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# Leachate and Groundwater Contamination from the Major Solid Waste Landfills in Indochina Peninsular Region

**By:**

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**Phetyasone Xaypanya**

# ABSTRACT

Landfill leachate is a mixed compound which contains varieties of significant harmful toxicities; it generated from the waste which contained various hazardous substances, and it is one of the main sources to groundwater contamination, as well as surface water and sediments contamination of surrounding areas. In this study, leachate, sediment, groundwater and surface water samples were collected to characterize and assess the level of contamination regarding both basic biological and chemical parameters, especially the heavy metals. Besides, the future risks to the groundwater of surrounding areas base on the current site conditions were also discussed. Three different landfill sites; Nonthaburi landfill in Bangkok, Thailand, Dangkor landfill in Phnom Penh, Cambodia and KM-32 landfill in Vientiane, Laos were selected as the main sites for this study. The method using in this study was a combination of in-situ and laboratory measurements. The in-situ or on-site measurement was mainly for the basic parameters, and the laboratory measurements were focused on both biological parameters and heavy metals. As for heavy metals, leachate was investigated in the deepest detailed study, i.e., dissolved, suspended solids and total heavy metal of leachate. The simulation study based on the current site conditions and management together with the possible changes of the site conditions (Pit depth, leachate height) and the ranges of important parameters (hydraulic conductivity, partitioning coefficient) were assessed to see the potential future risk to the surrounding groundwater.

The results of the leachate characterization were confirmed that almost biochemical parameters of the fresh leachates were greater than the effluent standards and showed higher concentrations than those measured for the leachate in large storage ponds. The concentrations of those parameters were higher in the dry season than the wet season for all fresh leachate samples of none-covered pit areas, but no significant seasonal difference was observed in the covered areas and large leachate storage ponds. The total heavy metal concentrations were many times larger than those dissolved in the liquid part of leachate and showed higher than the effluent and environmental standard, respectively. The majority of heavy metals were partitioned in the suspended solids, while the heavy metal content of sediment was higher than the suspended solids, and no clear seasonal change of heavy metal contents was confirmed for both suspended solids and sediment samples. The leachate qualities were mainly affected by the landfill site conditions, e.g., soil cover, the waste compaction level, waste thickness, dumping method, and leachate storage, and these conditions lead to different levels of dilution. There was no clear evidence of groundwater contaminated by the landfill leachates from this study results, and existing heavy metal concentrations in the ground waters were confirmed and lower than the environmental standard limit for all heavy metals of all landfills, except the high arsenic concentration as background value at the KM-32 landfill site. The observation well (OSW1) at Nonthaburi landfill was found to be a high and increasing trend of chloride, as high as the same level of leachate, but the leakage could come from the horizontal direction not from the aquifer as the well and surrounding pits, and leachate pond were closed. For the surface water of Dangkor landfill, the high concentration of physical parameters was confirmed. It can be concluded that the landfill leachate influenced the surrounding surface water of Dangnkor landfill with the seasonal effects and similar trends to the leachate. The results of simulation study show groundwater and contaminant transport in the underground were highly depended on the several landfill site conditions and management, such as groundwater level, pit depth (pit height), leachate height and geological conditions (hydraulic conductivity, Kc and partitioning coefficient, Kd). The pith height of the current landfill conditions should not be lower than the depth of 30m and 15m below ground surface as for Dangkor and Nonthaburi landfill case, respectively. Also, the suggestion of the leachate high inside the dumped pits should be controlled with a lower level as compared to the current practice for lesser risk to groundwater.

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# Abbreviations

AAS- Atomic absorption spectroscopy
AOX- Halogenated Organic Compounds
APHA- American Pharmacists Association
As- arsenic
ASEAN- Association of South-East Asian Network
$BOD_5$-biochemical oxygen demand
Cd-Cadmium
Cl –chloride
$C_{L-LC}$-heavy metal concentration of the liquid part of leachate
COD - Chemical oxygen demand
$C_{Org}$-organic concentration
Cr-chromium
$C_S$- steady-state concentration
$C_{solid}$-solid concentration
$C_{S-SED}$-heavy metal content of sediment
$C_{S-SS}$-heavy metal content of suspended solids
$C_{SS}$-suspended solids concentration
$C_{T-LC}$-total heavy metal concentration of leachate
Cu-coper
DL- fresh leachate (Direct leachate)
DL.B- direct leachate from area B
DL.C- direct leachate from area C
DO - dissolved oxygen
EC- electrical conductivity
FDM - fully implicit Finite-Difference Method
Fe-iron
GMS- Groundwater Modelling System
GW-groundwater
HDPE- High-density polyethylene
HF - Hydrofluoric acid
Hg- Mercury
$H_L$-leachate height
HM-Heavy metal
$H_P$- pit height
ICP-AES- Inductively Coupled Plasma - Atomic Emission Spectrometry
JICA- Japan International Cooperation Agency
Kc- hydraulic conductivity of clay
Kd-partition coefficient
Ks- hydraulic conductivity of sand
LDP- leachate discharge pond
LF- landfill
Liq- Liquid part of leachate
LPI- leachate pollution index
MOC -Method of Characteristics
MODFLOW- modular finite-difference flow model
MSW- Municipal solid waste

Abbreviation

MT3DMS -modular three-dimensional transport model
$NH_3$-ammonia
$NO_2$- Nitrite
$NO_3$-nitrate
Non-Org-Non-organic
OL-old landfill
Org- organic
ORP- oxidation-reduction potential
OSW- observation well (1-2)
Pb-Lead
Mn-manganese
pH- pouvoir hydrogène
PTFE-Polytetrafluoroethylene
SED-sediment
$SO_4$- Sulfate
SS- suspended solids
SW-surface water
TCLP- toxicity characteristic leaching procedure
TDS- total dissolved solids
Temp- temperature
TKN- total Kjeldahl nitrogen
TOC- total organic carbon
Turb- Turbidity
TVD- third-order Total Variation Diminishing
UNEP- United Nations Environment Programme
US EPA- United States Environmental Protection Agency
Vint- average velocity of fluid flow
WL- wetland
Zn-zinc
3R-reduce-reuse-recycle

# Chapter 1

# Introduction

## 1.1 Background and Problem Statement

Various environmental conditions of Indochina peninsular countries are the same to other developing countries in Southeast Asian and other regions. For example, they are facing solid waste problems as the result of rapid growth of population and economic condition. Municipal solid waste (MSW) management is one of the existing unsolved problems in the developing countries for the past decades up to the present, especially in the Association of Southeast Asian Network (ASEAN) region. Those countries have been facing a linear increase of municipal solid waste and waste management problems, especially the environmental risks by the landfill leachate, Pariatamby and Tanaka (2014). As rapid increasing of solid waste, more land is needed for the final disposal of these solid wastes, and issues related to waste disposal have become highly challenging for all countries. The landfill is a primary facility for municipal solid waste disposal in the most of the countries; especially in South East Asian region where many countries are still under developing country status, and some of them are still in the list of least developed countries. The increase of resource consumption results in massive amounts of solid wastes from various kinds of industries and domestic activities, which poses significant threats to human health and environment, Ziadat and Mott (2005). Landfill leachate is generated through the water supplies to the landfill waste compositions, by the precipitation, surface water infiltration, the groundwater percolation, and moist included in the waste. The concentration levels of contaminants depending on the way of disposing of the waste, as well as the waste management before reaching the waste disposal site, and also at the site disposal, such as the waste extraction and classification before dumping and final covering, Ole et al., (2000). Also, the leachate quality, quantity, and its characteristics are directly related to the waste management practice, climate condition, and waste composition characteristics, as well as the landfill operation method. The leachate could be a primary source of various contaminants and pollution. It is a severe concern for most of waste disposal facilities including sanitary landfills, controlled dumping, and open dumping facilities, to minimize the risk to the human health and environments in the nearby communities, El-Fadel et al., (1997). Moreover, Leachate quality is mainly influenced by waste characteristics including the waste composition, waste age, and site operation methods, such as compaction level, daily cover, pretreatment, liquid waste co-disposal, quality and quantity of water entering the landfill. One of the important factors affecting the leachate quantity and quality are the chemical reactions, such as biodegradation, adsorption, hydrolysis, dissolution, dilution, partitioning, and precipitation, Kjeldsen et al., (2002). In most cases, landfill leachate consists of organic matter (biodegradable and non-bio degradable), inorganic pollutants and hazardous substances. The hazardous substances in municipal solid waste are presented in the form of paints, mercury-containing wastes, batteries, vehicle maintenance products, and many other diffuse products, Slack et al., (2004, 2005). Although the actual sources of the hazardous substances could be discussed, the qualitative discussion on the effects of each source on the leachate quality is very difficult, especially for the situation of poor waste management as discussed above, Slack et al., (2004). Therefore, the leachate quality assessment is considered as a characterization of contaminant source, which is the first and the most important step for the environmental risk assessment of MSW disposal facility.

Huge volume of leachate are being produced in parallel with the rapid increase of solid waste for each country and region, as well as from around the world. The leachate problems were worsened by the fact that many landfills in developing countries do not have appropriate landfill facilities, such as bottom clay liner, leachate collection and controlling system, and the leachate treatment facility. This increases the possibility of dissipation of leachate through the landfill layers to contaminate groundwater, and also for surface water contaminations, Kanmani and Gandhimathi (2013). Solid waste disposal facilities, such as open dumps, controlled dump, landfills, sanitary/engineered landfills or incinerators represent a significant source of metals released to the environments, especially to the surrounding soils, Iwegblue et al., (2010). At the same time, the nearby areas or areas which locate in the downstream side of the landfills have higher possibility of groundwater contamination. Furthermore, the most of landfills and dumping facilities in the developing countries release a significant amount of contaminated leachate directly into its vicinity. The impacts of landfill leachates on the surface and groundwater have given rise to numbers of studies in recent decades. However, there are different levels of impact on human health and the environment; depending on the type of landfill and their management, which is including the management of the main source of leachate production as solid waste. Many studies have been confirmed that the concentration of various heavy metals usually exceeded the national and international organization standard limit as compared to both groundwater and effluent standards, Abu-Rukah and Al-kofahi, (2001) and Aderemi et al., (2011).

## 1.2 Significances of Landfill Sites in the Study Area

The common practices of solid waste management and disposals in developing countries are incomparable to those of developed countries, including the landfill sites covered in this study. Improper waste management leads to the dirty and unclean urban communities, while the major consequent impacts could be seen at the final waste disposal facilities. Excavated method or deep pit disposal of solid waste dumping is one of common practice in the Indochina peninsular region. In many cases, the existing deep pits at different purposes of digging origin have been simply used as solid waste dumping facility, e.g., digging for reclamation of lands from other areas, digging for infrastructure and house construction, and other commercial digging purposes. The common problems occurred in these landfills, and waste disposal facilities are an uncontrolled release of leachate to the surface water of nearby areas and creek, and also the possible risks to the groundwater contamination as deep pit disposal as shown in Figure 1.1. That is the results of improper landfill management with lack of important and necessary facilities, such as leachate controlled and treatment system. Besides, the uncovering of daily waste dumping at the sites is leading to the bad smell and potential for the production of larger leachate volume by the rainwater.

**Figure 1.1** Landfill and leachate situation of Indochina peninsular

On the other hands, the deeper pit for waste dumping could increase the possible risk to the groundwater as it reduces the thickness of the natural clay barrier to the aquifer. Figure 1.2 shows the schematic diagram which describes the leachate contamination mechanism to the environment, especially to surface water and groundwater, as well as to the agriculture and land of surrounding areas. Figure 1.2 also represents the situation of landfills in Indochina peninsular countries as they do not have proper management at the site. The advance landfill technology was not fully applied in these countries due to the limitation of the financial and technical support.

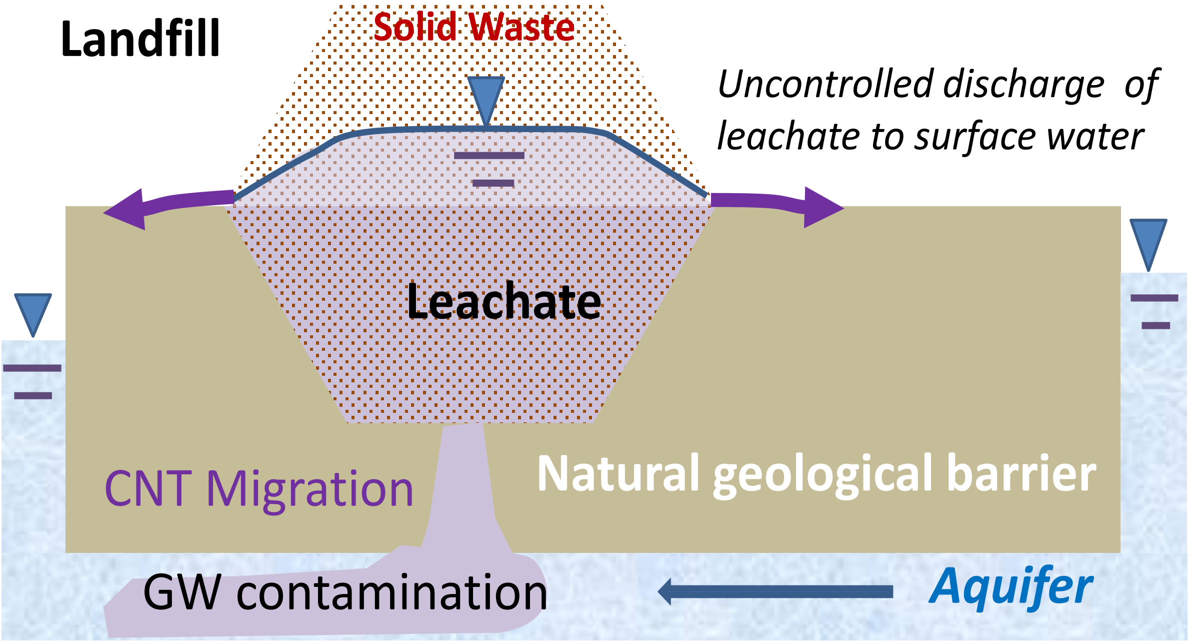
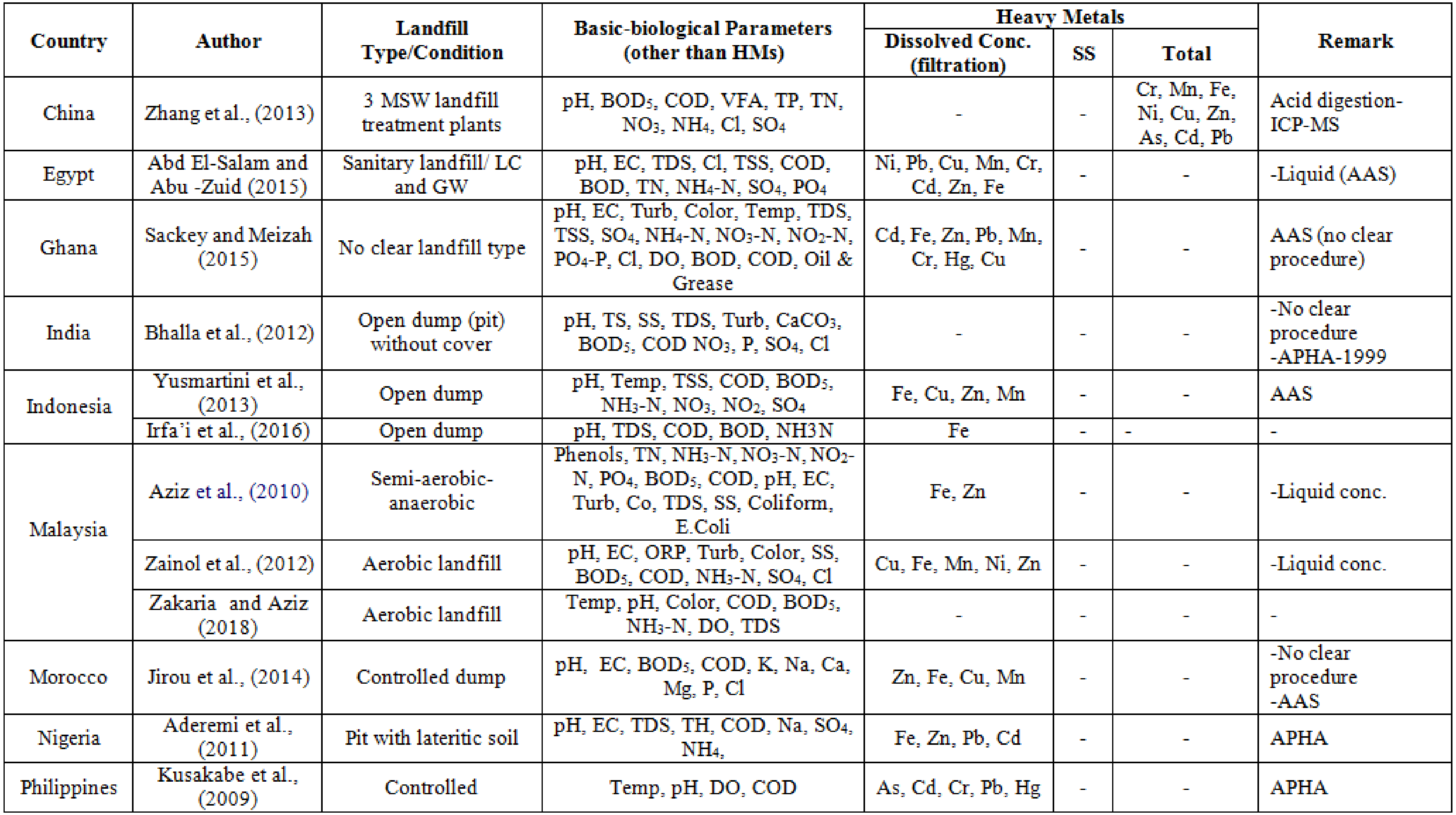


**Figure 1.2** The schematic of surrounding environment being contaminated by the landfill leachate

Since all landfill leachates around the world have their characteristics and uniqueness, they are based on many conditions and the surrounding environment. The landfills in the Indochina peninsula are also had their uniqueness as compared to other countries and regions. In these landfills, there are many significant differences, e.g., the solid waste management, waste composition, and another important factor is climate conditions due to the slight difference of the climate can be found for the different nearby country, while the significant difference can be found for the difference of the region.

**Table 1.1** The previous landfill leachate assessment across the regions



| Country | Author | Landfill Type/Condition | Basic-biological Parameters (other than HMs) | Heavy Metals: Dissolved Conc. (filtration) | Heavy Metals: SS | Heavy Metals: Total | Remark |
|---|---|---|---|---|---|---|---|
| China | Zhang et al., (2013) | 3 MSW landfill treatment plants | pH, $BOD_5$, COD, VFA, TP, TN, $NO_3$, $NH_4$, Cl, $SO_4$ | - | - | Cr, Mn, Fe, Ni, Cu, Zn, As, Cd, Pb | Acid digestion-ICP-MS |
| Egypt | Abd El-Salam and Abu -Zuid (2015) | Sanitary landfill/ LC and GW | pH, EC, TDS, Cl, TSS, COD, BOD, TN, $NH_4$-N, $SO_4$, $PO_4$ | Ni, Pb, Cu, Mn, Cr, Cd, Zn, Fe | - | - | -Liquid (AAS) |
| Ghana | Sackey and Meizah (2015) | No clear landfill type | pH, EC, Turb, Color, Temp, TDS, TSS, $SO_4$, $NH_4$-N, $NO_3$-N, $NO_2$-N, $PO_4$-P, Cl, DO, BOD, COD, Oil & Grease | Cd, Fe, Zn, Pb, Mn, Cr, Hg, Cu | - | - | AAS (no clear procedure) |
| India | Bhalla et al., (2012) | Open dump (pit) without cover | pH, TS, SS, TDS, Turb, $CaCO_3$, $BOD_5$, COD $NO_3$, P, $SO_4$, Cl | - | - | - | -No clear procedure<br>-APHA-1999 |
| Indonesia | Yusmartini et al., (2013) | Open dump | pH, Temp, TSS, COD, $BOD_5$, $NH_3$-N, $NO_3$, $NO_2$, $SO_4$ | Fe, Cu, Zn, Mn | - | - | AAS |
| | Irfa'i et al., (2016) | Open dump | pH, TDS, COD, BOD, NH3N | Fe | - | - | - |
| Malaysia | Aziz et al., (2010) | Semi-aerobic-anaerobic | Phenols, TN, $NH_3$-N, $NO_3$-N, $NO_2$-N, $PO_4$, $BOD_5$, COD, pH, EC, Turb, Co, TDS, SS, Coliform, E.Coli | Fe, Zn | - | - | -Liquid conc. |
| | Zainol et al., (2012) | Aerobic landfill | pH, EC, ORP, Turb, Color, SS, $BOD_5$, COD, $NH_3$-N, $SO_4$, Cl | Cu, Fe, Mn, Ni, Zn | - | - | -Liquid conc. |
| | Zakaria and Aziz (2018) | Aerobic landfill | Temp, pH, Color, COD, $BOD_5$, $NH_3$-N, DO, TDS | - | - | - | - |
| Morocco | Jirou et al., (2014) | Controlled dump | pH, EC, $BOD_5$, COD, K, Na, Ca, Mg, P, Cl | Zn, Fe, Cu, Mn | - | - | -No clear procedure<br>-AAS |
| Nigeria | Aderemi et al., (2011) | Pit with lateritic soil | pH, EC, TDS, TH, COD, Na, $SO_4$, $NH_4$, | Fe, Zn, Pb, Cd | - | - | APHA |
| Philippines | Kusakabe et al., (2009) | Controlled | Temp, pH, DO, COD | As, Cd, Cr, Pb, Hg | - | - | APHA |

**Table 1.1** The previous landfill leachate assessment across the regions (Cont.)

| Country | Author | Landfill Type/Condition | Basic-biological Parameters (other than HMs) | Heavy Metals | | | Remark |
|---|---|---|---|---|---|---|---|
| | | | | Dissolved Conc. (filtration) | SS | Total | |
| Sri Lanka | Sewwandi1 et al., (2012) | Leachate from 12 open dumping facilities | $BOD_5$, COD, TN, TP | Cr, Mn, Fe, Ni, Cu, Zn, As, Se, Sr, Cd, Sb, Pb | - | - | -No clear procedure<br>-No separated results |
| Taiwan | Fan et al., (2006) | Semi-sanitary Trench method | pH, $BOD_5$, COD, TS, DS, COD, VSS, TS, PtCo, TOC, K, Na, Ca, Mg | Pb, Cd, Hg, Cr, Cu, Fe, Mn, Ni, Zn | - | - | - ICP-AES<br>Probably liquid |
| Turkey | Banar et al., (2006) | Sanitary landfill | pH, TS, Temp, TDS, EC, SS, VS, COD, BOD, Oil & grease, Org, $SO_4$, Cl, $CaCO_3$, Acidity, Alkalinity, Phenol, $NO_3$, $NO_2$, Na, K, Ca | Fe, Cd, Cu, Pb, Zn, Ni | - | - | -No clear procedure.<br>-Varian Flame |

## 1.3 Level of Previous Landfill Leachate Study

As shown in Table 1.1, numbers of landfill leachate studies have been conducting from the past to the present across the regions, and also, some other studies were focused on the leachate treatment and remediation. Most of the studies have investigated the basic parameter which is in measurement**.** However, few of them have investigated the heavy metal composition of the leachate**,** especially in details on their partitioning. The leachate had two components, namely, liquid part and suspended solids (SS). Contaminants can exist in the two parts of the leachate. Although the liquid part is the major fraction in mass and volume, a few percentages of SS could adsorb some substances, especially heavy metals. Therefore, to know the leachate quality partitioning, in other words, separated concentrations in the liquid part and solid part should be investigated. However, many of the previous studies investigated the heavy metals but only assessing the liquid part as filtered samples. It can be confirmed from the table that less than 5 % of previous studies had checked for the total heavy metal contained in the leachate as separated part of leachate as the real condition of all landfill leachate, i.e. liquid part of leachate (Liq), solid part of leachate or suspended solids (SS) and the total concentration of the leachate (Total). Even though the newest studies by Irfa'i et al., (2016) and Zakaria and Aziz (2018) as for the landfill in Indonesia and Malaysia, respectively. These studies were also concerned only for the basic parameter, such as temperature (Temp), pH, electrical conductivity (EC), Turbidity (Turb), total dissolved solids (TDS), dissolved oxygen (DO), oxidation-reduction potential (ORP) and other biological parameters, i.e. Chemical oxygen demand (COD) and biochemical oxygen demand ($BOD_5$), Nitrite ($NO_2$), nitrate ($NO_3$), and ammonia ($NH_3$) and including the chloride (Cl). In addition, many of those studies have been emphasized that different waste, landfill condition as well as the location will lead to the difference the leachate quality and pollution and also the different level of contamination, it was due to each site condition is unique, Sewwandi et al., (2012), Banar et al., (2006), Jirou et al., 2014) and Zhang et al., (2013).

## 1.4 Objectives of the Study

Based on the pre-survey of previous studies, the current research will be a more intensive study based on leachate physical condition (the liquid part of leachate, solid part of leachate and the total concentration of leachate as for heavy metals). The detailed objectives of this study will be separated into two parts, general and specific objectives indicating as follows.

### 1.4.1 General Objective

The general objectives of this study are to characterize and assess the leachate quality and nearby groundwater of the three specific landfill site conditions in three countries located in Indochina peninsular region, namely Nonthaburi landfill (Nonthaburi Province, Bangkok metropolitan Thailand), Dangkor landfill (Phnom Penh, Cambodia), and KM-32 landfill (Vientiane, Laos). All of the related factors to the leachate quality and its consequent effects will be assessed.

### 1.4.2 Specific Objectives

The details and specific objectives of this study are set and listed as follows:

a. To Characterize

  - Landfill leachates with detailed leachate components; liquid part by filtering, solid part (suspended solid) and the total leachate
  - Landfill sites with its initial geological condition
  - Landfill sediments
  - Groundwater and surface water of those landfill vicinities

b. To link the basic parameters to chemical and biological parameters

c. To assess the influential factors on the leachate quality

d. To compare the leachate characteristics from the studied landfills and other landfills in ASEAN countries.

e. To do a simulation study on the contaminant transport in underground condition for those landfill areas.

  - Assessing the possible risks regarding the deep pit disposal to the groundwater
  - Assessing the possible risks regarding to the fluctuation of leachate height inside the leachate ponds and pits

- Assessing the possible risks regarding the geological and dimensionless parameters

## 1.5 Key Assessments of Current Research

The current research study is covered most of the details of leachates from those selected landfills of Indochina peninsula. Also, the study included the related consequent effects to the surrounding environments by the contaminated leachate, such as landfill sediment, surface water, and groundwater as well as the potential risks to the nearby groundwater regarding the current site conditions with the current leachate management. The main key assessment of this study can be found as shown in Table 1.2-1.5. A part of these key assessments listed in the table, the related parameters regarding physical and chemical condition to those key points were correlated and discussed to explain the specific behavior and characteristics of landfill leachates and its related consequent effects.

**Table 1.2** Key assessments of leachate samples for the current study

| Country | Landfill | Landfill Type/Condition | Basic Parameter | Heavy Metals | | | Organic for SS |
|---|---|---|---|---|---|---|---|
| | | | | Liq | SS | Total | |
| Cambodia | Dangkor | Controlled Dump | √ | √ | √ | √ | √ |
| Laos | KM-32 | Open Dump | √ | √ | √ | √ | √ |
| Thailand | Nonthaburi | Semi-sanitary | √ | √ | √ | √ | √ |

**Table 1.3** Key assessments of sediment samples for the current study

| Country | Landfill | Landfill Type/Condition | Organic Content | Particle Size distribution | Heavy Metals |
|---|---|---|---|---|---|
| Cambodia | Dangkor | Controlled Dump | √ | √ | √ |
| Laos | KM-32 | Open Dump | √ | √ | √ |
| Thailand | Nonthaburi | Semi-sanitary | √ | √ | √ |

**Table 1.4** Key assessments of surface and groundwater samples for the current study

| Country | Landfill | Landfill Type/Condition | Basic Parameters | Heavy Metals (Liquid) |
|---|---|---|---|---|
| Cambodia | Dangkor | Controlled Dump | √ | √ |
| Laos | KM-32 | Open Dump | √ | √ |
| Thailand | Nonthaburi | Semi-sanitary | √ | √ |

**Table 1.5** Key assessments for future groundwater risk regarding the site conditions and parameters for future risks to groundwater

| Country | Landfill | Landfill Type/Condition | Pit depth ($H_P$-m) | Leachate Height ($H_L$-m) | $K_C$ (m/s) | $K_d$ (L/kg) |
|---|---|---|---|---|---|---|
| Cambodia | Dangkor | Controlled Dump | √ | √ | √ | √ |
| Thailand | Nonthaburi | Semi-sanitary | √ | √ | √ | √ |

## 1.6 Expected Results

At the end of this research, some key findings are expected to obtain. The main points will be the leachate characteristics of three landfills from three different countries, namely Nonthaburi landfill in Bangkok, Thailand, Dangkor landfill in Phnom Penh, Cambodia and KM-32 landfill, Laos. The leachate will be deeply discussed as the total leachate, liquid part of leachate and the suspended solid as solid part of leachate. At the same time, the landfill sediment where the leachate was stored also will be characterized. The other main part of this study is the groundwater and surface water of the surrounding areas, which will be assessed as parallel. Finally, all the characteristics of the study concerns will be discussed and linked to the possible landfill site conditions and management.

## 1.7 Dissertation Structural Organization

This dissertation is compiled of seven (7) chapters, covering all of the related landfill leachate production areas and its consequent effects to the surrounding environments. The main discussion points for each chapter will be briefly explained as follows:

**Chapter 1** describes the importance of the leachate including the mechanism how the leachate generates as well as the leachate contamination level and their effects on the surrounding environments. Also, the overall and specific objectives of this study and the expected results are discussed.

**Chapter 2** expresses the related theories, as well as the research studies in the past for both regional and worldwide. The related literature is not only focusing on the leachate but also covering all the related consequent effects regarding the leachate quantity, quality, and its potential risks. Included in the chapter, the related literatures, such as landfill design, operation, and management. Moreover, the mechanisms of contaminant transport in the underground condition also described.

**Chapter 3** provides the site study information as the results of site investigation and primarily survey information collection including the general and particular to the landfill site condition. Also, some characteristic soil parameters from the laboratory measurement were included. The chapter covers all the related information which could be explained the leachate generation, quality and its effects on the surrounding environment in the current practice. The information also covers the specific site physical conditions, climate conditions, and related operation and management practices.

**Chapter 4** shows the details of leachate and sediment samples measurements, analysis, chemical processes and interpretation of the results obtained for each site conditions. The chapter also provides the very deep in details of site investigation and in-situ measurements, sample collection, as well as the analyzed procedures, to explain the leachate and sediment quality obtains from the measurements. In addition, various results from other studies and theories are included as a comparison.

**Chapter 5** characterizes the groundwater and surface water from the nearby areas of study landfill sites. The chapter also presents the site conditions which affect to the quality of surface and groundwater.

**Chapter 6** summarizes the current situation of all study landfills in order to conduct the simulation study. The common conditions of all landfill are the main inputs regarding the model boundary and geological conditions. This chapter also covers the detailed discussion of possible risks to the surrounding groundwater from the results of the simulation study. Finally, essential site conditions which could increase the potential risks to groundwater contamination also discussed.

**Chapter 7** emphasizes the main key findings and conclusion of the study, such as the main characteristics of leachate, sediment, groundwater and surface water as well as the potential risks to the surrounding environments. The influential factors to the leachate quality and investigation flow have included. In the end, the chapter explains the possible solutions and the recommendation to the local authorities where the study landfills located.

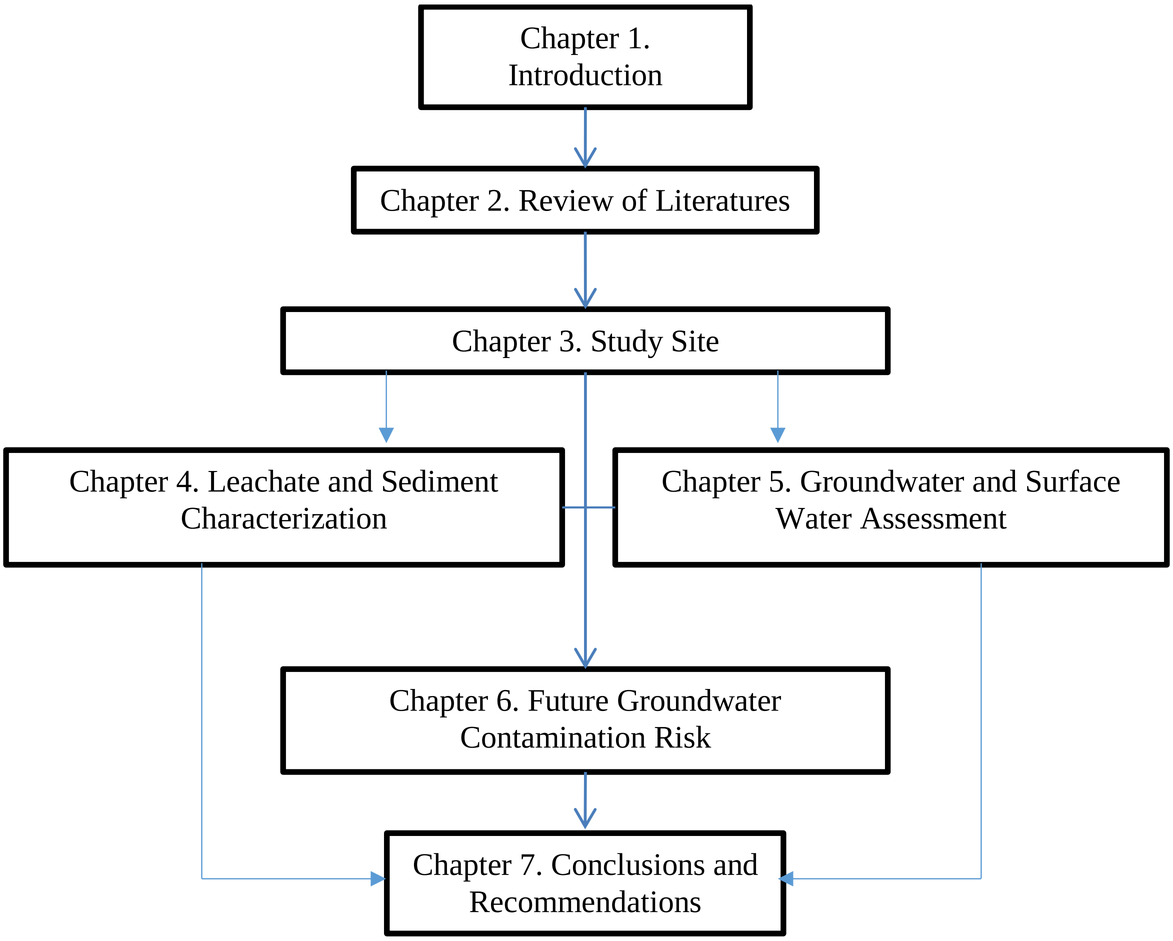


**Figure 1.3** The structure of dissertation

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# Chapter 2

# Review of Literatures

## 2.1 Introduction

Historically, landfilling has been the most common practice of managing solid waste. Landfills have developed throughout the years and decades from simple dump yards to highly engineered landfill systems in some countries. However, huge work remains and need to be done, and the many potential impacts could be caused to the surrounding environment if not properly designed and managed. Also, even if an advanced landfill is operating well with the current up-to-date technologies, the waste in those landfills will remain a constant potential source of contamination, after the closure of landfill site. That is why engineers and experts in the waste management field are continuously working to develop new technologies that will turn landfills into more sustainable systems.

## 2.2 Solid Waste

The term of solid waste is used to define any kind of refuse, garbage and sludge from wastewater treatment plant, water supply treatment plant, or air pollution control facility and other discarded material, resulting from industrial, commercial, mining, and agricultural operations, and from community activities. However, it is a very important concern to take note that the definition of solid waste is not limited to wastes that are physically solid. There are any solid wastes in the liquid form, semi-solid, or contained gaseous material. On the other hand, various materials are excluded from the definition of solid waste. These materials are excluded for many reasons, including public policy, economic impacts, and regulation by the related laws, lack of data or impracticability of regulating of the waste. The decision of excluding those materials from the solid waste definition is a result of either congressional action (embodied in the statute) or an EPA rulemaking. (US EPA Criteria for the Definition of Solid Waste and Solid and Hazardous Waste Exclusions, available at https://www.epa.gov/hw/criteria-definition-solid-waste-and-solid-and-hazardous-waste-exclusions)

### 2.2.1 Solid Waste Generation

In general, the primary sources of solid wastes are generated from households, offices, shops, markets, restaurants, public institutions, industrial installations, waterworks and sewage facilities, construction and demolition sites, and agricultural activities.

Waste generation is affected by socio-economic development, the degree of industrialization, and climate. Generally, the waste generation is related to the increase in population and economy, for example, greater the economic prosperity and the higher number of urban population, the greater amount of solid waste produced. The situation of waste generation in the South East Asian countries are shown in Figure 2.1, Amit Jain (2017). As currently report of annual solid waste generation in ASEAN countries, the generation rate per capita seems to have higher at the high economic countries, especially Singapore is the highest in the region. However, the annual solid waste generation is found to be Indonesia and followed by Thailand, while Vietnam, Philippines, and Malaysia are slightly lower.

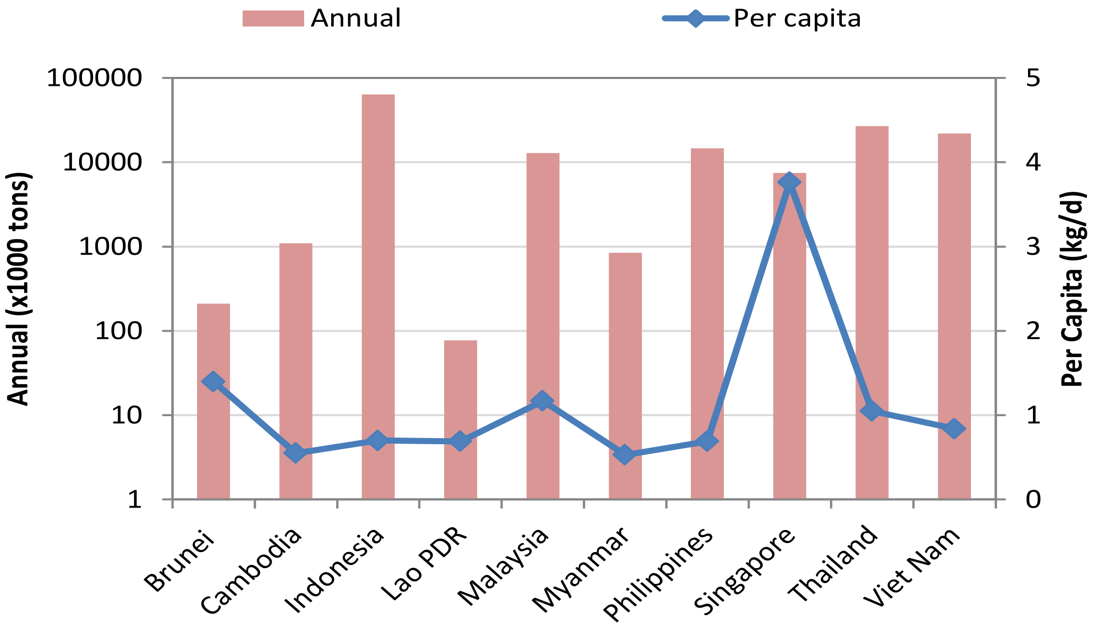


**Figure 2.1** Waste generation rates in the Southeast Asian Nations, Amit Jain (2017).

### 2.2.2 Solid Waste Composition

The solid waste composition can explain the waste characteristic which related to the source of the waste production. Wase composition is one of the main factors influencing emissions from solid waste treatment, as different waste components contain different amount of the portion in the final waste composition, such as organic compound (kitchen/food waste and garden waste). Waste composition classifications used to collect data on the waste composition of solid waste vary in different regions and countries.

In the ASEAN region, the solid waste composition is classified into ten components listed as follows:

(1) Food waste

(2) Garden/wood/grass (yard) and park waste

(3) Plastics

(4) Paper and cardboard

(5) Textiles

(6) bottle/glass

(7) Rubbers and leathers

(8) Ceramics/stones

(9) Metals

(10) Other

The type of waste component (1) to (5) contains most of the degradable organic compound (DOC) in MSW. Ash, dust, rubber, and leather also contain certain amounts of non-fossil carbon, but this is hardly degradable. Some textiles, plastics (including plastics in disposable nappies), rubber and electronic waste, contain the bulk part of fossil carbon in MSW. Paper (with coatings) and leather (synthetic) can also include small amounts of fossil carbon.

Waste composition characteristic is not only depended on the type of solid waste but also the influenced by other factors, such as geographical location, the population’s standard of living, energy source, and weather. The most fundamental step in waste source management is quantifying and qualifying the different types of waste being generated. It is important to have a system for the collection, segregation, and analysis of basic information about wastes, for example, the sources of wastes, the quantities of waste generated, their composition and characteristics, the seasonal variations and future trends of generation. That is the best way to identify the method to treat waste, since municipal, industrial, agricultural, hazardous and toxic wastes, as well as wastewater, require different treatment methods.

**Table 2.1** Waste composition for South East Asian countries, Amit Jain (2017)

| waste composition | Brunei | Cambodia | Indonesia | Laos | Philippines | Malaysia | Myanmar | Singapore | Thailand | Vietnam |
|---|---|---|---|---|---|---|---|---|---|---|
| Kitchen/food | 36 | 60 | 60 | 64 | 52 | 45.00 | 73 | 10.5 | 64 | 55 |
| Wood/grass | 0 | 0 | 0 | 0 | 0 | 0.00 | 0 | 8.6 | 1 | 0 |
| Plastic | 16 | 15 | 14 | 12 | 10.55 | 13.20 | 17.75 | 11.6 | 17.6 | 10 |
| Paper | 18 | 9 | 9 | 7 | 8.7 | 8.20 | 2.24 | 16.5 | 8 | 5 |
| Textile | 0 | 1 | 3.5 | 5 | 1.61 | 0.00 | 1.14 | 2.1 | 1.4 | 0 |
| Bottle/glass | 3 | 0 | 1.7 | 7 | 2.34 | 3.30 | 0.45 | 8.6 | 3 | 3 |
| Rubber/Leather | 0 | 1 | 6 | 3 | 0 | 0.00 | 0 | 0 | 1 | 4 |
| Ceramic/stone | 0 | 0 | 0 | 0 | 0 | 0.00 | 0 | 17 | 0 | 0 |
| Metal | 4 | 0 | 4.3 | 0 | 14.6 | 0.00 | 0 | 20.8 | 2 | 0 |
| Other | 23 | 14 | 1.5 | 2 | 10.2 | 30.30 | 5.42 | 4.3 | 2 | 23 |

### 2.2.3 Type of Solid Waste

In many countries and regions, solid waste divides based on the source of waste collecting. The source of solid waste classifies typically into five categories which are a municipal solid waste, industrial solid waste, and sewage sludge, agricultural wastes, and mining waste, Bishop (2000). The detailed explanations are discussed below:

**Municipal solid wastes (MSW):**

Municipal solid waste (MSW) is generally defined as nonhazardous waste from household, commercial, and institutional sources. Moreover, it has become a significant concern for most countries and regions; the amount of MSW generation is tremendously increased as the increase of economics, rapid urbanization, industrialization, the growth of population and lifestyle improvement. In general, municipal solid waste refers to all kinds of wastes collected by municipalities or other local authorities excluded hazardously and toxicity wastes from particular industries. However, the definition usually varies by the country. On the other way of saying, , MSW is mainly from household waste, garden (yard) and park waste, and Commercial/institutional waste including hotels and restaurants, constructions, and demolition wastes, street refuse collection activities, dead animals, abandoned vehicles, and another similarity of sources, US EPA (2014).

**Industrial solid waste**:

The solid waste from industrial sectors mean solid waste generally arise from two sources: one is processed wastes remaining after manufacturing a product, and another is commercial or institutional offices, include cafeteria garbage, dirt and gravel, masonry and concrete, scrap metals, trash, oil, solvents, chemicals, weed grass and trees, wood and scrap lumber, and similar wastes. Industrial solid waste - which may be solid, liquid or gases held in containers - is divided into hazardous and non-hazardous waste.

**Sewage sludge**:

Sewage sludge mainly means to the leftover solid waste or sludge from the domestic wastewater treatment. In many practices, sludge must be handled properly to ensure public safety and minimize environmental damage. The sludge separating processes was done by settling and decomposing by the bacteria. In most cases, sludge contains numerous known and unknown hazard materials, which including all the things get into the sewer system, such as household, medical, chemical and so on.

**Agricultural wastes**:

It means to all kinds of solid waste from the agricultural activities. Both crop residues that cannot be returned to the soil, and manure from animal feeding facilities. The agricultural waste is generally including the waste from the irrational application of intensive farming methods and the abuse of chemicals used in cultivation. Some remarkably affect the rural environments in particular and the global environment in general. The waste product is depending on the type of agricultural activities, Obi et al., (2016)

**Mining waste:**

The mining industry produces such large amounts of solid waste that particular emphasis should be given to this material. Unplanned spoil heaps impair the landscape, threaten landslides and pollute groundwater. Mine waste may need a raise in some forms, as stripped soil and coarse, broken, partly weathered rockover burden in open cast or strip-mining operation. The harm of mining waste vary on the type of mine and their operating methods, Letcher and Vallero (2011).

## 2.3 Leachate

Leachate is a contaminated liquid production of water percolated through waste, the contaminants have extracted from the waste materials. The leachate consists of many different organic and inorganic compounds that may be either dissolved or suspended, such as Organic matter, nutrient, inorganic salts, heavy metals (Hg, As, Cd, Pb, Mn, Cr, Fe, etc.), toxic compounds and others. As leachate combines with various contaminant substances, they will bring different type and level of potential pollution issues to the environment, for example, groundwater and surface waters of nearby areas. The landfill leachate is secondary contamination related to landfills.

### 2.3.1 Leachate Generation

Generally, leachate generation as a result of water percolation through the waste, those water can be identified as two primary sources; one is external water enters the waste, and another is within the waste generated leachate.

**External water**

(1) Most of the times, leachate generates from direct water which can be majorly from precipitation or snowmelt through the waste. The liquid should spend many years infiltrate through the landfill, during this period, they will contact with various chemical substances which are contained in the different kinds of waste, such as paints, plastic, oil, and many more inside the landfill. The water later then leaches and dissolves various constituents until it contains a load of heavy metals, chlorinated organic compounds, and other substances. In the end, they become the polluted liquid names landfill leachate. It can be harm nearby surface water and groundwater depending on the site conditions includes both the geology and topography. The leachate quality became severe after the mass of

rainwater washed landfill waste. Intension, quantity, frequency, and duration of rainfall related to the quantity of leachate. Also, the humid climate has a strong influence on the generation of leachate, Monroe (2001).

**(2)** The surface water and groundwater into the solid waste by inflow or infiltration. The surface water depends on the type of site and geological conditions. If landfill building under a sloping field, which has surface water, it will drop down into the landfill from the direction of topography. Otherwise, the groundwater is possible to infiltrate into the waste if the bottom of the landfill reaches or under the water table. The quantity of leachate is based on interface situation, such as tangent time, tangent position and flowing direction between groundwater and solid waste.

**Within the waste generated leachate**

**(1)** Quality of waste as a primary condition, the wet waste contains some moisture, which existed in the waste as its moisture and the adsorbed moisture from the atmosphere and/or rainwater. The biological processes, physical processes, as well as the chemical processes, are taking place there by the wet waste through compaction and organic decomposition in the landfill. The waste produced the waste moisture during waste placement, such as solid waste without pre-treatment into the landfill will produce leachate that is the primary source.

**(2)** Some of the organic components inside the waste, which is through the anaerobic decay, become heavy polluted liquid within the landfill. The total liquid production relates to components of waste, pH, temperature, and types of existing bacterias.

The generation of leachate also depends on other factors:

- Quality of wastes and its crumbling
- Techniques of landfilling and degree of waste compaction
- Age of landfill, and
- Precipitation, humidity

### 2.3.2 Leachate Composition and Characteristics

Generally, leachate consists of water, organic, inorganic and bacterial compounds together with solid as a small part. The definition of all the components consist of the leachate is challenging, complex, expensive and time-consuming. The leachate composition can divide into four parts based on the classification of pollutants present in the leachate; one is organic matter, such as COD (chemical oxygen demand) and TOC (total organic carbon); others are specific organic compounds, inorganic compounds, and heavy metals. However, the organic content of leachates is often measured by analyzing some of the parameters such as COD, BOD (biochemical oxygen demand) and TOC and dissolved organic carbon.

The contaminant concentration of landfill leachate can vary by order of magnitude between different field-scale landfill. On the other hand, the age as the phase of the landfill also significantly change the leachate-contaminated level, Daniel (1997). The different level of contaminant concentrations contains in landfill leachate between two phases are shown in Table 2.2. The higher concentrations for most of the parameters are found in the acetic phase, while in the methanogenic phase they are a few to ten times lower than that of the acetic phase. At the same time, some of the parameters are not affected by the phases. The average and rages of concentration values can be found in Table 2.3.

**Table 2.2** Leachate analysis with a different acetic and methanogenic phase, Daniel (1997)

| **Parameters (mg/l)** | **Average** | **Range** |
|---|---|---|
| **acetic phase** | | |
| pH (-) | 6.1 | 4.5-7.5 |
| BOD5 | 13000 | 4000-40000 |
| COD | 22000 | 6000-60000 |
| BOD5/COD (-) | 0.58 | |
| SO4 | 500 | 70-1750 |
| Ca | 1200 | 10-2500 |
| Mg | 470 | 50-1150 |
| Fe | 780 | 20-2100 |
| Mn | 25 | 0.3-6.5 |
| Zn | 5 | 0.1-120 |
| **methanogenic phase** | | |
| pH (-) | 8 | 7.5-9 |
| $BOD_5$ | 180 | 20-550 |
| COD | 3000 | 500-4500 |
| $BOD_5$/COD (-) | 0.06 | |
| $SO_4$ | 80 | 10-420 |
| Ca | 60 | 20-600 |
| Mg | 180 | 40-350 |
| Fe | 15 | 3-280 |
| Mn | 0.7 | 0.03-45 |
| Zn | 0.6 | 0.03-4 |

(-) no unit

**Table 2.3** Leachate analysis with no different phase, Daniel (1997)

| **Parameters (mg/l)** | **Average** | **Range** |
|---|---|---|
| Cl (mg/l) | 2100 | 100-5,000 |
| Na(mg/l) | 1350 | 50-4000 |
| K(mg/l) | 1100 | 10-2500 |
| alkalinity (mg CaCO3/l) | 6700 | 300-11500 |
| $NH_4$ (mg N/l) | 7500 | 30-30,000 |
| org N (mg N/l) | 600 | 10-4250 |
| total N (mg N/l) | 1250 | 50-5,000 |
| $NO_3$ (mg N/l) | 3 | 0.1-50 |
| $NO_2$ (mg N/l) | 0.5 | 0-25 |
| total P mg P/l) | 6 | 0.1-30 |
| AOX (μg Cl/l)* | 200 | 320-3,500 |
| As (μg /l) | 160 | 5-1600 |
| Cd (μg /l) | 6 | 0.5-140 |
| Co (μg /l) | 55 | 4-950 |
| Ni (μg /l) | 200 | 20-2050 |
| Pb (μg /l) | 90 | 8-1020 |
| Cr (μg /l) | 300 | 30-1,600 |
| Cu (μg /l) | 80 | 4-1,400 |
| Hg (μg /l) | 10 | 0.2-50 |
| * absorbable organic halogen | | |

### 2.3.3 Leachate Impacts

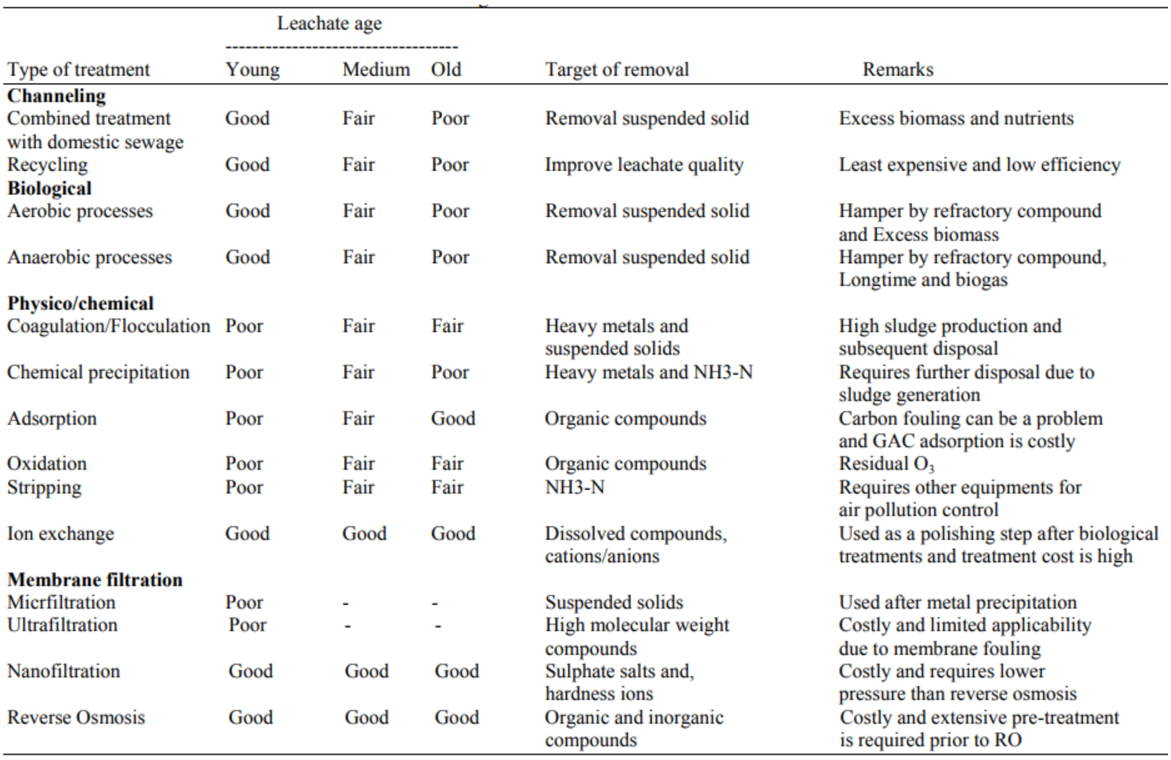
Leachate contains varieties of toxic and carcinogenic chemicals, which may cause harm to both human health and environments as presented in previous section (2.3.2). Many studies have confirmed the risks of leachate to environments via polluting the surface and groundwater. Furthermore, leachate contamination of groundwater can adversely affect industrial and agricultural activities that depend on water wells. Using contaminated water for irrigation can decrease soil productivity, increase the level of contaminated crops and possible movement and accumulation of toxic pollutants in the food chain, and finally, animals and humans consume crops growing in an area irrigated with contaminated water.

James (1977) confirmed that raw or undiluted leachate contains various substances that are potential threats to human health. Most of the landfill leachates contain concentrations of heavy metals exceed the groundwater standard, and many of them also exceed the effluent standard which even higher possible to harm the human health and environments. If solid waste is placed directly into the ground without proper liner system, or if leachate is allowed to drain directly into the surface water, it can cause severe damage to the environments. It can destroy life in a water resource by coating the bottom sediment so that feeding by the animal population is precluded.

### 2.3.4 Overview of Leachate Treatment Technology

There are many techniques and methods can be applied for treating the landfill leachate, but the effectiveness of each method depending on the leachate characteristics and the purpose of the target substance. Also, the leachate age is one of important factor affecting the leachate quality and its characteristics, as well as the efficiency of different treatment technique, Abbus et al., (2009). In their study, the detailed discussion on the characteristics of those potential leachate treatment methods regarding the specific leachate condition has been pointed out. However, a recommendation in applying techniques needs to consider the method adaptation, due to the complexity of the leachate component. The summary of treatment type and age of the leachates, which the age of leachate can be representing some of the leachate characters and consider of using the treatment method, as shown in Table 2.4.

