal in Asia. The application of bioreactor landfill is newly considered approach in this region.

Sanitary landfill

Sanitary landfill is an engineering facility for disposal MSW including operating to minimize public health and environmental impacts. Landfilling is the processes of placement and compaction MSW on the preparation land area that provides environmental protection facilities such as liners, leachate collection and treatment system, landfill gas controlling and cover layers.

Landfill operates by placement of MSW in multi layers or series of lifts. Each layer consists of cells which are MSW compaction. Daily covers (native soil or other material) are provided to control blowing of waste materials, prevent rodents and other disease vectors and to control water entering into the landfill. When completing one layer of landfill, intermediate cover is added and next layers are started. Final cover or top cover is provided when completing operation landfill. The final cover usually consists of multiple layers of soil and/or geomembrane materials for enhancing surface drainage intercept percolating water and support surface vegetation. Sectional view through a sanitary landfill is shown in Figure 2.1.

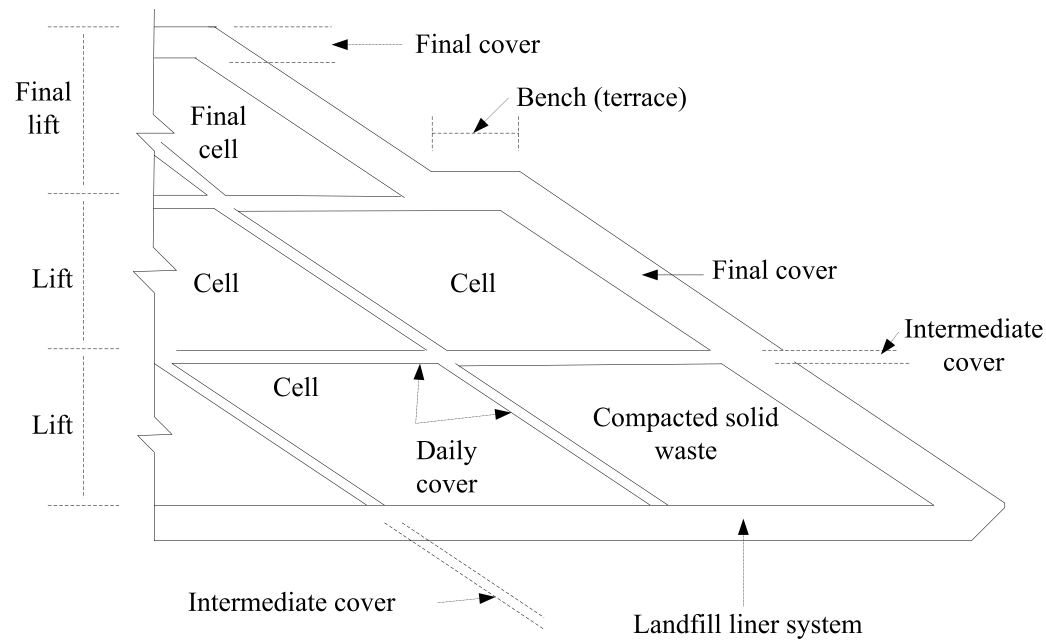


Figure 2.1 Sectional view through sanitary landfill

Bioreactor landfill

Generally, the pattern of construction and operation of conventional landfills has deep pits, liners (bottom layers) and caps (top cover layers). These designs and operations lead to anaerobic condition and limit moisture content that are necessary for biodegradation in landfill. Referred to as the "dry-tomb method", this conventional landfill can create environmental problems and health risks in long-term period. The efficiency of protection liners and caps is decreased or failed for long time operations or completed landfills. If moisture is permitted into landfills, the biological activity would happen again then the leachate and landfill gas are produced. Conventional landfill can not be considered as sites for final storage quality or sustainable landfill (Komilis et al., 1999).

Upgrading existing landfill technology from storage/containment (conventional landfill) to a process-based approach is called as bioreactor landfill (Chiemchaisri et al., 2002). In contrary to conventional landfill, bioreactor landfill is designed to maximize the infiltration of water into the waste. The bioreactor landfill is managed by controlling moisture content of the waste, recycling of nutrients and seeding of microorganisms by leachate recirculation system. It provides the moisture content into landfill for accelerating biodegradation process until stabilization. Stabilization means that the environment performance measurement parameters remain at steady level along the process implementation (United States Environmental Protection Agency, 2000). Figure 2.2 and 2.3 illustrate the schematic of convention landfill and bioreactor landfill, respectively.

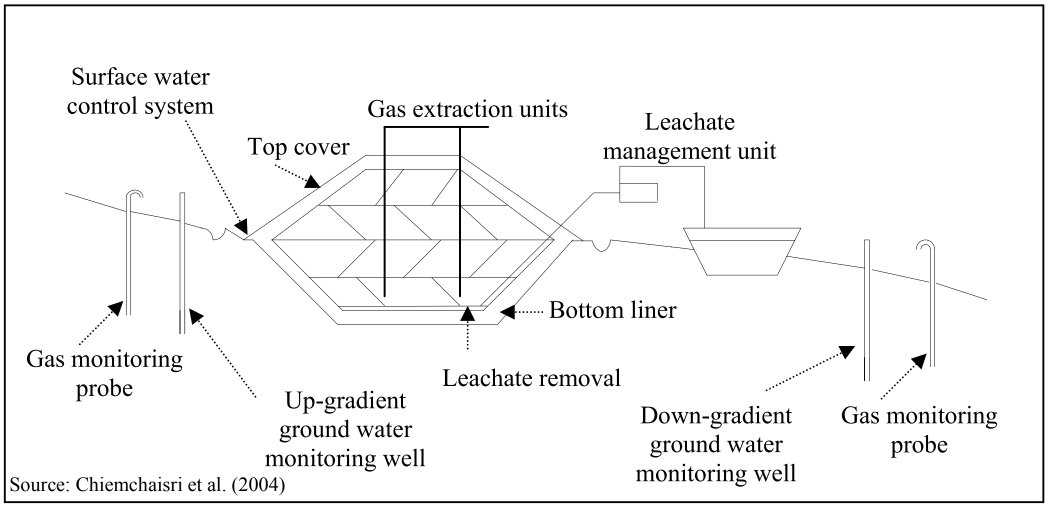


Figure 2.2 Schematic of conventional landfill

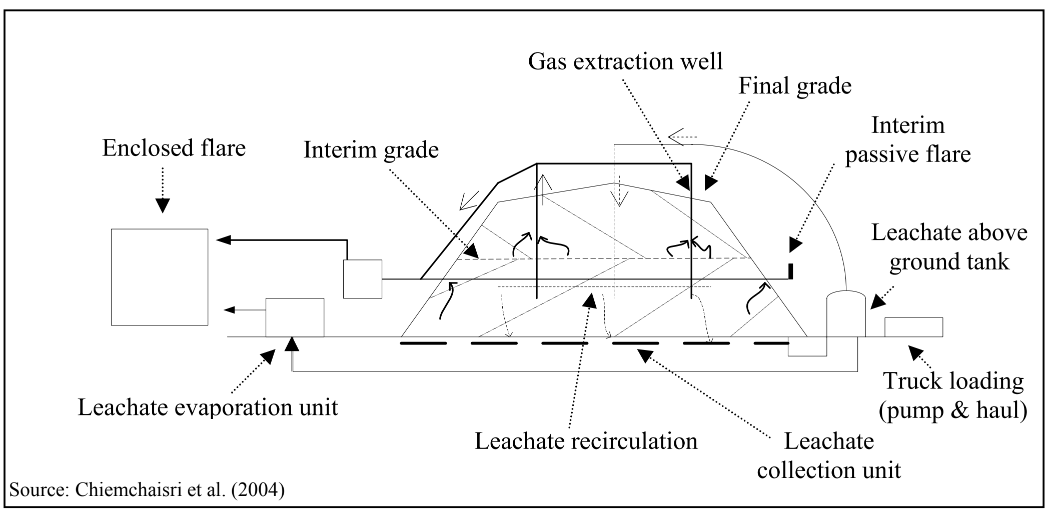


Figure 2.3 Schematic of bioreactor landfill

Bioreactor technology is selected by considering in fours reason: 1) to increase potential for waste to energy conversion, 2) to store and/or treat leachate, 3) to recover air space and 4) to ensure sustainability. The sustainability is most important in term of economic benefit because bioreactor technology reduce the cost of long-term monitoring and delayed siting of a new landfill (Reinhart et al., 2002).

Comparison the results of leachate characteristics between bioreactor landfill and conventional landfill had been studied by Reinhart and Al-Yousfi (1996); Reinhart and Towsend (1998), considering the stabilization of waste. The results are shown in Table 2.3 and 2.4. Table 2.3 presents the leachate characteristics as a function of decomposition phase. Table 2.4 compares all data from full-scale recirculating landfills. In conclusion from this study, the concentration of leachate constituents in both types of landfills is same pattern in sequential phases. Acid formation phase produced high strength of leachate more than other phase. In all phases, the strength of leachate of bioreactor is less than conventional landfill as a result of moisture content in landfill. Repeating recirculation of leachate reduces its concentration until stabilization. Furthermore, leachate recirculation provides appropriate condition for reducing the metal contamination by sulphide and hydroxide precipitation process. Other advantages of leachate recirculation are supporting gas production by providing organic material for conversion to methane gas under anaerobic condition, waste volume reduction by enhancing the settlement in depth of waste more than conventional landfill. For example, at the Sonoma County, California, pilot-scale landfill, leachate recirculated cell settled around 20% of its waste depth, for dry cells settled less than 8%. Long-term liability, bioreactor landfill operation provided cost saving of aftercare.

Thus, the difference between conventional and bioreactor landfill is that the bioreactor landfill operates with the leachate recirculation technique while the conventional landfill treats leachate offsite for disposal (Chiemchaisri et al., 2004).

In Asian countries, in comparison to many developed countries, the concept of bioreactor landfill is still relatively new. In South and Southeast Asia more than 90% of all landfills are non-engineering (Tränkler et al., 2005). Therefore, in developing countries, changing form normal disposal practice or open dumping to sanitary landfill or bioreactor landfill needs funds, knowledge and long time. However, improving dump site to suitable landfill design and operation should be done for environmental protection.

2.2 Stabilization Processes of MSW in Landfills

After MSW is placed in landfill, the biological, chemical and physical reaction will occur in landfill. Organic materials in MSW are decomposed by biological processes at which initial stage occur under aerobic condition in short period and CO_2 is principle gas produced. When oxygen is depleted, anaerobic condition will occur, organic materials are converted to CO_2, CH_4 and trace amount of ammonia (NH_3) and hydrogen sulfide (H_2S). In conclusion of biological transformation of organic fraction are as followed;

Aerobic decomposition

$$\text{Organic matter} + O_2 + \text{nutrients} \xrightarrow{\text{Microbes}} \text{new cells} + \text{resistant organic matter} + CO_2 + H_2O + NH_3 + SO_2^- + \text{heat}$$

Anaerobic decomposition

$$\text{Organic matter} + H_2O + \text{nutrients} \xrightarrow{\text{Microbes}} \text{new cells} + \text{resistant organic matter} + CO_2 + CH_4 + NH_3 + H_2S + \text{heat}$$

Table 2.3 Landfill constituent concentration ranges as a function of the degree of landfill stabilization

Parameter	Phase II Transition		Phase III Acid formation		Phase IV Methane fermentation		Phase V Final maturation	
	Conventional	Recirculating	Conventional	Recirculating	Conventional	Recirculating	Conventional	Recirculating
BOD (mg/L)	100-1,000	0-6,893	1,000-57,700	0-28,000	600-3,400	100-10,000	4-120	100
COD (mg/L)	480-18,000	20-20,000	1,500-71,000	11,600-34,550	580-9,760	1,800-17,000	31-900	770-1,000
TVA (mg/L as acetic acid)	100-3,000	200-2,700	3,000-18,800	0-30,730	250-4,000	0-39,000	0	-
BOD/COD	0.23-0.87	0.1-0.98	0.4-0.8	0.45-0.95	0.17-0.64	0.05-0.8	0.02-0.13	0.05-0.08
Ammonia (mg/L-N)	120-125	76-125	2-1,030	0-1,800	6-430	32-1,850	6-430	420-580
pH	6.7	5.4-8.1	4.7-7.7	5.7-7.4	6.3-8.8	5.9-8.6	7.1-8.8	7.4-8.3
Conductivity (μmhos/cm)	2,450-3,310	2,200-8,000	1,600-17,100	10,000-18,000	2,900-7,700	4,200-16,000	1,400-4,500	-

Source: Reinhart and Al-Yousfi (1996); Reinhart and Towsend (1998).

Table 2.4 Leachate constituents of conventional and recirculating landfills (summarizing all phases)

Parameter	Conventional	Recirculating
Iron (mg/L)	20-2,100	4-1,095
BOD (mg/L)	20-40,000	12-28,000
COD (mg/L)	500-60,000	20-34,500
Ammonia (mg/L-N)	30-3,000	6-1,850
Chloride (mg/L)	100-5,000	9-1,884
Zinc (mg/L)	6-370	0.1-66

Source: Reinhart and Al-Yousfi (1996); Reinhart and Towsend (1998).

Chemical reactions within landfill are for example, dissolution and suspension of waste materials and many compounds in the liquid percolating through the waste, evaporation of water and chemical compounds, oxidation-reduction reactions etc. For the physical reactions in landfill are, for instance, lateral diffusion of gases and emission of landfill gases to atmosphere, movement of leachate and settlement caused by consolidation and decomposition of landfilled material etc. (Tchobanoglous et al., 1993).

Environmental conditions which significantly impact on biodegradation include pH, temperature, nutrients, absence of toxin, moisture content, particle size and oxidation-reduction potential (Reinhart and Al-Yousfi, 1996).

Stabilization of MSW proceeds in five sequential phases as shown in Figure 2.4. The rate and characteristics of leachate production and landfill gas generation from landfill are varying in different phases. These variations can be used for monitoring stabilization of MSW landfill. Five phases of MSW decomposition and stabilization are described as follow;

Phase I: Initial adjustment phase

This phase relates with initial placement of MSW and accumulation of moisture within landfill. In this phase, biological decomposition occurs under aerobic conditions which oxygen present in the void spaces of MSW. Microorganisms are provided from soil material or other sources such as leachate recirculation, sludge, etc. Moisture content is entered with incoming MSW to landfill, soil material covers and rainfall. Most leachate produced during this phase results from the releasing of moisture during compaction and short-circuiting of precipitation through the MSW landfill. During this phase oxygen is rapidly consumed then produced carbon dioxide.

Phase II: Transition phase

This phase triggers the transformation from aerobic to anaerobic condition because of the depletion of oxygen within landfill. When landfill condition is anaerobic, nitrate and sulfate will be electron acceptors in biological conversion reactions and reduced to nitrogen gas and hydrogen sulfide gas, and displacement of oxygen by carbon dioxide. In this phase, pH of the leachate starts dropping due to the presence of organic acids and the effect of the elevated of carbon dioxide. By the end of this phase, chemical oxygen demand (COD) and volatile organic acids (VOA) or volatile fatty acids (VFA) can be detected in the leachate.

Phase III: Acid formation phase

The continuous hydrolysis (solubilization) of solid waste and biological activities of microorganisms which converse biodegradable organic content to intermediate volatile fatty acids at high concentrations. Decreasing in pH values is often observed, accompanied by metal species mobilization. Rapid consumption of substrate and nutrients are occurred in this phase.

Phase IV: Methane fermentation phase

Intermediate acids from phase III are consumed by methanogenic bacteria and converted to methane and carbon dioxide. Sulfate and nitrate are reduced to sulphides and ammonia, respectively. The pH values increase by the bicarbonate buffering system, this condition will support the growth of methanogenic bacteria. Heavy metals are removed by complexation and precipitation.

Phase V: Maturation phase

In this phase, nutrients and available substrate become limiting, and slowly biological activities. Gas production drops dramatically and leachate strength stays steady at lower concentrations. Reappearance of oxygen and oxidized species may be observed slowly. However, the slow degradation of resistant organic fractions may continue with the production of humic substances. During maturation phase, the leachate will often contain humic acid and fulvic acid, which are difficult to process further biologically.
(Techobanoglous et al., 1993; Reinhart and Al-Yousfi, 1996; Kjeldsen et al., 2002).

In addition, limitation of water entering the landfill is a possible reduction in the rate of landfill wasted stabilization (Tatsi and Zouboulis, 2002). Many previous studies consider the effect of landfill in long-term operation and aftercare. Landfill should be operated for enhancing biological processes which the methanogenic phase is reached at its earliest time. The results of enhancement biological processes are early reduction of the emission potential (leachate and landfill gas) and reduction of the aftercare phase (Stegmann et al., 2003).

2.3 Landfill Gas

Methane (CH_4) and carbon dioxide (CO_2) are predominate landfill gas (LFG). CH_4 generated in landfills typically excess of 45% of the total landfill gases and over 20 times more harmful than CO_2. Table 2.5 presents the typical constituents of landfill gas.

Table 2.5 Typical constituents found in MSW landfill gas

Component	Percent (dry volume basis)
Methane	45-60
Carbon dioxide	40-60
Nitrogen	2-5
Oxygen	0.1-1.0
Sulfides, disulfides, mercaptans, etc.	0-1.0
Ammonia	0.1-1.0
Hydrogen	0-0.2
Carbon monoxide	0-0.2
Trace constituents	0.01-0.6

Source: Tchobanoglous et al. (1993).

Landfill gas controlling system is employed to prevent emission of LFG into the atmosphere or the lateral and vertical movement through the surrounding soil. Furthermore, collection LFG can be used to produce energy. However, in many cases, collection LFG for energy recovery is not economical and LFG management still contains inherent risks (Tatsi and Zouboulis, 2002). As open dump site is predominant MSW disposal methods in Asia, the methane emissions from the MSW shallow dumpsites and without cover layer is less due to their more or less anoxic status (Hogland et al., 2005). However, improvement existing landfills should be designed to reduce methane emission. The biological oxidation of methane gas would be an inexpensive gas treatment system to reduce green house gas emitted from landfill (Visvanathan et al., 2003).

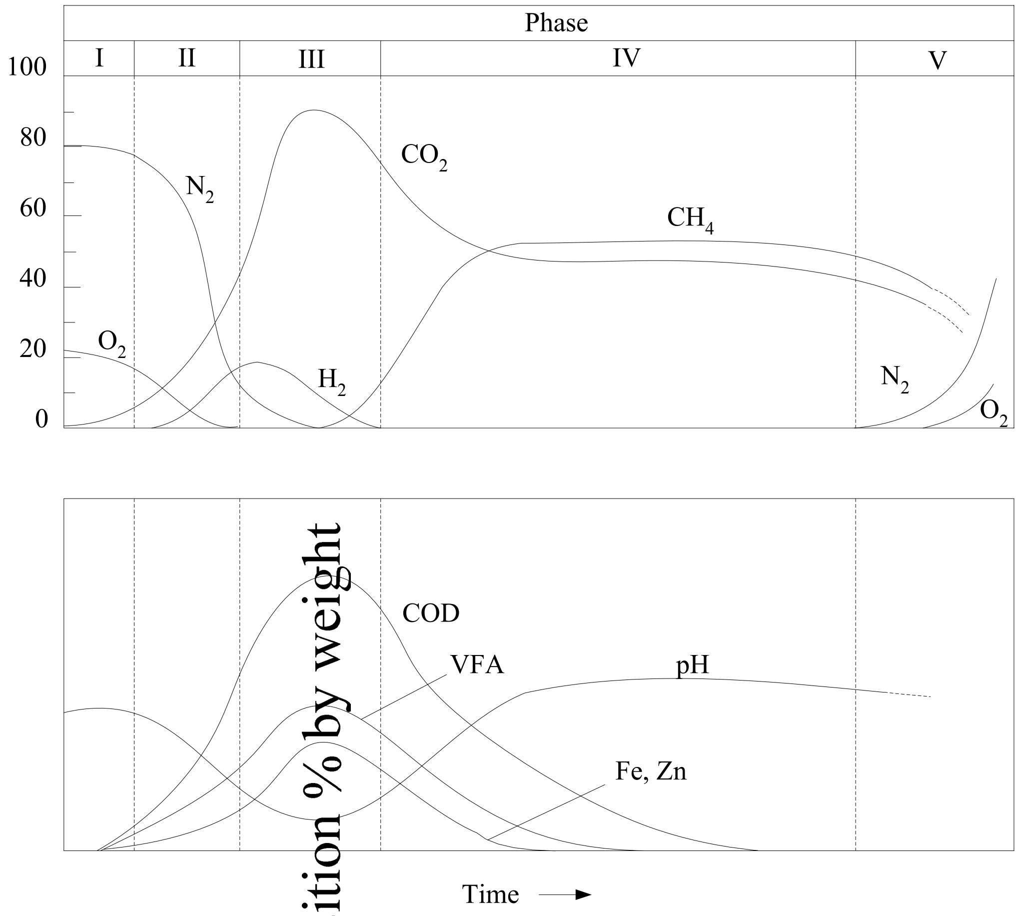


Figure 2.4 Landfill gas composition and leachate characteristics in five phases of MSW landfill stabilization

2.4 Landfill Leachate

2.4.1 Leachate Formation and Water Balance

Leachate is the percolation of precipitation, surface drainage and irrigation water into the landfill including the biological and chemical reaction of waste being disposed at the landfill. Leachate formation is an indicative of increased moisture content, which is associated with enhancing biodegradation in landfills (El-Fadel et al., 2002). Leachate generation can be determined directly by collecting leachate production from landfill site that has leachate collection system.

Generally, water balance of landfill is used to estimate leachate formation. The water balance components include water inflow, water outflow and water store within landfill.

Water inflow such as water entering from above which mainly is precipitation, water entering in solid waste and cover materials from which moisture is inherent in materials. Water outflow such as water leaving from the bottom is called leachate, water consumed in the formation of landfill gas and water lost as water vapor. The water balance components are presented in Figures 2.5 and 2.6. In addition, water lost as evaporation from landfill is determined or not that depend on local conditions (Techobanoglous et al., 1993; Manandhar and Tränkler, 2000).

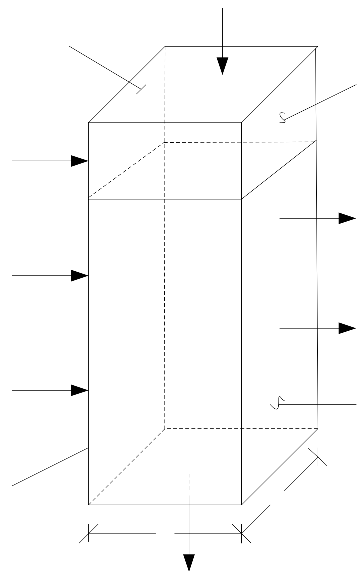


Figure 2.5 Definition sketch for water balance used to assess leachate formation in landfill

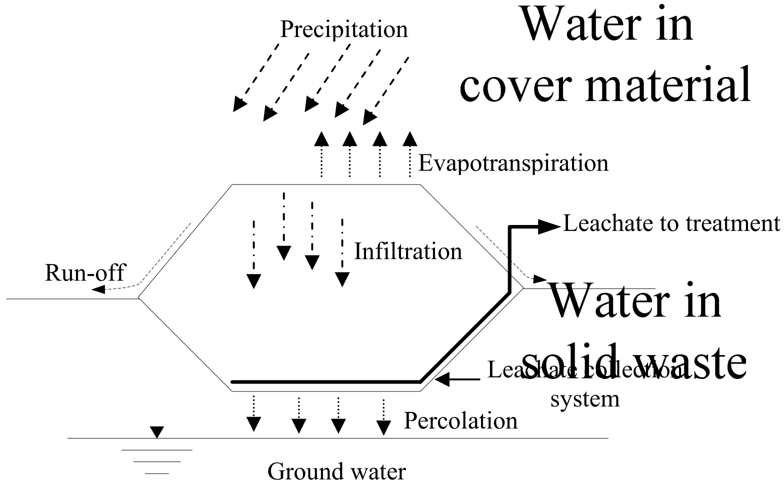


Figure 2.6 Water balance components in landfill

Control

Climatic water balance is one of simple approach for estimating quantity of leachate and deciding that landfill needs leachate collection system and bottom liner or not (Manandhar, 2000). The climatic water balance can be repressed in equation 2.1;

$$W = P - E_T \qquad \text{Equation 2.1}$$

Where, W = the quantity of moisture either lost or retention in the waste (mm)
P = the precipitation (mm)
E_T = the evapotranspiration from the landfill (mm)

Furthermore, leachate formation can be estimated by means of conventional hydrological water balance equation which is shown in equation 2.2;

$$L = P - R - E_T - \Delta S \qquad \text{Equation 2.2}$$

Where, L = quantity of percolate through the cover per unit area of soil cover (mm)
P = quantity of net precipitation per unit area (mm)
R = quantity of runoff per unit area (mm)
E_T = quantity of moisture lost through evapotranspiration per unit area (mm)
ΔS = change in the amount of moisture stored in a unit volume of landfill (mm)

Evaporation and surface runoff in the case of bare soil cover are dominant factors in water loss from the landfill surface and resulting reduced infiltration (Shrestha, 2001). In developing countries, where the refuse rarely is covered, the major portion of the precipitation would enter the fill. Flow in a vertical percolation layer is either downward (due to gravity drainage) or removed (via evapotranspiration).

Most of studies on water balance in landfill were performed in only Northern Hemisphere (Shrestha, 2001). The climatic condition is different in tropical region with Northern Hemisphere. The rainfall pattern is also different in the region. The water balance component in landfill might be different especially on evaporation due to variation in temperature as well as solar radiation. The runoff also varies with the type of soil used in the region. Landfill design and operation also affect leachate formation (El-Fadel et al., 2002). Less compaction MSW will accelerate leachate production because of compaction will reduce the filtration rate of water (Tatsi and Zouboulis, 2002).

The biodegradation changes the structure of the organic material, which is important for the retention and storage of water. These conditions result in very complicated kinds of leachate flow in landfill (Ehrig, 1983).

2.4.2 Leachate Characteristics

Composition of leachate varies depending upon the age of landfill and stabilization phase of waste degradation. Representative data on the characteristics of leachate are reported in Table 2.6.

Factors influence to leachate quality are processed refuse, depth of landfill, age of landfill, climate, landfill operation, co-disposal with sewage sludge, co-disposal with hazardous wastes and co-disposal with sorbitive waste (e.g. incinerator ash, fly ash, klin dust, limestone etc.) (Nakwan, 2002).

Table 2.6 Typical data on the composition of leachate from new and mature landfills

Constituent	Values, mg/L[a]		
	New landfill (less than 2 years)[b]		Mature landfill (greater than 10 years)
	Range[b]	Typical[c]	
BOD_5(5-day biochemical oxygen demand)	2,000-30,000	10,000	100-200
TOC (total organic carbon)	1,500-20,000	6,000	80-160
COD (chemical oxygen demand)	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 phosphorus	5-100	30	5-10
Ortho phosphorus	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
Sulfate	50-1,000	300	20-50
Total iron	50-1,200	60	20-200

[a] Except pH, which has no unit
[b] Representative range of values. Higher maximum values have been reported in the literature for some of the constituents.
[c] Typical values for new landfills will vary with the metabolic state of the landfill.
Source: Tchobanoglous et al. (1993).

2.4.3 Landfill Field Capacity

The quantity of water that can be held within body of landfill is referred as field capacity. The amount of water that excess of the landfill field capacity is defined as leachate. The field capacity (FC) can be estimated using the following equation 2.3 (Techobanoglous et al., 1993).

$$FC = 0.6 - 0.55\left(\frac{W}{10{,}000 + W}\right) \qquad \text{Equation 2.3}$$

Where; FC = field capacity (i.e., the fraction of water in the waste based on the dry weight of the waste)
W = overburden weight calculated at the mid height of the waste in the lift, lb

Yuen et al. (2001) had literature research and listed some field capacity values. Table 2.7 presents the field capacity of MSW reported in literature.

Table 2.7 Field capacity of MSW

Reported field capacity (v/v)	**Reference**
14	Zeiss and Major (1993)
29	Remson et al. (1968) and Schroeder et al. (1994)
20-30	Korfiatis et al. (1984) and Owesis et al. (1990)
29-42	Holmes (1980)
30-40	Straub and Lynch (1982)
44	Bengtsson et al. (1994)

Source: Yuen et al. (2001).

The field capacity is expected to change with time as a result of the change with waste density, composition and age of waste including affected by overburdening pressure and settlement (Yuen et al., 2001).

2.4.4 Leachate Management Options

Leachate management options are summarized by Tchobanoglous et al. (1993) including leachate recycling, leachate evaporation, treatment followed by disposal and discharge to municipal wastewater collection system.

Leachate recycling

Leachate recycling consists of collection and recirculation leachate in landfill. The leachate can be recirculated in many ways such as using horizontal trenches, vertical recharge wells, spray irrigation systems and surface application (Reinhart and Al-Yousfi, 1996; Reinhart et. al, 2002). Benefits of leachate recycling are: 1) treatment of leachate because high strength of pollutants in leachate will be decomposed again by biological activities and other reactions, 2) recovery of landfill gas (CH_4) which is the result of decomposition and 3) precipitation of metal and retained within landfill because the rise in pH within landfill when CH_4 is produced. In addition, leachate storage facility is necessary for large landfills.

Criteria for determining the efficiency of leachate recirculation on MSW landfill on solid waste stabilization is leachate generation and quality, landfill gas production and composition and landfill settlement (Morris et al., 2003). However, some operational problems associated with leachate recirculation were lack of appropriate recirculation technique and leachate ponding (Chiemchaisri et al., 2002).

Leachate evaporation

Leachate is storaged in the pond that has liner. It is evaporated by natural sunlight. However, lined leachate evaporation ponds may have covering or uncovering depending on the climatic condition of each location and operation decides.

Leachate treatment

Treatment of leachate by biological processes or physical/chemical processes and options are selected regarding to the concentration of pollutant in leachate that need to be removed.
Discharge to wastewater treatment plant

In case of landfill is located near a wastewater collection system or available to connect that system. Leachate can be discharged to system and treated at wastewater treatment plant. However, pre-treatment of leachate is necessary for reducing organic content before discharge to sewer.

2.5 Influence of Tropical Seasonal Variation on Landfill Leachate

Most landfill sites in Asia are located in a monsoon climate. Climatic condition in tropical countries such as Thailand, Malaysia, etc. can be characterized by rainy season and dry season. There is high intensity rainfall (up to 80 mm/day and above) in rainy season while dry season does not have rainfall. It has been observed that 220-250 days per year shows no rain at all and there exists distinct arid period of about 4 months. With a medium temperature of 28°C and an average sunshine duration of 6.8 hours the solar radiation is computed to be 18.8 MJ/m^2/day. This results in high evaporation rates around 50% (Manandhar and Tränkler, 2000).

Climatic variation can significantly affect the leachate quantity and quality (Visvanathan et al., 2003). During dry season leachate and gas production nearly stop and restarts immediately with the merge of the rainy season (Ranaweera and Tränkler, 2001).

Landfill lysimeters were simulated at Environmental Research Station of AIT, Thailand at least 3-4 years. Effects of tropical climatic correlation with leachate characteristics were studied by Tränkler et al., (2005) and Tabtimthai (2003). Mainly operation modes of study included: 1) Simulation of sanitary landfill with triple layer covers system, 2) Pre-treatment and pre-sorting effects on leachate generation and quality, 3) Effect of top cover design on leachate generation and 4) Effect of climatic influence on open dump simulation. Fives lysimeters were operated: sanitary landfill with standard top cover layer (reference), sanitary landfill with top cover layer (no barrier layer), sanitary landfill with top cover layer (one layer mixed with compost waste, no barrier layer), pre-treated waste landfill and open cell.

Normally, Thailand has three seasons, which are rainy season (from May until mid-November), winter season (from mid-November until mid-February) and summer season (from mid-February until mid-May). However, reality conditions of seasonal variation were observed in this study for determining relationship of weather condition and leachate generation, leachate characteristics etc.

Comparison and interpretation of all results were concluded that leachate generation and its quality are affected from;

- Climatic condition (rainy season and dry season): rainfall pattern effects leachate generation. During dry season means less or no precipitation due to small amount of leachate generation, less cumulative of leachate or stagnant discharge. During rainy season which normally had intensive rainfall, more leachate generation and highly cumulative than dry season. Furthermore, in term of leachate characteristics were found that fluctuation with phase of decomposition and rainfall pattern.

- Top cover layer design (standard cover, alternatives cover or no cover): open dump had only thin sand cover due to high water infiltration caused high leachate generation.
- Properties of MSW input (pre-treated waste, MSW compaction, moisture content of incoming MSW, etc.): pre-treated waste by composting result in lowest COD and TKN concentration and loading. On the other hand, open cell lysimeter produced highest COD and TKN loading (20% and 180%, respectively, more than sanitary landfill lysimeter).

In addition, settlement of landfill lysimeters was observed. Primary settlement of MSW in lysimeter determined during initially of MSW placement. After one year operation are defined as secondary settlement. Operation MSW with high compaction caused less settlement such as pre-treated waste lysimeter. In contrast, low compaction caused high settlement such as open cell lysimeter.

In case of open cell landfill lysimeter relate with tropical climatic condition, the study recommended that open cell should combine with leachate recirculation, because open cell practice which no top cover allows water infiltration. Thus, it provides moisture content for biodegrading of MSW. And as a result of highest leachate generation during rainy season (leachate formation more than 60% of the precipitation) in this operation, lechate should be stored and recirculated during dry season. This concept was supported by Hogland et al., (2005), Asian countries need to be improvements to the concept of leacahte recirculation with a secure liner system.

2.6 Hydrologic Evaluation of Landfill Performance Model

Determining water management of landfills need to understand leachate formation, factors influence leachate production, including model application. Hydrologic Evaluation of Landfill Performance (HELP) model is a tool to estimate of water balance for municipal solid waste landfill. The HELP model version 1, 2 and 3 was developed by the U.S. Army Engineer Waterway Experiment Station (WES). Use of HELP model is recommended by the U.S. Environmental Protection Agency (USEPA) and required by most states for evaluating closure design of hazardous land non-hazardous waste management facilities (Manandhar, 2000). Version 1 of HELP appeared in 1984 and the extensively reworked version 2 in 1988 and then version 3 in 1994.

The HELP model version 3 has been greatly enhanced beyond version 2 such as the increasing number of layers for modeling, expanding default soil/material texture list, offering matrix units (SI units), providing a variety of methods for specifying weather data etc.. Furthermore, the use of data files in version 3 is simple and convenient than version 2 (Schroeder et al., 1994; Berger et al., 1996).

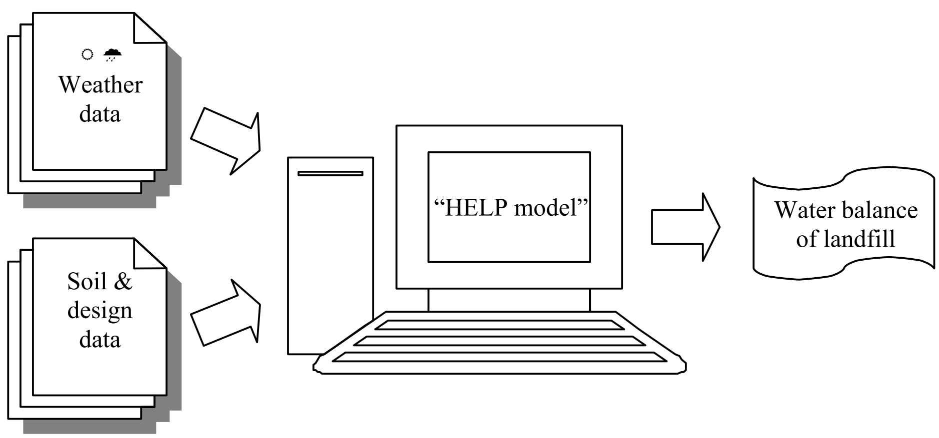
Model application, the HELP model is classified as quasi-two dimensional because several one-dimensional models (percolation vertically, drainage and surface runoff horizontally) are coupled (Berger et al., 1996). The model accepts weather data, soil and design data and uses solution techniques for water balance analysis. Generally, landfill system consists of the various combinations of vegetation, cover soils, waste cells, lateral drainage layers, low permeability barrier soils and synthetic geomembrane liners. The model facilitates rapid estimation of the amounts of runoff, evapotranspiration, drainage, leachate collection and liner leakage. The primary purpose of the model is to assist in the comparison of design alternatives (Schroeder et al., 1994). Important data inputs for HELP model application are as follow;

Weather data requirements

Weather data is necessary to have long term data from nearby meteorological stations. The weather data required in HELP model are classified into four groups: evapotranspiration, precipitation, temperature and solar radiation. Input data, the users can enter/edit data directly (manual option) or use other options of the model. Selecting options depends on the type of weather data being considered.

Soil and design data requirements

The design data requirements are landfill general information, layer data, lateral drainage layer design data, geomembrane liner data and runoff curve number information. The part of input layer data needs the soil/material data. The user may enter soil/material data by using the default soil/material option, the user-defined soil texture option, or manual option. The important information displaying from each option is porosity, field capacity, wilting point and hydraulic conductivity of the selected soil/material.



HELP model still has limitation of application. For example, the model has limits on the arrangement of layers in the landfill profile. The physical characteristics of landfill are constant over the modeling period. A more detailed description of the model can be found in the HELP model user's guide Version 3 (Schroeder et al., 1994).

Because of the complexity of model which considers various parameters, several studies use some generalization and essential default values. An example of for the HELP model application had been studied by Manandhar and Tränkler (2000) for Phitsanulok Landfill, Thailand. The boundary conditions of the input parameters for model application in this case studied are presented in Table 2.8. The model was applied for estimating the leachate generation in landfill and its response on rainfall variation.

The results of this case study are reported that leachate production in range 17-29% of amount of precipitation, the production rate in range 0.65-1.0 liters/m^2/day. The evaporation and surface runoff were dominant factors in water balance in landfill cover. However, the problems of model application are representative local data input such as runoff, infiltration and evapotraspiration parameters. The variation of short-term rainfall is leaded to runoff more than infiltration. Some factors such as biodegradation of MSW, high rainfall over short period were negligible. Thus, data inputs are very important for model application.

Table 2.8 Boundary conditions of the input parameters for the model application for Phitsanulok Landfill, Thialand: case studied

Data type	Real data	Empirical/ processed data	Default data
Precipitation data	+		
Daily precipitation values	+		
Evapotranspiration parameters data		x	*
Daily solar radiation values		x	
Daily sunshine hours values	+		
Daily temperature values	+		
Quarterly relative humidity	+	x	
Wind speed	+	x	
Maximum leaf area index			*
Evaporative zone depth			*
Soil data	+	x	*
Hydraulic conductivity of topsoil	+		
Field capacity		x	
Wilting point		x	
Porosity		x	
Barrier soil and gravel			*
Waste properties data			*
Saturated hydraulic conductivity			*
Porosity			*
Field capacity			*
Wilting point			*
Landfill design data	+		

Source: Manandhar and Tränkler (2000).

2.7 Monitoring *in situ* Moisture Content of MSW

As moisture content is a major factor for degradation of solid waste in landfills. The optimal moisture content for waste biodegradation is in range 40-70% while most of the conventional landfills reach moisture content of 20-30% (Guérin et al., 2004).

The estimation landfill moisture content is necessary for optimization moisture content in the whole waste mass (Grellier et al., 2005). Monitoring *in situ* moisture content is widely applied in bioreactor landfill. Several techniques are used for measuring landfill moisture content. The direct technique is gravimetric method. It consists in extracting waste samples and measuring their moisture content. Moisture content of solid waste samples are the loss of their weight after drying at temperature 103-105°C. However, it is an intrusive technique, localization data, unrepresentative of the heterogeneous waste mass, time consuming and an expensive prospect (Moreau et al., 2005; Grellier et al., 2005; Gawande et al., 2003; Yuen et al., 2000). To avoid these limitations, indirect technique is installing the devices which can monitor in situ moisture content in landfills.

In situ moisture content sensors have been developed primarily for use in the agriculture industry for soil moisture measurements and irrigation scheduling program. There are different types of probe available for soil moisture measurement. Time domain reflectometry/transmissometry, neutron probe, capacitance probe and electrical resistance probe are examples. These have been used to monitor *in situ* moisture content in landfills. For example, neutron probes were used in a full-scale experimental municipal solid waste landfill in Melbourne, Australia by Yuen et al. (2001). Time domain reflectometry was selected for monitoring *in situ* moisture content at bioreactor cell of Northern Oaks Recycling & Disposal Facility (NORDF) in Harrison, MI, USA (Zhao et al., 2003). Electrical resistance technique was applied in composite moisture, temperature and gas (MTG) sensors which installed in a full-scale bioreactor landfill in Florida (Gawande et al., 2003).

However, the sensors were originally designed for soil moisture measurement. Therefore, each technology has unique application difficulties when applied to landfills (Gawande et al., 2003). The main problem is the heterogeneity of MSW which is higher than soil. Using probe could have contaction problems with the waste and using many probes are necessary to derive an overall picture of waste moisture lead to high cost (Guérin et al., 2004).

In addition, the geophysical technique by measuring the electrical resistivity was developed to investigate moisture content in bioreactor landfills. Leachate diffusion into waste mass was evaluated by a two dimensional electrical resistance method. For example, 2D electrical resistivity cartography, electrical resistiviy topography electromagnetic slingram was applied to monitor the movement of leachate in landfill (Guérin et al., 2004; Grellier et al., 2005; Barina, 2005).

Chapter 3

Methodology

3.1 Introduction

This research focused on the investigation of open cell landfill operation with water management. The application of HELP model was used to simulate water balance. The main methodology can be divided into two tasks as follows;

1) Monitoring the open cell landfill lysimeters: This study was continuously operated, monitored and compared the effect of open cell landfill combined with leachate management in different lysimeter simulations.
2) Determining water management for open cell landfill lysimeters: This research was based on the experiment and application of HELP model to simulate water balance and water management. The tropical climatic data and significant data inputs of model were collected and analyzed.

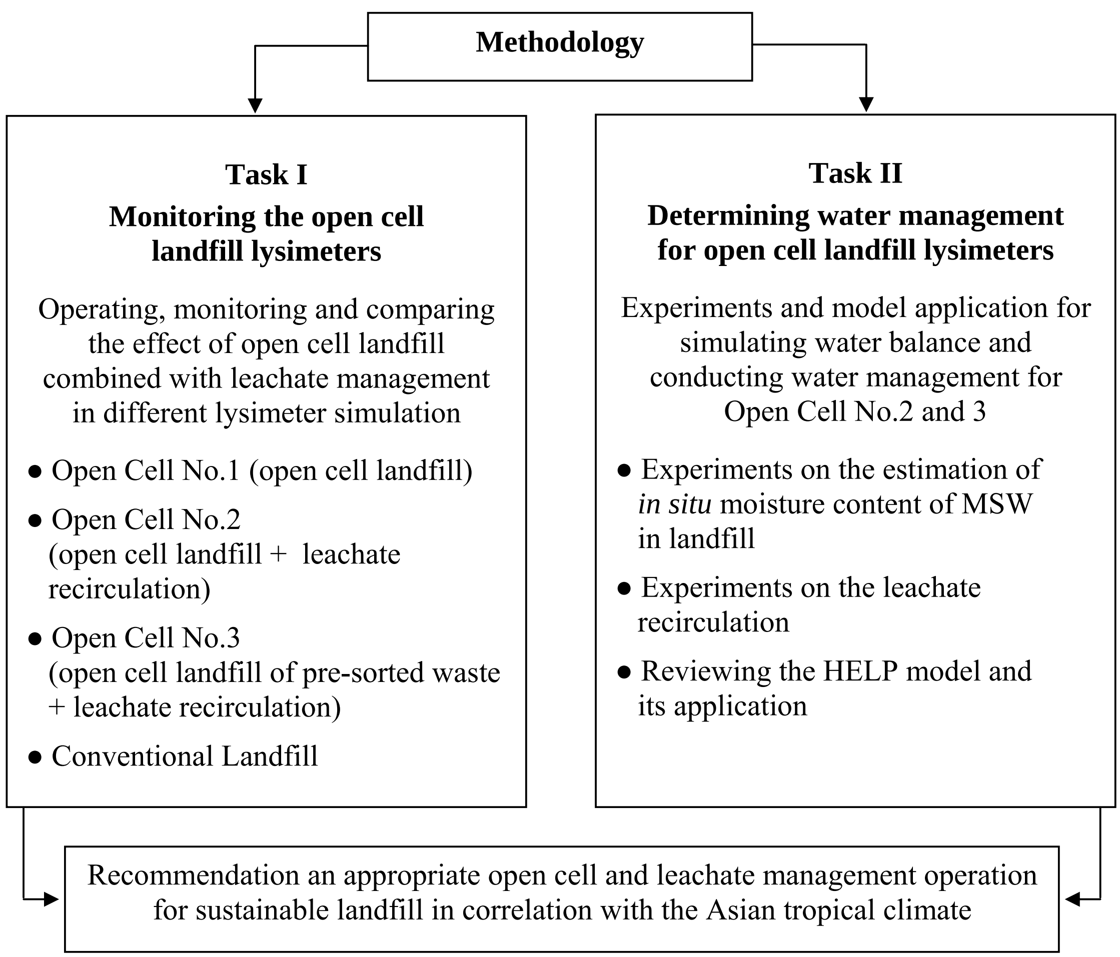
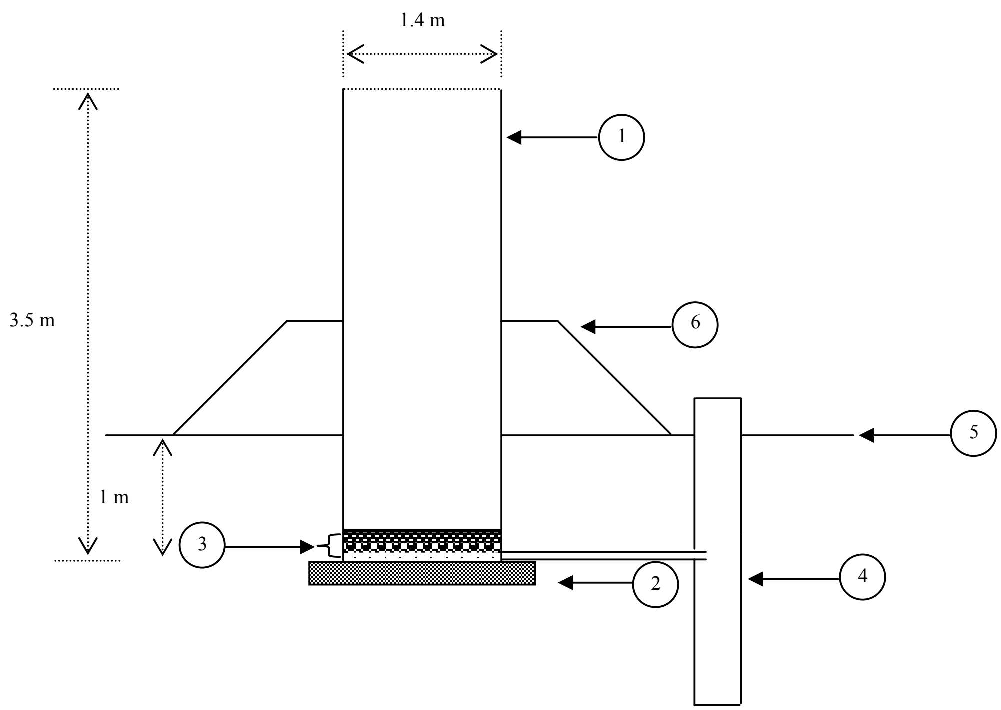


Figure 3.1 Flowchart of methodology

3.2 Task I: Monitoring Open Cell Landfill Lysimeters

The seven landfill lysimeters constructed at Environmental Research Station of AIT were used in the previous study. The details of landfill lysimeter construction are shown in Figure 3.2.



(1) Concrete rings reinforced with Ferro-cement and plastered inside and outside with two coating of waterproofing agent.

(2) Concrete base (0.2 m)

(3) Liner layer; geo-textile, leachate drainage with fine gravel (Ø = 5mm) and course gravel (Ø = 20 mm) to the height 0.2 m and leachate collection pipe (Ø = 80 mm) under the gravel layer with 3 mm holes on a 50 mm pitch and cover with plastic mess (respectively from top to down).

(4) Leachate collection tank (PVC pipe Ø = 0.2 m buried approximately 2.0 m below ground level).

(5) Ground level

(6) Vegetation cover

Figure 3.2 Details of landfill lysimeter

In this study, only four lysimeters were adopted and monitored with new operation by open cell practice and leachate recirculation system. The operation modes of lysimeter were shown in Table 3.1 and the details of Task I were presented in Figure 3.3.

Table 3.1 Details of landfill lysimeters design

Lysimeters	Operations			
	Input material	**Compaction density**	**Cover layer**	**Leachate recirculation**
Open Cell No.1	MSW from Taklong Municipality (placed in multi layers)	517 kg/m^3	No top cover layer, only 5 cm deep sand layer to avoid contact with external environment	No
Open Cell No.2	MSW from Taklong Municipality (placed in multi layers)	504 kg/m^3	No top cover layer, only 5 cm deep sand layer to avoid contact with external environment	Yes
Open Cell No.3	MSW from Taklong Municipality & pre-sorted waste (placed in multi layers)	582 kg/m^3	No top cover layer, only 5 cm deep sand layer to avoid contact with external environment	Yes
Conventional Landfill	MSW from Taklong Municipality (placed in multi layers)	740 kg/m^3 *	Intermediate cover (15 cm soil layer) and Top cover layer (40 cm drainage layer; sand, silt and clay mixture in the ratio 70:15:15, 20 cm barrier layer and 10 cm gravel foundation layer)	No

Note: * high compaction density as a result of overburden weight of top cover

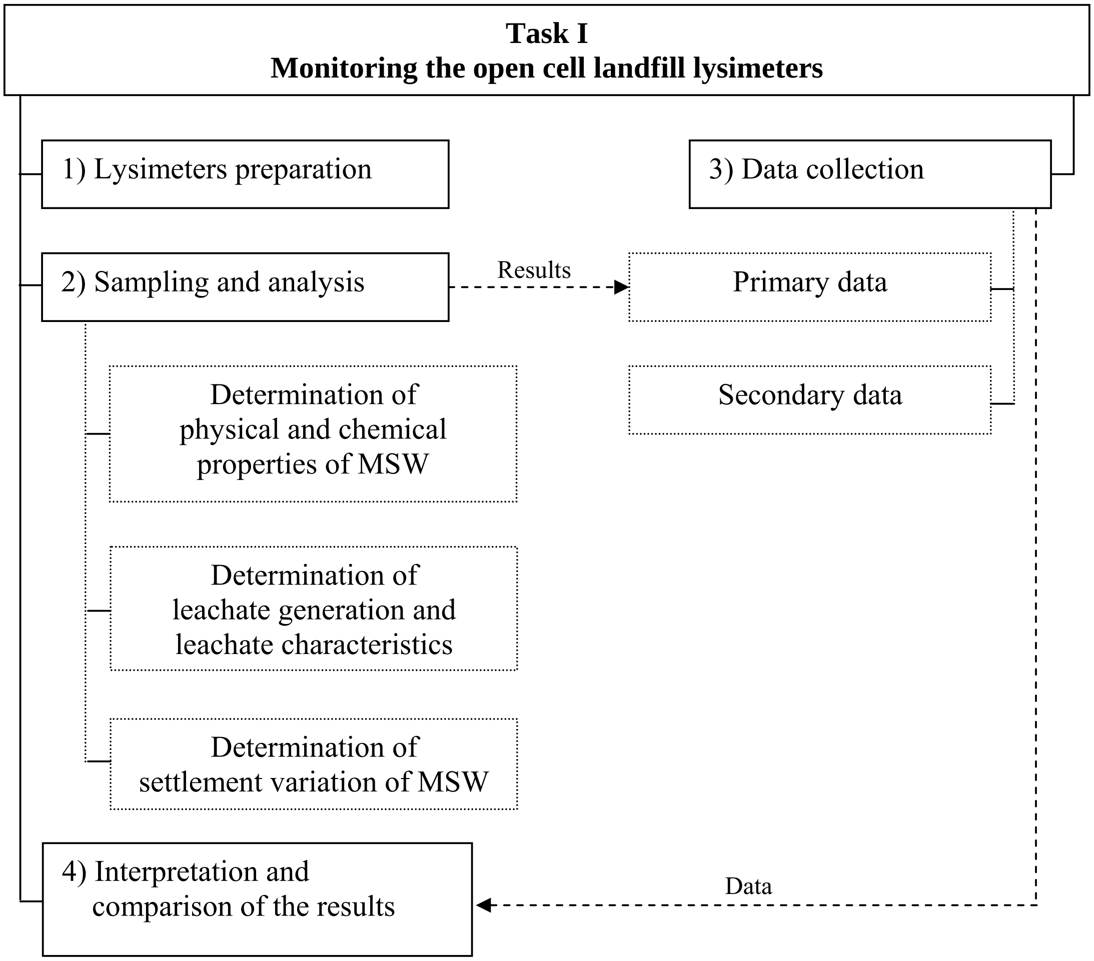


Figure 3.3 Flowchart of methodology of Task I

3.2.1 Lysimeters Preparation

The solid waste collected from Taklong municipality was placed directly into each lysimeter. Solid waste was filled in 3-4 layers approximately 60-80 cm every week until it reached about 2.4 m height of waste in lysimeters. The open cell landfill lysimeters did not have a top cover and 5 cm thick sand cover was used to avoid contact with the external environment. The Conventional Landfill had intermediate cover (15 cm soil layer) and top cover followed by the previous studies (40 cm drainage layer; sand, silt and clay mixture in the ratio 70:15:15, 20 cm barrier layer and 10 cm gravel foundation layer, respectively from top to down).

In case of open Cell No.3 lysimeter, the MSW was manually removed any potential combustible waste (e.g. paper, plastic, leather and rubber), non-combustible waste (e.g. ferrous metal, non-ferrous metal, glass, stone and ceramic), potential hazardous waste and bulky materials. The remaining MSW that mainly consisted of highly biodegradable organic fractions was dumped into this lysimeter. The details of lysimeter preparation were shown in Figure 3.4.

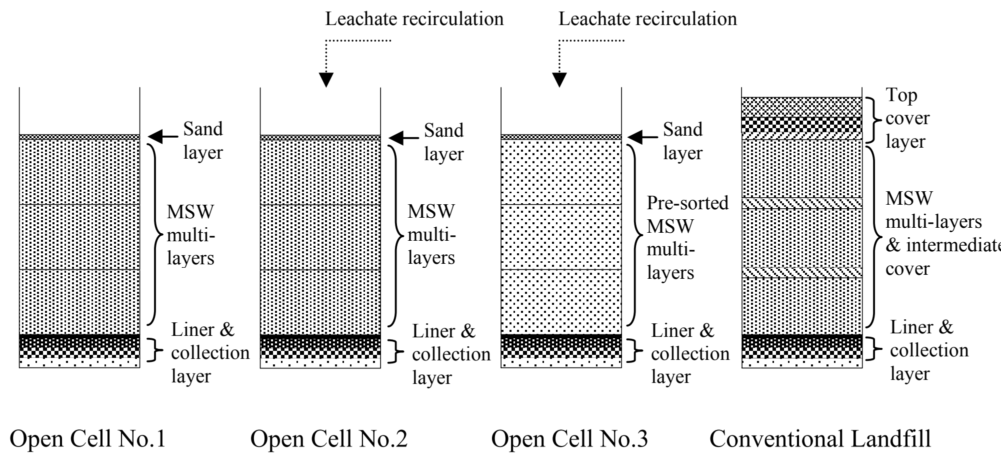


Figure 3.4 Flowchart of lysimeters preparation

3.2.2 Sampling and Analysis

Determination of physical and chemical properties of MSW

MSW was sampled by quartering method every loading of MSW at lysimeter site. Physical characteristics in terms of bulk density (kg/m^3) and compositions of MSW (% by weight) were determined. Determination of chemical characteristics in terms of moisture content (%MC), total solid (%TS), volatile solid (%VS), ash content (%ash content) and total organic carbon (%TOC) was considered. The details of MSW determination were shown in Table 3.2.

Table 3.2 Determination physical and chemical properties of MSW

Parameters	Analytical method	Instruments
MSW compositions	Quartering method, hand sorting and weighting	Balance
Bulk density	Quartering method and weighting	Balance
Moisture content	Gravimetric method (drying at temperature 103-105^{o}C)	Oven and Analytical balance
Total solid	Gravimetric method (100 - moisture content)	-
Volatile solid	Gravimetric method (ignition at temperature 550^{o}C)	Oven and Analytical balance
Ash content	Gravimetric method (total solid - volatile solid)	-
Total organic carbon	Walkley-Black method	Oven, Analytical balance and Titration apparatuses

Note: - Sampling and analysis of MSW properties were followed ASTM Standard (American Society for Testing and Materials) (1992) which modified by EEM laboratory.
- All units except bulk density (kg/m^3) are in % by weight.

Determination of leachate generation and leachate characteristics

Leachate was pumped by using submersible pump for determining leachate generation and around 300 ml of leachate was kept in sampling bottles and preserved for leachate characteristics analysis. The determination parameters included pH, conductivity, alkalinity, chemical oxygen demand (COD), biochemical oxygen demand (BOD_5), total kjeldahl nitrogen (TKN), ammonia nitrogen (NH_4-N), organic nitrogen (organic-N), volatile fatty acid (VFA), total solid (TS), volatile solid (VS), total suspended solid (TSS), total dissolve solid (TDS) and selected heavy metals. The frequency of sampling and analysis was once a week. The details of leachate determination were shown in Table 3.3.

Table 3.3 Determination of leachate characteristics

Parameter	Analytical method	Analytical instrument	Interference
pH	pH meter	pH meter	Undesirable matter attached to electrode
Conductivity	Conductivity meter	Conductivity meter	-
Alkalinity	Titrimetric method	Titration apparatuses	Soaps, oily matter, suspended solid, or precipitation
COD	Closed dichromate-reflux titrimetric method	Closed reflux apparatuses	Chloride ion and other reagent that activates the silver ion etc.
BOD_5	5 days incubation at 20°C	Incubator, titration apparatus, etc.	-
TKN	Kejeldahl method	Digestion and distillation apparatuses	Nitrate, inorganic salts and solids and organic matter
NH_3-N	Distillation and titrimetric method	Distillation and titration apparatuses	Volatile alkaline compounds and residual chlorine
VFA	Gas chromatograph	Gas chromatograph	-
TS	Gravimetric method (evaporation and dry at temperature 103-105^oC)	Oven and analytical balance	Large, floating particles or submerged agglomerates of nonhomogenous materials, visible floating oil and grease etc.
TSS	Gravimetric method (filtration and evaporation at temperature 103-105^oC)	(Same as total solid)	(Same as total solid)

Table 3.3 Determination of leachate characteristics (continue)

Parameter	Analytical method	Analytical instrument	Interference
TDS	Gravimetric method (filtration and evaporation at temperature 180°C)	Oven, analytical balance, filtration apparatuses, glass fiber filter dish, suction flask, etc.	(Same as total solid)
VS	Gravimetric method (ignition at temperature 550°C)	(Same as total solid)	Loss of ammonium carbonate and volatile organic matter during drying
Selected heavy metals (Mn, Cr, Cd, Pb, Ni, Zn and Cu)	Inductively Coupled Plasma-Optical Emission Spectrometry	Inductively Coupled Plasma-Optical Emission Spectrometry	Metrix effect, significant dissolved solid, ionization interference

Note: - Sampling and analysis of leachate was based on Standard Methods for the Examination of Water and Wastewater. (20th Ed.), APAH et al., (2000).
- All units are in mg/L except pH (no unit) and conductivity (mS/cm).

Determination of settlement variation of MSW

Settlement of MSW from each lysimeter was measured in term of total settlement variation. The frequency of settlement measurement was every two days at first month, every week at the second and third month and then once a month.

3.2.3 Data Collection

Primary data was the results of sampling and analysis of MSW properties, leachate quantity and quality, and settlement variation of MSW. Secondary data was the previous experimental data and literature review.

3.2.4 Interpretation and Comparison of the Results

Comparison of the results of different open cell landfill operation in terms of the leachate quantity, leachate quality, stabilization, biodegradability and settlement of MSW, all of these were determined and interpretive the results.

3.3 Task II: Determining Water Management for Open Cell Landfill Lysimeters

Water management of open cell landfill lysimeters, Open Cell No.2 and 3, was carried out by considering *in situ* moisture content of MSW in landfill, experiment on leachate recirculation and model application. Figure 3.5 illustrates the details of Task II.

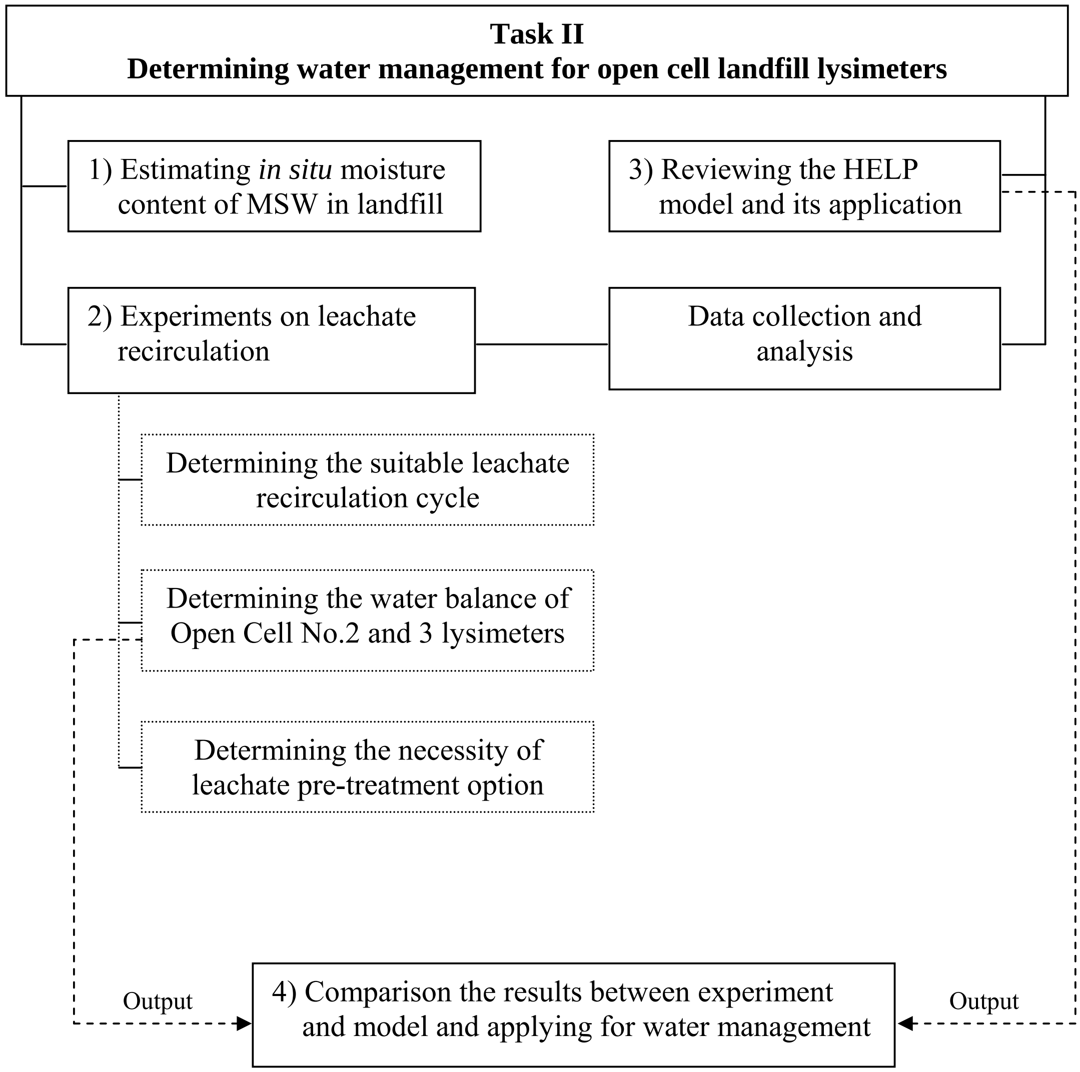


Figure 3.5 Flowchart of methodology of Task II

3.3.1 *In situ* Moisture Content Measurement Using an Electrical Resistance Sensor

Electrical resistance technique was selected and applied for indicating *in situ* moisture content of MSW of Open Cell No.2 and 3. The resistance measurement historically observed good co-relation between moisture content and electrical resistance (Gawande et al., 2003; Grellier et al., 2005; Guérin et al., 2005).

The electrical resistance moisture content sensor was designed to measure the electrical resistance occurring between two electrodes embedded in dry clay. Water moved from the surrounding waste to the sensor body. Changing resistance readings reflected the changes in moisture content of the sensor's media.

This sensor body was locally made from geotextile. The body of sensor had cylindrical shape with diameter 5 cm and 10 cm in height. Seven centimeters long piece of stainless steel rods were inserted through the center of the sensor body. Two electrodes were connected to the resistance conductors via copper wire. Resistance across the sensor electrodes was measured using resistance meter. Figure 3.6 shows the details of the electrical resistance moisture content sensor.

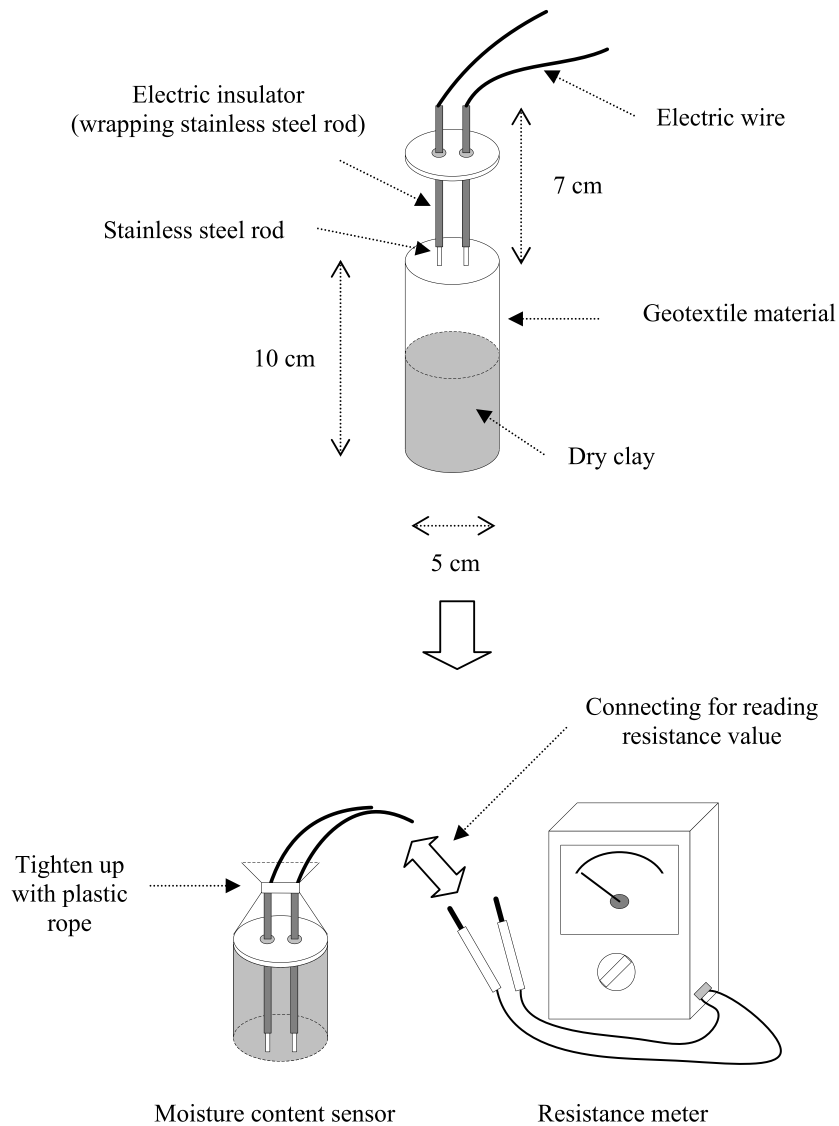


Figure 3.6 Electrical resistance moisture content sensor

The relationship between moisture content and electrical resistance of this sensor were obtained from experiment in laboratory. After that, the sensors were installed into Open Cell No.2 and 3 by drilling vertical holes. Both lysimeters had two moisture sensors. One sensor was installed at depth 0.3 m which was assumed as representative moisture content at the top level of lysimeter. Another sensor was installed at depth 1 m which assumed as representative moisture content at the middle level of lysimeter. The resistance values were obtained by resistance meter converting to estimate moisture content of MSW in landfill lysimeters.

3.3.2 Experiments on Leachate Recirculation

Determining suitable leachate recirculation cycle

At the beginning of operation, leacahte generation from Open Cell No.2 and 3 was pumped and collected into separate storage tanks. Whenever, the moisture content of MSW in landfill was not enough, leachate was recirculated on both lysimeters. Control of moisture content was conducted from the results of moisture content sensors, ambient condition data (e.g. temperature, rainfall, evaporation, etc.) and experiment at site. All of these investigations can provide the suitable leachate recirculation cycle (leachate recirculation rate and its frequency).

Determining water balance of Open Cell No.2 and 3 lysimeters

The main water inflow into lysimeters was precipitation and recirculated leachate. Water outflow was leachate production. Initial moisture content of MSW, water stored in the body of lysimeter and evapotranspiration were other factors to influence water balance. Climatic data and experimental data were collected and water balance was calculated by using water balance equation, as referred in Chapter 2 (section 2.4.1).

Determining the necessity of leachate pre-treatment

Leachate recirculation was provided by directly pumping it from the storage tanks into selected lysimeters. The storage tanks were the open tank, which allowed rainfall and evaporation. Therefore, the amount of water in these tanks was leachate adding precipitation and subtracting water loss as evaporation. The excess water needs further treatment before discharge.

Sampling and analysis of leachate recirculated in terms of TSS, pH and conductivity were determined. The results of analysis were investigated for balancing system and protection of clogging of leachate collection and recirculation system. The necessity of pre-treated leachate before recirculation was considered too. The flow charts of leachate management shows in Figure 3.7.

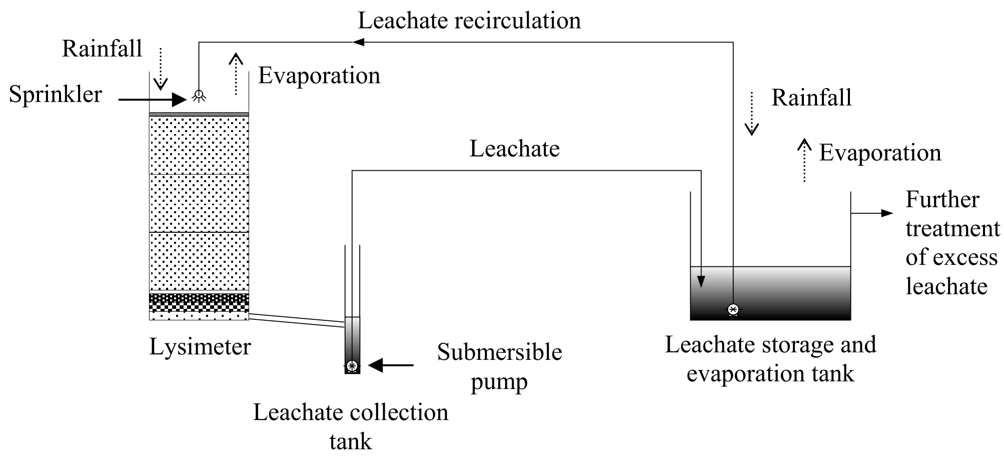


Figure 3.7 Flowchart of leachate management

3.3.3 The HELP Model and Its Application for Open Cell Landfill Lysimeter

The HELP model version 3.07 was selected for simulation water balance of open landfill lysimeters. Significant inputs were collected and assessed for model procedure.

Data collection and analysis

- Weather data was recorded by AIT Meteorological Station. Five years (2001-2005) daily rainfall, temperature, solar radiation, etc. were collected. These data were illustrated in Appendix A (Table A-1 to A-5). The other significant data for HELP model was obtained from the previous experimental data, literature review and available data from model.
- Soil and landfill design data were followed the specific design and operation of open cell landfill lysimeters. Using the default data from model was considered.

Modeling procedure

A comprehensive review on HELP model and its application was performed. The procedure followed the HELP model user's guide Version 3 (Schroeder et al., 1994). The water balance of Open cell No.2 and 3 lysimeters were modeled. Figure 3.8 presents the model flowchart.

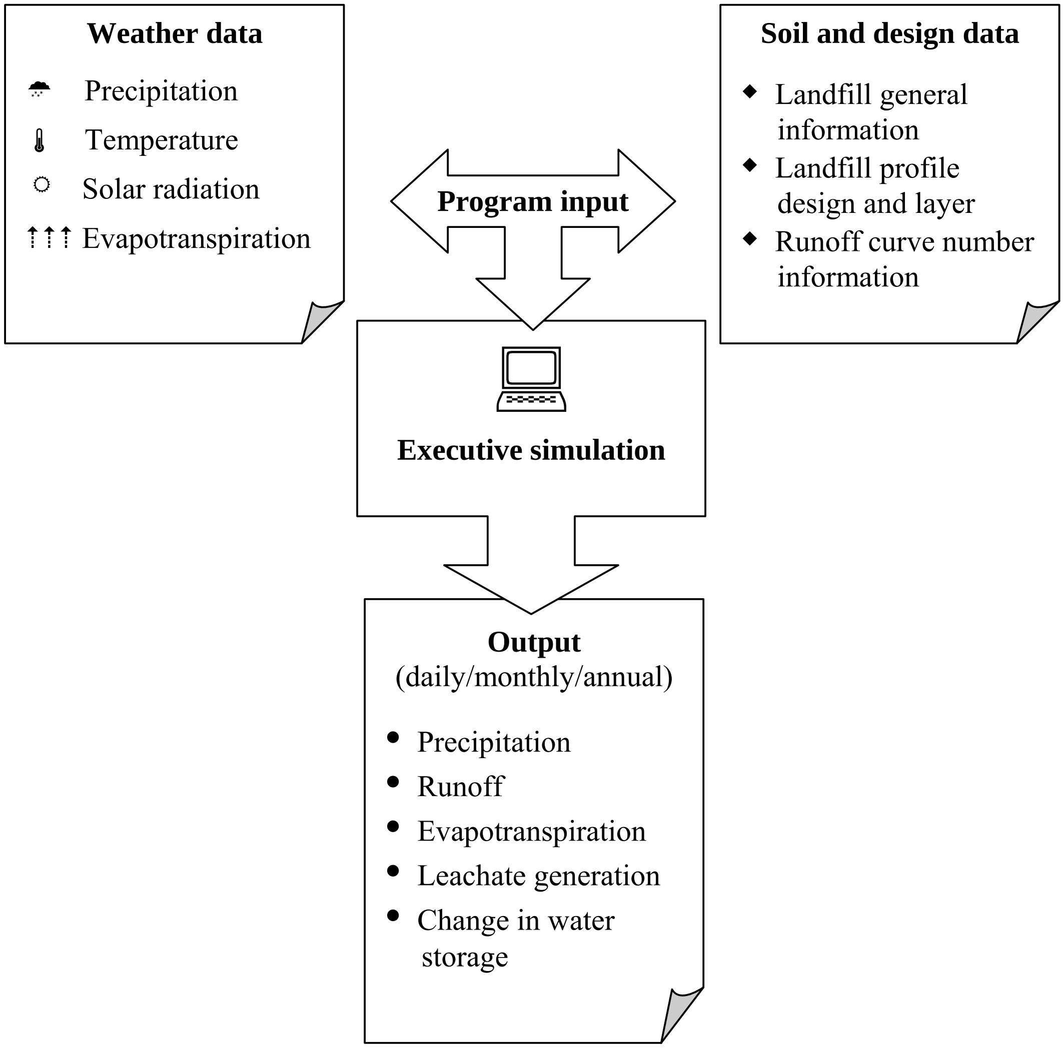


Figure 3.8 Model flowchart

3.3.4 Comparison of Water Balance from Experiment and HELP Model

A comparison on the model output for water balance components was done with the results of lysimeter experimented. The application of model for water management of open cell landfill lysimeters was considered in this study.

Chapter 4

Results and Discussion

4.1 Physical and Chemical Properties of MSW in Landfill Lysimeters

Generally, low and middle income Asian countries have a high percentage of food waste or compostable organic matter in the waste stream. The ranges of food waste in low and middle income countries are around 40-85% and 20-65 % of the total, respectively. In Thailand, MSW consists of food waste 38-67% of total waste. Paper and plastic ranged between 3-24% and 5-21%, respectively. The remaining portions of wastes were rubber, cloth, yard waste, glass, metals etc. (Visvanathan et al., 2004). In this study, all four landfill lysimeters had same source of MSW taken from Taklong Municipality, Pathumthani. The details of the compositions and other properties of MSW were presented in Appendix B (Table B-1). Figure 4.1 indicates that the major portion of MSW is food waste and the minor portions of solid waste are plastic and paper.

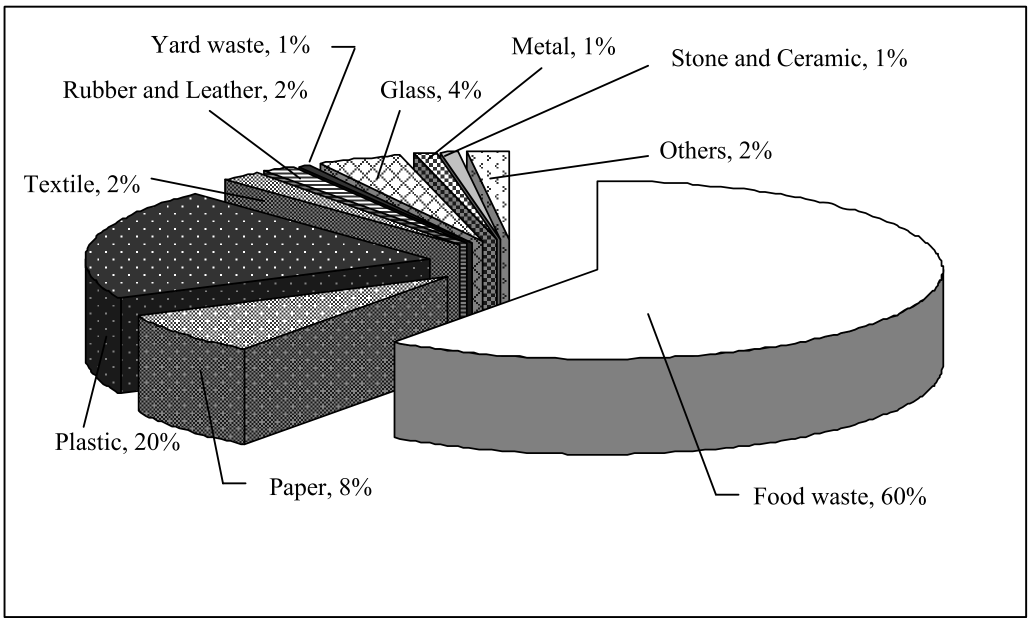


Figure 4.1 MSW compositions from Taklong Municipality

The above mentioned MSW has high moisture content. The results of analysis of solid waste samples showed that the average initial moisture content of MSW was 52% and the average bulk density was 280 kg/m^3. In addition, during lysimeters preparation, high intensive rainfall events were happened before complete filling. Thus, solid waste in each lysimeters also absorbed infiltrated water leading to high moisture content. Average total solid, volatile solid, ash content and total organic carbon of MSW were 48%, 89%, 11% and 85%, respectively. It is noted that the results of properties of MSW were determined based on the representative solid waste samples taken from entire MSW before placing it into each lysiemters or pre-sorted waste in case of Open Cell No.3. Therefore, the properties of MSW in Open Cell No.3 were different to be compared with other lysimeters because it mainly contained highly biodegradable organic fraction (compostable waste).