**Table 2.4** Effectiveness of leachate treatments vs. leachate age, Abbus et al., (2009)



| | Leachate age | | | | |
|---|---|---|---|---|---|
| Type of treatment | Young | Medium | Old | Target of removal | Remarks |
| **Channeling** | | | | | |
| Combined treatment with domestic sewage | Good | Fair | Poor | Removal suspended solid | Excess biomass and nutrients |
| Recycling | Good | Fair | Poor | Improve leachate quality | Least expensive and low efficiency |
| **Biological** | | | | | |
| Aerobic processes | Good | Fair | Poor | Removal suspended solid | Hamper by refractory compound and Excess biomass |
| Anaerobic processes | Good | Fair | Poor | Removal suspended solid | Hamper by refractory compound, Longtime and biogas |
| **Physico/chemical** | | | | | |
| Coagulation/Flocculation | Poor | Fair | Fair | Heavy metals and suspended solids | High sludge production and subsequent disposal |
| Chemical precipitation | Poor | Fair | Poor | Heavy metals and NH3-N | Requires further disposal due to sludge generation |
| Adsorption | Poor | Fair | Good | Organic compounds | Carbon fouling can be a problem and GAC adsorption is costly |
| Oxidation | Poor | Fair | Fair | Organic compounds | Residual $O_3$ |
| Stripping | Poor | Fair | Fair | NH3-N | Requires other equipments for air pollution control |
| Ion exchange | Good | Good | Good | Dissolved compounds, cations/anions | Used as a polishing step after biological treatments and treatment cost is high |
| **Membrane filtration** | | | | | |
| Micrfiltration | Poor | - | - | Suspended solids | Used after metal precipitation |
| Ultrafiltration | Poor | - | - | High molecular weight compounds | Costly and limited applicability due to membrane fouling |
| Nanofiltration | Good | Good | Good | Sulphate salts and, hardness ions | Costly and requires lower pressure than reverse osmosis |
| Reverse Osmosis | Good | Good | Good | Organic and inorganic compounds | Costly and extensive pre-treatment is required prior to RO |

Torreta et al., (2016) has classified the leachate treatment techniques into three main groups based on the leachate characteristics and ages. The three groups are consisting of (1), biological processes (aerobic or anaerobic); (2), chemical and physical processes and (3), a combination of physical-chemical and biological processes. The effectiveness was also varied and depended on the leachate characteristics, as well as the target removal parameters. There were several techniques have been introduced for each group of leachate treatment. However, the different technique has different advantages and limitation, e.g., economic concerns, technical concerns and also the space and material availability for each landfill site and region. The list of leachate treatment methods are shown as follows:

(1) Biological treatment

- ✧ Aerobic treatments
    - Aerated Lagoons (AL)
    - Constructed Wetlands (CWs)
    - Aerated Reactors (ARs)
    - Rotating Biological Contactors (RBCs)
    - Sequencing Batch Reactor (SBR)
    - Tricking Filters (TFs)

    - Moving Bed Bioreactor (MBBR)
    - Fluidized Bed Bioreactors (FBBR)
    - Membrane Biological Reactor (MBR)
    - Membrane-Aerated Biofilm Reactor (MABR)
    - Single Reactor High Activity Ammonium Removal Over Nitrite (SHARON)
- ✧ Anaerobic and Anoxic Treatment
    - Up-flow Anaerobic Sludge Blanket (UASB)
    - Submerged Anaerobic MBR (SAMBR)
    - Anaerobic Filter (AF)
    - Anaerobic Ammonium Oxidation (Anammox)

(2) Physical-Chemical Treatment

- ✧ Flocculation-Coagulation
- ✧ Separation Treatment with Membrane Filtration (MF)
- ✧ Air Stripping (AS)
- ✧ Adsorption by Activated Carbon (AC)
- ✧ Chemical Precipitation
- ✧ Ion Exchange
- ✧ Chemical Oxidation and Advanced Oxidation Processes (AOP)
- ✧ Electrochemical Processes

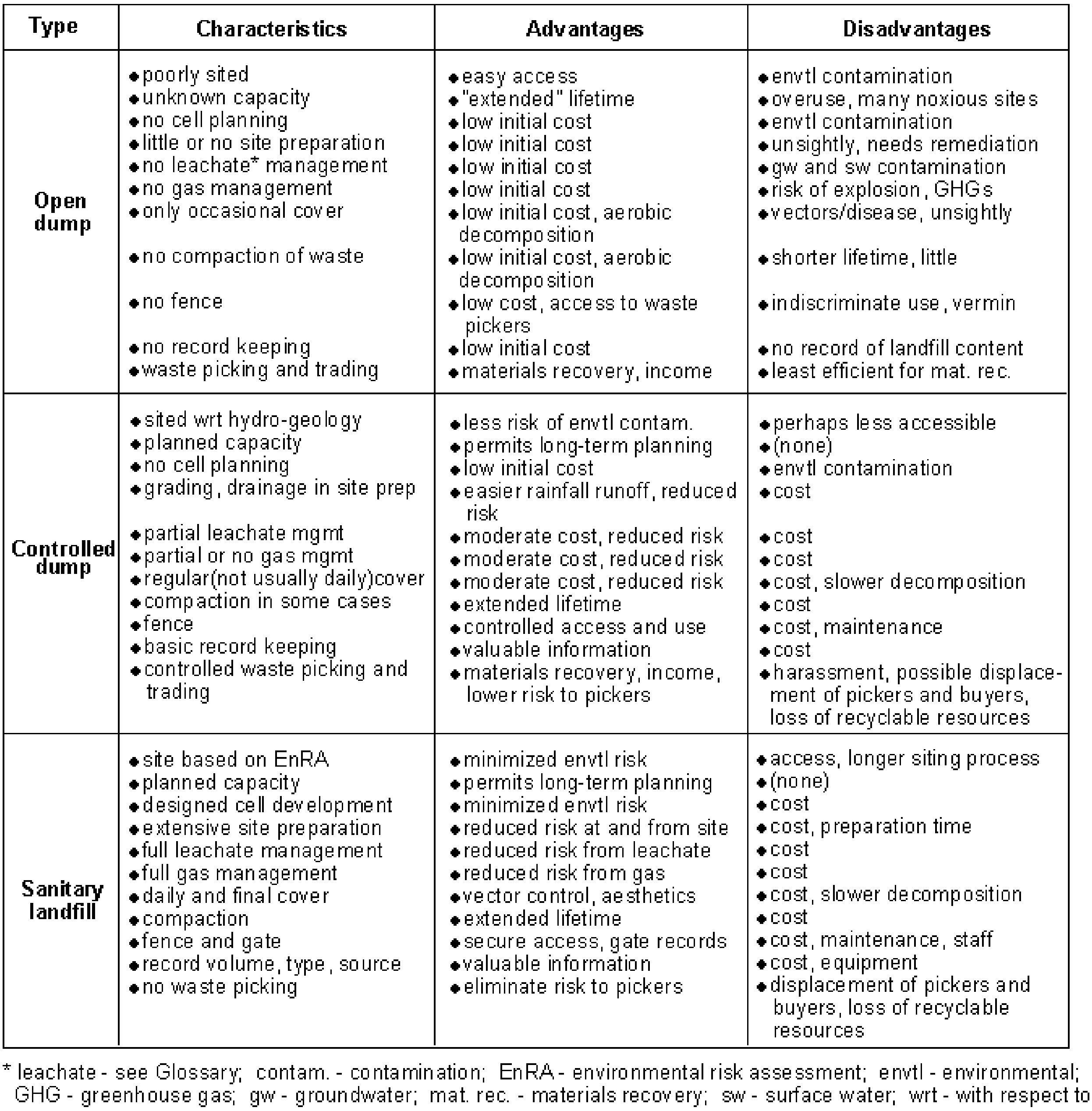
(3) Combination of Physical-Chemical and Biological Processes

- ✧ Combined Treatment Introduced in 2016
    - SAMBR-MBR (Synthetic Leachate, London)
    - SBBGR-EO (Italy)
    - SBR-Fenton Like-SBR Post-Oxidation (Estonia)
    - Photo-Electro-Fenton Process-Membrane Bio Reactor (India)
    - Trickling Filters-Electro-Coagulation (Magnesium-Based Anode) (Canada)
    - Fenton Process-Passive Aerated Immobilized Biomass (PAB) (Egypt)
    - Aerobic SBR-Zeolite Adsorption (Malaysia)
    - Co-Treatment Constructed Wetland-Adsorption by ZELIAC/Zeolite (Iran)
    - MBR-UF_EO (Quebec, Canada)
    - MBR-PAC to Activated Sludge-NF (Iran)

## 2.4 MSW Landfill Classification

The landfill has been classified differently depending on the country and region. However, based on the landfill guideline introduces by the United Nations Environment Programme (UNEP), section 6. There are three types of MSW landfills have been defined (open dumps, controlled dumps, and sanitary landfills). Their facilities and operating methods distinguish these three landfill types and mostly in developing countries landfill situation are in between open dump and controlled dump. The key characteristic and facilities including the key advantages and disadvantages are shown in Table 2.5.

**Table 2.5** Characteristics of MSW landfill by UNEP



| Type | Characteristics | Advantages | Disadvantages |
|---|---|---|---|
| **Open dump** | ◆poorly sited<br>◆unknown capacity<br>◆no cell planning<br>◆little or no site preparation<br>◆no leachate* management<br>◆no gas management<br>◆only occasional cover<br>◆no compaction of waste<br>◆no fence<br>◆no record keeping<br>◆waste picking and trading | ◆easy access<br>◆"extended" lifetime<br>◆low initial cost<br>◆low initial cost<br>◆low initial cost<br>◆low initial cost<br>◆low initial cost, aerobic decomposition<br>◆low initial cost, aerobic decomposition<br>◆low cost, access to waste pickers<br>◆low initial cost<br>◆materials recovery, income | ◆envtl contamination<br>◆overuse, many noxious sites<br>◆envtl contamination<br>◆unsightly, needs remediation<br>◆gw and sw contamination<br>◆risk of explosion, GHGs<br>◆vectors/disease, unsightly<br>◆shorter lifetime, little<br>◆indiscriminate use, vermin<br>◆no record of landfill content<br>◆least efficient for mat. rec. |
| **Controlled dump** | ◆sited wrt hydro-geology<br>◆planned capacity<br>◆no cell planning<br>◆grading, drainage in site prep<br>◆partial leachate mgmt<br>◆partial or no gas mgmt<br>◆regular(not usually daily)cover<br>◆compaction in some cases<br>◆fence<br>◆basic record keeping<br>◆controlled waste picking and trading | ◆less risk of envtl contam.<br>◆permits long-term planning<br>◆low initial cost<br>◆easier rainfall runoff, reduced risk<br>◆moderate cost, reduced risk<br>◆moderate cost, reduced risk<br>◆moderate cost, reduced risk<br>◆extended lifetime<br>◆controlled access and use<br>◆valuable information<br>◆materials recovery, income, lower risk to pickers | ◆perhaps less accessible<br>◆(none)<br>◆envtl contamination<br>◆cost<br>◆cost<br>◆cost<br>◆cost, slower decomposition<br>◆cost<br>◆cost, maintenance<br>◆cost<br>◆harassment, possible displacement of pickers and buyers, loss of recyclable resources |
| **Sanitary landfill** | ◆site based on EnRA<br>◆planned capacity<br>◆designed cell development<br>◆extensive site preparation<br>◆full leachate management<br>◆full gas management<br>◆daily and final cover<br>◆compaction<br>◆fence and gate<br>◆record volume, type, source<br>◆no waste picking | ◆minimized envtl risk<br>◆permits long-term planning<br>◆minimized envtl risk<br>◆reduced risk at and from site<br>◆reduced risk from leachate<br>◆reduced risk from gas<br>◆vector control, aesthetics<br>◆extended lifetime<br>◆secure access, gate records<br>◆valuable information<br>◆eliminate risk to pickers | ◆access, longer siting process<br>◆(none)<br>◆cost<br>◆cost, preparation time<br>◆cost<br>◆cost<br>◆cost, slower decomposition<br>◆cost<br>◆cost, maintenance, staff<br>◆cost, equipment<br>◆displacement of pickers and buyers, loss of recyclable resources |

* leachate - see Glossary; contam. - contamination; EnRA - environmental risk assessment; envtl - environmental; GHG - greenhouse gas; gw - groundwater; mat. rec. - materials recovery; sw - surface water; wrt - with respect to

### 2.4.1 Open Dumps

Open dumps are the lowest initial capital investment and operating cost among the three basic types of MSW landfills. Those costs can be included in the site acquisition, and some activities carried out by municipal officials. Additionally, numbers of open dumps were started off as controlled dumps and degraded due to lack of management and other resources, such as the financial support, technical support, and management. Since open dumps need the low initial costs and lack of expertise and equipment, these sites are very common in use among the developing countries. There is a high potential for significant risks to human health, the environment, and the economy. As MSW becomes more complex in industrializing countries, the potential risks are even higher as described. The contaminated groundwater and surface water of surrounding areas may never be returned to usable condition, and other environmental impacts may take long years to ameliorate. Open dumps attract numerous birds that feed on the wastes, which can make them more serious disease vectors than flies or rodents. The significant points of the open dump defined by the United Nations Environment Programme (UNEP) (2005) are as bellows:

- They are unplanned, particularly with respect to siting considerations. Open dumpsites are usually located in areas not feasible for such facilities because of the absence of proper siting considerations or criteria. They are usually located in any available vacant area, and are usually within a government-owned property.
- They are haphazardly operated. No general operational guidelines are governing the proper operation of the facility, and many operators of these dumpsites lack equipment as well as the necessary expertise. Often, the burning of waste is done to reduce the volume of waste and preserve disposal space at the site.
- There are no controls over waste inputs, either in quantity or composition (or both). Often, there is no control over the amount and/or type of waste that is disposed of in the site. If wastes other than municipal solid wastes, such as medical and toxic and hazardous wastes, are permitted for disposal in the site, the risks to public health and the environment become more significant.
- There are no controls over emissions of pollutants released due to waste decomposition. Open dumpsites do not have the necessary facilities and measures to control and safely manage liquid and gaseous by-products of waste decomposition.

### 2.4.2 Controlled Dumps

The controlled dump is a none-engineered disposal facility where the improvement is implemented on the operational and management aspects rather than on facility or fundamental structural requirements. Controlled dumps evolved due to the needs to close-open dumpsites and replace them with improved disposal facilities, and in consideration of the financial constraints of landfill gas utility. The controlled disposal site of wastes may be implemented over existing wastes (from previous open dumping operations) or on new sites.

### 2.4.3 Sanitary Landfill/Engineered Landfill

Sanitary landfill is an engineered disposal facility which designed, constructed, and operated in a manner that minimizes the impacts to public health and the environments. In contrast to open dumpsites and controlled dumps, a sanitary landfills undergo thorough planning right from the selection of the site up to post-closure management. Therefore, although it requires substantial financial resources, it is the most desirable and appropriate method of final waste disposal on land.

The design of a sanitary landfill will significantly affect by its safety, cost, and effectiveness over the lifetime of the facility. Essential items requiring attention in the design are listed in the following sections.

#### 2.4.3.1 Landfill Site Selection

In order to select an appropriate site for a landfill, several issues are to be considered:

- Neighborhood (distances from residential area, from waterways and water bodies, and from airports)
- Geological and hydrogeological conditions in the area
- Seismic conditions in the area
- Existence of groundwater and its current (and future) utilization
- Risk of flooding, subsidence and landslides
- Transport distances and existing infrastructure (e.g., access roads)
- Access to intermediate and final cover material
- Topography of site

### 2.4.3.2 Protective Cover

The protective cover layer of a sanitary landfill will consist of three components: covered vegetation, topsoil, and protectively covered soil

#### (a) Cover vegetation layer

As portions of the landfill cover are completed, native grasses and shrubs are planted, and the areas are maintained as open spaces. The vegetation is visually pleasing and prevents erosion of the underlying soils as shown in Figure 2.2.

#### (b) Top Soil

In order to protect the covered soil from erosion, topsoil is used to support and maintain the growth of vegetation (grass mainly) by retaining moisture and providing nutrients. The topsoil is more likely the agriculture soil for the better grows of protected grass or crops of erosion control.

#### (c) Protective cover soil

Protects the landfill cap system and provides additional moisture retention to help support the cover vegetation as shown in the below figure.

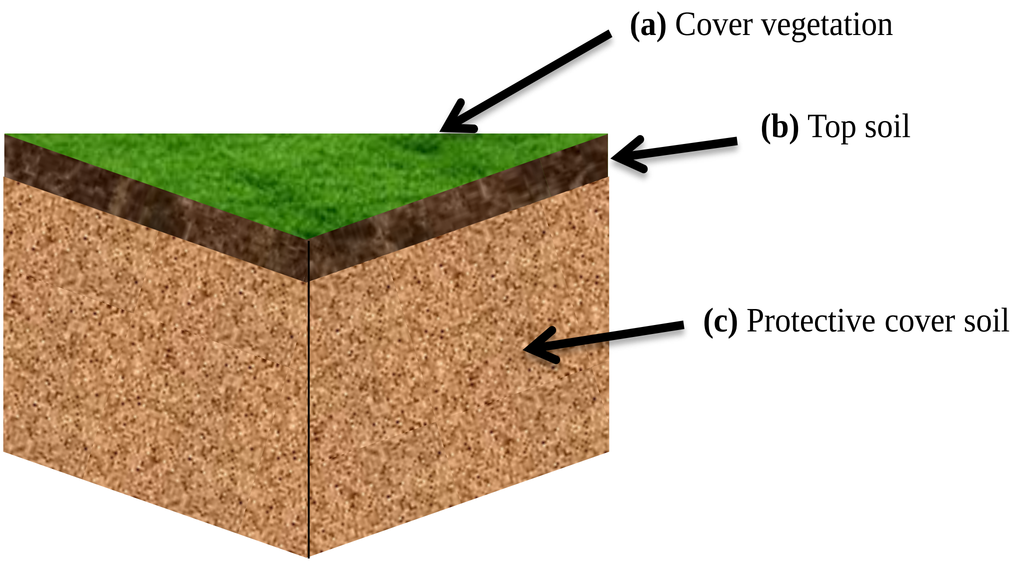


**Figure 2.2** Protective Cover of landfill

#### 2.4.3.3 Composite Cap System

**(d) Drainage Layer**

The main material for the drainage is mainly made of sand with fine size gravel, or a thick plastic mesh called a geonet drains excess precipitation from the protective cover soil to enhance stability and help prevent infiltration of water through the landfill cap system as shown in Figure 2.3. A geotextile fabric may be located on top of the drainage layer to provide separation of solid particles from the liquid.

**(e) Geomembrane**

A thick synthetic plastic layer forms a liner that prevents leachate from leaving the landfill and entering the environments. This geomembrane is typically made from a particular type of plastic called high-density polyethylene (HDPE). HDPE is impermeable and extremely resistant to attack by the compounds that contain the in leachate. The geomembrane layer also helps to prevent the escape of landfill gases shown in Figure 2.3.

**(f) Compacted Clay**

It is placed over the waste to form a cap when the landfill reaches the permitted height. This layer prevents excess precipitation from entering the landfill and forming leachate and helps to prevent the escape of landfill gas, thereby reducing odors as shown in figure

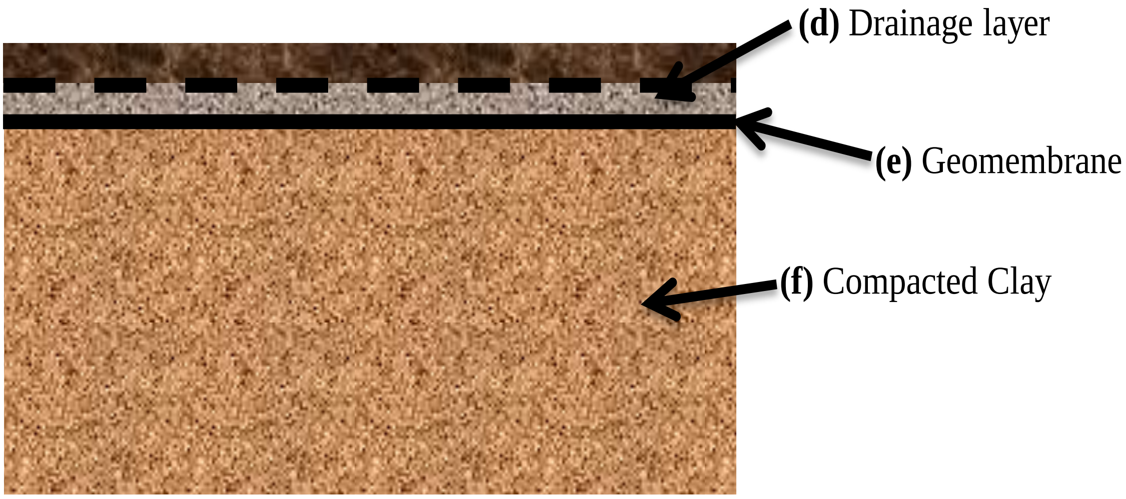


**Figure 2.3** Composite Cap System of landfill

#### 2.4.3.4 Working Landfill

**(g) Daily Cover**

At the end of each day working, the waste cells shall be covered with six to twelve inches of clay soil or other approved material, i.e., nearby soil or local soil. The daily cover can help in reducing the odors, keeps litter from scattering and helps deter scavengers as shown in Figure 2.4

**(h) Waste**

As waste arrives, it is compacted in layers within a small area to reduce the volume consumed within the landfill. This practice also helps to reduce odors, keeps litter from scattering and deters scavengers as shown in Figure 2.4

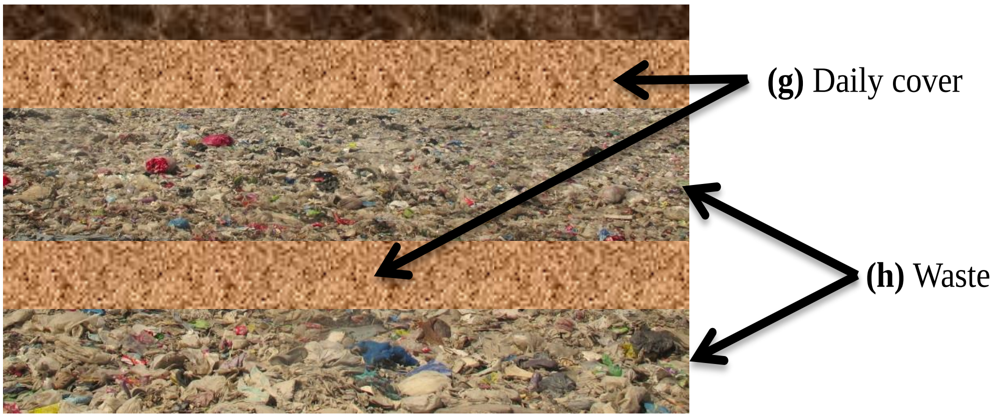


**Figure 2.4** Daily cover for working landfill

#### 2.4.3.5 Leachate Collection System

Leachate is a landfill liquid product that has filtered through the landfill. It consists primarily of precipitation with a small amount coming from the natural decomposition of the waste. The leachate collection system collects the leachate so that it can be removed from the landfill and properly treated or disposed of. The leachate collection system as shown in Figure 2.5 has the following components.

**(i) Landfill Leachate Collection Layer**

The layer of sand or gravel combination with a thick plastic mesh called a geonet or geotextile. It uses to collect the leachate and allows leachate to drain by gravity to the leachate collection pipe system then go to final distination ponds.

### (j) Geotextile

A geotextile fabric, similar in appearance to the field, may be located on top of the leachate collection pipe system to provide separation of solid particles from the liquid. It prevents clogging of the pipe system.

### (k) Leachate Collection Pipe System

Perforated pipes which are surrounded by a bed of gravels, transport collected leachate to specially designed low points called sumps. Pumps, located within the sumps, automatically remove the leachate from the landfill and transport it to the leachate management facilities for treatment or another proper method of disposal and (120 geomembranes is presented in next section (2.4.3.6.1).

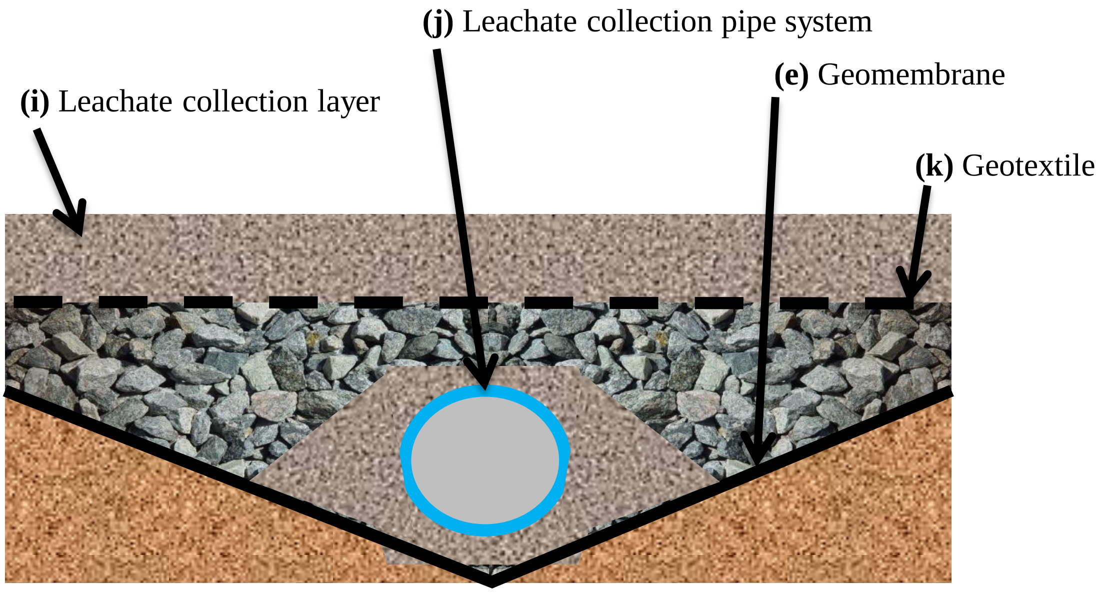


**Figure 2.5** Leachate collection system of landfill

### 2.4.3.6 Landfill Liner System

### 2.4.3.6.1 Composite Liner System

- **Geomembrane**

As introduced in (e), the thick synthetic plastic layer forms a liner that prevents leachate from leaving the landfill and entering the environments. This geomembrane is typically made from a particular type of plastic called high-density polyethylene (HDPE) as shown in Figure 2.6. HDPE is impermeable and extremely resistant to attack by the compounds that contain the in leachate. The geomembrane layer also helps to prevent the escape of landfill gas. According to Daniel (1997), there are three categories of polymers that can be used to make geomembrane; thermoset elastomers, thermoplastics, and bituminous.

- **Compacted Clay**

It is located directly below the geomembrane and forms an additional barrier to prevent leachate from leaving the landfill and entering the environment. This layer nomally helps to prevent the escape of landfill gas as shown in Figure 2.6

- **Prepared Subgrade**

The native soils beneath the landfill are prepared as needed prior to beginning landfill construction as shown in figure

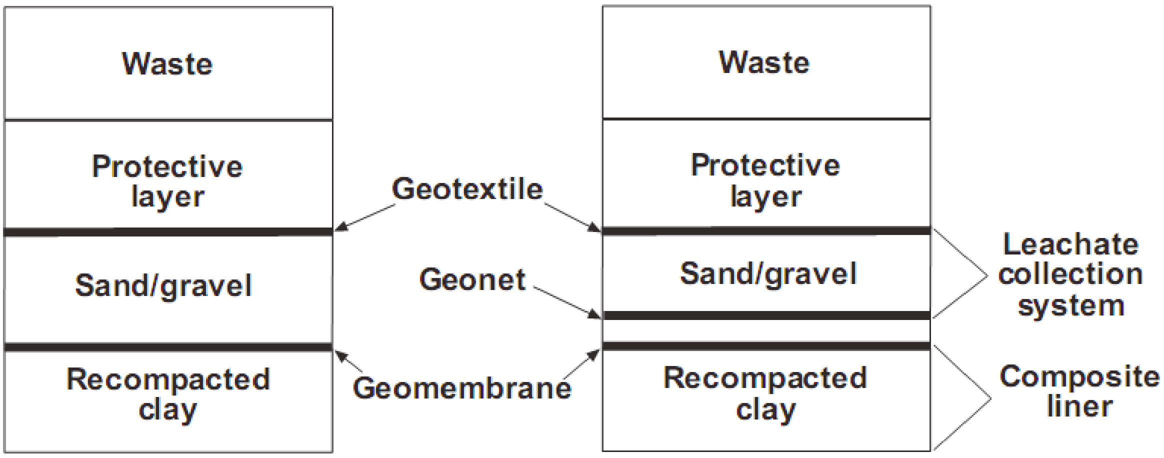


**Figure 2.6** Composite liner system of landfill (*http://ohioline.osu.edu*)

### 2.4.3.6.2 Double Landfill Liner System

A double liner consists of either two single liners, two composite liners, or a single and a composite liner as shown in Figure 2.7. The upper (primary) liner usually functions to collect the leachate, while the lower (secondary) liner acts as a leak-detection system and back up to the primary liner. Double landfill liner systems are used in some municipal solid waste landfills, and all hazardous waste landfills. Hazardous waste landfills may refer to the secure landfills, which are constructed for the disposal of wastes that once were ignitable, corrosive, reactive, toxic, or are designated as hazardous by the U.S. Environmental Protection Agency (U.S. EPA), Hughes et al., (2008). These wastes can have an inverse effect on human health and the environments if improperly landfill management. Hazardous wastes are produced by industrial, commercial, and agricultural activities. Hazardous wastes must be disposed in specific hazardous waste landfills. And also, hazardous waste landfills must have at least a double liner system with a leachate collection system above the primary composite liner and a leak detection system above the secondary composite liner.

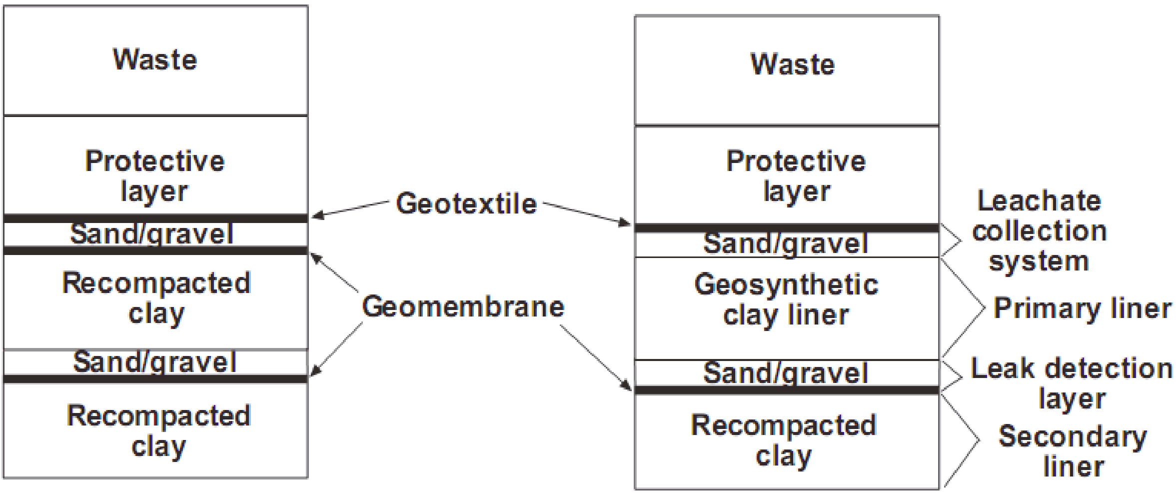


**Figure 2.7** Examples of double liner system (http://ohioline.osu.edu)

### 2.4.3.6.3 Single Liner System

Single liners as shown in Figure 2.8 consist of a clay liner, a geo-synthetic clay liner, or a geomembrane (specialized plastic sheeting). Single liners are sometimes used in landfills designed to hold construction and demolition debris (C&DD). Construction and demolition debris results from building and demolition activities and includes concrete, asphalt, shingles, wood, bricks, and glass. The landfills are not constructed for containing paint, liquid tar, municipal garbage, or treated lumber; consequently, a single liner system is usually adequate to protect the environments from the leakage of leachate from the none-hazardous waste landfill. It is cheaper in disposing of construction materials in a C&DD landfill than in a municipal solid waste landfill because C&DD landfills use only a single liner; therefore it is cheaper to build and maintain than other kinds of landfills.

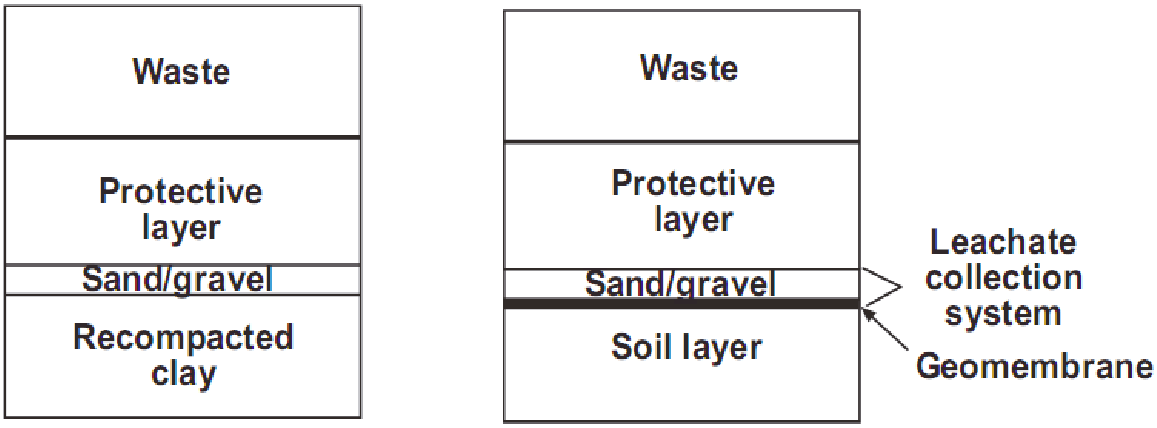


**Figure 2.8** The single liner system of the landfill (http://ohioline.osu.edu)

## 2.5 Method of Landfilling

There are many methods have been used for landfill in the past to the present; the different region has a different method of practices. According to Tchobanoglous and Kreith (2001) and Tchobanoglous et al., (1993), there three common practiced methods and have been using worldwide for solid waste landfills. The three methods consist of excavated cell/trench method, area method, canyon/depression method. Also, another method which is conventionally used, such as offshore/inshore reclamation for the country with limited land and/or coastal. These dumping methods are depending and applying based on the site condition, e.g., geography, geology or type of soil and groundwater table condition. The detailed discussion of each method will be described in the following:

### 2.5.1 Excavated Cell/trench Method

The excavated cell or trench method is ideally suited to the areas where the adequate depth of the groundwater level is enough to allow for the excavation of trenching or digging. After spreading and compacting of the waste, the soil excavated from the site is used as the daily cover materials. The second trench next to the first one is then excavated, and the excavated soil is used as a daily cover for the second trench and also the additional coverage for the first trench. The space between trenches must be at least 0.60m (2 ft.) should provide in order to separate the trenches.

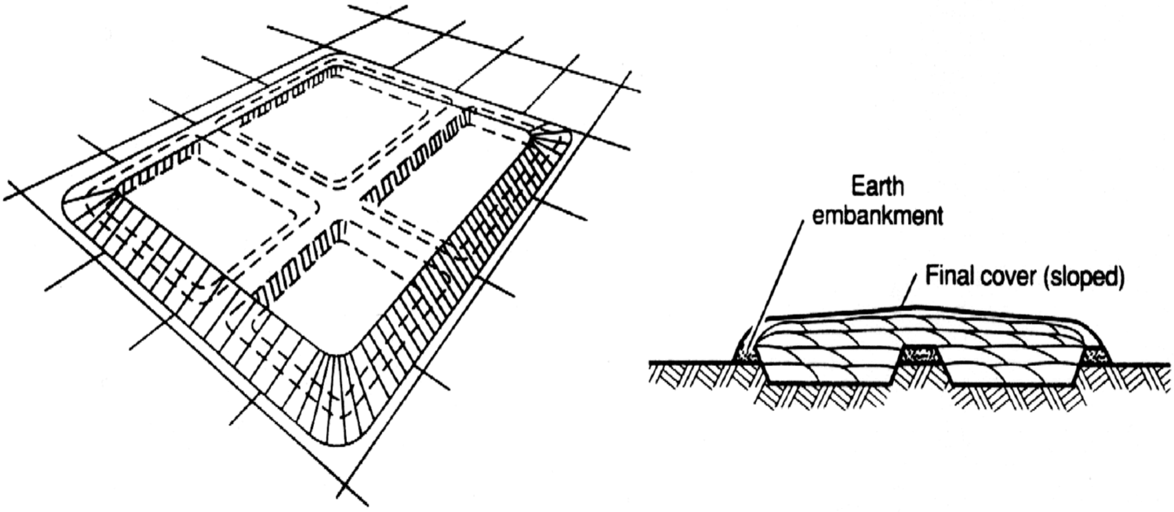


**Figure 2.9** Plan and cross-section of Excavated cell or Trench method, Tchobanaglous et al., (1993)

### 2.5.2 Area Method

The area method is widely used for most regions and site conditions. The method even more advantage for those of the sites with shallow groundwater conditions which is not suitable for the excavation of cells and place the waste, where the volume of solid waste to be disposed in the large areas. It is generally adopted on flat or gently sloping land, as well as ravines, valleys, quarries, abandoned strip mines, and other land depressions. In this method, the waste is spread over the working face and compacted by a landfill compactor or bulldozer. After each day, a soil cover is applied and compacted

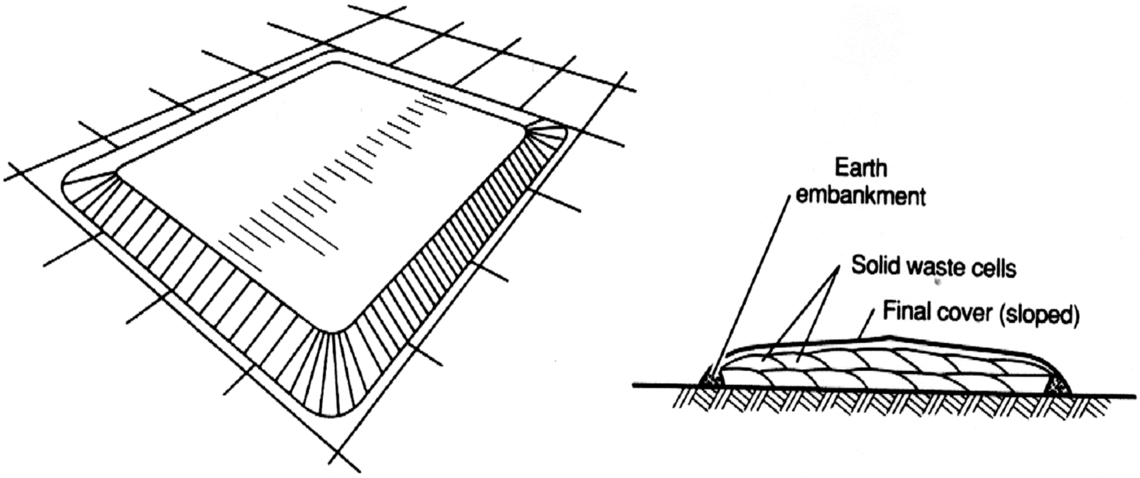


**Figure 2.10** Plan and cross-section of Area method, Tchobanaglous et al., (1993)

### 2.5.3 Canyon/depression Method

There is a variation of the area and trenching techniques; this method included the spreading and compaction of the waste on a slope and valley. The cover material is excavated directly in front of the working area, then spread over it and compact. A small excavation then becomes a part of the cell for the next day's waste disposal area. Even though this method is practical and straightforward but it is not commonly used because the liners and leachate collection systems need to be in installed before the waste disposal.

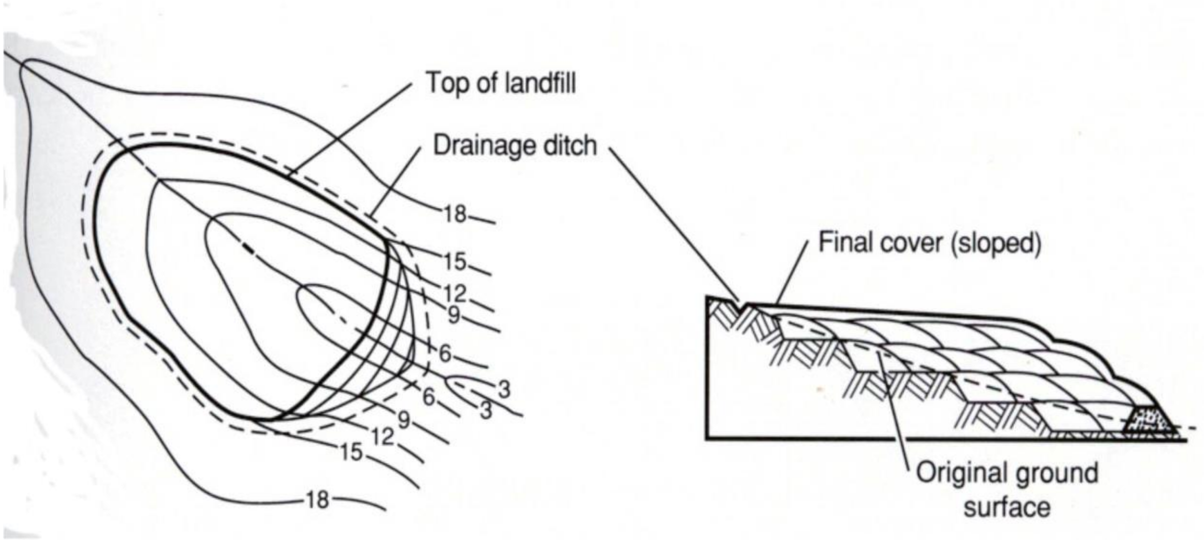


**Figure 2.11 Plan and cross-section of Canyon method,** Tchobanaglous et al., (1993)

## 2.6 Groundwater Contamination

Naturally-occurring processes and various human activities may reduce the quality of subsurface waters. Groundwater contamination can have a significant negative impact on humans and ecosystems. Solid waste disposal on land continues to be a major source of groundwater contamination. Infiltration through municipal and industrial refuse disposed of in landfill sites over a period generates leachate which contains various metals and organic and inorganic chemical species. According to Environment Canada, landfills pose a significant risk to groundwater across the country and major drinking water sources in groundwater-dependent communities like Elmira, Ontario, and Abbotsford, British Columbia has been contaminated by poor waste disposal practice, Environment Canada (2001). In the United Kingdom from a study conducted by Harris (1997) in a densely populated area, it was reported that landfill sites were numerically the most significant category of land use giving rise to groundwater pollution. Harris also reported that metallic compounds were the most commonly occurring contaminant and the pollution by organic compounds outweighed problems by inorganics.

Desaulniers et al., (1981) studied some of the naturally occurring causes of groundwater pollution who reported that surficial soils might often be characterized by a large concentration of total dissolved solids due to processes including sulfide oxidation, cation exchange, and carbonate mineral dissolution. Sulfate increase in the groundwater system has also been observed from gypsum dissolution when it is a common construction material disposed of landfill sites.

Howard and Gerber (1997) conducted a contaminant source audit for a 700 $km^2$ sub-region of the Greater Toronto Area and reported that the “impact potential” (i.e. the volume of water that would be contaminated to the standard by the available mass) exceeded 3 billion liters. BTEX and phenols, according to Howard and Gerber, represent the most serious problem; they suggested that biodegradation and volatilization may significantly alleviate risks. The other high-risk reported chemicals included copper, lead and cyanide primarily from landfills; sodium and chloride from de-icing chemicals; and nitrate from a combination of other sources. Drinking Water Standards therefore serve as an important basis for appraising groundwater quality and assessing chemical threats.

Regarding transport and fate characteristics, leachates are known to exhibit a wide range of behaviors. Contaminants in ground-water generally move in a plume with relatively little mixing or dispersion. Concentrations tend to remain high. These plumes of relatively concentrated contaminants move slowly through the aquifer and can be typically present for many years. Groundwater contamination often results in aquifers or parts of aquifers being damaged beyond repair, Freeze and Cherry (1979). Therefore, more emphasis should be directed towards developing processes and design standards that control the migration of dissolved contaminants through unsaturated soils that serve as containment barriers for aquifers beneath. Typical contaminant migration into the groundwater system is depicted below in Figure 2.12

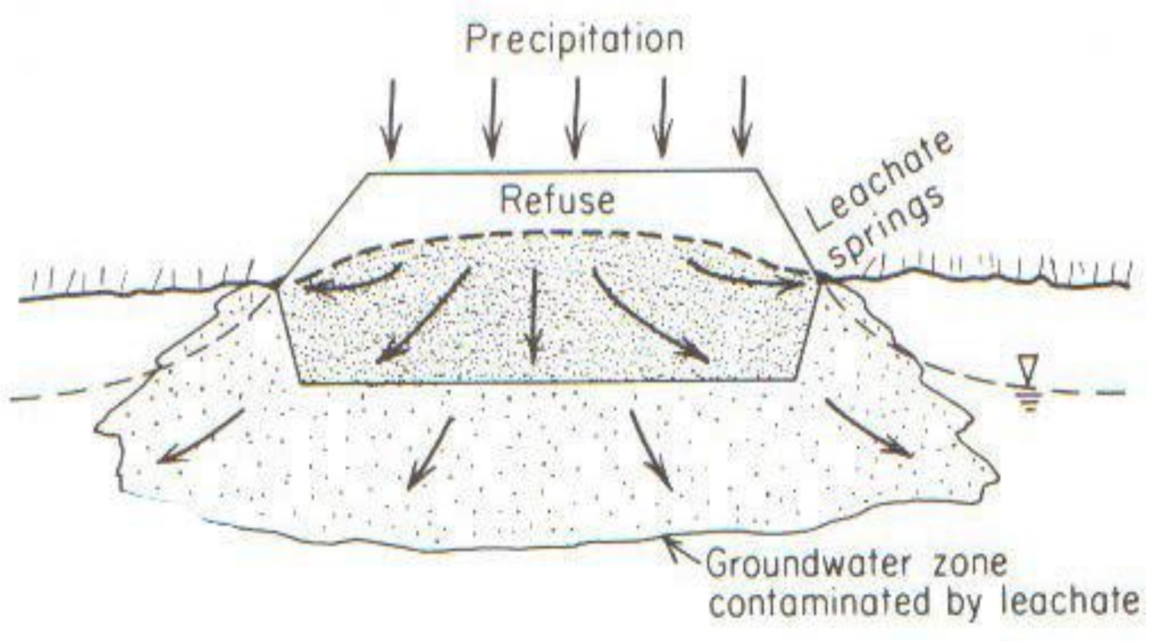


**Figure 2.12** Typical contaminant migration into the groundwater system, Freeze and Cherry (1979)

## 2.7 Contaminant Transportation in the Subsurface

Leachate together with existing contaminants that escape from a landfill unit may migrate through the unsaturated zone and eventually reach the water table and then get transported through the saturated zone to the point of discharge, i.e., a pumping well, a stream/river, a lake, etc.

Subsurface contaminant movement depends on many factors and conditions, such as the volume of the liquid component of the waste (leachate height), the chemical and physical properties of the leachate constituents, the loading rate, climate, and the chemical and physical properties of the subsurface (saturated and unsaturated zones). Some physical, chemical and biological processes also may influence the migration of leachate and groundwater. Complex interactions between these processes may result in specific contaminants being transported through the subsurface at different rates.

The following sections describe the different processes, which are mainly controlling contaminant and leachate transport in the subsurface of the landfill areas.

## 2.7.1 Physical Processes

### 2.7.1.1 Advection

Advection is the process by which motion of groundwater transports solute contaminants. The rate and direction of transport of a nonreactive solute will be same as that of groundwater flow. Advective transport is a function of the subsurface hydraulic conductivity, porosity, and hydraulic gradients, Freeze and Cherry (1979).

### 2.7.1.2 Hydrodynamic Dispersion

Hydrodynamic dispersion is a non-steady, irreversible mixing process by which a contaminant plume spreads as it is transported through the subsurface. It is a combination of mechanical dispersion and molecular diffusion. Mechanical dispersion results from variations in pore velocities within the soil or aquifer. Dispersion results in the spreading of solute along (longitudinal dispersion) and perpendicular (transverse dispersion) to the direction of groundwater flow. Longitudinal dispersion is typically one to two orders of magnitude higher than horizontal transverse dispersion. Increased dispersion results in a larger volume of the contaminated aquifer with lower concentrations. Advective transport and associated mechanical dispersion dominate the contaminant transport in formations of medium to high hydraulic conductivity.

Molecular diffusion occurs as a result of contaminant concentration gradients. Chemicals will move from areas of high concentration to areas of low concentration. Diffusion is driven by the solute concentration gradients according to Fick’s Law and is a slow process relative to advection in the highly permeable aquifers. The result of diffusion is dilution or reduction in the contaminant concentration. In formations of low hydraulic conductivity, including clay liners, diffusive transport is frequently the controlling mechanism, Kehew (2001), Zheng and Bennett (1995), USEPA (2011).

### 2.7.13 Mechanical Filtration

Mechanical filtration removes the groundwater contaminants that are larger than the pore spaces of the soil. Thus, the effects of mechanical filtration increase with decreasing pore size within a medium. Filtration occurs over a wide range of particle sizes. The retention of larger particles may effectively reduce the permeability of the soil or aquifer, USEPA (2011).

#### 2.7.1.4 Physical Sorption

Sorption is the tendency for a chemical to adsorb to the aquifer grains. It is a function of Van der Waals forces and the hydrodynamic and electrokinetic properties of soil particles. Sorption onto mineral surfaces is difficult to quantify, USEPA (2011).

#### 2.7.1.5 Multiphase Fluid Flow

Multiphase fluid flow occurs because many solvents and oils are highly insoluble in water, and it may transport in the underground as a separate liquid phase. If the viscosity and density of a fluid differ from that of water, the fluid may flow at a different rate and direction than the groundwater. If the fluid is denser than water, it may reach the bottom of the aquifer (top of an aquitard) and alter its flow direction to conform to the shape and slope of the aquitard surface, USEPA (2011).

#### 2.7.1.6 Hydraulic Conductivity

Hydraulic conductivity or in another word permeability is a measure of the ability of geologic media to transmit fluids. It is a function of the size and arrangement of water transmitting openings (pores and fractures) in the media and of the characteristics of the fluids like density, viscosity and so on, USEPA (2011).

#### 2.7.1.7 Secondary Porosity

Secondary porosity in rock may be caused by the dissolution of rock or by regional fracturing. In soils, desiccation cracks or fissures causes secondary porosity. Fractures or macro pores respond quickly to rainfall events and other fluid inputs and can transmit water rapidly along unexpected pathways. Secondary porosity can result in localized high concentrations of contaminants at significant distances from the facility. The relative importance of secondary porosity to hydraulic conductivity of the subsurface depends on the ratio of fracture hydraulic conductivity to intergranular hydraulic conductivity, USEPA (2011)

## 2.7.2 Chemical Processes

### 2.7.2.1 Precipitation/Dissolution

When the soluble concentration of a contaminant in leachate is higher than that of the equilibrium state, precipitation occurs. When the soluble concentration is lower than the equilibrium value, the contaminant exists in solution. The precipitation of a dissolved substance may be initiated by changes in pressure, temperature, pH, concentration, or redox potential. Precipitation of contaminants in the pore space of an aquifer can decrease aquifer porosity, Aller et al., (1987), USEPA (2011).

### 2.7.2.2 Chemical Adsorption/Desorption

Solutes become attached to the solid phase using adsorption. The organic carbon content of the porous medium and the solubility of the contaminant are the important factors that affect sorption, USEPA (2011).

### 2.7.2.3 Oxidation and Reduction Reactions

The Oxidation and reduction reactions involve the transfer of electrons and occur when the redox potential in leachate is different from that of the soil or aquifer environment. Redox reactions are important processes for inorganic compounds and metallic elements. It affects the solubility, complexing capacity, and sorptive behavior of constituents, and thus controls the presence and mobility of different substances in water, USEPA (2011).

### 2.7.2.4 Hydrolysis

Hydrolysis is the chemical breakdown of carbon bonds in organic substances by water and its ionic species $H_+$ and $OH_-$. Hydrolysis is dependent on pH and redox potential and is most significant at high temperatures, low pH, and low redox potential, USEPA (2011).

### 2.7.2.5 Ion Exchange

The capacity of soils to exchange cations is called the cation exchange capacity (CEC). CEC is affected by the type and the presenting of clay mineral, the amount of organic matter, and the pH of the soil, USEPA (2011).

#### 2.7.2.6 Complexation

Complexation involves reactions of metal ions with inorganic anions or organic ligands. The metal and the ligand bind together form a new soluble species called a complex. The complexation can either increase or decrease the concentration of a constituent in solution by forming soluble complex ions, USEPA (2011).

### 2.7.3 Biological Processes

Biodegradation of contaminants may result from the enzyme-catalyzed transformation of organic compounds by microbes. Naturally occurring bacteria within groundwater use organic chemicals as food sources and help break down of contaminants into degradation products. Contaminants can be degraded to harmless by-products or to more mobile and/or toxic products through one or more of several biological processes.

Depending on the types of organic compounds, degradation may occur under aerobic and anaerobic conditions. Oxygen is needed for aerobic organisms to degrade organic compounds. Under the aerobic degradation processes, electrons will be transferred from the organic material to oxygen (electron acceptor). This process reduces oxygen and transforms the organic material to carbon dioxide and a new compound. The anaerobic degradation process is similar to the aerobic degradation process except for that other common electron acceptors, such as nitrate, sulfate, and inorganic carbon, are used instead of oxygen, Kehew (2001), USEPA (2011).

## 2.8 Case studies of Leachate Assessment and Characterization

There are many case studies have been discussed on the landfill leachate characteristics for the last few decades. And most of them were pointed out the different type of contaminant and the pollution level depend on various factors, such as waste composition and condition, site conditions and location including the climate conditions and so on.

Fan et al., (2006) have presented the results of an investigation of three typical types of landfills in central Taiwan; closed landfill A, mixed landfill B (disposal of MSW with bottom ashes from MSW incinerators) and direct MSW landfill C, (disposal of MSW only). Several factors and parameters were included in the investigation, including basic parameters and heavy metals as well as the landfill age. These results indicated that the landfill age was negatively correlated with pH, COD, SS, VSS, TS, color, TOC, BOD, conductivity, and SS. On the other hand, the pH, BOD/COD, BOD/TOC and COD/TOC did not appear to have significant correlation with landfill age. The organic contents of leachate in closed landfill A were significantly less than active landfills B and C as predicted. But the leachate generated from mixed landfill B did not significantly reduce the organic contents when compared with landfill C. However, the mixed landfill site B had higher contents of DS, TS, and electrical conductivity, Na, Ca and Mg and lower Fe and Cr than active municipal landfill C. This might be due to the contents of bottom ash in landfill B. Landfill C had the highest Fe and Cr and the lowest Ca contents. Closed landfill A had a higher percentage of HA than active landfills B and C. An old landfill had a higher percentage of humic substances (HA and FA). The aromaticity of the closed landfill leachate A) was lower than that of active landfills B and C. In addition, the mixed landfill B had lower aromaticity than direct landfill leachate C. Leachate A contained the significant portions of aliphatic functional groups and higher contents of oxygen-possessing carbohydrate than those of activating landfills. One potential advantage of the mixed landfill was that it might help to reduce the toxicity of leachate.

Zainol et al., (2012) have reported a comparative study of leachate characterization of two landfills in the northern part of Malaysia. The two selected landfill namely Kuala Sepetang Landfill Site (KSLS) and Kulim Landfill Site (KLS) which are aerobic landfill. The results show the significant effect of landfill age to the leachate composition, especially the biodegradable fraction. Based on the characterization of landfill leachate, KSLS demonstrated low biodegradability BOD5/COD=0.19) compared with KLS (BOD5/COD=0.24). A wide range of measured parameters in both sites, such as colour, seemed to be affected by the rainfall, which caused dilution of the generated landfill leachate at the collection pond. The implementation of the most suitable treatment technology should be applied after fully understanding of leachate composition and concentration.

Banar et al., (2006) introduced the characteristics of urban landfill leachate in Turkey. Significantly the study was the first and only study in the landfill, which the author stated the importance of obtained data from the study. The dumping site investigated in this manuscript is essentially an unregulated dumping site that belongs to the Metropolitan Municipality of Eskisehir. The two sub-municipalities and vehicles of the two private companies working for collecting municipal wastes (410 ton/day), as well as medical wastes from hospitals and industrial wastes. The results confirm the different concentration level for different landfill, as well as the different location of the same landfill. BOD – COD ratio decrease as a decrease of landfill age. The color of LC from dark brown to black was mainly attributed to the oxidation of ferrous ion to ferric form and the formation of ferric hydroxide colloids and complexes with fulvic/humic substances. As the landfill age increased, the consequent increase in pH values caused a certain decrease in metal solubility.

Bhalla et al., (2012) have presented a comparative study on the characterization of leachate from municipal solid waste (MSW) landfilling sites of Ludhiana, India. The study included three none engineered landfill without any liner, drainage and cover lead to leachate paths to surrounding areas High organic, and inorganic materials higher than the permissible limits The leachate was highly affected by the landfill age, while the HMs existed at some domestic level but higher than the standard limit of the environment. The leachate then suggests applying for some suitable treatment techniques to a satisfactory level.

Zhang et al., (2013) investigated characteristics of leachate and concentrated leachate in three landfill leachate treatment plants. The composition of landfill leachate and concentrated leachate varied with landfills. Heavy metals, Cl- and $SO_4$ were removed small amounts during the process of landfill leachate treatment and accumulated in the concentrated leachate. Single stage anaerobic-aerobic treatment process mainly transformed the leachate $NH_4$ -N into $NO_3$ -N, which was accumulated in the concentrated leachate. The biodegradability of concentrated leachate was lower, compared with the landfill leachate, owing to its high concentrations of refractory organic matters including aromatic compounds, long-chain hydrocarbons, and halohydrocarbons, as well as its high toxicity with the presence of toluene, ethylbenzene, dibutyl phthalate and chlorobenzene which have been identified as USEPA priority environmental pollutants. Although higher microbial diversity was observed in the concentrated leachate, the function and activity of these microorganisms should be studied further to understand the characteristics of concentrated leachate better. These findings can provide fundamental information to select and optimize treatment processes for landfill leachate and concentrated leachate.

Naveen et al., (2016) have presented the urban municipal landfill leachate in term of physicochemical and biological concerns. The study investigates the physicochemical and biological characterization of landfill leachate and nearby water sources. It attempts to identify relationships between the key parameters together with understanding the various processes for chemical transformations. The results showed a high concentration of organic and inorganic constituents. Heavy metals concentration was in traces indicating that the waste dumped is predominantly municipal waste. Physical-chemical analysis showed significantly high salinity and alkalinity. Based on the $BOD_5$/COD ratio the Mavallipura landfill leachates were found to be medium aged. The clear distinction between the leachate samples and pond waters can be observed through the cluster analysis. Moreover, the microbiological analysis was also revealed a substantial difference among the compositions of microflora in the samples. High leachate pollution index (LPI) values indicated that leachate generated from landfill site is not stabilized and mature, and are still undergoing decomposition and thus have high chances to cross-contaminate nearby surface and ground waters. Based on the various analysis performed in the study possible linkages between the leachate and nearby water bodies were observed. The water quality in water bodies was found relative poor and enriched with ions and nutrients making it unsuitable for any use.

## 2.9 Case Studies of Groundwater and Surface Water Contamination

There are some studies have been pointed out the influence of landfill leachate on the groundwater and surface water, the level may depend on the leachate quality as well as the geological condition at the landfill sites. Some case studies on the groundwater contamination caused by the landfill leachate will be illustrated as follows:

Abu-Rukah and Al-Kofahi (2001) have presented the leachate from the major landfill in northern Jordan, El-Akader on the ground-water. Varieties of physical and chemical parameters were estimated, this includes pH, hardness, electrical conductivity, and total dissolved solids for the physical parameters. As for the chemical parameters are significant cations, Ca, Mg, Na, and K. Major anions, $HCO_3$, $NO_3$, Cl, and $SO_4$, major ions $PO_4$, and heavy metals, Pb, Fe, Mn, Cd, and Zn. El-Akader dump site receive both solid waste and waste-water, the average septage volume received at El-Akader site is 2305 $m^3$/day, and almost 217 tankers with the capacity of 11 $m^3$ discharge their loads at El-Akader site. The total volume of solid waste dumped into the site was estimated at about 400 tons/day. The results presented about the quality of underground water, and the effects of the El-Akader landfill site on the groundwater in the area of investigation. The water is non-potable because most of the physical and chemical parameters examined exceed the permissible limits. Some sites are not suitable for irrigation, because the conductivity is high and in addition have increased concentrations of chloride, bicarbonate, and nitrate.

Watananugulkit et al., (2003) investigated the impacts of leachate on the quality of surface water and groundwater around the On-nuch disposal site center in Bangkok. The physical, chemical and biological parameters were intensively assessed for this study. Water samples were collected from 5 stations in the rainy and dry season, while the leachate characteristics were recalled from the previous study. The results from this study showed poor quality of the surface water with high organic load (BOD) and suspended solids. The canal may become shallow in the future. This is indicated that the water should not be used for any domestic purposes. Finally, water quality in the dry season is worse than in the rainy season. And groundwater is not impacted by leachate from the waste disposal site. The water quality of groundwater in the dry season is better than in the rainy season.

Sabahi et al., (2009) presented the characteristics of leachate and groundwater at Municipal Solid Waste Landfill of Ibb City, Yemen. The leachate was sampled at three different locations of the landfill, at the landfill itself and 15 and 20 m downstream of this landfill. Groundwater samples collected from 5 boreholes to study the possible impact of leachate percolation into groundwater. The assessment was done only in dry season. Results showed the most leachates at landfill likely in methanogenic phase. Based on the high alkaline as pH value recorded about 8.46. The results also showed that for the 4 out of 5 monitored boreholes were contaminated, where the concentration of physicochemical parameters was above the standard limit of acceptable levels which required for drinking water adapted by Yemen's ministry of water and environment and by international standard. Therefore, the landfill is dangerous for the environment so government should do sanitary landfill to prevent further contamination to surface water, groundwater as well as soil.

Aderemi et al., (2011) assessed the groundwater contamination by leachate near a municipal solid waste landfill which located at the extreme east-west area of metropolitan Lagos, operated by Lagos Waste Management Authority (LAWMA) and referred to as Soluos. In their study, the extent of groundwater contamination, eight (8) sampling points was selected within 0.55 km radius of the landfill site from where the groundwater samples were taken and also the leachate samples were characterized as source of the contaminant.

The results obtained in their study showed that the leachate generated from the landfill site has a minimal impact on the groundwater quality in the locality. The soil stratigraphy of the site, being predominantly clay and lateritic clay, seems to have significantly influenced the low levels or absence of contaminants especially heavy metals in the groundwater samples. The observation of contaminated levels of Pb, Cd, and Zn in leachate and the presence of some conventional contaminants above the WHO permissible limits in some of the groundwater samples. It is an indication that in the absence of a leachate collection system, the uncontrolled accumulation of leachates overtime at the landfill base and it will represent a significant threat to the groundwater quality. The findings obtained from this assessment have shown that groundwater of the study area is unreliable regarding the safety of drinking water or supplying purposes. Therefore emphasizes the need to improve on waste management practices and construct appropriately engineered sanitary landfill sites to curtail the pollution of groundwater.

Dharmarathne and Gunatilake (2013) presented the characteristics of leachate and surface groundwater pollution at MSW landfill of Gohagada, Sri Lanka. In the study, the leachates sampled at nine different locations of the landfill were collected, while groundwater samples were collected using auguring at five locations. The assessment was focused on both physically and chemically characterized. Parameters measured were pH, Sulphate, Nitrate, Nitrites, Heavy metals (Pb, Zn, Ni, Cr, CO, Fe, Mn, and Cu). The results found most of the leachate samples showed high concentrations as compared to the effluent standard permits. The groundwater quality improves with the increase in distances of the borehole from the landfill site. As there is no natural or other possible reason for high concentration of these pollutants, it can be concluded that the leachate has a significant impact on groundwater quality near the areas of the Gohagoda landfill site. Samples collected during the dry season showed the lower concentration of elements and nutrients than the samples collected in the rainy season. That may be due to the enhanced leaching of material by the rain.