4.2 Influence of Operational Modes on Leachate Generation and Leachate Characteristics

Four landfill lysimeters were operated in different modes as discussed in Chapter 3 (section 3.2). The different operations affected the quantity and quality of leachate which are discussed in following section. The results of leachate generation and its characteristics are presented in Appendix B (Table B-2 to B-5).

4.2.1 Leachate Generation

Leachate generation is not constant and it depends on the initial moisture content, decomposition of solid waste, and the influence of climate (Tränkler et al., 2005). Figure 4.2 presents the relationship between rainfall and cumulative leachate generation from landfill lysimeters since July 2005 to February 2006.

This period covered both rainy and dry season. Furthermore, from December 2005, leachate recirculation mode was introduced on Open Cell No.2 and 3. This was due to the fact reduced moisture content in the lysimeters, due to reduced rainfall. The details will be further discussed in section 4.4.2.

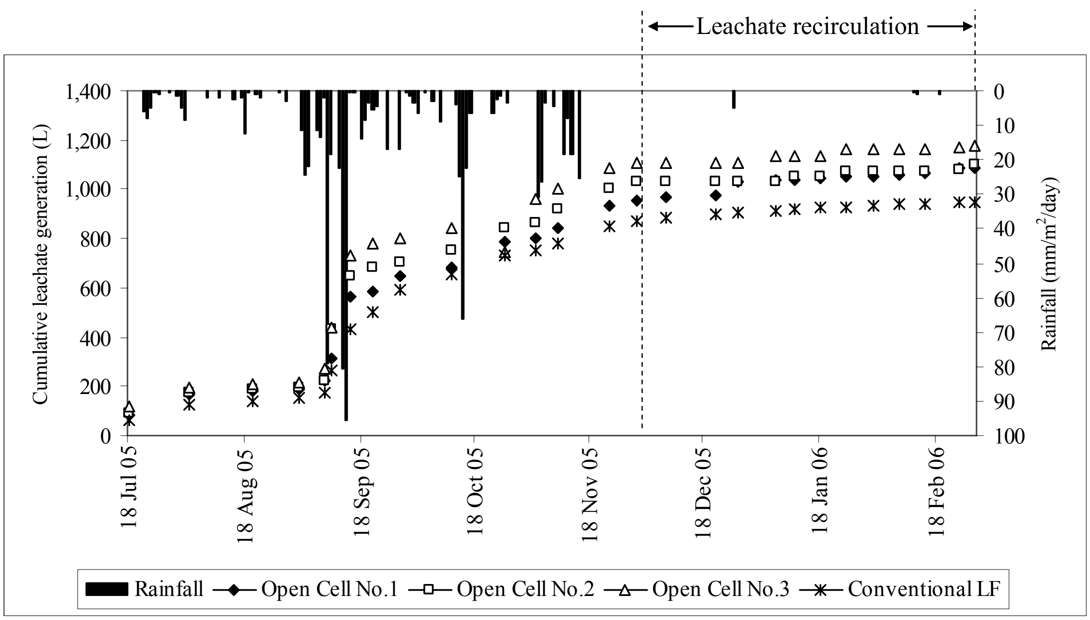


Figure 4.2 Relationship between rainfall and cumulative leachate generation from landfill lysimeters

First period of the operation was rainy season which started from July to mid-November 2005. High amount of leachate was generated which mainly based on initial moisture content of MSW, decomposition of waste and precipitation in this period. The leachate from all lysimeters was significantly increased on September 2005 which had high intensive rainfall with long duration. In addition, leachate recirculation was not necessary done for Open Cell No.2 and 3 in this period due to rainfall and available moisture above field capacity. Leachate was collected and stored in the leachate storage and evaporation tank.

Results of monitoring leachate production from landfill lysimeters in this first period were recorded that Open Cell No.3 produced high cumulative leachate generation. Because this lysimeter mainly contained highly biodegradable organic waste, low compaction density (580 kg/m^3) and no top cover layer. The rainfall was rapidly infiltrated into landfill. Furthermore, it was also expected that solid waste in this lysimeter would have initial moisture content higher than other lysimeters as discussed in section 4.1. While Conventional Landfill lysimeter contained general MSW, high compaction density (740 kg/m^3, as a result of overburden weight of top cover) and had top cover layer. It produced less amount of cumulative leachate than other lysimeters.

The second period was dry period which was very less or no rainfall. Thus, in this period, the leachate was produced in small amount. The cumulative leachate generation from Open Cell No.1 and Conventional Landfill was slowly increased. For Open Cell No.2 and 3, the stored leachate from the first period (rainy season) was used to recirculate into the lysimeters. Thus, leachate generation did not include the recirculated leachate. The purpose of lechate recirculation was to provide the moisture content for accelerating the biodegradation in landfill. In addition, the recirculation and evaporation of collected leachate was leading to the reduction in total amount of leachate remaining for treatment. The details will be further discussed in water management for open cell landfill (section 4.4.5).

4.2.2 Leachate Characteristics

Table 4.1 presents the concentration range of leachate characteristics from four landfill lysimeters. Leachate characteristics can be divided in four groups for discussing the results. This consists of pH and physical properties of landfill leachate, organic contents of landfill leachate, inorganic contents and Carbon and Nitrogen load of landfill leachate. The changes of leachate concentration can be used as biodegradation indicators (Yuen, 2001).

Table 4.1 Leachate characteristics of four landfill lysimeters

Parameter	Open Cell No.1	Open Cell No.2	Open Cell No.3	Conventional Landfill
pH	5.75-8.36	5.95-8.61	5.74-8.09	5.92-8.54
Conductivity	9.13-24	11.11-24.70	11.25-25	4.12-22.90
Alkalinity	3,000-15,000	4,600-14,000	5,135-13,665	4,665-11,000
COD	940-32,790	825-39,920	850-44,910	915-21,090
BOD	75-8,880	60-11,100	110-12,500	55-11,060
BOD/COD	0.1-0.6	0.1-0.9	0.1-0.8	0.1-0.8
VFA	0-25,225	0-10,790	0-21,325	0-14,070
TKN	705-1,980	530-2,035	670-1,835	140-1,525
NH_4-N	680-1,885	450-1,905	605-1,735	105-1,415

Table 4.1 Leachate characteristics of four landfill lysimeters (continue)

Parameters	Open Cell No.1	Open Cell No.2	Open Cell No.3	Conventional Landfill
Organic-N	25-285	45-165	30-225	35-275
TS	5,480-15,140	4,660-13,790	5,610-15,190	3,340-18,070
VS	1,210-10,755	980-8,435	1,020-11,510	1,065-10,290
TSS	145-2,285	110-1,490	205-1,720	135-1,705
TDS	3,670-14,445	3,870-13,170	4,950-14,090	2,540-16,925

Note: All values are in mg/L, except Conductivity in mS/cm.

1) pH and Physical Properties of Landfill Leachate

- pH

Initial pH of all lysimeters was in range 5.7-6 and then gradually increased. Figure 4.3 illustrates the variation of pH with time of landfill lysimeters. However, the pH values were fluctuating, for example, pH values of all Open Cell landfill lysimeters dropped nearly to 6 during 9 to 14 September 2005 which had heavy rainfall events (80-96 $mm/m^2/day$). In addition, it was observed that the continuous rainfall events during 2-22 September 2005 also lead to the pH values gradually decreased at that time. The decreasing of pH as a result of the excess moisture enhanced the biological activities and then complex organic was converted to easily water soluble organic acids (Tubtimthai, 2003). Normally, pH has correlate with VFA. The results also presented that pH of each lysimeters was increased with time because of the decreasing of VFA concentration. Referring to Figure 4.10 showed the decreasing trend of VFA from landfill lysimeters with time.

According to five sequential phase of stabilization of MSW, the pH of leachate from all landfill lysiemters indicated that the decomposition phase was moved from acidogenic to methanogenic phase within five months of operation and remained in range 7.5-8.5.

- Conductivity

Conductivity is a means to measure the ionic concentration within a solution. Solution of most inorganic compound is in the ionized form lead to conductivity. From Table 4.1, the conductivity of all lysiemters was in range 4-25 mS/cm. Figure 4.4 also presents the fluctuation of conductivity. During rainy season the conductivity values were fluctuated as a result of dilution (Tubtimthai, 2003). Similarly, during leachate recirculation period of Open Cell No.2 and 3 were presented that the conductivity values were decreased more than another two lysimeters. However, the difference was not much.

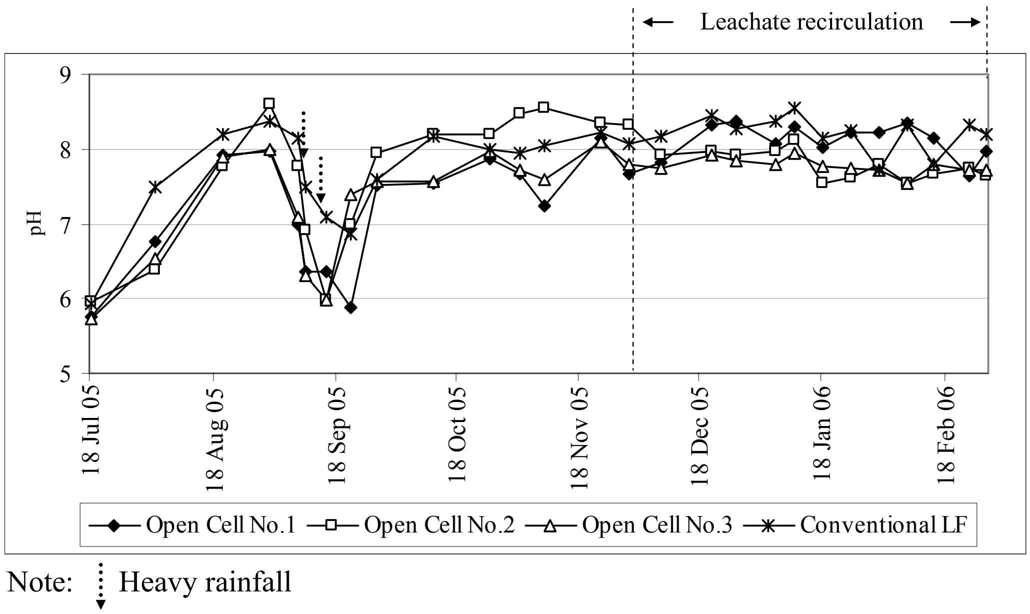


Figure 4.3 pH of lechate from landfill lysimeters

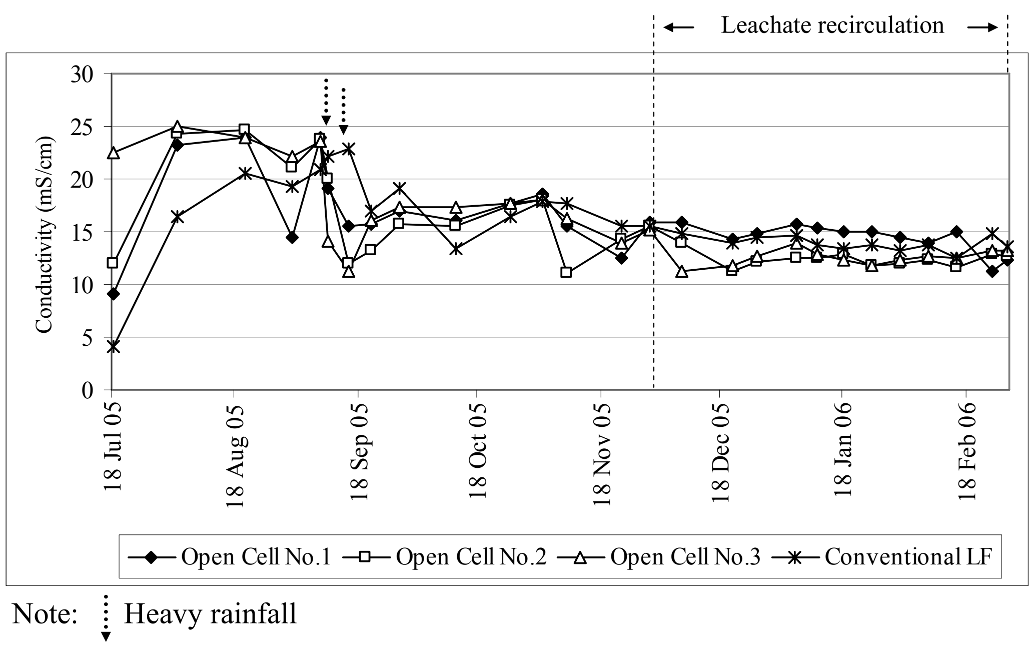


Figure 4.4 Conductivity of leachate from landfill lysimeters

- Alkalinity

Similarly, alkalinity of lysimeters had the variation pattern as pH and Conductivity. Figure 4.5 shows the change of alkalinity of all lysimeters. In methanogenic phase, the pH values is elevated, being controlled by the bicarbonate buffering capacity system, and consequently supports the growth of methanogenic bacteria (Reinhart et al., 1996). Alkalinity showed the high value at the beginning and then maintained around 4,000-6,000 mg/L at the end of study period.

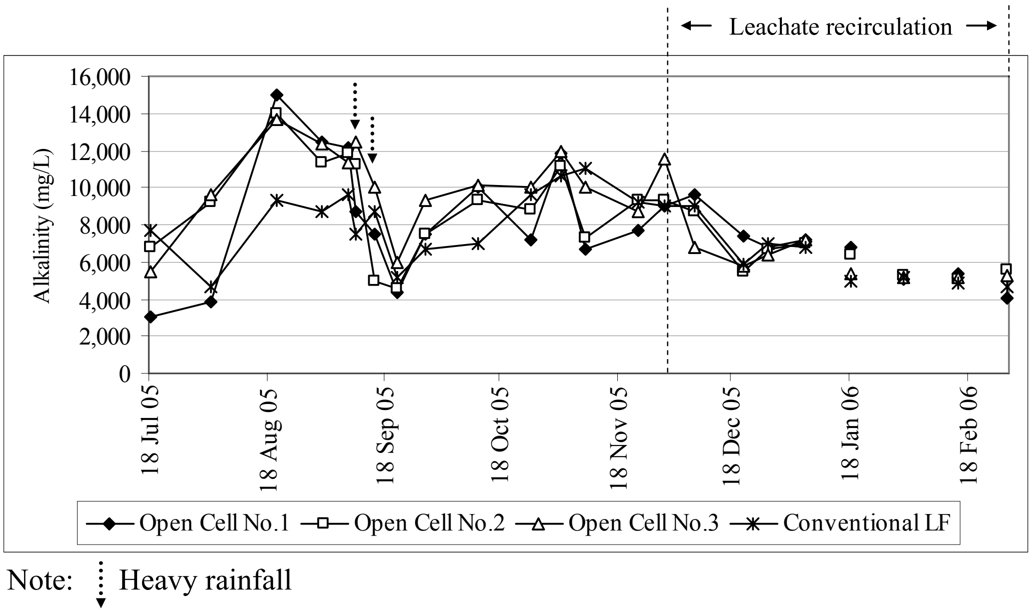


Figure 4.5 Alkalinity of leachate from landfill lysimeters

- TS, VS, TSS and TDS

Total Solid means the summation of dissolved (filterable) and non-dissolved (non-filterable) solids. Refer to Table 4.1 TDS was the main fraction of TS. TDS also fluctuated widely had followed similar trend as conductivity. The high values of leachate conductivity reflect the large content of soluble inorganic (Tatsi and Zouboulis, 2002).

2) Organic Contents of Landfill Leachate

The organic contents of leachate are dependent upon the kind of decomposition condition (aerobic, anaerobic acetic production or anaerobic methane production) (Ehrig, 1983). For Open Cell landfill lysimeters had main two conditions. At the top of lysimeters was partial-aerobic condition as a result of no top cover while at the bottom of lysimeters was anaerobic condition. The condition of Conventional Landfill was anaerobic.

- COD and BOD

At the beginning of operation, the COD and BOD concentration of all lysimeters were high concentration and then gradually decreased with time. Figure 4.6 to 4.7 presents the fluctuation of COD and BOD concentration from landfill lysimeters.

During rainy season, Open Cell landfill lysimeters produced high concentration of COD and BOD more than Conventional Landfill lysimeters as a result of high percolation of rainfall. The rapid increasing concentration of organic pollutant was presented in short time during heavy rainfall due to leaching out of pollutant. After that, the concentration was significantly decreased due to the acceleration of biodegradation by moisture infiltrated. The concentration of organic contents in leachate was fluctuated and the trend of strength was declined with time.

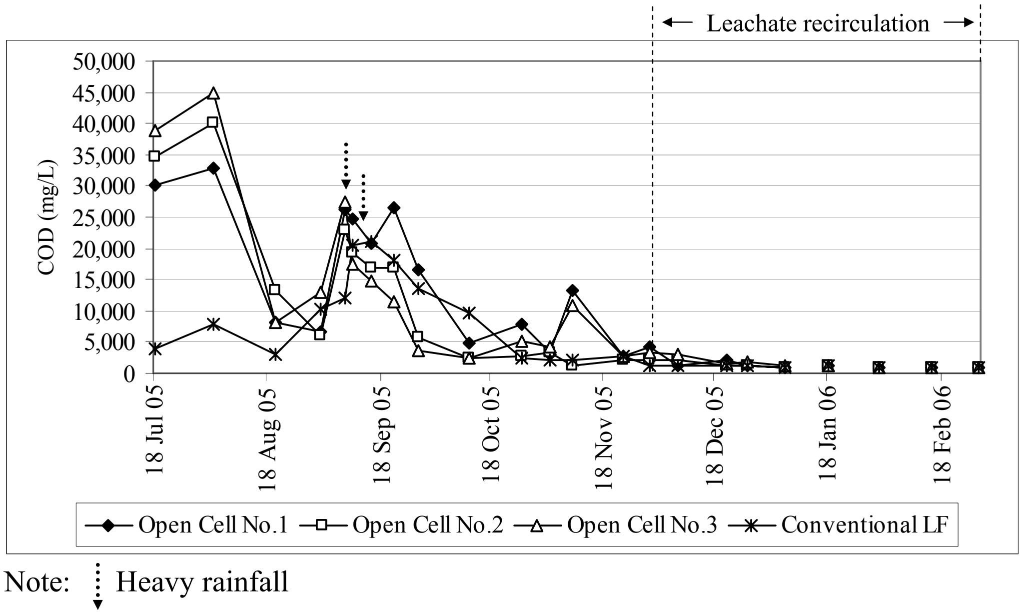


Figure 4.6 COD of leachate from landfill lysimeters

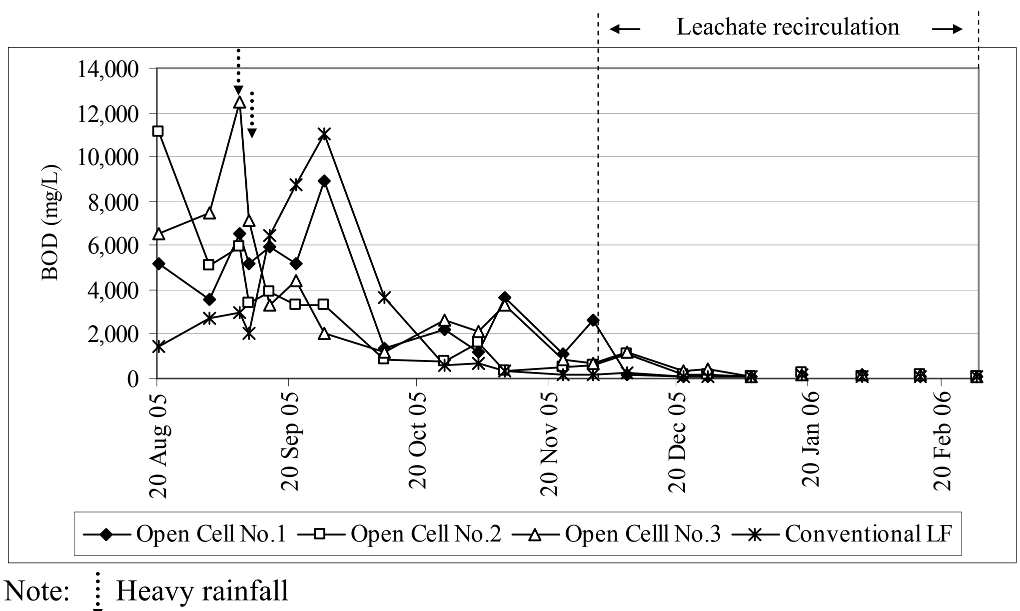


Figure 4.7 BOD of leachate from landfill lysimeters

The influence of leachate recirculation was considered. Figure 4.8 and 4.9 show the fluctuation of COD and BOD during recirculation period. It was observed that the strength of leachate from Open Cell No.2 and 3 was higher than other two lysimeters at the beginning of recirculation as a result of leaching out of pollutant. After that, COD and BOD of leachate were gradually decreased and slightly lower than other lysimeters. Therefore, leachate recirculation can be improved the quality of leachate. However, at the end of study period, the concentration of COD and BOD of all lysimeters were very low and it did not significantly differ between each lysimeter. Due to the lysimeters were operated under rainy season around five months (July - November 2005) before recirculation mode was introduced. Thus, the decomposition of solid waste was already accelerated by available moisture content.

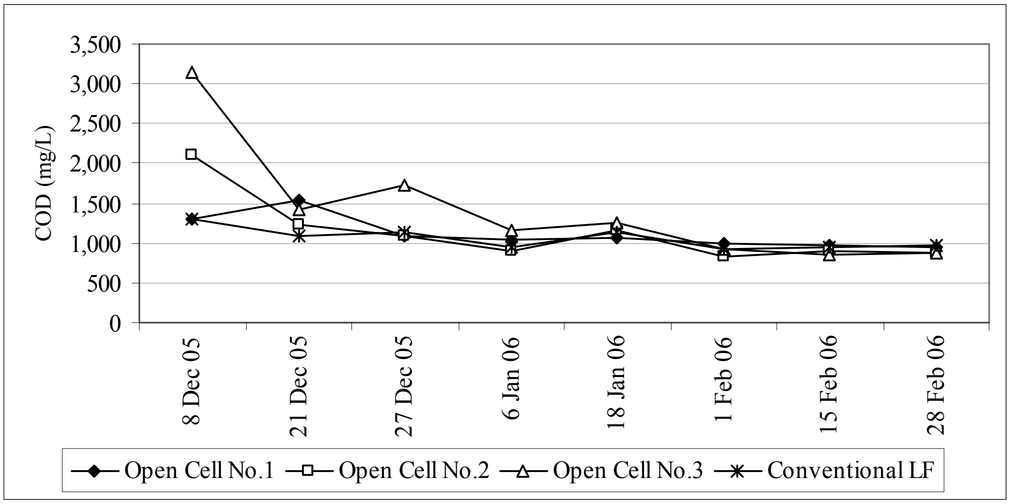


Figure 4.8 COD of leachate from landfill lysimeters (during recirculation period)

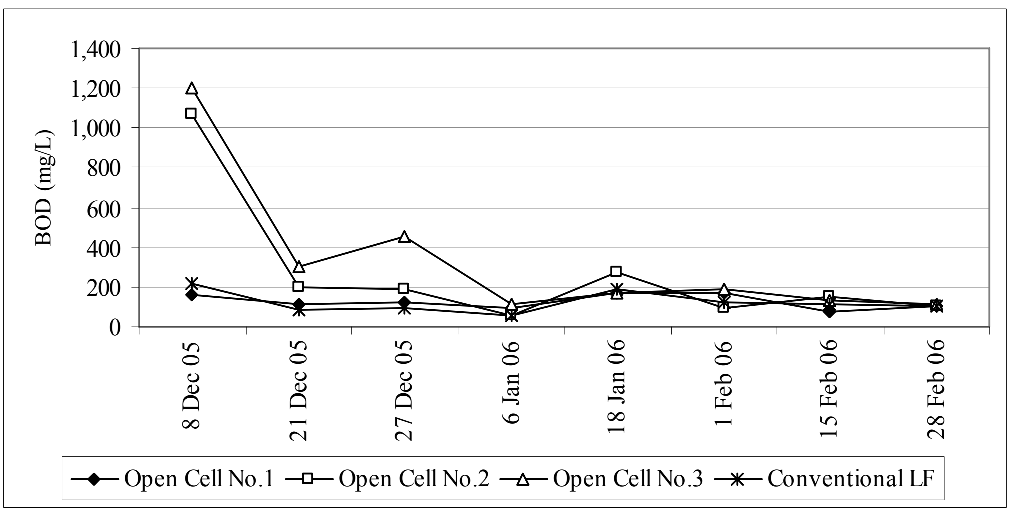


Figure 4.9 BOD of leachate from landfill lysimeters (during recirculation period)

As the BOD/COD ratio were used to indicate the changes in the amount of biodegradable composition in the leachate and the BOD/COD ratio would decrease as the biodegradation of organic waste occurs. A ratio of 0.4-0.8 implies a highly biodegradation (Ehirg, 1983; Tatsi and Zouboulis, 2002). The initial BOD/COD ratio of leachate from landfill lysimeters was in the range of 0.5-0.9, showing a good biodegradability of the organic contents and then decreased with time to 0.1 at the end of study period.

- VFA

VFA mainly found in leachate during the acidogenesis phase of decomposition in landfills (Nakwan, 2002). Figure 4.10 shows VFA concentration from each lysimeter. At the beginning of operation, VFA values were very high because of the decomposition of organic contents. These complex organics are converted to water-soluble fatty acids such as acetic acid, propionic acid, butyric acid etc. The high amount of fatty acids causes the lower pH. The VFA values were gradually decreased with time. It was observed the low concentration and less variation between each lysimeters. The low concentration of VFA (all acids in acedogenesis was consumed by methanogenic bacteria) was implied that the landfill lysimeters were in the methanogenic phase. Note that the VFA concentration in this phase was not significantly observed.

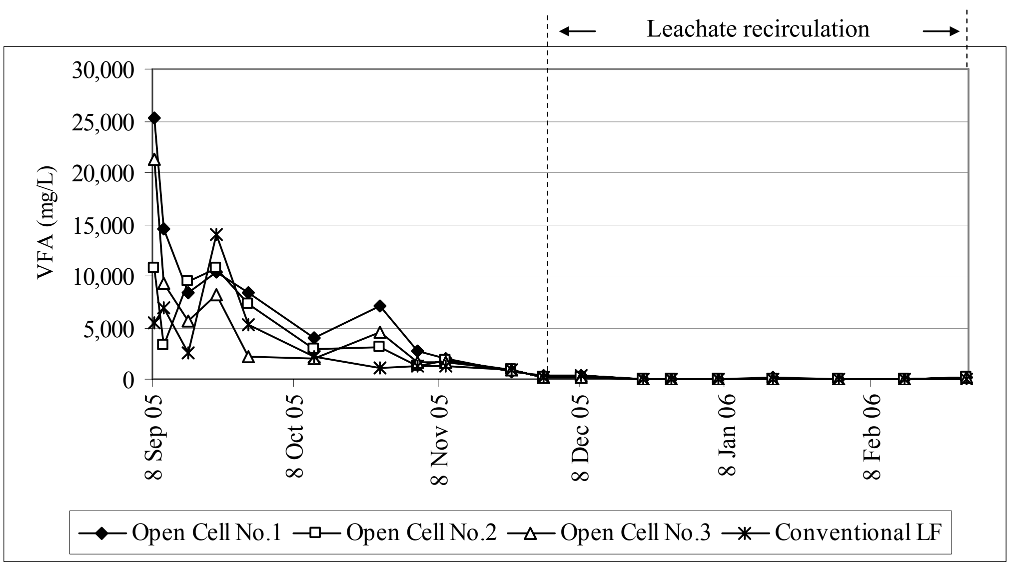


Figure 4.10 VFA of leachate from landfill lysimeters

3) Inorganic Contents of Landfill Leachate

- TKN, NH_4-N and Organic-N

The great majority of Total Kjeldahl Nitrogen (TKN) content is found to be in ammoniacal form (Tatsi and Zouboulis, 2002). Refer to Table 4.1, the leachate contained high concentration of NH_4-N which was about 75-98% of TKN. Figure 4.11 illustrates the variation of TKN from all lysimeters. The concentration values of TKN were fluctuating and showed a decreased trend with time as like COD. However, at comparable time, it was observed that the fluctuation of TKN concentration was less than the COD concentration. The Open Cell landfill lysimeters produced low concentration of TKN during heavy rainfall events as a result of dilution of pollutant. The TKN values of Conventional Landfill were not fluctuated much as Open Cell landfill lysimeters. During recirculation period, Open Cell No.2 and 3 also produced lower concentration of TKN than other lysimeters. After eight months of operation, the TKN concentration of Open Cell No.1,2, 3 and Conventional Landfill were 705, 665, 700 and 660 mg/L, respectively.

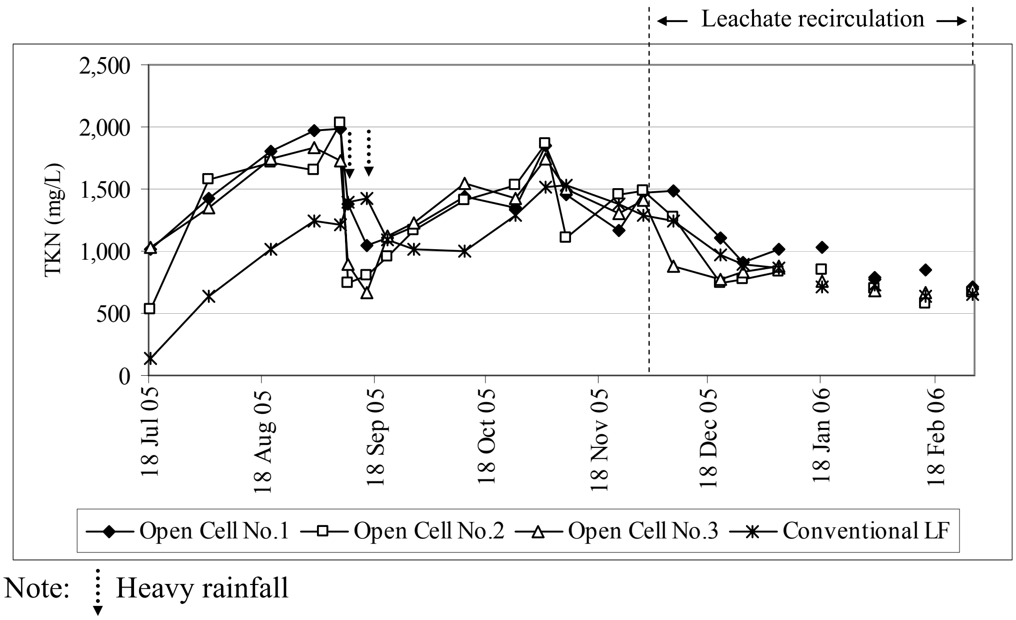


Figure 4.11 TKN of leachate from landfill lysimeters

- Heavy metals

The contamination of heavy metals in leachate was investigated at the end of study period. Therefore, the concentration of heavy metals from landfill lysimeters was observed very low because neutral pH was supporting the immobilization of metals. Comparison the concentration of heavy metals with the surface water quality standard (type III) in Thailand was found that it was not higher than the standard values. The results were indicated that Mn and Zn less than 1 mg/L, Cu and Ni less than 0.1 mg/L, Cr and Pb less than 0.05 mg/L and Cd less than 0.005 mg/L.

4) Carbon and Nitrogen Load

The specific cumulative load of the COD and TKN is calculated from the leachate generation and its composition is based from the starting weight (wet basis) of waste in the individual lysimeter (Tränkler et al., 2005). The specific cumulative COD and TKN load from landfill lysimeters were presented in Figure 4.12 and 4.13, respectively.

The results showed that the specific COD and TKN load discharged from all Open Cell lysimeters were higher than Conventional Landfill. At the end of study period, the specific cumulative COD load presented the constant trend as results of low concentration of COD and low leachate generation. After eight months of operation, the specific cumulative COD load values of Open Cell No.1, 2, 3 and Conventional Landfill were 9,805, 9,445, 10,510 and 5,975 mg/kg solid waste, respectively.

The specific cumulative load pattern of TKN differed slightly from that of COD. The loading of TKN from all lysimeters gradually increased during rainy period. The Open Cell No.1 presented the highest specific cumulative TKN load. Whereas, the Conventional Landfill produced the low specific cumulative TKN load. Tränkler et al. (2005) also indicated with the results of open cell simulation that the low compaction density with high organic content and without a cover may have permitted the system to obtain a partial aerobic condition. This could have improved the stability of the inorganic compounds followed by an instant leaching of solid waste by direct rainfall. As mentioned above, the top of lysimeters was partial-aerobic condition as a result of no top cover while at the bottom of lysimeters was anaerobic condition. The specific cumulative TKN load values of Open Cell No.1, 2, 3 and Conventional Landfill were 740, 670, 700 and 615 mg/kg solid waste, respectively.

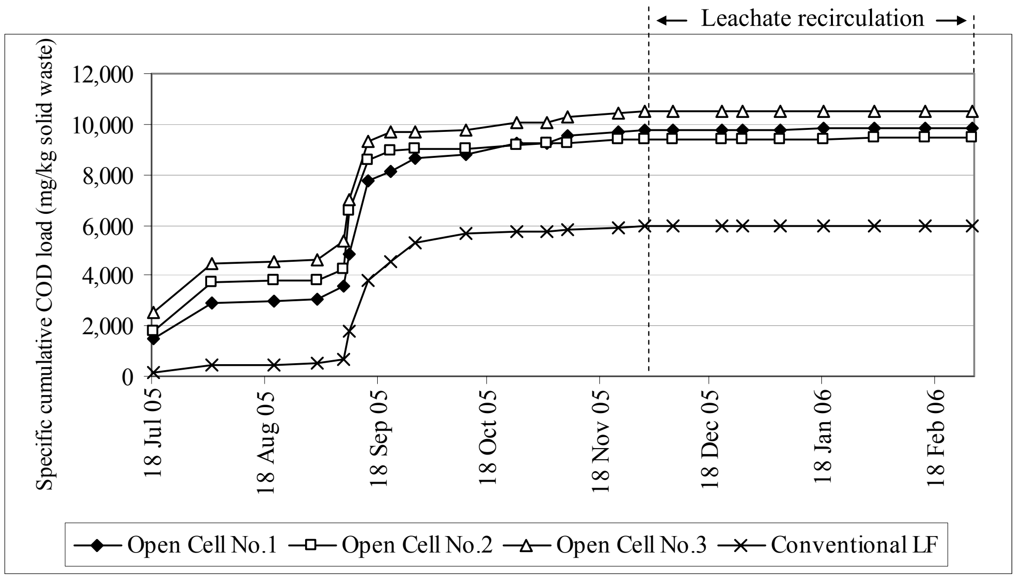


Figure 4.12 Specific cumulative COD load from landfill lysimeters

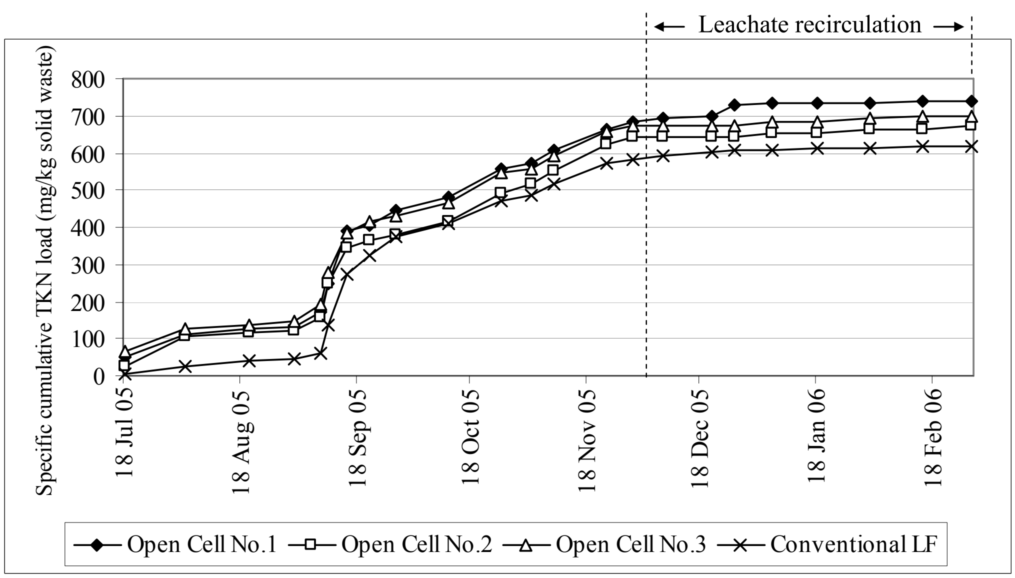


Figure 4.13 Specific cumulative of TKN load from four landfill lysimeters

4.3 Settlement of Landfill Lysimeters

Settlement extends the life of the landfill because the final site development is limited by elevation and not by volume or quantity. Thus, the settlement allows additional waste to be placed on completed areas (Reinhart and Townsend, 1998). The results of monitoring of settlement variation from the different operation of landfill lysimeters is presented in Figure 4.14.

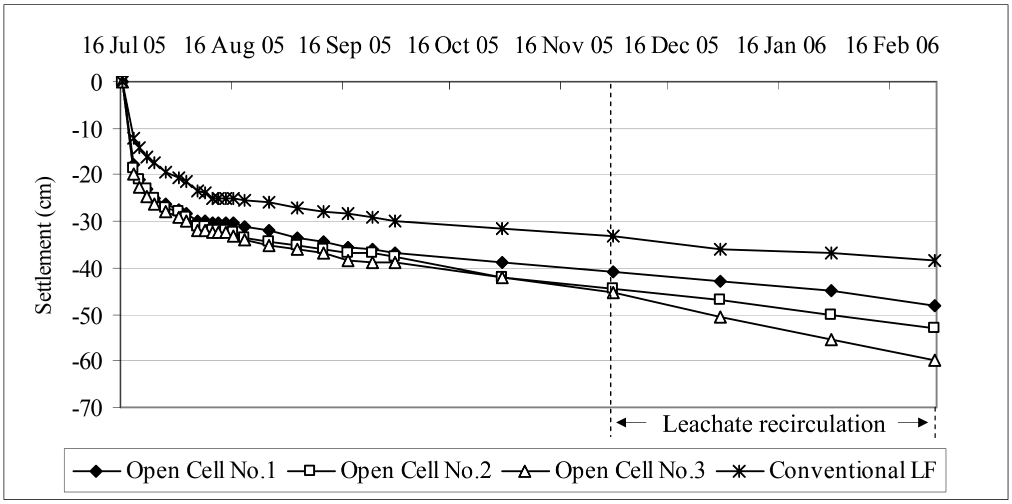


Figure 4.14 Settlement within landfill lysimeters since completion fill

In the first month of landfill lysimeters operation, settlement of MSW was high because of primary compression due to self-weight and the decomposition of waste. The settlement of Open Cell No.1, 2, 3 and Conventional Landfill were 13, 14, 16 and 10% of initial height, respectively. The settlement variation depends on many factors such as the degree of initial compaction, solid waste compositions and the biological processes that cause the landfill settlement follow a non-uniform pattern (Tabtimthai, 2003). Primary settlement will occur rapidly, usually within the first month of landfill, followed by a substantial amount of secondary compression over and extended period of time (Ashford et al., 2000). All Open Cell lysimeters with low compaction (500-580 kg/m^3) had high settlement, while Conventional Landfill with high compaction (740 kg/m^3) had the lowest settlement.

After starting recirculation into Open Cell No.2 and 3, the settlement rates increased higher other two lysimeters. The settlement was enhanced by liquid flow and accelerated biodegradation by leachate recicrculation. The variation of settlement was attributed to the biodegradation of solid waste.

After eight months of operation, the settlement of each lysimeters resulted in 21, 23, 29 and 16 % of initial height of Open Cell No.1, 2, 3 and Convetional Landfill, respectively. Settlement of Open Cell No.3 which had highly biodegradable organic fraction waste and leachate recirculation showed the highest settlement rate.

4.4 Water Management for Open Cell Landfill Lysimeters

The need to understand water management at landfill sites is an important issue especially in tropical countries. The previous study (Tabtimthai, 2003) demonstrated that tropical seasonal variations influenced on landfill leachate generation and its characteristics. The open cell landfill simulation showed that the highest cumulative leachate generation during monsoon and leachate ceased out during the dry period due to heavy loss of moisture by evaporation. Water management can be conducted by leachate storage during rainy season and recirculation during the dry season enhanced the waste stabilization (Tränkler et al., 2005). Figure 4.15 illustrates the concept of water management for open cell landfill in tropical climate. The water management of open cell landfill was investigated in this study by experiments and model application.

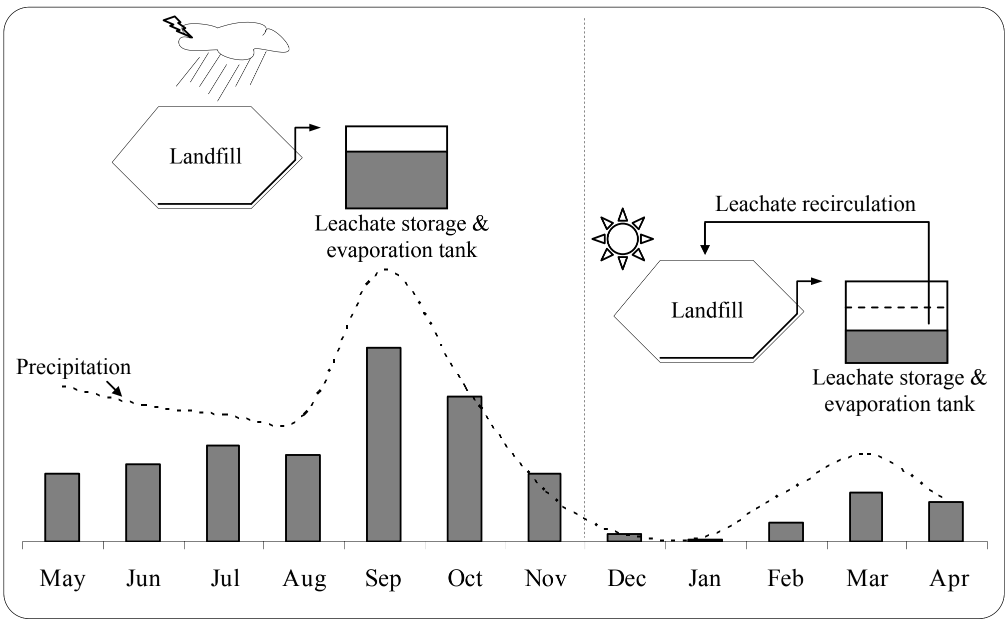


Figure 4.15 Concept of water management for open cell landfill in tropical climate

4.4.1 *In situ* Moisture Content of MSW in Landfill Lysimeters

Estimation of *in situ* moisture content of MSW in landfill lysimeters was necessary for leachate recirculation. The electrical resistance sensor was experimented to provide the relationship between moisture content and electrical resistance. The experiments were carried out by recording the amount of water added and resistance varied until the media of sensor was saturated. Note that because this sensor was be used in landfill that contain highly conductive leachate (9-25 mS/cm), comparison with the conductivity of distilled water and tap water which has around 0.03 and 0.26 mS/cm, respectively. Therefore, leachate was used as moisture added for providing the relationship.

The laboratory experiments were presented that the electrical resistance had good co-relation with moisture content. The trend of electrical resistance values was decreased when increased moisture or water moved to the media of sensor. Figure 4.16 provides the curve and equation of this relationship. The percentage of saturated water of sensor was in range 35-40%. Thus, the sensor was expected to estimate the moisture content up to this percentage saturated. However, laboratory experiment was noted that the water was directly absorbed to the media of sensor, it did not has the waste surrounded the sensor.

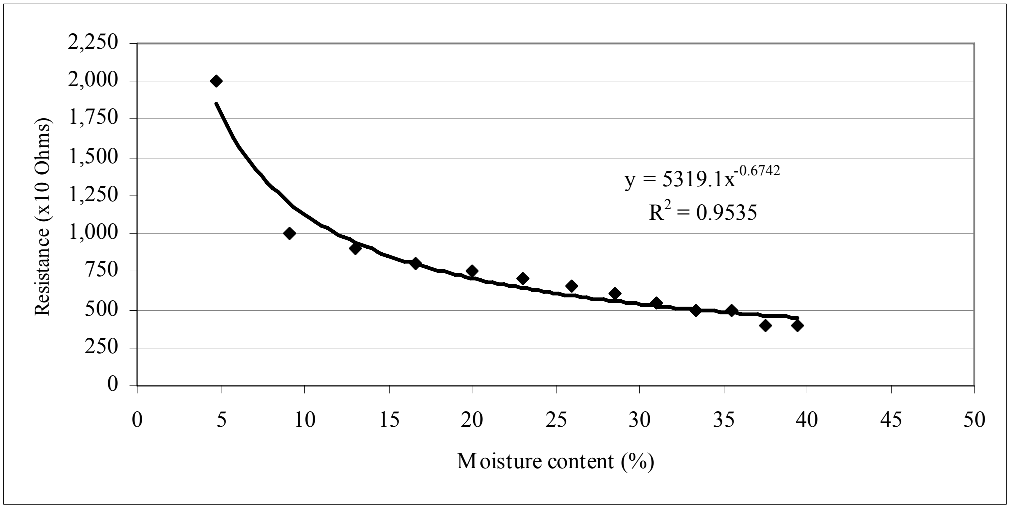


Figure 4.16 Relationship between electrical resistance and moisture content

4.4.2 Leachate Recirculation

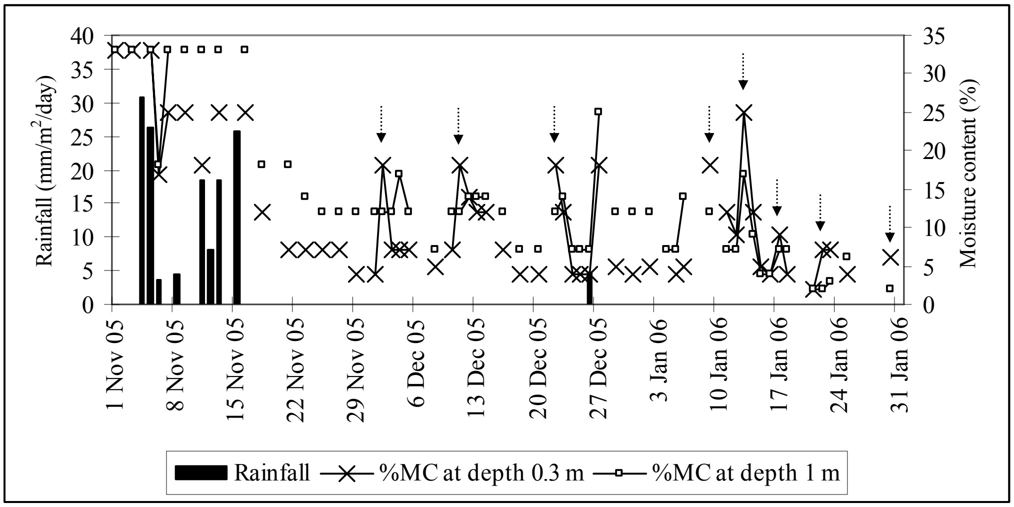
The leachate recirculation was provided by considering the *in situ* moisture content and experiments at site.

Field experiments on estimating in situ moisture content of MSW in landfill lysimeters

In field experiments, the moisture content sensors were installed in Open Cell No.2 and 3 as mentioned in Chapter 3 (section 3.3.1). The electrical resistance was measured by using resistance meter and then converted to moisture content with experimental equation. The moisture content estimated at the top level (at depth 0.3 m) of landfill lysimeters was determined for providing appropriate amount and frequency of leachate recirculation. Maintaining the moisture content at top level around 20-30 %MC was assumed. Figure 4.17 and 4.18 show the results of maintaining moisture content of MSW in Open Cell No. 2 and 3 lysimeters, respectively.

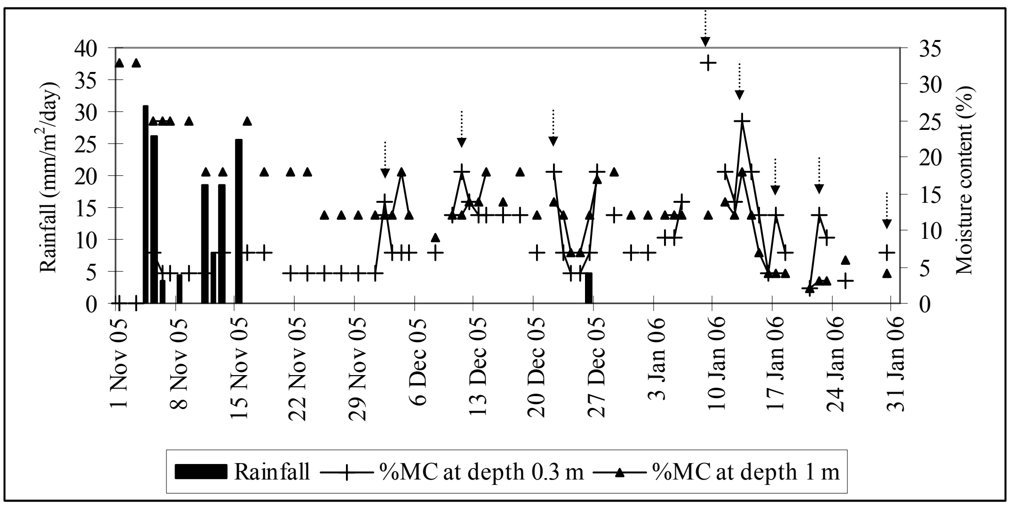
After installing the sensors, there were observed that percentage of moisture content (%MC) of MSW at depth 1 m from both lysimeters were around 33%. It was accorded the rainfall which provided the moisture at that time. From December 2005, the lack of rainfall was started and accorded the results of moisture content sensors; the moisture content of MSW was decreased. Therefore, leachate recirculation was provided to maintain the %MC.

It was observed that the %MC at top level was increased after recirculation, when it was increased up to the decided moisture, the recirculation was stopped. Thus, the sensors can be used to estimate the amount of leachate to recirculate and maintain the moisture content of MSW within landfill lysiemters.



Note: Leachate recirculation

Figure 4.17 Maintaining moisture content of MSW for Open Cell No.2



Note: Leachate recirculation

Figure 4.18 Maintaining moisture content of MSW for Open Cell No.3

The overview results showed that the sensors which were installed at middle level (at depth 1 m) had highly moisture content more than top level. The difference of %MC of MSW between top level and middle level were in range 0-20% and the average difference of %MC between two levels around 5%.

However, the results also presented that the moisture content was rapidly decreased next two or three days after recirculation. Therefore, the trial and error experiments on leachate recirculation were carried on by considering the amount and frequency of recirculation. In addition, it was observed that leachate recirculation should be recirculated at low flow rate and intermittent application. The slow distribution of leachate with long duration into landfills lead to slowly infiltrate included prevents the flooding in landfill. The heterogeneous nature of landfills often leads to preferential moisture flow paths that can result in uneven moisture distribution (Gawande et al, 2003).

However, after using the sensors for three months, the accuracy of sensors was decreased. The results were not as reliable as it was at start of the sensor installation. This indicated the rapid degradation of the sensor performance with time within the lysimeter. For example, the moisture content was increased very low even recirculation with high amount of leacahte or more frequency recirculation. Thus, the moisture content sensors should be improved. The sensor calibration experiments should be conducted.

From February 2006, the sensors were not further used to estimate moisture content. Recirculation was continued based on the average values of previous recirculation rate and considering ambient condition. The actual total volumes of leachate recirculated to lysimeters and leaving landfills were measured.

The results of experiments for two months (December 2005 and January 2006) on both Open Cell landfill lysimeters were used to estimate the recirculation rate. The condition within Open Cell No.2 and 3 landfill lysimeter was difference. However, the overall results showed that the average recirculation rate was not much difference. The average leachate recirculation rates for Open Cell No.2 and 3 were 8.82 and 9.44 L/day, respectively. It was noted that leachate was not recircalated everyday depending on the results of moisture sensors. The frequency of recirculation was once a week. The average drained leachate from Open Cell No.2 and 3 were 7.53 and 8.35 L/day, respectively. The average leachate recirculation rates from both lysimeters were used for estimating the recirculation rate. In addition, the flow rate of distribution leachate into both lysimeters also was adjusted to be the low flow rate.

On February 2006, the average temperature was 28.8ºC which was little bit higher than December 2005 and January 2006. This month also had slight rainfall. Leachate recirculation rate and frequency were estimated based upon information. However, in practices, lechate recirculation rates were adjusted in many times according to the amount of drained leachate. It was observed that the amount of drained leachate varied depending on the field capacity of landfill lysimeter. The average recirculation rate for Open Cell No.2 and 3 was 7.50 and 5.79 L/day, respectively. The frequency of recirculation was two times per week. The average drained leachate from Open Cell No.2 and 3 were 9.10 and 6.54 L/day, respectively. The results of experiments on leachate recirculation were presented in Appendix B (Table B-6 and B-7). In addition, it was observed that the quantity of drained leachate during recirculation period was equal or more the amount of leachate recirculation. These indicated the landfill lysiemeters were reached the field capacity as a result of continuous recirculation. According to Yuen et al. (2001) indicated that if a cell has reached its field capacity when water is added, an equal quantity leachate will drain out of the cell to restore moisture equilibrium. The amount of leachate leaving was higher than leachate entering because the heterogeneous nature of waste within lysimeters leads to preferential moisture flow paths. Furthermore, in long term operation, the compostable waste was almost degraded and then remained the low biodegradable fractions such as plastic bags, foam, can etc. which had less absorption capacity.

Leachate treatment option

From January 2006, monitoring the characteristics of leachate recirculated in terms of pH, conductivity and TSS were determined. The results showed pH in range 8.78-9.16, conductivity in range 6.19-9.18 mS/cm and TSS in range 165-370 mg/L. TSS values were very low because the partial suspended solid was settled in storage tanks (as primary sedimentation tanks). Therefore, the clogging of recirculation system was not significant to pre-treatment of leachate. However, it was observed that the trend of conductivity and TSS were increased with time (Appendix B, Table B-8). Therefore, in long term operation, the quality of leachate was not suitable for recirculation and it should be further treated.

4.4.3 The HELP Model and Its Application for Open Cell Landfill Lysimeters

This part focused on the analyses of data collected and the use of HELP model to predict the water balance components of Open Cell landfill lysimeters.

Analyses of data

- Weather data

The weather data required in the HELP model was precipitation, temperature, solar radiation and evapotranspiration. The real daily precipitation, mean temperature and solar radiation data collected from the Meteorological office of AIT were input into the model for simulation. The weather data was presented in Appendix A. The evapotranspiration was computed by HELP model.

The evapotranspiration is the combined processes by which water is transferred from the earth's surface to the atmosphere; evaporation of liquid water from the soil surface and water intercepted by plants plus transpiration by plants (Shrestha, 2001). The evapotranspiration data based upon the location, maximum leaf area index, starting and ending of growing season, evaporative zone depth, average annual wind speed and quarterly relative humidity. These were mostly taken from the database of the model (Manandhar, 2000). In this study, the database was provided from the Map of Weather Generator of WHI UnSat Suite Plus versions 2.2.0.2 (Waterloo Hydrologeologic, Inc., 2002). Tantichanthakarun (2004) also used this source of data bases to evaluate the water balance of bioreactor landfill lysimeters. Bangkok was selected from the map because of nearest weather station. Table 4.2 shows the details of evapotranspiration parameters which input for model.

Table 4.2 Evapotranspiration parameters

Parameters	Unit	Values
Station latitude	degree	13.7
Maximum leaf area index	-	0
Start of growing season	day	93
End of growing season	day	337
Evaporative zone depth	cm	5
Average annual wind speed	KPH	14.5
Average 1st quarter relative humidity	%	73
Average 2nd quarter relative humidity	%	77
Average 3rd quarter relative humidity	%	83
Average 4th quarter relative humidity	%	81

Source: Waterloo Hydrologeologic, Inc. (2002).

The 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 vegetation is growing. As there was no vegetation in the landfill lysimeters, maximum leaf area index for bare ground is zero (Schroeder et al., 1994).

Another critical parameter in estimating soil water evaporation is evaporative zone depth. The evaporative zone depth is defined as the maximum depth from which water may be removed by evapotranspiration. The program does not permit the evaporative depth to exceed the depth to the top of the topmost barrier soil layer. Similarly, the evaporative zone depth would not be expected to extend very far into a sand drainage layer. This parameter influences the storage of water near the surface and also directly affects the computations for evapotranspiration and runoff. The evaporative zone depth must be grater than zero. The guidance recommends the depth according to the soil type; in sands the depth may be about 4-8 inches (10-20 cm), in silts about 8-18 inches (20-40 cm) and in clays about 12-60 inches (25-150 cm) (Schroeder et al., 1994). In this study, Open Cell landfill lysimeters did not have top cover and the topmost layer was 5 cm thick sand. Therefore, the evaporative zone depth was assumed to be 5 cm.

- Soil and design data

Input parameters for soil and design data were landfill general information, landfill profile design and runoff curve number information. Landfill general information required project title, landfill area, percentage of landfill area where runoff is possible and the method of initialization moisture storage (user specified or program initialized to near steady state). In this study, assuming landfill area was one hectare and no runoff from landfill lysimeter. The initial moisture content of the layers was computed as nearly steady-state values by the program. Schroeder et al. (1994) indicated that the initial moisture content of MSW is a function of the composition of the waste; reported values for fresh waste range from about 0.08-0.20 v/v. The average is around 0.12 v/v for compacted MSW.

Specific soil and design data of Open Cell No. 2 and 3 landfill lysimeters were input into the model. All profiles of both landfill lysimeters except the thickness of MSW within the lysimeters were same. The MSW layer was assumed to be a single lift in landfill lysimeter because the total thickness of MSW was not high.

Layer data, four types of layers (vertical percolation, lateral drainage, barrier soil liner and geomenbrane liner) are permitted to specify in model. For simulation, lysimeters had four layers that were classified following the rules of program. It was assumed that there is no or small amount of percolation from the barrier soil layer and the entire percolated water form top reaches the collection system (Manandhar, 2000). The model contains a default soil database of characteristics for 42 types of material (soil, waste and geosynthetics). The soil characteristics and the runoff curve number were assigned by using the default option of model. Table 4.3 presents the information of layer properties.

Table 4.3 Information of layer properties

Layers	Types	Thickness (cm)	Total Porosity[a] (v/v)	Field Capacity[b] (v/v)	Wilting Point[c] (v/v)	Initial soil water content (v/v)	Saturated Hydraulic Conductivity[d] (cm/sec)
Layer 1 (sand)	Vertical percolation	5	0.437	0.062	0.024	0.024	5.8×10^{-3}
Layer 2 (MSW)[e]	Vertical percolation	OC2=226 OC3=203	0.671	0.292	0.077	0.292	1.0×10^{-3}
Layer 3 (gravel)	Lateral drainage	20	0.397	0.032	0.013	0.032	3.0×10^{-1}
Layer 4 (concrete base)	Barrier soil	20	0.427	0.418	0.367	0.427	1.0×10^{-7}

Note: a Total Porosity: the soil water storage/volumetric content at saturation (fraction of total volume).

b Field Capacity: the soil water storage/volumetric content after a prolonged period of gravity drainage from saturation corresponding to the soil water storage when a soil exerts a soil suction at 1/3 bar.

c Wilting Point: the lowest soil water storage/volumetric content that can be achieved by plant transpiration or air-drying that is the moisture content where a plant will be permanently wilted corresponding to the soil water storage when a soil exerts a soil suction of 15 bars.

d Saturated Hydraulic Conductivity: the rate at which water drains through a saturated soil under a unit pressure gradient.

e Using default value from model, the typical MSW that has been compacted ($312\ kg/m^3$)

Source: Schroeder et al. (1994).

Water balance simulation for Open Cell landfill lysimeters

After input all data, HELP model simulated the results such as daily, monthly and annual output of precipitation, runoff, evapotranspiration, lateral drainage collected and percolation/leakage through layer. It was noted that the open cell landfill lysimeters did not have vegetation. Therefore, only evaporation was occurred from these landfill lysimeters. Leachate production from open cell landfill lysimeter is the summation of lateral drainage through layer 3 (gravel layer) and percolation through layer 4 (concrete base layer). As the profiles of Open Cell No.2 and 3 were same and the thickness of MSW layer was not different much. The simulations of Open Cell No.2 were selected to discuss in this part. The details of all output of both lysimeters were presented in Appendix B (Table B-9 and B-10).

Figure 4.19 shows the output of the simulation based on the monthly average data of five years (2001-2005). The model output illustrated that the cumulative leachate generation and the evaporation were 69 and 31% of annual rainfall, respectively. The change in water storage in landfill was varied depended upon the infiltrating rain, evaporation and leachate generation components. In addition, in point of view of open cell operation, the rainfall or leachate recirculation should be rapid infiltrate into the landfill more than water loss by evaporation. The evaporation should be less due to limited water storage at the surface of landfill because of no top cover and vegetation. Therefore, leachate generation was the main component of water balance which needs to manage for open cell landfill lysimeter operation.

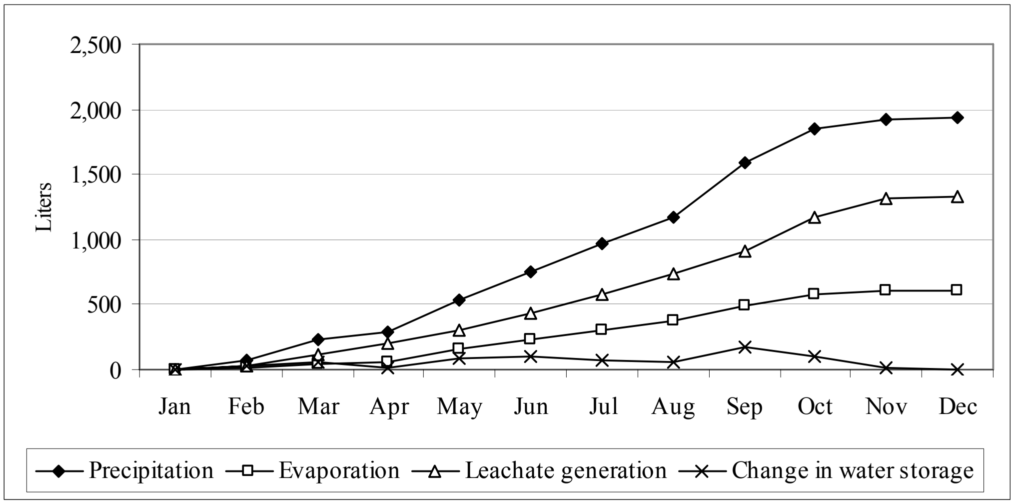


Figure 4.19 Cumulative water balance components of Open Cell landfill lysimeter

4.4.4 Comparison of Water Balance from Experiment and HELP Model

A comparison between the output of HELP model and the measured data in the experiment has been done in this study. The purpose of this comparison was to investigate the application of model for water management.

In the filed experiment, the leachate generation and leachate recirculation components were recorded. The precipitation was taken from secondary data. The evapotranspiration component was taken from HELP model. It was computed in model by using the modified Penman method (Schroeder et al., 1994). This method seems to be good for estimating potential evapotranspiration in tropical countries (Shrestha, 2001).

In HELP model version 3, the program allows leachate recirculation to be simulated. The leachate recirculation rate is specified as a percentage of leachate collected. Therefore, the leachate is continuous recirculated through the period of simulation. In contrary, the field experiment was recirculated whenever the moisture content of solid waste within landfill was not enough. Therefore, the model was used to simulate the water balance components only during July - November 2005 (the period where the leachate recirculation was not introduced).

As mentioned above, the precipitation and evapotranspiration components of water balance of experiment and HELP model were same. The leachate generation was considered in comparison. The results from experiment and model simulation were tabulated in Appendix B (Table B-11). The results of both lysimeters were not much difference. The water balance of Open Cell No.2 was selected to discuss in this part because this lysimeter contained the mixed MSW. This condition was similar MSW properties in model simulation. Figure 4.20 presents the comparison of leachate generation between experiment and model.

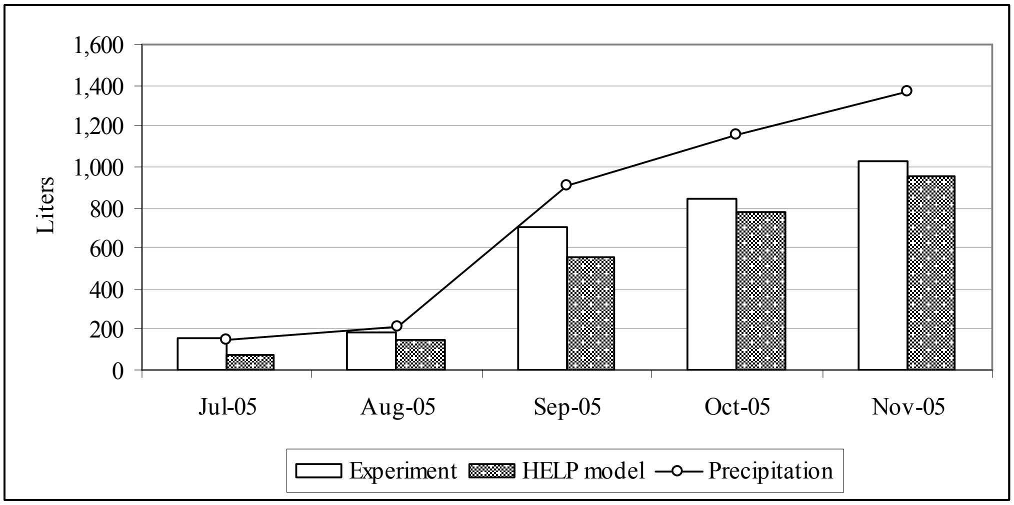


Figure 4.20 Comparison of leachate generation between experiment and HELP model

The results showed that the estimated leachate generation by model was lower than the experiment in range 8-51%. At the beginning of operation period, the gap was high (51%). Due to in the field experiment, the solid waste had high initial moisture content, high decomposition rate and high absorption capacity. In contrary, the model specified the initial moisture content equal to the field capacity. The changes in physical and chemical properties of solid waste were not simulated in model (Schroeder et al., 1994). The model estimated the leachate generation based on the hydraulic properties of each layers of landfill. After that, the gap was decreased because the leachate generation from experiment and model varied depending on the precipitation.

The water balance was used for predicting the amount of leachate which was managed. The overall results presented that the predicted leachate generation from model fit the measured data in field experiment quite well. Therefore, in long-term basis, the HELP model can be applied to estimate the leachate generation from Open Cell landfill lysimeters. The HELP model was a good tool for planning purposes more than accurate prediction. However, the leachate recirculation can not applied in model. Therefore, in this study, the application of model for water management was limited.

4.4.5 Influence of Operational Modes on Water Management

Refer to water management for open cell landfill in tropical climate (Figure 4.13). It consisted of storage, evaporation and recycling of leachate. In this study, leachate generation from Open Cell No.1 and Conventional Landfill was collected and stored in closed tanks. While, leachate generation from Open Cell No.2 and 3 was managed by storing it into the separate open tanks (storage and evaporation tanks). These tanks were also received rainfall during rainy season. At the same time, the evaporation of stored water was occurred by solar radiation. During dry period, stored leachate was introduced into Open Cell No.2 and 3. The evaporation of stored leachate in this period was very high. These actions resulted in reduction the leachate remaining in storage tanks. Figure 4.21 presents the variation of leachate remaining in each tank through the operational period.

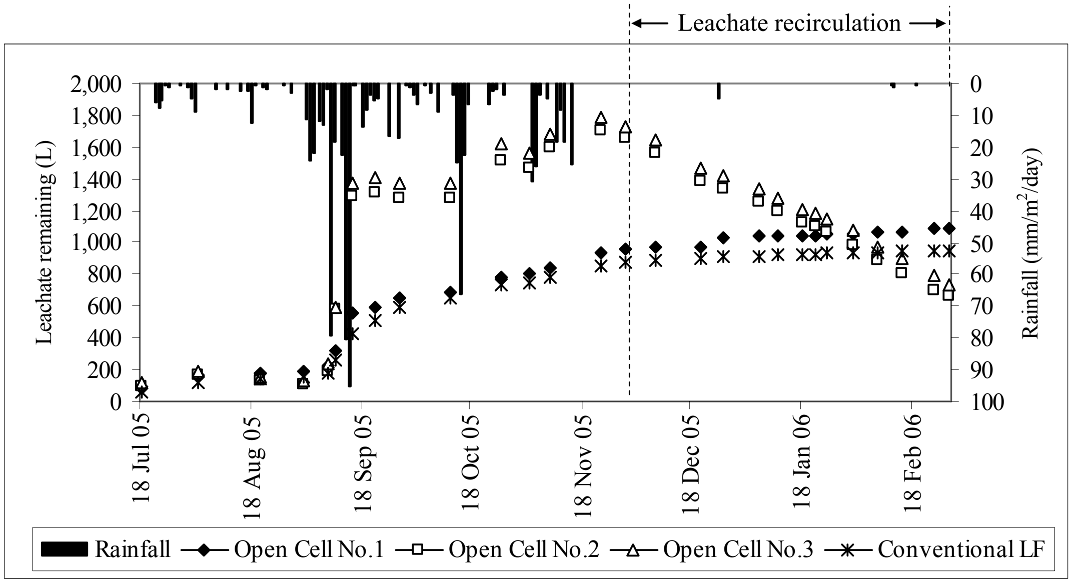


Figure 4.21 Results of water management of landfill lysimeters

The results of water management of Open Cell No.2 and 3 showed the high leachate remaining in the tanks during rainy period. The peak leachate remaining of Open Cell No.2 and 3 was 1,700 and 1,785 L, respectively. It was noted that from July to August 2005, leachate was stored in the small open tanks because of small amount of leachate generation and less rainfall. The high reduction in amount of remaining leachate was observed during dry season as results of leachate recirculation and evaporation. The remaining of leachate from these two lysimeters at the end of operation period was around 665 and 740 L, respectively. While the remaining leachate from Open Cell No.1 and Conventional Landfill was 1,090 and 950, respectively. Furthermore, the volume of leachate remaining in the tanks of Open Cell No.2 and 3 was gradually reduced until the next rainy season. Therefore, water management reduced the amount of leachate for treatment. At the same time, leachate recirculation accelerated the stabilization of waste and increased the settlement of landfill lysimeters.

The concentration of pollutant of leachate remaining in the storage and evaporation tank varied depending on the dilution by rainfall and increasing strength because of water loss by evaporation. The small amount of leachate with high concentration of pollutant was easy to handle.

In addition, the excess leachate remaining more than requirement in dry period was not necessary. Therefore, the reduction excess leachate remaining should be considered. Refer to the flowchart of water management of landfill lysimeters (Figure 3.7); the main points which were considered for water management were leachate generation from landfill lysimeter and leachate remaining in storage tank. In this case, the simple option to improve the water management of Open Cell landfill lysimeters was determined. Figure 4.22 shows the options of improving water management for Open Cell landfill lysiemters.

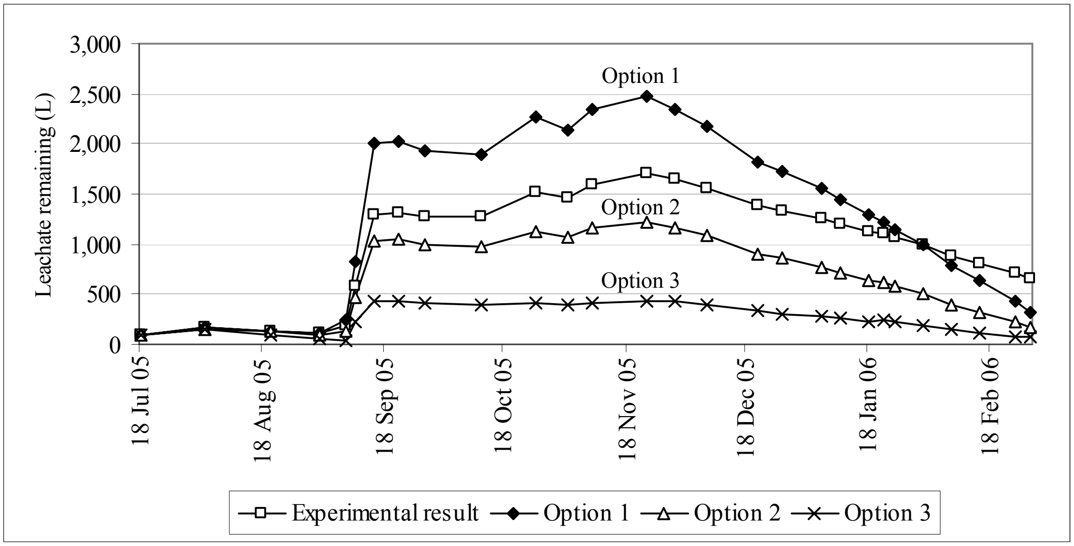


Figure 4.22 Options of improving water management for open cell landfill lysimeter

Three options were suggested to improve water management for open cell landfill lysimeter;

- Option 1: Increasing surface area of storage and evaporation tank (from 2.5 m^2 to 5 m^2). This option can reduce leachate remaining around 50% from experimental result. This option provided high peak of leachate remaining during rainy season but it also reduced the leachate remaining during dry season by high evaporation.

- Option 2: Limiting rainfall come in the storage and evaporation tank by covering 1/4 open space of the tank by transparent roof. This option can reduce leachate remaining around 70% from experimental result. It was noted that prohibiting the rain fall into the tank lead to not enough water remaining for recirculation because of high evaporation.

- Option 3: Decreasing the surface area of storage and evaporation tank (from 2.5 m^2 to 1 m^2) and covering the tank. This option can reduce leachate remaining around 90% from experimental result.

The results indicated that the most important factor of water management to reduce the remaining leachate was evaporation. Thus, increasing the evaporation rate was necessary for water management to achieve the small amount of leachate. However, selecting any option based on the minimum leachate remaining requirement. Leachate should be remained enough for recirculation purpose through the cycle of operation period. Determining the disposal of cumulative sludge in leachate remaining was also importance because high cumulative sludge was not appropriate for recirculation system.

In practice, the water management of Open Cell landfill should be considered the whole system. The design and operation open cell landfill should provide enough leachate for recirculation and at the same time minimize the leachate remaining. Figure 4.23 shows the water management components. The water management can estimate by following equation;

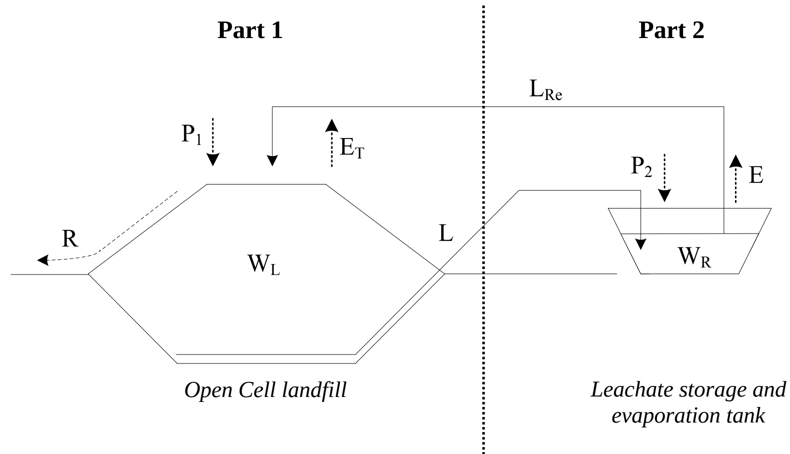


Figure 4.23 Water management components of Open Cell landfill

Water management equation;

$$W_L = (P_1 + L_{Re}) - (R + E_T + L) \qquad \text{Equation 4.1}$$

$$W_R = (P_2 + L) - (E + L_{Re}) \qquad \text{Equation 4.2}$$

Combine Equation 4.1 and 4.2;

$$W_L + W_R = P_1 + L_{Re} - R - E_T - L + P_2 + L - E - L_{Re}$$

Thus, $W_R = (P_1 + P_2) - (E_T + E) - R - W_L$ Equation 4.3

W_L = the quantity of moisture storage in landfill (Liter)
W_R = the quantity of water remaining in the storage tank (Liter)
P_1 = the quantity of precipitation come in landfill (Liter)
P_2 = the quantity of precipitation come in storage tank (Liter)
R = the quantity of runoff from landfill (Liter)
E_T = the quantity of evapotranspiration from landfill (Liter)
E = the quantity of evaporation from storage tank (Liter)
L = the quantity of leachate generation from landfill (Liter)
L_{Re} = the quantity of leachate recirculation (Liter)

From Equation 4.3, each water management component has other factors to determine. For example, the surface runoff relates with the top cover design. The vegetation enhances the evapotranspiration and storage partial moisture within the surface of open cell landfill. The increasing or decreasing surface area of storage tank influences the water remaining. Therefore, the understanding of water management for open cell landfill can be conducted by considering in details of these parameters. The minimum water remaining was also investigated to balance the system.

Chapter 5

Conclusions and Recommendations

The comprehensive lysimeter simulation of open cell landfill operation by combining with water management reveals that;

1. Open cell operation by combining with leachate recirculation (Open Cell No.2 and 3) showed lower concentration in COD, BOD and TKN than in Open Cell No.1 and Conventional Landfill. However, as a result of starting operation landfill lysimeters under rainy season around five months (July - November 2005) lead to the high decomposition of solid waste which was accelerated by the available moisture content. Therefore, during recirculation period (December 2005 - February 2006), the less difference in concentration of leachate constituents between each lysimeter was observed.

2. Open Cell No.3 produced the highest cumulative leachate generation, specific cumulative COD load and settlement rate because it contained the highly biodegradable waste and combined with leachate recirculation mode.

3. After eight months of operation period, the specific cumulative COD load from Open Cell No.1, 2, 3 and Conventional Landfill were 9,805, 9,445, 10,510 and 5,975 mg/kg solid waste, respectively. It also presented the constant trend. While, the TKN load showed the slight increasing trend. The specific cumulative TKN load from Open Cell No.1, 2, 3 and Conventional Landfill were 740, 670, 700 and 615 mg/kg solid waste, respectively.