## 2.10 Leachate and Groundwater Migration Models

Most of the models are a simplified representation of the real field systems, and consequence of being cannot fully reproduce or predict all of real site characteristics. The errors are introduced as a result of simplifying assumptions, insufficient/lack of data, uncertainty in existing data, not proper/poor understanding of the processes influencing the fate and transport of contaminants, and the limitations of the model itself. Hence, results of the models should be interpreted as the estimates of ground-water flow and contaminant transport in those site conditions, US EPA (2011).

There are several reports present the detailed discussions of issues related to and associated with model selections, applications, and validations. EPA's Exposure Assessment Group has developed suggested recommendations and guidance on model validation, Versar (1987). Then Weaver et al., (1989) discuss on mathematical model options for selection and field validation. Also, Donigian and Rao (1990) address each of these issues and present various options for developing a framework for model validation.

As each site is unique, the modeler needs to determine the important conditions and processes at a specific site for each study, then select the most suitable model. The computer models also can be used to make predictions on leachate generation, as well as the leachate migration. However, these predictions are highly dependent on the quantity and quality of the available data, USEPA (2011). The most advantage of the computer modeling is that a large amount of data can process, while experimental modification can provide related supports, in order that many possible situations for a given problem can be studied in great details.

From the last few decades to the present, tens of computer codes have been developed to simulate the soil-groundwater systems in various aspects. Some of that software are Groundwater Modelling System (GMS), Groundwater Vistas, Visual MODFLOW, MODFLOW SURFACT, POLLUTE and many more; they are being used all over the world by different hydrogeologists, hydrologists, and environmentalists, Boulding and Ginn (1995). A computer program called MODFLOW (three-dimensional block-centered finite-difference groundwater flow model) has been developed by McDonald and Harbaughin (1988) which is in the form of modular three- Dimensional groundwater flow model for US Geological Survey.

MODFLOW can simulate a wide range of flow in the porous media, varieties of systems and the standard including groundwater flow, transport of contamination. While MT3DMS is a three-dimensional multi-species contaminant transport model to simulate the solute transport processes. Basically, it is based on the **advection-dispersion** formulation for modeling of the saturated and unsaturated zone, also interaction between surface water and subsurface water. MT3DMS contains many different techniques includes the third-order of Total Variation Diminishing-TVD, it was fully implicit Finite-Difference Method-FDM, and particle tracking based Method of Characteristics (MOC). There has been a wide development in MT3DMS since the first released in 1990 which was known as MT3D. It supports all of the different species for mass transport simulation. Visual MODFLOW combines MT3DMS and MODFLOW to flow and transport modeling under different condition, Seyed et al., (2010), Harbaugh (2005) and Zheng (2009).

Some case studies related to contaminant transport and groundwater flow modeling using GMS, MT3DMS, and Visual MODFLOW has been reported as follows:

Chen et al., (2016) have reported the case study of groundwater and contaminant transport at a landfill site condition in the central part of Taiwan, by using the GMS system. In their simulation, the total mass of contaminants in the aquifer increased by the average of 72% (about 65% for ammonium nitrogen and 79% for chloride) after ten years. The simulation showed a plume of contaminated groundwater that extends 80 m in length and 20 m in depth northeastward from the landfill site in this study. Although the results showed that the concentrations of ammonium nitrogen and chlorides in most parts are low; they were 3.84 and 467 mg/L, respectively.

Mondal and Singh (2009) have investigated the contaminant migration at an industrial belt by constructing a mass transport model using ‘Visual MODFLOW’ and ‘MODPATH’. The study has indicated that even if the pollutant sources were reduced to 50% of the present level, TDS concentration level in the groundwater, even after 20 years, would not be reduced below 50% of it.

Rajamanickam and Nagan (2010) have conducted a groundwater quality model study using ‘Visual MODFLOW’ at Amaravathi River Basin of Karur District, Tamil Nadu. The model is used for simulation of the groundwater quality for 15 years under different scenarios. The results of simulation study showed that, even if the effluent meets the discharge standards for the next ten years, groundwater quality cannot be improved and if the units go for zero discharge, improvement in the quality of groundwater can be observed in few years.

Seyed and Mustapha (2011) have presented a case study on the movement of phosphorus pollution in Seri Petalling landfill leachate. ‘Visual MODFLOW’ was used to predict subsurface and surface migration of pollution within ten years. The prediction shows phosphorus migrated widely to further places such as river and it has an adverse effect on the environment, animal, and human.

Rao et al. (2011) assessed the groundwater contamination from a hazardous dump site in Ranipet, Tamil Nadu in India. Tanneries located in an industrial and development area of Ranipet manufactured chromate chemicals from 1976 to 1996. Chromium levels in the groundwater were found as high as of 275 mg/l in this area. The available hydrogeological, geophysical and groundwater quality databases have been used to construct a groundwater flow and mass transport model to assess the groundwater contaminations. It has calibrated for 30 years. The migration has been found to be very slow, with a groundwater velocity of 10m/year. It also has been reported that the untreated effluent discharge in parallel to the chromium dump site is the most influential in the migration of contaminants.

A study to assess groundwater in Auja-Tamaseeh basin in Tulkarem area-West Bank was conducted by Samhan and Ghanem (2012). A steady-state calibration flow model, as well as solute transport model, was built using the ‘Visual MODFLOW’ software. A stress period of 10 years (2005 - 2015) was assigned in the study and its tendency to the groundwater contamination. The results show that there is a pollution risk due to the human activities in the area.

## 2.11 Summary and the Need for Current Study

The critical review of the literature showed that the chemical composition of the leachate from a municipal solid waste landfill site depends upon the age, characteristics of waste, seasonal variation, subsurface condition, decomposition rate etc. According to the literature, it is proved that a municipal solid waste landfill leachate is a composition of mixed contaminants. While transporting leachate through surrounding soil, the chemicals present in that is liable to change the properties of soil. The effect of the leachate on soil properties may depend upon the concentration of chemicals, period of contact of the soil with the chemicals and type of the soil. From the study of literature, it is observed that the research on changes in engineering properties of soil due to the presence of mixed contaminants in leachate is limited.

The significant observation from numbers of literature have reviewed, many of them have focused on the leachate quality but not very deep in details. Most of them were only one concentration value (liquid part by filtering) was presented for the heavy metal assessment in the previous researches on the leachate study. And many of them presented the basic physical and chemical parameters but not much on heavy metals with clear description of the procedure of leachate sample preparation. The summary of the mentioned information of the past works was presented in Table 1.1.  Since in the complexity of the leachate, physically, at least leachate can be separated into two parts (liquid and solid). The concentration of measured parameters should also be presented in accordingly, especially for the heavy metal concentration, since heavy metals can be partitioned on the sold part.  Therefore, the current study is objected to studying in very deep details of the leachate, and the results will be focused on the separated parts; liquid part (filtered concentration), solid part (suspended solids) and the total concentration.

Also, the contaminant transport in underground conditions was currently have been studied by many researchers. However, most of them were intensively focused on the specific landfill site, and others focused on some parametric studies. And as of the best of my knowledge reviewing the previous research studies, there is none of them has been serious concern about the changing of site condition, particularly for the deep pit disposal in ASEAN region. Therefore, in order to fill those gaps, the current study aims to investigate the landfill site conditions, which are common in this region, on the groundwater environments by using GMS software to simulate the future risks from the leachate.

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# Chapter 3

# Study Sites

This chapter presents the general and necessary information using in the analysis, discussion, and interpretation of the measurement results. The chapter starts with the site locations of this study, then the site characteristics, which include all of the site conditions, such as the layout of all pit based on the landfill management, pit design, and geological conditions. Moreover, the municipal solid waste situation and its basic characteristics, the climate conditions are also discussed in this chapter.

## 3.1 Location of the Study Sites

The sites of this study are the three significant landfills located in three different countries in Indochina Peninsular region, Nonthaburi landfill in Nonthaburi Province Thailand, Dangkor landfill in Phnom Penh, Cambodia and KM-32 landfill in Vientiane, Laos.

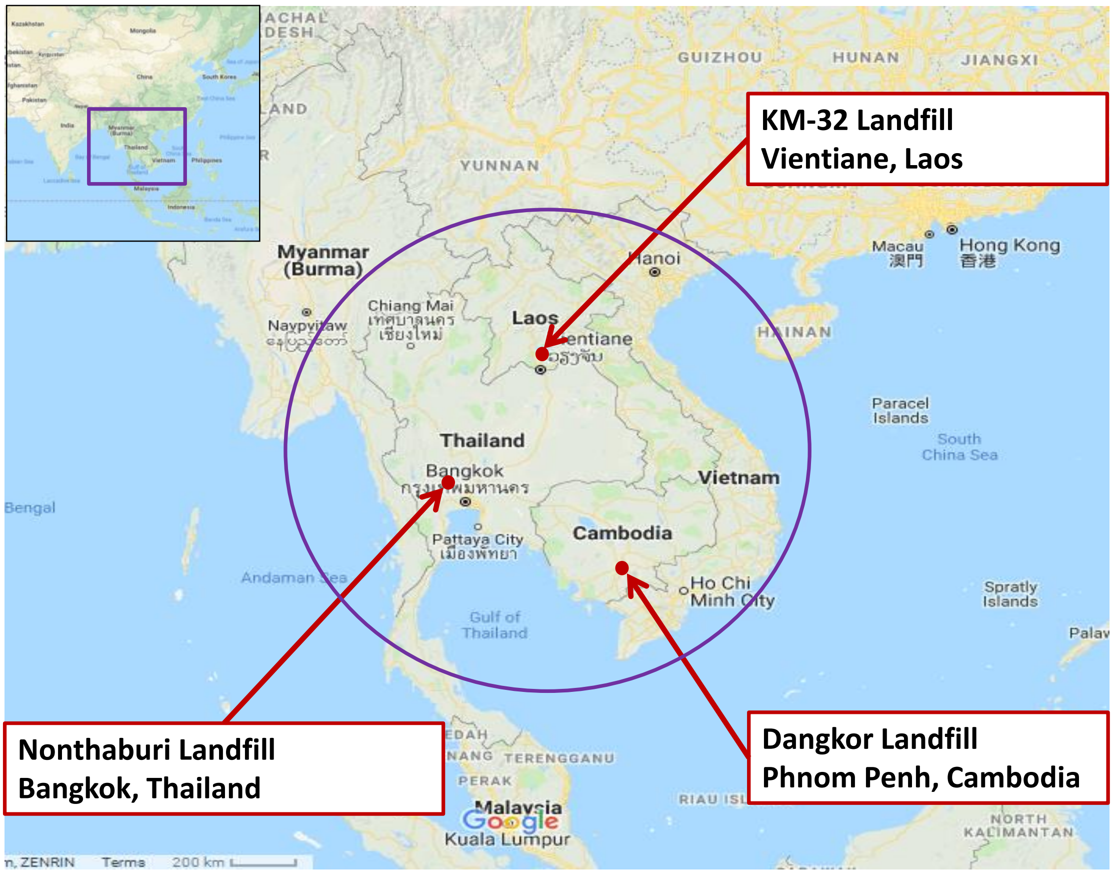


**Figure 3.1** Locations of all landfill sites of the study

Nonthaburi province is one of the provinces in Bangkok metropolitan region; the most densely populated next to Bangkok. The other two landfills are located in the capital cities of the two countries which are considered as the highest number of population city. These three landfills are serving as only one landfill for each city with many basic similarities, such as climate and environmental condition, the lifestyle of the people, and also the culture and belief.

## 3.2 Site Condition and History

The summaries of basic information of all three landfill sites are shown in Table 3.1.

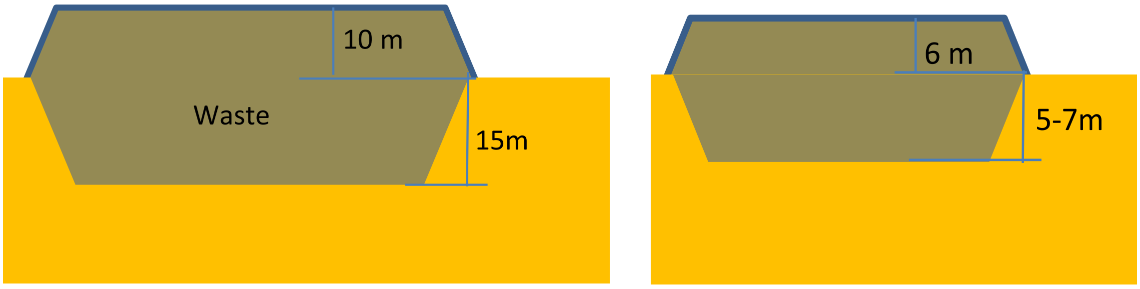
**Table 3.1** Summary of landfill information

| **Items** | **Nonthaburi landfill, Thailand** | **Dangkor landfill Cambodia** | **KM-32 landfill Laos** |
|---|---|---|---|
| Coordination | 14˚0’58’’ N and 100˚18’53’’E | 11˚28’59’’N and 104˚53’11’’E | 18˚4’48’’ N and 102˚50’49’’E |
| Year of operation | 1982 | 2009 | 2008 |
| Waste receive (tons/d) | 1,300 | 1,800 | 500 |
| Total landfill size (ha) | 77 | 31.4 | 100 |
| Elevation (MSL-mean sea level) | 5 | 11 | 190 |
| Area of closed dumping pit (ha) | 34 | 11 | 24 |
| Leachate pond area (ha) | 28 | 1 | 12 |
| Active area (ha) | 20 | 5.5 | 8 |
| Excavated /future area (ha) | 0 | 3.8 | 12 |
| Depth of pit (m) | Old pit = 5; New = 15 | Area A, B = 10; C, D = 30 | Pit No. 1-7 = 3 |
| H. of garbage from surface (m) | Old=4-5; New=10 | Area A, B = 10; C=-1, D=-24 | Pit No. 1-7 = 3 |
| Volume of waste ($m^3$) | 8,488,000 | 3,727,000 | 1,840,000 |
| Volume of leachate ($m^3$) | 1,156,800 | 356,800 | 180,000 |
| Leachate treatment system | None | None | None |
| Daily soil cover | Occasional | None | None |
| Final soil cover | 80% | A-B=100%, C-D=0% | None |
| Soil type (bottom soil) (m/s) | Clayey, $K=10^{-(9-10)}$ | Sandy Clay, $K=10^{-(7-8)}$ | Clay (CH), $K=10^{-(9-10)}$ |

### 3.2.1 Nonthaburi Landfill

Nonthaburi landfill is about 60 km from the city center of Bangkok to the northwest with an approximate area of 77 ha. According to the landfill authority, the average daily received waste was 800 tons/d in 2000, which increased more than 60% up to 1300 tons/d in 2015. From 1982 to 2004, the landfill operated as open dumping facility mainly in the old area (OL1), simple pits were dug and moved around, and many ponds had dug for leachate storage and changed from time to time. In 2004, the fund was available for improvement of landfill facilities; area A and B were developed as a sanitary landfill and received garbage from 2005-2006.; more than million cubic meters of garbage in the old area had transferred to these new landfill areas and also other landfills in a different location. From 2007-2009, the old area (OL2) was operated as a semi-sanitary landfill by a local company. In August 2009, a new semi-sanitary landfill (area E) had started its operation, and it is planned to be the last landfill area. Beside landfill E, there is a large and deep pond. In the early stage of operation of area E, this pond was a water reservoir, but it started to receive the leachate from landfill E and became leachate discharge pond (LDP) in early 2012.

**Figure 3.2** Plan view and layout of Nonthaburi landfill



(a) (b)

**Figure 3.3** Cross-section of the dumped pits: (a) area E; (b) Closed area-OL 2

**Table 3.2** Summary of history and activities of Nonthaburi landfill

| Landfill | Period | Activity description | Remark |
|---|---|---|---|
| Nonthaburi | 1982-2004 | - Started its operation in the area of 10.8 ha as a dump site, the depth below the ground surface about 5 m<br>- In 1997, the 19.2 ha of nearby area was purchased to extend the lifetime of the site<br>- The accumulation of solid waste reached its peak in 2004, forming a huge mountain of 20-25 m height above the ground level. The approximate solid waste volume was about 1.17M $m^3$ (million $m^3$) with the waste density of 0.75 Tons/$m^3$ | Old landfill area (OL1) |
|  | 2005-2006 | - The remediation works began with two engineered landfill cells (sanitary landfill A and B) constructed. The 1.5mm HDPE geomembrane and geotextile were used in this sanitary landfill.<br>- The size of area A-B was about 6.8 ha; the pit depth was about 12 m below the ground surface with the waste height of 10m above ground level. The total waste volume was about 1.3 $Mm^3$ at the peak volume.<br>- Large open dump pile (OL1) was closed and covered by soil on the top part of the dumpsite. Half of the solid waste was transferred to the new sanitary landfill (area A-B), and the height of waste in OL1 reduced until about 12 m. | Area A & B |
|  | 2007-2008 | - The area of 8.5 ha, name as OL2 (areas C-D in the past). As earlier time OL2 is formed of 2 pits (C & D) before closing and covering as one (OL2) for the current zoning. This area was also applied as sanitary landfill with the placing of HDPE geomembrane and geotextile, same as area A-B | OL2 |

| | | | |
|---|---|---|---|
| | | - The depth was about 5-6 m below ground level and about 10m above the ground surface.<br>- The leachate treatment facility was constructed in 2006 and started its operation in 2007 | |
| | 2009-present (2018) | - The new area (area E) has been started with the approximate size of about 19 ha. The area was designed as sanitary landfill with four small zoning insides. The first 2 zones in front were filled in 2015, and the last two zones at the back are filling and expect to fill up until the end of 2019.<br>- The existing large natural reservoir nearby the active dumpsite area E, was used as leachate discharge pond in 2012. The size is about 13 ha with the depth of approximately 16 m below ground surface. | Area E |

### 3.2.2 Dangkor Landfill

Dangkor Landfill in Phnom Penh is one of the largest dumpsites in Cambodia. The dump site occupied an area of 31.4 ha, and this landfill is about 14 km from Phnom Penh city center JICA (2005). Starting its operation in August 2009 with daily waste received of about 1,200 tons/d which has rapidly increased to 1,800 tons/d in 2015. There are two areas as zoning; Areas A-B and Areas C-D. Areas A-B with pit depth of 10m was opened from August 2009 and closed in Feb 2016, and covered by soil in October 2016. Area C (5.5 ha) was started right after the closing of Areas A-B. Pit depth of area C is very deep about 30 m below ground surface. In May 2016, a waste fire broke in the deep pit, and many tons of garbage was burned. In the mean times, Area D was also excavated with similar pit depth to Area C with the approximate area of 3.82 ha, extending the dumping capacity.

**Figure 3.4** Plan view and layout of Dangkor landfill

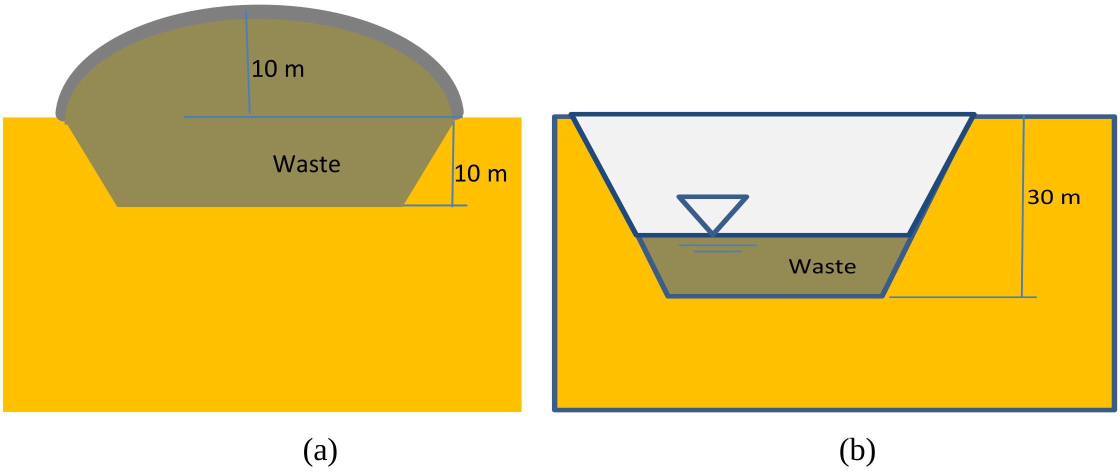


**Figure 3.5** Cross-section of the dumped pits: (a) closed areas A-B; (b) active areas C-D

**Table 3.3** Summary of history and activities of Dangkor landfill

| Landfill | Period | Activity description | Remark |
|---|---|---|---|
| Dangkor | 2009-2016 | - The areas A-B was started its operation with an approximate area of 11 ha. The dumpsite was initially designed by JICA as sanitary landfill including the leachate treatment system at the corner near to the creek.<br>- In the implementing stage, the local authority was not able to follow the original design due to the lack of funding. Then the dumpsite was constructed as simple excavated pit without any geomembrane, and leachate treatment facility was canceled. The pit depth is about 10 m and the waste height later at the peak of about 10m.<br>- The area was closed in early 2016 (Feb) and started to cover by soil in Oct 2016 till early 2017 for the covering completion. | Areas A-B |
| | 2016-2017 | - Immediately at the closing time of Areas A-B, area C started to receive the waste. The size of area C is about 5.5 ha with the significant depth about 30m, regarding the height of the waste above the ground surface was not confirmed at the moment.<br>- In April to May 2016, area C was fired with the unknown of the source. The fire burned the significant amount of the waste inside the pit, but the fire was not much effect to the surrounded area due to the pit is very deep, which could be the effective protector of extended fire to the nearby area. | Area C |
| | 2017-2018 | - In July 2017, while area C was filled up about 95 % of the pit depth below ground level. Area D was started with the similar depth to area C, but the shape was not so clear at that time of visit, the whole area D size is about 3.8 ha as origin, but the extent can be up to 7.3 ha in total area.<br>- The amount of waste by the time of visit was about 200-300 $m^3$, as the waste elevation was filled the first step of the pit. | Area D |

### 3.2.3 KM-32 Landfill

Similarly, the KM-32 landfill is the biggest and only MSW disposal site in Vientiane capital after old landfill at KM-18 was closed. It started its operation from August 2008, with an approximate area of 100 ha, and the distance from Vientiane capital center is about 32 km. The garbage volume accepted has continuously increased from 250 tons/d in 2008 to 500 tons/day in 2015. The dumping started with pit No.1 and No.2 in Aug 2008, and then the dumping of pit No.3 and No.4 was begun in Feb 2009 while pit No.1 and No.2 were still in the active condition. Pit No.5 was designed to be the leachate pond; then the authority decided to put the garbage into the pond instead of keeping as leachate storage, and pit No.5 was closed in Sept 2012. In late 2016, pit No.6 and No.7 were done, and some garbage has already put in both pits. In the area serving pit No.8 to No.11 the excavation work has not been done but a small amount of garbage found in that area.

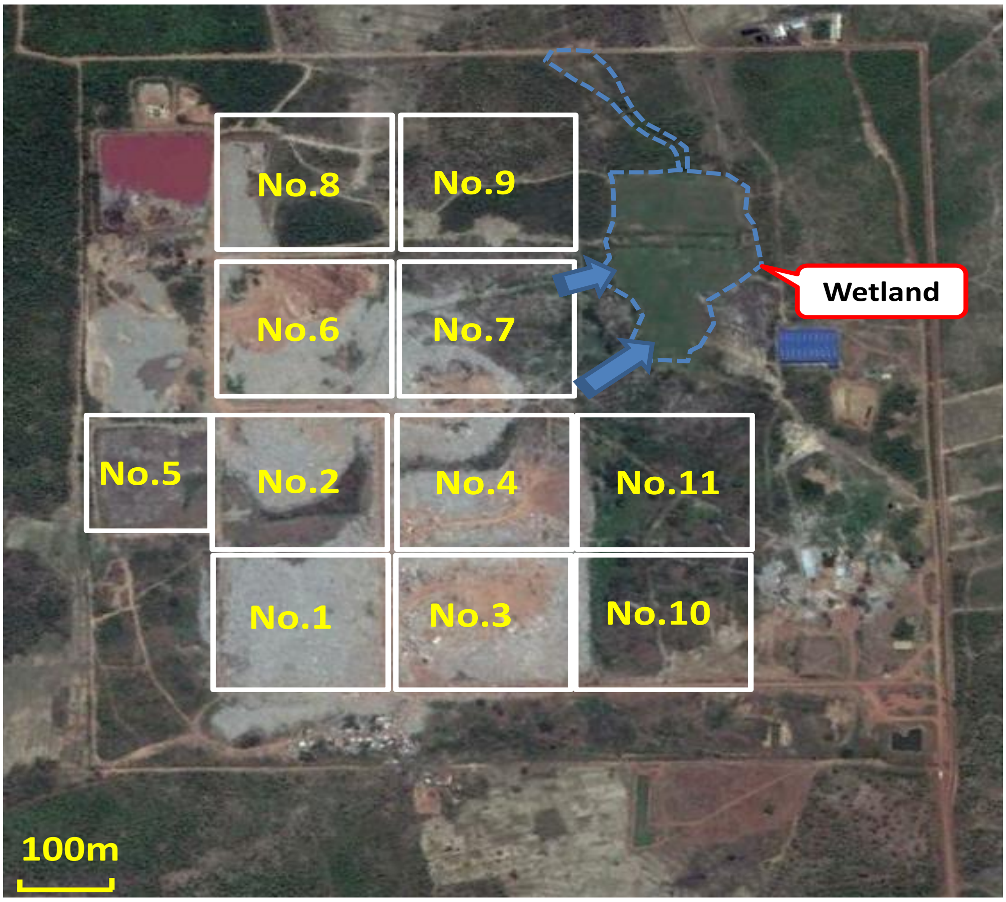


**Figure 3.6** Plan view and layout of KM-32 landfill

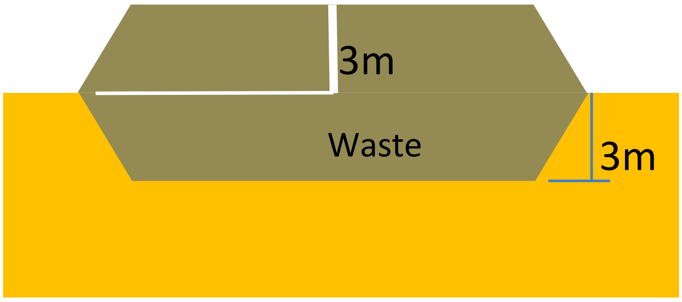


**Figure 3.7** Cross-section of the dumped pits for all segments

**Table 3.4** Summary of history and activities of Km-32 landfill

| Landfill | Period | Activity description | Remark |
|---|---|---|---|
| KM-32 | 2008-2009 | - The landfill was started with the pit No. 1-2 in the second half of the year 2008. The total area is about 100 ha, while all the pits were designed by JICA and the size is 200 x 200 [m]. However, during the implementation, the design was not applied due to the budget was not available. The pit size was only designed that the local authority could follow, while the rest of facilities, for example, leachate treatment facility, daily soil cover and other technical methods of dumping were omitted.<br>- The waste was filled up within a short time due to the pit depth was quite shallow about 3 m and other 3m for the height of the waste pile. | Pit No.1-2 |
| | 2009-2013 | - In Feb 2009, the pit No. 3 and 4 were started to receive to garbage, while pit No. 1-2 is not yet fully closed, some waste was still fill up at some corner of the pit.<br>- The pit No. 5 was also excavated in the purpose of constructing leachate pond, to store the leachate from the current pits. Pit number 5 was different in term of size compared to another pit; the size is about 150 x 170 [m].<br>- In early 2012, the authority was agreed to use pit N0. 5 as dumping pit instead of leachate storage pond, and the waste was filled up at the end of 2012.<br>- The leachates from all pits are directly drained to the lower part of dumping areas as a temporary pond. Two dikes were conducted to slow down the flow as retention before releasing to the surrounding areas.<br>- The 0.6 m diameter concrete pipe connected all the pits in order to drain to leachate during the rainy season because none of the pumping systems | Pit No. 3-4-5 |

| | | | |
|---|---|---|---|
| | | applied to control the leachate level. In this landfill, the leachate flow was not observed in the dry season, especially in the low pond (wetland area) where the huge amount of leachate was confirmed in the rainy season. | |
| | 2014-2017 | - Pit No. 6 and No. 7 were officially received the garbage in early 2013, which pit No. 6 was partly excavated.<br>- Pit No. 7 and No. 8 was started the following time without proper record by the landfill authority.<br>- Regarding pit No. 9-10-11, none of the activity has been observed until the last visit in Oct 2017. However, the little amount of garbage was distributed in some parts of these areas. | Pit No. 6-7-8 |

## 3.3 Geological Condition

### 3.3.1 Nonthaburi Landfill:

According to soil investigation, reported by KRUNGTHEP GROTECHNIQUE Co., Ltd (2013). Two (2) boreholes (OSW 1 and OSW 2) have investigated see Figure 3.8 for the detailed location and Figure 3.9 for the soil profile connecting both boreholes.

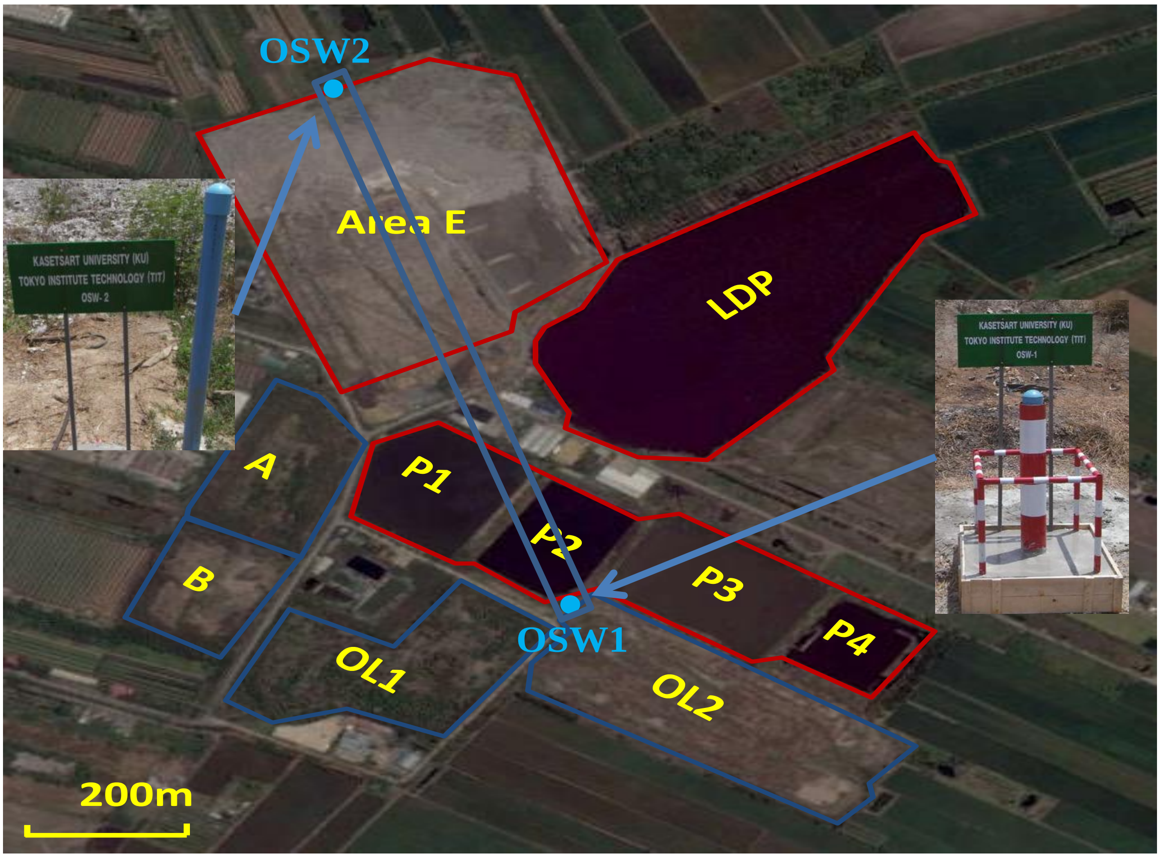


**Figure 3.8** Boreholes information of Nonthaburi landfill

For borehole BH-1 or OSW1, the top layer about 3.50 m thick is waste materials, from 3.50 to 5.00 m is soft to medium clay layer with low plasticity. The depths from 5.00 to 18.50 m, the soft to medium clay layer with high plasticity. The soil layer between the depths of 18.50 to 21.50 m is a medium clay layer with low plasticity. The depth of 21.50 to 28.95 m is medium dense to dense sand with silt.

Borehole BH-2 or OSW2 was drilled on the dike as the border of area E. The uppermost layer at a depth of about 2.00 m is the existing dike layer which is hard clay with low plasticity. Below the existing dike layer to the depth of 8.00 m is soft to medium clay layer with low plasticity. Moreover, the depths of 8.00 to 15.50 m is soft to medium clay have high plasticity. The third layer is a medium clay layer with low plasticity to the depth of 21.50 m. Moreover, the last layer, dense to very dense silty sand, between the depths of 21.50 to 30.45 m.

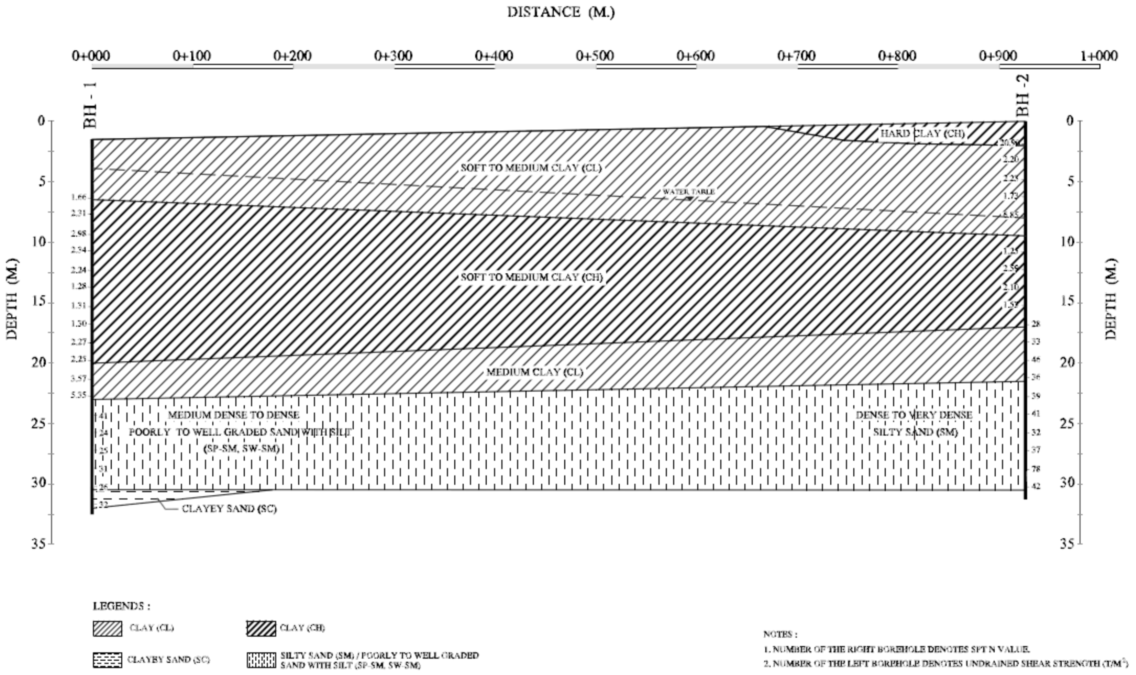
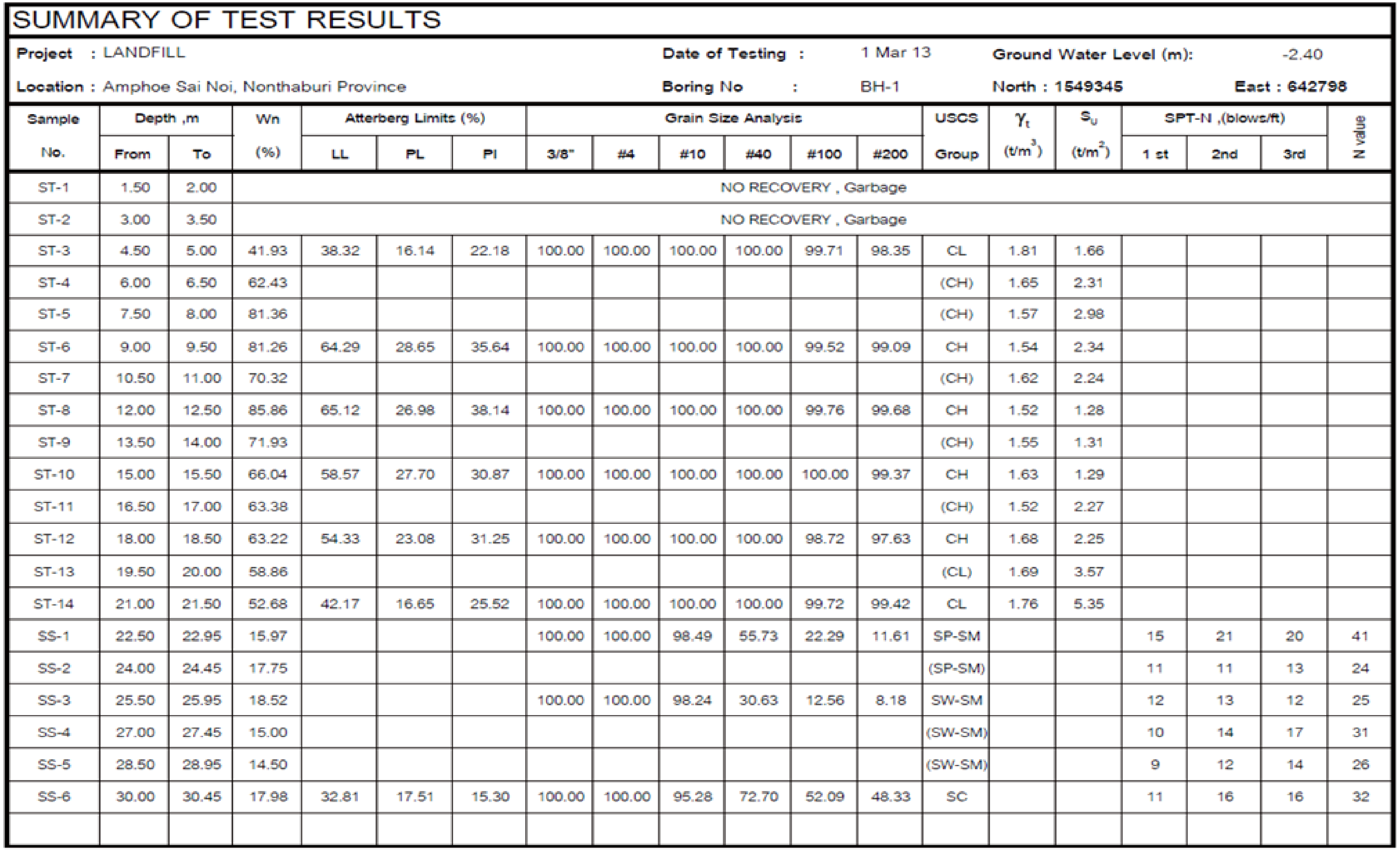


**Figure 3.9** Soil profiles of 2 boreholes at Nonthaburi site

At the same time, according to the study of Miyano (2016). The permeability test for the soil sample of the same borehole at different depths: the Oedometer test measured 6-6.5 m, 13.5-14 m and 18-18.5 m. From the test result of the depth of 18m as the landfill bottom and assume to be the natural clay liner barrier, the values were confirmed as low as of $1x10^{-10}$ to $3.3x10^{-10}$ m/s.

**Table 3.5** Summary of soil property of OSW1 (BH-1)

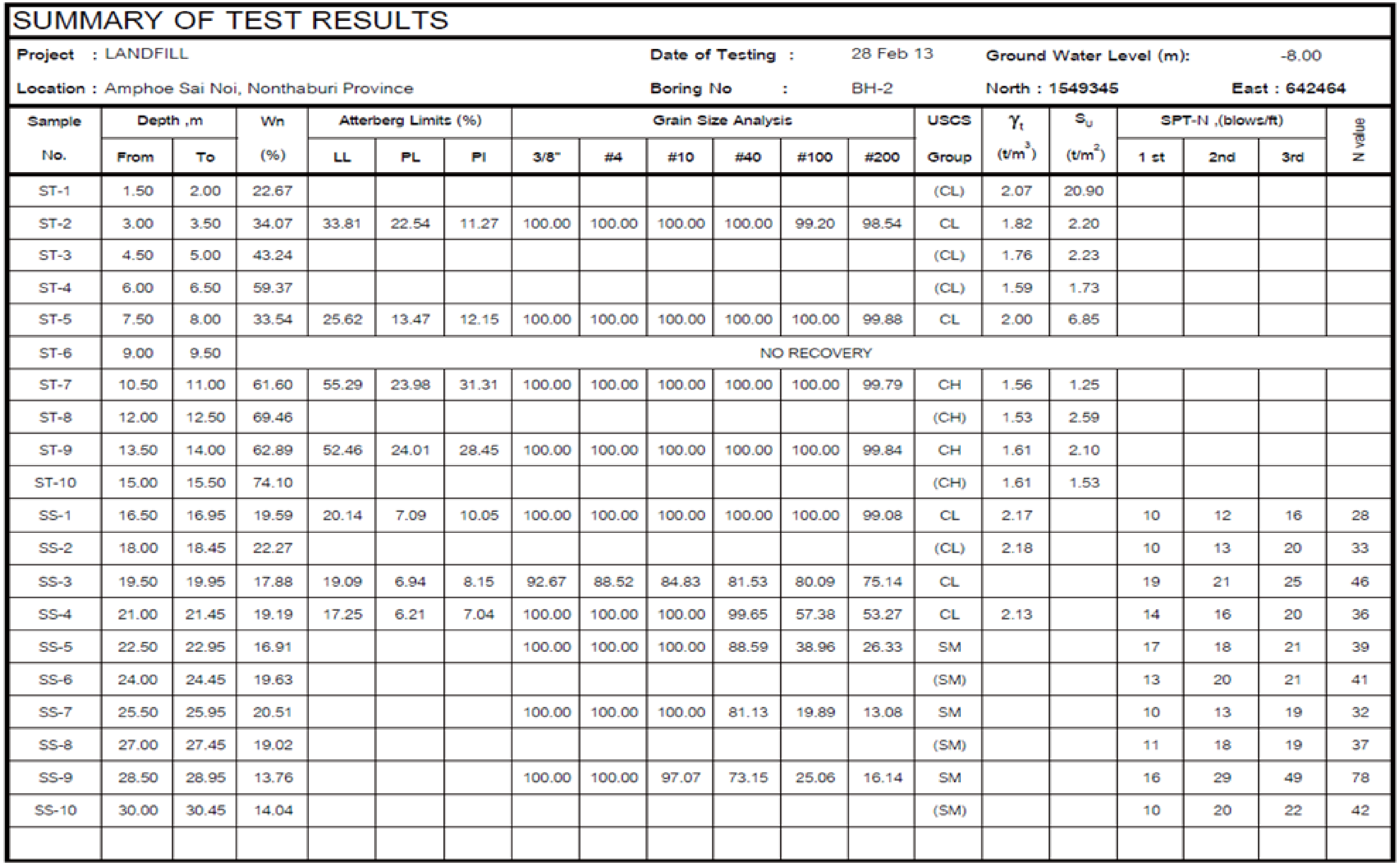


SUMMARY OF TEST RESULTS

**Project** : LANDFILL
**Date of Testing** : 1 Mar 13
**Ground Water Level (m):** -2.40
**Location** : Amphoe Sai Noi, Nonthaburi Province
**Boring No** : BH-1
**North : 1549345**
**East : 642798**

| Sample | Depth ,m | | Wn | Atterberg Limits (%) | | | Grain Size Analysis | | | | | | USCS | $\gamma_t$ | $S_u$ | SPT-N ,(blows/ft) | | | N value |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| No. | From | To | (%) | LL | PL | PI | 3/8" | #4 | #10 | #40 | #100 | #200 | Group | (t/m$^3$) | (t/m$^2$) | 1 st | 2nd | 3rd | |
| ST-1 | 1.50 | 2.00 | NO RECOVERY , Garbage | | | | | | | | | | | | | | | | |
| ST-2 | 3.00 | 3.50 | NO RECOVERY , Garbage | | | | | | | | | | | | | | | | |
| ST-3 | 4.50 | 5.00 | 41.93 | 38.32 | 16.14 | 22.18 | 100.00 | 100.00 | 100.00 | 100.00 | 99.71 | 98.35 | CL | 1.81 | 1.66 | | | | |
| ST-4 | 6.00 | 6.50 | 62.43 | | | | | | | | | | (CH) | 1.65 | 2.31 | | | | |
| ST-5 | 7.50 | 8.00 | 81.36 | | | | | | | | | | (CH) | 1.57 | 2.98 | | | | |
| ST-6 | 9.00 | 9.50 | 81.26 | 64.29 | 28.65 | 35.64 | 100.00 | 100.00 | 100.00 | 100.00 | 99.52 | 99.09 | CH | 1.54 | 2.34 | | | | |
| ST-7 | 10.50 | 11.00 | 70.32 | | | | | | | | | | (CH) | 1.62 | 2.24 | | | | |
| ST-8 | 12.00 | 12.50 | 85.86 | 65.12 | 26.98 | 38.14 | 100.00 | 100.00 | 100.00 | 100.00 | 99.76 | 99.68 | CH | 1.52 | 1.28 | | | | |
| ST-9 | 13.50 | 14.00 | 71.93 | | | | | | | | | | (CH) | 1.55 | 1.31 | | | | |
| ST-10 | 15.00 | 15.50 | 66.04 | 58.57 | 27.70 | 30.87 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 99.37 | CH | 1.63 | 1.29 | | | | |
| ST-11 | 16.50 | 17.00 | 63.38 | | | | | | | | | | (CH) | 1.52 | 2.27 | | | | |
| ST-12 | 18.00 | 18.50 | 63.22 | 54.33 | 23.08 | 31.25 | 100.00 | 100.00 | 100.00 | 100.00 | 98.72 | 97.63 | CH | 1.68 | 2.25 | | | | |
| ST-13 | 19.50 | 20.00 | 58.86 | | | | | | | | | | (CL) | 1.69 | 3.57 | | | | |
| ST-14 | 21.00 | 21.50 | 52.68 | 42.17 | 16.65 | 25.52 | 100.00 | 100.00 | 100.00 | 100.00 | 99.72 | 99.42 | CL | 1.76 | 5.35 | | | | |
| SS-1 | 22.50 | 22.95 | 15.97 | | | | 100.00 | 100.00 | 98.49 | 55.73 | 22.29 | 11.61 | SP-SM | | | 15 | 21 | 20 | 41 |
| SS-2 | 24.00 | 24.45 | 17.75 | | | | | | | | | | (SP-SM) | | | 11 | 11 | 13 | 24 |
| SS-3 | 25.50 | 25.95 | 18.52 | | | | 100.00 | 100.00 | 98.24 | 30.63 | 12.56 | 8.18 | SW-SM | | | 12 | 13 | 12 | 25 |
| SS-4 | 27.00 | 27.45 | 15.00 | | | | | | | | | | (SW-SM) | | | 10 | 14 | 17 | 31 |
| SS-5 | 28.50 | 28.95 | 14.50 | | | | | | | | | | (SW-SM) | | | 9 | 12 | 14 | 26 |
| SS-6 | 30.00 | 30.45 | 17.98 | 32.81 | 17.51 | 15.30 | 100.00 | 100.00 | 95.28 | 72.70 | 52.09 | 48.33 | SC | | | 11 | 16 | 16 | 32 |
| | | | | | | | | | | | | | | | | | | | |

**Table 3.6** Summary of soil property of OSW2 (BH-2)



SUMMARY OF TEST RESULTS

**Project** : LANDFILL
**Date of Testing** : 28 Feb 13
**Ground Water Level (m):** -8.00
**Location** : Amphoe Sai Noi, Nonthaburi Province
**Boring No** : BH-2
**North : 1549345**
**East : 642464**

| Sample | Depth ,m | | Wn | Atterberg Limits (%) | | | Grain Size Analysis | | | | | | USCS | $\gamma_t$ | $S_u$ | SPT-N ,(blows/ft) | | | N value |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| No. | From | To | (%) | LL | PL | PI | 3/8" | #4 | #10 | #40 | #100 | #200 | Group | $(t/m^3)$ | $(t/m^2)$ | 1 st | 2nd | 3rd | |
| ST-1 | 1.50 | 2.00 | 22.67 | | | | | | | | | | (CL) | 2.07 | 20.90 | | | | |
| ST-2 | 3.00 | 3.50 | 34.07 | 33.81 | 22.54 | 11.27 | 100.00 | 100.00 | 100.00 | 100.00 | 99.20 | 98.54 | CL | 1.82 | 2.20 | | | | |
| ST-3 | 4.50 | 5.00 | 43.24 | | | | | | | | | | (CL) | 1.76 | 2.23 | | | | |
| ST-4 | 6.00 | 6.50 | 59.37 | | | | | | | | | | (CL) | 1.59 | 1.73 | | | | |
| ST-5 | 7.50 | 8.00 | 33.54 | 25.62 | 13.47 | 12.15 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 99.88 | CL | 2.00 | 6.85 | | | | |
| ST-6 | 9.00 | 9.50 | NO RECOVERY | | | | | | | | | | | | | | | | |
| ST-7 | 10.50 | 11.00 | 61.60 | 55.29 | 23.98 | 31.31 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 99.79 | CH | 1.56 | 1.25 | | | | |
| ST-8 | 12.00 | 12.50 | 69.46 | | | | | | | | | | (CH) | 1.53 | 2.59 | | | | |
| ST-9 | 13.50 | 14.00 | 62.89 | 52.46 | 24.01 | 28.45 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 99.84 | CH | 1.61 | 2.10 | | | | |
| ST-10 | 15.00 | 15.50 | 74.10 | | | | | | | | | | (CH) | 1.61 | 1.53 | | | | |
| SS-1 | 16.50 | 16.95 | 19.59 | 20.14 | 7.09 | 10.05 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 99.08 | CL | 2.17 | | 10 | 12 | 16 | 28 |
| SS-2 | 18.00 | 18.45 | 22.27 | | | | | | | | | | (CL) | 2.18 | | 10 | 13 | 20 | 33 |
| SS-3 | 19.50 | 19.95 | 17.88 | 19.09 | 6.94 | 8.15 | 92.67 | 88.52 | 84.83 | 81.53 | 80.09 | 75.14 | CL | | | 19 | 21 | 25 | 46 |
| SS-4 | 21.00 | 21.45 | 19.19 | 17.25 | 6.21 | 7.04 | 100.00 | 100.00 | 100.00 | 99.65 | 57.38 | 53.27 | CL | 2.13 | | 14 | 16 | 20 | 36 |
| SS-5 | 22.50 | 22.95 | 16.91 | | | | 100.00 | 100.00 | 100.00 | 88.59 | 38.96 | 26.33 | SM | | | 17 | 18 | 21 | 39 |
| SS-6 | 24.00 | 24.45 | 19.63 | | | | | | | | | | (SM) | | | 13 | 20 | 21 | 41 |
| SS-7 | 25.50 | 25.95 | 20.51 | | | | 100.00 | 100.00 | 100.00 | 81.13 | 19.89 | 13.08 | SM | | | 10 | 13 | 19 | 32 |
| SS-8 | 27.00 | 27.45 | 19.02 | | | | | | | | | | (SM) | | | 11 | 18 | 19 | 37 |
| SS-9 | 28.50 | 28.95 | 13.76 | | | | 100.00 | 100.00 | 97.07 | 73.15 | 25.06 | 16.14 | SM | | | 16 | 29 | 49 | 78 |
| SS-10 | 30.00 | 30.45 | 14.04 | | | | | | | | | | (SM) | | | 10 | 20 | 22 | 42 |

From the information present in table 3.4~3.5, the further parameters can be derived as shown in table 3.6 and table 3.7 as OSW1 and OSW2, respectively. The value in this section will be used as for the input data of the simulation study in chapter 6.

**Table 3.7** Clay property of OSW1 (BH-1)

| OSW1 | Depth | | Wn | γt<br>(t/m3) | ρs<br>(t/m3) | e | n |
|---|---|---|---|---|---|---|---|
| | From | To | | | | | |
| ST1 | | | | | | | |
| ST2 | | | | | | | |
| ST3 | 4.5 | 5 | 41.93 | 1.81 | 2.74 | 1.15 | 0.53 |
| ST4 | 6 | 6.5 | 62.43 | 1.65 | 2.78 | 1.73 | 0.63 |
| ST5 | 7.5 | 8 | 81.36 | 1.57 | 2.93 | 2.38 | 0.70 |
| ST6 | 9 | 9.5 | 81.26 | 1.54 | 2.74 | 2.23 | 0.69 |
| ST7 | 10.5 | 11 | 70.32 | 1.62 | 2.87 | 2.02 | 0.67 |
| ST8 | 12 | 12.5 | 85.86 | 1.52 | 2.75 | 2.36 | 0.70 |
| ST9 | 13.5 | 14 | 71.93 | 1.55 | 2.56 | 1.84 | 0.65 |
| ST10 | 15 | 15.5 | 66.04 | 1.63 | 2.79 | 1.84 | 0.65 |
| ST11 | 16.5 | 17 | 63.38 | 1.52 | 2.27 | 1.44 | 0.59 |
| ST12 | 18 | 18.5 | 63.22 | 1.68 | 2.95 | 1.86 | 0.65 |
| ST13 | 19.5 | 20 | 58.86 | 1.69 | 2.85 | 1.68 | 0.63 |
| ST14 | 21 | 21.5 | 52.68 | 1.76 | 2.94 | 1.55 | 0.61 |

**Table 3.8** Clay property of OSW2 (BH-2)

| OSW2 | Depth | | Wn | γt<br>(t/m3) | ρs<br>(t/m3) | e | n |
|---|---|---|---|---|---|---|---|
| | From | To | | | | | |
| ST1 | | | | | | | |
| ST2 | 3 | 3.5 | 34.07 | 1.82 | 2.53 | 0.86 | 0.46 |
| ST3 | 4.5 | 5 | 43.24 | 1.76 | 2.62 | 1.13 | 0.53 |
| ST4 | 6 | 6.5 | 59.37 | 1.59 | 2.45 | 1.45 | 0.59 |
| ST5 | 7.5 | 8 | 33.54 | 2 | 3.01 | 1.01 | 0.50 |
| ST6 | 9 | 9.5 | | | | | |
| ST7 | 10.5 | 11 | 61.6 | 1.56 | 2.38 | 1.47 | 0.59 |
| ST8 | 12 | 12.5 | 69.46 | 1.53 | 2.42 | 1.68 | 0.63 |
| ST9 | 13.5 | 14 | 62.89 | 1.61 | 2.61 | 1.64 | 0.62 |
| ST10 | 15 | 15.5 | 74.1 | 1.61 | 2.94 | 2.18 | 0.69 |
| SS1 | 16.5 | 16.95 | 19.56 | 2.17 | 2.81 | 0.55 | 0.36 |
| SS2 | 18 | 18.45 | 22.27 | 2.18 | 2.96 | 0.66 | 0.40 |
| SS3 | 19.5 | 19.95 | 17.88 | | | | |
| SS4 | 21 | 21.45 | 19.19 | 2.13 | 2.72 | 0.52 | 0.34 |

### 3.3.2 Dangkor Landfill

JICA (2005) has reported the results of soil testing of Dangkor areas. Five (5) boreholes along the areas A-B have been drilled, and boring location details are shown in Figure 3.10 while the soil profiles in each borehole as shown in Figure 3.11. The result summaries are shown as the followings:

- The geological stratum until 11m in depth is mostly stiff clay strata, whose permeability is on the scale of 10-8cm/s. smaller than 10-7cm/s.
- Each borehole shows that there is a sand stratum of 0.5-4m in thickness between 11-15m in depth. The permeability of the sand strata is on the order of 10-3cm/s.
- The borehole No.5 shows that there is a sand stratum between 3.0-6.2m in depth. The borehole No.1 and No.4 also show the sand strata, while there are no sand strata in this depth. Therefore it is expected that the sand strata spread to the east, but there is not enough data to determine the starting point of the strata.

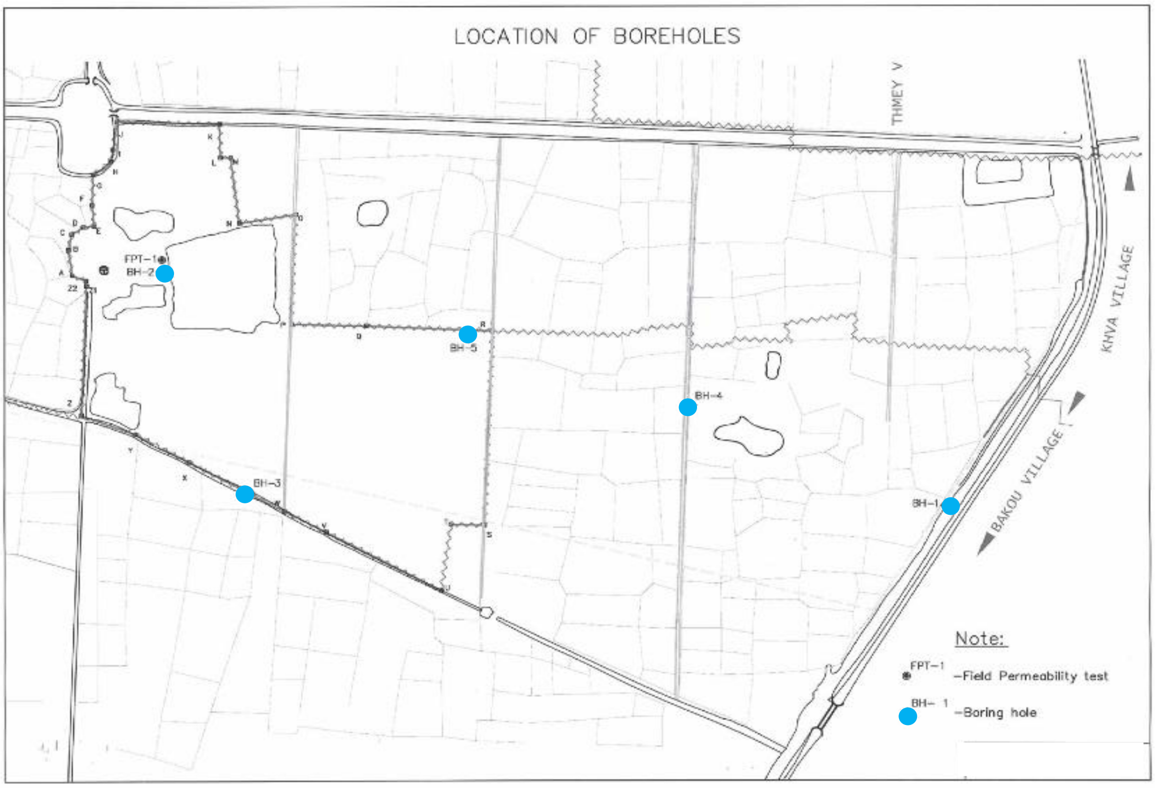


**Figure 3.10** Borehole locations along the areas A-B of Dangkor landfill

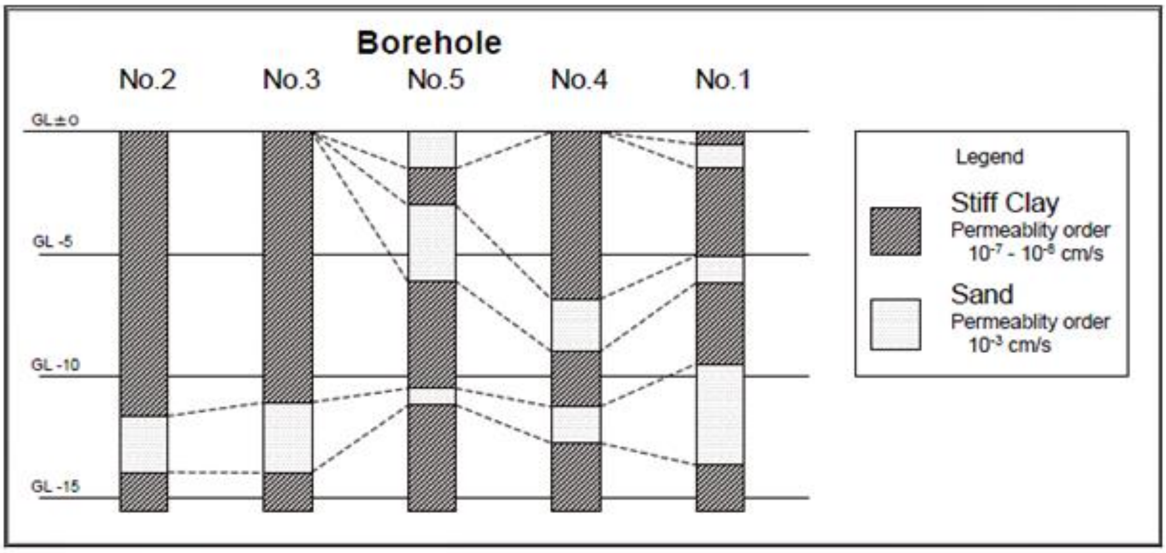


**Figure 3.11** Soil profiles of Dangkor landfill areas A-B

### 3.3.3 KM-32 Landfill

There is no previous study on the geology condition in this landfill site. However, during the field visit to KM-32 landfill, soil samples were collected and confirmed the permeability by the Oedometer test together with falling head permeability test. Since the soil has only one layer of the depth of 3 m, the results show quite low Kc as other landfills. The permeability of the soil is about 1 x $10^{-8}$ to $3.10^{-9}$ m/s.