4. The electrical resistance moisture content sensors were used to estimate the moisture content of solid waste within landfill lysimeters. The results of monitoring indicated the moisture content of solid waste at middle level higher than top level of landfill lysimeter. Leachate recirculation was introduced to maintain the moisture content of solid waste. However, the accuracy of sensor was decreased due to the rapid degradation of the sensor performance with time within the lysimeter.

5. Leachate should be recirculated at low flow rate and intermittent application to prevent the flooding in landfill. The uniform distribution of leachate was also significant for wetting all waste. In long term operation, the amount of leachate leaving from landfill lysimeters was more or equal with the amount of leachate recirculation. This indicated that the landfill lysimeter was reached its field capacity as results of recirculation and also the decreasing field capacity with time.

6. Leachate recirculation for Open Cell No.2 and 3 lead to waste volume reduction more than Open Cell No.1 and Conventional Landfill.

7. The results of simulation water balance of open cell landfill lysimters from experiment and HELP model agreed that the leachate generation was the main component of water balance (around 70% of total precipitation) which needs to manage for open cell landfill. Comparison the results of predicted leachate generation from model with measured data presented that model estimated leachate

generation lower than actual data in range 8-51% from experiment. The recirculation mode was limited in model application because in field experiment the leachate was recirculated whenever moisture content not enough while the program allowed continuous recirculation.

8. The water management of open cell landfill lysimeters by storage, evaporation and recycle of leachate showed the reduction in amount of remaining leachate. The Open Cell No.2 and 3 had lower leachate remaining around one and half fold compared with Open Cell No.1 and Conventional Landfill. In this case, the evaporation was significant factor of water management.

9. The advantages of water management for open cell landfill were the providing leachate recirculation for accelerating waste stabilization and reduction the leachate remaining for treatment. Therefore, the water management equation was provided for application in design and operation open cell landfill.

From the above given conclusion, the following recommendation could be further implied for future study;

1. Monitoring the performance of open cell landfill operation by combining with leachate recirculation should be continued for long period including evaluation of landfill waste stability.

2. Experiment on the water management by investigating the minimum water remaining for leachate recirculation through the operation period should be determined. Enhancing the evaporation by using solar radiation or heating technique also should be considered to minimize the water remaining for treatment.

3. Experiments to improve moisture content sensor should be continued. The relationship between leachate recirculation patterns, moisture content and temperature should be considered.

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Appendices

Appendix A: Weather Data

Table A-1 Weather data 2001 at AIT

Date	January			February			March			April			May			June		
	Temp. (°C)	Rainfall (mm)	Solar Radiation (MJ/m^2)	Temp. (°C)	Rainfall (mm)	Solar Radiation (MJ/m^2)	Temp. (°C)	Rainfall (mm)	Solar Radiation (MJ/m^2)	Temp. (°C)	Rainfall (mm)	Solar Radiation (MJ/m^2)	Temp. (°C)	Rainfall (mm)	Solar Radiation (MJ/m^2)	Temp. (°C)	Rainfall (mm)	Solar Radiation (MJ/m^2)
1	27.8	0.0	19.0	13.4	0.0	21.3	27.1	15.1	20.2	30.3	0.0	24.4	28.5	13.5	21.5	30.3	0.0	25.8
2	24.6	0.0	20.7	27.4	0.0	21.6	29.8	0.0	21.6	30.8	0.0	15.5	28.8	28.7	17.1	29.3	16.1	14.9
3	25.3	0.0	23.6	27.4	0.0	15.3	30.5	0.0	21.1	30.8	0.0	19.0	28.8	19.3	14.2	28.5	0.0	22.6
4	25.8	0.0	21.6	27.8	0.0	18.2	29.3	0.0	17.6	30.8	0.0	23.0	28.8	0.0	21.2	29.8	0.0	22.4
5	26.8	0.0	19.7	28.5	0.0	14.8	29.3	0.0	21.0	31.0	0.0	21.9	29.8	0.0	21.5	29.5	0.0	23.4
6	25.5	0.0	13.4	29.0	0.0	18.7	29.8	0.0	18.5	30.8	0.0	20.0	29.8	0.0	24.6	30.5	42.7	27.5
7	25.3	0.0	18.0	29.0	0.0	15.3	30.3	0.0	20.3	31.3	0.0	25.1	30.4	7.5	28.8	30.1	0.0	24.6
8	28.0	6.3	11.0	28.3	4.9	10.5	31.1	0.1	19.2	31.3	0.0	21.4	28.9	0.0	29.2	27.5	5.7	13.5
9	28.0	0.0	20.0	28.4	0.0	20.1	30.1	46.3	6.5	31.8	0.0	26.0	30.0	0.0	27.0	29.3	24.0	22.5
10	28.0	0.0	20.0	27.9	0.0	11.9	30.1	46.3	6.3	32.0	0.0	22.6	29.8	0.0	27.9	27.9	21.2	17.0
11	28.0	0.0	16.0	26.1	0.0	21.6	22.7	6.6	7.9	32.2	0.0	25.5	31.0	8.0	26.0	28.5	3.9	17.9
12	28.0	0.0	15.1	27.3	0.0	19.9	23.1	5.2	7.2	32.0	0.0	20.0	29.0	15.7	24.9	28.5	0.0	22.3
13	28.8	0.0	14.7	28.5	0.0	20.6	23.1	23.1	14.8	31.4	0.0	19.9	28.0	2.7	28.0	29.1	0.0	20.2
14	27.8	3.7	8.4	28.5	0.0	15.7	24.1	0.0	18.7	30.5	0.0	22.7	30.8	0.0	24.2	29.8	0.0	21.5
15	26.8	3.0	19.5	28.4	0.0	23.4	26.4	36.4	21.5	30.4	59.3	17.5	30.8	19.6	27.6	28.8	0.0	23.9
16	26.4	0.0	16.0	26.9	0.0	21.9	27.3	0.0	25.7	29.1	0.0	21.3	30.0	0.0	15.6	29.0	0.0	23.7
17	26.1	0.0	20.4	23.9	0.0	21.2	28.4	0.0	15.9	29.2	0.0	21.8	30.5	1.2	20.2	29.1	0.0	22.6
18	26.2	0.0	18.3	25.0	0.0	20.5	28.5	1.6	22.9	31.3	0.0	24.3	30.3	0.0	17.9	30.5	0.0	25.4
19	27.1	0.0	11.5	25.8	0.0	18.5	28.5	38.8	20.1	32.0	0.0	27.2	28.3	0.0	22.0	30.6	0.0	25.7
20	28.4	0.0	20.8	25.8	0.0	19.5	27.3	0.0	22.3	31.5	0.0	28.4	29.4	6.5	20.6	30.6	0.0	26.0
21	28.5	0.0	18.0	26.3	0.0	19.7	29.8	0.0	10.9	31.5	0.0	27.8	28.9	0.0	26.2	30.7	0.0	26.3
22	28.3	0.0	19.1	26.3	0.0	16.0	28.5	13.3	10.3	31.0	0.0	23.4	30.9	20.8	27.3	30.0	0.0	27.9
23	28.5	0.0	17.3	31.5	0.0	23.1	28.6	27.5	14.2	32.0	0.0	24.0	30.1	0.0	22.4	30.3	0.8	23.6
24	28.5	0.0	21.2	26.6	0.0	23.3	28.3	0.0	16.2	31.5	0.0	24.1	30.6	3.7	22.3	30.0	0.0	17.7
25	28.8	0.0	20.4	27.3	0.0	24.2	28.3	1.3	18.4	31.2	0.0	20.9	15.8	4.6	25.6	30.9	5.6	19.0
26	29.0	0.0	20.5	27.0	0.0	21.0	28.2	0.3	27.1	32.5	0.0	19.4	29.0	5.8	20.9	30.2	4.7	24.7
27	28.7	0.0	19.7	27.0	0.0	18.8	28.5	0.0	27.3	30.8	0.0	23.6	28.5	0.0	20.9	30.5	0.0	20.5
28	28.4	0.0	21.6	27.0	0.0	18.9	29.5	0.0	26.8	30.7	0.0	21.8	29.8	0.0	24.3	30.8	0.9	12.5
29	29.0	0.0	14.2				30.1	0.0	26.4	30.9	0.0	22.4	30.4	0.0	18.6	30.0	0.0	21.6
30	27.3	0.0	19.3				30.4	0.0	24.2	30.6	0.0	18.8	30.1	0.0	18.7	29.4	22.0	21.6
31	27.3	0.0	19.6				30.8	0.0	18.8				30.5	3.3	29.1			

Table A-1 Weather data 2001 at AIT (continue)

Date	July			August			September			October			November			December		
	Temp. (°C)	Rainfall (mm)	Solar Radiation (MJ/m^2)	Temp. (°C)	Rainfall (mm)	Solar Radiation (MJ/m^2)	Temp. (°C)	Rainfall (mm)	Solar Radiation (MJ/m^2)	Temp. (°C)	Rainfall (mm)	Solar Radiation (MJ/m^2)	Temp. (°C)	Rainfall (mm)	Solar Radiation (MJ/m^2)	Temp. (°C)	Rainfall (mm)	Solar Radiation (MJ/m^2)
1	28.4	0.0	28.6	30.5	0.0	23.9	30.5	0.0	27.2	29.6	4.7	21.8	28.5	0.0	18.9	28.0	0.0	19.6
2	30.2	10.0	23.2	30.0	0.0	21.3	30.0	0.0	29.4	29.3	1.7	25.2	28.5	53.7	13.3	27.9	0.0	18.0
3	30.4	0.0	20.6	30.2	0.6	20.6	31.3	0.0	24.8	30.3	0.0	17.7	28.2	0.0	18.1	28.3	0.0	16.3
4	30.8	0.0	29.1	29.0	20.1	25.2	31.6	0.0	26.7	29.7	0.0	22.9	29.6	0.2	18.9	26.6	0.0	8.2
5	28.8	0.3	18.5	26.8	6.8	18.4	31.5	0.0	24.4	29.9	3.5	20.9	29.5	0.0	21.8	27.9	0.0	17.9
6	28.6	0.0	28.3	27.6	16.8	14.5	30.3	9.4	20.4	29.5	0.9	20.2	29.8	0.0	22.5	28.5	0.0	18.9
7	29.5	3.1	17.6	28.4	0.2	20.6	30.7	18.5	26.1	29.5	1.6	18.8	30.0	0.2	19.1	28.9	0.0	18.6
8	28.5	4.7	16.5	28.8	0.0	23.1	30.0	4.0	21.9	29.3	12.4	18.1	29.8	0.0	22.0	27.6	0.0	21.0
9	28.9	39.1	12.6	28.7	0.7	23.2	29.3	7.9	14.9	29.8	84.3	20.8	29.0	0.0	22.0	27.6	0.0	21.5
10	28.6	0.0	20.9	28.7	1.2	12.8	29.6	0.2	24.8	27.7	1.9	14.7	27.3	0.0	24.3	27.1	0.0	20.0
11	29.2	15.5	16.9	26.7	0.5	13.6	30.5	0.0	28.1	29.5	5.8	26.2	26.0	0.0	21.6	27.0	0.0	14.7
12	29.5	0.0	21.7	28.3	1.5	23.3	31.5	57.1	25.8	31.3	0.0	20.2	26.0	0.0	23.7	27.4	0.0	20.8
13	30.0	0.0	27.6	28.3	0.0	26.3	30.1	14.2	26.2	31.3	0.0	21.4	26.6	0.0	18.6	27.5	0.0	16.0
14	29.1	0.0	25.5	28.3	14.3	16.6	30.8	20.3	24.4	31.8	34.7	19.4	25.3	0.0	16.1	29.0	0.0	17.2
15	28.4	0.0	22.6	29.8	0.0	28.2	29.5	0.0	30.6	31.5	4.6	19.3	24.3	0.0	18.9	26.6	0.0	19.8
16	29.8	0.0	16.7	30.3	12.2	19.0	29.8	0.0	24.2	31.9	5.5	26.0	23.6	0.0	15.8	27.3	0.0	16.4
17	29.1	0.3	23.8	29.9	0.0	20.6	29.8	2.2	26.6	29.8	0.0	26.9	25.1	0.0	23.6	28.5	0.0	19.4
18	28.9	0.0	23.9	29.3	11.3	21.6	31.2	7.4	27.4	29.4	27.9	19.8	25.3	0.0	22.3	29.4	0.0	17.8
19	30.1	0.0	27.6	28.8	0.0	28.3	30.3	0.0	26.7	29.4	22.5	8.9	24.1	0.0	24.9	28.8	0.0	15.5
20	29.9	2.9	25.0	30.7	0.0	25.2	30.3	0.0	30.1	28.3	0.0	21.8	24.4	0.0	21.7	28.0	0.0	20.5
21	29.7	1.5	18.5	30.5	2.6	18.5	30.0	53.6	25.6	30.3	0.0	24.6	23.0	0.0	22.9	27.3	0.0	18.0
22	28.6	22.8	17.6	31.3	0.0	30.0	30.6	1.4	15.7	29.5	0.0	21.2	22.8	0.0	23.4	26.0	0.0	22.2
23	29.1	0.0	19.0	31.3	0.0	26.8	30.0	1.1	23.4	26.1	21.5	11.3	23.8	0.0	23.5	22.2	0.0	20.8
24	31.0	25.4	29.5	31.8	0.0	28.0	29.3	0.7	24.4	27.8	0.3	18.5	24.1	0.0	22.3	22.1	0.0	20.1
25	30.8	1.4	29.2	31.3	0.0	26.4	28.8	0.3	16.9	29.0	37.6	29.3	25.1	0.0	21.3	22.7	0.0	19.9
26	31.3	0.0	28.2	30.5	0.0	26.1	29.0	3.1	16.9	30.8	1.5	17.8	24.6	0.0	21.6	23.3	0.0	17.9
27	31.6	0.0	26.6	31.2	1.9	19.9	29.4	5.6	17.1	29.2	0.0	24.8	23.3	0.0	22.0	23.6	0.0	20.3
28	30.2	0.3	21.0	30.3	0.0	18.3	31.5	0.0	24.8	28.9	1.7	21.2	24.6	0.0	22.9	25.6	0.0	17.7
29	28.9	0.0	27.8	30.9	22.2	18.6	28.8	21.2	18.2	29.1	0.0	17.0	25.4	0.0	21.3	25.3	0.0	17.8
30	30.1	0.0	29.1	29.8	0.3	15.4	28.9	16.6	20.7	29.3	1.4	25.8	26.6	0.0	22.1	23.4	0.0	20.7
31	30.7	0.0	27.6	28.9	0.0	18.0				30.8	8.5	15.1				23.6	0.0	20.3

Table A-2 Weather data 2002 at AIT

Date	January			February			March			April			May			June		
	Temp. (°C)	Rainfall (mm)	Solar Radiation (MJ/m^2)	Temp. (°C)	Rainfall (mm)	Solar Radiation (MJ/m^2)	Temp. (°C)	Rainfall (mm)	Solar Radiation (MJ/m^2)	Temp. (°C)	Rainfall (mm)	Solar Radiation (MJ/m^2)	Temp. (°C)	Rainfall (mm)	Solar Radiation (MJ/m^2)	Temp. (°C)	Rainfall (mm)	Solar Radiation (MJ/m^2)
1	24.4	0.0	21.2	26.8	0.0	20.0	30.3	0.0	22.9	31.4	0.0	21.8	32.3	0.0	17.7	31.0	0.0	25.0
2	24.1	0.0	21.4	26.4	0.0	21.8	30.3	0.0	19.1	30.8	0.0	17.2	31.8	0.0	21.2	30.5	0.0	21.4
3	24.1	0.0	20.3	28.0	0.0	17.8	29.4	0.0	18.8	31.0	0.0	21.4	31.0	37.0	16.7	30.4	0.0	21.1
4	23.9	0.0	18.7	28.1	0.0	18.2	30.0	0.0	17.4	31.4	0.0	25.4	29.0	0.2	23.8	30.4	4.5	19.5
5	24.4	0.0	19.9	27.8	0.0	13.3	30.1	4.8	19.5	31.3	0.0	24.8	29.6	17.1	19.4	30.3	2.7	23.9
6	24.9	0.0	19.5	29.0	0.0	19.8	28.9	23.4	12.4	30.5	0.0	26.1	27.1	0.0	25.5	30.3	0.0	21.1
7	23.6	0.0	19.8	28.3	0.0	19.3	25.2	17.6	6.1	31.4	0.0	25.5	30.3	0.0	25.1	31.0	3.1	18.4
8	24.1	0.0	21.1	28.5	0.0	18.1	22.4	0.3	7.2	31.3	0.0	27.2	30.8	0.0	22.6	31.1	0.0	22.7
9	24.1	0.0	19.3	28.9	0.0	19.9	26.7	0.0	22.7	29.5	0.0	24.0	30.3	0.0	14.1	30.8	0.0	19.6
10	24.3	0.0	18.9	29.1	0.0	18.8	27.4	0.0	23.3	32.4	0.0	25.5	30.5	0.8	24.3	30.4	4.7	16.4
11	25.1	0.0	22.2	29.0	0.0	17.8	28.5	0.0	17.5	32.4	0.0	20.9	27.6	15.8	10.4	29.9	0.5	19.4
12	25.1	0.0	17.8	29.3	0.0	21.5	29.5	0.0	18.2	31.3	0.0	11.7	29.5	0.4	21.9	30.3	0.0	17.9
13	25.9	0.0	19.3	29.8	0.0	22.7	29.8	0.0	21.8	30.2	0.0	22.8	28.3	16.1	13.8	30.1	0.0	20.7
14	26.5	0.0	16.9	30.4	0.0	21.0	30.4	0.0	23.4	31.4	0.0	21.4	28.9	2.8	15.0	29.9	0.0	22.7
15	26.6	0.0	17.5	29.3	0.0	20.5	31.0	0.0	22.1	31.1	0.0	22.0	29.8	0.0	23.7	30.8	2.6	20.2
16	27.4	0.0	21.1	28.8	0.0	19.9	30.9	0.0	24.3	30.5	0.0	16.3	31.0	4.2	18.5	29.9	0.0	24.5
17	26.8	0.0	17.8	28.8	0.0	22.6	30.6	0.0	22.8	31.1	0.0	25.5	29.0	0.3	16.0	30.0	0.0	23.2
18	27.5	0.0	19.0	28.8	0.0	20.3	29.3	0.4	17.5	31.8	0.0	25.7	29.6	1.6	19.9	30.8	3.1	20.3
19	26.9	0.0	16.6	29.3	0.0	22.1	29.9	0.0	23.4	31.8	0.0	19.0	28.9	23.7	15.8	29.8	11.7	20.9
20	27.9	0.0	17.8	28.8	0.0	23.7	30.0	0.0	23.7	31.6	0.0	21.2	26.8	4.3	8.2	28.8	1.4	15.7
21	28.0	0.0	15.8	28.3	0.0	20.8	30.8	0.0	18.6	31.4	0.0	27.6	29.3	7.9	23.2	29.8	25.3	15.8
22	27.8	0.0	17.2	28.3	0.0	16.8	31.1	0.0	24.9	32.2	0.0	23.8	29.8	0.0	21.2	30.0	0.0	20.5
23	26.4	0.0	20.7	30.3	0.0	21.5	30.8	0.0	22.6	27.1	0.8	15.7	30.3	0.0	24.5	29.4	0.0	21.5
24	27.3	0.0	22.0	30.3	0.0	20.3	30.1	0.0	22.2	31.4	0.0	20.4	31.5	0.6	23.1	30.0	3.7	17.8
25	27.3	0.0	16.6	29.7	30.0	15.7	30.0	0.0	18.8	30.0	0.0	22.2	31.5	0.0	15.5	29.3	0.0	13.9
26	27.6	0.0	17.1	28.9	0.0	19.3	31.4	0.0	21.6	30.3	0.0	23.0	30.8	29.5	21.5	30.4	1.4	19.1
27	27.4	0.0	16.7	28.9	0.0	18.3	31.5	0.0	21.5	30.8	0.0	21.2	29.8	0.0	25.5	30.5	29.4	14.0
28	28.3	0.0	18.4	29.3	0.0	24.0	31.5	0.0	23.6	31.0	0.0	23.2	29.5	1.1	18.3	29.8	0.0	19.0
29	27.5	0.0	20.2				31.2	0.0	25.5	30.1	0.0	19.2	29.5	0.0	23.6	30.3	0.0	24.2
30	25.6	0.0	22.2				31.8	0.0	23.6	31.6	0.0	19.3	31.0	8.1	25.5	30.5	0.0	22.1
31	26.4	0.0	22.8				31.7	0.0	21.6				29.5	0.0	25.1			

Table A-2 Weather data 2002 at AIT (continue)

Date	July			August			September			October			November			December		
	Temp. (°C)	Rainfall (mm)	Solar Radiation (MJ/m^2)	Temp. (°C)	Rainfall (mm)	Solar Radiation (MJ/m^2)	Temp. (°C)	Rainfall (mm)	Solar Radiation (MJ/m^2)	Temp. (°C)	Rainfall (mm)	Solar Radiation (MJ/m^2)	Temp. (°C)	Rainfall (mm)	Solar Radiation (MJ/m^2)	Temp. (°C)	Rainfall (mm)	Solar Radiation (MJ/m^2)
1	30.3	0.0	18.6	29.5	16.8	16.7	29.3	15.8	18.6	29.3	0.0	19.1	28.5	8.7	18.0	28.5	0.0	17.2
2	30.6	0.0	19.6	30.3	1.3	22.0	28.5	0.0	19.8	30.0	15.4	14.4	28.0	0.2	15.2	28.0	0.0	15.7
3	31.0	15.3	17.1	30.0	3.5	18.7	29.5	0.0	19.7	29.9	4.3	23.4	27.8	0.0	19.1	28.9	0.0	12.3
4	29.6	1.7	20.6	29.0	0.0	20.7	29.0	0.0	20.1	29.3	0.0	18.4	27.3	0.0	20.0	29.8	9.0	18.3
5	30.8	6.2	20.9	29.3	7.2	18.6	29.8	0.0	21.4	29.8	0.4	18.2	25.8	0.0	24.7	29.5	0.0	17.6
6	29.4	0.0	19.7	28.1	0.4	16.6	29.4	0.0	21.3	30.1	20.8	19.4	25.6	0.0	24.1	29.8	0.0	13.0
7	29.3	3.1	18.4	30.5	0.0	22.4	29.3	0.0	22.5	27.1	0.3	13.5	26.5	0.0	20.9	29.0	0.8	16.2
8	31.0	58.7	16.1	29.6	0.0	22.5	29.5	0.3	22.1	28.0	0.0	24.3	28.3	0.0	16.3	31.0	6.7	14.1
9	29.1	0.0	17.2	29.5	0.0	19.7	29.0	14.5	19.8	27.1	0.0	23.2	26.1	0.0	13.8	28.8	0.2	8.6
10	30.3	0.0	16.7	28.9	0.0	19.4	29.5	8.4	23.4	26.3	0.0	24.3	27.5	0.0	22.6	26.4	0.0	18.1
11	30.6	4.3	18.6	30.4	0.0	20.8	29.0	0.6	19.7	25.0	0.0	26.1	29.8	27.2	16.8	28.0	0.0	21.7
12	30.5	0.0	21.9	29.8	0.0	14.7	29.5	0.0	22.9	25.0	0.0	24.4	29.3	2.7	19.9	27.3	0.0	19.7
13	29.8	0.0	20.4	29.3	0.0	18.9	29.8	0.0	26.9	26.8	0.0	24.0	30.3	0.0	22.8	27.4	0.0	19.1
14	30.5	0.0	21.6	29.1	0.0	17.3	30.2	4.4	27.3	26.9	0.0	24.2	29.8	0.0	21.5	27.8	0.0	18.2
15	29.8	8.1	15.8	30.0	0.0	18.7	29.6	0.4	26.7	26.9	0.0	20.3	30.3	0.0	18.4	28.0	0.0	16.0
16	28.8	5.1	16.2	27.8	2.8	15.2	28.8	0.0	22.1	28.7	0.0	18.7	30.7	0.0	18.4	27.8	0.0	16.8
17	29.8	0.0	14.9	28.8	0.2	15.1	28.8	0.0	22.3	29.4	30.9	15.2	30.9	0.0	20.2	27.6	0.0	15.9
18	29.8	3.4	15.1	29.2	0.0	18.8	29.8	0.0	21.3	29.5	0.0	18.9	31.3	0.0	22.4	29.5	0.0	18.5
19	29.0	0.0	22.4	28.4	0.0	19.2	29.3	10.2	21.2	29.3	0.1	20.1	28.3	0.0	21.5	29.9	0.0	17.4
20	30.4	0.0	22.2	29.2	0.2	16.8	29.0	0.8	18.2	30.0	12.4	17.6	27.9	0.0	17.3	30.0	0.1	17.1
21	30.4	0.0	17.0	27.8	6.7	16.7	29.3	13.0	23.1	29.8	0.0	22.2	29.3	1.8	19.8	29.9	0.0	17.0
22	29.9	0.0	20.7	29.5	12.6	20.6	28.0	10.9	7.6	29.3	2.6	19.5	28.5	0.1	18.9	27.0	0.0	19.5
23	29.5	0.0	19.0	30.0	0.0	21.4	27.1	9.9	15.3	30.5	2.8	25.0	28.5	4.6	12.2	28.8	0.0	16.2
24	30.0	0.0	17.7	30.4	0.8	17.2	28.6	19.7	17.8	29.5	0.0	21.1	28.8	0.0	15.7	28.4	0.0	15.2
25	29.5	0.0	15.2	29.9	44.4	10.2	28.8	51.6	18.8	29.0	0.0	24.5	30.0	0.0	18.5	28.1	0.0	18.8
26	30.0	0.0	18.3	29.3	1.2	22.7	28.1	0.0	21.3	28.8	35.6	14.2	27.5	0.0	20.9	29.3	0.0	17.0
27	29.9	0.0	16.9	29.9	0.0	24.7	29.5	58.2	22.6	28.3	0.3	14.9	27.3	0.0	16.0	28.3	0.5	13.9
28	30.5	0.0	19.2	29.9	3.8	23.2	29.2	0.0	18.0	27.3	7.9	9.3	28.0	0.0	18.2	24.8	0.0	13.3
29	29.8	27.2	11.7	29.3	9.8	20.9	29.9	0.0	20.7	29.1	0.0	16.5	28.0	0.0	20.4	25.8	0.0	15.9
30	28.5	1.3	13.5	28.6	4.0	21.1	29.9	0.4	19.7	29.0	0.0	18.5	28.5	0.0	18.7	27.5	0.0	18.9
31	29.5	0.0	18.7	29.3	9.8	21.6				29.8	19.4	13.5				27.9	0.0	16.3

Table A-3 Weather data 2003 at AIT

Date	January			February			March			April			May			June		
	Temp. (°C)	Rainfall (mm)	Solar Radiation (MJ/m^2)	Temp. (°C)	Rainfall (mm)	Solar Radiation (MJ/m^2)	Temp. (°C)	Rainfall (mm)	Solar Radiation (MJ/m^2)	Temp. (°C)	Rainfall (mm)	Solar Radiation (MJ/m^2)	Temp. (°C)	Rainfall (mm)	Solar Radiation (MJ/m^2)	Temp. (°C)	Rainfall (mm)	Solar Radiation (MJ/m^2)
1	29.0	0.0	18.1	27.1	0.0	17.9	29.6	0.0	20.0	29.0	0.0	20.7	29.0	27.2	37.8	30.1	0.0	18.2
2	28.0	0.0	20.0	27.5	0.0	20.2	30.5	3.7	20.2	30.3	0.0	27.1	27.8	0.3	23.2	30.0	33.2	17.1
3	28.5	0.0	14.4	27.8	0.0	21.3	30.6	0.0	22.3	31.0	0.0	26.3	30.3	0.0	26.2	28.8	19.8	14.6
4	26.4	0.0	18.8	26.1	0.0	21.7	30.9	0.0	21.9	31.5	0.0	26.7	31.3	0.0	26.5	29.8	7.2	19.0
5	26.3	0.0	19.0	24.4	0.0	22.2	30.8	0.0	25.0	31.7	0.0	24.3	32.3	0.0	26.2	30.5	2.7	20.2
6	27.5	0.0	16.9	24.0	0.0	23.0	29.8	0.0	20.5	31.3	0.0	15.1	33.2	0.0	26.8	30.5	1.8	24.6
7	27.6	0.0	19.9	24.8	0.0	21.9	30.3	0.0	23.7	31.0	0.0	23.2	33.3	0.0	24.8	30.5	3.1	26.2
8	26.1	0.0	17.8	26.1	0.0	20.9	27.9	5.5	18.5	31.0	0.0	20.8	33.2	0.0	26.2	30.8	0.0	28.6
9	25.8	0.0	17.6	26.0	0.0	18.6	27.6	2.7	21.3	31.5	0.0	22.5	30.5	0.0	23.4	30.5	0.0	22.3
10	25.0	0.0	19.7	25.8	0.0	17.5	28.5	0.0	19.4	31.9	0.0	22.5	28.3	25.3	16.6	31.5	12.2	26.9
11	23.6	0.0	20.0	29.0	0.0	18.4	29.1	0.0	21.9	31.5	0.0	24.3	30.5	0.0	26.4	30.0	0.0	27.1
12	21.1	0.0	21.2	28.6	48.3	16.4	29.8	0.0	21.6	31.7	0.0	24.6	31.0	38.4	19.5	30.4	0.0	24.4
13	21.4	0.0	20.7	27.9	0.0	16.9	29.3	23.6	22.2	31.9	0.0	24.6	29.4	0.0	22.9	30.3	0.0	24.2
14	23.2	0.0	20.8	28.3	22.4	15.9	26.7	0.2	11.4	31.9	0.0	24.9	30.8	0.0	24.8	31.0	0.0	26.6
15	24.0	0.0	20.1	29.1	0.0	22.2	28.3	0.0	23.7	32.2	0.0	27.2	30.8	30.7	25.2	30.8	6.7	25.7
16	24.6	0.0	19.8	29.5	0.0	18.2	27.4	11.3	14.8	31.3	0.0	18.5	29.5	0.0	25.6	31.3	21.1	23.1
17	25.3	0.0	19.7	30.5	0.0	20.5	29.4	0.0	23.2	30.8	0.0	21.2	27.6	0.0	25.7	30.1	12.8	20.2
18	26.5	0.0	19.6	29.3	46.2	16.2	30.3	0.0	23.9	31.9	0.0	26.3	29.0	2.8	27.4	30.0	0.4	27.5
19	25.6	0.0	19.3	29.5	0.0	21.0	30.6	0.0	21.3	31.4	0.0	21.9	31.3	0.0	22.2	29.3	0.0	23.2
20	27.0	0.0	21.7	29.5	0.0	20.1	30.3	1.6	23.8	32.3	0.0	24.0	30.4	62.2	22.0	29.5	4.7	17.0
21	25.8	0.0	21.1	29.0	0.0	17.5	29.2	13.2	15.0	31.5	0.0	23.0	29.4	21.8	27.1	29.5	2.9	18.2
22	26.9	0.0	21.2	29.4	0.0	22.5	29.0	0.1	18.0	31.7	0.0	22.7	30.0	0.0	27.6	29.8	29.8	14.0
23	26.9	0.0	18.9	30.0	0.0	20.8	30.0	0.0	21.7	31.5	0.0	24.5	28.1	0.0	28.2	27.8	1.6	12.3
24	27.5	0.0	21.1	30.0	0.0	20.2	29.3	0.0	21.4	31.5	0.0	20.1	30.5	0.0	26.6	28.8	0.0	25.5
25	27.0	0.0	18.8	29.6	0.0	19.4	29.0	7.0	21.8	30.8	0.0	20.0	31.0	0.0	22.1	30.0	0.0	26.2
26	29.0	0.0	20.7	29.8	27.2	20.8	27.8	0.0	16.8	31.0	2.6	15.5	31.0	0.0	20.0	29.3	11.6	25.1
27	28.8	0.0	21.8	29.7	0.0	21.4	29.5	0.0	19.3	31.3	0.0	22.3	29.8	0.0	28.7	27.5	2.1	22.4
28	27.3	0.0	18.0	29.5	0.0	18.7	29.0	3.3	17.8	31.3	0.0	25.0	31.0	0.0	26.3	27.1	2.6	22.4
29	25.9	0.0	18.0				29.0	0.0	19.3	31.1	0.4	16.9	30.8	0.0	26.0	30.0	50.8	26.7
30	26.1	0.0	20.7				29.9	0.0	22.5	31.0	0.0	25.5	31.3	1.4	21.4	28.0	29.1	18.0
31	27.6	0.0	20.2				29.7	14.1	23.2	0.0	0.0	0.0	31.0	4.1	21.0			

Table A-3 Weather data 2003 at AIT (continue)

Date	July			August			September			October			November			December		
	Temp. (°C)	Rainfall (mm)	Solar Radiation (MJ/m²)	Temp. (°C)	Rainfall (mm)	Solar Radiation (MJ/m²)	Temp. (°C)	Rainfall (mm)	Solar Radiation (MJ/m²)	Temp. (°C)	Rainfall (mm)	Solar Radiation (MJ/m²)	Temp. (°C)	Rainfall (mm)	Solar Radiation (MJ/m²)	Temp. (°C)	Rainfall (mm)	Solar Radiation (MJ/m²)
1	28.5	2.9	13.7	29.9	0.0	28.3	28.4	0.0	22.1	28.1	73.0	11.0	28.3	0.0	19.4	25.4	0.0	18.0
2	28.2	1.2	17.1	29.8	1.3	22.3	29.4	2.4	21.1	29.6	8.3	17.6	28.6	0.0	20.2	25.0	0.0	17.4
3	28.8	0.0	20.7	29.5	1.3	22.4	29.6	0.0	20.5	27.3	17.3	14.9	28.7	0.0	18.9	24.6	0.0	13.4
4	30.7	0.0	22.5	29.1	7.6	18.6	29.7	0.0	21.5	28.5	0.0	16.6	28.4	0.0	20.3	24.5	0.0	17.1
5	28.8	0.0	20.6	28.9	53.2	24.3	27.3	10.4	22.2	30.3	0.2	17.1	28.7	0.0	19.0	25.8	0.0	17.4
6	28.3	2.5	16.0	28.7	0.0	17.4	29.3	17.1	21.0	29.6	0.3	17.5	30.0	0.0	18.9	26.5	0.0	12.3
7	27.4	2.5	14.5	29.3	0.0	19.3	29.3	0.4	18.7	29.8	16.6	16.9	26.7	0.0	16.8	26.3	0.0	15.3
8	28.6	2.9	18.8	27.4	20.7	21.1	29.3	0.0	18.3	30.1	0.3	18.4	26.3	0.0	18.2	27.3	0.0	15.4
9	28.8	17.6	22.2	30.5	0.0	21.1	29.8	0.0	24.3	30.1	0.1	16.8	29.3	0.0	19.0	29.0	0.0	17.4
10	29.3	12.9	27.9	30.6	0.0	24.7	29.8	26.2	16.1	29.4	0.0	16.0	29.4	0.0	17.4	28.3	0.0	16.0
11	29.5	28.4	21.4	30.3	0.0	20.5	28.0	1.1	16.1	30.8	4.8	14.4	28.8	0.0	19.2	28.1	0.0	11.6
12	30.8	0.0	25.2	31.2	0.0	23.0	29.9	14.0	16.8	25.9	0.0	19.9	27.6	0.0	18.1	28.4	0.0	16.6
13	28.3	0.0	16.1	31.6	0.0	24.7	26.8	5.5	9.8	25.8	0.0	14.8	28.6	0.0	18.1	25.8	0.0	17.8
14	28.8	0.0	13.2	30.5	14.1	26.2	27.8	0.1	13.1	29.0	31.2	16.1	28.8	0.0	16.1	25.3	0.0	16.6
15	29.1	0.0	22.6	30.4	0.0	23.7	29.4	2.6	20.6	26.9	9.4	14.9	24.8	0.0	17.0	23.4	0.0	18.1
16	30.4	55.6	23.9	28.6	0.0	16.7	28.9	2.7	21.5	27.7	0.0	19.9	24.9	0.0	17.7	23.7	0.0	16.5
17	29.8	3.9	22.7	28.3	0.0	16.3	30.2	0.0	20.1	28.9	0.0	16.5	28.8	0.0	16.1	26.4	0.0	16.0
18	30.2	54.5	26.3	28.3	12.6	13.6	29.9	11.9	18.8	29.8	0.0	18.6	29.4	0.0	15.9	25.8	0.0	15.3
19	30.8	0.0	25.4	29.1	52.7	19.1	27.1	36.5	18.0	29.4	0.0	18.3	29.5	0.0	13.3	28.0	0.0	13.7
20	30.8	2.9	23.6	29.5	0.0	12.8	26.8	12.5	17.4	29.6	0.0	19.8	29.6	0.0	12.7	24.1	0.0	15.3
21	30.3	2.9	25.5	29.4	0.0	13.2	30.6	4.1	17.6	28.8	0.0	19.2	28.1	0.0	14.9	21.3	0.0	16.2
22	29.6	0.0	17.6	30.0	0.6	20.2	28.3	0.0	18.5	29.8	0.0	19.8	30.0	0.0	18.2	23.4	0.0	16.0
23	29.3	0.0	12.5	29.3	2.4	19.0	30.4	0.0	19.6	27.8	6.4	9.8	29.8	0.0	18.3	24.5	0.0	16.9
24	27.1	0.0	10.4	28.0	2.8	17.6	30.3	34.7	17.9	27.3	17.2	8.8	28.0	0.0	18.5	24.9	0.0	15.8
25	25.4	0.0	10.0	29.3	4.1	20.7	28.3	43.6	16.7	28.5	0.0	17.1	30.4	0.0	14.6	26.0	0.0	16.3
26	27.1	0.0	10.7	29.3	1.2	14.9	29.1	15.5	21.2	28.6	0.5	18.4	28.0	2.2	10.2	26.3	0.0	16.3
27	29.5	0.0	23.9	29.8	0.4	22.6	28.0	0.0	14.6	29.3	0.0	17.2	27.5	0.0	18.2	24.1	0.0	15.7
28	29.3	0.0	21.4	29.2	0.2	17.9	27.6	2.3	17.3	28.5	0.0	20.8	26.8	0.0	18.2	23.8	0.0	14.9
29	29.8	0.0	22.2	30.0	0.0	25.3	29.8	16.6	16.5	28.8	0.0	21.0	26.3	0.0	18.2	25.0	0.0	15.5
30	29.2	3.8	19.6	29.8	8.8	18.0	27.2	43.0	18.5	28.0	0.0	21.0	25.3	0.0	17.0	25.8	0.0	15.5
31	29.4	14.2	22.0	27.9	0.0	13.7				26.2	0.0	20.0	0.0	0.0	0.0	26.5	0.0	15.9

Table A-4 Weather data 2004 at AIT

Date	January			February			March			April			May			June		
	Temp. (°C)	Rainfall (mm)	Solar Radiation (MJ/m^2)	Temp. (°C)	Rainfall (mm)	Solar Radiation (MJ/m^2)	Temp. (°C)	Rainfall (mm)	Solar Radiation (MJ/m^2)	Temp. (°C)	Rainfall (mm)	Solar Radiation (MJ/m^2)	Temp. (°C)	Rainfall (mm)	Solar Radiation (MJ/m^2)	Temp. (°C)	Rainfall (mm)	Solar Radiation (MJ/m^2)
1	26.0	0.0	17.8	29.8	0.0	15.2	29.5	0.0	19.2	32.5	0.0	20.1	31.3	0.0	18.2	31.8	0.0	21.6
2	26.5	0.0	16.5	29.8	0.0	17.8	29.8	0.0	19.6	32.3	0.0	20.3	31.5	0.0	14.4	31.8	0.0	24.1
3	26.8	0.0	17.3	30.0	0.0	15.6	30.2	0.0	16.8	32.3	0.0	21.3	32.3	0.0	11.3	32.2	0.0	23.7
4	24.3	0.0	15.9	30.5	0.0	15.5	29.5	0.0	16.2	31.8	0.0	18.3	32.6	1.3	15.7	31.5	0.0	19.7
5	26.9	0.0	16.0	30.5	0.0	15.9	30.3	0.0	15.5	32.0	0.0	21.4	32.3	0.0	7.6	32.5	1.0	18.2
6	26.8	0.0	15.8	29.5	0.0	14.6	30.0	0.0	17.2	33.3	0.0	22.9	28.4	11.4	17.9	31.0	0.0	19.2
7	25.5	0.0	16.5	28.3	5.5	11.8	30.0	0.0	16.1	33.3	0.0	21.8	31.4	4.6	15.1	31.4	0.2	16.6
8	25.4	0.0	15.2	26.3	54.0	6.6	28.0	0.0	21.4	33.3	0.0	21.2	28.5	13.1	15.7	30.0	0.4	16.4
9	25.5	0.0	13.6	23.6	0.0	17.2	27.9	0.0	18.4	33.3	0.0	19.0	29.3	0.0	15.3	31.0	0.0	12.5
10	25.3	0.0	12.3	24.3	0.0	20.1	29.0	0.0	19.1	32.5	0.0	13.9	30.2	5.9	19.2	30.7	1.3	14.8
11	27.8	1.2	12.0	24.5	0.0	18.7	29.8	0.0	18.8	33.3	0.0	20.7	31.8	8.0	19.0	30.3	28.8	12.6
12	25.9	1.6	8.4	25.5	0.0	20.1	31.2	0.0	16.9	33.3	0.0	22.3	30.9	0.0	23.3	31.3	0.8	16.8
13	25.8	0.0	14.4	31.8	0.0	20.4	31.5	0.0	16.8	32.0	5.3	21.9	30.8	0.0	21.1	30.0	6.3	15.6
14	26.8	0.0	15.4	24.8	0.0	18.9	31.5	0.0	17.4	33.2	0.0	22.0	31.3	17.2	20.2	28.5	3.1	12.7
15	27.3	0.0	10.6	23.6	0.0	18.5	31.5	0.0	16.7	33.3	0.0	22.8	27.9	17.3	20.2	30.3	1.9	14.5
16	27.6	0.0	11.6	24.0	0.0	19.2	31.8	0.0	19.7	33.0	0.0	23.5	30.5	0.0	19.8	29.9	0.3	16.2
17	28.0	0.0	12.7	25.8	0.0	18.5	30.4	0.0	20.6	33.5	0.0	24.5	31.5	12.4	15.8	29.5	0.0	15.9
18	28.5	0.0	17.5	26.7	0.0	18.5	30.3	0.0	16.7	34.0	0.0	21.9	30.5	0.0	22.2	29.0	23.0	6.6
19	28.7	0.0	15.7	27.1	0.0	15.0	31.4	0.0	12.2	34.0	0.0	20.2	32.0	0.0	19.3	28.5	2.6	11.3
20	29.0	0.0	15.3	26.5	0.0	11.2	30.8	0.0	11.9	28.0	0.0	19.9	32.0	23.2	11.2	29.1	2.5	9.3
21	28.3	0.0	15.7	27.7	0.0	14.9	31.5	0.0	14.7	33.8	0.0	19.3	29.5	1.3	4.0	31.4	0.0	22.6
22	27.2	0.0	13.5	28.5	0.0	16.3	32.0	8.0	17.4	33.3	0.0	22.2	27.4	5.9	9.3	31.2	0.0	21.9
23	27.3	0.0	16.3	28.8	0.0	17.0	32.2	0.0	19.3	33.3	0.0	19.4	26.3	0.0	24.5	31.3	0.2	14.7
24	25.6	0.0	17.6	28.5	0.0	18.3	32.7	0.0	20.4	33.3	0.0	20.7	29.5	0.0	23.2	31.0	0.0	23.3
25	22.4	0.0	18.0	30.0	0.0	20.6	32.1	0.0	21.3	33.0	0.0	17.9	31.5	0.0	19.8	30.5	0.0	20.8
26	23.3	0.0	17.7	29.3	0.0	19.8	32.0	0.0	19.6	33.3	0.0	21.1	31.8	0.0	10.8	31.3	0.0	21.2
27	25.3	0.0	17.6	28.3	0.0	19.3	31.5	0.0	17.6	33.3	0.0	20.0	29.3	8.8	20.4	30.4	0.0	18.5
28	26.2	0.0	16.5	27.9	0.0	20.1	32.6	0.0	19.4	32.8	0.0	6.3	31.4	0.0	18.2	30.1	0.0	18.7
29	27.4	0.0	15.0	28.0	0.0	19.0	32.9	0.0	19.8	32.6	0.0	22.0	28.9	0.0	17.8	31.3	0.0	21.6
30	28.0	0.0	11.8				33.0	0.0	21.5	29.1	13.1	18.7	32.0	0.0	22.7	31.4	0.0	23.6
31	28.8	0.0	12.9				32.1	0.0	19.5	26.5	0.0	15.9	32.5	0.0	21.0			

Table A-4 Weather data 2004 at AIT (continue)

Date	July			August			September			October			November			December		
	Temp. (°C)	Rainfall (mm)	Solar Radiation (MJ/m^2)	Temp. (°C)	Rainfall (mm)	Solar Radiation (MJ/m^2)	Temp. (°C)	Rainfall (mm)	Solar Radiation (MJ/m^2)	Temp. (°C)	Rainfall (mm)	Solar Radiation (MJ/m^2)	Temp. (°C)	Rainfall (mm)	Solar Radiation (MJ/m^2)	Temp. (°C)	Rainfall (mm)	Solar Radiation (MJ/m^2)
1	32.0	0.0	22.4	30.3	0.5	14.3	31.9	2.8	18.5	29.1	16.3	13.1	28.8	0.0	18.6	27.3	0.0	18.0
2	31.9	0.0	21.3	30.0	0.0	15.9	28.5	2.1	14.7	28.3	15.4	12.9	28.0	0.0	18.0	28.5	0.0	17.4
3	32.5	0.0	23.6	29.3	0.3	16.6	29.8	4.8	11.3	28.3	0.0	18.8	28.4	0.0	19.2	29.5	0.0	16.8
4	32.8	3.1	23.7	30.0	20.5	14.5	27.1	25.1	14.2	28.3	0.0	20.2	27.8	0.0	18.2	27.3	0.0	15.6
5	31.8	0.3	21.0	30.8	83.5	22.0	28.5	0.1	14.2	28.3	0.0	17.4	28.5	0.0	17.0	25.8	0.0	16.2
6	32.2	0.0	18.2	28.4	0.0	18.2	30.8	0.0	22.4	28.3	0.0	12.6	31.8	0.0	17.6	24.9	0.0	16.0
7	32.0	3.7	11.1	30.5	0.0	22.4	30.3	21.6	16.8	29.0	0.0	14.9	30.6	0.0	20.0	26.0	0.0	17.4
8	30.1	0.0	19.6	30.5	2.9	20.8	29.1	0.0	14.5	29.8	0.0	17.5	29.3	0.0	17.5	25.1	0.0	15.8
9	31.3	1.2	22.5	30.3	1.6	19.8	29.9	3.5	18.7	29.8	0.0	17.5	30.3	0.0	17.7	23.8	0.0	16.2
10	30.3	9.9	20.9	30.3	0.0	17.1	29.8	0.0	11.6	29.5	0.0	17.3	30.8	0.0	16.6	25.0	0.0	16.6
11	32.7	0.0	20.7	28.3	15.0	9.4	30.3	0.0	17.0	29.5	14.3	13.2	31.0	0.0	17.4	26.5	0.0	17.0
12	29.6	0.0	16.1	31.0	0.0	20.2	31.1	6.8	13.9	29.0	0.0	17.6	30.4	0.0	15.7	26.3	0.0	17.1
13	31.5	0.0	20.6	30.3	0.0	21.1	29.6	8.6	18.0	29.6	0.0	15.3	31.5	0.0	18.4	24.7	0.0	17.1
14	31.5	0.0	20.0	27.6	0.0	21.1	27.6	0.9	15.4	29.9	0.0	18.6	32.0	0.0	17.4	24.0	0.0	17.0
15	30.8	0.0	16.1	29.8	0.0	15.9	28.0	0.3	17.7	29.3	0.0	16.1	31.3	0.2	16.7	24.0	0.0	17.2
16	30.0	0.0	24.8	30.7	0.7	19.5	29.4	0.0	22.0	29.3	0.0	14.7	30.4	0.0	15.1	24.6	0.0	16.7
17	32.7	0.0	23.8	30.5	7.3	22.7	29.4	2.1	10.2	28.0	0.0	17.8	28.8	0.0	16.6	24.8	0.0	16.2
18	32.5	9.8	24.6	31.4	31.4	20.4	27.8	4.2	10.6	29.9	0.0	18.4	27.5	0.0	15.6	25.8	0.0	14.9
19	31.3	0.0	22.1	30.3	32.9	12.5	28.8	0.0	18.5	29.0	0.0	17.4	27.5	0.0	17.4	25.5	0.0	16.6
20	32.0	30.6	15.6	28.9	0.0	15.6	28.9	5.5	15.4	28.6	0.0	18.0	26.8	0.0	19.3	24.8	0.0	15.6
21	30.3	0.0	18.0	31.0	13.7	23.4	28.9	53.6	16.9	28.7	0.0	18.2	25.8	0.0	19.4	24.5	0.0	15.9
22	31.3	0.0	16.0	30.0	0.0	20.0	28.9	0.1	18.5	28.8	0.0	17.9	24.4	0.0	18.6	24.7	0.0	15.6
23	30.8	0.2	19.6	31.6	0.0	24.6	29.8	0.0	22.6	28.5	0.0	17.1	25.4	0.0	18.5	25.8	0.0	13.5
24	30.8	30.8	21.2	31.0	0.0	22.0	29.8	0.0	18.4	27.8	0.0	17.2	29.0	0.0	16.4	26.3	0.0	15.6
25	30.5	6.0	16.6	32.0	0.0	23.2	30.0	0.0	16.6	29.3	0.0	19.4	29.0	0.0	11.8	25.8	0.0	15.6
26	30.0	6.7	16.7	31.6	0.0	23.0	30.3	0.5	21.3	27.5	0.0	18.0	28.3	0.0	16.8	26.0	0.0	16.6
27	29.8	0.2	18.2	32.3	0.0	19.1	30.8	0.0	17.1	27.8	0.0	19.7	28.3	0.0	16.3	25.8	0.0	16.4
28	30.4	5.2	16.9	32.0	0.0	20.9	30.5	0.0	19.5	28.3	0.0	17.8	28.8	0.0	16.7	25.3	0.0	17.1
29	29.5	0.0	19.2	32.0	0.0	21.1	29.3	0.0	18.2	30.5	0.0	17.0	27.8	0.0	16.7	23.8	0.0	17.7
30	30.9	0.0	20.6	31.9	0.2	17.8	26.9	7.3	12.2	30.3	0.0	18.2	27.4	0.0	18.2	25.0	0.0	17.0
31	30.8	0.0	18.4	31.5	0.0	20.4				28.4	0.0	18.6				25.3	0.0	16.2

Table A-5 Weather data 2005 at AIT

Date	January			February			March			April			May			June		
	Temp. (°C)	Rainfall (mm)	Solar Radiation (MJ/m^2)	Temp. (°C)	Rainfall (mm)	Solar Radiation (MJ/m^2)	Temp. (°C)	Rainfall (mm)	Solar Radiation (MJ/m^2)	Temp. (°C)	Rainfall (mm)	Solar Radiation (MJ/m^2)	Temp. (°C)	Rainfall (mm)	Solar Radiation (MJ/m^2)	Temp. (°C)	Rainfall (mm)	Solar Radiation (MJ/m^2)
1	23.1	0.0	21.5	29.5	0.0	13.1	30.8	0.0	19.1	33.0	0.0	12.2	32.3	0.0	20.5	30.8	9.6	21.2
2	21.6	0.0	17.6	30.0	0.0	14.3	30.9	0.0	17.1	31.3	0.0	11.4	32.3	0.0	17.7	30.4	0.0	22.1
3	22.6	0.0	17.2	29.0	0.0	15.9	31.2	0.0	18.7	31.4	58.3	9.7	32.3	0.0	18.6	30.6	37.0	20.5
4	24.0	0.0	16.6	29.1	0.0	15.2	29.0	0.0	15.3	25.5	8.1	7.0	32.5	0.0	18.1	30.3	0.0	18.7
5	24.0	0.0	17.5	29.8	0.0	18.6	26.3	0.0	14.2	27.3	0.0	10.6	33.5	0.0	21.7	31.0	0.2	19.0
6	24.8	0.0	15.7	29.3	0.0	18.8	23.1	0.0	19.8	29.0	0.0	13.9	34.0	18.2	22.0	30.8	0.0	22.5
7	25.5	0.0	16.0	29.7	0.0	16.1	25.3	0.0	18.6	30.4	4.6	10.7	31.5	0.0	16.7	31.0	0.0	20.0
8	26.0	0.0	14.6	29.5	0.0	15.6	27.3	0.0	18.1	31.8	0.0	13.9	29.3	0.0	9.7	31.5	0.0	20.8
9	26.2	0.0	14.0	29.9	0.0	13.9	29.0	0.0	18.1	31.8	0.0	14.0	31.1	0.0	23.1	30.8	4.1	20.6
10	26.5	0.0	17.0	30.3	0.0	15.5	29.8	0.0	18.9	32.5	0.0	14.3	32.0	0.0	22.6	30.0	0.0	17.0
11	25.6	0.0	17.5	29.8	0.0	13.1	30.0	0.0	17.0	33.2	0.0	11.2	32.3	7.4	22.3	29.1	0.0	19.0
12	26.9	0.0	14.7	26.8	0.0	13.7	27.8	0.0	16.7	33.8	0.0	11.7	31.7	0.4	20.0	31.3	0.0	19.7
13	27.8	0.0	12.7	29.1	0.0	13.3	31.2	0.0	18.2	32.3	1.6	13.0	31.3	2.5	20.2	31.1	0.2	19.7
14	28.3	0.0	14.6	29.8	0.0	18.0	31.1	0.0	15.6	30.8	0.0	14.0	31.8	42.2	22.9	31.1	0.0	19.5
15	21.8	0.3	6.7	30.3	0.0	18.9	27.9	0.0	10.7	29.8	32.4	10.4	31.3	5.0	19.6	30.0	0.0	16.4
16	24.3	0.0	11.1	30.3	0.0	18.8	29.3	4.3	13.7	28.5	0.0	6.4	32.2	0.2	17.7	32.0	4.5	16.4
17	25.8	0.0	12.7	31.0	0.0	19.6	30.3	0.0	13.5	31.5	0.0	10.8	30.4	3.1	15.5	29.6	0.0	13.0
18	27.0	0.0	12.2	30.3	0.0	18.5	30.8	0.0	14.2	31.5	2.1	9.3	31.0	0.2	16.1	31.3	0.0	19.5
19	26.5	2.2	11.9	30.0	0.0	17.9	30.8	0.0	16.6	31.3	0.5	10.3	30.5	29.3	14.4	30.6	7.3	16.8
20	28.0	0.0	12.1	30.3	0.0	15.9	31.0	0.0	17.9	30.0	0.0	11.4	26.8	2.6	8.9	30.3	12.6	16.8
21	28.0	0.0	13.7	30.8	0.0	16.9	31.2	0.0	19.5	31.0	0.0	9.4	29.8	1.0	13.1	30.3	0.0	20.8
22	27.8	0.0	14.5	31.0	0.0	14.6	31.6	0.0	21.2	31.0	0.0	11.8	28.5	0.5	22.8	29.9	0.0	20.6
23	27.5	0.0	13.5	30.8	0.0	18.5	31.8	0.0	17.5	32.5	0.0	12.8	30.1	0.0	14.2	30.5	12.2	17.6
24	28.1	0.0	13.7	30.8	0.0	19.3	32.0	0.0	14.5	32.3	0.0	11.2	30.9	0.0	23.0	29.9	0.2	20.8
25	28.0	0.0	14.3	30.8	0.0	19.3	29.9	2.5	15.2	31.8	0.0	11.7	30.9	0.0	16.2	30.8	51.0	18.0
26	27.9	0.0	14.8	31.0	0.0	19.4	29.0	65.0	8.0	33.0	0.0	14.1	30.9	0.0	23.1	30.2	0.0	23.8
27	29.3	0.0	16.9	30.6	0.0	16.7	30.0	0.0	17.6	33.0	0.3	13.4	31.9	0.0	21.8	30.8	0.0	21.0
28	29.0	0.0	16.4	29.3	0.0	18.6	31.3	0.0	20.6	32.0	0.0	13.8	32.0	0.0	22.3	31.9	1.3	18.5
29	29.0	0.0	15.8				31.5	0.0	22.0	32.8	0.0	11.1	32.3	26.5	21.9	29.5	0.0	14.9
30	29.1	0.0	14.8				32.5	0.0	16.5	33.3	0.0	13.8	30.3	8.6	20.7	30.7	0.0	23.2
31	29.3	0.0	15.6				32.5	0.0	21.1				30.3	1.1	20.5			

Table A-5 Weather data 2005 at AIT (continue)

Date	July			August			September			October			November			December		
	Temp. (°C)	Rainfall (mm)	Solar Radiation (MJ/m^2)	Temp. (°C)	Rainfall (mm)	Solar Radiation (MJ/m^2)	Temp. (°C)	Rainfall (mm)	Solar Radiation (MJ/m^2)	Temp. (°C)	Rainfall (mm)	Solar Radiation (MJ/m^2)	Temp. (°C)	Rainfall (mm)	Solar Radiation (MJ/m^2)	Temp. (°C)	Rainfall (mm)	Solar Radiation (MJ/m^2)
1	30.8	0.0	19.1	27.8	4.8	9.2	31.0	0.0	14.4	31.5	1.3	18.3	27.9	0.0	16.8	28.9	0.0	17.5
2	30.5	0.0	17.1	28.3	8.7	13.3	32.3	11.3	21.5	31.1	3.4	16.0	30.1	0.0	15.6	30.3	0.0	15.9
3	31.5	0.0	19.4	29.5	0.0	20.3	30.5	24.5	20.4	30.8	6.6	21.3	30.8	0.0	15.3	29.5	0.0	11.0
4	31.3	31.4	22.5	29.3	0.0	19.2	29.3	22.1	5.3	30.9	0.2	12.9	30.4	30.8	18.1	29.5	0.0	14.3
5	28.4	0.0	14.6	29.5	0.0	14.3	29.6	0.0	16.9	29.3	0.5	10.6	28.5	26.2	9.7	28.5	0.0	13.1
6	31.0	0.0	24.3	29.8	0.0	15.5	31.3	11.6	19.3	29.9	0.0	13.3	29.3	3.5	12.5	29.4	0.0	14.7
7	30.7	0.0	22.3	30.3	0.0	14.9	29.4	13.3	14.4	30.3	3.0	17.1	30.0	0.0	16.6	27.2	0.0	13.5
8	26.6	0.0	15.4	30.1	2.0	15.7	28.8	2.0	10.4	30.0	0.0	20.1	29.9	4.5	14.0	26.5	0.0	20.0
9	29.8	0.0	19.5	29.8	0.0	14.5	29.0	79.1	8.2	28.8	9.0	14.8	28.8	0.0	15.6	27.0	0.0	19.6
10	30.5	0.0	20.1	30.0	0.0	17.3	29.0	18.2	16.8	30.0	0.0	18.6	29.8	0.0	18.2	27.0	0.0	20.0
11	31.9	0.0	20.9	29.8	1.9	15.0	29.3	0.0	17.3	30.7	0.0	16.6	30.0	18.6	10.7	27.5	0.0	17.6
12	29.5	18.6	10.2	29.3	0.0	11.3	27.9	22.3	16.6	29.8	0.0	19.1	29.3	8.0	10.3	27.8	0.0	15.2
13	25.8	24.9	6.2	30.5	0.0	14.9	28.8	80.5	15.5	30.5	3.8	20.2	29.5	18.5	14.3	27.1	0.0	18.8
14	29.3	0.0	20.6	30.3	0.0	13.3	28.8	95.5	3.9	29.5	24.7	13.5	30.1	0.0	12.3	26.4	0.0	17.9
15	30.9	0.0	21.0	30.0	2.5	15.2	28.9	0.6	14.7	30.5	66.0	17.3	30.0	25.6	8.1	24.6	0.0	12.1
16	29.8	0.0	21.4	30.3	0.0	18.3	28.9	0.6	19.0	29.3	22.2	14.4	30.0	0.0	14.4	24.5	0.0	13.6
17	31.0	0.0	23.0	30.3	2.2	17.4	28.9	0.0	21.8	29.5	6.6	18.3	29.8	0.0	17.3	24.8	0.0	16.5
18	31.6	0.0	22.6	30.9	12.6	15.8	29.3	13.8	18.5	29.8	0.0	18.8	29.0	0.0	12.9	22.9	0.0	19.4
19	32.0	0.0	21.4	29.8	0.5	14.7	28.0	8.3	14.4	29.9	0.0	18.4	29.0	0.0	12.2	22.3	0.0	19.3
20	30.9	0.0	20.6	30.0	0.0	15.9	30.4	3.7	19.5	29.6	0.0	18.9	28.1	0.0	18.3	23.3	0.0	18.0
21	30.0	0.0	16.5	31.8	1.1	17.9	30.0	5.5	16.8	29.5	0.0	19.1	25.9	0.0	19.4	22.8	0.0	12.2
22	29.5	6.2	17.0	30.3	1.8	16.0	30.5	4.5	22.9	29.5	0.0	19.9	25.4	0.0	18.7	21.2	0.0	11.0
23	28.6	7.8	13.2	30.5	0.0	19.6	30.6	0.0	19.8	28.5	6.6	13.6	23.3	0.0	14.2	22.6	0.0	15.9
24	27.9	5.1	13.9	30.5	0.0	22.2	30.8	0.0	20.4	27.9	2.3	12.0	25.3	0.0	15.8	21.8	0.0	10.2
25	29.3	0.7	14.4	32.1	0.0	23.3	30.2	16.7	21.2	28.3	1.7	10.5	25.4	0.0	16.7	26.3	0.0	13.4
26	29.0	1.1	15.3	32.1	0.0	19.7	30.5	0.0	20.3	30.0	0.0	19.9	27.6	0.0	10.4	26.3	4.8	12.1
27	29.5	0.0	20.7	30.8	0.3	11.3	31.6	0.0	21.1	28.7	3.5	14.3	28.9	0.0	17.8	26.1	0.0	9.4
28	29.8	0.0	20.0	31.0	0.0	18.6	31.3	16.9	14.6	30.4	0.0	17.1	29.7	0.0	15.8	27.1	0.0	11.5
29	30.1	0.3	20.6	31.5	2.8	17.5	29.9	0.0	12.7	29.8	0.0	17.8	28.4	0.0	18.8	26.0	0.0	16.4
30	29.0	0.0	15.3	30.8	0.0	19.5	28.9	0.3	14.6	29.5	0.0	15.1	28.4	0.0	16.4	26.0	0.0	17.7
31	29.3	1.4	17.2	31.1	0.0	18.3				29.1	0.0	19.2				26.3	0.0	18.2

Table A-6 Weather data 2006 at AIT

Date	January			February		
	Temp. (°C)	Rainfall (mm)	Solar Radiation (MJ/m^2)	Temp. (°C)	Rainfall (mm)	Solar Radiation (MJ/m^2)
1	26.0	0.0	13.6	28.7	0.0	18.3
2	28.5	0.0	13.0	29.5	0.0	18.2
3	27.9	0.0	16.3	29.6	0.0	16.7
4	28.0	0.0	14.3	28.8	0.0	16.9
5	29.0	0.0	14.2	27.0	0.0	17.8
6	28.1	0.0	13.9	27.8	0.0	18.4
7	26.6	0.0	17.5	27.4	0.0	19.3
8	24.7	0.0	14.2	26.7	0.0	17.7
9	24.6	0.0	17.4	28.4	0.0	19.0
10	23.7	0.0	20.1	28.3	0.0	17.8
11	24.4	0.0	18.6	28.8	0.0	17.5
12	25.9	0.0	18.4	28.0	0.8	12.3
13	26.8	0.0	17.4	23.0	0.8	3.6
14	26.8	0.0	14.2	27.5	0.0	19.5
15	26.3	0.0	15.6	28.5	0.0	17.5
16	27.5	0.0	10.3	29.8	0.0	14.4
17	28.1	0.0	19.2	29.4	0.0	12.9
18	27.8	0.0	14.1	28.8	0.0	15.0
19	27.7	0.0	19.8	29.7	0.8	15.6
20	26.9	0.0	20.6	29.5	0.0	12.2
21	26.5	0.0	19.3	30.4	0.0	15.8
22	27.0	0.0	18.1	30.6	0.0	16.0
23	27.3	0.0	19.4	29.6	0.0	20.3
24	26.1	0.0	17.0	29.3	0.0	18.2
25	24.4	0.0	18.3	29.5	0.0	14.8
26	24.4	0.0	19.7	30.8	0.0	15.9
27	25.2	0.0	19.3	30.8	0.0	19.2
28	24.8	0.0	17.1	30.8	0.0	20.7
29	25.1	0.0	17.4			
30	26.6	0.0	16.9			
31	27.0	0.0	16.5			

Appendix B: Tabulation of Data

Table B-1 Physical and chemical properties of MSW from Taklong Municipality, Pathumthani (Thailand)

Properties of MSW (% by weight)	Sampling No.1 2 Jul 05	Sampling No.2 9 Jul 05	Sampling No.3 16 Jul 05	Average	Typical (1)	Typical (2)
1. MSW compositions						
Organic waste						
a) Food waste	63	57	60	60	20-65	40-65
b) Paper	8	11	4	8	8-30	2-25
c) Plastic	25	18	18	20	2-6	4-20
d) Textile	2	1	3	2	2-10	1-8
e) Rubber and Leather	0	0	5	2	1-4	1-5
f) Yard waste and Wood	0	1	1	1	1-10	0-10
Inorganic waste						
g) Glass	1	5	5	4	1-10	1-15
h) Metal	1	2	1	1	1-5	1-7
i) Stone and ceramic (including bones and shells)	0	2	0	1	-	0-5
Others	0	3	3	2	-	1-20
2. Moisture Content	54	47	54	52	-	20-70 (3)
3. Total Solid	46	53	46	48	-	-
4. Volatile Solid	91	92	85	89	-	-
5. Ash	9	8	15	11	-	-
6. Total Organic Carbon	92	86	78	85	-	-
7. Bulk density (kg/m^3)	220	300	320	280	300	170-350

Source: (1) Tchobanologlous et al. (1993).

(2) Visvanathan et al. (2004).

(3) The high moisture content (40-70%) is generated from tourist spots located in east, north, south and central part of Thailand, whereas MSW generated from the northeast provinces has low moisture content (20-22%) (Visvanathan et al., 2004).

Table B-2 Characteristics of leachate from Open Cell No.1

Date	Cummulative leachate (L)	pH	Conductivity (mS/cm)	Alkalinity (mg/L)	COD (mg/L)	BOD_5 (mg/L)	VFA (mg/L)					
							Total	Acetic	Propionic	Isobutyric	Butyric	Valeric
18 Jul 05	87	5.75	9.13	3,000	30,235							
3 Aug 05	166	6.75	23.30	3,835	32,790							
20 Aug 05	180	7.92	24.00	15,000	8,035	5,175						
1 Sep 05	185	7.98	14.44	12,500	6,745	3,600						
8 Sep 05	221	7.00	24.00	12,165	26,070	6,530	25,225	6,500	5,260	905	9,180	3,380
10 Sep 05	316	6.35	19.04	8,750	24,705	5,190	14,595	3,565	3,980	1,440	3,590	2,020
15 Sep 05	561	6.36	15.49	7,500	20,685	5,965	8,310	1,970	1,920	1,290	2,330	800
21 Sep 05	586	5.88	15.79	4,400	26,485	5,145	10,330	2,765	3,830	2,000	985	750
28 Sep 05	646	7.52	16.93	7,500	16,585	8,880	8,335	840	1,985	3,660	720	1,130
12 Oct 05	686	7.53	16.13	10,000	4,760	1,375	4,075	465	1,000	2,400	40	170
26 Oct 05	784	7.88	17.69	7,165	7,965	2,210	7,080	5,955	140	740	160	85
3 Nov 05	802	7.66	18.58	11,835	3,305	1,200	2,800	2,255	170	50	145	180
9 Nov 05	842	7.24	15.49	6,665	13,390	3,620	1,970	325	425	185	485	550
23 Nov 05	930	8.15	12.45	7,665	2,610	1,125	640	335	70	0	235	0
30 Nov 05	956	7.67	15.97	9,000	4,310	2,665	305	110	50	70	50	25
8 Dec 05	966	7.83	15.90	9,665	1,290	165	315	80	55	85	55	40
21 Dec 05	976	8.31	14.30	7,400	1,535	115		0	0	0	0	0
27 Dec 05	1,028	8.36	14.89	6,835	1,100	120	45	0	0	45	0	0
6 Jan 06	1,037	8.07	15.74	7,165	1,035	95	0	0	0	0	0	0
11 Jan 06	1,040	8.30	15.33									
18 Jan 06	1,046	8.03	15.08	6,790	1,060	170	245	0	135	110	0	0
25 Jan 06	1,050	8.22	15.04									
1 Feb 06	1,053	8.23	14.38	5,065	1,005	170	4	4	0	0	0	0
8 Feb 06	1,060	8.35	13.87									
15 Feb 06	1,063	8.14	14.96	5,335	980	75	79	0	61	5	10	3
24 Feb 06	1,085	7.64	11.24									
28 Feb 06	1,087	7.96	12.24	4,100	940	100	105	14	71	6	11	3

Table B-2 Characteristics of leachate from Open Cell No.1 (continue)

Date	TKN (mg/L)	NH_4-N (mg/L)	Org-N (mg/L)	TS (mg/L)	VS (mg/L)	TSS (mg/L)	TDS (mg/L)	Heavy metals (mg/L)						
								Mn	Cr	Cd	Pb	Ni	Zn	Cu
18 Jul 05	1,010	785	225											
3 Aug 05	1,430	1,230	200	5,810	2,790	2,140	3,670							
20 Aug 05	1,800	1,680	120	7,990	3,855	640	7,350							
1 Sep 05	1,965	1,885	80	13,580	8,700	1,410	12,170							
8 Sep 05	1,980	1,805	175	12,255	8,200	2,285	9,970							
10 Sep 05	1,385	1,325	60	13,025	8,730	810	12,215							
15 Sep 05	1,045	1,020	25	12,790	8,285	705	12,085							
21 Sep 05	1,105	960	145	15,140	10,755	695	14,445							
28 Sep 05	1,195	1,055	140	11,135	8,905	665	10,470							
12 Oct 05	1,440	1,350	90	8,585	1,580	690	7,895							
26 Oct 05	1,350	1,245	105	12,510	1,700	815	11,695							
3 Nov 05	1,850	1,695	155	8,605	1,210	655	7,950							
9 Nov 05	1,455	1,170	285	12,570	1,780	680	11,890							
23 Nov 05	1,160	1,055	105	6,350	1,395	990	5,360							
30 Nov 05	1,470	1,325	145	8,760	3,385	600	8,160							
8 Dec 05	1,485	1,435	50	5,480	1,395	490	4,990							
21 Dec 05	1,105	1,020	85	6,835	1,270	190	6,645							
27 Dec 05	905	880	25	8,060	1,910	190	7,870							
6 Jan 06	1,010	985	25	7,650	1,430	270	7,380							
11 Jan 06						415								
18 Jan 06	1,035	965	70	7,745	1,740	455	7,290	0.135	0.009	0.000	0.001	0.123	0.157	0.009
25 Jan 06						435								
1 Feb 06	790	745	45	7,885	1,715	215	7,670	0.177	0.012	0.001	0.001	0.088	0.041	0.001
8 Feb 06						290								
15 Feb 06	845	820	25	8,260	1,990	335	7,925							
24 Feb 06						150								
28 Feb 06	705	680	25	6,355	1,290	145	6,210							

Table B-3 Characteristics of leachate from Open Cell No.2

Date	Cummulative leachate (L)	pH	Conductivity (mS/cm)	Alkalinity (mg/L)	COD (mg/L)	BOD_5 (mg/L)	VFA (mg/L)					
							Total	Acetic	Propionic	Isobutyric	Butyric	Valeric
18 Jul 05	90	5.95	12.01	6,830	34,740							
3 Aug 05	175	6.38	24.20	9,165	39,920							
20 Aug 05	186	7.77	24.70	14,000	13,185	11,100						
1 Sep 05	194	8.61	21.00	11,335	5,950	5,100						
8 Sep 05	225	7.77	23.80	11,835	22,965	5,925	10,790	1,980	1,145	4,190	2,515	960
10 Sep 05	434	6.92	19.99	11,250	19,280	3,390	3,290	945	1,050	50	815	430
15 Sep 05	647	5.99	11.92	5,000	16,870	3,945	9,445	2,160	2,120	3,250	1,135	780
21 Sep 05	682	6.98	13.26	4,600	16,760	3,280	10,685	1,980	3,520	3,285	1,050	850
28 Sep 05	706	7.94	15.67	7,500	5,855	3,275	7,220	1,125	5,380	415	85	215
12 Oct 05	750	8.20	15.51	9,335	2,380	825	2,995	365	770	1,620	110	130
26 Oct 05	841	8.19	17.56	8,835	2,825	730	3,125	2,410	70	495	100	50
3 Nov 05	861	8.48	17.96	11,165	3,305	1,575	1,270	940	100	30	90	110
9 Nov 05	920	8.55	11.11	7,335	1,090	350	1,805	290	410	185	450	470
23 Nov 05	1,005	8.34	14.37	9,335	2,210	535	825	400	95	0	330	0
30 Nov 05	1,031	8.32	15.45	9,335	2,155	595	255	90	45	55	45	20
8 Dec 05	1,031	7.93	14.00	8,665	2,095	1,070	245	65	40	60	45	35
21 Dec 05	1,031	7.97	11.29	5,465	1,220	200		0	0	0	0	0
27 Dec 05	1,031	7.92	12.12	6,665	1,100	190	32	0	0	32	0	0
6 Jan 06	1,051	7.96	12.47	7,000	910	60	0	0	0	0	0	0
11 Jan 06	1,051	8.13	12.46									
18 Jan 06	1,052	7.54	12.77	6,375	1,150	275	63	0	0	0	6	57
25 Jan 06	1,075	7.62	11.86									
1 Feb 06	1,075	7.79	11.90	5,265	825	90	5	5	0	0	0	0
8 Feb 06	1,075	7.53	12.33									
15 Feb 06	1,076	7.66	11.66	5,065	910	155	80	11	54	4	9	2
24 Feb 06	1,082	7.75	12.77									
28 Feb 06	1,102	7.65	12.73	5,565	875	100	101	18	63	6	11	3

Table B-3 Characteristics of leachate from Open Cell No.2 (continue)

Date	TKN (mg/L)	NH_4-N (mg/L)	Org-N (mg/L)	TS (mg/L)	VS (mg/L)	TSS (mg/L)	TDS (mg/L)	Heavy metal (mg/L)						
								Mn	Cr	Cd	Pb	Ni	Zn	Cu
18 Jul 05	530	450	80											
3 Aug 05	1,580	1,455	125	4,660	3,400	790	3,870							
20 Aug 05	1,710	1,580	130	10,740	7,930	1,490	9,250							
1 Sep 05	1,645	1,580	65	13,030	7,800	1,010	12,020							
8 Sep 05	2,035	1,905	130	13,790	8,435	620	13,170							
10 Sep 05	735	660	75	8,635	6,770	870	7,765							
15 Sep 05	805	740	65	9,575	6,870	630	8,945							
21 Sep 05	960	895	65	10,255	6,385	670	9,585							
28 Sep 05	1,170	1,035	135	9,680	6,675	520	9,160							
12 Oct 05	1,415	1,330	85	7,345	1,250	405	6,940							
26 Oct 05	1,525	1,365	160	7,635	1,215	190	7,445							
3 Nov 05	1,860	1,785	75	7,770	1,400	890	6,880							
9 Nov 05	1,100	1,035	65	5,115	980	350	4,765							
23 Nov 05	1,455	1,290	165	6,855	1,075	410	6,445							
30 Nov 05	1,485	1,360	125	7,400	1,845	370	7,030							
8 Dec 05	1,265	1,205	60	6,225	2,440	355	5,870							
21 Dec 05	740	680	60	5,890	1,440	510	5,380							
27 Dec 05	775	730	45	6,460	1,665	320	6,140							
6 Jan 06	840	775	65	5,810	1,310	230	5,580							
11 Jan 06						200								
18 Jan 06	855	770	85	6,765	1,570	410	6,355	0.358	0.003	0.001	0.004	0.044	0.044	0.002
25 Jan 06						295								
1 Feb 06	695	635	60	6,030	990	110	5,920	0.172	0.000	0.000	0.003	0.014	0.009	0.025
8 Feb 06						185								
15 Feb 06	575	515	60	6,450	1,135	310	6,140							
24 Feb 06						170								
28 Feb 06	665	590	75	6,795	1,040	275	6,520							

Table B-4 Characteristics of leachate from Open Cell No.3

Date	Cummulative leachate (L)	pH	Conductivity (mS/cm)	Alkalinity (mg/L)	COD (mg/L)	BOD_5 (mg/L)	VFA (mg/L)					
							Total	Acetic	Propionic	Isobutyric	Butyric	Valeric
18 Jul 05	120	5.74	22.50	5,500	38,930							
3 Aug 05	198	6.54	25.00	9,665	44,910							
20 Aug 05	211	7.90	24.00	13,665	8,240	6,525						
1 Sep 05	218	7.99	22.10	12,335	13,090	7,500						
8 Sep 05	270	7.10	23.50	11,335	27,310	12,500	21,325	3,605	2,935	9,295	3,920	1,570
10 Sep 05	440	6.31	14.06	12,500	17,475	7,110	9,230	2,890	2,945	2,375	505	515
15 Sep 05	730	5.97	11.25	10,000	14,660	3,280	5,680	950	920	1,740	1,460	610
21 Sep 05	780	7.38	16.05	6,000	11,380	4,450	8,220	1,925	2,885	2,355	505	550
28 Sep 05	800	7.57	17.27	9,335	3,705	2,070	2,190	365	1,065	430	120	210
12 Oct 05	844	7.57	17.38	10,165	2,380	1,210	1,965	1,055	300	500	20	90
26 Oct 05	944	7.98	17.72	10,000	5,040	2,665	4,545	3,480	105	735	160	65
3 Nov 05	958	7.72	18.10	12,000	4,080	2,100	1,610	1,275	105	30	90	110
9 Nov 05	1,000	7.59	16.27	10,000	10,710	3,290	1,615	280	310	130	440	455
23 Nov 05	1,090	8.09	13.95	8,665	2,610	870	995	590	85	0	320	0
30 Nov 05	1,110	7.80	15.25	11,500	3,330	710	225	85	40	40	40	20
8 Dec 05	1,110	7.73	11.25	6,835	3,145	1,200	165	40	25	40	35	25
21 Dec 05	1,110	7.91	11.76	5,765	1,425	305		0	0	0	0	0
27 Dec 05	1,110	7.85	12.69	6,335	1,730	450	25	0	0	0	25	0
6 Jan 06	1,133	7.80	13.96	7,165	1,160	110	0	0	0	0	0	0
11 Jan 06	1,133	7.94	12.82									
18 Jan 06	1,133	7.77	12.38	5,415	1,250	175	72	0	5	67	0	0
25 Jan 06	1,163	7.75	11.80									
1 Feb 06	1,163	7.72	12.32	5,200	925	185	6	6	0	0	0	0
8 Feb 06	1,163	7.54	12.59									
15 Feb 06	1,165	7.78	12.57	5,135	850	135	71	0	56	4	9	2
24 Feb 06	1,171	7.71	13.27									
28 Feb 06	1,176	7.71	13.28	5,300	865	110	93	17	60	5	9	2