**Figure 3.12** Soil pit profile of KM-32 landfill

## 3.4 Soil Characterization

In this study, some of the important parameters regarding the clay soil property were conducted to confirm the geological information. The soil samples were taken from each site during the field visit. The soil sample from Nonthaburi landfill was used the sample taken from the borehole of the observation well 1 (OSW1) at the 18 m. As for Dangkor landfill, the soil samples were taken for both clay and sandy part in the middle of the dumped pit. Also, at KM-32 landfill, the soil was taken from the new pit at the bottom part of the landfill. The following basic soil properties were measured accordingly to the laboratory guidelines of each test which will be discussed in each section.

### 3.4.1 Particle Size Distribution

The soil particle size distribution is based on the Japanese geotechnical society standard (JGS 0131-2009) test for particle size distribution of soils. In this study, the results can reach only the sieve analysis, while the hydrometer part was not performed due to the time limitation. However, the smallest open mesh size is 0.075 mm, which can be helpful to discuss as the fine particle for each site condition regarding the clay soil as a natural barrier of the landfill contamination. The results showed in Figure 3.13 as basic clay condition which will be used in the discussion part of the following chapter for both the leachate quality and simulation study.

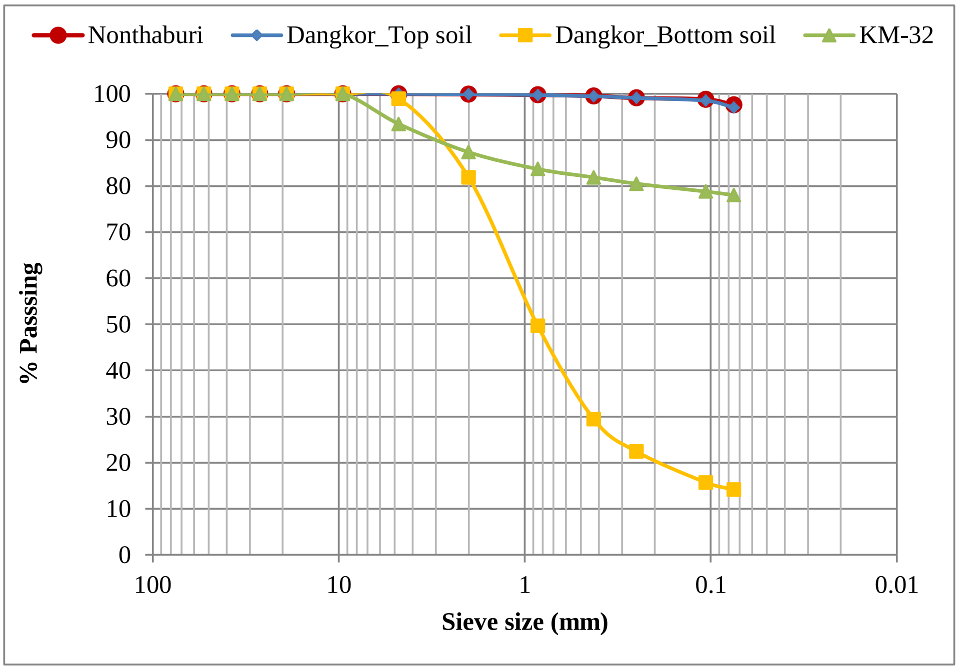
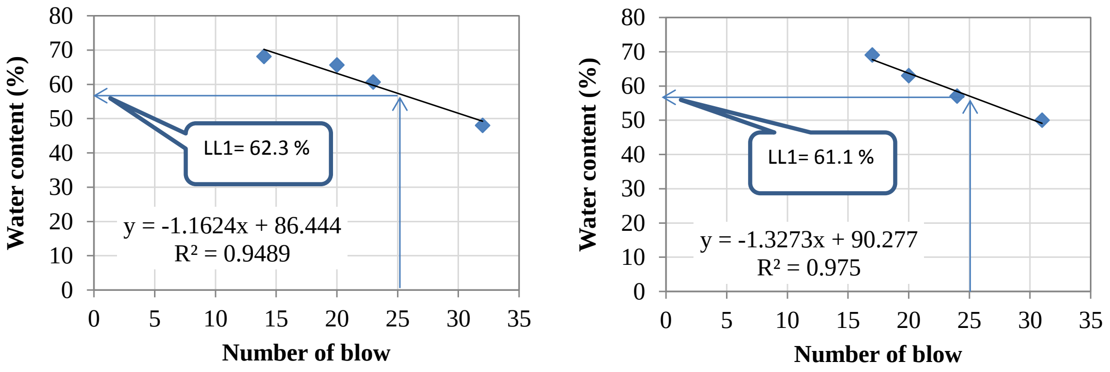


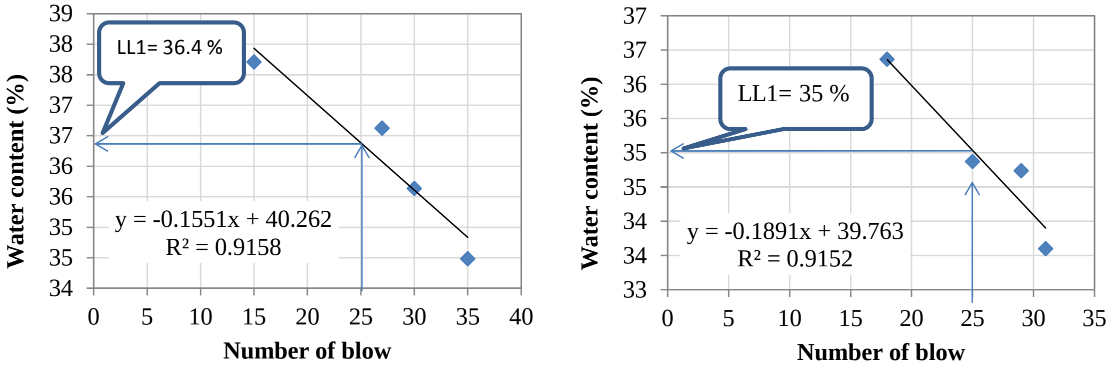
**Figure 3.13** Grain size distributions for the soil of three sites

### 3.4.2 Atterberg Limit Test

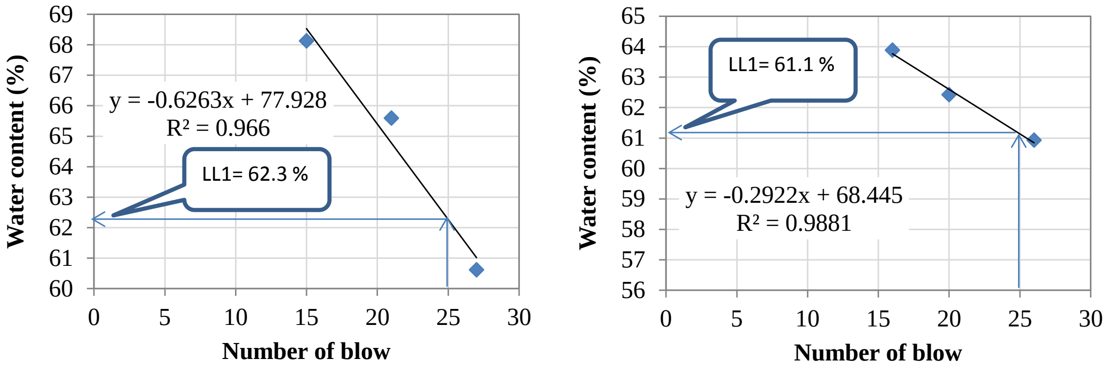
The test of Atterberg limit is based on the ASTM D 4318 – Standard test method for the liquid limit, plastic limit, and plasticity index of soil. Figure 3.14 shows the liquid limit obtaining from the experiments, while all of the Atterberg limits were shown in Table 3.9. From these limit values; the soil classification can be identified as clay silt, CL, and CH for the Nonthaburi, Dangkor and KM-32 landfill, respectively.



(a) Nonthaburi Landfill



(b) Dangkor Landfill



(c) KM-32 Landfill

**Figure 3.14** the liquid limit for the clay for each landfill

**Table 3.9** Summary of Atterberg limit for clay layer

| | **Nonthaburi** | **Dangkor** | **KM-32** |
|---|---|---|---|
| **LL** | 57.23925 | 35.71 | 61.70525 |
| **PL** | 24.5 | 21.23797 | 28.16885 |
| **PI** | 32.73925 | 14.47203 | 33.5364 |

### 3.4.3 Specific Gravity of Clay

The soil specific gravity investigation in this study has followed the method of density bottle as per IS 2720 (part III/Sec 1)-1980. The measurement was done as three-time measurements and the average as final. Table 3.10 shows the summary of the specific gravity of clay soil from each landfill site and the results are in the range of normal clay as well as similar to the geological study report for the OSW1 and OSW2 as presented in section 3.3.1 as for Nonthaburi landfill.

**Table 3.10** Summary of soil specific gravity for all sites

| | **Nonthaburi landfill** | **Dangkor** | **KM-32** |
|---|---|---|---|
| **Gs** | 2.72 | 2.7 | 2.66 |

### 3.4.3 Soil Permeability or Hydraulic Conductivity

The soil permeability test in this study was using Oedometer equipment as explained by Amatya (2002), and then the hydraulic conductivity was obtained by indirect value as a calculation by the following equation.

Based on the theory of Terzaghi; parameter $c_v$ is computed using the square root of time method, as given by follthe owing equation:

$$\mathrm{C_v} = \frac{0.848\mathrm{H}^2}{\mathrm{t_{90}}} \ldots\ldots 3.1$$

Where,

H = the total thickness of consolidating stratum

$t_{90}$ = the observed compression-time curve at 90% of compression

The hydraulic conductivity, K, using the indirect method can be computed from the following equation:

$$k = c_v * m_v * \gamma_w \ldots\ldots 3.2$$

Where,

$c_v$ = the coefficient of consolidation

$m_v$ = the coefficient of volume change

$\gamma_w$ = the unit weight of water

Figure 3.15 shows the schematic of consolidation and hydraulic conductivity test by using Oedometer test while Figure 3.16 (a) ~(b) show the results of hydraulic conductivity calculated by the indirect methods. Also, Table 3.11 summarizes the ranges of hydraulic conductivity at the different loading stage; increasing as 10~20~40~80~160~320~640 Kpa.

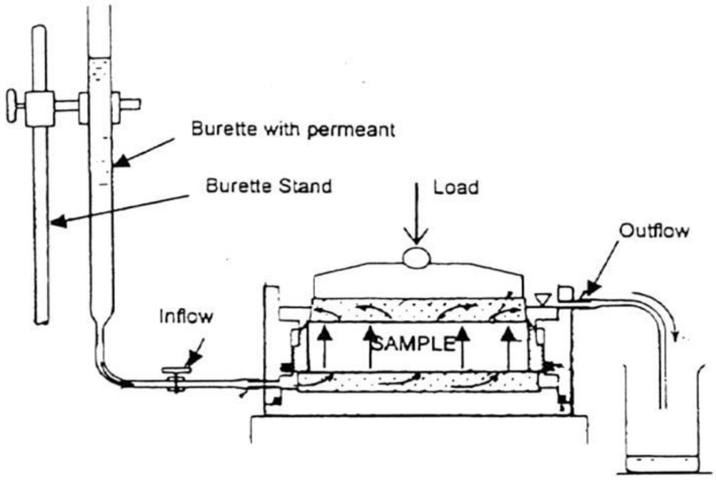
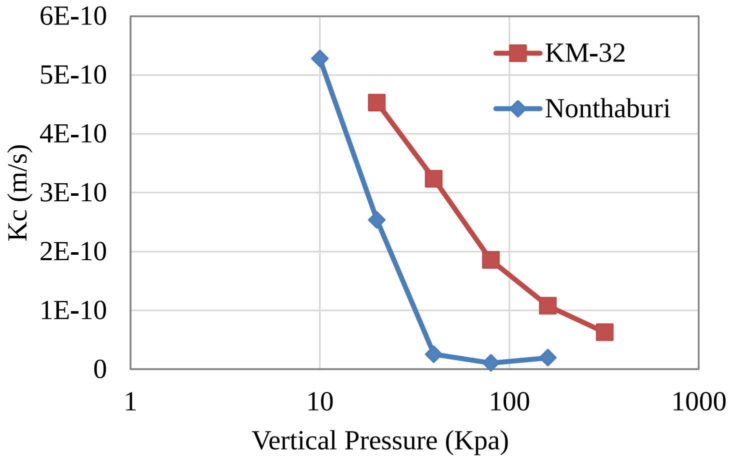
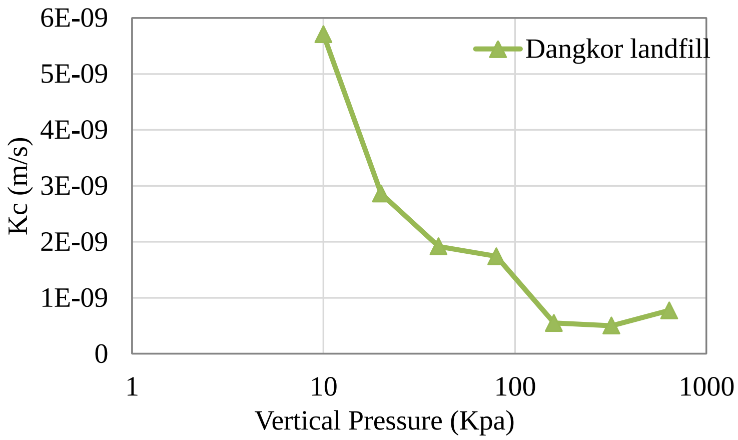


**Figure 3.15** Schematic of consolidation and hydraulic conductivity test with Oedometer mold



(a)



(b)

**Figure3.16** Soil permeability at different loading stage

**Table 3.11** Soil permeability ranges

| | **Nonthaburi** | **Dangkor** | **KM-32** |
|---|---|---|---|
| **Kc (m/s)** | $4.2*10^{-9}$~$1.9*10^{-11}$ | $5.7*10^{-9}$~$7.7*10^{-10}$ | $3.1*10^{-9}$~$6.2*10^{-11}$ |

**Figure 3.17** Figure of sieve analysis

**Figure 3.18** Atterberg limit (LL and PL)

**Figure 3.19** Soil specific gravity measurement

**Figure3.20** Hydraulic conductivity by Oedometer

## 3.5 Climate Conditions

Indochina peninsular region is a region of topical monsoon climate. There are two seasons can be identified for these three countries. The wet (rainy) season starts from May or June and ends in October or November as for early and late starts/ends for some years. The climate information for the three cities which covers the three landfill sites was obtained from the related organizations, i.e. climate of Bangkok was from world weather and climate information, specific Bangkok, Thailand. The climate information for Phnom Penh and Vientiane was received from the department of meteorology and hydrology of both countries. The detailed discussion of some key parameters affecting the leachate quality at the landfill site condition will be revealed as follows:

### 3.5.1 Temperature

The temperatures of these three cities are quite similar in term of general ranges and trends. However, there are some differences in term of detailed values in each period. The temperature of Vientiane where KM-32 landfill located in shows the lowest as compare to Bangkok and Phnom Penh area, especially in the mid-dry season (winter period) the average temperature shows as low as of 21 ˚C (degree Celsius) in December and January while the highest temperature is in April to May about 28 ˚C. It is clear evidence that Vientiane is located in the higher elevation about 190 MSL (mean sea level); while Bangkok and Phnom Penh areas are about 5-10 MSL.

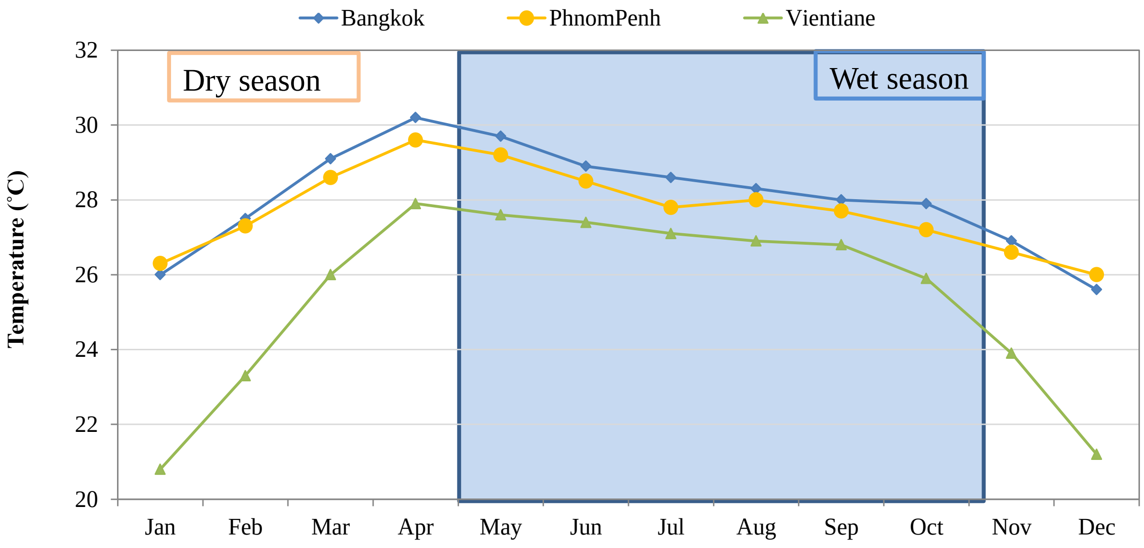


**Figure 3.21** Average of monthly temperature for the areas of landfill location

### 3.5.2 Sunlight

The numbers of sunlight hours in these cities are also a similar trend for all areas. The fewer sunlight hours were found during the wet season about 4.7 to 7 hrs/day from May to October. Bangkok area is also found the largest time of sunlight, especially from January to April each year. While Phnom Penh shows larger than other from May to September, and Vientiane area seems to be low compared to other but has the similar time with Bangkok area in early dry season from October to December.

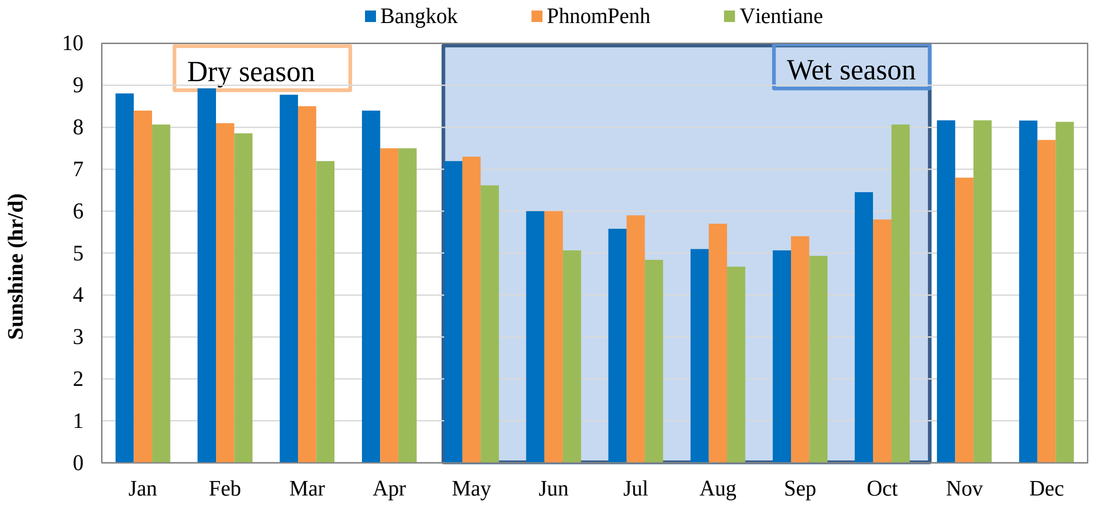


**Figure 3.22** Average of monthly sunlight for the areas of landfill location

### 3.5.3 Precipitation

The rainfall or amount of precipitation shows higher for the Vientiane area and quite similar for Bangkok and Phnom Penh areas, but Phnom Penh has a longer period of the rainy season, even though after the end of the wet season, i.e., from November to January, the rainfall still existed. The average annual rainfall shows that Vientiane is the highest about 2000mm/yr, while Bangkok and Phnom Penh are lower about 1400 and 1500 mm/yr, respectively.

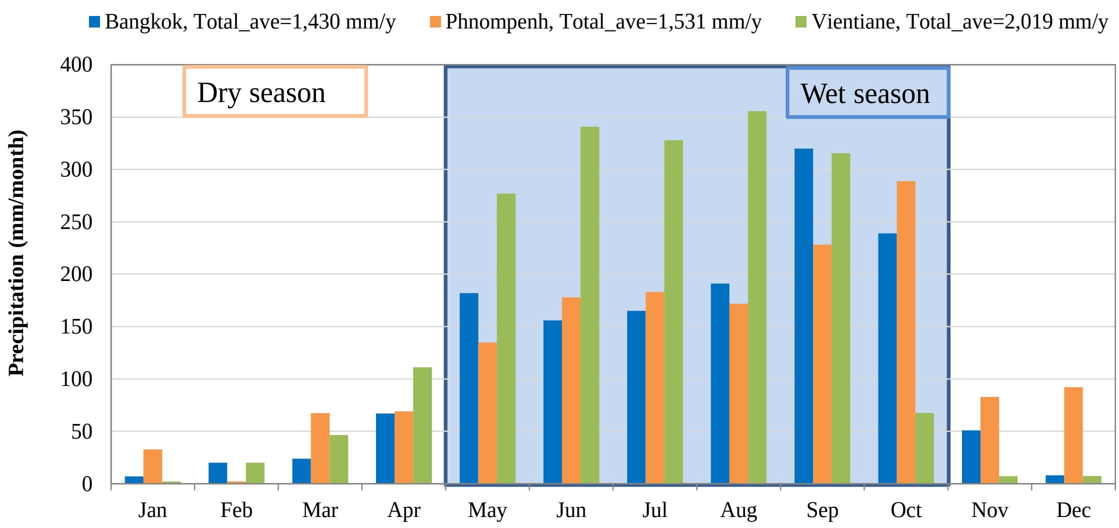


**Figure 3.23** Average of monthly precipitation for the areas of landfill location

## 3.6 Waste Characteristics

Municipal solid waste (MSW) characteristics in the three countries are similar regarding the major portion of an organic compound as shown in Figure 3.24 Nonthaburi landfill has the highest percentage of organic waste; followed by KM-32 and Dangkor landfills (the organic waste can be the combination of kitchen/food waste and wood/grass as garden waste). The composition is also similar to those reported by other studies on other ASEAN country landfills (10 countries in the same region) as found the same range of organic portion introduced in chapter 2, section 2.2.2. Also, in another region such as Haiti and Bangladesh, the organic mixtures are contained about 62% and 65%, Feniel and Culot (2009) and Sujauddin et al., (2008). While in central Nigeria, the organic compound was ranged from 23.4 to 57.5% between low to high-density population area, Sha'Ato et al., (2007). Since wood/grass is counted as organic materials and KM-32 landfill has accepted all kinds of wastes, while Nonthaburi and Dangkor have accepted the minor amount of agriculture waste. For the second largest component is plastic, ranging from 13 to 21%, and the rests are distributed as a little portion go to paper waste (7-10%), textile (1-5%), bottle/glass, rubber/leather, Ceramic/stone, metal and others are about 1.5-3%.

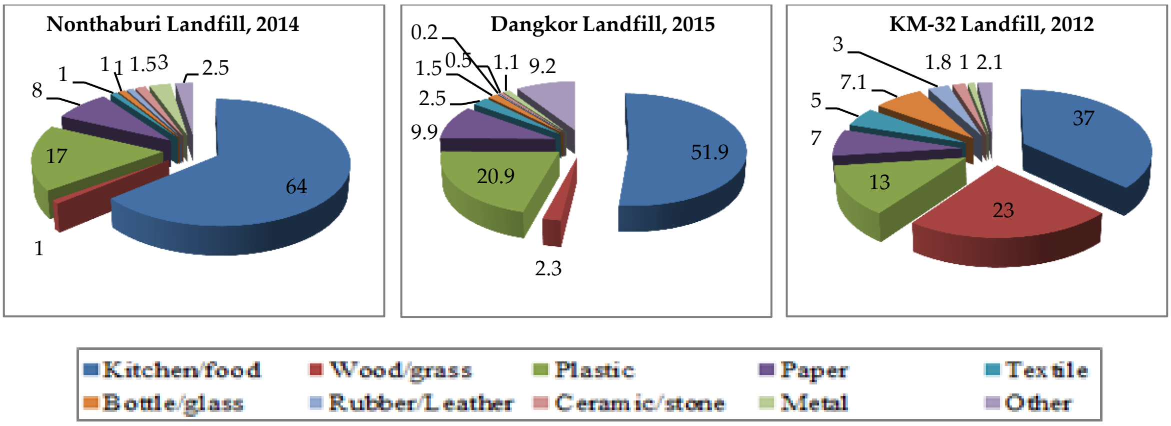


**Figure 3.24** Waste compositions in percent (%)

### 3.7 The Similarity and Differences of the Sites

All three landfills are serving as the solid waste disposal facility of the municipal area with highly dense population but without proper waste segregation system. Another similarity is a geological condition of the low permeable soil as natural clay liner JICA (2005) and Miyano (2016). Importantly, thanks to the deep low permeable geological sublayer, these three landfills have the same method of dumping namely excavated or trench method. Nonthaburi landfill is the longest history and contains the most significant leachate storage with five supporting ponds, sharing the leachate when needed, and these ponds are using as leachate pre-treatment system. Dangkor landfill has the deepest pit of the active area as in Areas C and D about 30 m below the ground surface, which could increase the potential risk of the groundwater contamination in the future. KM-32 landfill has the largest area among them; the landfill is separated into 11 segments with the shallow garbage layer about 6m (3m pit depth and 3m waste pile height). The leachate is drained to the natural wetland then flow out to the lower backside area during the rainy season, and no leachate is produced out of the waste pile during the dry season.

Based on the landfill guideline of United Nations Environment Programme (UNEP) as presented in chapter 2, section 2.4, three landfill types are defined: 1.) open dump, 2.) controlled dump, and 3.) sanitary landfill; depending on the facilities and the dumping methods. From the site observation and information obtained from site visits; Nonthaburi landfill can be classified as semi-sanitary landfill, while the Dangkor landfill would be a controlled dump, and KM-32 landfill is open dumping facility.

**Table 3.12** Summary of key similarities and differences between the three landfills

| Similarities | Significances/differences |
|---|---|
| - The same method of dumping as excavated or trench method<br>- Low permeable geological foundation as natural clay liner, (Kc=$10^{-(8-9)}$ m/s by Oedometer test<br>- No proper solid waste separation at the source and site<br>- High organic materials contained in the solid waste composition<br>- No leachate treatment system<br>- No proper leachate drainage facilities and management<br>- Uncontrolled leachate flow to the surrounding areas, especially for Dangkor and KM-32 landfill | **Nonthaburi landfill:**<br>- The longest history with many changes of dumping areas.<br>- Combination of both opened dumping facility and sanitary landfill pits<br>- Huge leachate discharge pond, which will be a highly contaminated area in the future after the closure<br>**Dangkor landfill:**<br>- Significant depth of the pits in the ongoing dumping areas C-D, about 30m below ground surface level. It will be a risk to the groundwater contamination if the future.<br>- The leachate is draining to the natural creek and surrounded areas for the closed dumped areas A-B, which could be a risk to the surface and surrounded agriculture fields.<br>**KM-32 landfill:**<br>- Large opened space with shallow depth of the waste pits, about 3m below ground surface and 3 m waste pile height.<br>- Inclined waste dumping area, which is easy for waste to get flush by surface water and drained to the lower part backside of the landfill areas. Also, there will be a high risk to the surface and surrounded agriculture soils. |

## 3.8 Summary

The chapter was covered all needed information collecting from three sites, and also the necessary soil parameters were measured at the laboratory to ensure the site and geological information is sufficient for the discussion related to the leachate quality, as well as the simulation study input parameters in the later chapter.

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# Chapter 4

# Leachate and Sediment Characterization

This chapter will discuss the details of leachate and sediment sample measurements, analysis, and interpretation of the results of the site conditions regarding leachate and sediment quality. The detailed discussions will be based on the site investigation, in-situ and laboratory measurements, including sample collection and preparation procedures. Also, the analysis method will be discussed. In addition, various results from other studies and theories are included as a comparison. Some parts of this chapter are presented in the Environments **2018**, *5*, 65 by Xaypanya et al., (2018).

## 4.1 Introduction

The landfill is a primary facility for municipal solid waste disposal in the most of the countries; especially in the developing countries. The increase of resource consumption results in massive amounts of solid wastes from various kinds of industries and domestic activities, which poses significant threats to human health and environment as contaminated leachate production. Leachate quality, quantity, and its characteristics are directly related to the waste management practice, climate condition, and waste characteristics as well as the landfill operation method, and the leachate could be a primary source of various contaminants and pollution. It is a severe concern for both sanitary landfills and open dumping facilities, to minimize the risk to the human health and environment in the nearby communities, El-Fadel et al., (1997). Also, Leachate quality is mainly influenced by waste characteristics including the waste composition, age, and site operation methods such as compaction level, daily cover, pretreatment, liquid waste co-disposal, quality and quantity of water entering the landfill. Moreover, another important factor is chemical reaction such as biodegradation, adsorption, hydrolysis, dissolution, dilution, partitioning, and precipitation, Kjeldsen et al., (2002). The type and concentration level of the contaminants in the leachate depends on the way of disposal together with waste composition, as well as the waste segregation before its final disposal, Ole et al., (2016). The leachate problem was worsened by the fact that many landfills in developing countries lack appropriate landfill facilities, such as bottom liner, leachate collection, and treatment system - increasing the possibility of groundwater and surface water contaminations, Kammani et al., (2013). In most cases, landfill leachate consists of organic matter (biodegradable and non-bio degradable), inorganic pollutants and hazardous substances. Hazardous substances in municipal solid waste (MSW) are presented in the form of paints, mercury-containing wastes, batteries, vehicle maintenance products, and many other diffuse products, Slack et al., (2004) and Umar et al., (2010). The consequence of contaminated leachate from the landfills will be the potential risks to surface and groundwater of surrounding areas, as well as the leachate storage ponds will create the huge volume of contaminated sediment as they are long-time adsorption, particularly the heavy metals.

## 4.2 Objectives

The overall objectives are to investigate and assess the quality of leachate and sediment collected from the three major landfill cities of three different countries. Also, linking those parameters with each other to see their correlations are confirmed.

1. To investigate the leachate quality for both physical and chemical properties as deep in details of heavy metals contained in each component, i.e., liquid part of leachate, solid part or suspended solids and the total concentration of the leachate
2. To assess influential factors to the leachate qualities and correlation of those assessed parameters
3. To investigate the quality of sediments in the various locations in the landfill for discussing the long-term effects of accumulated contaminant
4. To link the basic parameters to chemical and biological parameters
5. To compare the leachate characteristics from the studied landfills to other landfills in ASEAN countries and another region.

## 4.3 Methodology

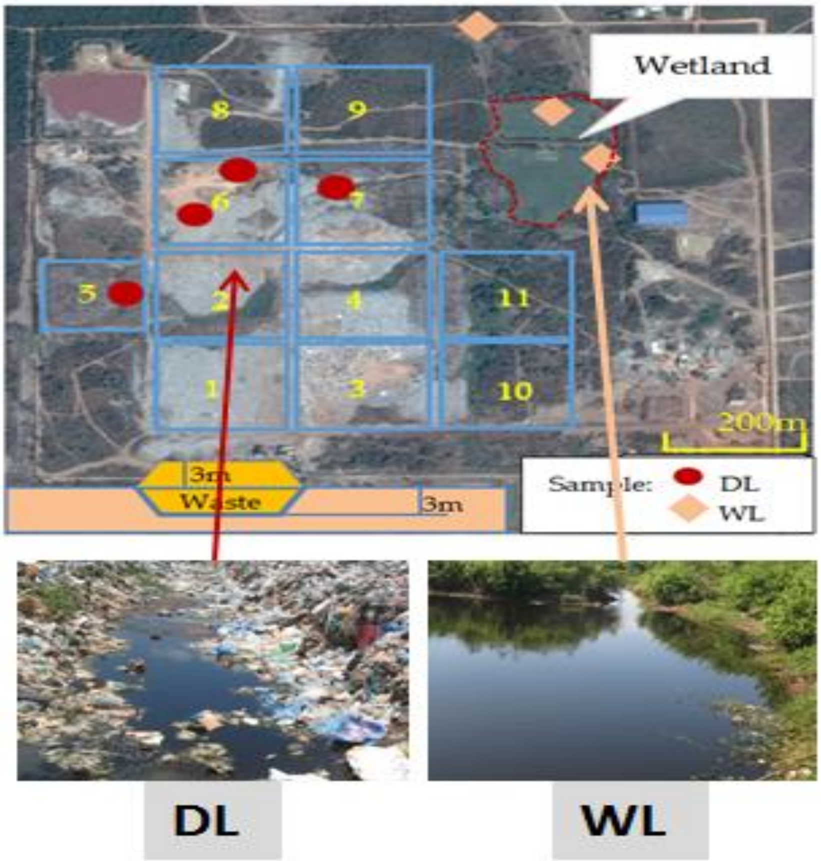
Two kinds of measurements were conducted in this study. One is the in-situ measurements which are done during the field visits and site investigations for the basic parameters of leachate, by using Multi-parameter Water Quality Meter “HORIBA-U50”, and the other is the laboratory measurements for the biochemical parameters including heavy metals with the selected samples from each landfill site.

### 4.3.1 Sample Location and Description

The sample collections at Nonthaburi landfill were made from 2015 to 2018, three times in wet seasons and three times in dry seasons. Also, from the period of 2015 – 2017, five times of sampling and site investigations were conducted at Dangkor landfill (two in wet and three in dry seasons), and four times field visit at the KM-32 landfill (two in wet and two in dry seasons). The sample names for this study are based on each site condition as shown in Figure 4.1. Two main types of leachate samples were collected for Nonthaburi landfill; one is DL where the leachates were taken from leachate drain ditch along the toe of waste pile, and another is LDP, the leachate from leachate discharge pond. Similarly, at Dangkor landfill, DL.B is named for the leachate collected from Areas A-B as fresh leachate, and the area was closed from early 2016, and DL.C was collected from inside pit C as active and deep pit condition. Also, at the KM-32 landfill, DL was named for leachate collected from the dumped area, while WL was collected from the natural wetland which located at the lower part of the disposal facility. Figure 4.2 shows the first physical visualization of samples. Additionally, the sediment samples were collected from the leachate sampling site, except at the site where leachate collected from the waste pile, DL.C at Dangkor, DL in KM-32 landfill.

(a) Nonthaburi landfill

(b) Dangkor landfill



(c) KM-32 landfill

**Figure 4.1** Locations of the study sites, and landfill plan of sampling points superimposed on Google Earth image, the pit depth and waste height of the dumping facility.

(a) (b) (c)

**Figure 4.2** The appearance of leachate and sediment samples: (a) Nonthaburi landfill, (b) Dangkor landfill and (c) KM-32 landfill

### 4.3.2 Onsite Measurement

The in-situ measurement was performed together with sample collection during the site visit, and investigation (Figure 4.3). Some of the important basic parameters were measured at the site to assess the leachate quality such as such as temperature (Temp), pH, dissolved oxygen (DO), oxidation-reduction potential (ORP), electrical conductivities (EC), total dissolved solids (TDS) and salts. The in-situ measurements were done by using field toolkit “HORIBA-U50” Horiba (2009) for those mentioned parameters. At the same time, to confirm the sampling location, GPS photo tagger and Garmin Oregon were used in this study.

**Figure 4.3** Field toolkits and in-situ measurement and samplings

### 4.3.3 Laboratory Measurements

Leachate samples were separated into two parts as physical property basis; one is liquid part of leachate, and another is suspended solids or solid part of leachate, see Figure 4.4 for separating process. The liquid part of leachate was obtained by filtering through the 0.45 μm pore size (syringe filter was applied in this study), while the suspended solids was obtained via the total solid of leachate reduction by the total dissolved solids (TDS). The ideally of leachate separation due to the consequent effects of each component will be different, i.e. the liquid part will have the potential effect to surrounding groundwater because of suspended solid will not pass through the clay liner as barrier below the dumped pit of the landfills. On the other hands, the total leachate concentration will have the potential effects to the surface water of the surrounding soils and creeks as current landfill practice in the study sites with an uncontrolled release of leachate to the nearby areas.

As for sediment, the saturated sediments were also filtered to assess the concentration of heavy metals in the liquid part due to most of the sediment was in the wet condition. The other part of sediment was dry up by the electrical oven dry overnight at 105-110 ˚C, the sediment latter then proceed similarly to the solid part of leachate for the heavy metal measurement as present in the section 4.3.3.2. Then the final heavy metal contents were reduced by the concentration of the liquid part of leachate.

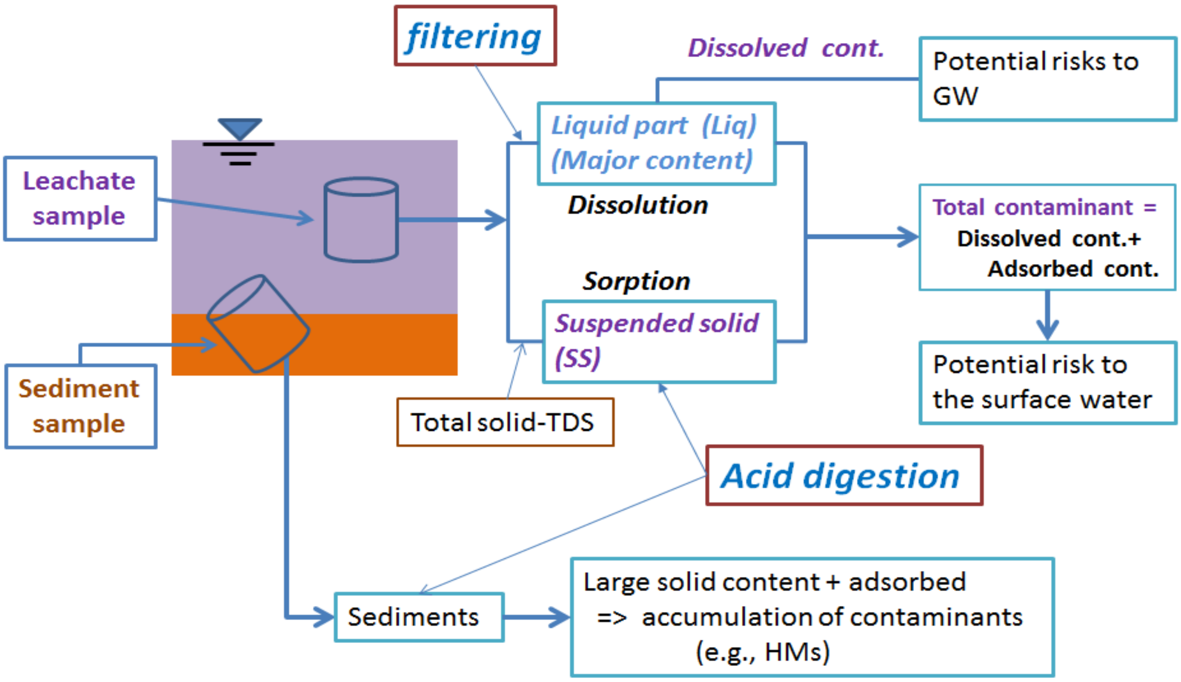


**Figure 4.4** Sample preparation processes

#### 4.3.3.1 Basic and Biological Parameters

Some of the important basic and biochemical parameters measured in this study were defined regarding the commonly found and necessary to discuss the leachate quality. Outside of the basic parameters measured at the fields as on-site or in-situ measurement, a set of parameters have been defined to perform at the laboratory, such as biochemical oxygen demand ($BOD_{5)}$, Chemical oxygen demand (COD), ammonia ($NH_3$), nitrate ($NO_3$), Nitrite ($NO_2$) and total Kjeldahl nitrogen (TKN). The analyzing method for these parameters, the methods for the examination of water and wastewater was used in this study, APHA (2005).

As for the chloride (Cl), the equipment named “SALMATE 100/W” was used in order to measure the Chloride ion (Cl) concentration for all leachate samples. The raw leachate samples were three times measurement and took the average as final measuring concentration. The equipment range of measurement is from 10 to 30,000 ppm, and the accuracy is (+/-) 0.4 %, according to the user manual.

**Figure 4.5** SALMATE-100/W for Cl measurement

#### 4.3.3.2 Preparation and Measurement of the Liquid Samples:

The heavy metal composition is the main target parameters of the assessments of this study, but those mentioned basic parameters are also necessary. To measure heavy metal concentration contained in leachate; the leachate samples were filtered by using syringe filter with 0.45µm pore size or using centrifuge in prior to filter for some leachate samples as high solid component samples, then the filtered solutions were measured by using ICP-AES (Inductively Coupled Plasma - Atomic Emission Spectrometry). The details of preparation can also see in Figure 4.6.

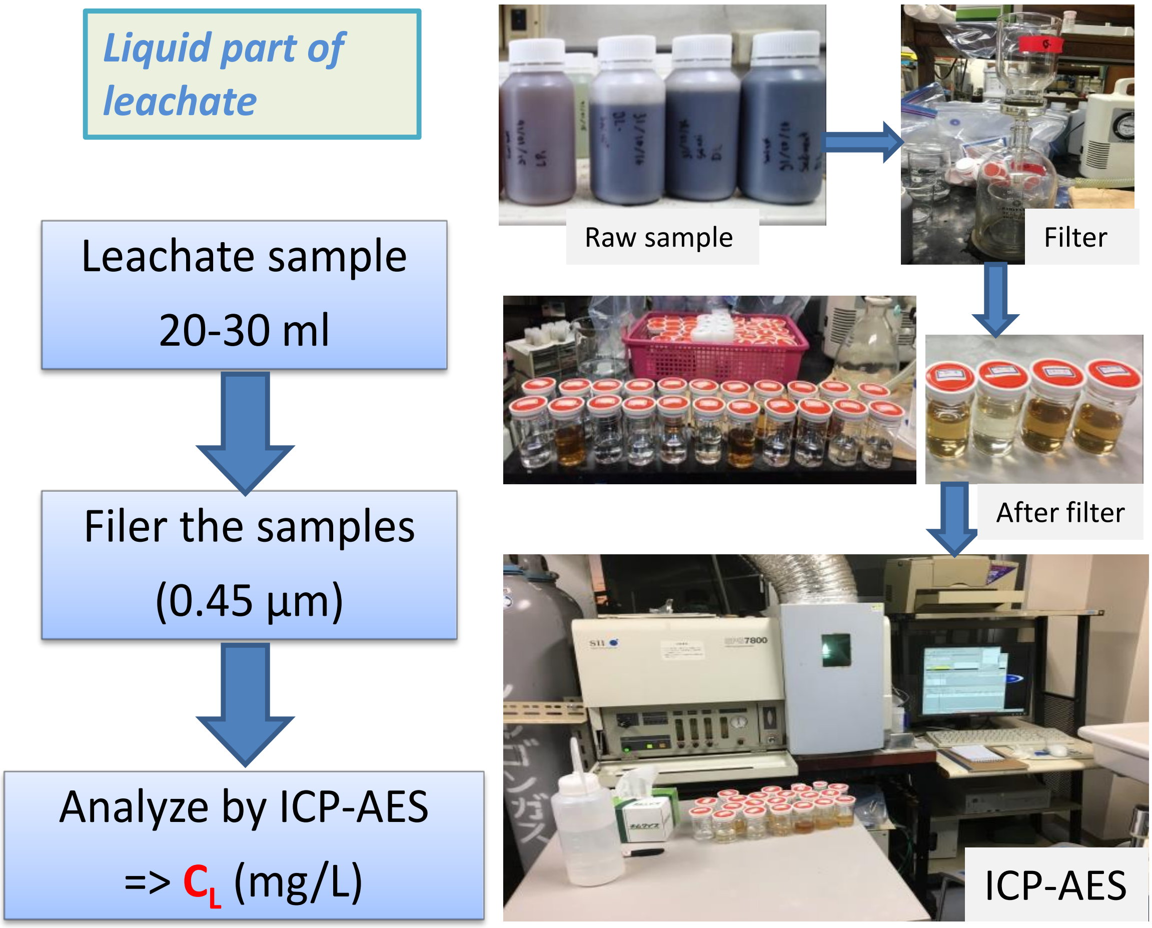


**Figure 4.6** Measurement process of liquid part of leachate ($C_L$)

#### 4.3.3.3 Preparation and Measurement of Suspended Solids and Sediment

To evaluate the heavy metals existed in the sediment and the suspended solids in the leachate samples; the acid digestion method was applied to use in this study. In the method associated to Figure 4.7, 30 ml of 36% HF (Hydrofluoric acid) was used to digest the 0.20 g dry weight of sediment or suspended solid, after overnight oven-dry of the uniformly mixed sample for a certain amount at 105-110c; the weight and volume were recorded. The digestion process was performed by stirring the mixing compound using 50 ml PTFE (Polytetrafluoroethylene) beaker approximately 24 hr at 380 rpm without heating. The solution was then filtered by using a disposable syringe filter with 0.45µm pore size and analyzed by ICP-AES as the final stage for heavy metal concentration measurement.

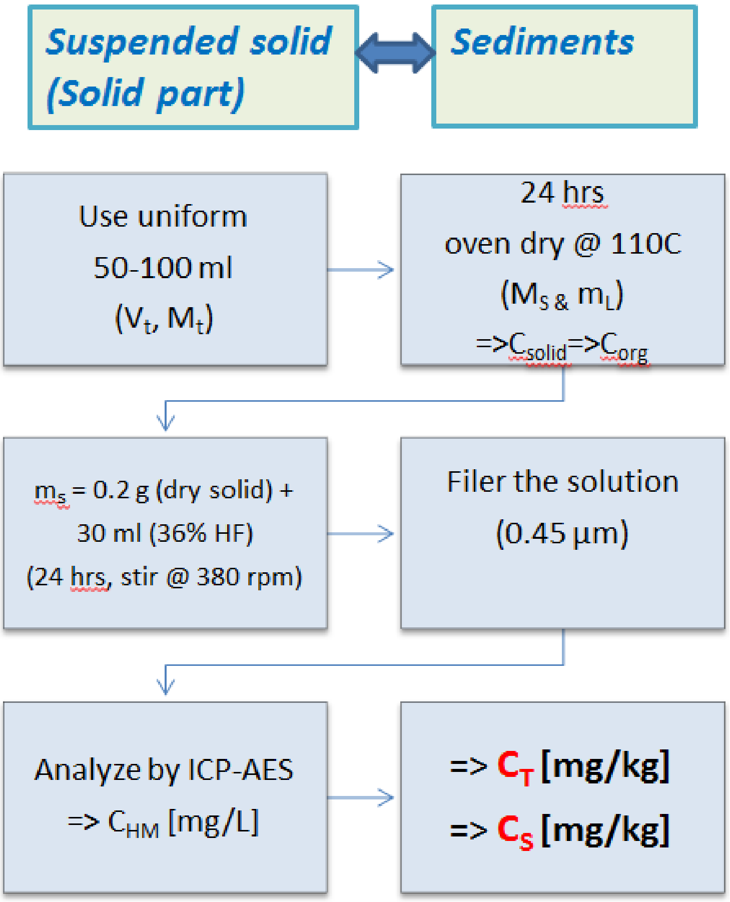


**Figure 4.7** Heavy metal measurement processes for suspended solids and sediment samples

### 4.3.3.4 Organic Content Measurement

The ignition loss method stated in ASTM D2974-78 (Method D) was used to investigate the organic contents for both suspended solids and sediment. The homogenous leachate samples and sediment were thoroughly mixed in the glass container; then oven dries at the temperature of 105-110 C, the samples were measured weight and volume as before and after the oven dry. The oven dried samples were then used for the further ignition loss by using the furnace with the higher temperature of 700 C at the last increasing step. The samples were then measuring until the constant weight can be confirmed.

(a) (b)

**Figure 4.8** (a) High temperature furnace; (b) silica container

### 4.3.3.4 Particle Size Distribution of Sediment

The method applied to the sediment grain size analysis was used in the same method as mention in chapter 3 section 3.4.1 following the JGS 0131-2009.

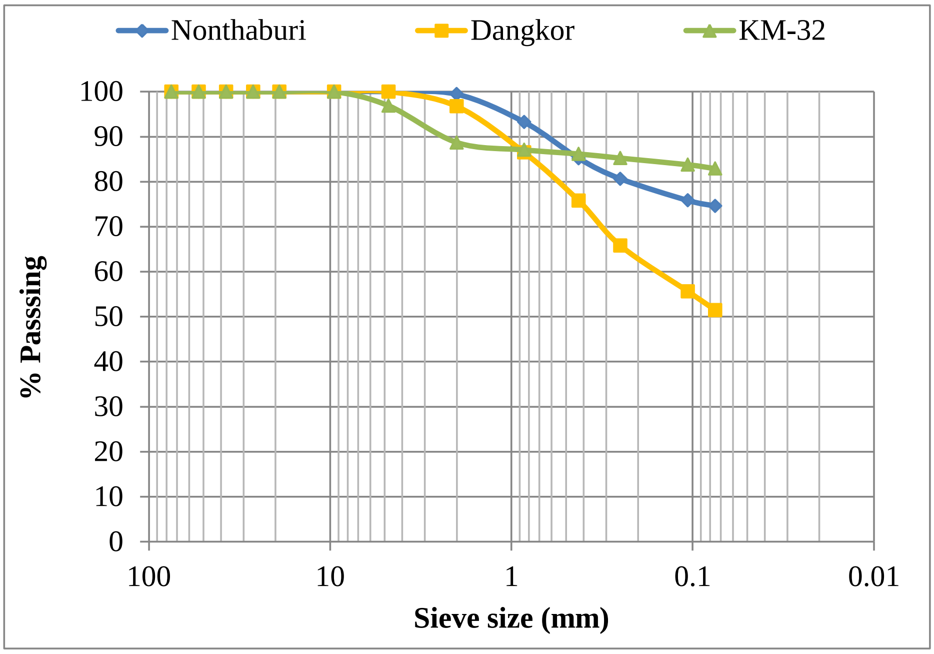


**Figure 4.9** Sediment particle size distributions

## 4.4 Results

### 4.4.1 Leachate Characteristics

#### 4.4.1.1 Physical Property of the Leachate

The physical properties of the leachate samples can separate into two parts; one is the liquid part which is accounting as major part of the leachate, while another one is a solid part, which usually exists small amount in the leachate samples. Figure 4.10 shows the average portion of the liquid and solid part contains in the leachate samples. The results demonstrate the similarity regarding the fresh leachate from Nonthaburi and Dangkor landfill, while KM-32_DL slightly lower and similar to Dangkor area C.  The sample appearance can explain the amount of solid concentration as the level of darkness and transparency showed in Figure 4.2 of the previous section.

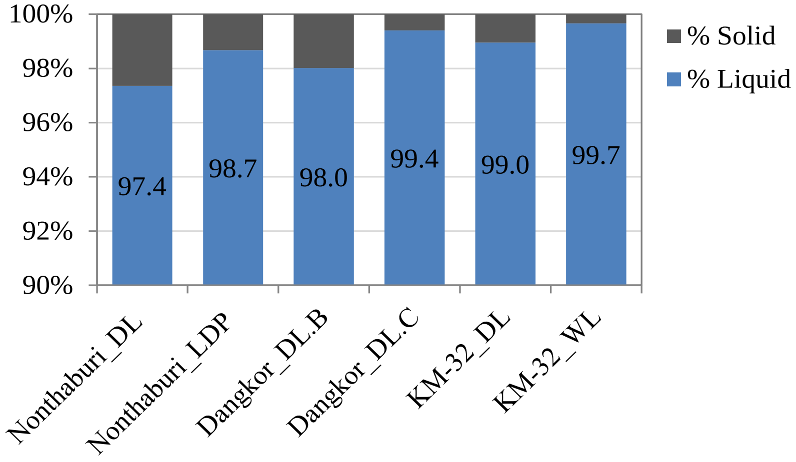


**Figure 4.10** physical properties of leachate samples

#### 4.4.1.2 Basic and Biochemical Parameters

Table 4.1 shows the summary of in-situ and laboratory measurements for essential biological and chemical parameters, which are presented in the range (Max-Min) and the average, for the samples collected in wet and dry seasons. The effluent standards of the three countries are also included in the table. In the three sites, the wet (rainy) season starts from May or June and ends in November or December as for early and late starting and ending of the seasons for specific years. Besides pH and temperature, the most of parameters including oxidation-reduction potential (ORP), turbidity (Turb), electrical conductivity (EC) and the total dissolved solids (TDS) were found higher during the dry season than the wet season, especially for Dangkor and KM-32 landfill. It is mostly due to the dilution of the rainwater. However, the waste fire in Area C of the Dangkor landfill that occurred before the sampling in the wet season of October 2016 could have caused the large difference. Similar variations in ORP, Turb, EC, and TDS were reported by some previous studies by Ziyang et al., (2009), Slem et al., (2008), Aziz et al., (2015), Aziz et al., (2010). Chemical oxygen demand (COD) and biochemical oxygen demand ($BOD_5$) were found to be very much higher than the effluent standard limit of Thailand, IEAT (2016), which is similar to Cambodia, Laos, and Japan, MOEC (1999), MONREL (2009) and MOE (2015). The $BOD_5$ and COD were high concentrations for most samples, but slightly lower for the KM-32 landfill compared to the others. The high concentrations found in the Nonthaburi DL and Dangkor DL.B samples are partly attributed to soil cover, which could prevent water percolation into the waste to some extent. This range of COD indicated that the landfills were in the methanogenic phase, Christensen (2001). Also, no significant seasonal changes were observed in the LDP of Nonthaburi landfill compared to the fresh leachate (DL sample), which could be partially attributed to the buffer effect of the huge leachate pond.

There have been associated results to this study, as reported in previous studies for other landfills in other countries, Ghafari et al., (2010), Zhong et al., (2008) and Canziani et al., (2006). Nitrite ($NO_2$), nitrate ($NO_3$), and ammonia ($NH_3$) were measured for some samples from the sites. The ammonium concentrations showed very high value, particularly for the Nonthaburi DL and Dangkor DL.B samples. Although the data is limited, the higher nitrite and nitrate concentrations in the LDP samples than in the DL samples at the Nonthaburi site could indicate the nitrification of the LDP with an oxidation environment, which is confirmed by the ORP values. The total Kjeldahl nitrogen (TKN) was measured only for the samples from the Nonthaburi site, which also showed significant differences between fresh leachates (DL) and those stored in the LDP; these were higher for the DL than the LDP. Compared to the standard, very high chloride (Cl) concentrations were observed for the Nonthaburi sites and the Dangkor DL.B, ranging from 3000–5000 mg/L. Tanchuling et al. (2015) conducted a similar study on a landfill in the Philippines and also reported a high chloride concentration in the leachate, ranging from 2400–3500 mg/L. They found relatively high chloride concentrations in the shallow wells near the landfill and discussed the possibility of chloride as a tracer for the investigation of groundwater contamination by the landfill, which could be applicable for the study sites with high Cl concentrations in the leachates.