Table B-4 Characteristics of leachate from Open Cell No.3 (continue)

Date	TKN (mg/L)	NH_4-N (mg/L)	Org-N (mg/L)	TS (mg/L)	VS (mg/L)	TSS (mg/L)	TDS (mg/L)	Heavy metal (mg/L)						
								Mn	Cr	Cd	Pb	Ni	Zn	Cu
18 Jul 05	1,035	810	225											
3 Aug 05	1,345	1,315	30	6,330	3,610	1,380	4,950							
20 Aug 05	1,750	1,570	180	7,900	4,470	1,200	6,700							
1 Sep 05	1,835	1,735	100	15,190	7,650	1,100	14,090							
8 Sep 05	1,720	1,645	75	14,933	11,510	1,720	13,215							
10 Sep 05	895	855	40	10,230	8,220	715	9,515							
15 Sep 05	670	630	40	9,900	6,845	795	9,105							
21 Sep 05	1,125	915	210	12,980	7,350	1,150	11,830							
28 Sep 05	1,225	1,105	120	11,607	3,970	1,180	10,425							
12 Oct 05	1,540	1,435	105	9,455	1,650	415	9,040							
26 Oct 05	1,430	1,240	190	6,436	1,245	1,305	5,130							
3 Nov 05	1,745	1,625	120	8,609	1,215	825	7,785							
9 Nov 05	1,505	1,370	135	12,453	2,370	1,215	11,240							
23 Nov 05	1,300	1,205	95	7,135	1,270	595	6,540							
30 Nov 05	1,415	1,280	135	6,961	1,500	555	6,405							
8 Dec 05	875	775	100	5,612	2,770	545	5,070							
21 Dec 05	775	695	80	6,503	1,700	410	6,095							
27 Dec 05	825	720	105	7,725	1,155	1,185	6,540							
6 Jan 06	875	805	70	5,708	1,565	455	5,255							
11 Jan 06						385								
18 Jan 06	765	685	80	7,197	1,820	950	6,245	0.332	0.003	0.001	0.000	0.058	0.192	0.010
25 Jan 06						315								
1 Feb 06	685	625	60	6,671	1,090	295	6,375	0.317	0.003	0.001	0.001	0.042	0.311	0.025
8 Feb 06						330								
15 Feb 06	670	605	65	6,885	1,230	405	6,480							
24 Feb 06						205								
28 Feb 06	700	630	70	6,885	1,020	430	6,455							

Table B-5 Characteristics of leachate from Convetional Landfill

Date	Cummulative leachate (L)	pH	Conductivity (mS/cm)	Alkalinity (mg/L)	COD (mg/L)	BOD_5 (mg/L)	VFA (mg/L)					
							Total	Acetic	Propionic	Isobutyric	Butyric	Valeric
18 Jul 05	60	5.92	4.12	7,665	3,780							
3 Aug 05	122	7.50	16.49	4,665	7,870							
20 Aug 05	142	8.20	20.60	9,335	2,885	1,440						
1 Sep 05	152	8.38	19.30	8,665	10,315	2,700						
8 Sep 05	172	8.15	20.90	9,665	12,000	2,975	5,450	1,420	935	1,510	1,080	505
10 Sep 05	264	7.50	22.10	7,500	20,485	2,030	6,900	1,655	1,790	1,235	1,430	790
15 Sep 05	429	7.08	22.90	8,750	21,090	6,410	2,525	460	500	840	495	230
21 Sep 05	504	6.86	17.03	5,200	18,000	8,750	14,070	2,885	3,845	4,920	1,000	1,420
28 Sep 05	593	7.60	19.05	6,665	13,660	11,060	5,305	1,310	3,530	130	95	240
12 Oct 05	655	8.18	13.38	7,000	9,520	3,650	2,180	270	565	1,165	80	100
26 Oct 05	732	8.00	16.44	9,665	2,420	575	1,125	880	35	140	50	20
3 Nov 05	751	7.95	17.80	10,665	2,040	675	1,300	1,030	90	20	70	90
9 Nov 05	783	8.05	17.68	11,000	2,180	370	1,225	235	250	100	320	320
23 Nov 05	853	8.22	15.47	9,165	2,810	170	980	600	90	0	290	0
30 Nov 05	870	8.08	15.57	9,000	1,175	145	220	90	35	35	40	20
8 Dec 05	882	8.18	14.89	9,000	1,290	215	295	75	55	65	60	40
21 Dec 05	897	8.44	13.84	5,865	1,100	85	0	0	0	0	0	0
27 Dec 05	907	8.28	14.41	7,000	1,140	95	0	0	0	0	0	0
6 Jan 06	914	8.38	14.71	6,835	950	55	0	0	0	0	0	0
11 Jan 06	918	8.54	13.81									
18 Jan 06	924	8.14	13.39	4,915	1,140	185	61	0	5	56	0	0
25 Jan 06	929	8.24	13.72									
1 Feb 06	935	7.72	13.19	5,135	915	125	3	3	0	0	0	0
8 Feb 06	938	8.32	13.67									
15 Feb 06	942	7.78	12.58	4,865	950	120	69	0	54	4	8	3
24 Feb 06	946	8.31	14.76									
28 Feb 06	948	8.20	13.51	4,665	970	100	83	11	56	4	9	3

Table B-5 Characteristics of leachate from Convetional Landfill (continue)

Date	TKN (mg/L)	NH_4-N (mg/L)	Org-N (mg/L)	TS (mg/L)	VS (mg/L)	TSS (mg/L)	TDS (mg/L)	Heavy metal (mg/L)						
								Mn	Cr	Cd	Pb	Ni	Zn	Cu
18 Jul 05	140	105	35											
3 Aug 05	630	575	55	3,340	1,670	800	2,540							
20 Aug 05	1,015	895	120	7,570	2,810	570	7,000							
1 Sep 05	1,245	1,160	85	11,790	2,490	310	11,480							
8 Sep 05	1,220	1,185	35	10,145	3,555	155	9,990							
10 Sep 05	1,395	1,300	95	16,465	8,570	1,270	15,195							
15 Sep 05	1,430	1,360	70	18,070	10,290	1,145	16,925							
21 Sep 05	1,090	950	140	15,830	9,090	1,565	14,265							
28 Sep 05	1,015	860	155	14,600	6,570	1,705	12,895							
12 Oct 05	995	910	85	8,935	2,425	955	7,980							
26 Oct 05	1,290	1,230	60	7,815	1,350	410	7,405							
3 Nov 05	1,520	1,350	170	8,010	1,100	390	7,620							
9 Nov 05	1,525	1,415	110	7,905	1,645	340	7,565							
23 Nov 05	1,370	1,265	105	7,235	1,350	335	6,900							
30 Nov 05	1,290	1,175	115	7,150	1,340	290	6,860							
8 Dec 05	1,245	1,185	60	5,635	1,325	205	5,430							
21 Dec 05	975	700	275	6,950	1,410	135	6,815							
27 Dec 05	895	845	50	7,945	2,015	365	7,580							
6 Jan 06	870	820	50	7,360	1,065	175	7,185							
11 Jan 06						270								
18 Jan 06	705	665	40	7,445	1,930	305	7,140	0.307	0.006	0.001	0.000	0.064	0.045	0.003
25 Jan 06						365								
1 Feb 06	720	665	55	7,215	1,395	260	6,955	0.280	0.009	0.000	0.000	0.056	0.049	0.025
8 Feb 06						450								
15 Feb 06	630	565	65	7,165	1,480	335	6,830							
24 Feb 06						315								
28 Feb 06	660	580	80	7,955	1,550	290	7,665							

Table B-6 Experiments on leachate recirculation for Open Cell No.2

Month	Average Temperature (^oC)	Rainfall (mm/m^2/month)	Leachate drainage volume (L)	Leachate recirculation		
				Volume (L)	Frequency (times/month)	Flow rate of distribution (L/min)
Jul-05	29.9	98	164	0	0	0
Aug-05	30.3	41	30	0	0	0
Sep-05	29.8	451	517	0	0	0
Oct-05	29.8	161	85	0	0	0
Nov-05	27.7	136	188	0	0	0
Dec-05	26.0	5	223	290	3	3.14
Jan-06	26.4	0	244	257	5	2.70
Feb-06	28.8	2	255	210	7	2.50

Table B-7 Experiments on leachate recirculation for Open Cell No.3

Month	Average Temperature (^oC)	Rainfall (mm/m^2/month)	Leachate drainage volume (L)	Leachate recirculation		
				Volume (L)	Frequency (times/month)	Flow rate of distribution (L/min)
Jul-05	29.9	98	189	0	0	0
Aug-05	30.3	41	30	0	0	0
Sep-05	29.8	451	587	0	0	0
Oct-05	29.8	161	89	0	0	0
Nov-05	27.7	136	179	0	0	0
Dec-05	26.0	5	284	372	3	4.93
Jan-06	26.4	0	234	213	5	3.45
Feb-06	28.8	2	183	162	7	2.50

Note: During Dec 05 to Feb 06 (recirculation period), leachate drainage was the summation of leachate generation and recirculated leachate

Table B-8 Characteristics of leachate recirculated

Date	Open Cell No.2			Open Cell No.3		
	pH	Conductivity (mS/cm)	TSS (mg/L)	pH	Conductivity (mS/cm)	TSS (mg/L)
13 Jan 06	9.11	6.19	165	8.92	6.80	180
17 Jan 06	9.00	6.34	210	8.80	6.89	205
22 Jan 06	8.83	6.88	210	8.83	7.19	200
30 Jan 06	9.00	6.90	205	8.90	7.20	175
10 Feb 06	8.80	7.78	220	8.78	7.50	185
16 Feb 06	8.91	8.82	265	8.84	8.99	240
24 Feb 06	9.06	8.94	275	9.04	9.04	270
28 Feb 06	9.06	9.18	370	9.16	9.08	300

Note: The leachate recirculation was provided from December 2005. Sampling and analysis the characteristics of leachate recirculated was monitored from January 2006 to investigate the necessary of pre-treatment leachate before recirculaiton.

Table B-9 Cumulative water balance components of Open cell No. 2 from HELP model

Month	Cumulative (L)			
	Precipitation	Evapotranspiration	Leachate generation	Change in water storage
January	6	3	3	0
February	79	14	30	35
March	225	48	117	60
April	284	61	203	20
May	538	158	300	80
June	757	235	428	94
July	965	304	584	77
August	1,173	378	732	63
September	1,594	497	917	180
October	1,850	579	1,174	97
November	1,923	601	1,308	14
December	1,930	604	1,324	1

Note: The results based on the average monthly over five years (2001-2005)

Table B-10 Cumulative water balance components of Open cell No. 3 from HELP model

Month	Cumulative (L)			
	Precipitation	Evapotranspiration	Leachate generation	Change in water storage
January	6	3	3	0
February	79	14	32	33
March	225	48	122	55
April	284	60	206	17
May	538	158	308	72
June	757	235	435	88
July	965	304	594	67
August	1,173	378	738	57
September	1,594	497	931	166
October	1,850	579	1,187	83
November	1,923	601	1,312	9
December	1,930	605	1,324	1

Note: The results based on the average monthly over five years (2001-2005)

Table B-11 Comparison water balance components of Open Cell No. 2 and 3

Month	Cumulative leachate generation (L)					
	Open Cell No.2			Open Cell No.3		
	Experiment	HELP model	% difference	Experiment	HELP model	% difference
Jul-05	160	78	51	180	83	54
Aug-05	187	146	22	209	146	30
Sep-05	707	558	21	795	582	27
Oct-05	845	779	8	935	794	15
Nov-05	1,031	949	8	1,110	962	13

Appendix C: Photographs

Figure C-1 Landfill lysimeters set up at Environmental Research Station of AIT

Figure C-2 Storage and evaporation tanks for Open Cell No.2 and 3 (During rainy season)

Figure C-3 Storage and evaporation tanks for Open Cell No.2 and 3 (During dry season)

Figure C-4 Leachate recirculation

Figure C-5 Electrical resistance moisture content sensors and its using

Sustainable Landfill Operation by Combining Open Cell and Water Management Strategies

Examination Committee: Prof. C. Visvanathan (Chairperson)

Dr. Preeda Parkpian

Dr. U. Glawe

Presented by: Wiyada Wisiterakul

Why Open Cell Operation by Combining with Water Management?

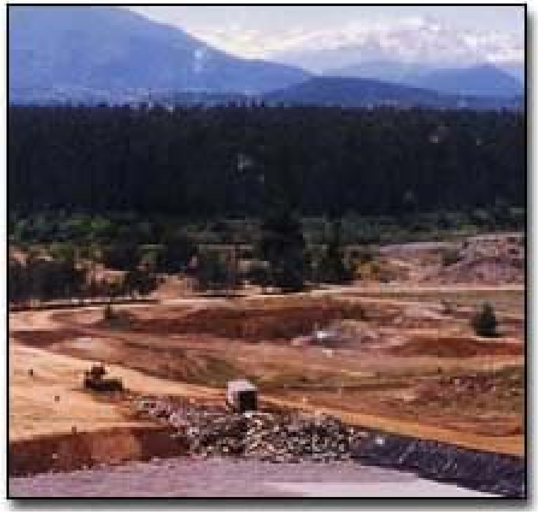
- Traditional disposal practices in Asia
- Landfill technology

    Sanitary Landfill

    Bioreactor Landfill

- Tropical seasonal variation influences on landfill leachate

Sanitary Landfill

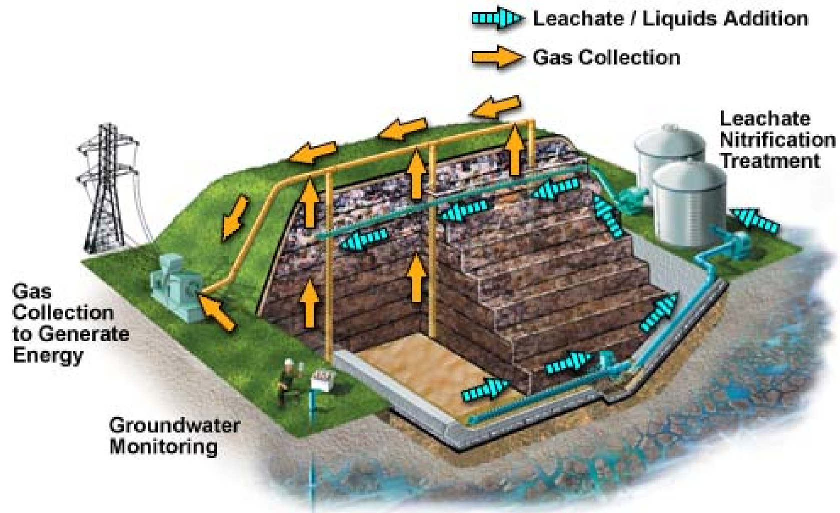


- Storage/containment system
- Minimize infiltration of water

⬇

- Slow degradation rate
- Long term aftercare

Bioreactor Landfill



- Process-based approach
- Leachate recirculation

⬇

- Accelerating the waste stabilization in short time
- Energy recovery

Objectives of Study

- To determine the influence of **leachate recirculation** on Open Cell landfill lysimeters
- To determine **water management** of Open Cell landfill lysimeters by experiment and HELP model application
- To recommend an appropriate **Open Cell landfill** and **leachate management option** for sustainable landfill in correlation with the Asian tropical climate

Methodology

Task I

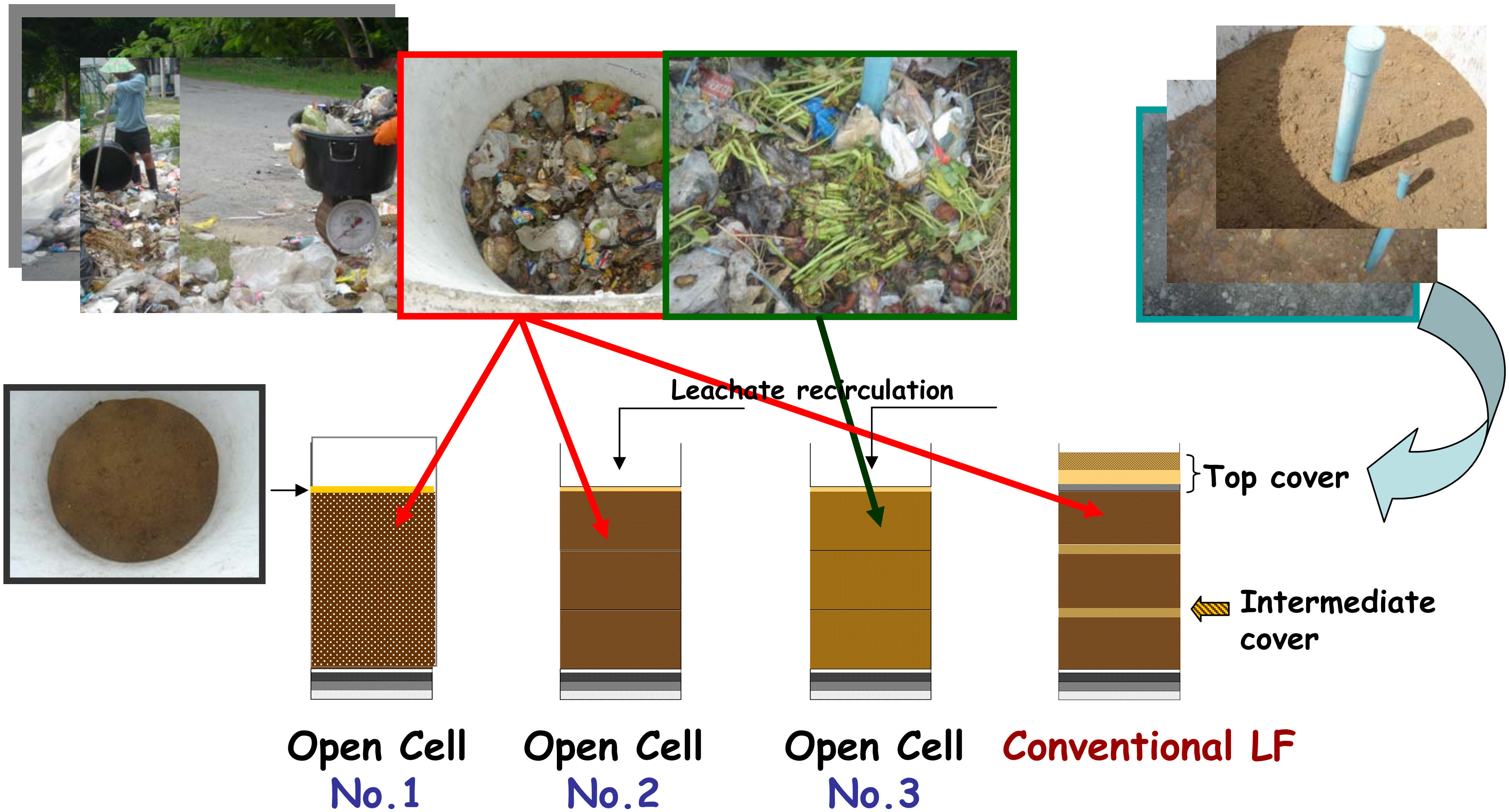
Monitoring
four landfill lysimeters

Task II

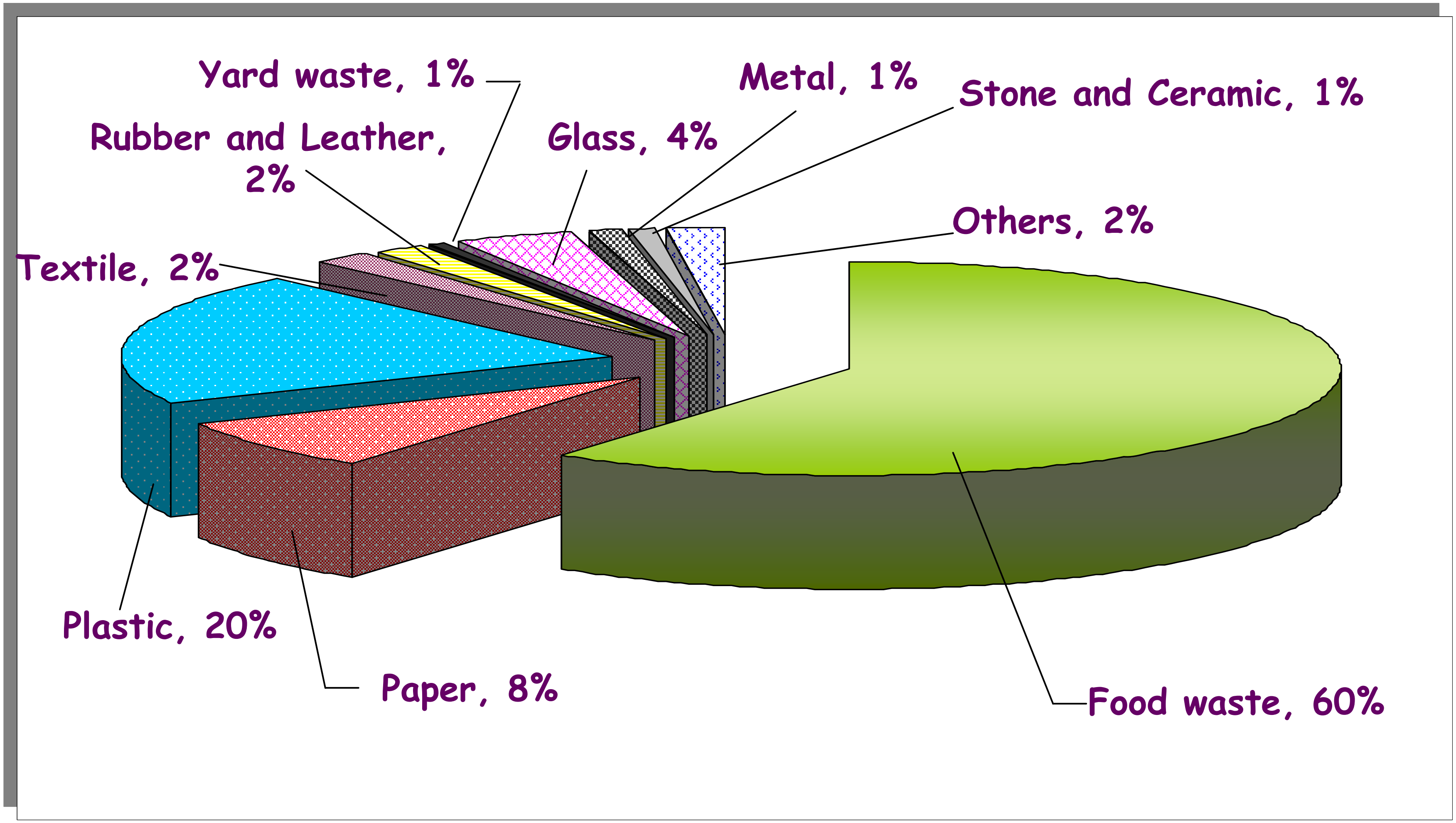
Determining
water management

Landfill lysimeters at AIT

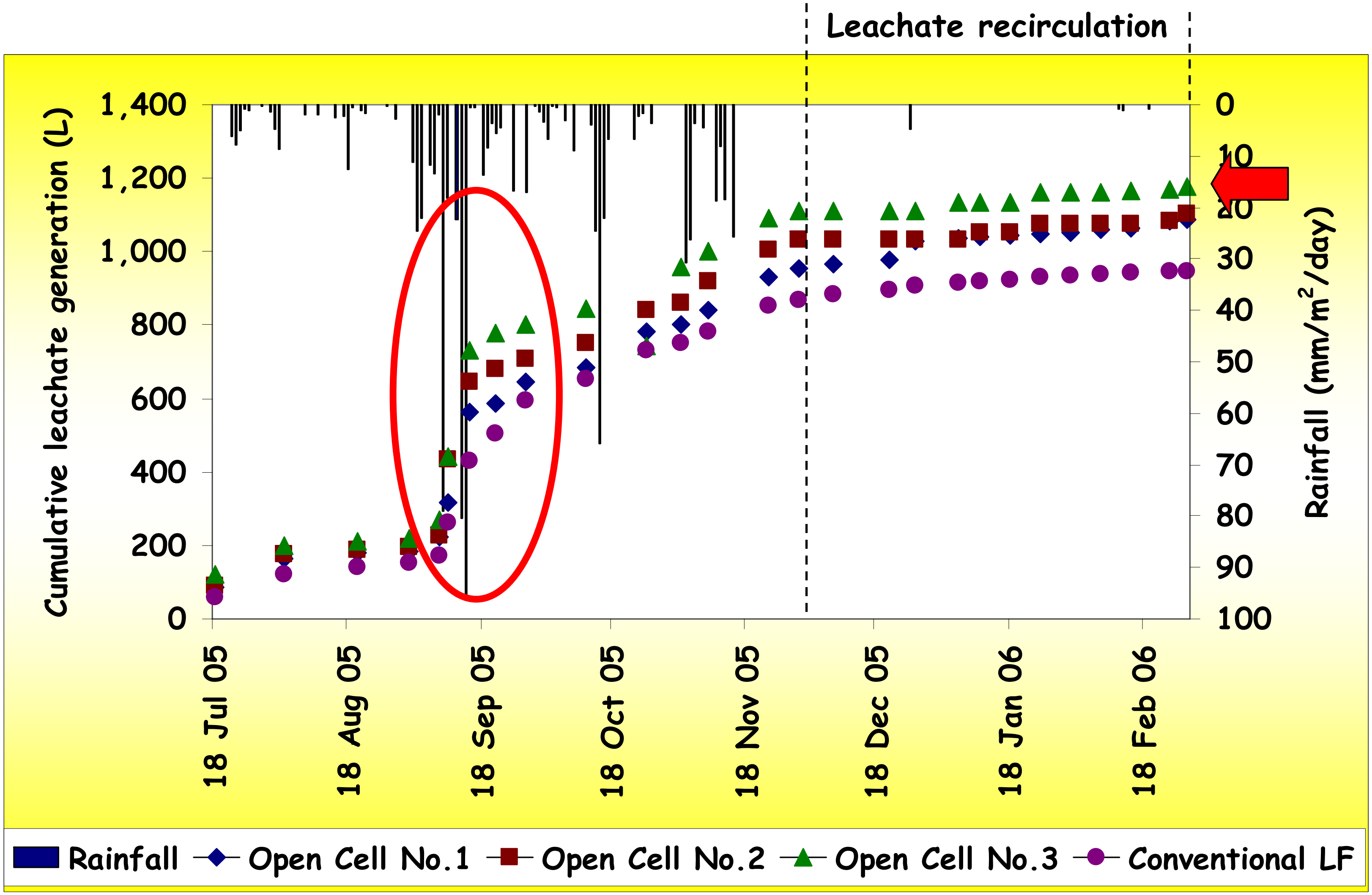
Task I: Lysimeters Preparation



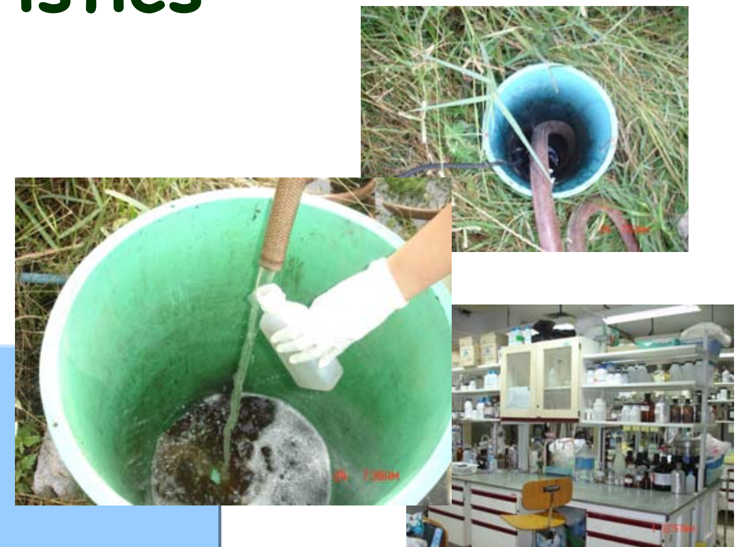
Task I: MSW Properties



Task I: Leachate Generation



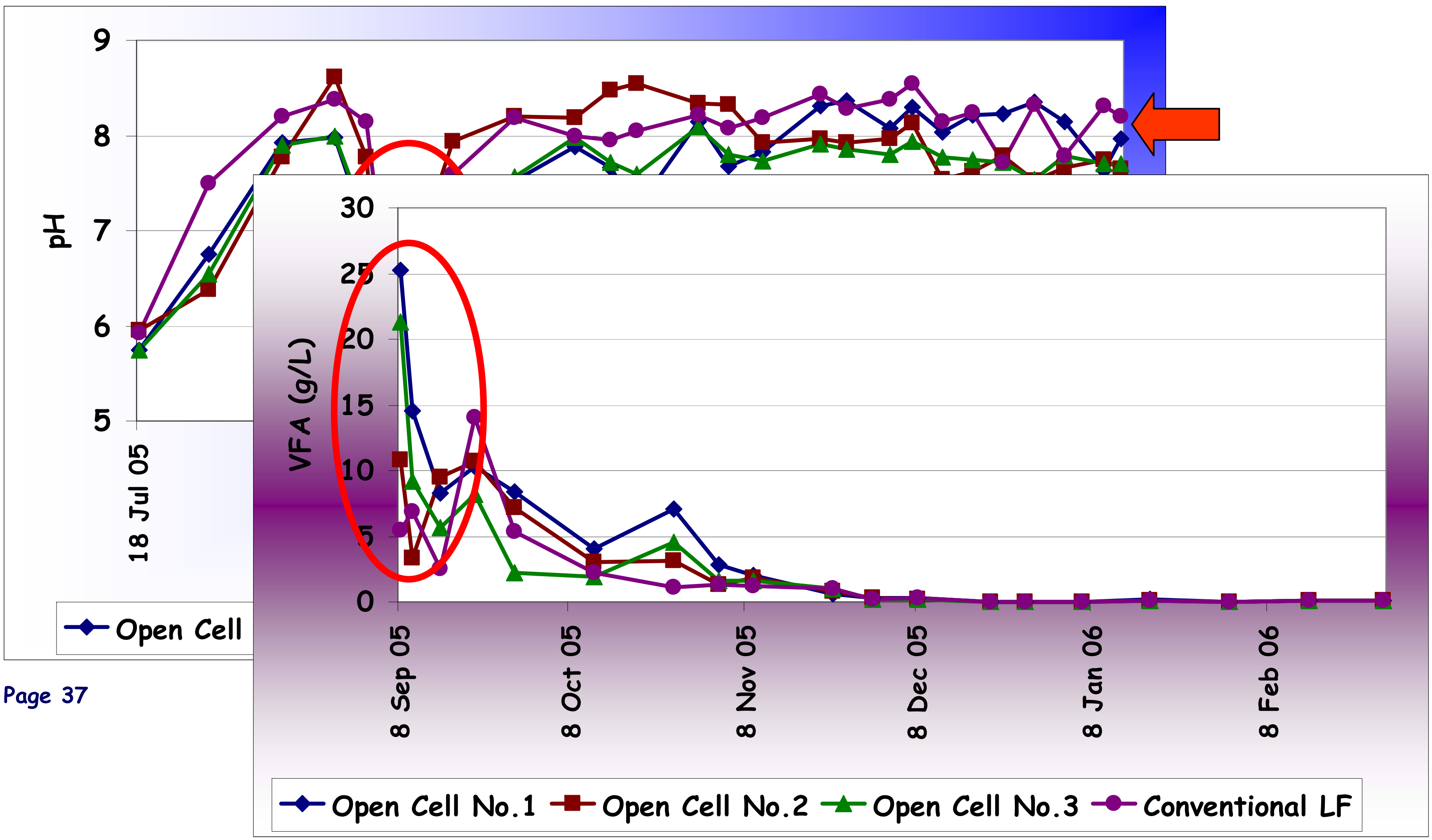
Task I: Leachate Characteristics



Parameters

- **pH**, Conductivity, Alkalinity, TS, VS, TDS and TSS
- Organic contents: **COD**, **BOD** and VFA
- Inorganic contents: **TKN**, NH_4-N and Organic-N
- **Carbon and Nitrogen load**
- Heavy metal: Mn, Cr, Cd, Pb, Ni, Zn and Cu

Task I: Leachate Characteristics (pH & VFA)



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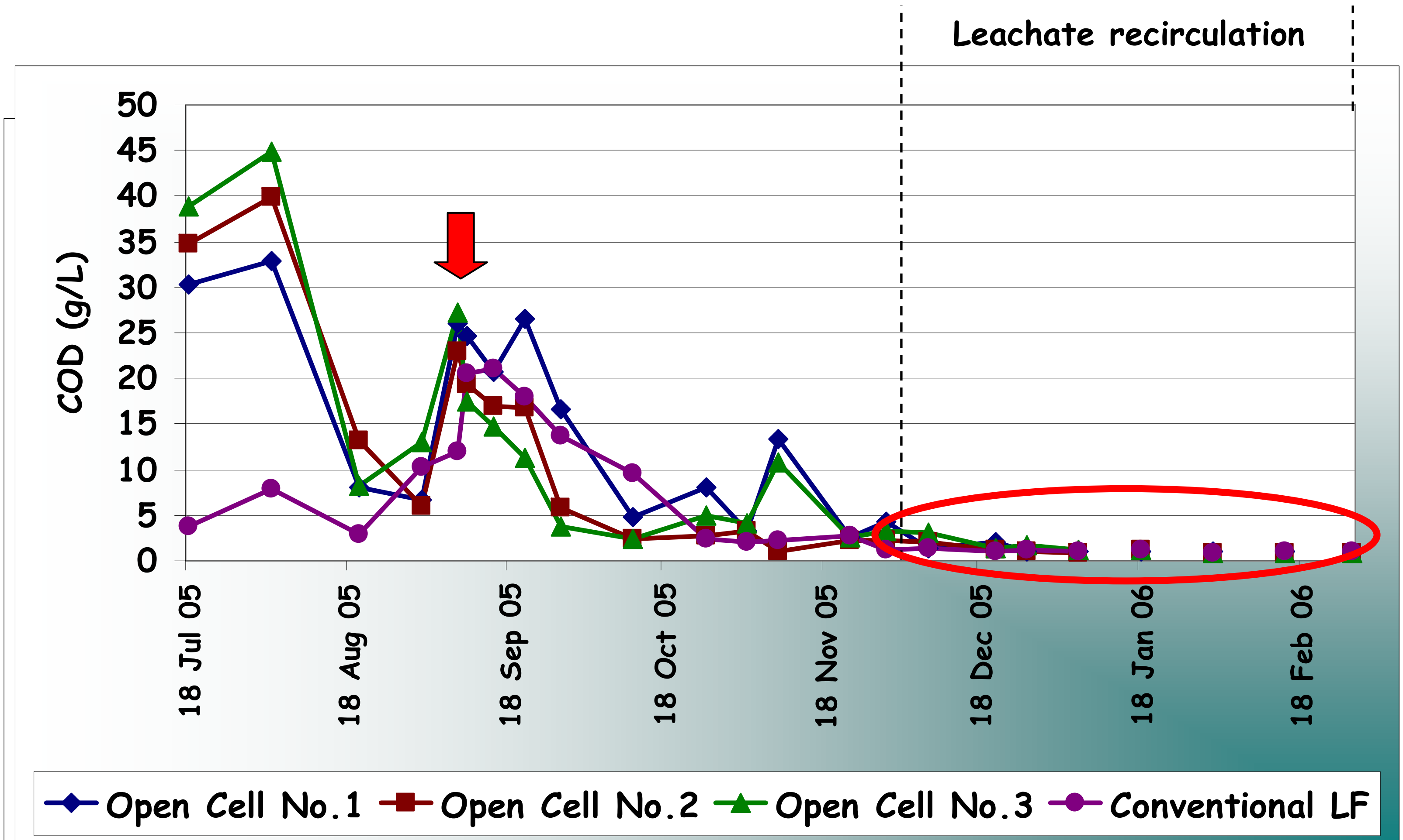
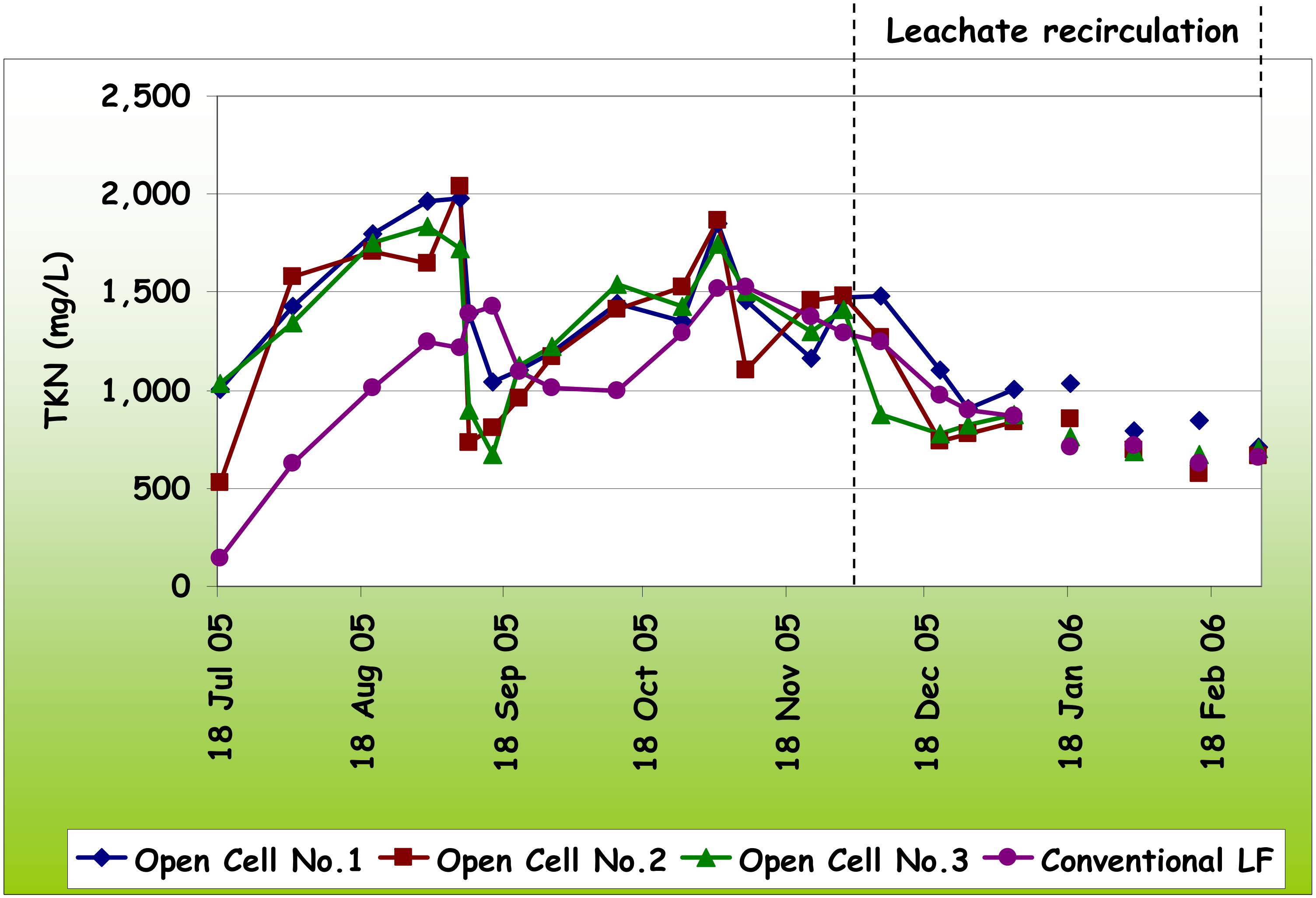
Task I: Leachate Characteristics (COD)