**Table 4.1** Basic biological parameters of leachate samples

| Parameter | Season | Nonthaburi Landfill | | | | | | Dangkor Landfill | | | | | | KM-32 Landfill | | | | | | Effluent Standard |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | DL | | | LDP | | | DL.B | | | DL.C | | | DL | | | WL$ | | | |
| | | Max | Min | Ave | Max | Min | Ave | Max | Min | Ave | Max | Min | Ave | Max | Min | Ave | Max | Min | Ave | |
| Temp | Dry | 37 | 33 | 35 | 35 | 31 | 34 | 38 | 29 | 33 | 38 | 35 | 36 | 33 | 28 | 30 | - | - | – | 40*;<br>45** |
| (°C) | Wet | 35 | 32 | 33 | 35 | 31 | 33 | 36 | 25 | 31 | - | - | 33# | 33 | 30 | 31 | 33 | 31 | 31 | |
| pH | Dry | 8.0 | 7.5 | 7.8 | 8.2 | 7.4 | 7.8 | 8.2 | 8.1 | 8.1 | 7.6 | 7.3 | 7.5 | 7.9 | 7.07 | 7.6 | - | - | | 5.5-9*; 5-9**; 6-9.5*** |
| | Wet | 7.6 | 7.3 | 7.5 | 8.1 | 7.0 | 7.8 | 8.3 | 7.9 | 8.1 | - | - | 7.90# | 7.9 | 7 | 7.5 | 8.2 | 8 | 8.03 | |
| ORP | Dry | -300 | -380 | -340 | 190 | -23 | 100 | -70 | -350 | -210 | -120 | -280 | -200 | -10 | -160 | -100 | - | - | - | NA |
| (mV) | Wet | -260 | -400 | -310 | 200 | -1 | 100 | -40 | -30 | -35 | - | - | 80# | 70 | -250 | -90 | 80 | 60 | 70 | |
| EC | Dry | 38.8 | 31.8 | 35.2 | 29.8 | 16.8 | 20.9 | 40.6 | 20 | 38 | 22 | 3 | 13 | 14.5 | 3.2 | 8.6 | - | - | $ | 7.5* |
| (mS/cm) | Wet | 28.9 | 20.3 | 24.1 | 18.6 | 10.2 | 15.0 | 27 | 15 | 26 | - | - | 2.0# | 3.8 | 3.6 | 3.7 | 3.7 | 3.3 | 3.5 | |
| Turb (NTU) | Dry | 1,000 | 950 | 970 | 450 | 180 | 320 | 1,000 | 470 | 730 | 870 | 170 | 520 | 1,000 | 195 | 590 | - | - | - | 20* |
| | Wet | 1,000 | 700 | 800 | 440 | 100 | 270 | 600 | 550 | 570 | - | - | 220# | 1,000 | 60 | 380 | 360 | 70 | 120 | |
| DO | Dry | 6 | 5.8 | 5.9 | 8.2 | 7 | 7.8 | 6.2 | 3.3 | 4.7 | 8.6 | 7.3 | 7.9 | 11.9 | 6 | 9.2 | - | - | - | >1** |
| (mg/l) | Wet | 8 | 5.8 | 7.7 | 9.8 | 6.6 | 8.2 | 8.3 | 7.8 | 8.1 | - | - | 7.6# | 10.5 | 8.7 | 9.6 | 10.5 | 10.1 | 10.3 | |
| TDS (mg/l) | Dry | 23,500 | 19,700 | 21,700 | 18,500 | 10,400 | 13,000 | 24,800 | 11,500 | 20,700 | 13,500 | 2,200 | 6,000 | 7,000 | 2,000 | 4,900 | - | - | - | 3,000*<br>2000**<br>3500*** |
| | Wet | 17,900 | 6,800 | 13,500 | 11,500 | 6,300 | 9,300 | 22,900 | 8,150 | 15,000 | - | - | 1,200# | 2,500 | 2,300 | 2,400 | 2,300 | 1,100 | 1800 | |
| COD (mg/l) | Dry | 7,750 | 2,050 | 3,380 | 2,320 | 470 | 1,500 | 7,900 | 2,540 | 2,900 | NM | NM | NM | 1,080 | 570 | 770 | - | - | - | 120*;<br>100**;<br>160*** |
| | Wet | 3,120 | 2,300 | 2,730 | 1,800 | 610 | 1,170 | - | - | 2,100# | - | - | 610# | 390 | 350 | 370 | 670 | 510 | 590 | |

NA-Not Available; NM-Not Measured; $-No WL sample in dry season
#: Only one sample; *: Thailand (IEAT, 2016); **: Cambodia (MOEC, 1999); ***: Laos (MONREL, 2009)

**Table 4.1** Basic biological parameters of leachate samples (Cont.)

| Parameter | Season | Nonthaburi Landfill |  |  |  |  |  | Dangkor Landfill |  |  |  |  |  | KM-32 Landfill |  |  |  |  |  | Effluent Standard |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  |  | DL |  |  | LDP |  |  | DL.B |  |  | DL.C |  |  | DL |  |  | WL$^{\$}$ |  |  |  |
|  |  | Max | Min | Ave | Max | Min | Ave | Max | Min | Ave | Max | Min | Ave | Max | Min | Ave | Max | Min | Ave |  |
| BOD$_5$ (mg/l) | Dry | 1,060 | 410 | 760 | 780 | 350 | 230 | NM | NM | NM | NM | NM | NM | 200 | 120 | 170 | - | - | - | 20*;<br>80**;<br>40*** |
|  | Wet | 1,230 | 530 | 750 | 560 | 130 | 320 | NM | NM | NM | NM | NM | NM | 180 | 120 | 150 | 280 | 50 | 170 |  |
| NO$_2$ | Dry | - | - | 19# | NM | NM | NM | - | - | 0.9# | NM | NM | NM | NM | NM | NM | - | - | - | NA |
| (mg/l) | Wet | - | - | 2# | 210 | 13 | 112 | - | - | <0.5 | - | - | 21# | - | - | 48# | - | - | 22# |  |
| NO$_3$ | Dry | - | - | 2# | NM | NM | NM | NM | NM | NM | NM | NM | NM | NM | NM | NM | - | - | - | 20** |
| (mg/l) | Wet | 1.9 | 0.4 | 1.2 | 29 | 3.3 | 13.9 | - | - | 2# | - | - | 3.4# | - | - | 11# | - | - | 3.2# |  |
| NH$_3$ | Dry | 2,350 | 270 | 1,060 | 210 | 110 | 150 | - | - | 920# | NM | NM | NM | NM | NM | NM | - | - | - | 7** |
| (mg/l) | Wet | 1,970 | 560 | 1,150 | 200 | 110 | 150 | - | - | 780# | - | - | 26# | - | - | 100# | - | - | 50# |  |
| TKN | Dry | 1,570 | 360 | 1,190 | 360 | 240 | 290 | NM | NM | NM | NM | NM | NM | NM | NM | NM | - | - | - | 100* |
| (mg/l) | Wet | 7,910 | 1,150 | 3,030 | 260 | 210 | 250 | NM | NM | NM | NM | NM | NM | NM | NM | NM | NM | NM | NM |  |
| Cl | Dry | 4,974 | 3,370 | 4,410 | 5,750 | 4,380 | 5,050 | 4,260 | 2,250 | 3,250 | - | - | 2,050# | 1,200 | 290 | 650 | - | - | - | 700**;<br>500*** |
| (mg/l) | Wet | 4,510 | 3,130 | 3,630 | 5,300 | 3,770 | 4,450 | - | - | 2,730# | - | - | 290# | 390 | 330 | 360 | 370 | 340 | 350 |  |

NA-Not Available; NM-Not Measured; $^{\$}$-No WL sample in dry season
#: Only one sample; *: Thailand (IEAT, 2016); **: Cambodia (MOEC, 1999); ***: Laos (MONREL, 2009)

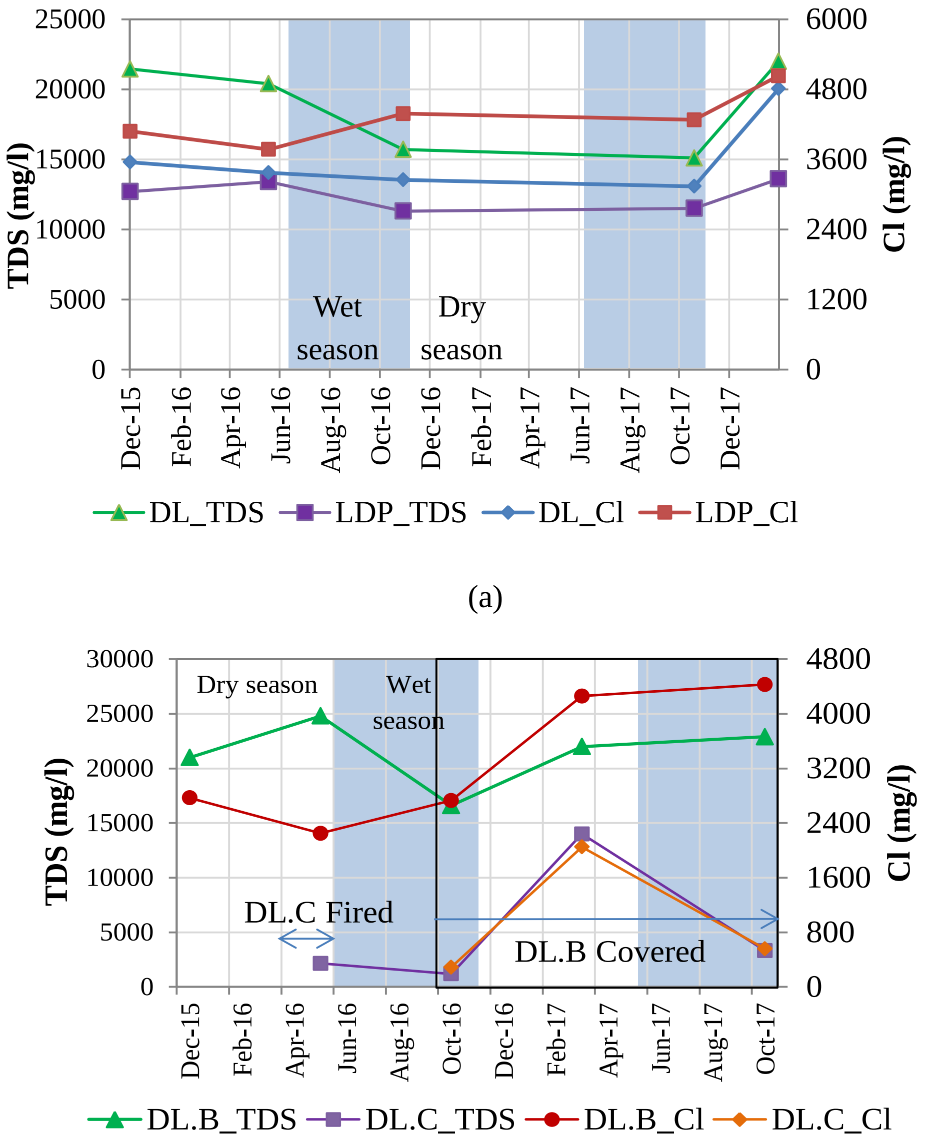
#### 4.4.1.3 Concentration Variation over Time

Figure 4.11 shows the concentration of Chloride (Cl) and total dissolved solids (TDS) measured at three landfills over the period of investigation. The details for each significant parameter will be discussed as follows:

Figure 4.11(a) presents the particular results of Cl concentration measured at Nonthaburi landfill. The results show some seasonal variation could be confirmed in the site, but the slight difference could be found as shown in the average value (Table4.1). The increased trend of Cl for the large leachate discharge pond (LDP) has been found due to Cl is conservative chemical, which could be deposited in the storage pond. On the other hands, fresh leachate (DL) shows almost constant values over a period of the investigation due to the huge volume of garbage inside the area E with partly covered and the leachate is mixing between old and new in the same area as active zone.

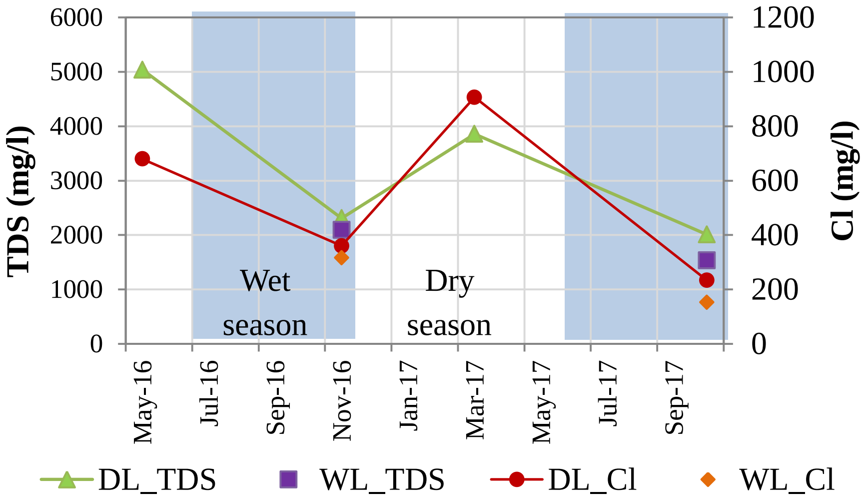
Figure 4.11 (b) shows the significant increase of Cl concentration after the covering of areas A-B at Dangkor landfill. It is due to the less water percolation through waste as dumped pit has been protecting by the soil cover, and also it leads to the extremely decreasing amount of leachate production, but high contaminant concentration could be seen. At the same time, the samples from area C shows low concentration compared to areas A-B, and the seasonal effect was observed, due to the very deep opened pit condition, which contains the huge volume of water during wet season. In addition, a big fire occurred in the early stage of dumping in area C could be one of the key factors affecting contaminant concentrations found in the later fieldwork of October 2016. It is due to fire bringing up the clear water as many contaminants could adsorb by the charcoal productions of burning. Also, it is a good adsorbent for the existed heavy metals containing in the leachate.

Figure 4.11 (c) shows the Cl concentration exists in the samples of the KM-32 landfill, which found the significant change in seasons for the leachate sample as a higher concentration in the dry seasons than in wet seasons. It is due to the KM-32 landfill has a large opened space and shallow waste thickness, leading to the high dilution in the rainy season. The conditions are quite similar to the area C of Dangkor landfill, but leachate is not stored as much as the Dangkor area C. The low compaction of the waste aggregate in KM-32 landfill can also be one of the factors to the shorter retention time of water percolation into the waste. In addition, Cl concentrations of leachates from wetland area were slightly lower than those of dumping areas. It is because of leachates from wetland area are the leachate which has mixed with nearby surface water, and flows out to lower surrounding areas through the outlet of the landfill. The contaminated leachates from areas A-B of Dangkor landfill can be a potential risk to both surface water and agricultural soil because leachate was drained to the creek and surrounding rice fields. While leachate from Area C can be a potential risk to the groundwater due to the very deep pit of 30m can reduce the thickness of natural clay as a barrier to protect groundwater from the contaminated leachate. Also, the contaminated leachates from the KM-32 landfill are also a potential risk to the agriculture areas, due to the leachate was directly drain to the paddy field in the lower part of the landfill area.



(a)

(b)



(c)

**Figure 4.11** TDS and Cl variation overtimes: (a) Nonthaburi landfill, (b) Dangkor landfill and (c) KM-32 landfill

### 4.4.1.4 Relationship between Basic and Biochemical Parameters

Figure 4.12(a) shows the relationship between Cl and TDS concentration. Although the ranges of concentrations were quite different for Nonthaburi DL and Dangkor DL.B compared to KM-32 and Dangkor DL.C, a positive correlation can be seen in the relationship for all the data from the three landfills. Cl concentrations of LDP were relatively higher than those of the DL samples, which imply the accumulation of Cl in the storage pond as a conservative chemical. The relationship between BOD5 and COD measured for the samples of Nonthaburi and KM-32 (Figure 4.12(b)) shows a positive correlation, and there were higher $BOD_5$ and COD in Nonthaburi than in the KM-32 landfill. The low organic contents of the KM-32 landfill could be attributed to the high waste wash rate for the open dumping practice, which does not use cover soils and which has a shallow waste depth, compared to the Nonthaburi landfill. The $BOD_5$/COD ratios of the DL samples ranged from 0.1 to 0.6 for the two landfills. The relatively low $BOD_5$/COD ratio of the LDP and WL sample could indicate that biological decomposition is taking place in the storage ponds. Similar results to those discussed above were found by previous studies of other landfills Canziani et al., (2006), Bashir et al., (2007) and Aziz et al., (2005).

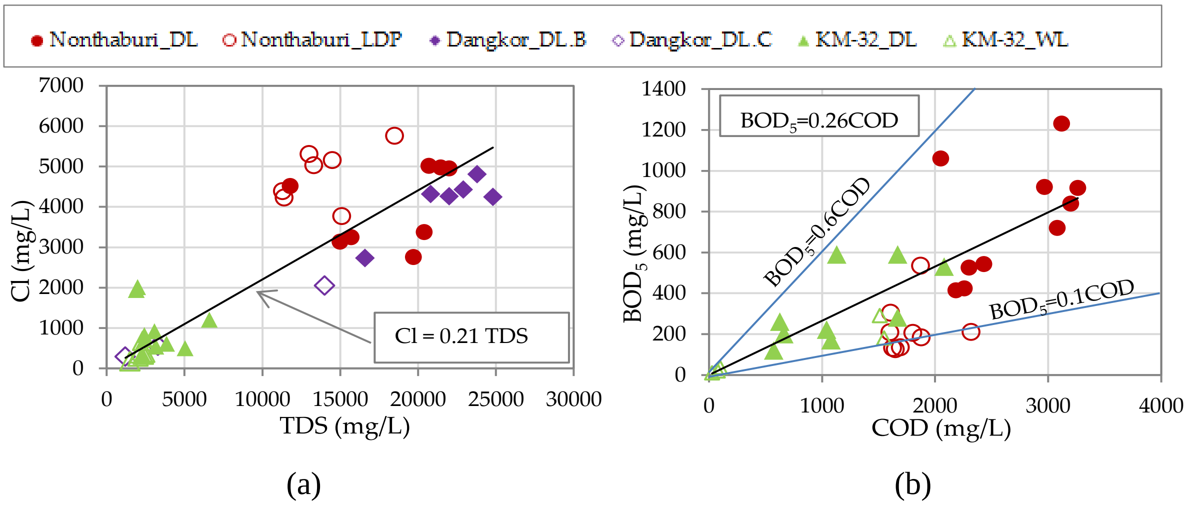


**Figure 4.12** Relationship: (a) Cl and TDS; (b) $BOD_5$ and COD

Figure 4.13(a) shows the relationship between COD and TDS for the leachates in this study. Although COD includes the organics in the suspended solids, there is relatively good correlation if all the data from the three sites are compared. However, specific differences can be seen between different sites and different types of leachate. For example, the COD/TDS ratios of the Nonthaburi LDP samples were smaller than the DL, and almost no correlation can be seen for the data from KM-32. This relatively small COD for the LDP could be due to the sedimentation of organic materials under the still conditions in the huge pond. Figure 4.13(b) shows the relationship between the COD and suspended solids concentration ($C_{SS}$). Although the measured points are limited, a good correlation can be confirmed. From the regression line shown in the figure, it can be inferred that SS is the major source of organics in the leachate.

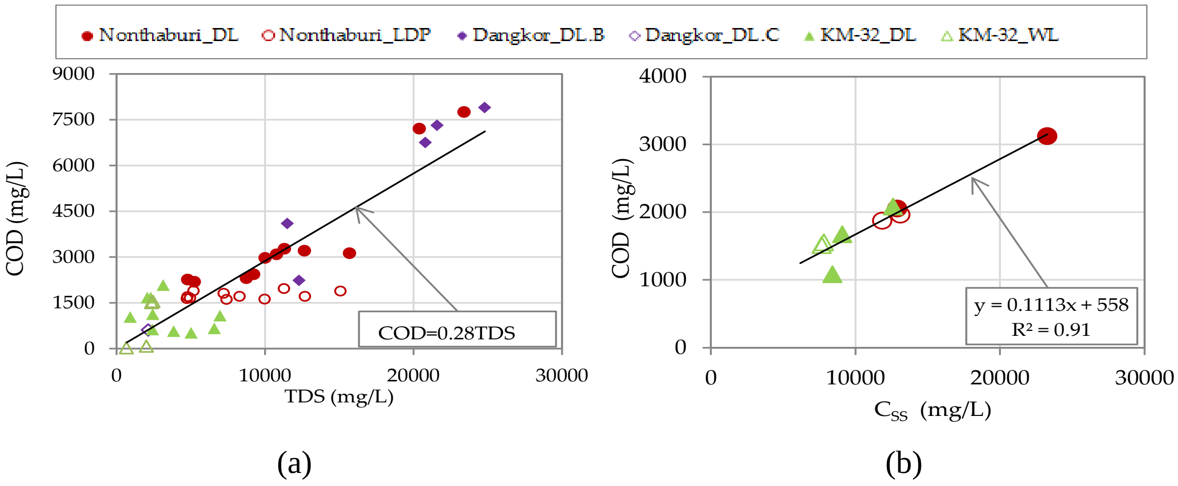


**Figure 4.13** (a) COD and TDS; (b) COD and suspended solids concentration ($C_{SS}$)

### 4.4.1.5 Suspended Solids Property

Figure 4.14 shows the portion of organic and non-organic compound consisted of the suspended solids of leachate. However, it was more than 21% of organic material contained in the suspended solid as for the lowest case, and the highest case was about 56%. The measurement results show some differences in organic content in the suspended solid for the selected landfill leachates. The organic content contained in the fresh leachate were higher than the large leachate pond, and wetland as for Nonthaburi and KM-32 case, while fresh leachate from closed and covered areas A-B in Dangkor landfill was higher than the leachate from the opened deep pit of area C.

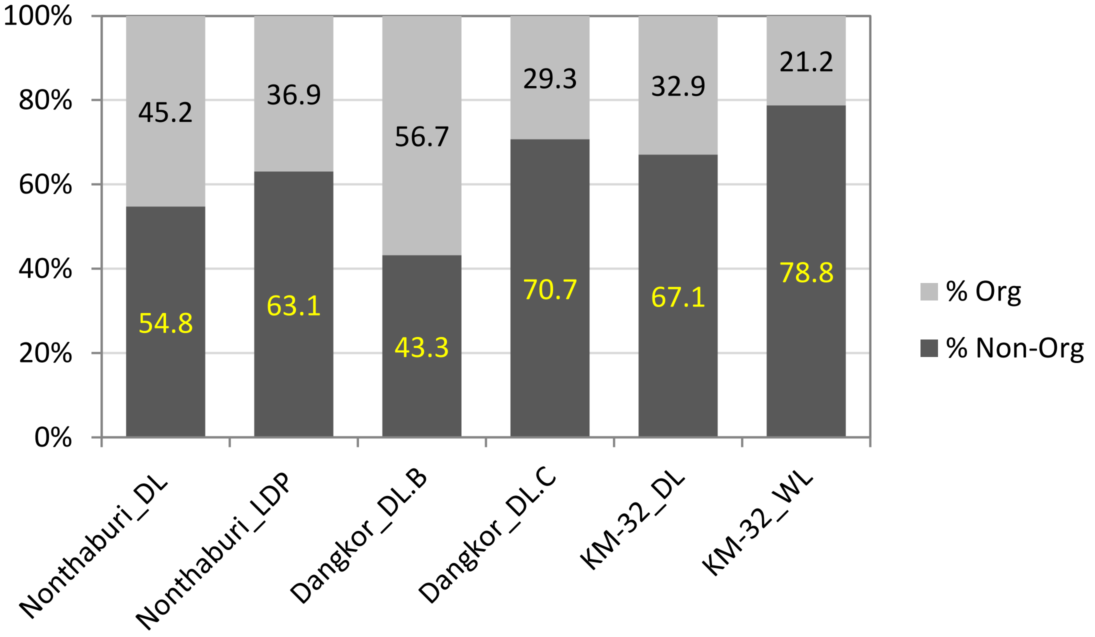
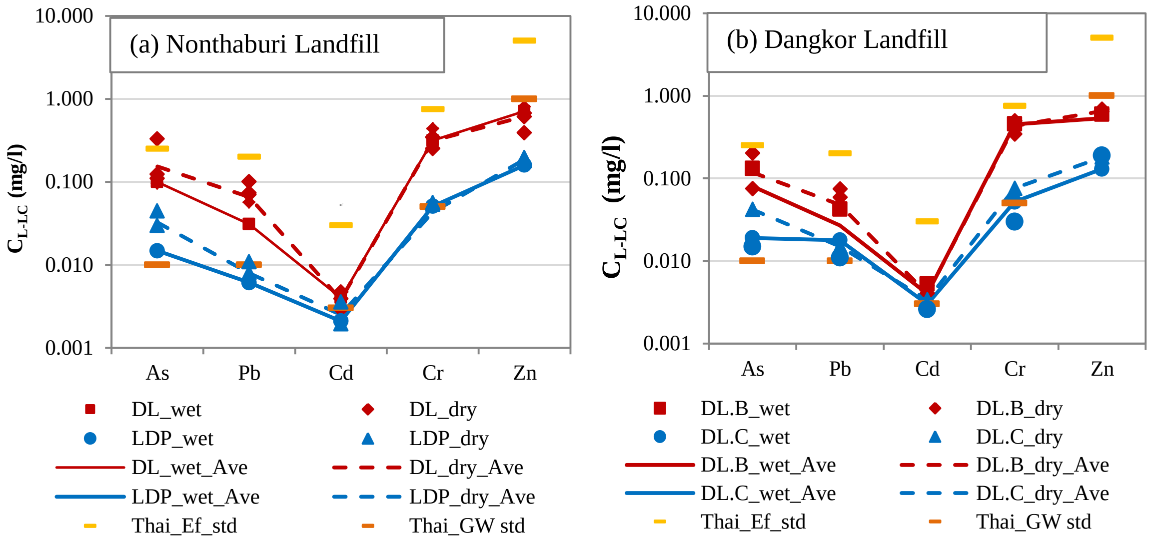


**Figure 4.14** Initial suspended solids properties

### 4.4.1.6 Dissolved Heavy Metals in the liquid part of leachate

Figure 4.15 (a–c) show the dissolved heavy metal (HM) concentrations in the liquid part of leachates ($C_{L\text{-}LC}$) sampled at the three landfills. Five harmful HMs- arsenic (As), lead (Pb), cadmium (Cd), chromium (Cr) and zinc (Zn) were measured. These HMs have commonly been found for most leachates in past and current studies. The average values for the dry and wet seasons were also shown in the figures. The averages of the measured HM concentrations of the fresh leachate (DL) from the three landfills, excluding the Dangkor DL.C samples, are compared in Figure 4.15 (d). The industrial effluent and groundwater standards of Thailand, IEAT (2016) are also indicated in the figures as the references. Regarding the effects of the sites and seasonal conditions on HMs, similar trends can be pointed out as discussed in the basic parameters in Table 4.1. In particular, the fresh leachate samples (DL) had higher concentrations than those found in the LDP and WL at the Nonthaburi and KM-32 landfill. As for the Dangkor landfill, the HM concentrations of the DL.B samples from the closed and covered area were larger than the DL.C samples taken from the ongoing deep pit landfill. No significant different of HM concentration in the wet and dry season for the closed and covered areas (DL of area E of Nonthaburi landfill and DL.B of areas A-B of Dangkor landfill), except for Pb. However, the slight differences in the seasonal difference were found for the samples from the opened dumped pit DL.C of Dangkor landfill, which can be caused by the dilution of the rainwater. The magnitude order of the HM concentrations is quite similar at the three landfills. The highest and lowest were Zn and Cd, respectively, and the other HMs were in the order Cr, As and Pb. The concentrations of fresh leachates were the highest for the Nonthaburi landfill and the lowest for the KM-32 landfill. The Dangkor DL.C samples had the similarly small concentration to those of the KM-32 DL samples.



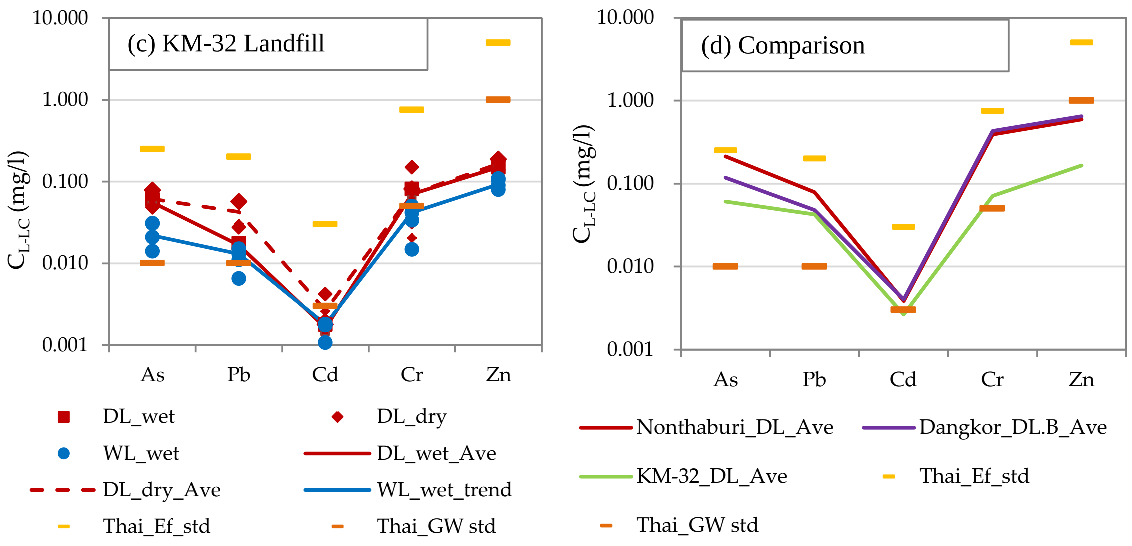


**Figure 4.15** Heavy metal concentration of the liquid part of leachate samples ($C_{L-LC}$) and comparison of average leachate concentration

Beside the HM contents in the disposed of residue, several reasons can be considered for the concentration differences between the sites, and the types of leachate at each site. The volume of water percolating over the unit volume of waste could be one of the major controlling factors for the HM concentrations. The KM-32 landfill has a wider opened space and thinner waste layer compared to the other landfills, and no soil cover had been provided until the time of the sampling, which is similar to the conditions in Dangkor Area C (DL.C). The redox condition of the disposed waste and leachate also affects the HM solubility and concentration, Weiner and Mathews (2003) and Bashir et al., (2009). Waste segregation was not fully applied in these landfills. Therefore, the presence of high Cr in the leachate samples was due to the presence in the waste mixture of Pb-Cr batteries, colored polyethylene bags, discarded plastic materials and empty paint containers, Mor et al., (2006) and Parth et al., (2011). The high concentration of Zn in the leachates could be attributed to the disposal of batteries, fluorescent lamps, food waste and burning tires at the site, Aderemi et al., (2011) and Moturi et al., (2004). However, the effects of pH and ORP could not be confirmed by the measurements in this study.

The maximum concentrations of all the HMs were more than the groundwater standard (GW std) and even close to or above the effluent standards, and the average concentrations were all over the groundwater environmental standard, with the exception of Zn. Although the low permeability of the geological barrier has protected the groundwater, such high concentrations in the liquid part of the leachate could be a potential risk of groundwater contamination in the surrounding area in the future, especially for the Dangkor landfill, which has dump pits with a significant depth of about 30 m from the ground surface of the ongoing landfill in areas C and D.

#### 4.4.1.7 Total Heavy Metals in the Leachate

As explained in Section 2.3.3.2, the total HM concentration of the leachate ($C_{T\text{-}LC}$) was also measured for the same HMs discussed in the previous section (As, Pb, Cd, Cr, and Zn). The total HM concentration is presented in Figure 4.16 for the wet and dry seasons, together with the dissolved HM concentration of the liquid part of the leachate ($C_{L\text{-}LC}$). Thai industrial effluent and groundwater standards are also indicated in the figure. Similar trends of seasonal variation for both $C_{T\text{-}LC}$ and $C_{L\text{-}LC}$ could be confirmed, namely with higher values for the dry season and lower values for the wet season. The most significant point confirmed by the figure is the large difference between the liquid part and the total concentration, about 2–20, 3–30, 17–50, 2–10 and 2–7 times larger for the latter than the former for As, Pb, Cd, Cr and Zn, respectively. The total HM concentrations are at significant levels, especially for Cd, Pb, and As, which are more than a few times greater than the effluent standard. A leachate treatment facility has not been implemented in these landfills, and uncontrolled discharge or leakage of leachate often happens. Under such conditions, leachate with such high HM concentrations could be a source of surface water contamination and soil contamination of surrounding water bodies and agricultural fields.

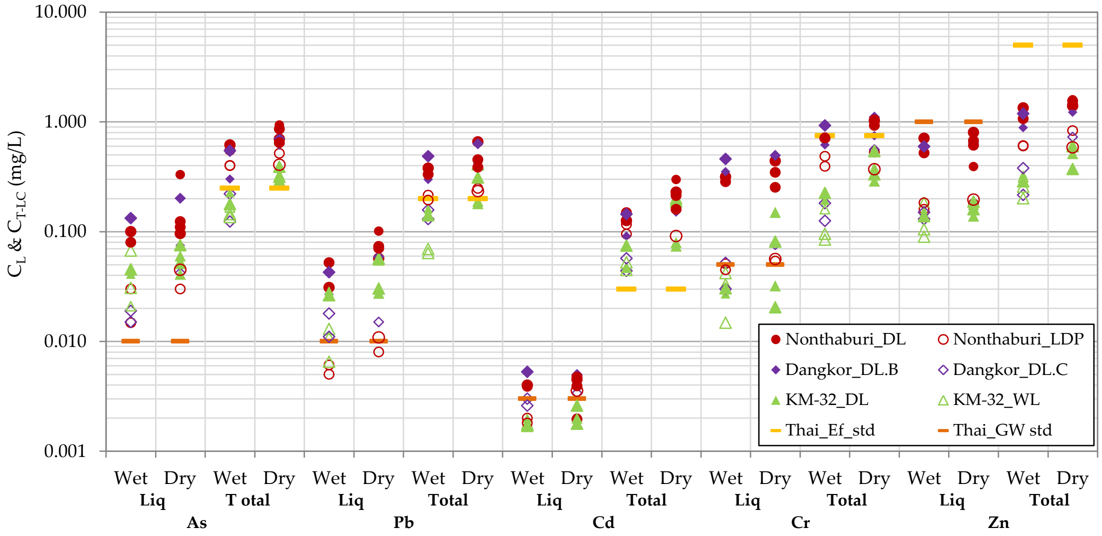


**Figure 4.16** Heavy metal concentrations of total (Total) and liquid part (Liq) of the leachate

### 4.4.1.8 Influencing of Suspended Solid on the HM Concentration

The relationship between total HM concentration ($C_{T\text{-}LC}$) and SS concentration ($C_{SS}$) of leachates was assessed in Figure 4.17. Relatively good linear correlations can be seen for arsenic, and the other HMs shows some positive relationships, but not high correlation. However, if we consider in each site separately; the correlation will be higher than the combination of all landfills, especially the Dangkor landfill. It is due to the properties of various leachates from the different landfill sites and condition, e.g., soil cover, active or inactive, and composition of SS. The difference of SS component can be confirmed by the level of leachate appearance, clear, dark, brown and pink color of leachate at a different landfill and location (Figure 4.1). Another factor is the difference in the metal portion contained in the solid waste composition as a primary source of HM concentrations presented in Chapter 3, section3.5.

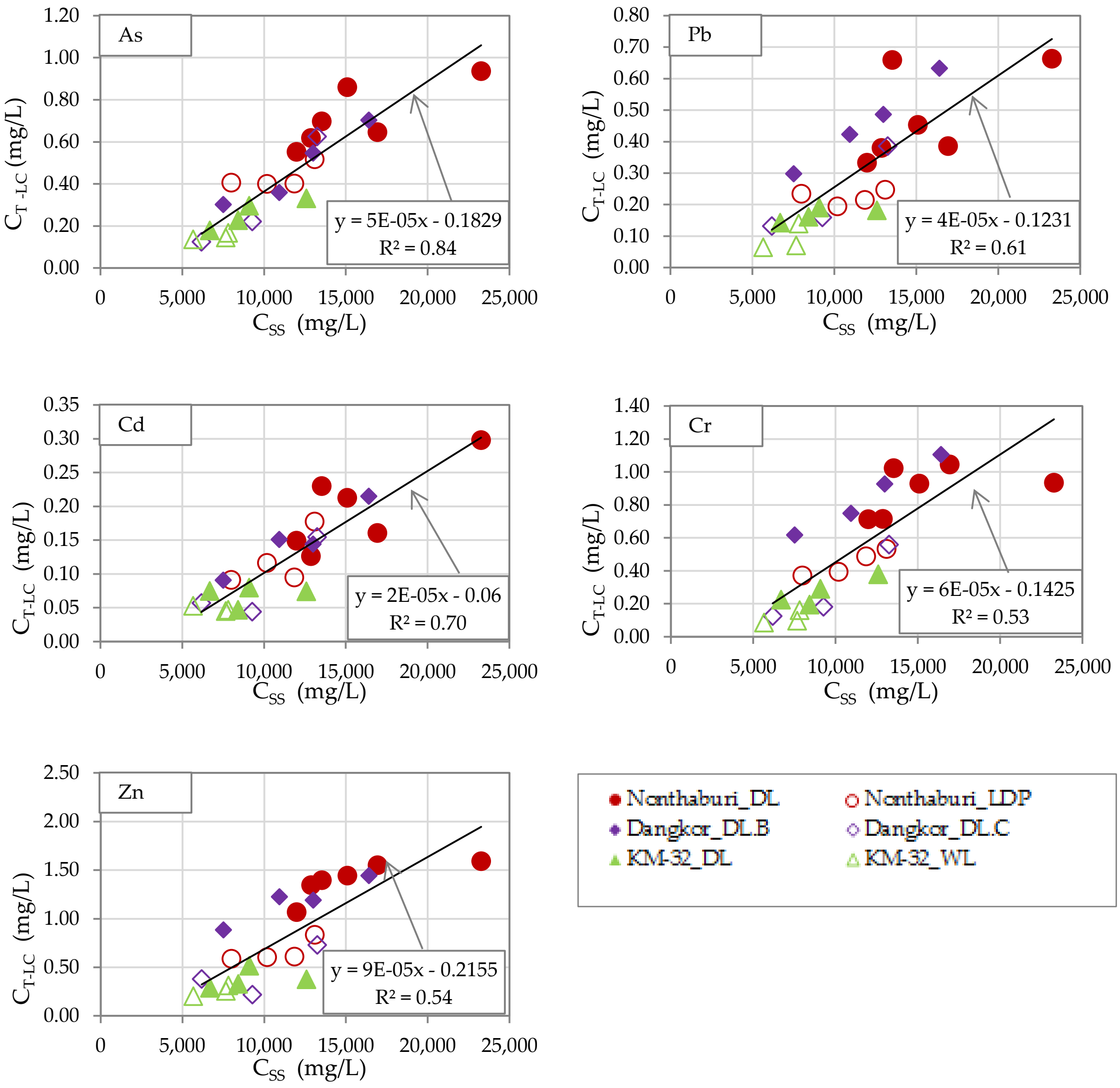


**Figure 4.17** Relationship of total heavy metal concentration of Leachate ($C_{T\text{-}LC}$) and suspended solid concentration ($C_{SS}$)

#### 4.4.1.9 Suspended Solids Composition of Leachate

The leachate samples as a contaminant source were separated into two parts. One was the liquid part (Liq), which accounted for the main part of the leachate, and the other was the suspended solids (SS) or solid part, which was usually a small fraction of the leachate. The amount of SS depends on the leachate quality, which is related to waste composition, age, precipitation and the location where the leachate is stored, e.g., drainage canal, storage pond. Figure 4.18 (a) shows the relationship between the SS concentration ($C_{SS}$) and solid concentration ($C_{solid}$) with positive increasing trends. The suspended solids concentration of the leachates ranged from 5500–23,300 mg/L, while the solid concentration was as high as 43,000 mg/L, about two times higher than $C_{SS}$. As depicted in Figure 4.18 (b), the organic concentration of the leachate ($C_{org}$) also shows a positive relationship with $C_{SS}$. The organic content contained in the leachate samples ranged from 1600–8200 mg/L. Although the particle size of the SS was not measured, the high percentage of fine particles could be expected and came from the clay materials used as covering soil, which is shown in a later section. The Nonthaburi leachates contained a relatively high SS concentration, while the KM-32 landfill leachates had the lowest. As for the different types of leachate at each site, the similar differences to the basic parameters discussed in the previous section confirmed that the DL samples contained a higher amount of solids and SS than the LDP and wetland for the Nonthaburi and KM-32 landfill, respectively. For the Dangkor landfill, the leachate samples collected from the closed area (DL.B) were considerably higher than the ongoing dumping area (DL.C), especially for the organic content. This is mostly attributed to the waste fire that broke out in the early stage of Area C (DL.C), as discussed in the previous section (4.41.6). However, in the DL.C samples, the rate of organics increased rapidly from 1800 mg/L to 5200 mg/L in November (2016) and March (2017). This was due to the rapid increase of garbage volume inside Area C, and no more fires occurred, as before. In addition, the seasonal variations of $C_{solid}$, $C_{SS,}$ and $C_{org}$ for all samples at all the sites were confirmed as having a higher concentration in the dry season than the wet season.

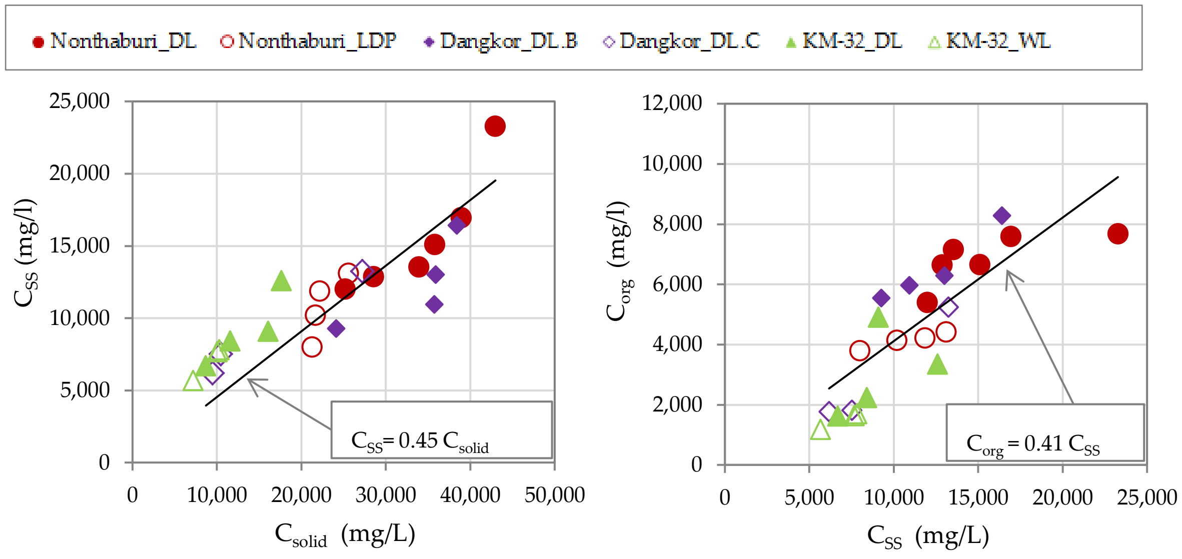


**Figure 4.18** (a) Relationship of SS concentration ($C_{SS}$) and solid concentration ($C_{solid}$) of the leachate; (b) relationship of organic content ($C_{org}$) and SS concentration ($C_{SS}$)

#### 4.4.1.10 Heavy Metal Contents in the Suspended Solid of Leachate

Figure 4.19 shows the HM contents in the unit mass of SS ($C_{S\text{-}SS}$) and SS concentration ($C_{ss}$). The HM contents were calculated using the SS concentration of the total and the liquid part of the leachate samples. As seen in the figure, although the SS concentration of the leachate was higher in the dry season than in the wet season, no clear seasonal differences can be seen for $C_{S\text{-}SS}$ in all the landfills. The magnitude order of the $C_{S\text{-}SS}$ in this set of HMs is Nonthaburi > Dangkor > KM-32 landfill. This order is confirmed for the total concentration ($C_{T\text{-}LC}$) in Figure 4.16. The magnitude order of the $C_{L\text{-}LC}$ for the sites and the HMs could be attributed to the order of the $C_{SS}$ and $C_{S\text{-}SS}$. Both $C_{SS}$ and $C_{S\text{-}SS}$ are affected by the properties of SS, especially organic content and fine particle content. The higher these SS concentrations are, the greater the suspension of the particles and the greater the partitioning of the HMs in the SS.

$$\mathbf{C_{T\text{-}LC} = C_{L\text{-}LC} + C_{SS}.C_{S\text{-}SS}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(4.1)}$$

Where, $C_T$ -Total HM concentration [mg.L$^{-1}$], **$C_{L\text{-}LC}$** -HM in the liquid part of leachate [mg.L$^{-1}$], **$C_{SS}$** - suspended solid concentration [mg.L$^{-1}$], **$C_{S\text{-}SS}$** - HM content of SS [mg.kg$^{-1}$]

The above simple equation (Eq.4.1) can be the best pattern to explain the large difference between total and dissolved HM concentrations, and it is to confirm the seasonal variation of HM concentration in the total concentration that mainly affected by the suspended solid concentration ($C_{SS}$) as discussed and confirmed in Figure 4.19, with the high $C_{SS}$ in the dry season than the wet seasons. The over trend in the period of this study is maybe too short to conclude the change over time for HM concentration in the leachate.

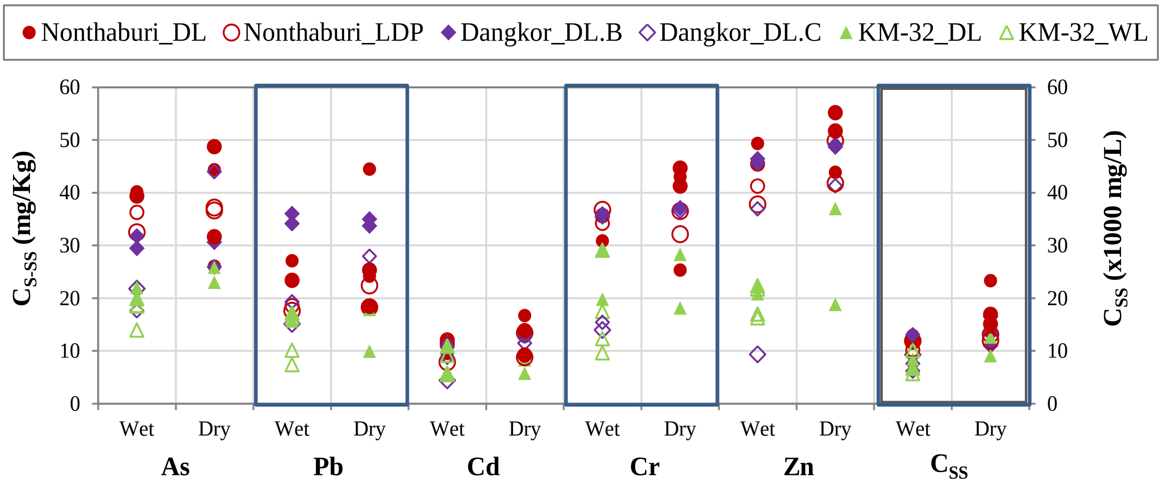


**Figure 4.19** Heavy metal contents of suspended solids ($C_S$-$_{SS}$) of leachate samples

The HMs contained in the SS per unit volume of leachate ($C_{SS}$*$C_{S\text{-}SS}$) are plotted with the total HM concentrations ($C_{T\text{-}LC}$) in Figure 4.20. The plots for Pb and Cd are very close to the 1:1 line, which means that the HM contents in the liquid part was very small and about 80–99% of the total contents were partitioned in the SS, Cd is the highest of removal from the metal solution (individual and mixed), Eres et al., (2005). For As and Cr, the contents were also adsorbed in the SS by about 80–90%, with some exceptions, but not less than 60%. However, the Zn was less partitioned on the SS compared to the other metals, and some points showed less than 50%. Elliott et al. reported that Zn had the lowest sorption capacity for the organic soils, Elliott et al., (1986). The SS in the leachates contained high organic content, similar to their sample condition. As a general trend, it can be said that the SS part contents became smaller as the total concentration increased, especially for As and Cr.

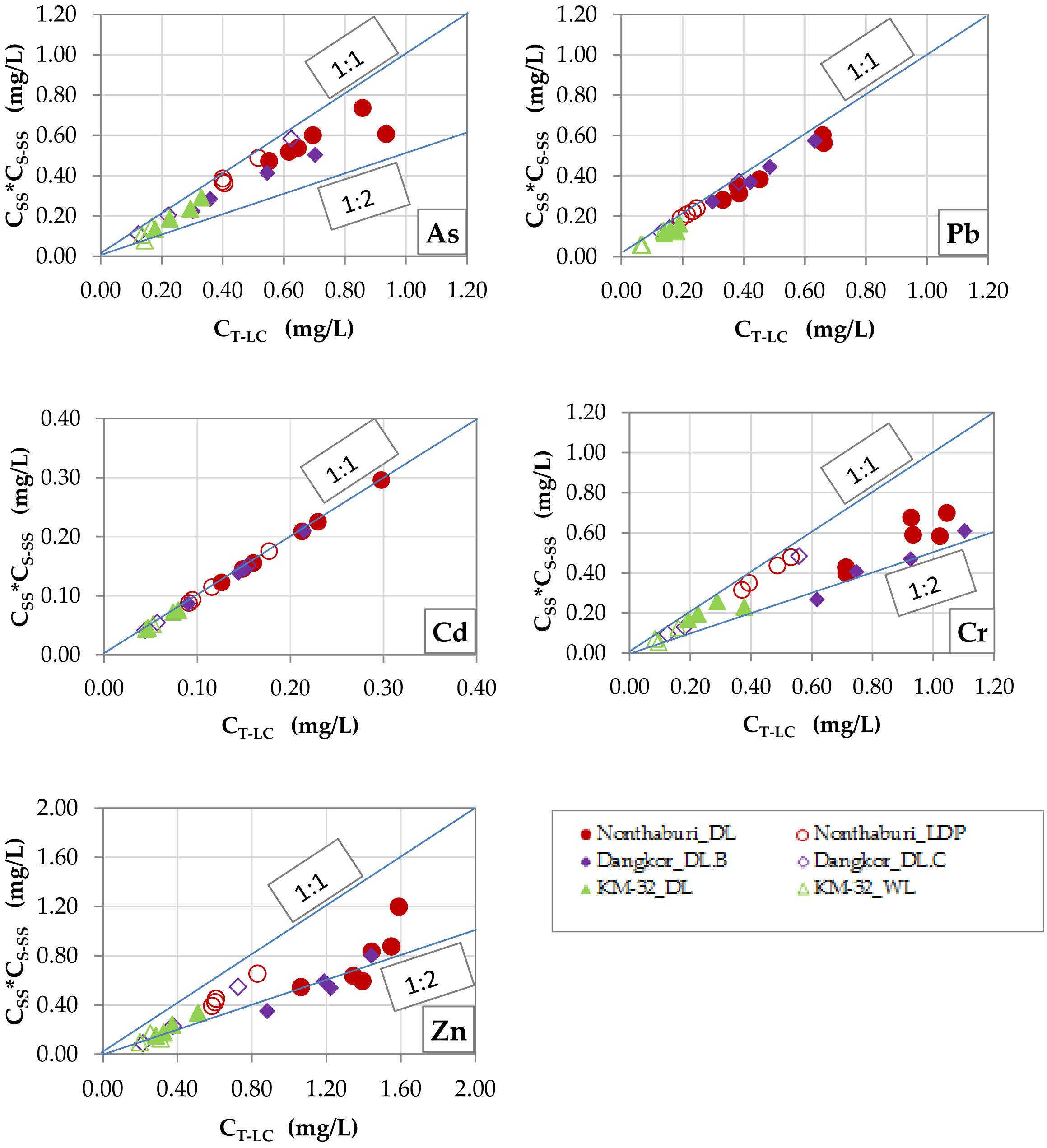
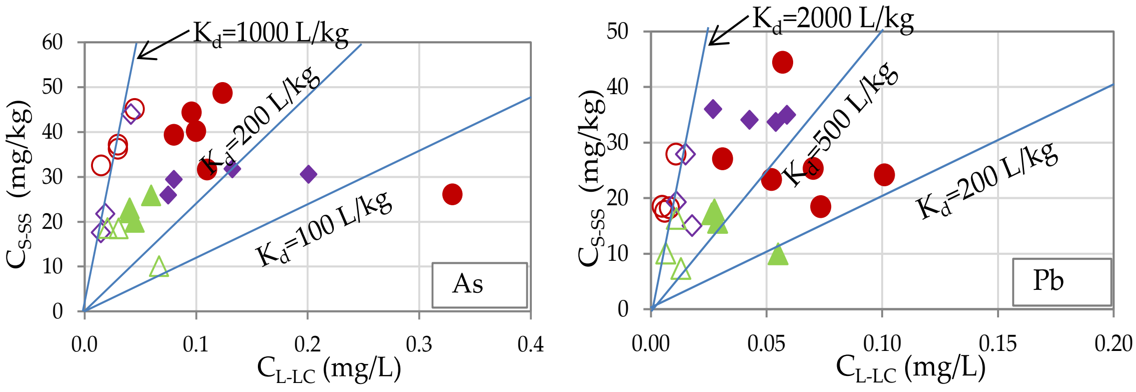


**Figure 4. 20** Relationship of HM concentration adsorbed in SS ($C_{SS}*C_{S\text{-}SS}$) and total heavy metal concentration of Leachate ($C_{T\text{-}LC}$)

As large portions of the harmful heavy metals Pb, Cd, As and Cr in the leachate are partitioned in the SS, simple physical filtration and sedimentation of the SS fraction from the leachate could significantly decrease the total HM concentration [58]. This is considered the easiest and cheapest manner of leachate treatment to reduce the potential environmental risk to the areas surrounding the landfills.

### 4.4.1.11 Correlation of HM in SS and Liquid Part of Leachate

The relationships of the heavy metal contents in the SS ($C_{S\text{-}SS}$) and dissolved HM concentrations in the liquid part of the leachate ($C_{L\text{-}LC}$) are shown in Figure 4.21. They show some correlations but no clear relationship, as neither linear nor non-linear isotherms could be seen in the figures. This is due to the limited amount of data, and also to the difference in the composition of the SS. Furthermore, the sorption might not necessarily take place under the measured $C_{L\text{-}LC}$. Nonetheless, the data points could provide an apparent partitioning coefficient, $K_d$ (~$C_{S\text{-}SS}/C_{L\text{-}LC}$). The data points of Cd show the highest $K_d$, ranging from 2000–5000 L/kg, which can be attributed to a very low liquid part concentration. However, not only for Cd but also the other HMs, the $K_d$ values tend to be larger. The relationship of Zn somehow shows the maximum sorption capacity as the constant $C_{S\text{-}SS}$ values for the DL data from Nonthaburi landfill and the DL.B data from Dangkor landfill. This non-linear partitioning behavior could be a reason for the relatively low fraction of Zn in the SS in the leachate, and the trend towards part fractions of HMs in the SS to the total concentration, as presented in Figure 4.20. Despite this, As, Cr and Pb show a wide range of $K_{d,}$ ranging from about 100–2000 L/kg. From the relatively high $K_d$ values in the Nonthaburi LDP samples, it could also be inferred that the HMs were adsorbed in the suspended solids under relatively large $C_{L\text{-}LC}$ before entering the leachate storage pond. It should be mentioned that the SS properties are not the only controlling factors, but that the HM contents in the waste composition are also a key factor in this matter. One of the pieces of evidence that should be pointed out is that the waste from the Nonthaburi landfill contains a higher amount of metal in its composition than the other landfills (Chapter 3, section 3.5), which could result in higher concentrations ($C_{L\text{-}LC}$ and $C_{T\text{-}LC}$) of most of the elements than in the other landfills.



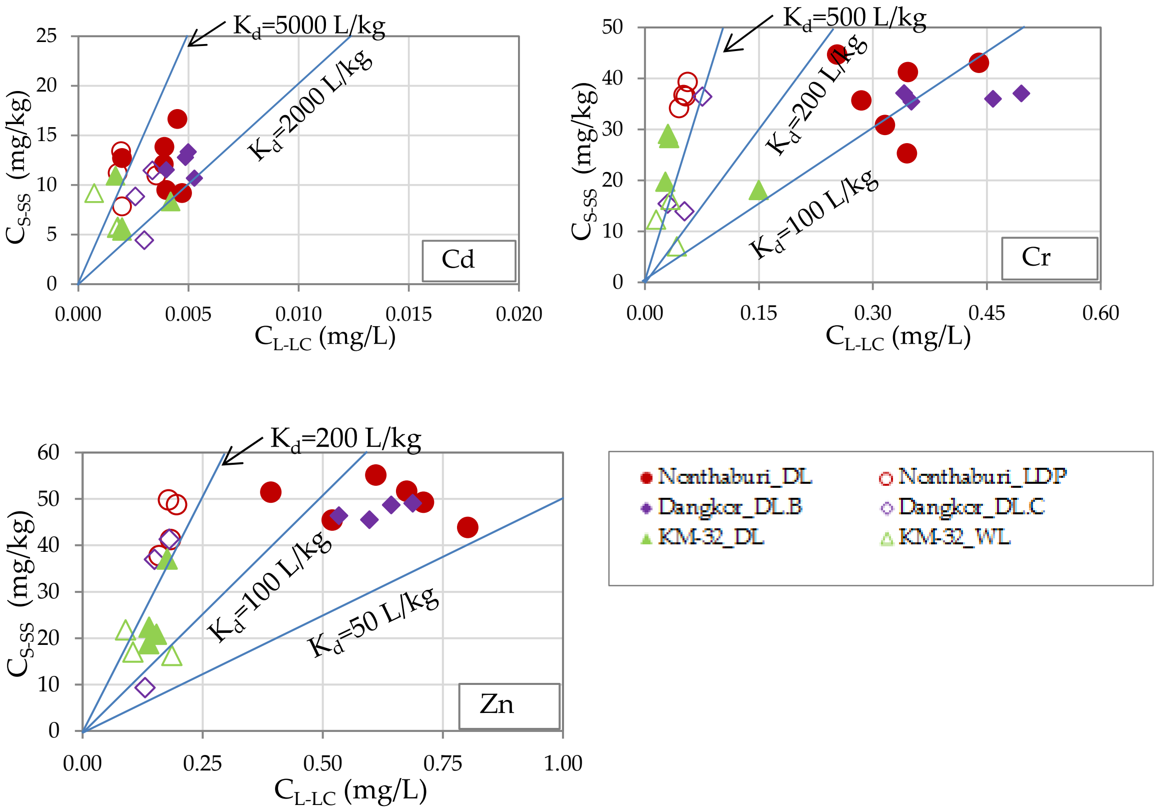


**Figure 4.21** Relationship of the heavy metal content of suspended solids ($C_{S\text{-}SS}$) and liquid part of leachate ($C_{L\text{-}LC}$).

#### 4.4.1.12 Correlation of HM in SS and Organic Content

Organic content ($C_{org}$) is also a key parameter affecting the heavy metal content present in the SS. Figure 4.22 shows the relationships between the HM contents of the SS and the organic contents of the leachate. Although some scatterings are observed, there are positive correlations between all the HMs and the organic content. The scattering is due to the differences of the leachate characteristics at the different sites, regarding the heavy metal concentration of the liquid part and other related sorption behaviors, such as the difference in adsorption capacity, reaction, and oxidation, as confirmed by a previous study, Elliott et al., (1986).

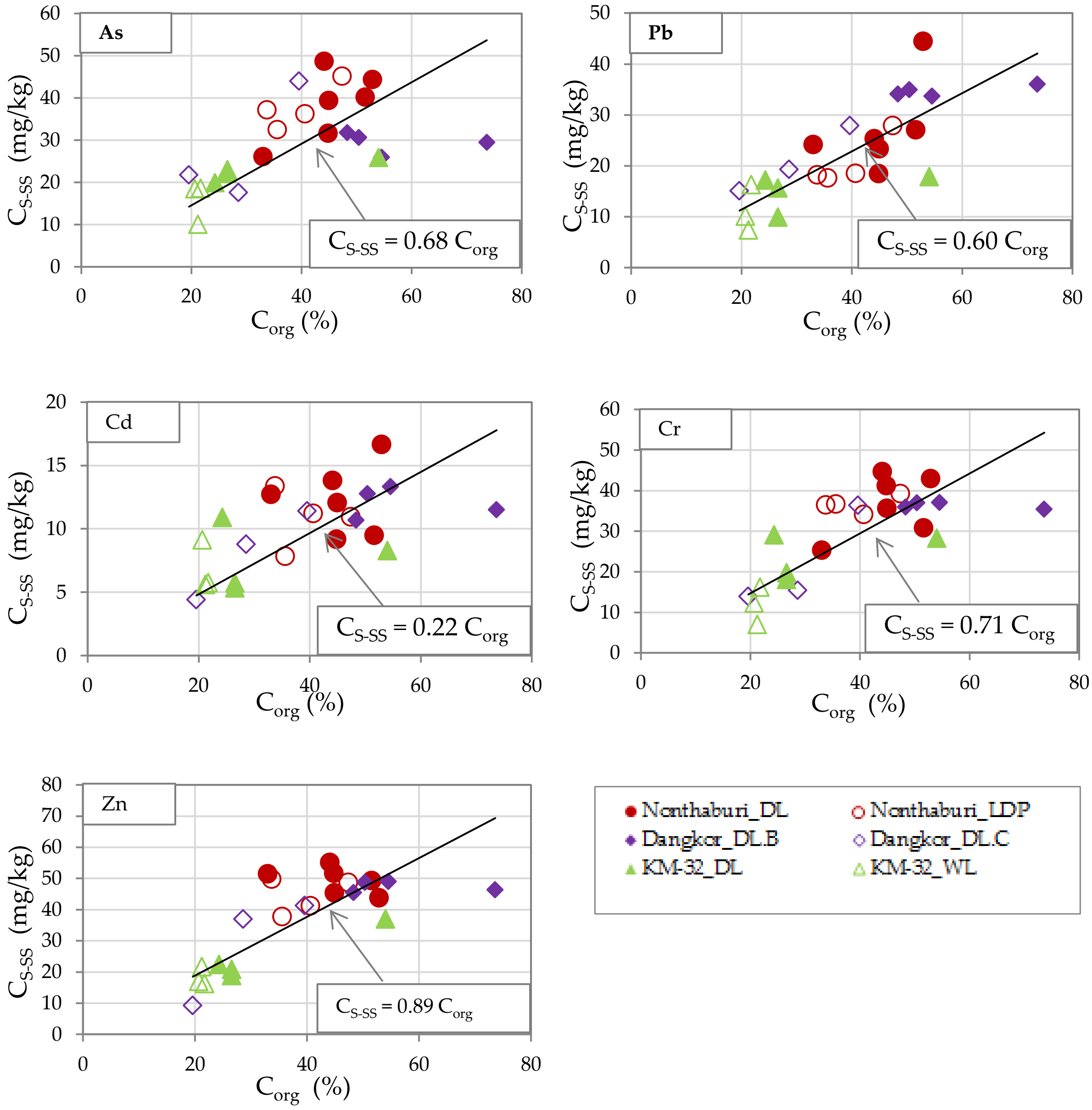


**Figure 4.22** Relationship of the heavy metal concentration of suspended solids ($C_{S\text{-}SS}$) and organic content of leachate ($C_{org}$)

### 4.4.1.13 HM Variation and Monitoring

Figure 4.23 shows the combination of HMs contained in the solid and liquid part of leachate for Nonthaburi landfill. The HM contents of SS are in the primary vertical axis, and HM concentrations of the liquid part of leachate are in the sub-axis. Results show the clear level of HM contents and concentrations between fresh leachate (DL) and leachate from the leachate discharge pond (LD); DL is higher for all assessed HMs of all fieldworks. The general trend overtimes was not so clear but the difference for each time of sampling has been confirming with a slightly higher concentration in the dry season than wet season. It is due to the variation of the sample condition for each time, which depends on the amount and type of the waste together with the amount of water or precipitation for each period. The complex waste composition without separation at the source and site could explain the different trend of each element at a different time as found in this study.