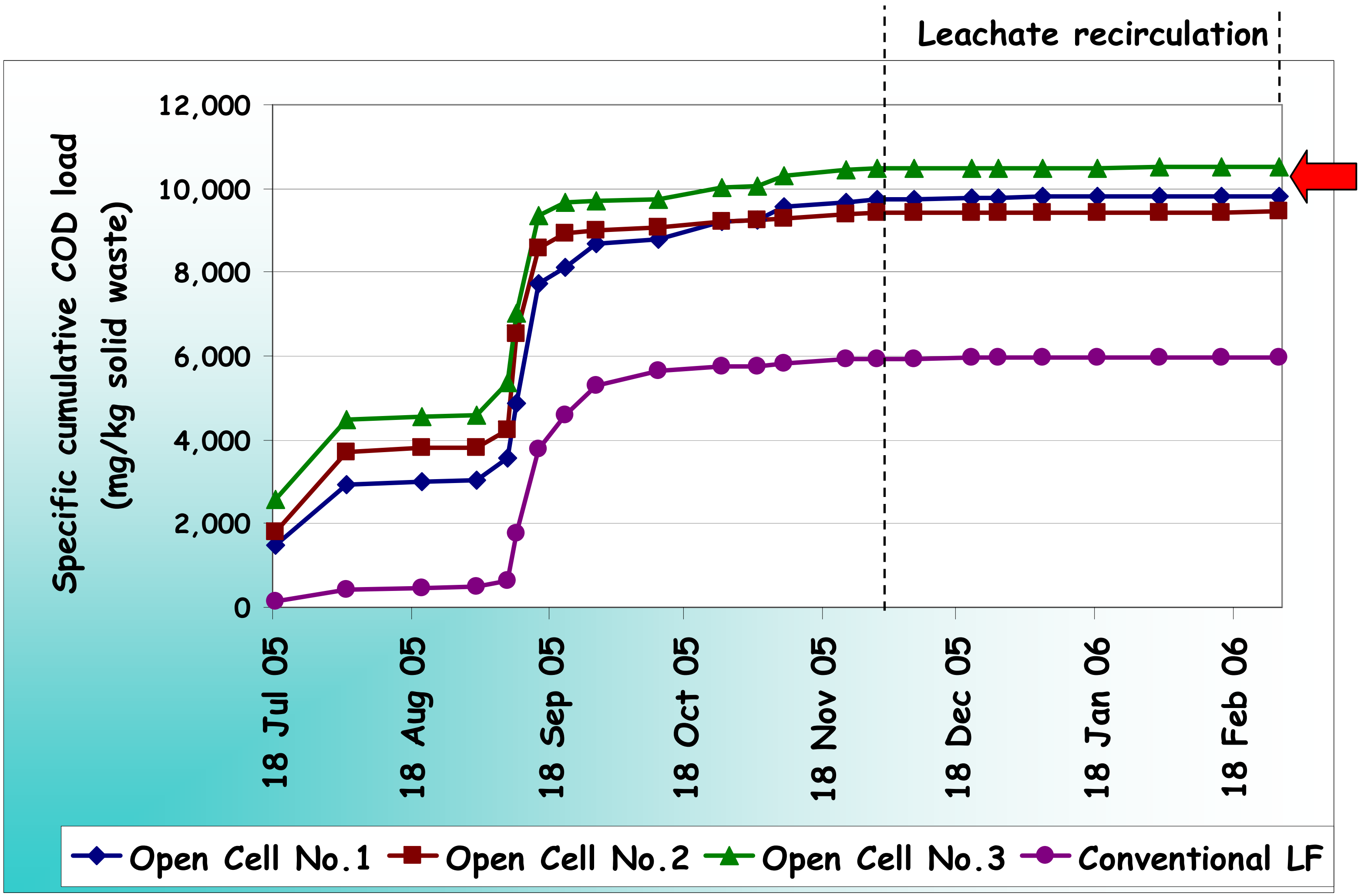


Open Cell No.1 Open Cell No.2 Open Cell No.3 Conventional LF

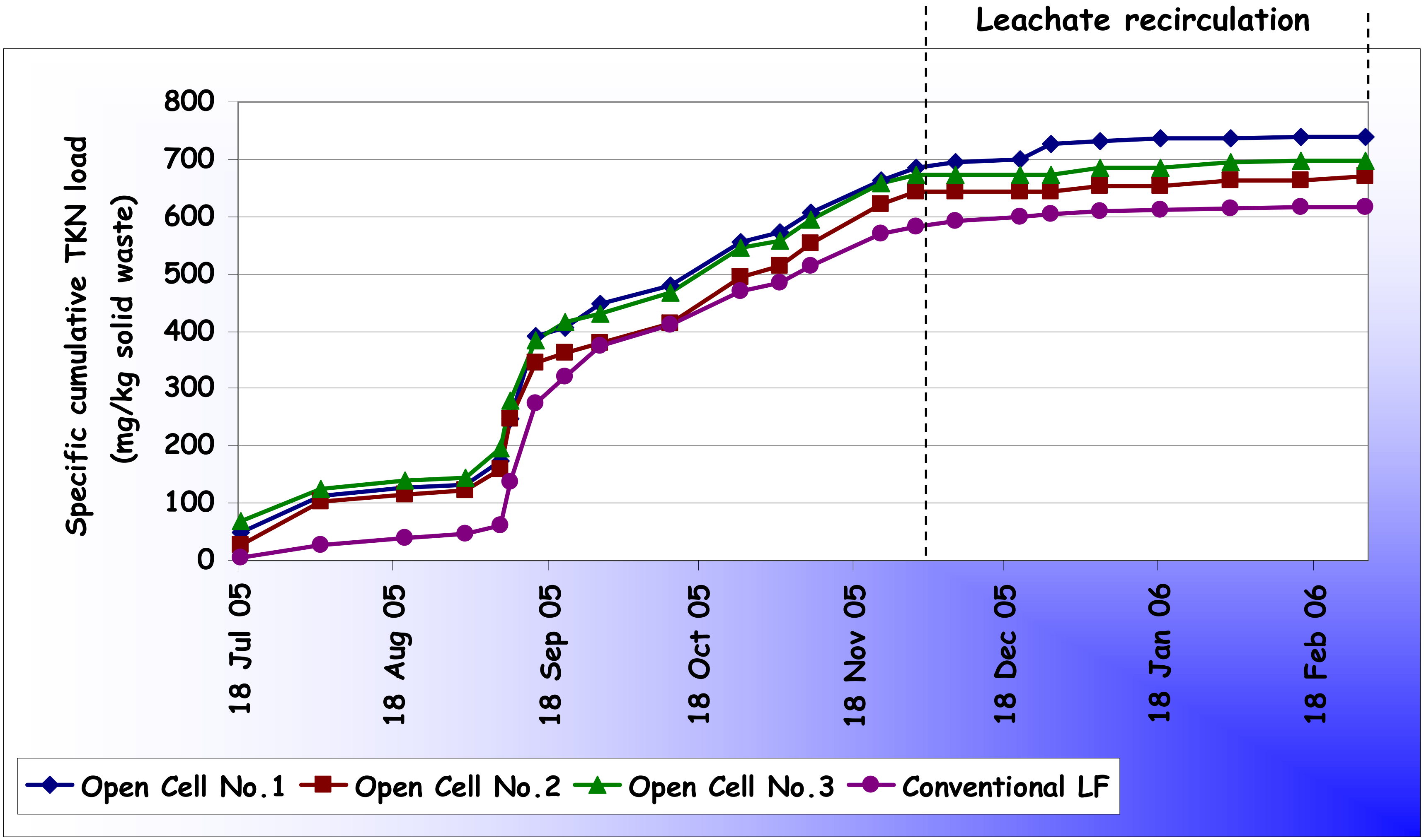
Task I: Leachate Characteristics (TKN)



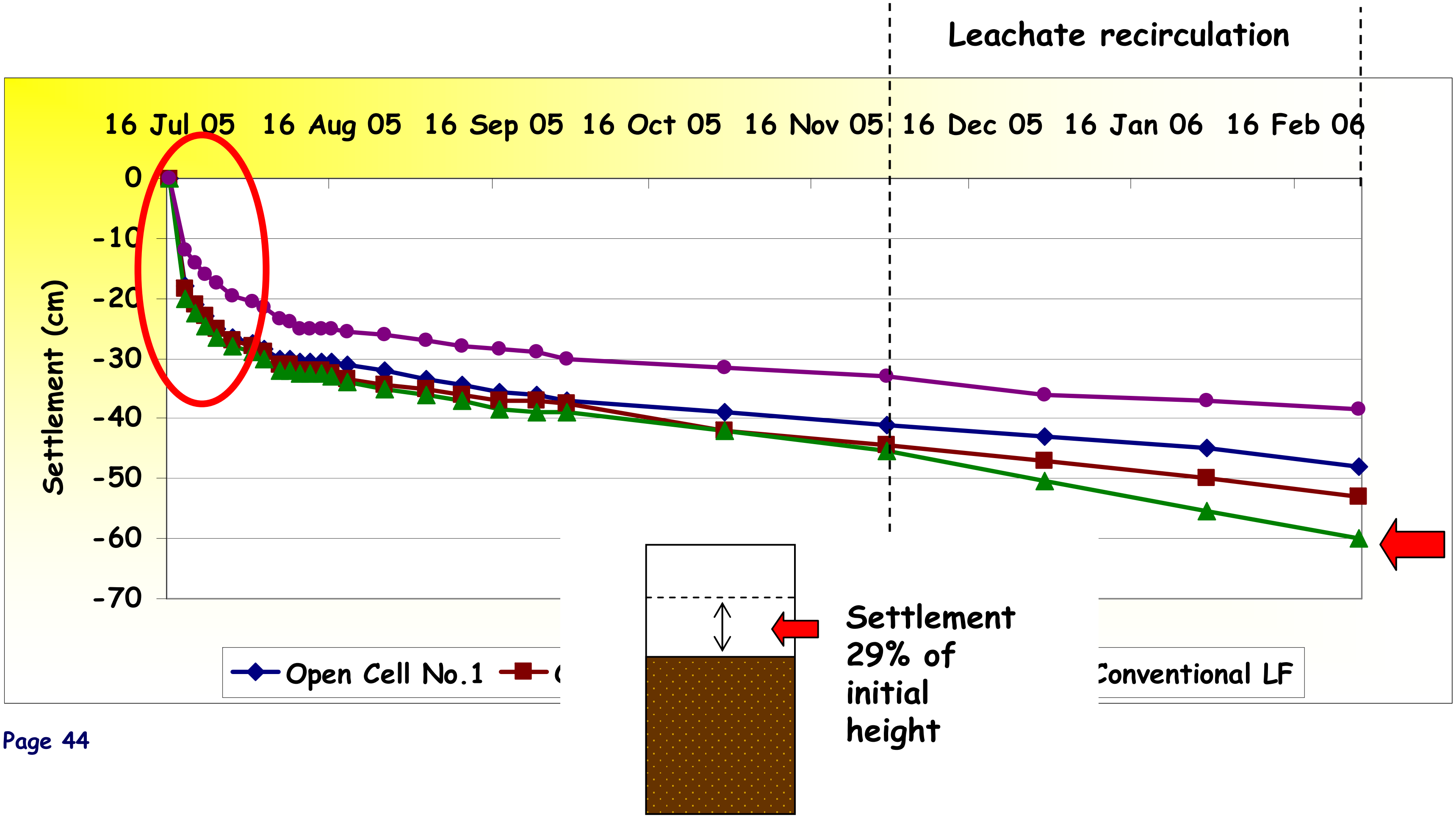
Task I: Leachate Characteristics (COD load)



Task I: Leachate Characteristics (TKN load)

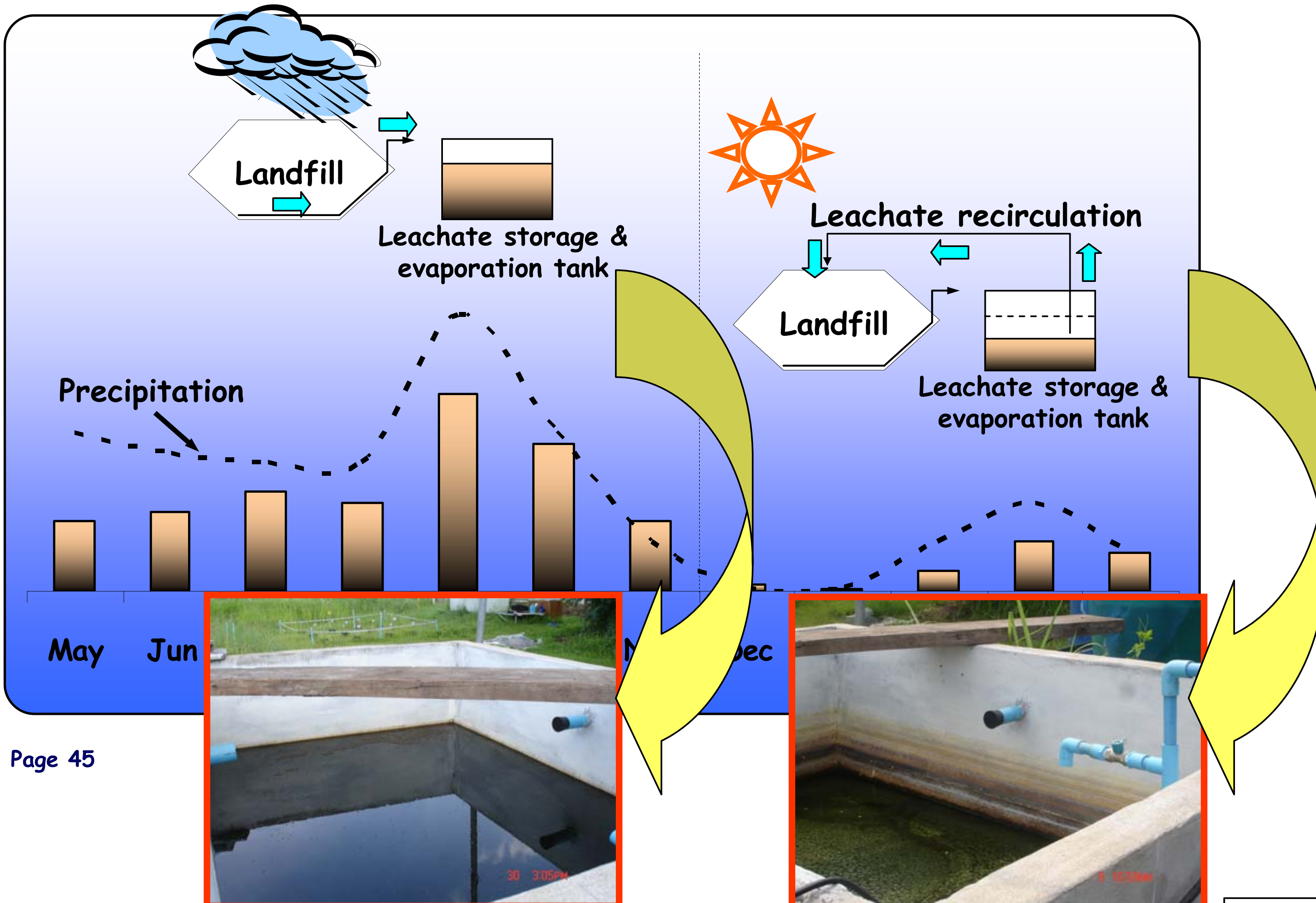


Task I: Settlement



Open Cell No.3

Task II: Water management



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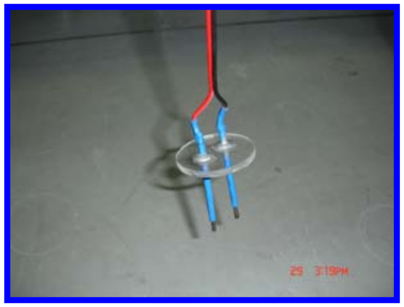
Task II: Leachate recirculation

Electrical resistance moisture content sensor



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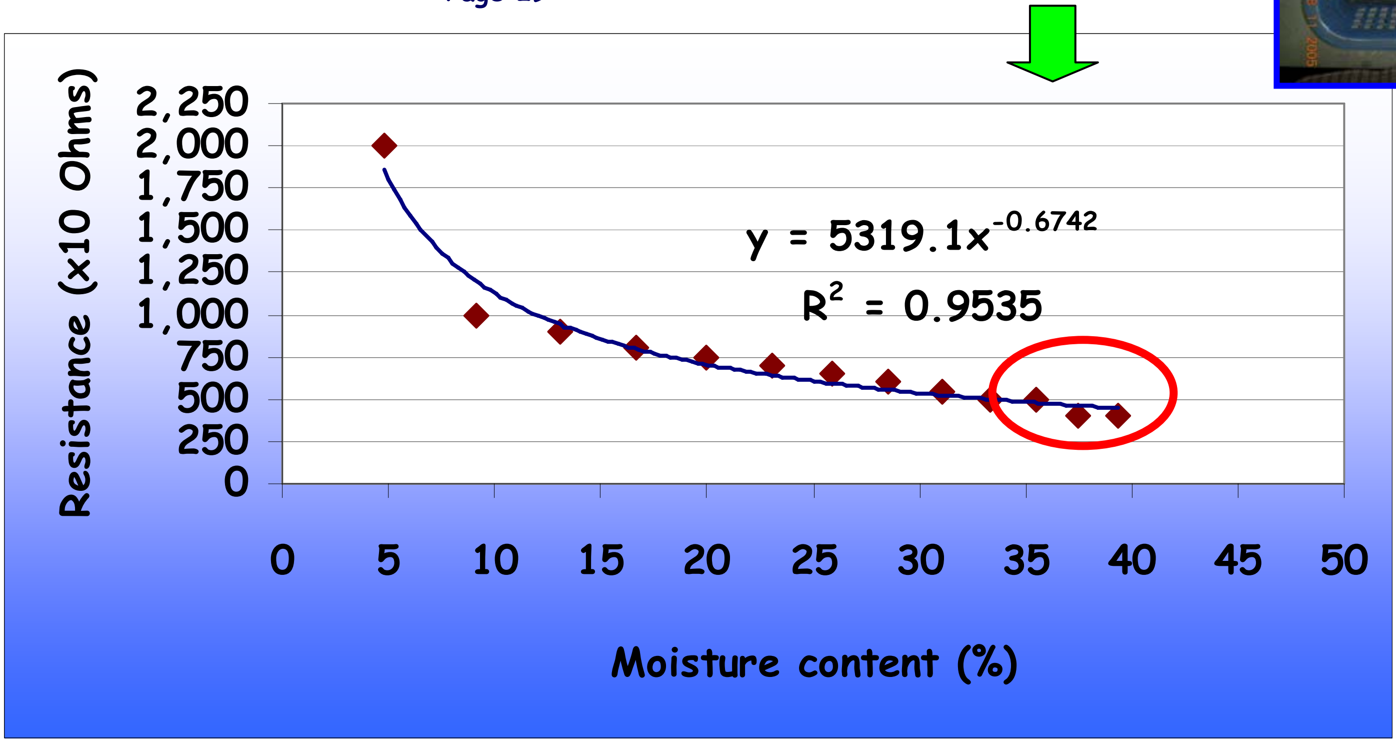

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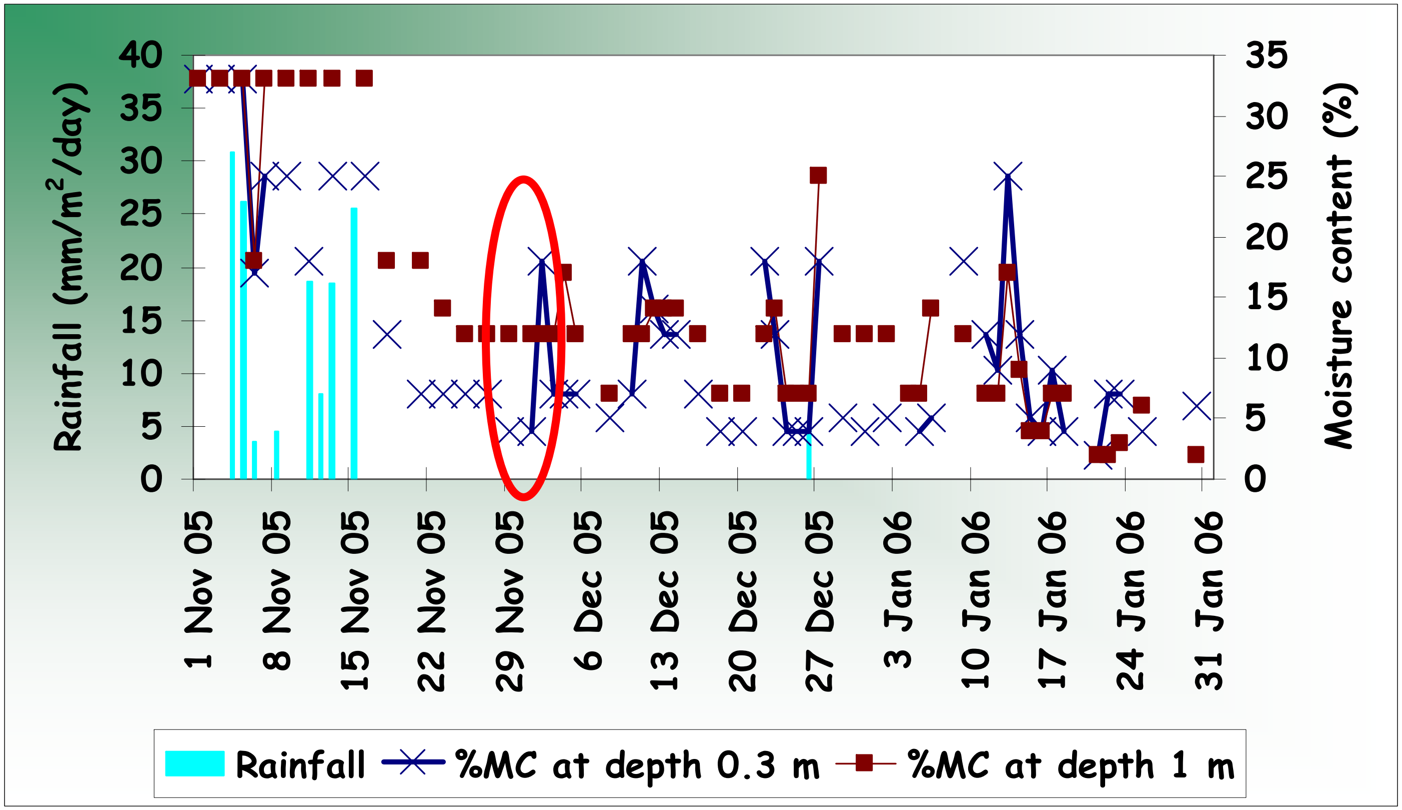
Task II: Leachate recirculation



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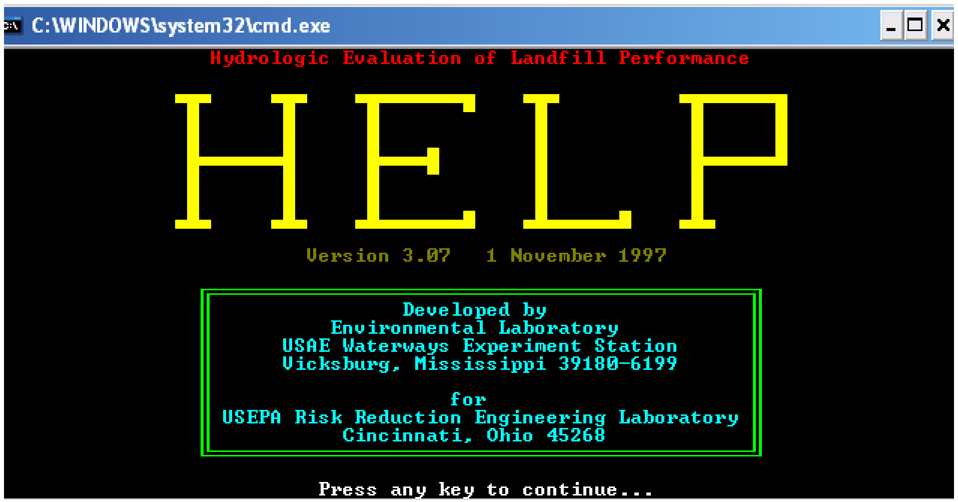
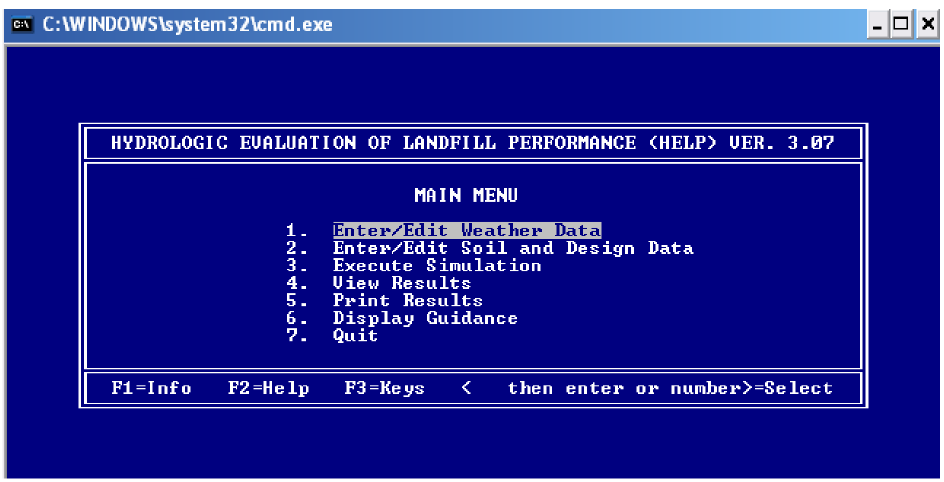
Task II: HELP model





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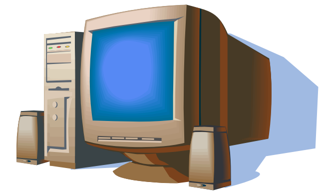
Input:



Weather data

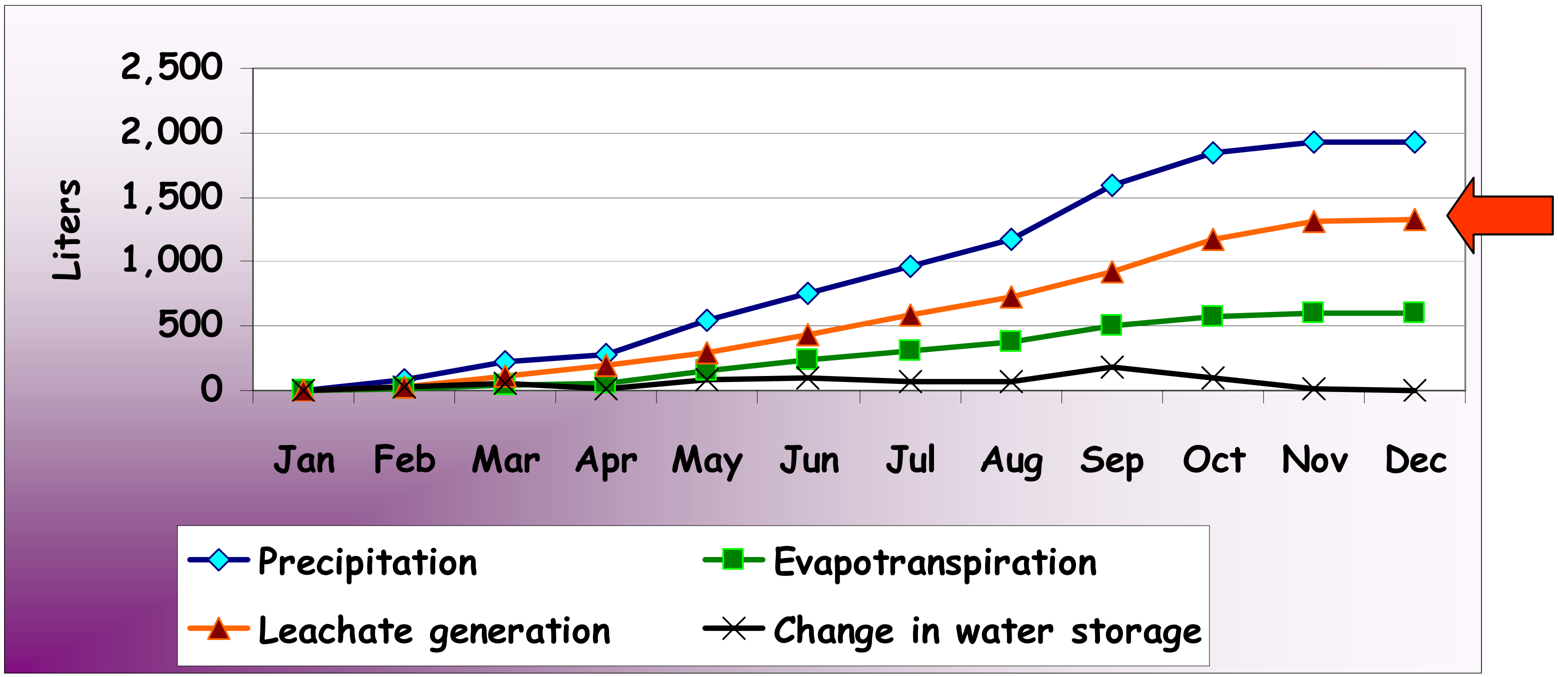
- precipitation
- temperature
- solar radiation
- evapotranspiration

Soil and design data

- landfill general information
- landfill profile
- runoff curve number

Task II: HELP model

Output:



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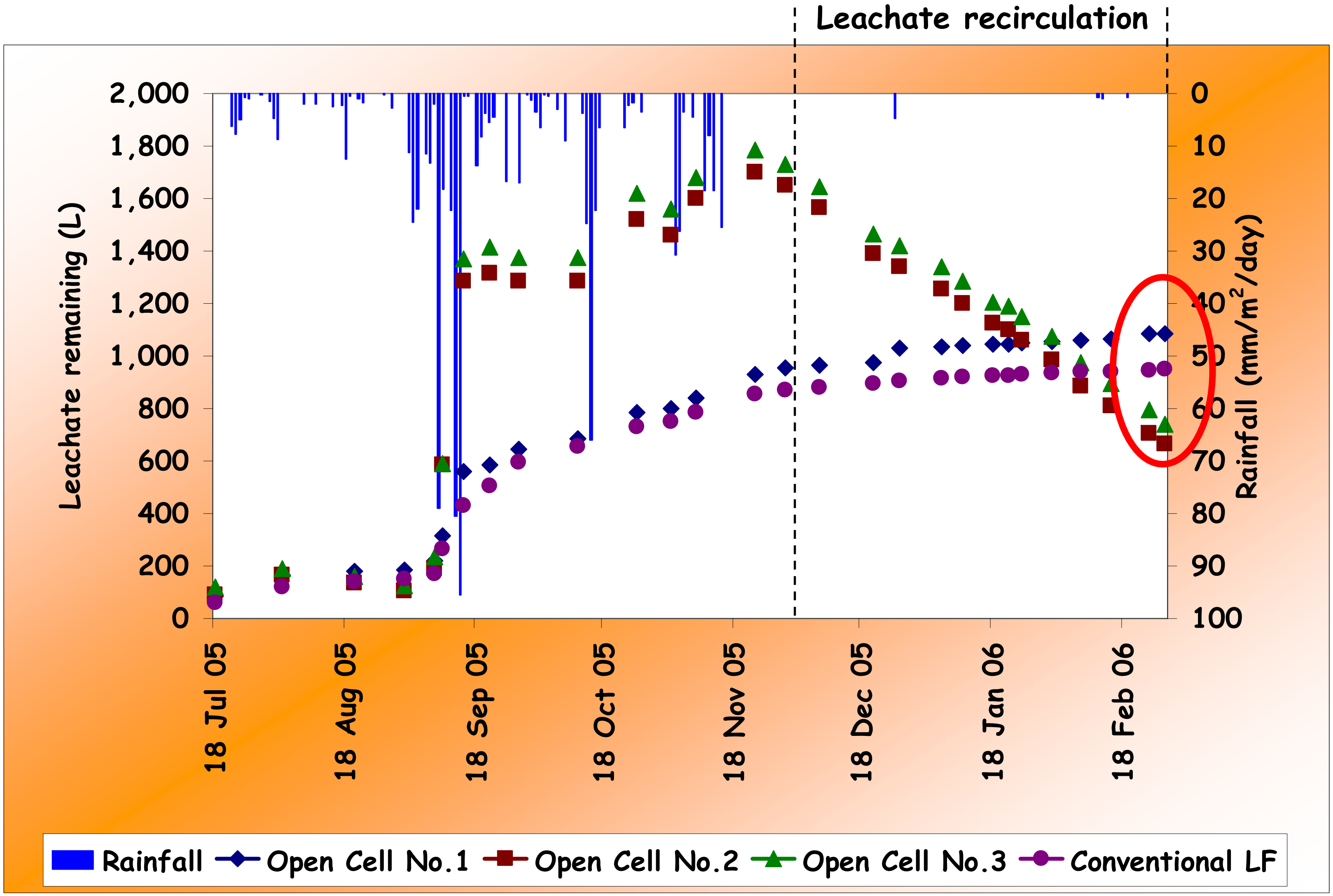
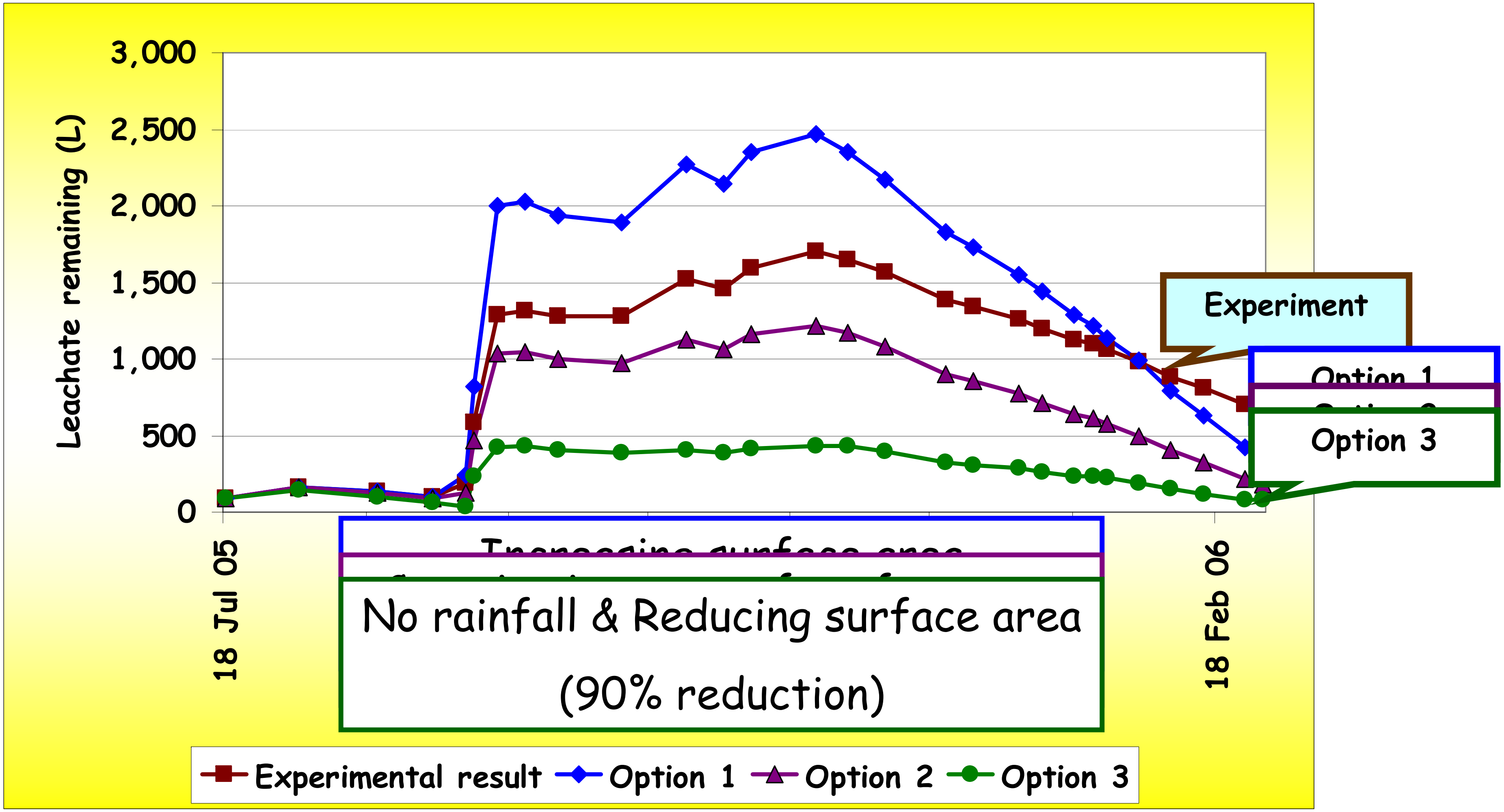
Water Management for Open Cell



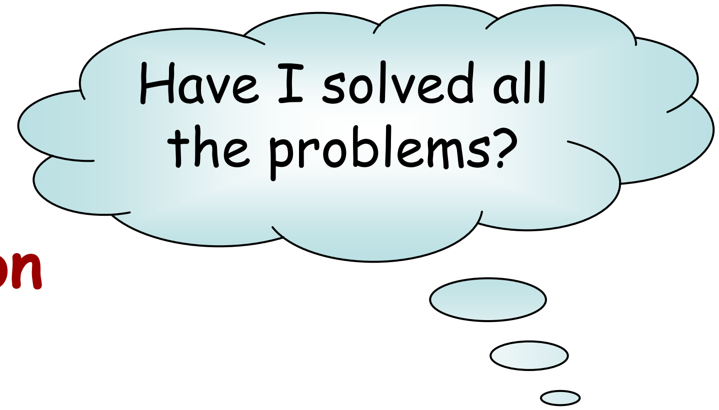
Task II: Options of improving water management for Open Cell landfill lysimeters



Conclusions

- **Open Cell landfills:** lower concentration of pollutant, higher specific cumulative COD and TKN load and higher settlement than **Conventional Landfill**
- **Open Cell No.3:** highest cumulative leachate generation, specific cumulative COD load and settlement rate
- **Leachate recirculation:** low flow rate, intermittent application, uniform distribution ⇔ Moisture content sensor
- **Water management:** for Open Cell No.2 and 3 lead to 30% reduction in volume of leachate for treatment compared with Open Cell No.1 and Conventional landfill ⇔ Evaporation

Recommendations



- **Influence of leachate recirculation on Open Cell landfill**

  Long term of monitoring Open Cell landfill lysimeters

- **Water management**

  Further on experiments to improve moisture content sensor

  Investigation on the water management by enhancing the evaporation to minimize leachate for treatment


Thank you