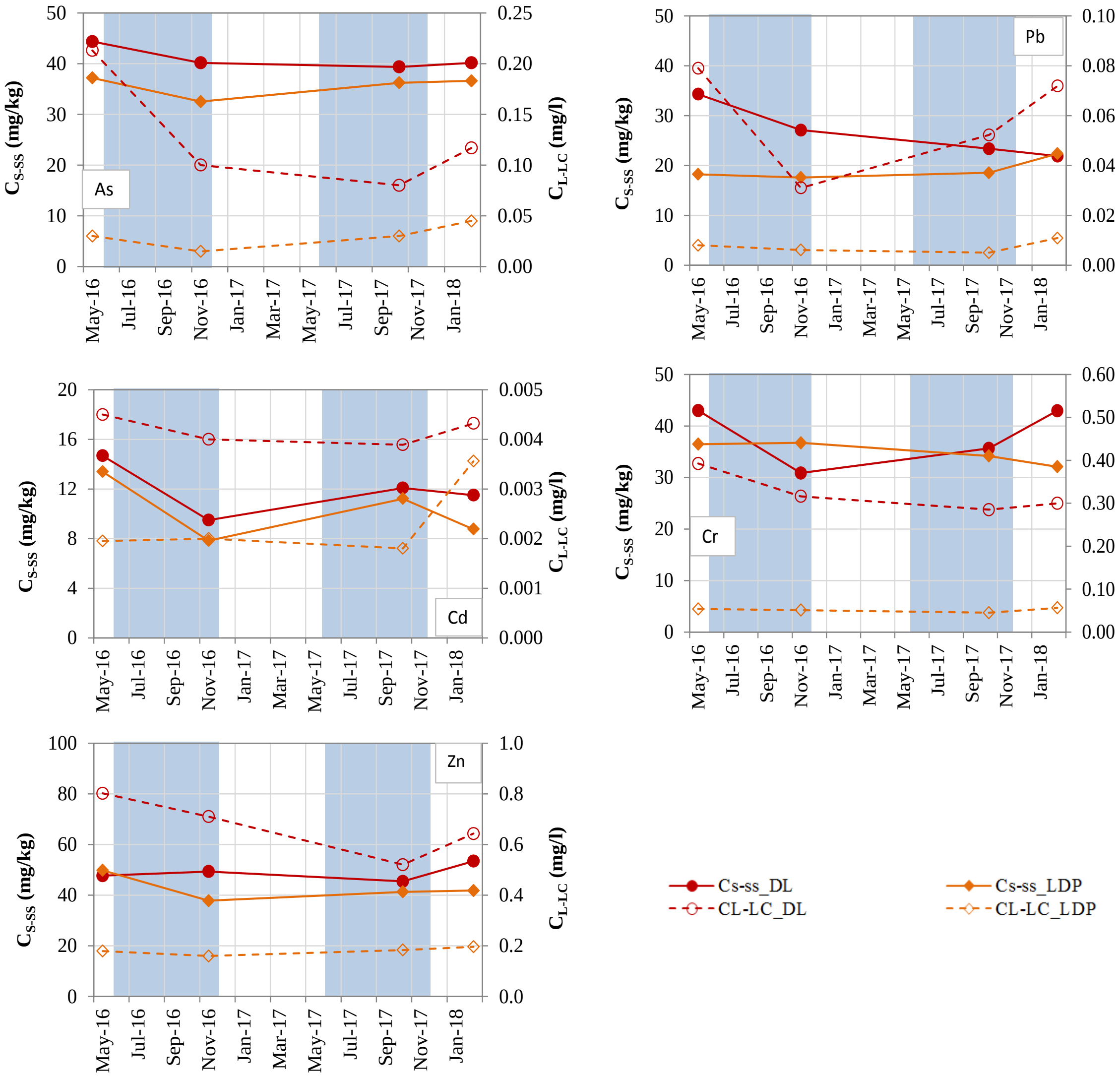


**Figure 4.23** HM Variation of Nonthaburi landfill

Figure 4.24 shows the HM contents and concentrations for both solid and liquid part of leachate varies in times. Results found quite a similar trend to the basic parameters as shown in Figure 4.8 (b). Small differences in the season can be confirmed for the leachate from covered areas A-B (DL.B) and the very large difference in the season can be seen for the opened pit of area C (DL.C). The only reason is that the closed area after covering, it can be helped in protecting the huge water from precipitation, while the opened pit has the huge dilution in the wet season. The higher HM content and concentration of opened pit (DL.C) for the latest wet season as compared to the first wet season in this study is due to the increase of waste volume with three times larger than the earlier. Also, before the first wet season fieldwork, the waste fire broke into the pit, the huge volume of garbage had burned and produced some amount of charcoal at the bottom of the pit. Therefore, the low HMs in the leachate for both portions could be due to the adsorption of HMs by the bottom charcoal as many studies have been confirmed on the HM removal by the activated carbon, Al-Omair and El-Sharkawy (2007); Karnib et al., (2014).

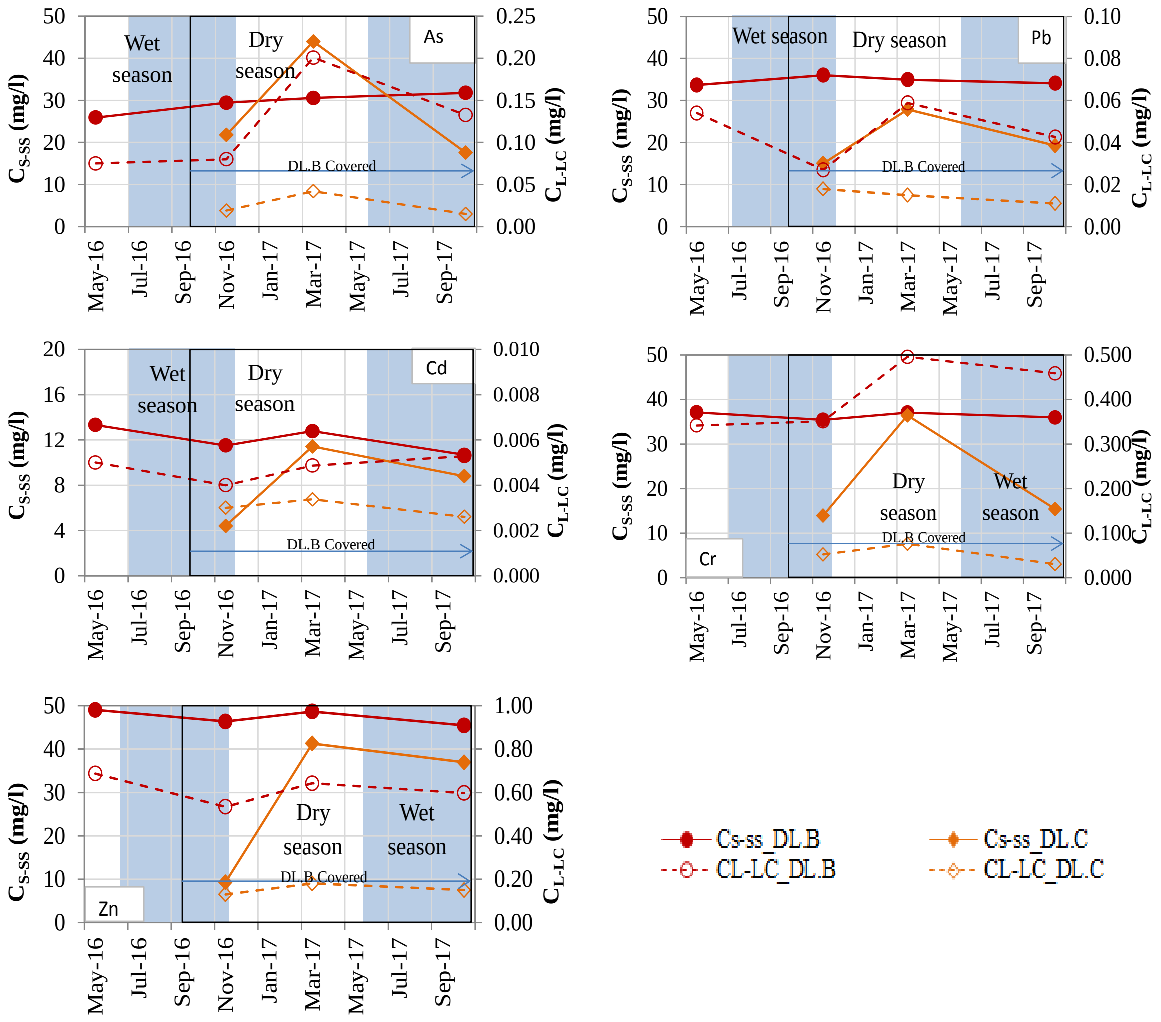


**Figure 4.24** HM Variation of Dangkor landfill

Figure 4.25 shows the monitoring data regarding HM contents and concentration of solid and liquid part of leachate for KM-32 landfill. The results show higher HM contents and concentration in the dry season than wet season, especially for fresh leachates. Even though the difference in the season has been confirmed in this landfill but the increase/decrease trends cannot be confirmed, it may due to the time of investigation is not long enough to see such kinds of trends.

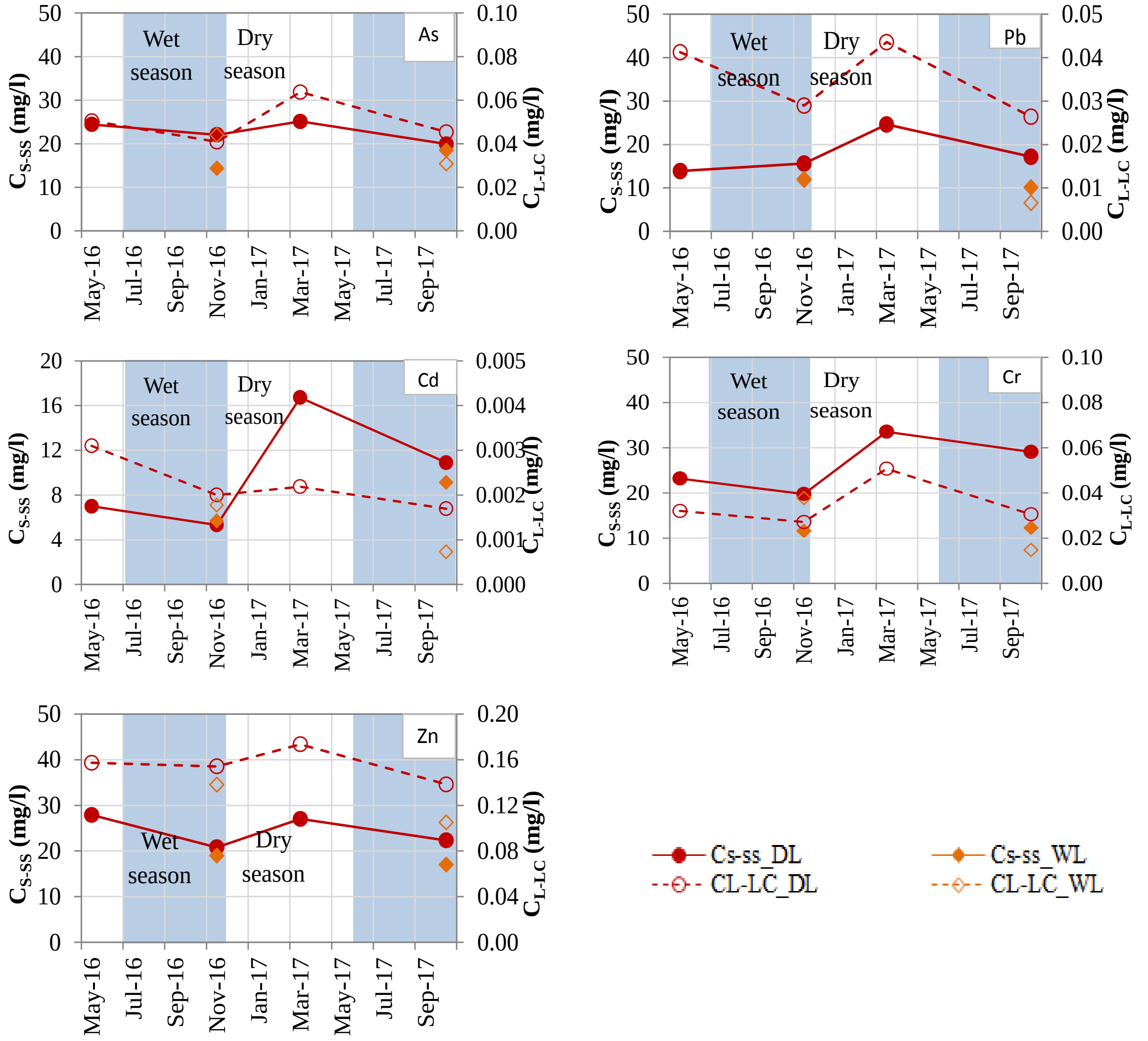


**Figure 4.25** HM Variation of KM-32 landfill

### 4.4.1.14 Comparison of Leachate Quality

The leachate qualities obtained in this study are compared to those reported for the other landfill sites in Table 4.2. In the table, site conditions such as waste age, waste thickness, landfill type, and dumping method are also shown. In terms of the basic parameters, COD and $BOD_5$, the Indonesian site Yusmartini et al., (2013) is similar to the KM-32 landfill, the Taiwanese and Philippine sites, Fan et al., (2006); Kusakube et al., (2009) are close to the Nonthaburi landfill leachate and Dangkor landfill area A-B, and the Indian site, Bashir et al., (2010) contains higher organic matter than the others but similar EC to that of the Nonthaburi and Dangkor leachates. Regarding the heavy metal concentrations, only one type of concentration was reported for each compared site on either filtered sample concentration, which is equivalent to the liquid part concentrations, or no specification was made regarding the type. Although the available data are very limited, the liquid part concentrations from the compared sites have the same range as those of the study sites. The unspecified concentrations at the Indian site are much larger than the liquid part concentrations of the other sites and in a similar range as the total HM concentrations of the study sites. However, in detail, relatively higher Pb and lower Cd were observed for the Indian site than the study sites.

Due to the lack of information on the influential factors and conditions, it is very difficult to identify the crucial factors on the leachate quality. However, it can be said that the continuing accumulation of the various leachate quality data together with site conditions is of vital importance for the improvement of solid waste management in developing countries.

**Table 4.2** Summary of the leachate quality of different landfills (units are in mg/L, unless specified)

| Parameter | Nonthaburi DL | Dangkor DL.B | KM-32 DL | Indonesia | Philippines | Taiwan | India |
|---|---|---|---|---|---|---|---|
| Age * | Mid | Mid | Young-Mid | Old | Old | Mid | Old |
| Waste Height (m) | 25 | 20 | 6 | - | 40 | - | 20 |
| Landfill type | Semi-sanitary | Controlled dump | Open dump | Open dump | Controlled dump | Semi-sanitary | Open dump |
| Dumping method | Trench method | Trench method | Trench method | - | Semi-canyon | Trench method | Trench method |
| pH | 7.3 ~ 8.0 | 7.9 ~ 8.3 | 7.0 ~ 7.9 | 6.8 ~ 7.5 | 7.9 | 7.3 ~ 8.4 | 6.9 |
| EC (mS/cm) | 20.3 ~ 38.8 | 15 ~ 40.6 | 3.2 ~ 14.5 | - | - | 7 ~ 40.6 | 24.5 |
| TDS | 6800 ~ 23500 | 8100 ~ 24800 | 2000 ~ 7000 | - | - |  | 27,950 |
| COD | 2050 ~ 7750 | 2100 ~ 7900 | 350 ~ 1080 | 290 ~ 350 | 6904 | 2480 | 27,200 |
| BOD$_5$ | 410 ~ 1230 | - | 120 ~ 200 | 145 ~ 218 | - | 26 ~ 492 | 19,000 |
| As (Liq) | 0.096 ~ 0.33 | 0.075 ~ 0.20 | 0.048 ~ 0.079 | - | 0.022 | - | - |
| As (Total) | 0.62 ~ 0.94 | 0.30 ~ 0.70 | 0.23 ~ 0.33 |  |  |  |  |
| Pb (Liq) | 0.03 ~ 0.10 | 0.012 ~ 0.074 | 0.016 ~ 0.057 | - | 0.04 | 0.0005 ~ 0.09 | 1.54 $^{\$}$ |
| Pb (Total) | 0.38 ~ 0.66 | 0.29 ~ 0.63 | 0.16-0.19 |  |  |  |  |
| Cd (Liq) | 0.0029 ~ 0.0048 | 0.0030 ~ 0.0050 | 0.0015 ~ 0.0042 | - | <0.003 | < 0.01 | 0.06 $^{\$}$ |
| Cd (Total) | 0.13 ~ 0.30 | 0.09 ~ 0.21 | 0.05 ~ 0.08 |  |  |  |  |
| Cr (Liq) | 0.32 ~ 0.44 | 0.034 ~ 0.49 | 0.02 ~ 0.15 | 0.04 ~ 0.05 | 0.11 | 0.12 ~ 0.52 | 0.29 $^{\$}$ |
| Cr (Total) | 0.71 ~ 1.02 | 0.62 ~ 1.10 | 0.19 ~ 0.38 |  |  |  |  |
| Zn (Liq) | 0.39 ~ 0.80 | 0.53 ~ 0.68 | 0.13 ~ 0.19 | 0.05 ~ 0.06 | - | 0.003 ~ 0.56 | 2.21 $^{\$}$ |
| Zn (Total) | 1.35 ~ 1.60 | 0.88 ~ 1.44 | 0.31 ~ 0.51 |  |  |  |  |

*: Young = age < 5 yrs; Mid-age = 5 < age < 10; Old = age > 10, $^{\$}$: no explanation of type of concentration
Note: Indonesia, Yusmartini et al., (2013); Philippines, Kusakabe et al., (2009); Taiwan Fan et al., (2005) and India- Bashir et al., (2010)

### 4.4.2 Influencing of Waste Thickness and Leachate Quality

Due to the different pit depth and waste height from the ground surface, each disposal sites has different waste thickness. Figure 27 shows the relationship between the waste height and the assessed parameters, such as TDS, chloride concentration (Cl), COD, and total HM concentrations (As, Cr and Zn). The waste heights were estimated from the data of three landfill sites as the average total waste thickness from the bottom of the pit to the top of the waste. The thickness of Area C in Dangkor changed as the depth of waste in the pit increased. The values of the all assessed parameters show good correlation with the waste thickness, namely, the larger the thickness is, the higher the concentration. Although there should be many other factors influencing the leachate quality, it can be said that the waste thickness is one of the important factors on the leachate quality.

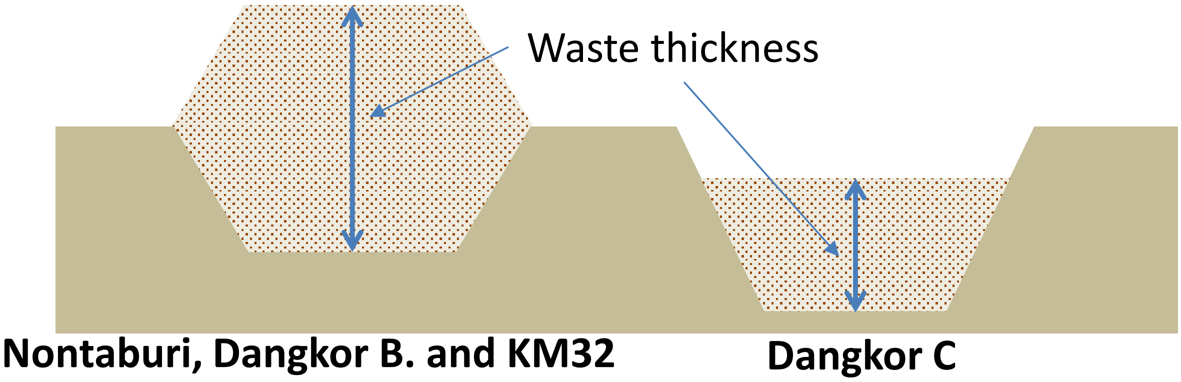
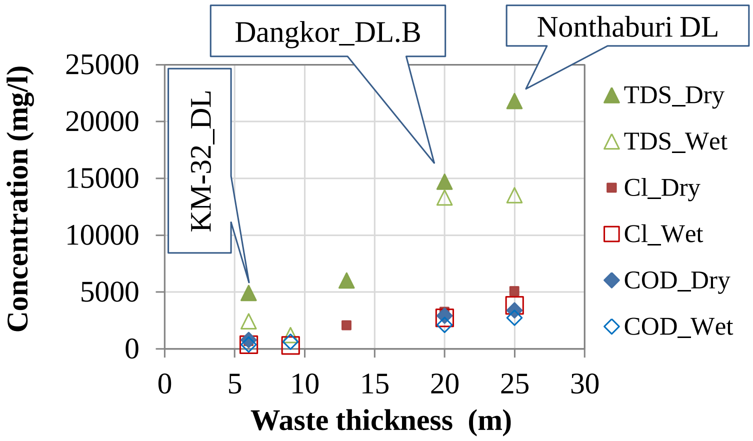
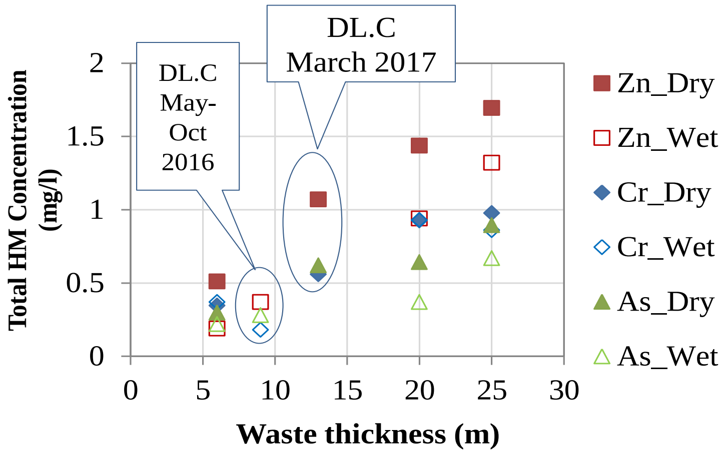


**Figure 4.26** Characteristics of Waste Pile Height



(a)

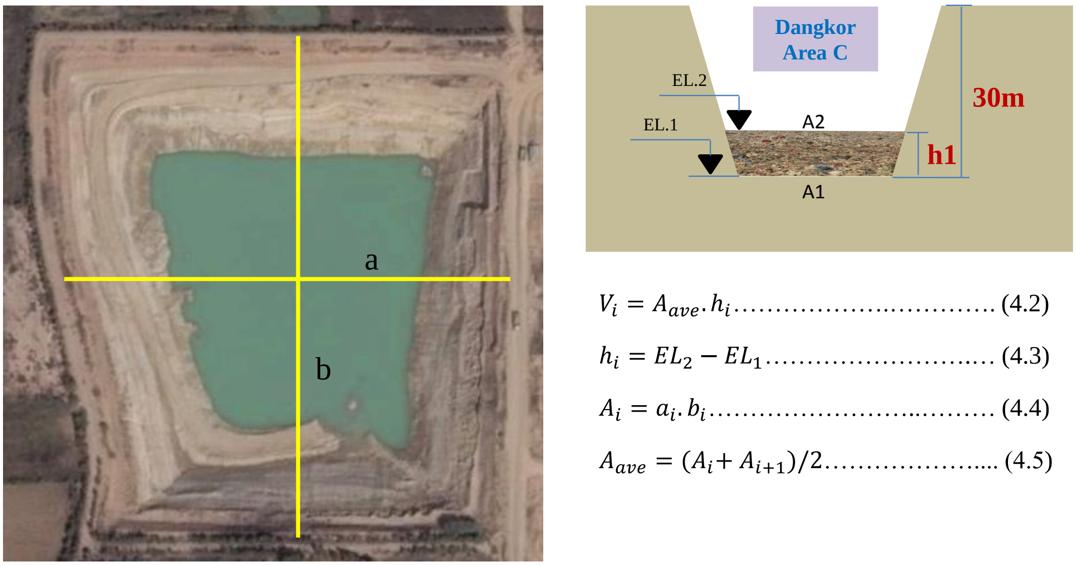


(b)

**Figure 4.27** Relationship: (a) Waste Height VS TDS-Cl-COD; (b) Waste height VS Total concentration of As-Cr-Zn

### 4.4.3 Deep Pit Disposal Variation in Time

Figure 12 shows the calculation information and methods; the observed data have investigated and collected during the field visits. The waste volume was calculated based on the Eq.2, while the supporting data was the combination of the measured, observed and GPS data as the height of waste inside the pit changed. As for the size and area estimation, the Google data and the size measured from the investigation together with the pit designed information was used, i.e., the designed slope of 1:1.5 and the shape size information



$$V_i = A_{ave}.h_i \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(4.2)}$$

$$h_i = EL_2 - EL_1 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(4.3)}$$

$$A_i = a_i.b_i \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(4.4)}$$

$$A_{ave} = (A_i + A_{i+1})/2 \ldots\ldots\ldots\ldots\ldots\ldots \text{(4.5)}$$

**Figure 4.28** Top plan and cross-section of area C for deep pit disposal of waste height and volume calculation

There are several times of site visit and investigations, in-situ measurements and sample collections at Dangkor landfill as pointed out in Figure 4.28-4.29. The graph shows the rapid increase of solid waste volume in the dumping area C, together with the increasing height inside the pit. The pictures of site situation for each time visit were included and explained how the dumpsite changed over time. It is clear evidence that the waste generation is very high rate because the huge pit (area C) was filled within the short time less than a two-year period. Even though the waste fire occurred in early time, big amount of solid waste was burned, but the dumped pit was filled up shortly, and the total amount of the waste is about 1.14M $m^3$(Million cubic meters). Also, as observed during the latest field visit (October 2017), area D has been filling up about 5-6 m depth, and the solid waste volume was about 250,000$m^3$, meaning the total volume of solid waste in this period was about 1.4M $m^3$. It is due to the improper solid waste separation and management for both at the source and site of this area.

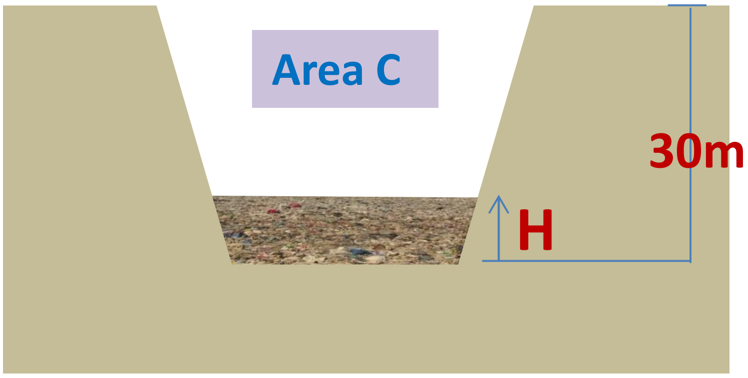


**Figure 4.29** Waste height observed at area C of Dangkor landfill

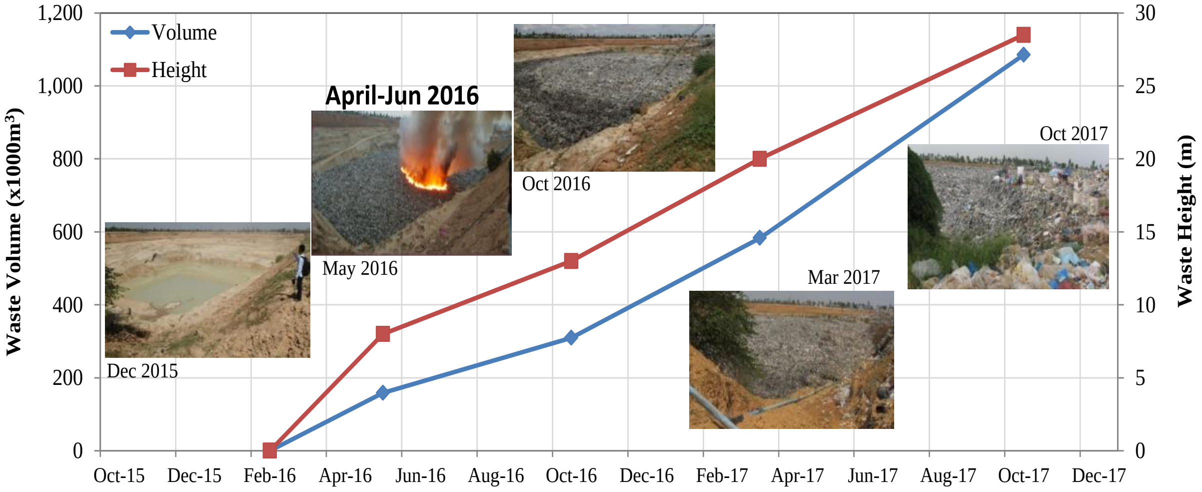


**Figure 4.30** The change over time of area C of Dangkor landfill

### 4.4.4 Sediment

#### 4.4.4.1 Physical Property

Sediment samples were collected at the DL and LDP sampling points of the Nonthaburi landfill and the DL.B sampling points of the Dangkor landfill. As in the KM-32 landfill, there was no cover soil placed on the waste and no sediments accumulated in the dumping area; the sediment samples were only collected at the natural wetland (WL). The particle size distribution and organic contents of the sediment samples were measured by sieve analysis and the ignition loss test. The same set of heavy metals (As, Pb, Cd, Cr and Zn) as measured for the total and liquid part of the leachate were also investigated for the sediments. Figure 4.30 shows the fractions of organic and non-organic matter and the fine and coarse particles of the sediments. The organic contents were about 9–10% for the DL samples of the Nonthaburi and Dangkor sites and the WL sample of the KM-32 site, while it was 17% for the LDP samples of the Nonthaburi landfill. These organic contents are much smaller than those in the SS of the leachate (Figure 4.18b). The fine particle fraction of the Dangkor landfill sample was the lowest, at about 50%. The erosion of the new cover soils of Area A-B, containing a relatively large sand fraction, is the reason for the low fine particle fraction. Nonetheless, all sediment samples contained quite a significant amount of fine particles, at more than 50% as for the lowest case. This large fine particle content could be a cause of high heavy metal adsorption in the sediment due to the large surface area of the interface, Parizanganeh (2007).

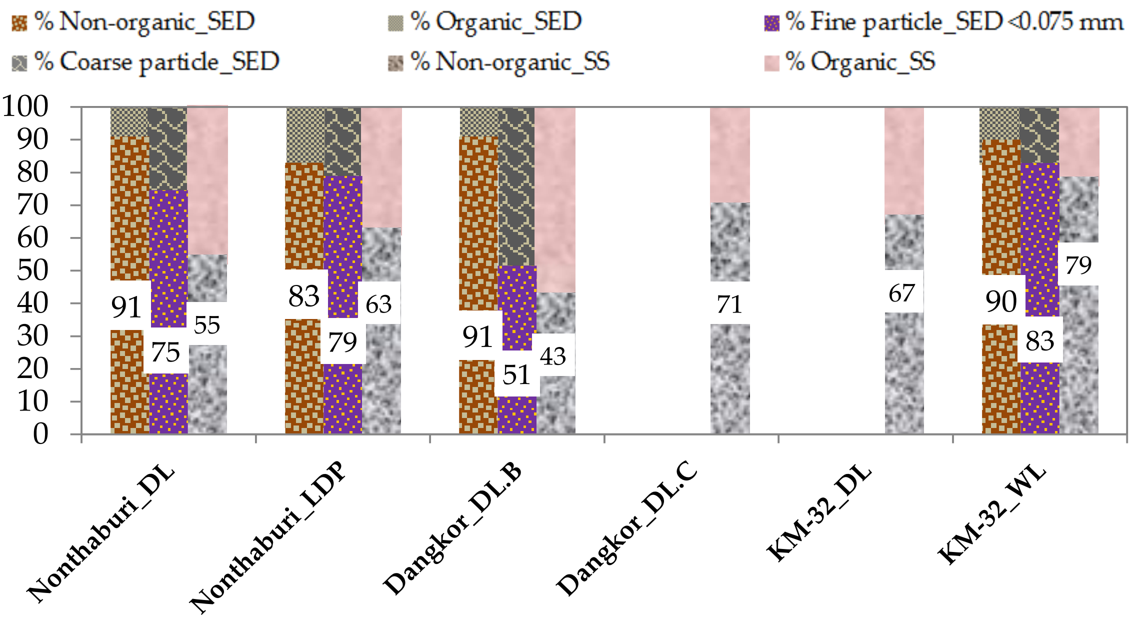


**Figure 4.31** The physical property of sediment and suspended solids

### 4.4.4.2 Heavy Metal Contents

Figure 4.31 presents the heavy metal contents ($C_S$) of the sediment samples together with that of the suspended solids of the leachate (SS) for comparison. All HM contents of the sediments were higher than that of the suspended solids, about 1.5–5 times, except for arsenic, which was about 1.2–1.5 times higher. The sediments contained a relatively large amount of fine particles, as discussed above section, which could capture HMs better than the SS of the leachate. Also regarding the sediments, the highest contents for most of the heavy metals were observed for the DL sampling points at the Nonthaburi site. However, as a general trend, the differences in the HM contents of the sediment and the SS were larger for the LDP and WL samples than the DL samples, both in the Nonthaburi and KM32 landfills. This could be attributed to the accumulation effects in the leachate storage. As a result, the differences in the HM contents in the sediments between the sites, as well as the locations, were smaller than that of HM contents of the SS.

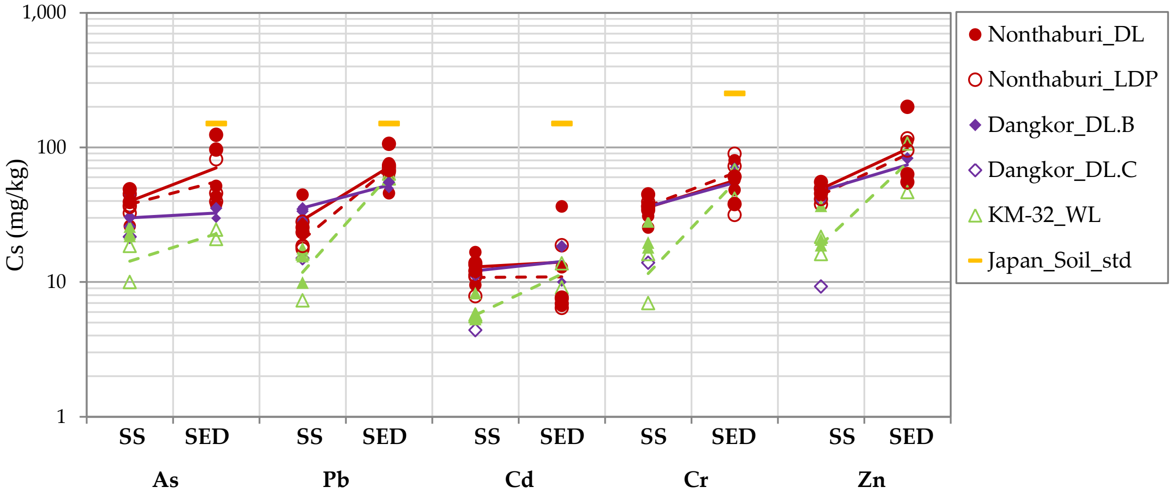


**Figure 4.32** The heavy metal content of suspended solids of leachate (SS) and sediment (SED)

Since the large areas of the leachate storage pond exist in Nonthaburi landfill (LDP), the massive volume of contaminated sediments will be caused a problem in the future. Therefore, the treatment or removing of the sediments should be considered after the closure of the landfills.

### 4.4.5 Comparison of HM Contents

All the observed HM contents of the sediment were lower than the limit specified by the Soil Contamination Countermeasure Act of Japan, SCCA (2007), which is shown as "Japan_Soil_std". Similarly to the HM contents of the SS (Figure 10), no evident seasonal change was confirmed in the sediment, as was also discussed in a previous study, Olubunmi et al., (2010). The observed ranges of HM contents in the SS and sediments are summarized in Table 4, with the reported range of HM contents in the normal soils, Bradl (2005). Almost all the observed HM contents are in the range of normal soil, except for Cd, which was larger than the normal soil. The relatively high organic contents compared to the normal inorganic soil could be a possible reason for the large Cd content.

**Table 4.3** The HM contents of this study and commonly found in normal soils (ppm)

| Heavy metal | Nonthaburi landfill | | | | Dangkor landfill | | KM-32 landfill | | Normal soil | |
|---|---|---|---|---|---|---|---|---|---|---|
| | DL_SS | DL_SED | LDP_SS | LDP_SED | DL.B_SS | DL.B_SED | DL_SS | WL_SED | Ave | Range |
| As | 26-45 | 37-52 | 32-37 | 39.5 | 25-31 | 29-36 | 22-26 | 21-25 | 7.2 | 0.1-55 |
| Cr | 25-43 | 48-80 | 35-37 | 72.4 | 35-37 | 38-71 | 18-28 | 42-68 | 40 | 10-150 |
| Pb | 24-44 | 45-76 | 17-17.6 | 66.2 | 29-40 | 50-55 | 9-18 | 59-64 | - | 2-300 |
| Cd | 10-16 | 6-36 | 7-13 | 18.7 | 8-15 | 10-18 | 5-8 | 9-13 | 0.35 | 0.001-2 |
| Zn | 43-51 | 53-110 | 37-50 | 116.2 | 46-49 | 64-83 | 18-37 | 46-107 | 90 | 1-900 |

The large leachate storage pond in the Nonthaburi landfill (LDP) could accumulate a massive volume of contaminated sediments at the bottom, which could be a source of contaminants in the future. For the proper estimation of the future risk associated with the sediments, quality and quantity investigations are necessary, including a TCLP (toxicity characteristic leaching procedure), US EPA Test Method 1311 (1992) of the sediments. Then, depending on the evaluated risk, the treatment or removal of the sediments would be a main concern, together with the treatment of a huge volume of the leachate stored in the LDP for the rehabilitation of the Nonthaburi landfill site after the closure of the landfill

### 4.5 Principal Component Analysis

The principal component analysis (PCA) was also applied in this study, to see how the assessed parameters of leachates and sediments correlated to each other. It is the additional points of view apart of one-one correlations have been presented in earlier sections. The PCA theories and equations using in this study are same as previous books written by Petter J. Swaw, (2003) and Jolliffe, (2002). On the other hands, to get the PCA results as combining of many parameters in the same figure which will present in the later sections; R-language version 3.5.1 together with the RStudio version 1.1.456 was used as tool to generate those correlations and related linkage behaviors.

#### 4.5.1 PCA of Leachate

Figure 4.32 and Figure 4.33 shows the combination of basic parameters and total HM concentration of all three landfill leachates, respectively. The graph shows the close correlation between pH, TDS, COD, Corg, Cl and $BOD_5$ and no correlation to turbidity. However, this group of parameters has a negative correlation to the ORP. At the same time, the graph also shows the samples distinguish between the landfill samples. The results from this analysis confirm the magnitude order between the landfill for the basic parameter as lowest concentration for the KM-32 landfill and higher for Nonthaburi landfill with a similar level to the Dangkor DL.B.

As for total HM concentrations showed in Figure 4.33, there was a low correlation with the pH and organic concentration in this study. However, all of HMs has similar concentration level and some correlation.

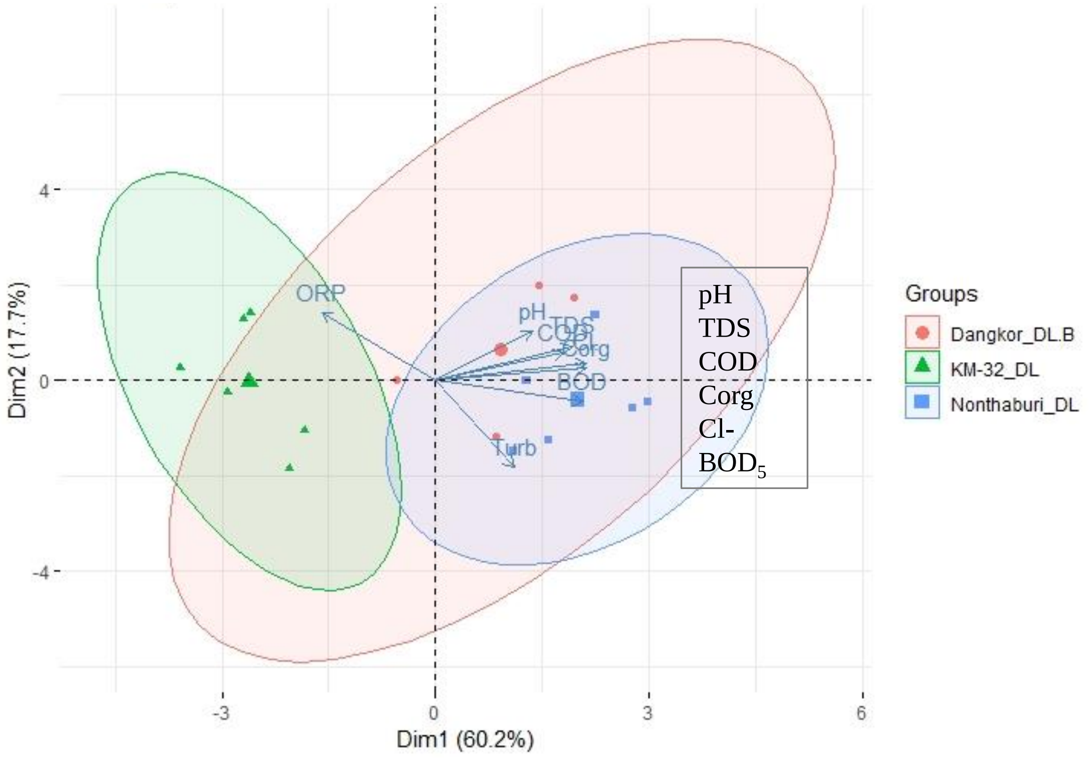


**Figure 4.32** The combination of all three landfill leachates for basic parameters

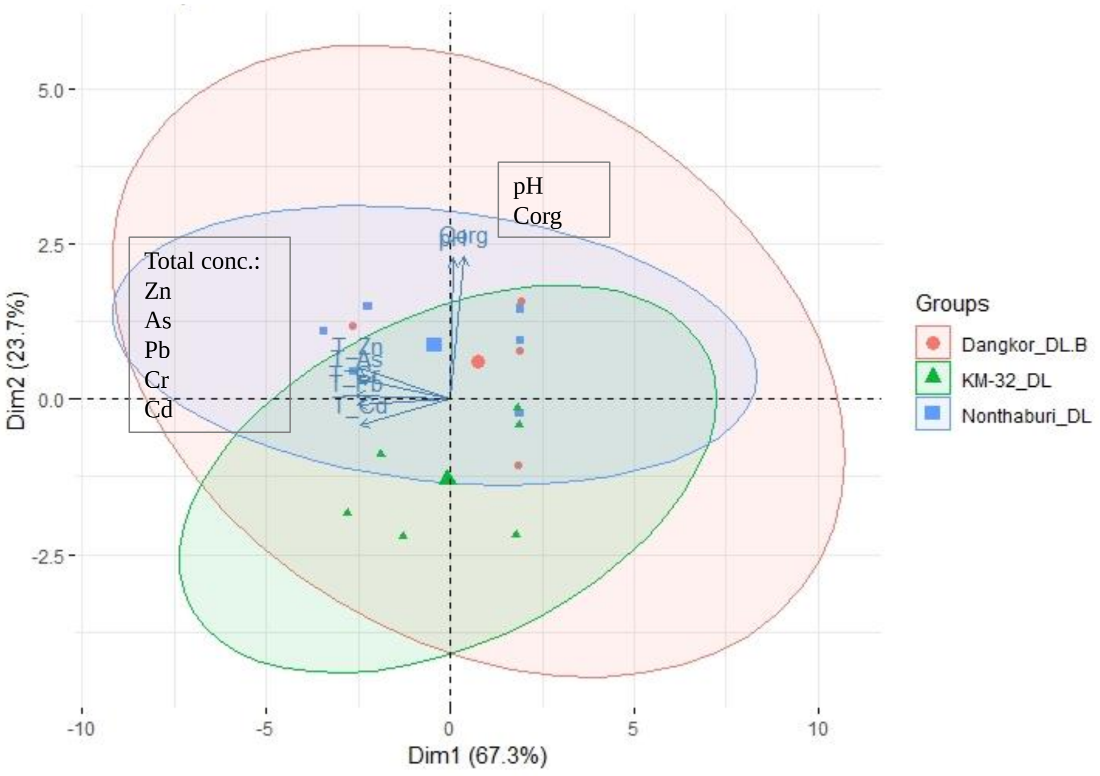


**Figure 4.33** The combination of all three landfill leachates for heavy metals

In the detailed results of each landfill site for this study, Figure 4.34, Figure 4.35 and Figure 4.36 show the site separation of basic parameters as of Nonthaburi, Dangkor, and KM-32 landfill, respectively. Nonthaburi landfill shows some correlation similar to the combining data of all three landfill with a slight difference in negative correlation of Cl and pH to those parameters as show the higher concentration found in LDP samples, while ORP is the same trend as combination data due to the negative recharge of ORP for DL samples. As for the major parameters DL samples have higher concentration compared to LDP as confirmed in the previous sections. Dangkor landfill results also show the similar trend to the combined data of three landfill sites and show a different level of contamination between DL.B and DL.C samples as already confirmed in the previous sections that DL.B has the higher concentration for all parameters. The KM-32 landfill shows low correlation between the basic parameters as we can see the scatter points have been found in the previous one-one correlations due to unstable condition at the landfill site. And very few data point for the wetland as sample collection was not able to collect in the dry season because the dry up of leachate in the wetland and less leachate reduction in the landfill area.

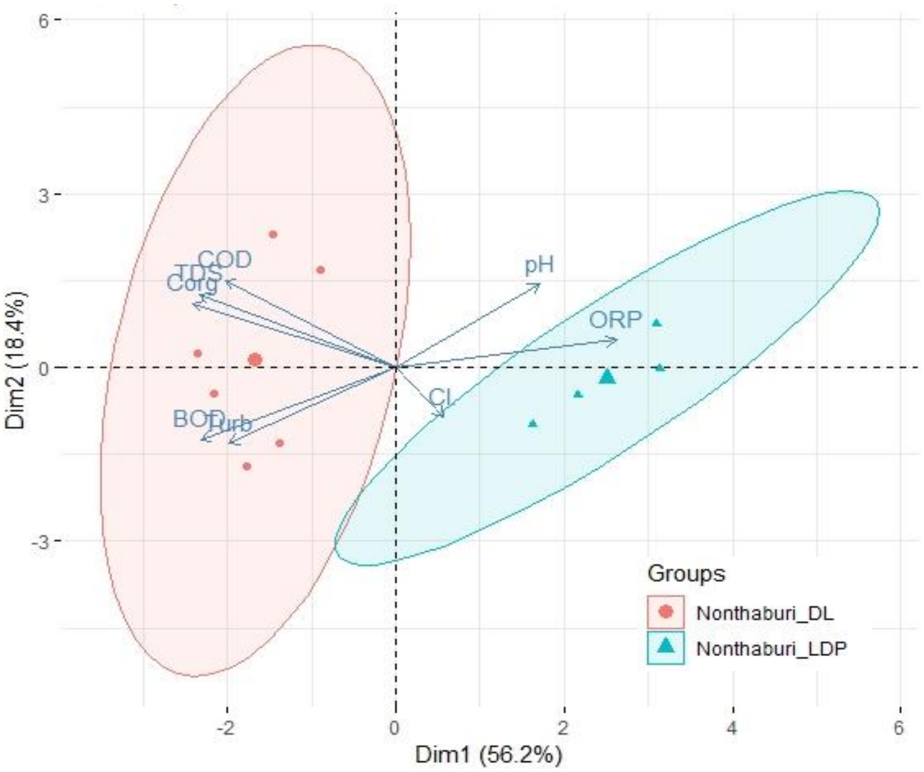


**Figure 4.34** The combination of basic parameters of Nonthaburi landfill

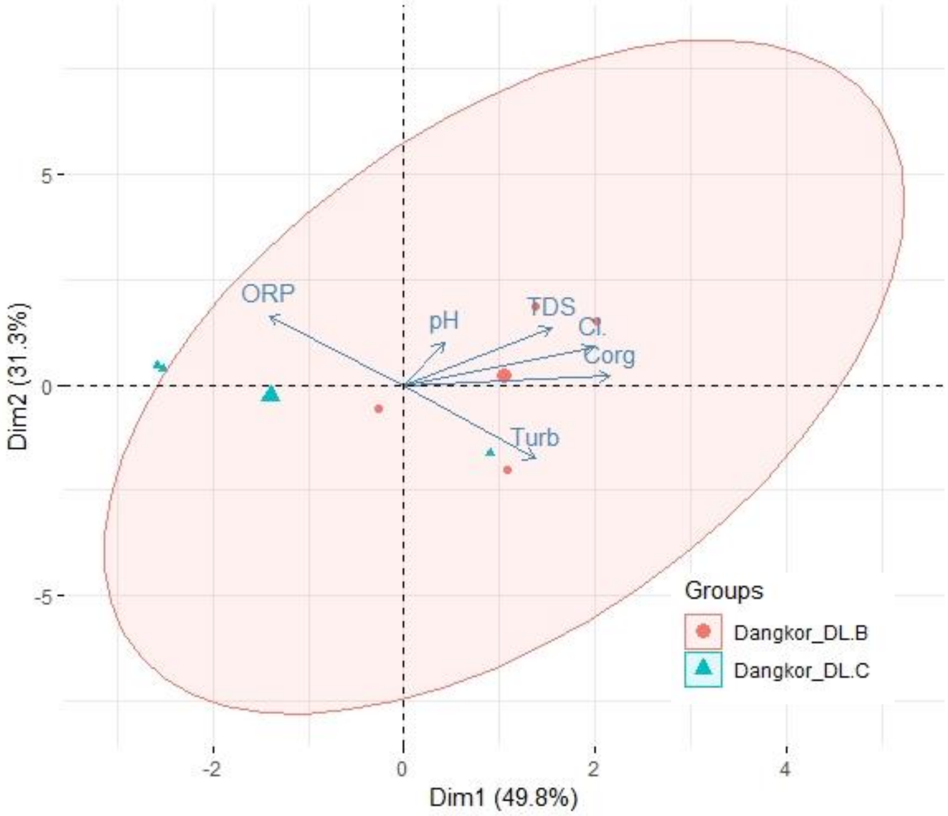


**Figure 4.35** The combination of basic parameters of Dangkor landfill

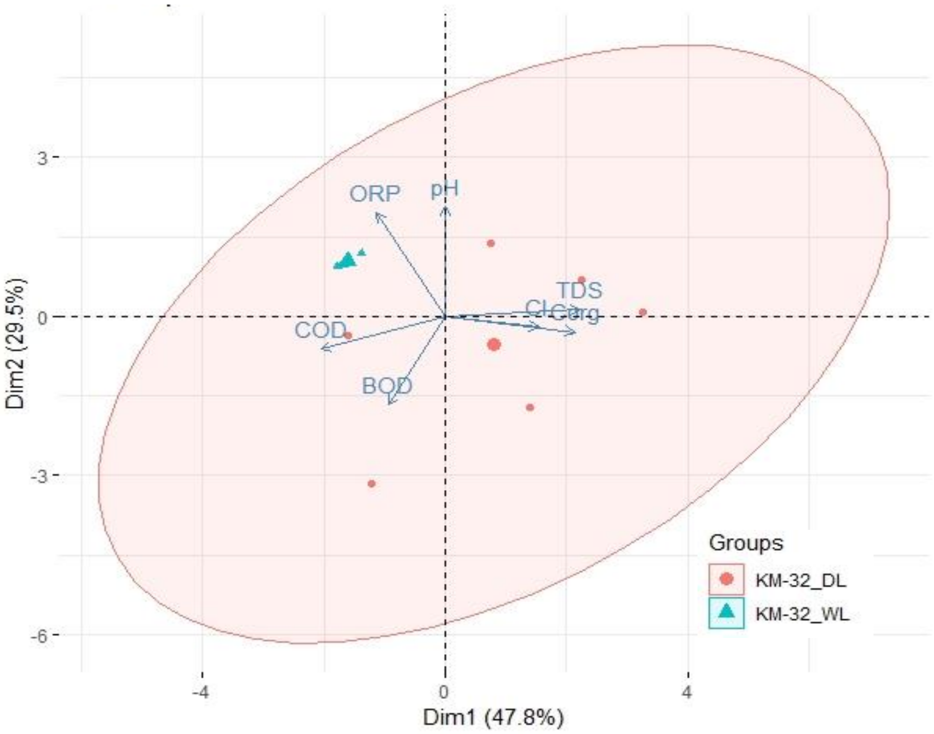


**Figure 4.36** The combination of basic parameters of KM-32 landfill

Figure 3.37 shows the correlation of dissolved heavy metal concentration of Nonthaburi landfill as the confirmed result of the analysis. Similar to the total heavy metal concentration found in the combination data for all three landfills; all the HM concentrations have a similar level and some correlation with each other but the negative relationship to the pH, while the level difference between DL and LDP has been confirmed in this graph.

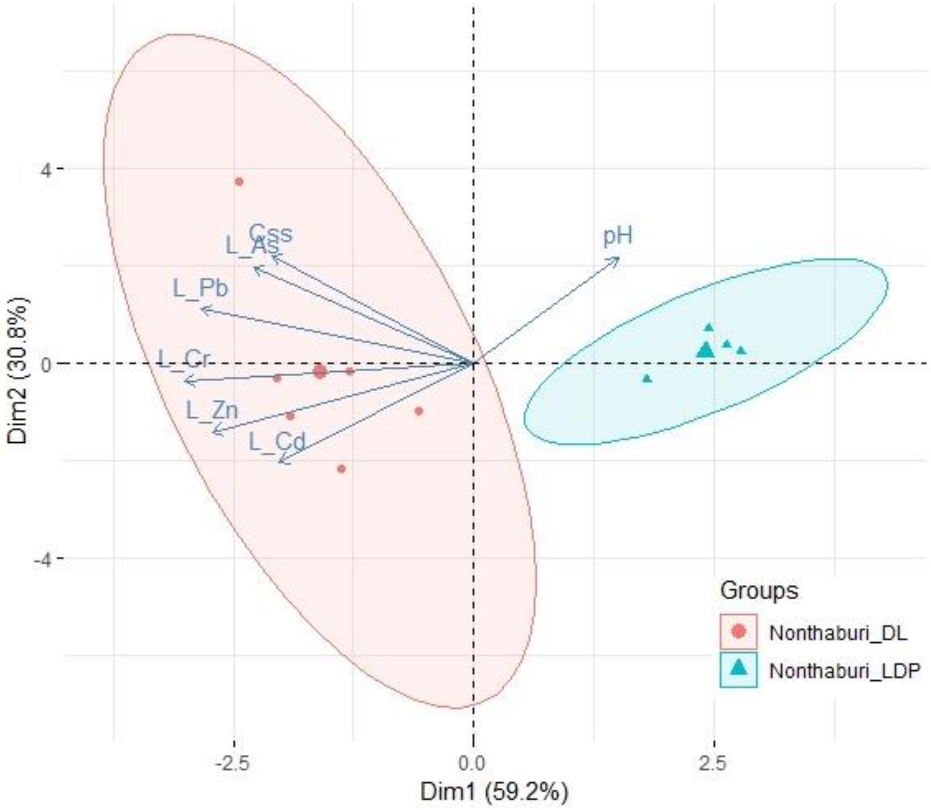


**Figure 4.37** The combination of dissolved heavy metals of Nonthaburi landfill

### 4.5.1 PCA of Sediment

Figure 4.38 shows the results of PCA of sediments of three landfill sites, with the limit number of the sediment samples the grouping of sample separation could not be made. However, some correlations can be observed among the HM contents and to the organic concentration, but higher correlation could be confirmed for the percent of particle fineness as compared to organic content.

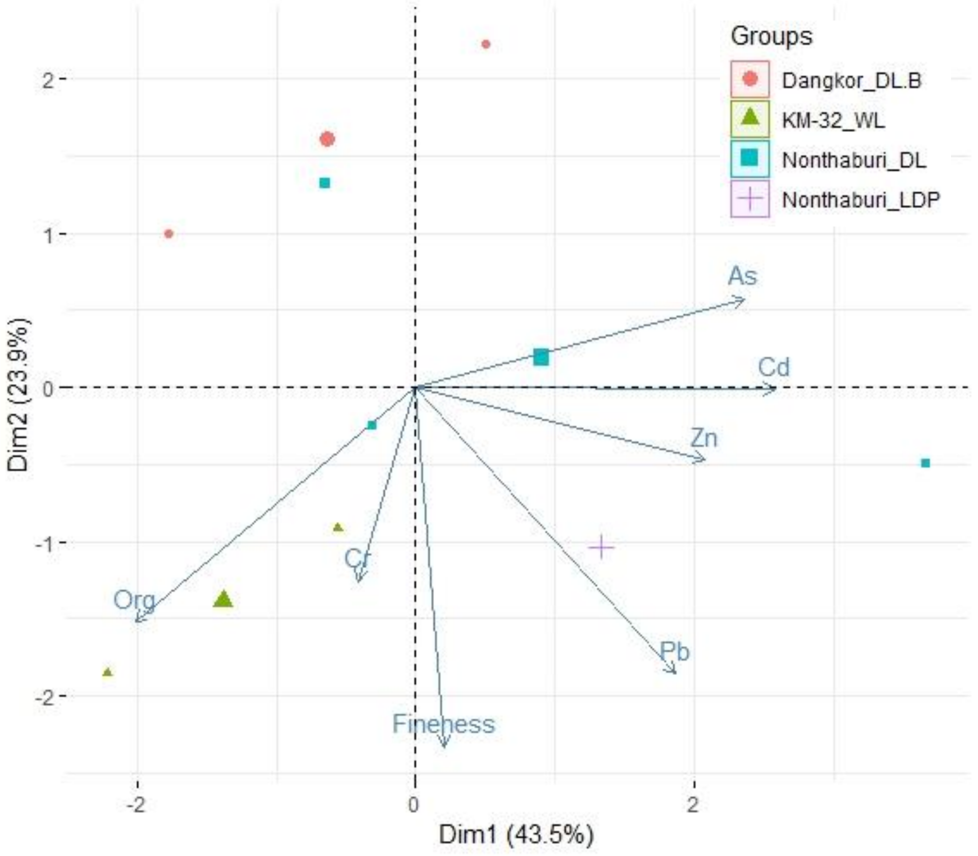


**Figure 4.38** The combination of all three landfill sediments

## 4.6 Conclusion

Leachate and sediment samples were collected from three tropical landfills in Indochina peninsular countries—Nonthaburi province landfill in Thailand, Dangkor landfill, Phnom Penh City in Cambodia, and the KM-32 landfill, Vientiane City in Laos and assessed by in-situ and laboratory measurements. The landfills have received similar waste through the same disposal method, i.e., excavated deep pits on the low permeable geological barrier. The key findings from the study are listed as follows:

(1) Most of the basic biological and chemical parameters of the fresh leachates showed higher concentrations in the dry seasons than in the wet seasons, while no significant seasonal variations were found in the samples taken from a large leachate pond. Most of the parameters showed high concentration compared to the industrial effluent standard, especially the leachate from the Nonthaburi landfill and the Dangkor closed landfill.

(2) Positive correlations of the leachate quality parameters are confirmed for both the physical and chemical properties, such as suspended concentration ($C_{SS}$) and solid

concentration ($C_{solid}$), organic content ($C_{org}$) and $C_{SS}$, chloride concentration and TDS, $BOD_5$ and COD, COD and TDS, and COD and $C_{SS}$.

(3) The total heavy metal concentration of the leachates was about 2 to 50 times larger than the dissolved heavy metal concentrations in the liquid part of the leachates, implying that the major part of the heavy metal (HM) contents in the leachates, about 50 to 99%, are partitioned in the suspended solids.

(4) The total and the dissolved liquid part HM concentrations of the leachates are several times higher than the industrial effluent and groundwater standard, respectively, suggesting that there are risks of surface water and groundwater contamination under the current landfill management practices, for example, no leachate collection or treatment facilities and high leachate levels in the deep disposal pit. However, considering the fact that a significant portion of the heavy metals in the leachates is partitioned to the suspended solids (SS), simple physical filtration or sedimentation of the SS from the leachate could significantly decrease the total HM. Such a simple treatment could reduce the pollution risk to the surrounding water and soil.

(5) The partitioning of heavy metals on the suspended solids of the leachates is affected by many factors. Although clear isotherm could not be obtained from the relationship between the liquid part HM concentration and the SS part HM contents, mainly due to the unknown conditions of the SS and the adsorbing process, the effect of the liquid part concentration, type of HM, and organic contents can be confirmed from the various measurements.

(6) No significant seasonal variations of HM contents was observed for the sediment and the suspended solids of the leachate. The heavy metal content per unit solid mass was about 1.2–5 times higher for the sediments than the suspended solids. Considering the large volume of sediments and relatively high HM contents, the sediments could be a future risk of groundwater contamination, especially for the large leachate discharge pond on the Nonthaburi landfill site.

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# Chapter 5

# Groundwater and Surface Water Characterization

This chapter will discuss the characteristics of groundwater and surface water from the nearby areas of study landfill sites. The chapter also presents the site conditions which are linked to the qualities of surface and groundwater.

## 5.1 Introduction

The municipal solid waste management is one of the existing unsolved problems in the developing countries. Those countries have been facing a linear increase of municipal solid waste and waste management problems, especially the environmental risk by the landfill leachate. Additional land is needed for the ultimate disposal of these solid wastes, and issues related to disposal have become highly challenging for most countries, Idis et al., (2004). Landfill leachate is the liquid residue resulting from the various chemical, physical and biological processes taking place within the landfill. The leachate could be a primary source of various contamination and pollution to the surrounding environments, e.g., surface water and groundwater in particular. The leachate is generated mainly by excess rainwater percolating through the waste layers in a landfill. The leachate problem has been worsened by the fact that many landfills in developing countries lack appropriate landfill facilities, such as bottom liner, leachate collection, and treatment system, which increases the possibility of groundwater and surface water contaminations, Kanmani and Gandhinmathi (2013). Hazardous substances in MSW are presented in the form of paints, mercury-containing wastes, batteries, pharmaceuticals, vehicle maintenance products and many other diffuse products, El-Fadel et al., (1997). Heavy metals are one of the common non-degradable pollutants found in the leachate, of which continuous accumulation could cause an acute risk to human and public health, Slack et al., (2005). The leachate quantity and quality depend on site conditions, such as weather and geological conditions, the waste composition and age, waste disposal practice, Bashir et al., (2009).

## 5.2 Objectives

- To investigate the groundwater and surface water quality for both physical and chemical properties.

- To assess the influence of contaminated leachates to surface and groundwater of surrounding landfill areas.

## 5.3 Methodology

The general processes of all assessments are the same process to the leachate characterization as presented in chapter 4. The method was started with the site investigation; identify the groundwater location which can be used as measured points of influenced contamination of the groundwater. It was mainly based on the existing wells of each landfill site. The potential surface water contaminated from the landfill leachates, the Dangkor landfill and KM-32 landfill sites have a high chance, due to the uncontrolled release of leachate to surrounding areas were observed during the field sampling and site investigation.

The following details of the process for the current chapter will be presented and described in below sections.

### 5.3.1 Sample Location and Description

The sampling period and the number of sampling collections were the same with leachate and sediment samples. There were five fieldworks at Nonthaburi landfill from 2015 to 2018 (Two times for wet season and three times for dry season). Also, there were five field visits to Dangkor landfill from 2015 – 2017 (two times in wet and three times in dry seasons). Simultaneously, four field visits and investigations at KM-32 landfill were also conducted (two times for both wet and dry seasons). The details of groundwater and surface water are described in the following sections.

#### 5.3.1.1 Nonthaburi Landfill

At the site of Nonthaburi landfill, two of the observation wells name as OSW1 and OSW2 were used as the observed points of the closest distance for the potential groundwater contamination by the landfill leachate. As for the further distance, one groundwater sampling well was selected to assess the current leakage of leachate contamination. The well is used for the community water use with the 900m away from the landfill area E. The detailed locations of the sampling points are shown in Figure 5.1 with the combination of leachate sampling points as a source of contamination.

Figure 5.2 shows the cross-sectional profile and surrounding environments of OSW1, which is quite a significant condition regarding the well location. The OSW1 is located close to old dumped pit on one side while another side is old leachate pond with the distance of about 5m from both of old dumped pit and old leachate pond. The depth of the old pit is about 6-7m below the ground surface while the pond 2 is about 3-4 m. The well depth is about 30m with the depth of clay layer is about 21m from the ground level, while the sand layer as aquifer layer is from 21 m, KRUNGTHEP GROTECHNIQUE Co., Ltd (2013). Within these conditions, the potential leakage of contaminant to the well may not come from the groundwater interaction but it may leakage via the horizontal leakage.

At the same time, Figure 5.3 shows the cross-sectional profile and the condition of OSW2, which is another significant change due to OSW2 located on the dike as pit edge of the active landfill (area E). Since dumped pit of area E has a significant depth of about 15 m as the shallowest and the deeper part, the depth mays up to 18m. According to the site engineer, this landfill was started as an engineered landfill, geomembrane has been placed but there might be several leakage holes due to the improper placing, and some evidence of broken geomembrane can be seen at the site. However, OSW2 was removed by some activities and no further assess from Oct 2016.

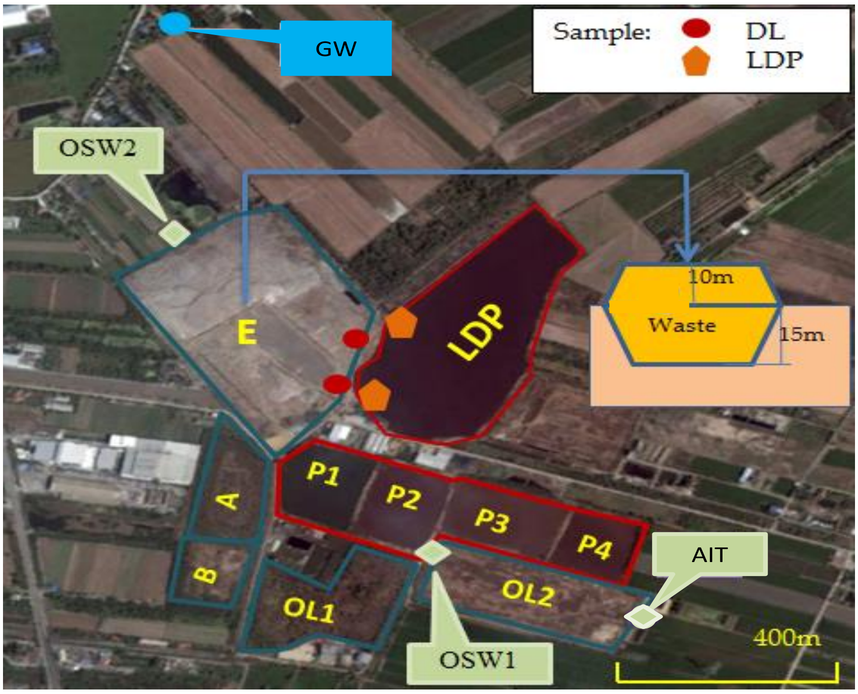


**Figure 5.1** Groundwater sampling point locations of Nonthaburi landfill

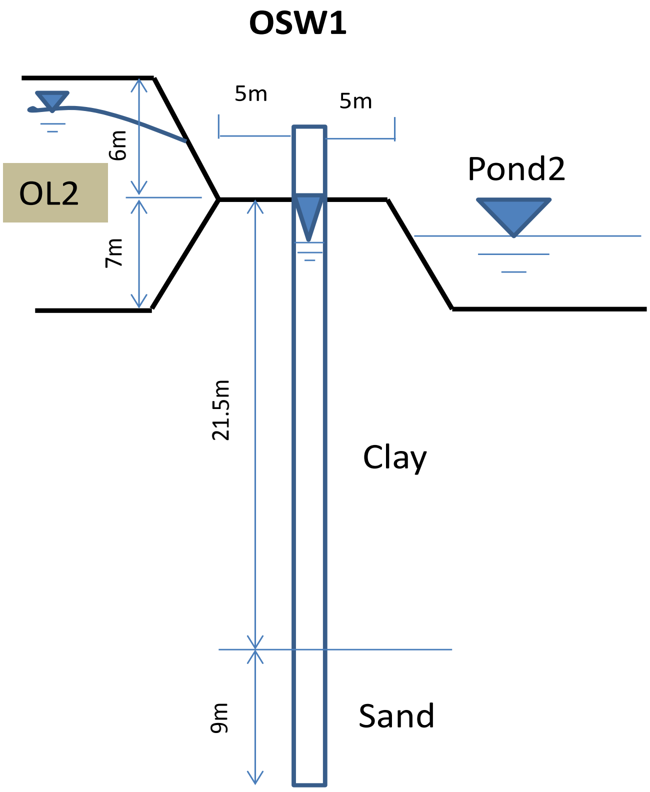


**Figure 5.2** The observation well 1 (OSW1) conditions and profile

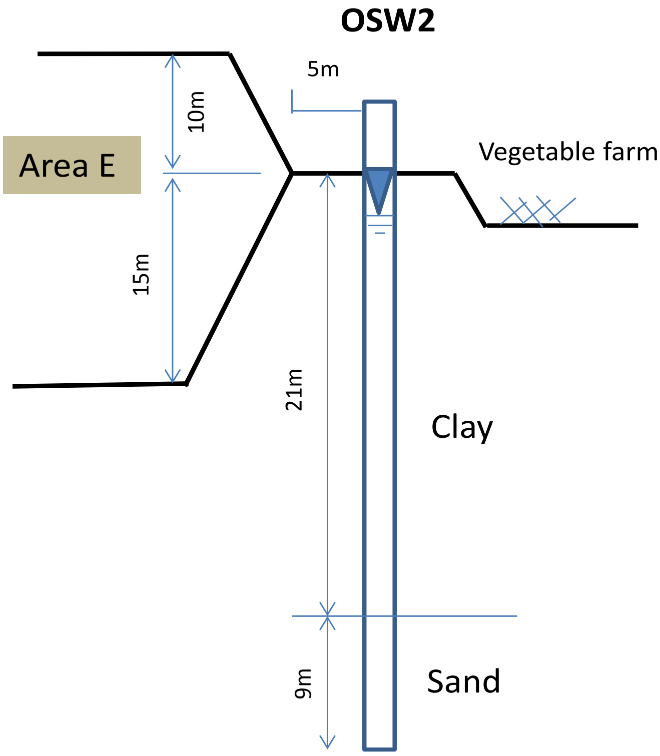


**Figure 5.3** The observation well 2 (OSW2) conditions and profile

#### 5.3.1.2 Dangkor Landfill

At the Dangkor landfill, the existing wells were identified and used as the groundwater monitoring in this study as shown in Figure 5.4. One well is inside the landfill close to areas A-B named as GW1 while another is located on the downstream side about 1 km from the dumped pit (areas A-B) called GW2. As an observation, Dangkor landfill has been released the fresh leachate, especially from closed areas A-B. At the front side, the leachate was directly recharged to the natural creek, while at the back side fresh leachate was also recharged to the large pond as a natural wetland. Therefore as for Dangkor landfill, 3 points of surface water have been investigated for the influence of the landfill leachate. The surface water samples were named as SW1, SW2 and SW3 for the first point at the upstream of released of fresh leachate to the creek (SW1), while the SW3 is downstream of the creek about 900m from the SW1, and SW2 was at the wetland of backside release of the fresh leachate.

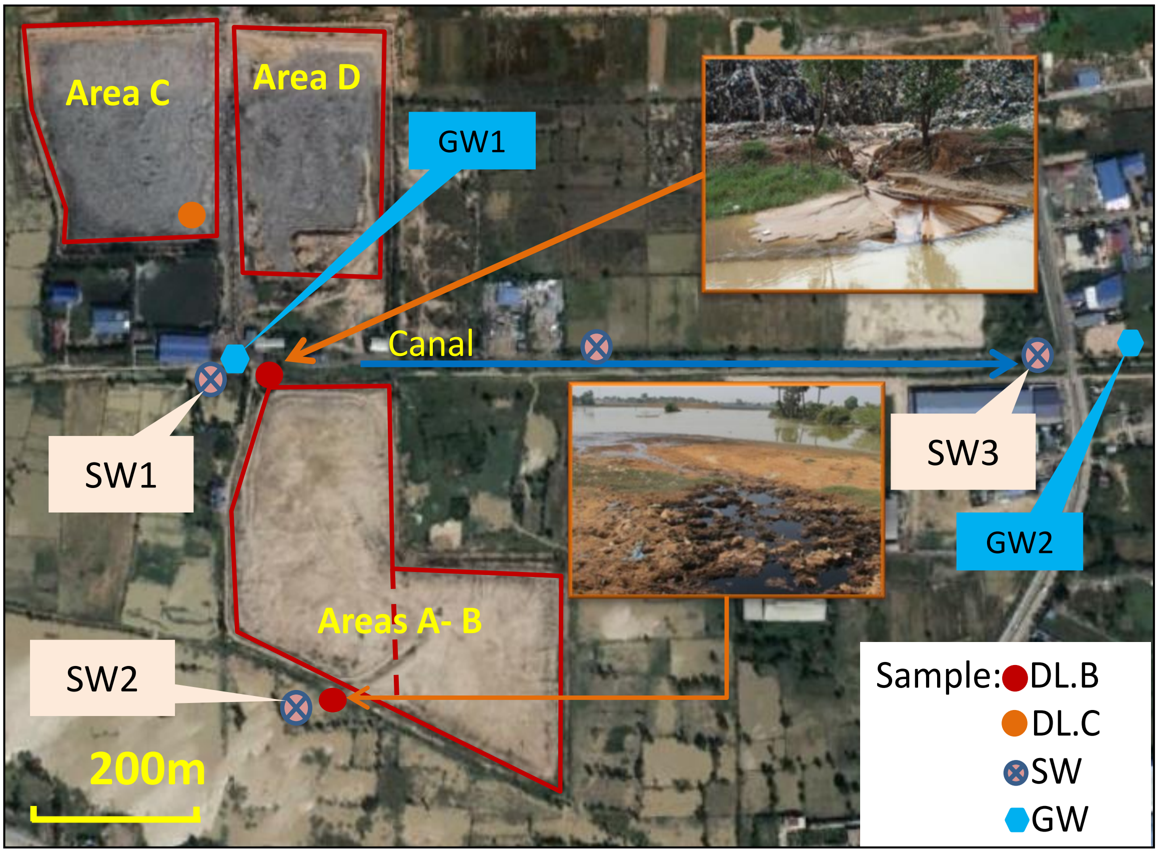


**Figure 5.4** The locations groundwater and surface water sampling points of Dangkor landfill

#### 5.3.1.1 KM-32 Landfill

Figure 5.5 shows the groundwater sampling point locations. There are four existing water wells around the landfill, and these wells were selected to use as groundwater sampling points as for observation the leakage of leachate contamination to surrounding groundwater. GW1 is the nearest existing groundwater about 400m from the segment number 2 and GW2 is about 600m. For the other two groundwater wells are located outside the landfill area; GW3 is located at the backside or downstream side of the landfill as compared to surface water direction about 800m and GW4 is located in the front side about 900 m to the dumping area. The well depths in this area are about 35-40m according to the well owners but no proper information about the aquifer or the depth of water table. On the other hands, the landfill leachate was also direct recharged to the lower area at the backside especially in the wet season, but none of surface water sampling point could be selected due to the complicated of the area and also the low contamination level of this landfill. However, as long-term recharge and accumulated at the agricultural area at the backside, the potential increase in the level of contamination in the soil will be raised.

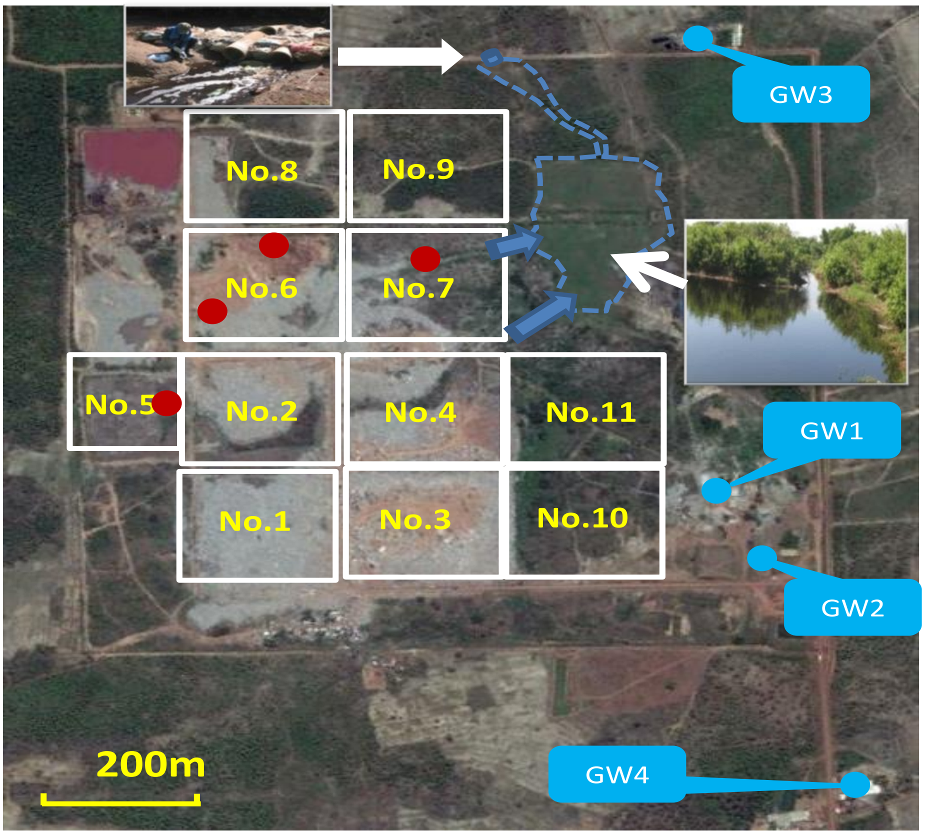


**Figure 5.5** Sampling location of groundwater of KM-32 landfill

### 5.3.2 In-situ Measurement

The basic parameters were measured at the site to assess the groundwater and surface water quality as essential evaluation parameters, such as temperature, pH, ORP, EC, Turb, DO, TDS, and Salt. The in-situ measurements were done by using Multi-parameter Water Quality Meter "HORIBA-U50" for those mentioned parameters. At the same time, to confirm the sampling location, GPS photo tagger and Garmin Oregon 64st were used in this study.

### 5.3.3 Laboratory Measurement and Calculation

The surface and groundwater samples taken from those 3 landfills were used to measure the heavy metal concentration. The samples were filtered by using syringe filter with 0.45 μm pore size, then analyze for the HMs (As, Pb, Cd, Cr and Zn) by using ICP-AES (Inductively Coupled Plasma - Atomic Emission Spectrometry). Besides, SALMATE 100/W was also used to measure the chloride (Cl) concentration.

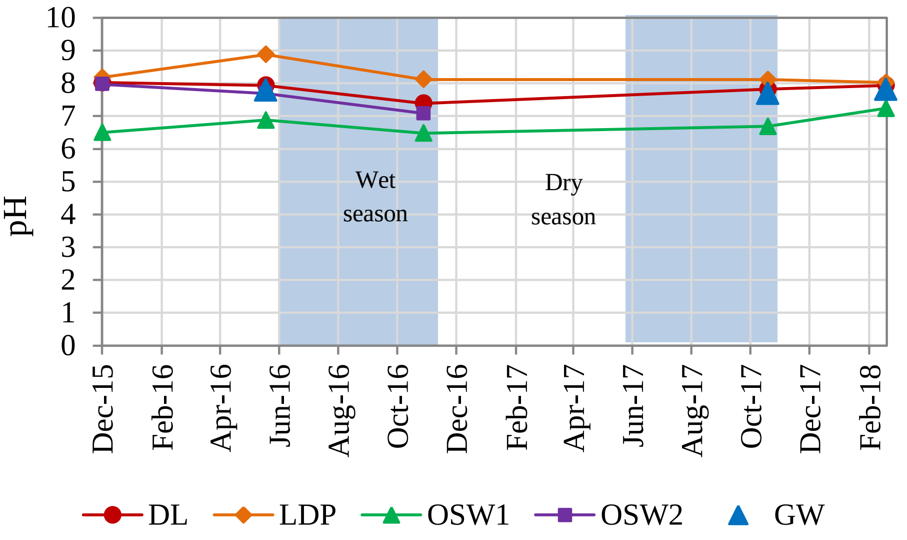
## 5.4 Results and Discussions

The results of the measurements in this chapter are separated into two parts, one is basic parameters, and another is heavy metals. In this study, Chloride (Cl) will be used as a conservative tracer chemical to evaluate the influence of contaminated leachate to the surrounding groundwater; due to Cl is less adsorption in the clay and most kinds of soils as compared to most of the heavy metals which have higher adsorption ability. The detailed results and discussions are shown in the following sections.

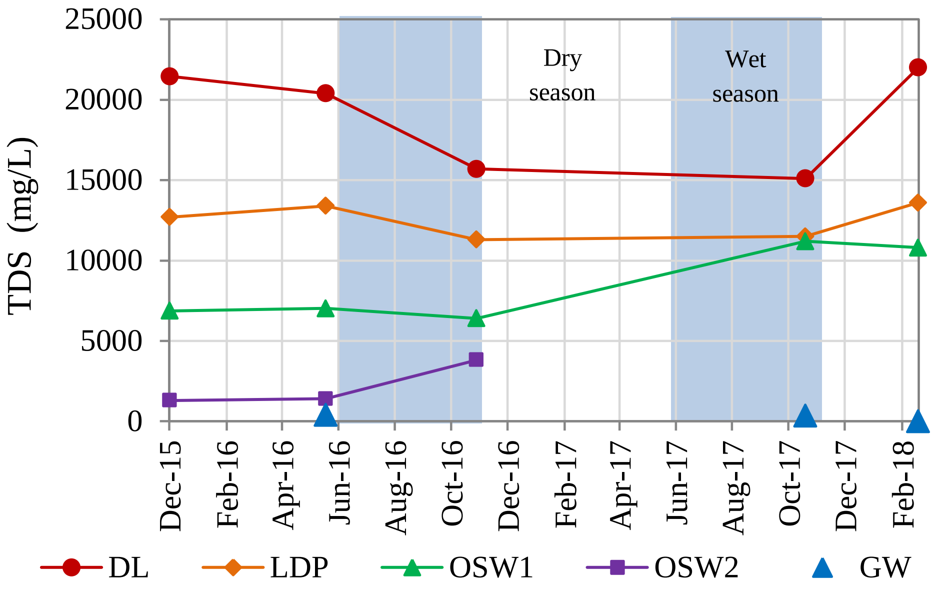
### 5.4.1 Nonthaburi Landfill

#### 5.4.1.1 Basic Parameters

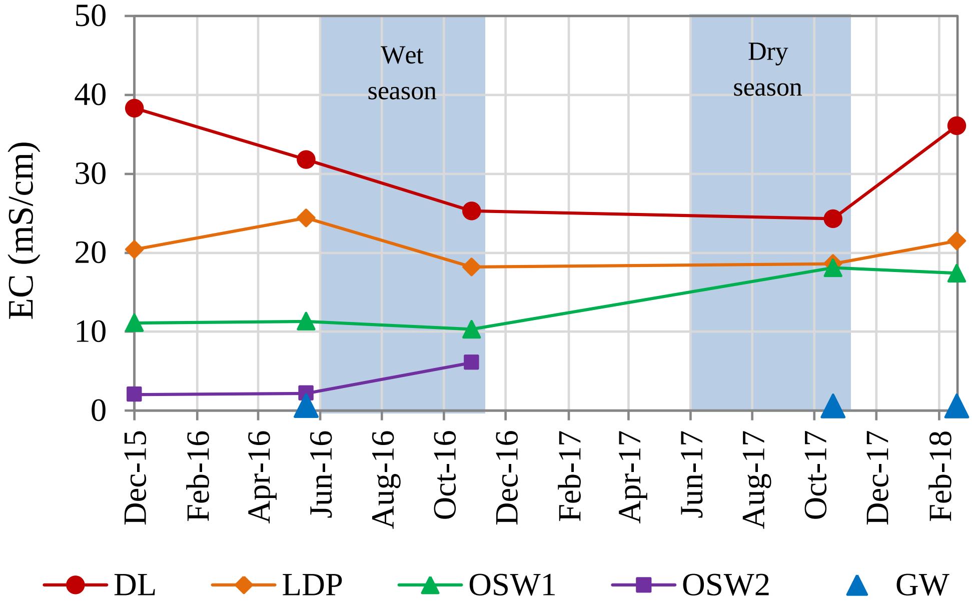
In evaluating the quality of groundwater of surrounding landfill areas, the basic parameters are necessary factors and essential in assessed parameters. Figure 5.6 shows the monitoring data of basic parameters of the whole period of this study. The results were mainly obtained from in-situ measurement for observation wells (OSW1-2) and community groundwater (GW) together with fresh leachate (DL) and leachate discharge pond (LDP) as the source of contamination. Figure 5.6 (a) presents the results of pH of those mentioned samples. The results show a slight change in time for all sampling locations regardless of the seasons, and all of them were in the range of industrial effluent standard limit of Thailand about 5.8-9. However, LDP samples show the highest pH compared to others, meaning the organic and biodegradation processes in the large pond were reduced, according to Bahalla et al., (2012). The OSW1 shows the lowest as being influenced by the nearby dumped pit and old leachate pond via the leakage horizontally as some of the evidence of soil cracking holes can be observed in the dry season. On the other hands, the pH of GW and OSW2 were close to 7, meaning the GW quality is in good condition. Regarding total dissolved solids (TDS) and electrical conductivity (EC) as shown in Figure 5.6 (b) & (c) was found the similar trends that the highest concentration was on DL samples, followed by LDP and with the increased trend of OSW1 especially from Oct 2016. Also, OSW2 had the increasing trend at the lower level due to the location is closed to the deep dumped pit of area E. As for groundwater (GW) at the community well is the lowest trend as compared to other samples for both parameters. It can be the supporting evidence of the groundwater situation in this area. At the same time, Figure 5.6 (d) & (e) showed the results of oxidation-reduction potential (ORP) and dissolved oxygen (DO). DL samples were showed the negative and lowest values for both parameters as less oxidizing of DL samples condition, while LDP samples had the decreasing trend and the seasonal effects as a lower concentration in the wet season than dry seasons. It was due to the more massive amount of fresh leachate recharges to the LDP in the wet season, and the settle down of suspended solid during the dry season as less turbulence. As for OSW 1 and OSW2 were the same trends as LDP with lower concentration. In the meantime, GW shows the stable values for the ORP and higher DO as compare to other samples, the same conclusion of the previous parameter can also be drawn in this matter.



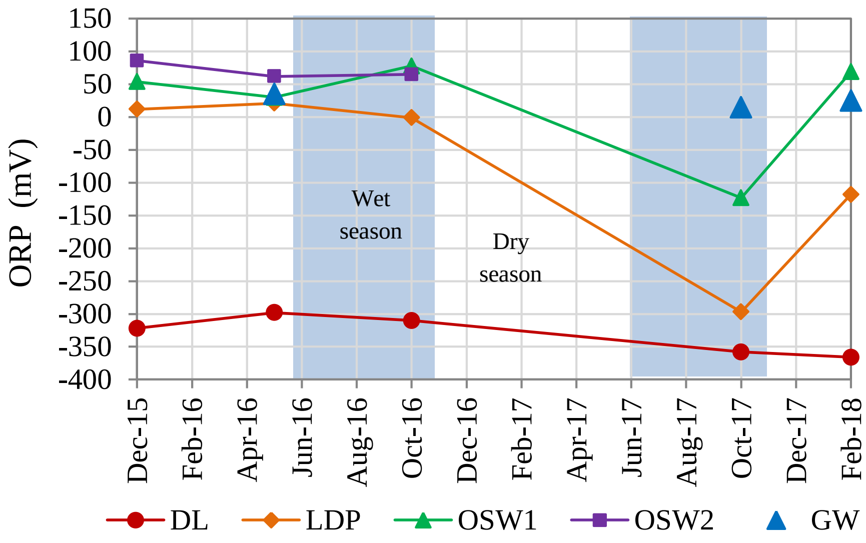
(a)


TDS (mg/L)
25000
20000
15000
10000
5000
0
Dry season
Wet season
Dec-15
Feb-16
Apr-16
Jun-16
Aug-16
Oct-16
Dec-16
Feb-17
Apr-17
Jun-17
Aug-17
Oct-17
Dec-17
Feb-18
DL
LDP
OSW1
OSW2
GW

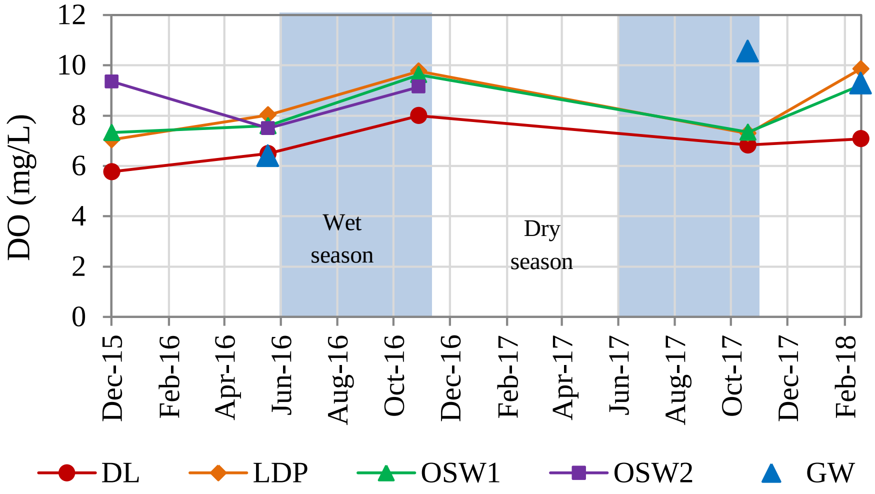
(b)


EC (mS/cm)
50
40
30
20
10
0
Wet season
Dry season
Dec-15
Feb-16
Apr-16
Jun-16
Aug-16
Oct-16
Dec-16
Feb-17
Apr-17
Jun-17
Aug-17
Oct-17
Dec-17
Feb-18
DL
LDP
OSW1
OSW2
GW

(c)



(d)

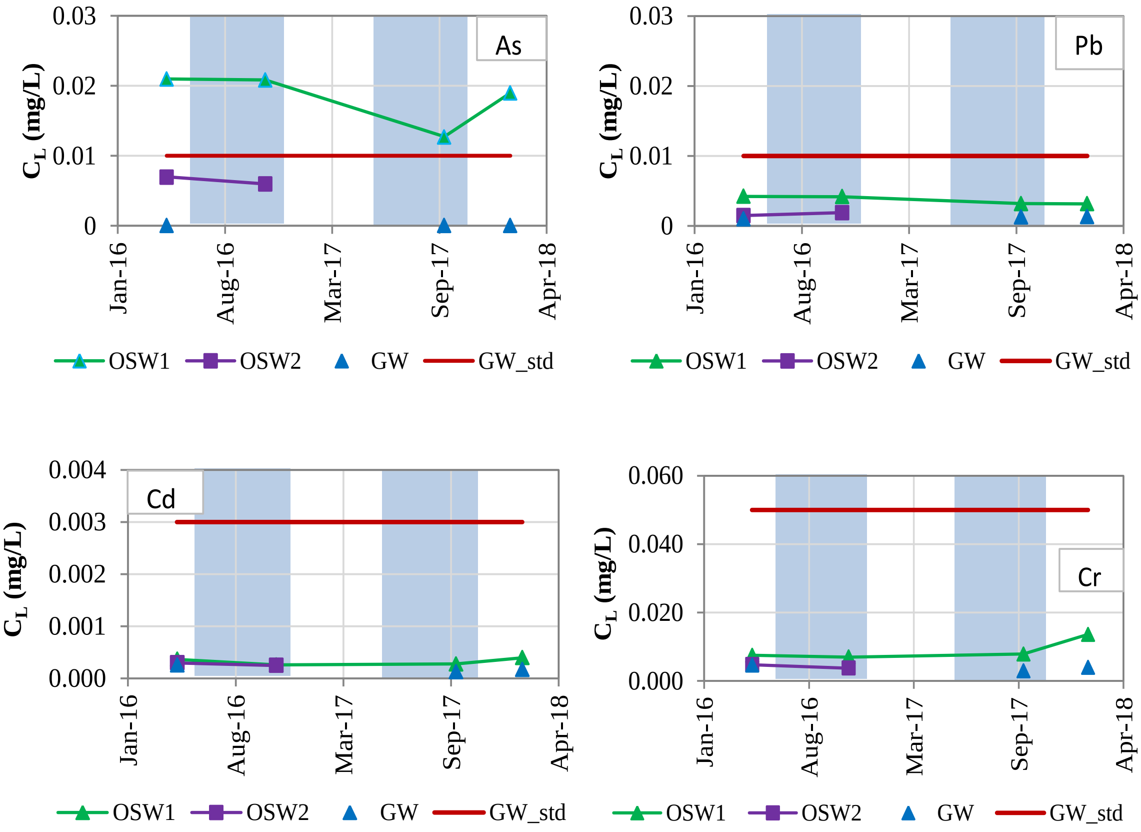


(e)

**Figure 5.6** Observe basic parameters of Nonthaburi landfill

### 5.4.1.2 Heavy Metal

The same set of HMs assessed for leachate quality was also used to examine the influence of leachate to the water environment of OSW1, OSW2, and groundwater (GW), and to describe their current quality as shown in Figure 5.7. The results of the mentioned samples were presented together with the groundwater standard of Thailand for all assessed HMs. All the assessed HMs as liquid part concentrations are lower than the groundwater standard limit of Thailand for all of the groundwater samples (OSW1, OSW2, and GW), except arsenic (As) of OSW1, which is about two times higher than the groundwater standard limit. It was due to the naturally existing of arsenic and the additional leaching from the landfill leachate as also found in the basic parameters in the previous section. Also, same as the basic parameters; GW is the lowest concentration of all assessed HMs as compared to OSW1 and OSW2, the commonly found magnetic order of these three assessed samples are OSW1>OSW2>GW and no clear seasonal variation for all assessed heavy metals. The level of dark sample color does indicate not only the TDS and SS concentration but also the heavy metal concentration contained in the leachate, as shown in Figure 5.8. Since GW is still low concentration as compared to groundwater standard of Thailand, the current situation of groundwater in this area is safe and has not been contaminated by the leachate from Nonthaburi landfill.



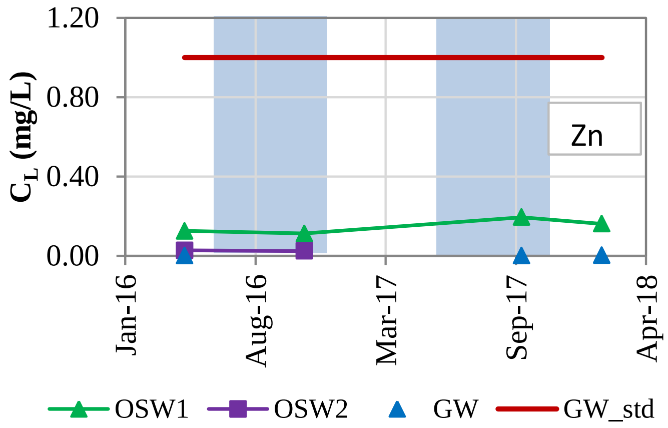


Figure 5.7 Observed HM concentration of Nonthaburi landfill

(a) (b) (c)

**Figure 5.8** Sample pictures: (a) OSW1, (b) OSW2 and (c) GW

### 5.4.1.3 Groundwater Contamination

As for chloride (Cl) which is the most important parameter in this chapter, due to it is a conservative as tracer chemical of groundwater contamination, the results of Cl concentration is shown in Figure 5.9. The Cl concentration of OSW1 was gradually increased during the period of the current study; it is clear evidence that the surrounded dumped pit and ponds have contaminated OSW1 since short distance well (OSW1) has the early arrival of Cl with the rapid increase of concentration. The expansion of the Cl concentration plume can cause by the horizontal leakage, due to the location of OSW1 is closed to the old dumped pit as shown in Figure 5.1 and Figure 5.2. Even though the OL2 is considered as an old dumped pit, but leachate production from this area still can be seen, especially in rainy season meaning the thickness of covering system of OL2 may not be enough to protect inside dumped waste from the infiltration of rainwater fully. At the same time, the increasing trend of Cl concentration in OSW1 was also observed, but the level of concentration is low as compared to OSW1, it may due the liner system of area E is better barrier since geomembrane has been placed, and also the age of area E is younger as compared to OL2 dumped area.

However, at the downstream groundwater well in the community area, which is about 800 m away from the landfill. There is no evidence of the arrival of Cl since the results of Cl concentration of GW is only about 5-20 mg/L, it is can be the background value of the groundwater. This concentration value is largely different from the one found in leachate and OSW1 which is about 5000 mg/L. As combining the results of all assessed parameters, it can be concluded that GW has not been affected by the leachate of Nonthaburi landfill. However, the potential of the future risks will be the concerns as the deep pit of area E and leachate pond of LDP are significant, and it is shallowed the thickness barrier of natural clay of the landfill bottom which is only GW protector. On the other hands, the increase of Cl concentration observed in OSW1 currently, can be good evidence of the future expansion of further areas and reach the groundwater.

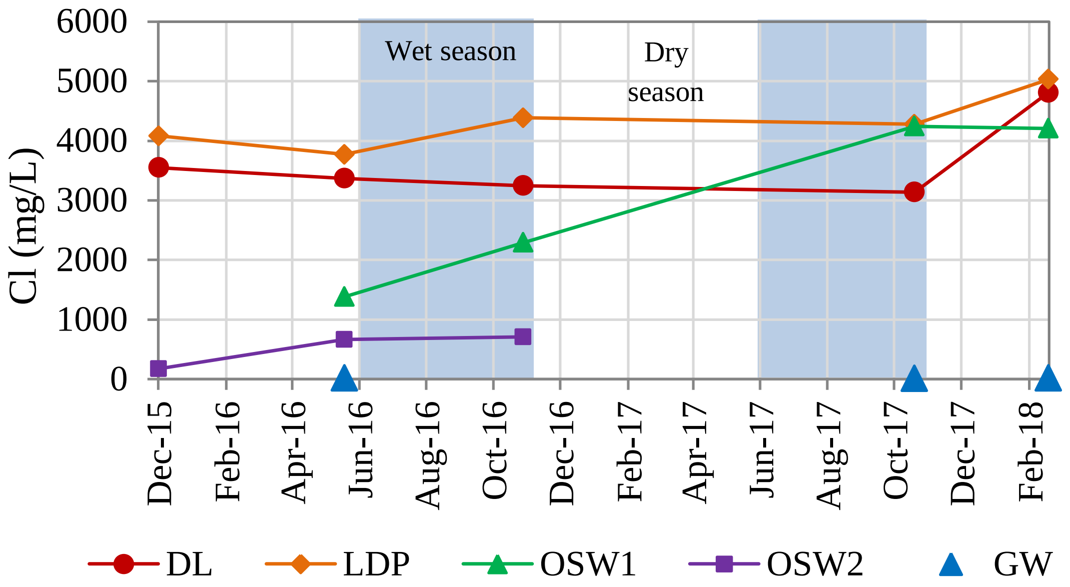


**Figure 5.9** Chloride concentrations of Nonthaburi landfill

## 5.4.2 Dangkor Landfill

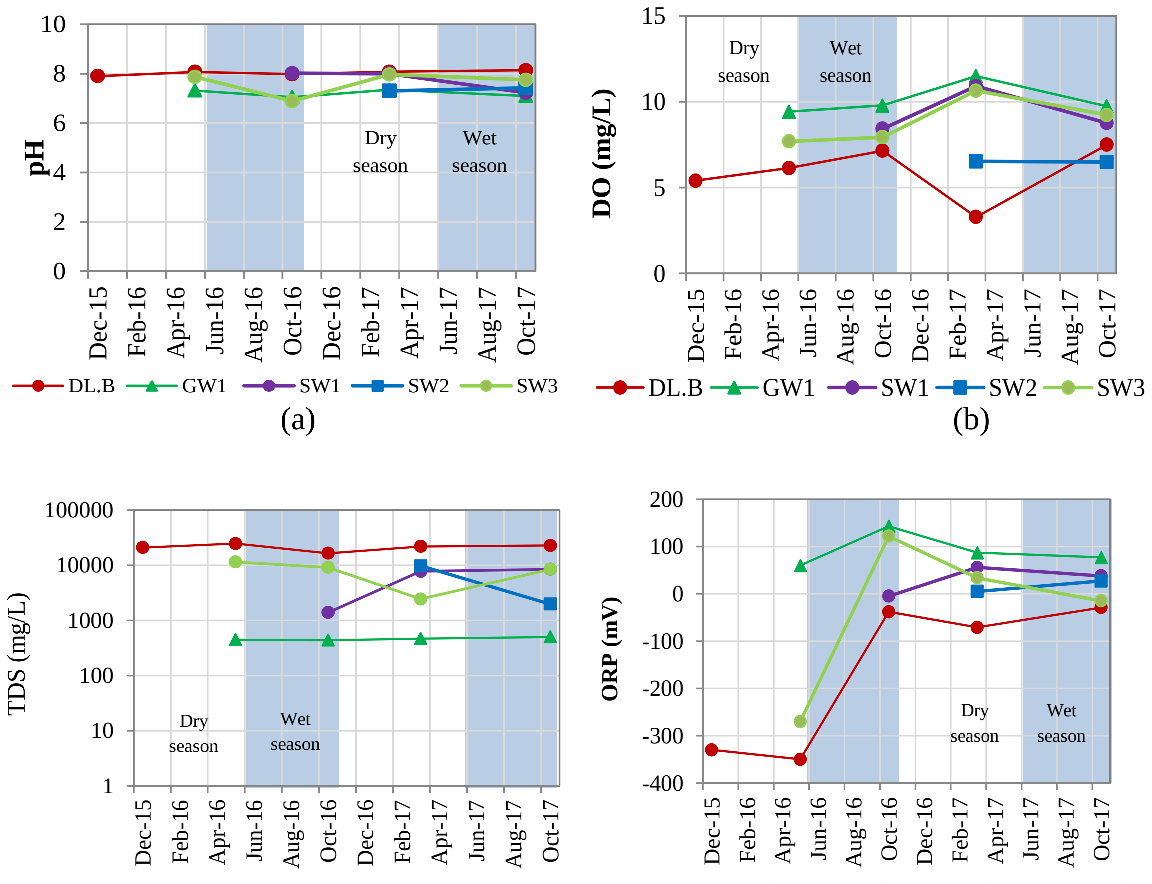
### 5.4.2.1 Basic and Biochemical Parameters

At the Dangkor landfill, the same set of parameters measured at Nonthaburi landfill is applied in assessing the groundwater and surface water quality situation. The most concerns in this landfill site are the deep pit disposal and uncontrolled release of leachate to surrounding as observed during the field visits. There will be potential risks in the future as to both groundwater and surface water due to these landfill conditions. Figure 5.10 shows the results of important basic parameters which measured at the site as in-situ measurements for groundwater and surface water of selected samples. Also, the results measured for the leachate samples were included as for comparison as fresh leachate is the primary source of contamination to the surface and groundwater of surrounding landfill areas.

Figure 5.10 (a) shows the results of pH for all compared samples, the pH results are almost constant (value) for pH of DL and GW sample.  The pH values of GW are close to 7, while SWs (1-3) have some change regarding the seasons due to the effects of the leachate on changing of surface water quality. The clear evidence of SW3 influenced by the landfill leachate was that pH in the dry season was close to DL pH values and in the wet season, pH was close to GW samples. The ranges of pH in these measured samples are in the allowable ranges of the environmental standard of Thailand.

Figure 5.10 (b) shows the dissolved oxygen (DO) concentration; DL samples show the seasonal difference with the significant change after covering by soil. At the same time, SW3 has the closest evidence of being influenced by the leachate from areas A-B due to DO at an earlier time was close to DL samples but the increased trend has been found after the cover of areas A-B. To this matter, the covering may affect the amount of leachate discharge to the creek; therefore the concentration level was reduced as a consequence. As for SW2, the DO concentration was almost constant due to the condition of the pond was disturbed by the agricultural activities of the nearby community, i.e., ducked growing in the pond and the mixing of domestic wastewater partly. As for SW1, it seems to be a small effect due to the sampling point located at the upstream of leachate discharge point, but some effects may cause by the other landfill activities as well. For the GW, the concentration also affected by the season due to the movement of water level inside the well as well as the movement and changing of the underground water.

Figure 5.10 (c) shows the results of total dissolved solids (TDS) for the same samples. The constant TDS of GW can be confirmed and also the drop down of SW3 after covering of areas A-B, while SW1 shows a small increase but it may be due to the different source. The little leftover water at the upstream point was also disturbed by some activities, such as from the small recycling factory at the nearby location. The similar condition of SW2 was found due to the smaller amount of leachate supplying to creek and pond in the dry season can be confirmed as compared to the wet season. As for ORP shown in Figure 5.10 (d), the increased trends of ORP for DL and SW3 samples was reduced due to the concentration level of contamination. Moreover, the GW is higher ORP with a slight change in the seasons.



(a) (b)

(C) (d)

**Figure 5.10** Basic parameter of groundwater and surface water of Dangkor landfill

Since chloride (Cl) is the common chemical used to assess the influence of leachate to other water environments, especially the nearby groundwater. Figure 5.11 shows the concentration levels of Cl for a different sample. Groundwater samples were found to be the lowest concentration of Cl with a slight change in the season, while the surface water shows quite large difference change in the season and the higher concentration can be found in SW3 due to the location is the downstream point of the leachate drain to the creek. As combining the results of Cl concentration and other basic parameters, the groundwater has not been influenced by the leachate due to the significant increase or high level of Cl cannot be confirmed, even though the location of GW1 is close to areas A-B. However, the effects of landfill leachate on the surface water were found in this landfill, especially for SW3 which is the most sensitive to the amount to the concentration of a contaminant as for basic parameters, while SW1 and SW2 were also found some influence from the landfill leachate of areas A-B. SW1 may not only affect by the leachate from areas A-B but also affect by the waste recycle activity at the upper location which is about 100m along the creek.

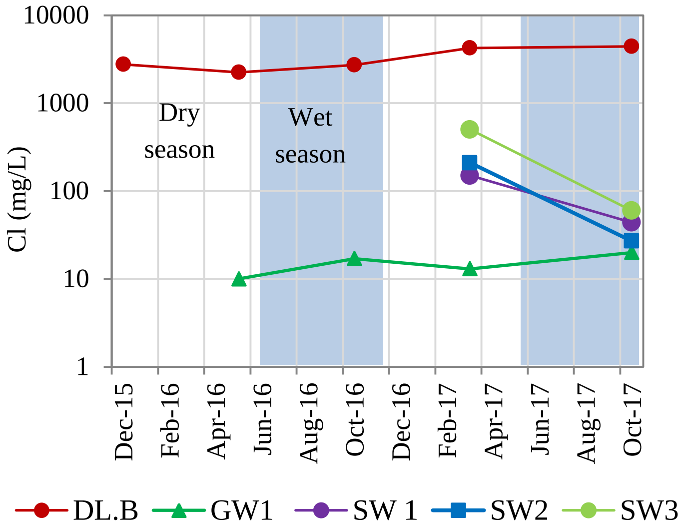
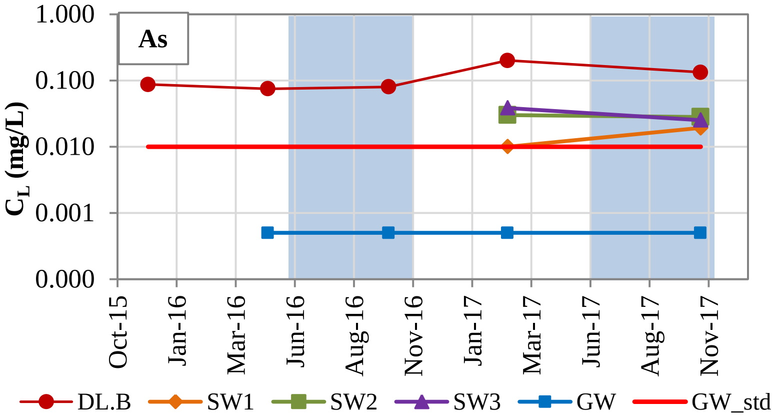


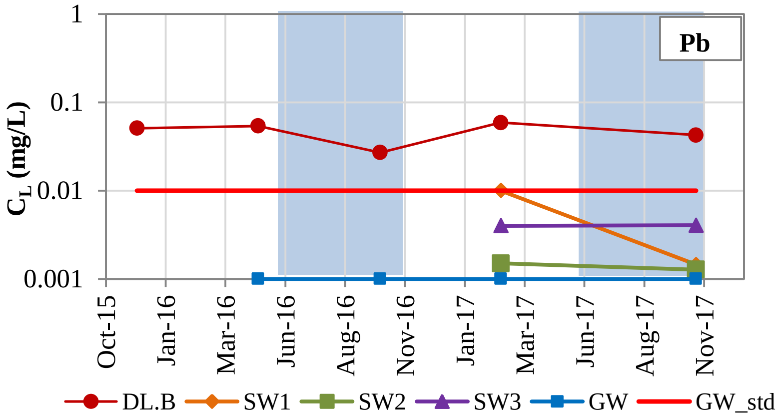
**Figure 5.11** Chloride concentrations of Dangkor landfill

### 5.4.2.2 Heavy Metal Concentrations

The low heavy metal concentrations were confirmed for groundwater samples, except for Zn. As presented in Figure 5.12, arsenic (As), lead (Pb), cadmium (Cd) and chromium (Cr) show low concentration as of groundwater with the small changes for the different fieldwork or season. The HM concentrations found in GW is quite far from the environmental groundwater standard, even though as of Zn with some existing level of concentration but still lower than the limit. For HM concentration in surface water, the high concentration can be found especially for arsenic, which all SW samples were found higher than the standard limit and slightly lower than the concentration found in leachate.

All surface water samples were in the similar ranges of HM levels, and some vary as for different HM and sampling time, it may be due to the uncertain of field sample for each period of fieldwork regarding the homogeneous of leachate. The surface water quality at Dangkor landfill was influenced by the contaminated leachate since many pieces of evidence have been found in both basic parameters and heavy metals. These concentrations are mainly affected by the site conditions as well as the current practice of landfill management, i.e., uncontrolled release of fresh leachate, covering and leachate drainage/storage system. Since this is the results of liquid part concentration, the chemical adsorption effects will also be the cause of slight HM variation found in this study.





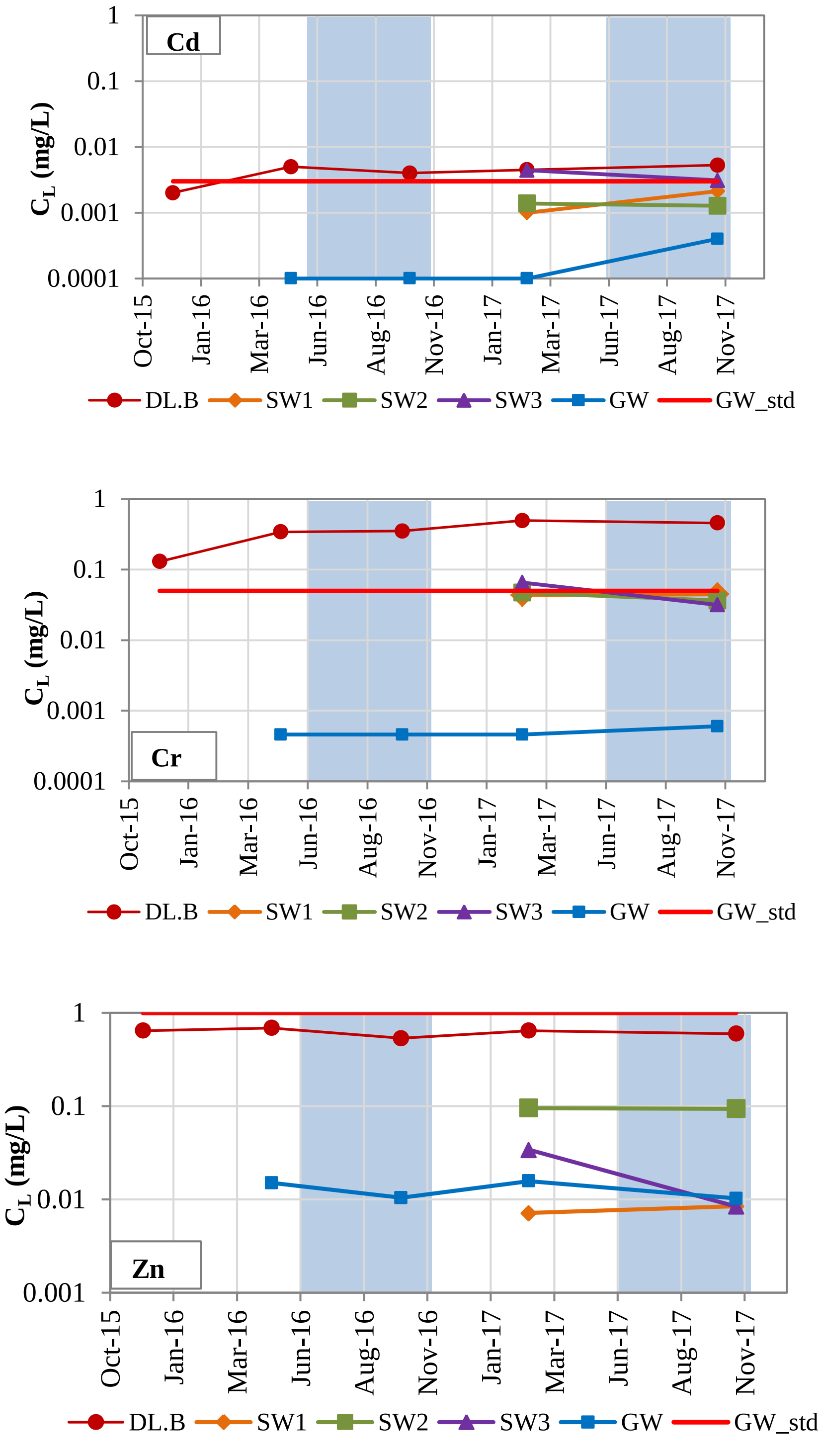
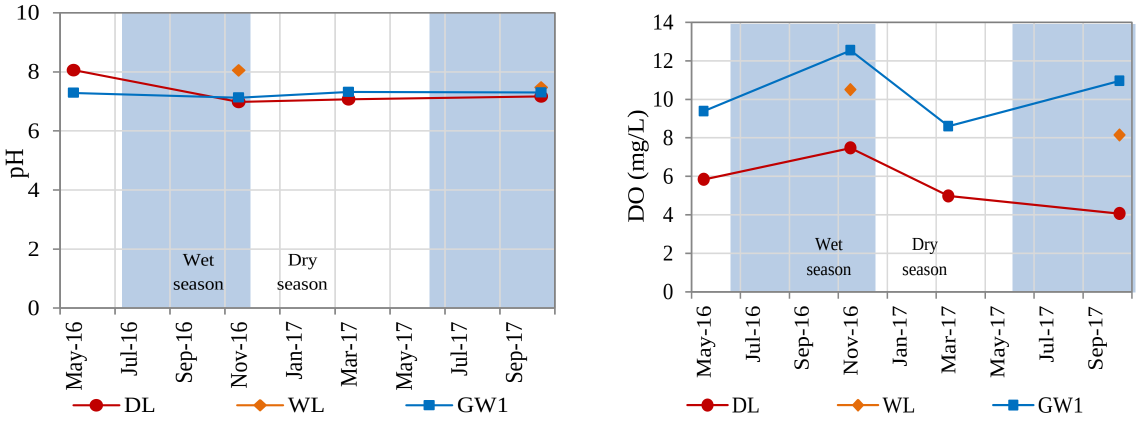


**Figure 5.12** Observed HM concentrations of Dangkor landfill

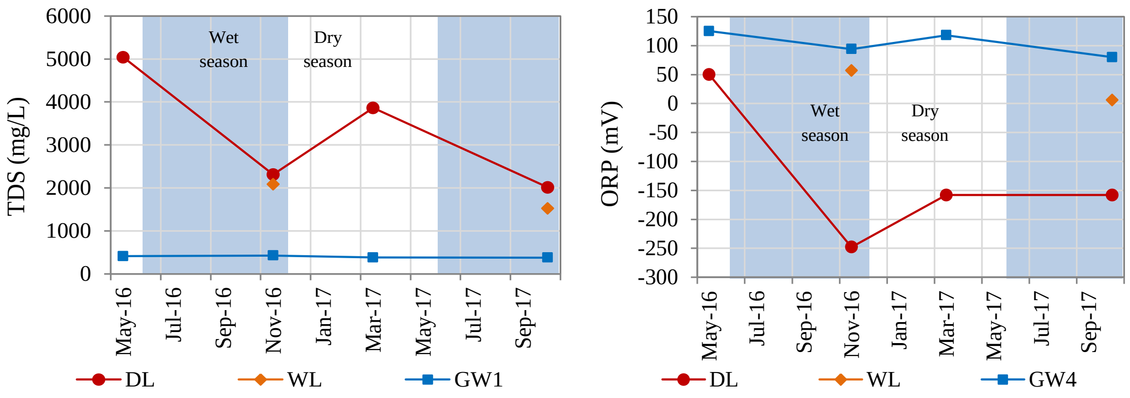
## 5.4.3 KM-32 landfill

### 5.4.3.1 Basic and Biochemical Parameters

KM-32 landfill is another landfill site in which all sets of parameters have been applied in the assessment processes. Figure 5.13 shows the basic parameters measured at the site of the Km-32 landfill for the whole period of this study. The same trends and behavior of pH values were also found in KM-32 landfill as an almost constant value with the groundwater pH close to 7 which is present the essential quality of groundwater is good in terms of acidity as shown in Figure 5.13 (a). The pH values in the wetland (WL) area was slightly higher than others as a reduction of organic or suspend solid level to alkalinity as compare to fresh leachate (DL). Figure 5.13 (b) shows DO concentration which is highly affected by the seasonal changes as for GW. It is because of the heavy rain during the rainy season. Therefore the big dilution from the rainwater occurred as can be seen by the seasonal variation of assessed parameters. As for TDS shown in Figure 5.13 (c), the big difference in the seasons was found for the leachate (DL) samples, while in the groundwater samples were almost constant throughout the year regardless the seasons. The seasonal variation of DL samples was due to the high dilution as high precipitation and a shallow waste layer of the KM-32 landfill as presented in chapter 3 of the climate information. Figure 5.13 (d) shows the results of ORP, which also found the effect of seasonal change via dilution as higher ORP in the wet season than the dry season and more oxidation potential during the rainy season as for leachate. Moreover, as same as to other basic parameters that GW samples have a small change in the season and positive values regarding the ORP.



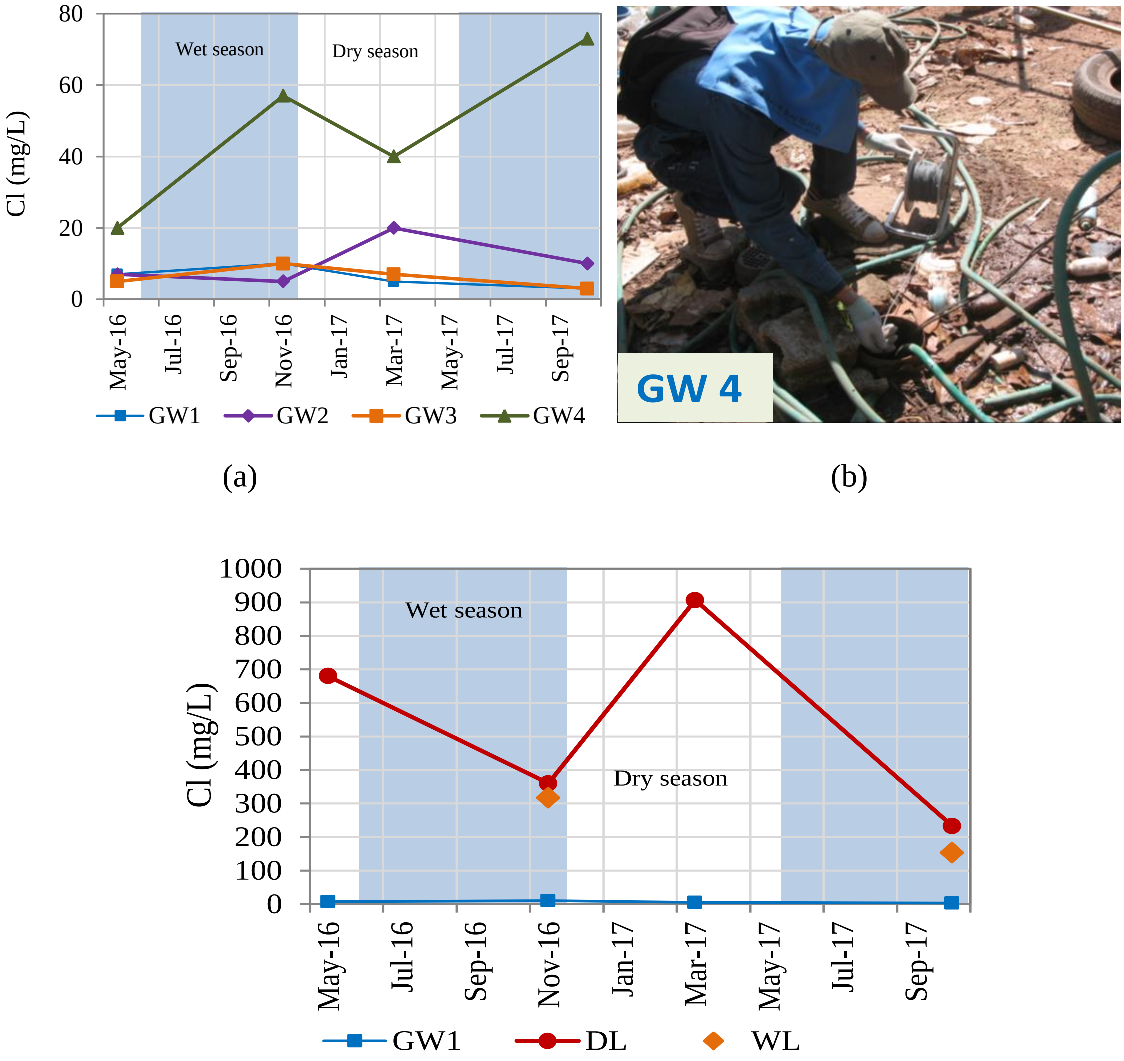
(a) (b)



(c) (d)

**Figure 5.13** Observed basic parameter of KM-32 landfill

Figure 5.14 shows the chloride (Cl) concentration, which is an important parameter in assessing the groundwater contaminated from the leachate as all leachate samples show a high concentration of Cl. Figure 5.14 (a) shows the Cl concentration for all groundwater sampling points, which includes 4 groundwater sampling wells (GW1, GW2, GW3, and GW4). The locations of those GWs are shown in Figure 5.5. As shown in Figure 5.14 (a), all the groundwater samples were a low concentration of Cl, except GW4 with the high Cl concentration as well as the increasing trend in time. There is no link to the landfill leachate effect in this manner as the nearest GW1 has not shown any high concentration throughout the time of the investigation. It is due to the infiltration from the surface water near the well. The well condition is located at the plastic recovery factory without the good protection of reaching of the surface water as shown in Figure 5.14 (b). Therefore, the possible infiltrate/overflow of water used for valued garbage washes, especially plastic bottles, which can be reached easily. Figure 5.14 (c) shows the Cl concentration of fresh leachate (DL), leachate from the wetland (WL) and groundwater (GW1) in order to evaluate the influence of leachate to the groundwater. The results show very far difference between leachate and groundwater sample, with a very low concentration of Cl in the nearest groundwater samples. Therefore, it can be concluded the groundwater has not been influenced by this landfill leachate as found same results in the other two landfills as discussed in the previous sections.



(a) (b)

**(c)**

**Figure 5.14** Chloride concentrations of KM-32 landfill

### 5.4.3.2 Heavy Metal Concentrations

The HM concentrations found in groundwater samples were quite similar for all of the groundwater wells; therefore GW1 was selected as a representative of all groundwater samples from landfill area. Figure 5.15 shows HM concentration of GW1 together with the concentration of HMs in the leachate as a source of contamination and groundwater environmental standard as for comparison. The results show low concentrations for most of the assessed heavy metals with lower than the groundwater environmental standard limit, except arsenic (As). Arsenic was found equivalence to the environmental standard limit since the first time of investigation and similar concentration level of the later investigations. There is no link to the leachate-contaminated to groundwater since Cl as conservative tracer chemical has not been confirmed as a high concentration of the nearby groundwater. It is not possible for heavy metal to reach groundwater earlier than the Cl; due to the chemical adsorption characteristics of HMs are higher as compared to Cl which can be negligible. The presence of high arsenic in GW1 is the background value from the natural existing As from the ground.

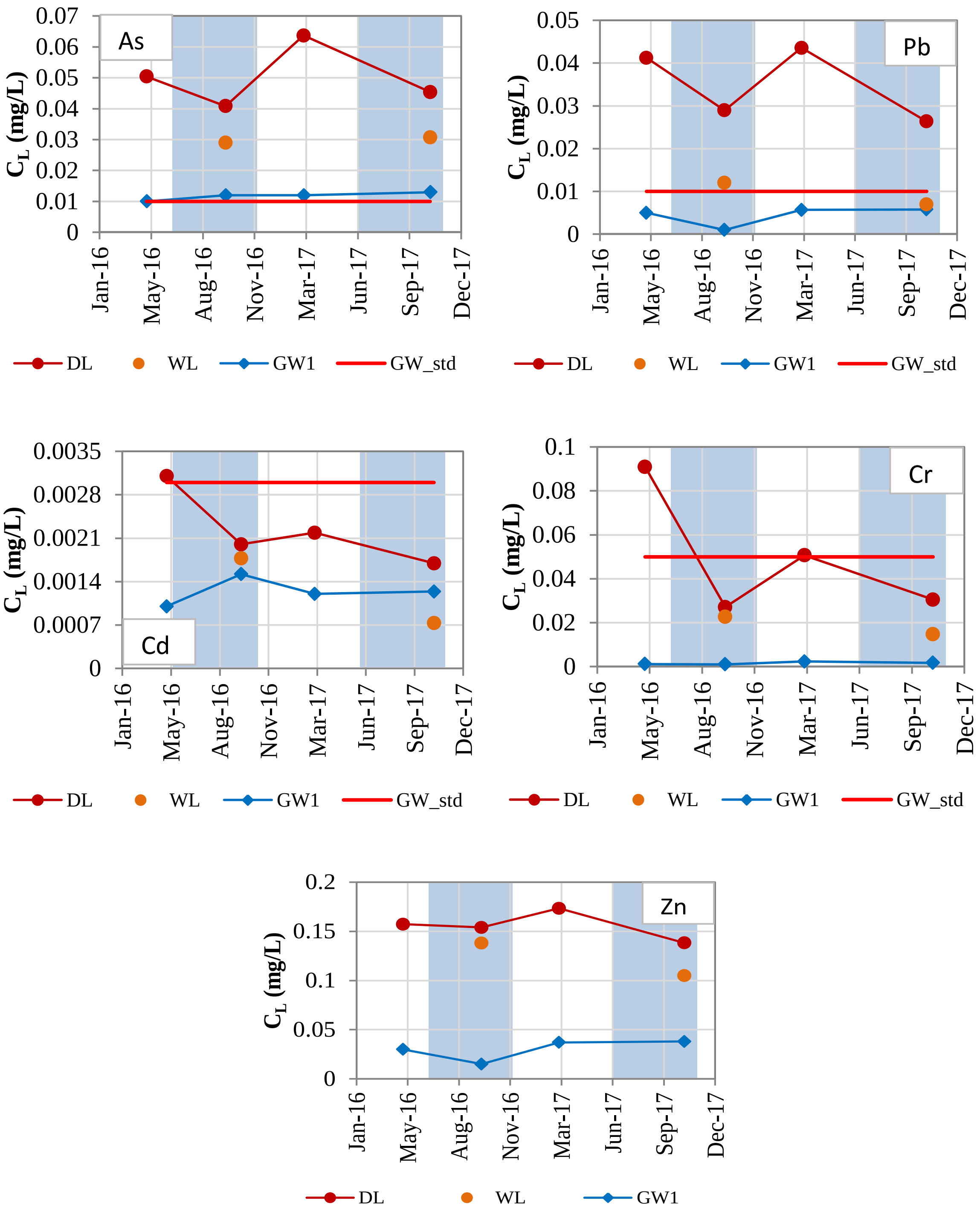


**Figure 5.15** HM concentration observe in time of KM-32 landfill

## 5.5 Conclusion

The leachates and nearby groundwater and surface water at the Nonthaburi, Dangkor and KM-32 landfills have been collected, assessed and monitored of both basic parameters and heavy metals. The key conclusions could be listed as follows

1. The contaminated landfill leachates were not influenced to the nearby groundwater of surrounding landfill areas for all study sites of the period of investigation. According to very low Cl- concentration as a tracer chemical was confirmed for all groundwater samples compared to the leachate samples. It is due to the low permeable geological barrier of the natural clay layer at the landfill bottoms, which confirmed by the Oedometer test about $10^{-10}$ m/s to $10^{-8}$ m/s.

2. Most of the existed heavy metals contained in the groundwater samples are lower than the leachate samples, and the concentrations are in between the environmental and effluent standard.

3. Surface water was influenced by the landfill leachates as a high concentration of both basic parameters, and heavy metals were confirmed, which was similar level with slight lower than the concentration found in the leachate. Moreover, the major part of the contaminant is partitioned in the suspended solids, the filtration of leachate as pre-treatment will reduce the huge contamination level of surface waters.

4. Significant seasonal variation for the surface water quality can confirm as a higher concentration in the dry seasons than wet seasons. It is due to the direct recharge of leachate to surface water and the dilution effects from the rainwater.

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# Chapter 6

# Future Groundwater Contamination Risk

This chapter summarizes the current situation of all study landfills in order to conduct the simulation study. The common conditions of all landfill are the main inputs regarding the model boundary and geological conditions. The chapter also covers the detailed discussion of possible risks to the surrounded groundwater as the results of the simulation study. Also, the important site conditions which affecting the possible risks of groundwater contaminations were included.

## 6.1 Introduction

In general, landfill leachate causes a lot of environmental problems, i.e., unpleasant smells in the air for nearby area, landfill gas which is harmful to the ozone layer, the leakage of the contaminated leachate to water environment and so on. Among these significant problems, the most concerns and risky is the leachate leakage to the groundwater as many countries and region are using groundwater as the main source of water use. Currently, numbers of landfill leachate caused groundwater pollution. Many cases in different conditions have been reported around the world. The main factors of groundwater contamination by MSW landfill leaks into groundwater and aquifers because of rainfalls. The mechanism of groundwater contamination by the flow, it spreads into the river system and pollutes the surrounding ecosystem.

Now a day, many specialized computer software packages have been created and used to solve contaminant transport problems in the groundwater system and aquifer. However, Groundwater Modeling System (GMS), is the most powerful software package using the modular finite-difference flow model (MODFLOW), the particle-tracking post-processing model (MODPATH), the modular three-dimensional transport model (MT3DMS). The main purpose of using GMS software is to predict the spreading of contaminant concentration by inputting various initial conditions, such as hydraulic head, groundwater flow direction, the concentration of contaminants (can be specific chemical) and other related geological data e,g. Hydraulic conductivity, porosity chemical adsorption and many more. Numbers of studies have been reported that contamination transport in underground condition and aquifers by using the GMS software package at present, Al-Yaqout and Hamoda, (2008); Babiker et al., (2004).

In chapter 4, characterizing the landfill leachate from the sites of this study, the results showed high contamination level had been confirmed for both basic parameters and assessed heavy metals. Most of them were higher than the standard limit for both affluent and groundwater standard. Also, in chapter 5, groundwater and surface water characterization, the results were found the current expansion of nearby leachate has contaminated the nearest observation wells at the Nonthaburi landfill, especially OSW1 with the rapid increase of chloride concentration, as high as of the same level found in the leachate. Moreover, from chapter 3, site study. The investigation was found the common site condition among the three study landfill, and the range of some parameter based on the site condition was set.

## 6.2 Objectives

1. To assess the potential risks to the groundwater based on the typical site conditions.

2. To discuss the effects of site conditions (Pit Height, leachate Height) and key geological parameters (Kc & Kd)

## 6.3 Method

In this study, among the numbers of groundwater modeling software, the groundwater modeling system (GSM) is selected to use as the main tool for groundwater and contaminant transport simulation. The three-dimensional groundwater flow model MODFLOW and three-dimensional solute transport model MT3DMS are used for simulating groundwater flow and contamination transport.

### 6.3.1 Simulating Process

The detailed process of this simulation study, and step by step procedure for applying to a groundwater flow model and contaminant transport model is presented in Figure 6.1.

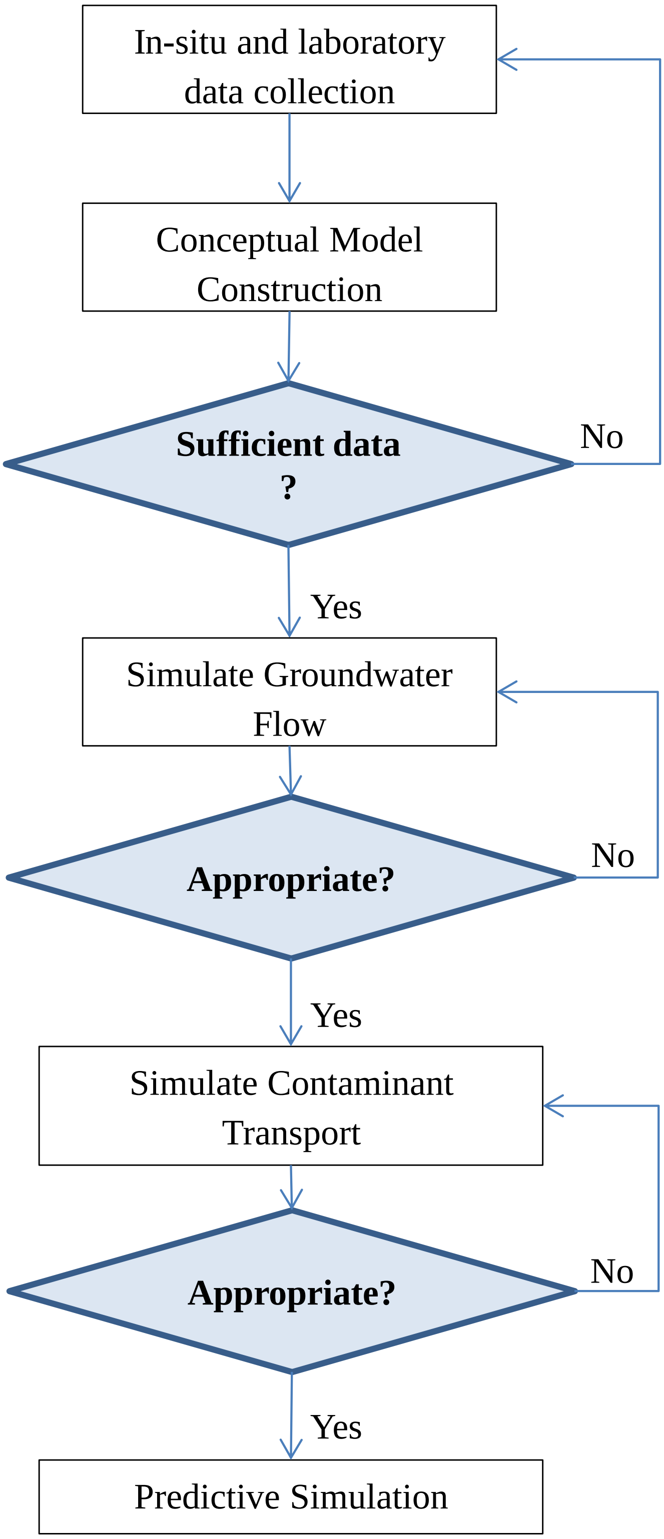

**Figure 6.1** Flowchart of simulation processes

**Step 1** Data collection: in this step, the in-situ information and measurement including laboratory measurement are needed as input data for the simulation, such as the shape and depth of the dumped pit, leachate height and other geological information, i.e., soil profile, hydraulic head, groundwater flow direction, topographic elevation. Also, as a contaminant and current expansion plume, leachate and groundwater chemistry from the laboratory are needed.

**Step 2** Construction of a conceptual model: The conceptual model association with the information collected in step 1, to establish the model geometry which can be used to test and simulate for both groundwater flow and contaminant transportation.

**Step 3** Simulation of groundwater flow model: To run the MODFLOW package and simulate groundwater flow on the specific model, then groundwater flow directions and the hydraulic heads until the simulation matches/closest to the in-situ observations to be optimized.

**Step 4** Simulation of the contaminant transport model: After the groundwater flow model is confirmed as appropriate flow, the contaminant source location as inside the dumped pit in this study, and contaminant concentration values are input into the model but assume as a percentage (using 100 mg/L). Then the MT3DMS package is run to simulate the transport of contaminants in groundwater, including both vertical and horizontal direction as for clay and sand part respectively.

**Step 5** Predictive simulations: After the trial results as compared to the calculations, the model is used to predict future groundwater flow and contaminant transport in the designed geometry mesh. The model is used to estimate the potential risks by various possible landfill condition found by the site investigation.

### 6.3.2 Governing Equations

The partial differential equations, describing the groundwater flow use in GMS as a confined aquifer and introduce by Harbaugh, (2005), and Zheng and Wang, (1998):

For the groundwater flow model:

$$\boldsymbol{\frac{\partial}{\partial x}\left[K_x\frac{\partial h}{\partial x}\right]+\frac{\partial}{\partial y}\left[K_y\frac{\partial h}{\partial y}\right]+\frac{\partial}{\partial z}\left[K_z\frac{\partial h}{\partial z}\right]-W=S_S\frac{\partial h}{\partial t}}\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(6.1)$$

h: the potentiometric head [m],

K: permeability [m/s],

W: a volumetric flux per unit volume representing sources and/or sinks of water [1/s],

$S_S$: Specific storage of the porous material [1/m],

t: time[s]

The partial differential equation describing the fate and transport of contaminants of species k in three-dimensional, transient groundwater flow systems can be written as follows:

$$\frac{\partial(\theta C^k)}{\partial t} = \frac{\partial}{\partial x_i}\left[\theta D_{ij}\frac{\partial C^k}{\partial x}\right] - \frac{\partial}{\partial x_i}(\theta v_i C^k) + q_s C_s^k + \sum R_n \quad \text{…………...(6.2)}$$

$\theta$: the porosity of the subsurface medium, dimensionless,

$C^k$: the dissolved concentration of species k [g/m$^3$],

$x_i$, the distance along the respective Cartesian coordinate axis [m],

$D_{ij}$: the hydrodynamic dispersion coefficient tensor[m$^2$/s]

$v_i$: the seepage or linear pore water velocity [m/s],

$C_s^k$: the concentration of the source or sink flux for species k[g/m$^3$],

$q_s$: the volumetric flow rate per unit volume of aquifer representing fluid sources (positive) and sinks (negative) [1/s],

$\sum R_n$: the chemical reaction term[g/m$^3$/s]

### 6.3.3 Contaminant and Groundwater Transportation

#### 6.3.3.1 Transport by Advection

Advection is the transport of dissolved substances along with the groundwater flow. It is mainly due to the hydraulic gradient. The amount of substances transported by advection is determined by the substance concentration and flow rate in the pore water. The velocity flow is calculated by the following equation 6.3

$$v_{int} = \frac{v}{n} = \frac{K}{n}\frac{dh}{dl} \quad \text{……………………………………………………….(6.3)}$$

Where,

$v_{int}$ = average linear velocity (L/T)

$K$ = hydraulic conductivity (L/T)

$n$ = effective porosity

$dh/dl$ = hydraulic gradient (L/L)

Since the substance in the pore water is moving along the individual streamlines and the actual movement is restricted within the gap, the moving speed of the substance in the pore water is larger than the average cross-sectional flow velocity by the bending rate of the soil particle Become. The advection flux is expressed as Eq 6.4

$$J_x = v_{int} nC \ldots\ldots (6.4)$$

And Jx is the advection flux, and C is the substance concentration

### 6.3.3.2 Dispersion

The flow velocity of the groundwater may be both greater and less than the average linear velocity. When observing the ground and the groundwater flowing through the ground with a macroscopic viewpoint, the moving speed of each substance is different from factors such as the size of the gap in the ground, the difference in the bending rate at each streamline, and the friction of the fluid. Mixing due to this difference in speed is called mechanical dispersion. In groundwater flow, it is impossible to consider mechanical dispersion and molecular diffusion separately. From this, a hydraulic dispersion coefficient is defined by integrating. Assuming that the dispersion flux follows the first law of Fick, the dispersion flux is expressed as Eq 6.5.

$$\text{Dispersion mass flax} = D_h \frac{\partial c}{\partial x} \ldots\ldots (6.5)$$

$$D_h = D_e + D_m = D_e + \alpha_L v_x \ldots\ldots (6.6)$$

Where,

$D_h$ is a hydraulic dispersion coefficient,

De is a molecular diffusion coefficient

Dm is a mechanical dispersion coefficient, and

$\alpha_L$ is a longitudinal dispersion coefficient

### 6.3.3.3 Diffusion

Diffusion is a process in which a material is irreversibly moved by random molecular motion. By this random molecular motion contaminants are transported from high concentration to low concentration. For this reason, diffusion is believed to be transported by contaminant concentration gradients (Shackelford, 1989).

Diffusion is a transport process with a very slow migration rate of pollutants and is not important in soils with high permeability like sand as a practical matter. However, the movement of pollutants by diffusion is very important in soils like clay where the water permeability is less than $10^{-8}$ m/s (Shackelford, 1991) Steady diffusion and transient diffusion Or nonstationary diffusion

### Diffusive mass flux in solution

The diffusion of pollutants and chemical substances in aqueous solution is generally done according to Fick's first law. When Fick's first law is applied to the one-dimensional diffusion phenomenon, it can be written as follow.

$$J_d = -D_0 \frac{\partial C}{\partial x} \qquad (6.7)$$

Where $J_d$ is the diffusion flux and $D_0$ is the diffusion coefficient. The negative sign before the diffusion coefficient is because the concentration gradient is negative.

### Diffusive mass flux in soil

According to Shackelford (1989), the diffusion in the earth needs to be smaller than in the case of only the aqueous solution. The following three reasons are cited as reasons for this:

- The effective movable cross-section of the aqueous solution decreases with soil since the soil is porous, the bending rate is large

Movement is restricted by chemical interaction between the aqueous solution and soil surface

Effect of reduction in cross-sectional area of flow:

Eq 6.6 defines the flux in the total cross section of the flow. Here, Eq. 6.7 can calculate the diffusion flux based on the reduction of the permeability cross section of the soil by introducing the volume moisture content (θ) (Shackelford and Daniel, 1991)

$$f_d = -D_0 \theta (\frac{\partial C}{\partial x}) \qquad (6.8)$$

$$\theta = nS_r \qquad (6.9)$$

$S_r$ is saturation degree of soil. When the saturation degree is 100%, Eq 6.8 is rewritten as Eq.6.10

$$f_d = -D_0 n (\frac{\partial C}{\partial x}) \qquad (6.10)$$

**Effect of tortuous pathway:**

The bending rate specifies the degree of influence on the movement of water molecules in the porous material. Based on this bend rate Eq.6.10 is modified as Eq.6.11.

$$f_d = -D_0 \tau n (\frac{\partial C}{\partial x}) \quad (6.12)$$

$$\tau = (\frac{L_f}{L_{fe}})^2 \quad (6.13)$$

Where, τ is the bending rate, $L_f$ is the length of the streamlines in the linear state, and $L_{fe}$ is the length of the streamlines affected by the porous material. In any case, $L_{fe}$ becomes larger than $L_f$, and the flexion rate becomes 1 or more. The flexion rate is saturated soil 0.01-0.84, unsaturated soil 0.025-0.57 (Shackelford and Daniel, 1991).

It is considered that the bend rate is actually influenced not only by the bend of the streamlines due to the porous material but also by the interaction between the solutes in the aqueous solution or between the solute and the soil in the aqueous solution. In this sense, not the flexion rate defined by Eq 6.13, but the apparent flexion rate τ such as Eq 6.14 is used as the flexion rate considering the above-mentioned influence.

$$D_e = \tau_a D_0 \quad (6.14)$$

### 6.3.3.4 Advective-Diffusive Equation

The advection diffusion equation can be derived from the assumption that the totalof change due to chemical reaction and the mass of the inflow / outflow flux in the reference element is equal to the mass increase in the reference element per unit time. It is also necessary for this application condition that the soil is homogeneous, isotropic and saturated, and the Darcy's rule is effective.

We assume that the above conditions are satisfied and derive a one-dimensional advection diffusion equation. From Eq. 6.4, 6.5 the flux passing through the unit cross-sectional area per unit time is Eq. 6.15, and the total flux m contained in the reference element is Eq 6.16

$$\mathrm{J} = \mathrm{n} v_{int} C - D_{hl} n \frac{\partial C}{\partial x} \quad (6.15)$$

$$\mathrm{m} = \mathrm{nC} + (1 - \mathrm{n}) \rho_s C_s \quad (6.16)$$

Where,

$\rho_s$- the dry unit volume weight of the soil. By using Eq 6.15, 6.16, the general one-dimensional advection diffusion equation is determined as shown in Eq.6.17

$$\frac{\partial m}{\partial t} = -\nabla J \pm R \pm \lambda m$$

$$\frac{\partial}{\partial t}\{nC + (1-n)\rho_s C_s\} = -\frac{\partial}{\partial x}\left\{n v_{int} C - D_{hl} n \frac{\partial C}{\partial x}\right\} \pm R \pm \lambda\{nC + (1-n)\rho_s C_s\} \text{……..(6.17)}$$

R-represents the chemical reaction, and λm represents the flux change due to the biological reaction, etc., respectively.

In Eq.6.17, assuming that flux changes due to chemical reactions, biological reactions, etc. are ignored, steady flow and soil skeleton are not deformed, Eq 6.18 can be obtained:

$$\frac{\partial C}{\partial t} = D_{hl}\frac{\partial^2 C}{\partial x^2} - v_{\text{int}}\frac{\partial C}{\partial x} - \frac{\rho_b}{n}\frac{\partial (C_s)}{\partial t} \text{…………………………………..…………(6.18)}$$

Where Cs is the amount of contaminants adsorbed to the soil per unit mass. Assuming that a linear relationship holds between C and Cs, Eq 6.19 is obtained:

$$\frac{\partial C}{\partial t} = D_{hl}\frac{\partial^2 C}{\partial x^2} - v_{\text{int}}\frac{\partial C}{\partial x} - \frac{\rho_b}{n}\frac{\partial (K_d C)}{\partial t}$$

$$\left(1+\frac{\rho_b}{n}K_d\right)\frac{\partial C}{\partial t} = D_{hl}\frac{\partial^2 C}{\partial x^2} - v_{\text{int}}\frac{\partial C}{\partial x} \text{ ………………………………………..…..(6.19)}$$

$$R_d\frac{\partial C}{\partial t} = D_{hl}\frac{\partial^2 C}{\partial x^2} - v_{\text{int}}\frac{\partial C}{\partial x}$$

And Rd is a retardation coefficient

$$R_d = 1 + \frac{(1-n)\rho_s K_d}{n} \text{…………………………………………………………..(6.20)}$$

The retardation coefficient is Eq 6.20 , nd it is represented by the Kd as dispersion coefficient.

### 6.3.3.5 Peclet Number

A peclet number is a dimensionless number representing the ratio of advection and mechanical dispersion. The definition formula is shown in Eq. 6.21.

$$P_e = \frac{v_{\text{int}} d}{D_d} \; or \frac{v_{\text{int}} L}{D_L} \text{ …………………………………………………………(6.21)}$$

Where, d and L are the characteristic length, $D_d$ is the molecular diffusion coefficient, and $D_L$ is the mechanical dispersion coefficient in the longitudinal direction. When the flow velocity is remarkably small, it is found that the ratio of the dispersion coefficient and the diffusion coefficient takes a constant value of approximately 0.7. In the longitudinal direction, it is thought that advection and dispersion dominate the transport of substances when the Peclet number is about 0.2 or less for diffusion,when the pellet number is about 6 or more.

### 6.3.4 Specific Site Selection and Condition

In this chapter, the site selection conditions are based on the common conditions found for those three landfills. However, the Nonthaburi landfill and Dangkor landfill are higher risks for the groundwater contamination, as deep pit disposal which is severe concerns in this study. Figure 6.2 shows the common practice of deep pit disposal of the region as the worse cases threatened the nearby groundwater, since there are significant about 15 m and 30 m in depth as for Nonthaburi and Dangkor landfill, respectively. Outside of these three landfills, another landfill in Siem Reap, Cambodia found even deeper, about 40 m below ground level. Therefore, the common and potential risk condition of this simulation is deep pit disposal, which is the main factor of shortening the natural clay liner below the landfill pits. As for the pit size, the Dangkor landfill is about 150x220 [m], while Nonthaburi landfill about 400x450 [m] of the current ongoing dumping area.

**Figure 6.2** The common landfill site condition in Indochina peninsula

### 6.3.4 Numerical Model Construction

The numerical of two representative landfills were constructed by using package MODFLOW in this study. The rectangular grid pattern was used to divide the model domain for both vertical and horizontal cells in MOD FLOW package to calculate groundwater table condition in each cell.

Based on the previous data collection from the field investigation in combination with the literature and previous studies, the model geometry and mesh size was designed with the sufficient width and length to avoid the effects of the boundary. The mesh size is 1500m in length and 800m in width, distance from the landfill to the upstream boundary is 450m, in order to keep long distance in the downstream side as contamination plumes supposed to be extended. The same geometry mesh was applied in both cases with the difference in depth as both landfill sites have different depth of aquifer layer. As for Nonthaburi landfill case, since the depth of aquifer layer is about 21 m below ground surface; therefore the depth of geometry mesh was set of 30m (X=1500m, Y=800m, Z=30m). Also, the depth of geometry mesh was set of 70m Dangkor landfill case; referring to the information from the landfill site engineer provided the depth of aquifer layer is about 50m from the ground level, the mesh size of Dangkor landfill case: X=1500m, Y=800m, and Z=70m. Figure 6.3 shows the common 3 dimension geometry mesh for this study, together with axis position at the center of the landfill pit. The grid size was separated into two levels as for X and Y axis, one is the father landfill site with the grid size of 10x10 [m], while the grid size inside the landfill and surrounding of 100 m from the landfill edge was set of 5x5 [m]. In addition, the depth of each layer in the Z axis (for both prositive and negative sides) in vertical direction, the layer depth was also separated into 3 zones: from ground level to bottom of the pit, from pit bottom to aquifer and for the aquifer layer as 4 – 1 - 4 [m] but in the transition the layer depth was adopted to 2 m, to avoid the jump of largely different of the layer depth.

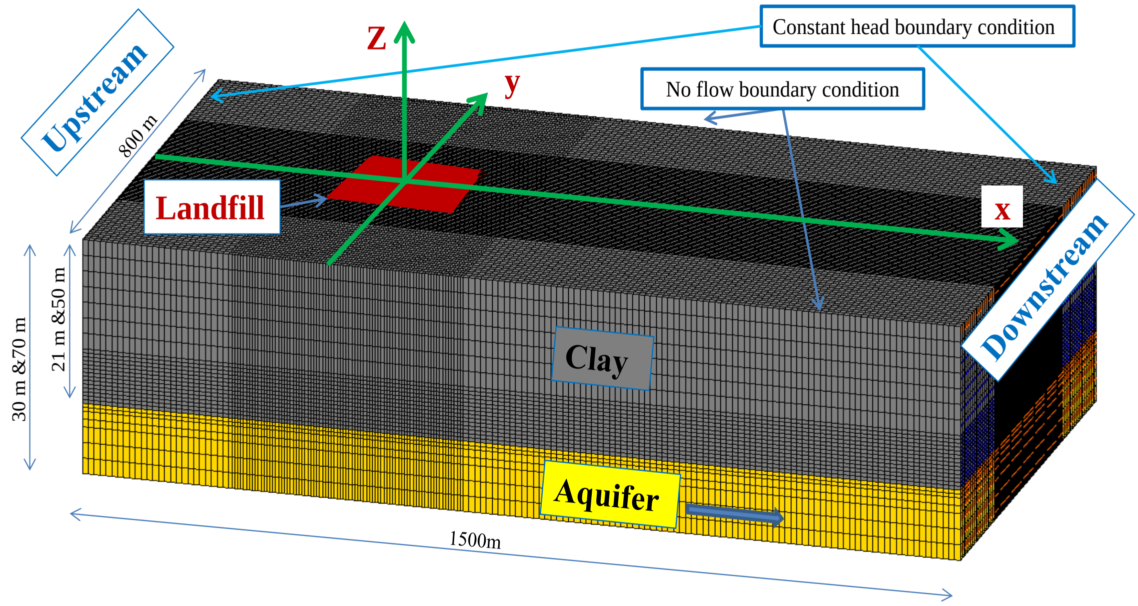

**Figure 6.3** Model geometry and initial boundary condition

### 6.3.5 Boundary Condition

The Figure 6.3 from the previous section, the upstream and downstream boundary is represented the constant head boundaries, and the rest two boundaries are considered as no-flow boundary. The details of the necessary condition of both cases are shown in Figure 6.4 and Figure 6.5 as for Nonthaburi and Dangkor landfill case. The red notations ($H_P$, $H_L$, Kc, and $K_d$) are the variable parameters used in this simulation, which are considered as the most important parameters regarding the current landfill site conditions.

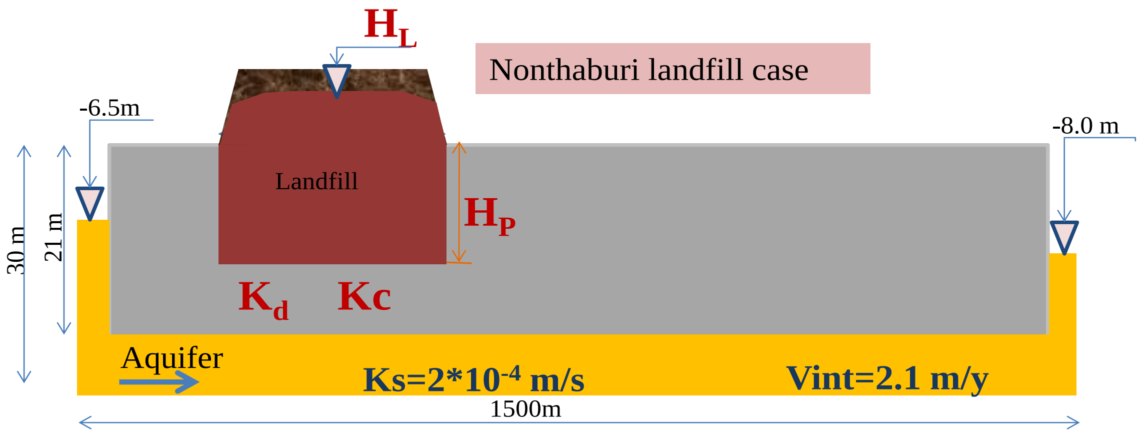

**Figure 6.4** Basic conditions of Nonthaburi landfill case

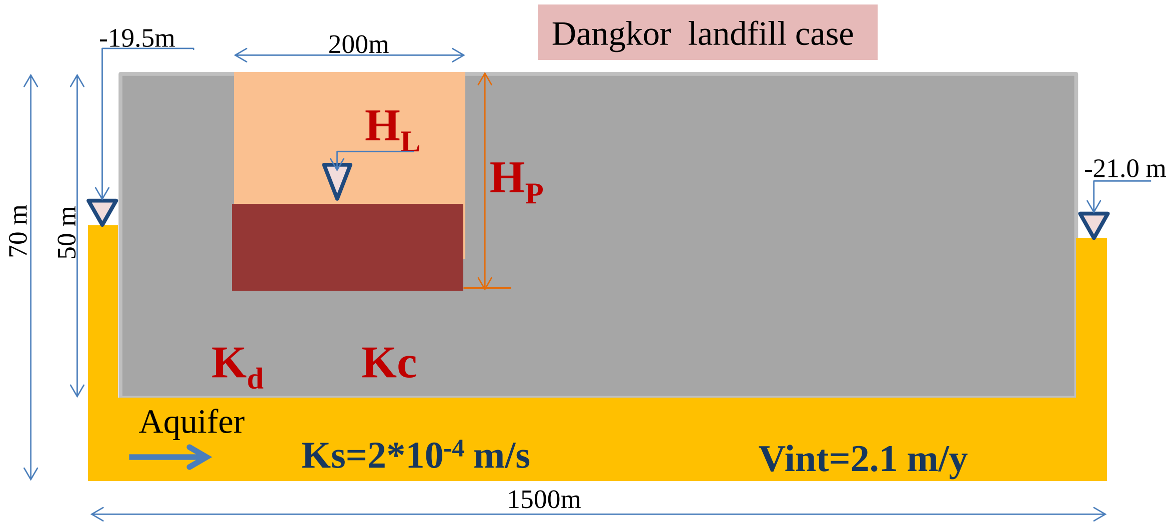

**Figure 6.5** Basic conditions of Dangkor landfill case

### 6.3.6 Input Parameters

The details of the basic/fixed condition of the numerical model and input parameters are presented in Table 6.1. This information is mainly obtained from the site investigations, site observations, site engineer interview, and the laboratory measurements, especially in chapter 3 for the site conditions, as well as the parametric studies. However, at the real site conditions and environment, many of them may not constant depends on the onsite activities as well as the change of the climate and surrounding environments.

**Table 6.1** Fixed conditions and input parameters

| Landfill | Unit | Nonthaburi | Dangkor | Remark |
|---|---|---|---|---|
| Geometry length | m | 1500 | 1500 | Fixed |
| Geometry width | m | 800 | 800 | |
| LF Center to US. edge | m | 450 | 450 | |
| Aquifer EL(depth from ground EL) | m | -21 | -50 | |
| Head. Aquifer EL. US | m | -6.5 | -19.5 | |
| Head. Aquifer EL. DS | m | -8.0 | -21.0 | |
| Hydraulic gradient in Aquifer | | 0.001 | 0.001 | |
| Head of Aqui @ LF. US | m | -6.9 | -19.9 | |
| Head of Aqui @ LF. DS | m | -7.1 | -20.1 | |
| Porosity (clay) | | 0.65 | 0.6 | |

| | | | | |
|---|---|---|---|---|
| Porosity (sand) | | 0.3 | 0.3 | |
| Contaminant concentration | mg/L | 100 | 100 | |
| Hydraulic conductivity (Ks) | m/s | $2*10^{-4}$ | $2*10^{-4}$ | |
| $V_{int}$ (aquifer) | m/y | 2.1 | 2.1 | |

### 6.3.7 Variable Parameters

The variable parameters set in this study are based on the site investigation and observation. The ranges were estimated the possible movement and vary within the site conditions. Table 6.2 presents the variable case study values which used in the Dangkor landfill case, while Table 6.3 presents the variable parameter values for Nonthaburi case. Also, each landfill has the basic site conditions which are the current landfill site situation observed at the landfill during the site investigation.

The ranges of the variable parameters have been set regarding the field and laboratory testing, as well as the literature. The description on the ranges and definition will be explained as follows:

- Pit Height ($H_P$) is the depth of the dumped pit which is counted from the ground level to the bottom of the pit or calculated as landfill depth. The range of $H_P$ as for Dangkor landfill case is ranged from 20m, 30m and 40m is due to the current depth of dumping area is 30 m while the worst case can be reached 40 m as one example can be seen at the site of landfill in Seam Reap, Cambodia with the depth of about 45 m from the ground surface (From interview). Moreover, as for Nonthaburi case, the current depth is about 15 m, while some part of the dumped pit was reached to 18m, therefore the pit height of this landfill set as 10m, 15 and 18m.

- Leachate Height ($H_L$) is the height of leachate inside the leachate pond or inside dumped pit was normally cannot be found in the landfill in developing countries including these three landfill sites. However, it is possible to have different height of leachate inside the pit, especially during the waste filling; the clear evidence can be seen in Dangkor landfill area C. Therefore, the ranges of $H_L$ should be set in between the depth of the pit or pit height, but in many cases, the waste usually filled up over the ground surface as current landfill practice about 10m above the ground level for both Dangkor and Nonthaburi landfill. So, in this study was set three different leachate height below ground level for Dangkor and leachate height above the ground surface for the Nonthaburi landfill as shown in Table 6.2 ~6.3.

- Hydraulic conductivity (Kc) is the water permeability to the clay which depends on the soil or clay property. In this study, Kc was set a bit higher than the measured values at stated in chapter 3, section 3.4.3 which quite low permeable soil for all landfill site. However, in the real field condition regarding the complexity of underground condition, the higher permeability may occur. Therefore, the Kc in this study was set as the slightly higher range as shown in Table 6.2 ~6.3.
- As for the partition coefficient ($K_d$) is mainly influenced by the chemical retardation factor. Even though in this study simulation, Cl was used as a tracer chemical but in the reality leachate contains various kind of heavy metals which can be affected by $K_d$. So, the Kd values set in this simulation is based on the literature but smaller values should investigate due to many heavy metals or elements have less absorption as for the worst case for the better future consideration in the design stage of the landfill.

**Table 6.2** Variable parameters and basic site conditions of Dangkor landfill

| **Pit Height** ($H_P$-m) | **Leachate Height** ($H_L$-m) | $K_C$ (m/s) | $K_d$ (L/kg) |
|---|---|---|---|
| 20 | 0* | $5x10^{-8*}$ | 0* |
| 30* | -10 | $1x10^{-8}$ | 0.001 |
| 40 | -15 | $5x10^{-9}$ | 0.005 |
|  | -20 |  | 0.01 |

Note: * Basic landfill site condition

**Table 6.3** Variable parameters and basic site conditions of Nonthaburi landfill

| **Pit Height** ($\mathbf{H_P}$-m) | **Leachate Height** ($H_L$-m) | $\mathbf{K_C}$ (m/s) | $\mathbf{K_d}$ (L/kg) |
|---|---|---|---|
| 10 | 0* | $1x10^{-8*}$ | 0* |
| 15* | +3 | $5x10^{-9}$ | - |
| 18 | +7 | $1x10^{-9}$ | - |

Note: * Basic landfill site condition

## 6.4 Results and Discussions

### 6.4.1 Basic Landfill Site Condition of Dangkor landfill

Before the discussion on the key important parameter variations, the basic condition of the current landfill practice needs to be introduced and discussed as a baseline condition for the further comparison once site condition or management changed. The results of a simulation study for the site basic condition presents as following.

#### 6.4.1.1 Groundwater Flow Model Simulation

The results of groundwater flow simulation of this study mainly depend on the hydraulic gradient of groundwater in the aquifer layer as for horizontal flow direction in the aquifer layer shown in Figure 6.6. According to the head difference of groundwater in the upstream and downstream is 1.5 m with the distance of 1500 m. Therefore the hydraulic gradient in the aquifer part is 0.001. As for the hydraulic gradient in the clay layer as the vertical direction, as of basic landfill condition, the head difference in the landfill leachate and aquifer is 20, and the clay layer thickness is 20m so, the hydraulic gradient in the clay layer is 1. The other factors affecting the flow are the hydraulic conductivity and porosity of the clay and aquifer material as provided in the Figure.

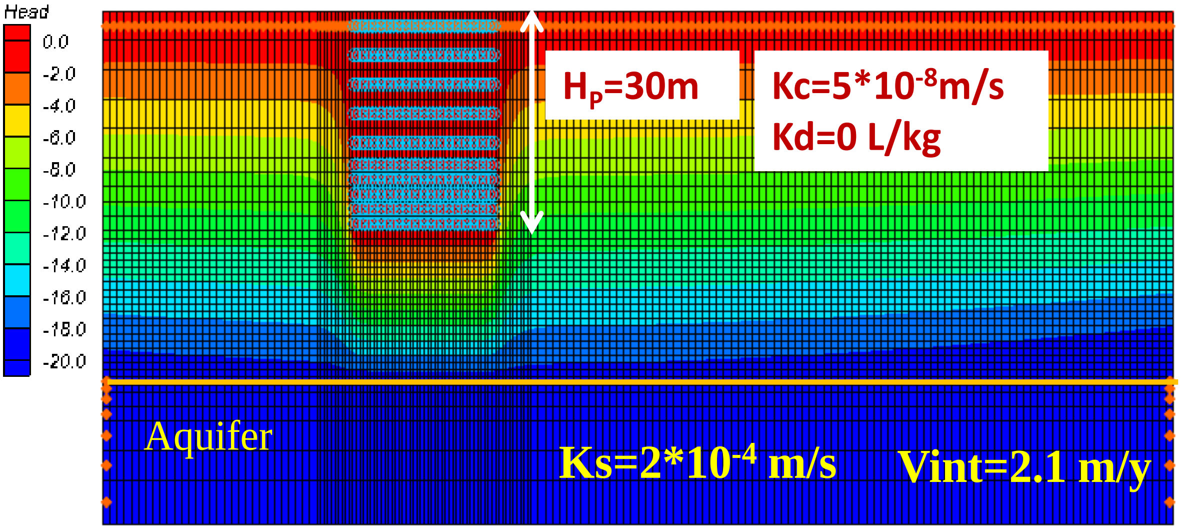

**Figure 6.6** Contour of groundwater flow at Dangkor landfill

### 6.4.1.2 Contaminant Transport

The contaminant transportation plume can be confirmed for the landfill site basic condition, shown in Figure 6.7 and Figure 6.8 as for vertical and horizontal expansion. In this condition, the plume was gradually expansion in time, with the average velocity of about 0.5 m/y in the clay layer. The shape of contaminant plume was slightly extended in the horizontal direction in the clay layer, but once the plume reached the aquifer layer, the traveling or velocity was increased due to the increase of hydraulic conductivity in aquifer layer.

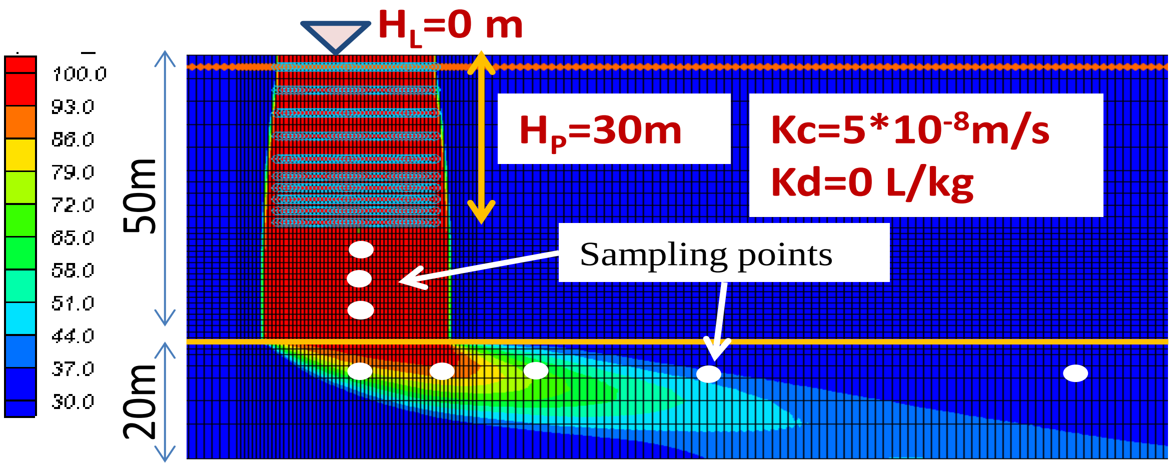

**Figure 6.7** Vertical plume of contaminant transport at the center cross-section of Dangkor landfill

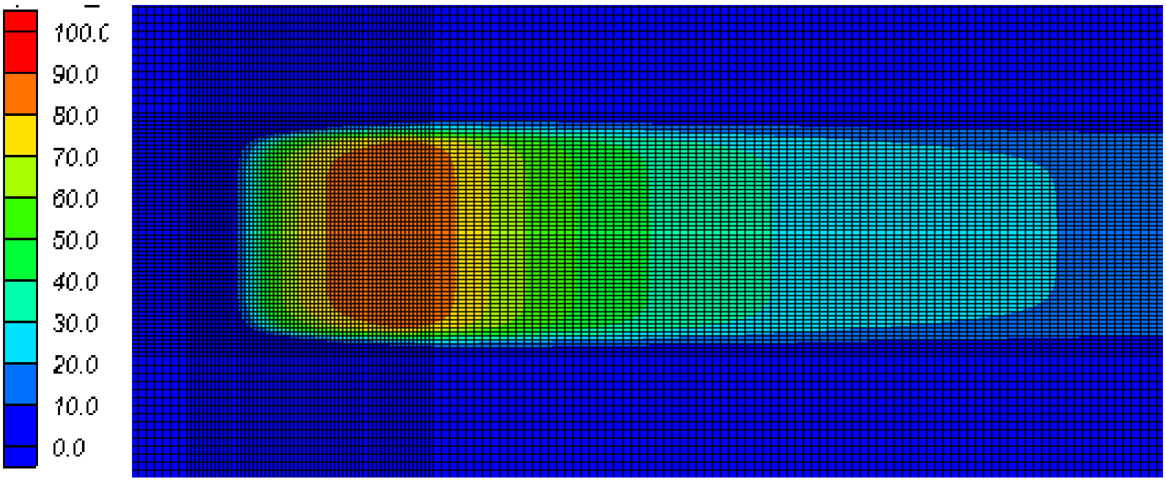

**Figure 6.8** Horizontal plume of contaminant transport at a depth of 55m of Dangkor landfill

Figure 6.9 and Figure 6.10 show the breakthrough curve for each sampling point in the vertical and horizontal directions of the same cross-section, respectively. The vertical sampling point location was at a depth of 35, 40 and 45 m below the ground level. The results of simulation confirmed the delay of arrival time for different sampling location; the closer to the landfill pit is the shorter time of arrival of contaminant. Also, the steady state concentration of contaminant as an equilibrium condition was reached the original concentration level for all sampling points in the clay layer. As for horizontal distance of contaminant expansion in the aquifer layer as the sampling points of 0, 100, 200, 400 and 800 m downward. The central part and landfill downstream edge sampling points had the same arrival time of contaminant but the difference in steady-state concentration level; the landfill downstream edge point has a higher concentration in equilibrium concentration due to the central contamination plume had passed through this point, while central landfill point was located in the lower concentration plume. That is also the effect of groundwater flow velocity in the aquifer is fast as compared to the velocity in clay part. The other conclusion is that the farther distance in the aquifer is the longer time of arrival of the contaminant with lower concentration as compared to the closest points.

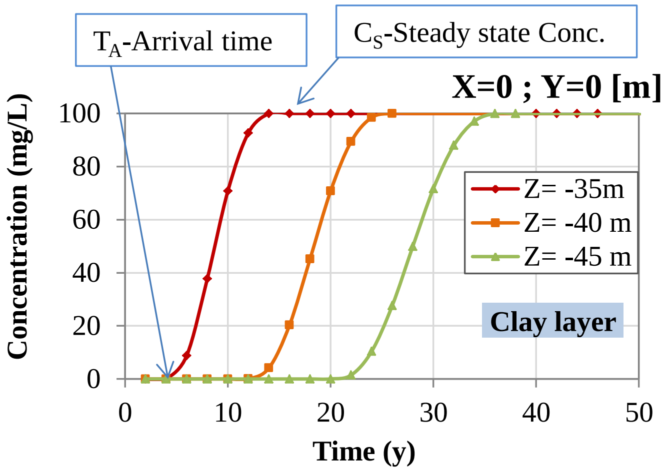

**Figure 6.9** Breakthrough curves in clay layer of basic site conditions at Dangkor landfill

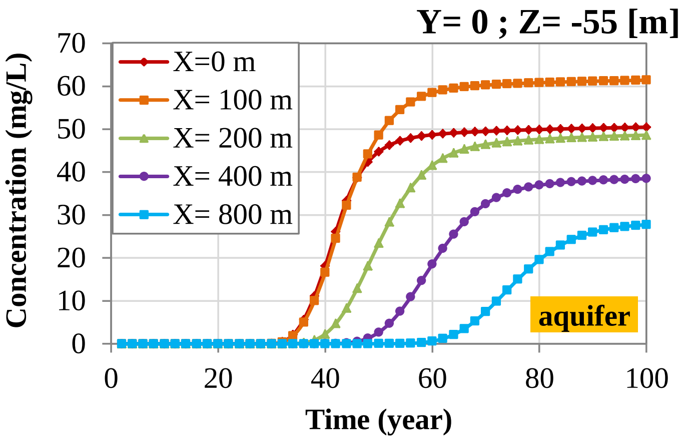

**Figure 6.10** Breakthrough curves in a sand layer of basic site conditions at Dangkor landfill

### 6.4.2 Effects of Pit Height at Dangkor Landfill

To evaluate the effects on the landfill pit height ($H_P$) to the leachate quality, two sampling point was selected as one for the representative of vertical expansion as clay part, and another is for the horizontal expansion in the aquifer. In the clay part as the vertical direction, the sampling point of the 45 m below ground surface was chosen, while in the sand (aquifer part) the point of 400 m were selected to discuss the contamination plume and other behaviors. As shown in Figure 6.11, with the same of other conditions, the pit height was varied as the depth of the pit changed from 20m, 30m, and 40m below ground level.

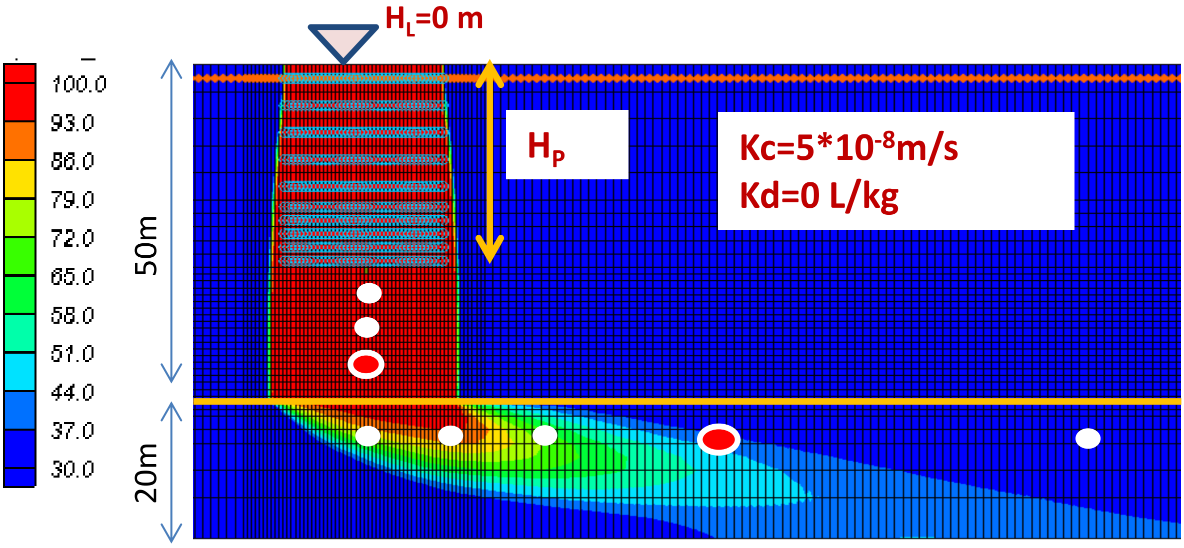

**Figure 6.11** Vertical plume of contaminant transport with sampling points at Dangkor landfill

Figure 6.12 and Figure 6.13 shows the breakthrough curves of sampling points of different pit height for the clay and sand part, respectively. In the clay part, even though the same interval of pit height increases but the inclination of contaminant concentration was quite different as compared to each other for all cases of the pit heights. The pit height of -40 m was the highest incline and shortest time to reach the steady state condition, while the pit height of -30m has lower incline with the same level of concentration at the steady state condition. Moreover, as for the case of -20 m and -12 m pit height, the inclinations of breakthrough curve concentrations were much lower as compared to those two previous cases. It was due to the hydraulic head difference in the clay and sand (aquifer) layer, which is the main factor controlling the landfill bottom pressure and relatively affecting to the contaminant transportation, Farouk et al., 2015. As for aquifer layer sampling point, the inclination of contaminant concentration is the difference for different pit height. Also, it can be confirmed that the different pit height made difference level of contaminant concentration for at the equilibrium state in this simulation study.

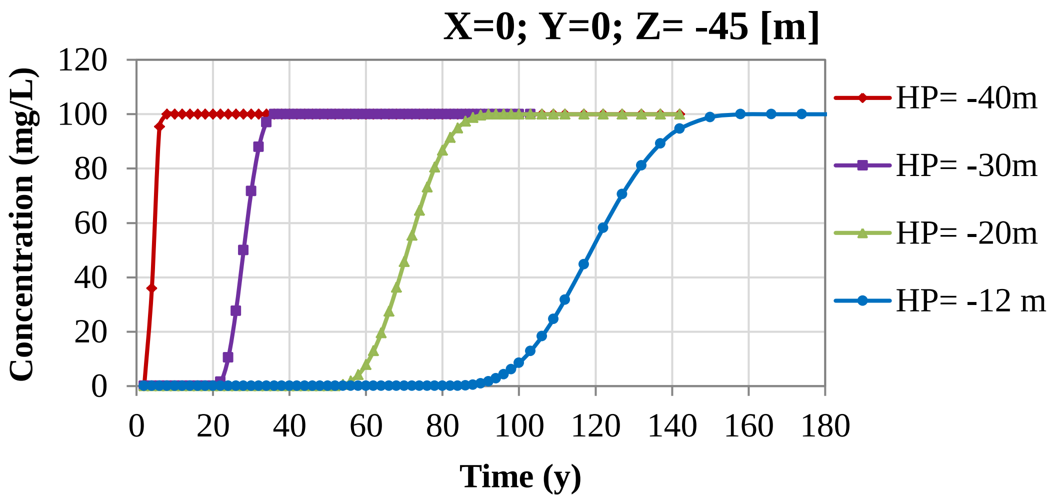

**Figure 6.12** Breakthrough curves in the clay layer of $H_P$ variation at Dangkor landfill

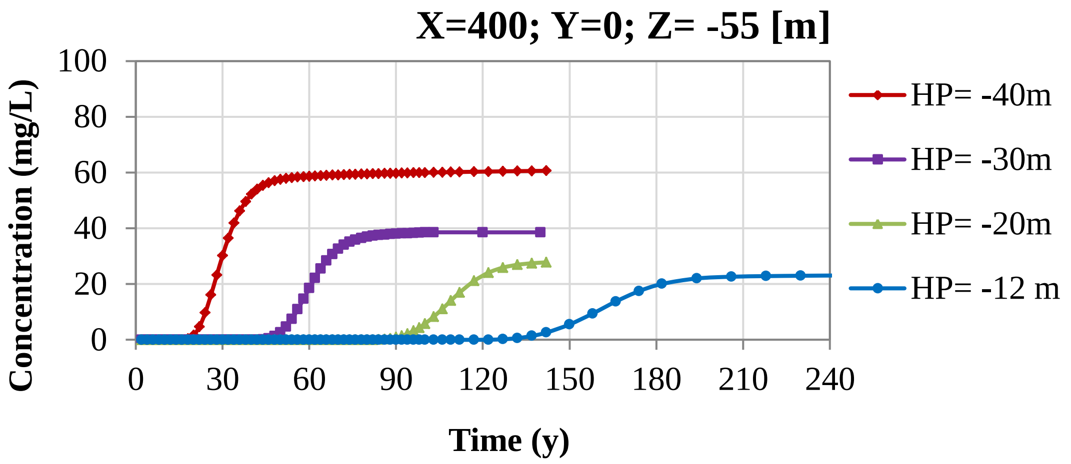

**Figure 6.13** Breakthrough curves in a sand layer of $H_P$ variation at Dangkor landfill

Also, Figure 6.14 shows the comparisons of the arrival time and steady state concentrations of the contaminant at the equilibrium condition for all study cases of variable pit heights. In the clay part at the point of sampling, the arrival time of contaminant was quite similar among the pit height of -12, -20, and -30 m, but significant difference for the pit height of -40m as compared to those shallower pit heights. As intensively observe, the difference arrival time interval between pit height of -40m and -30m was 16 years, while the difference between pit height of -30m and -20m was 32 years, and the difference between pit height of -20m and -12 m is also 31 years. Moreover, all of the heights show the steady state concentration of 100 mg/L, as high as of the initial contaminant concentration. As for the sand or aquifer part of sampling point of 400 m downstream side from the landfill center, the arrival time intervals were a slight increase in time but no significant difference, i.e., about 10-years increase of each different pit height. However, the contaminant at the equilibrium state was found largely the difference between the pit height of -40m and -30m, with the concentration of about 60 mg/L and 40 mg/L, respectively. On the other hands, the concentration of contaminant of the pit height of -20 and -12 m was 22 and 28 mg/L.

According to these two sampling points which located in different soil layer, it can suggest the pith height of the current landfill conditions should not lower than the depth of 30 m below ground surface, due to the significant change after the height of pit lower than -30m was confirmed. The shallower pit height will be the big reduction risks to the groundwater contamination from the landfill leachate.

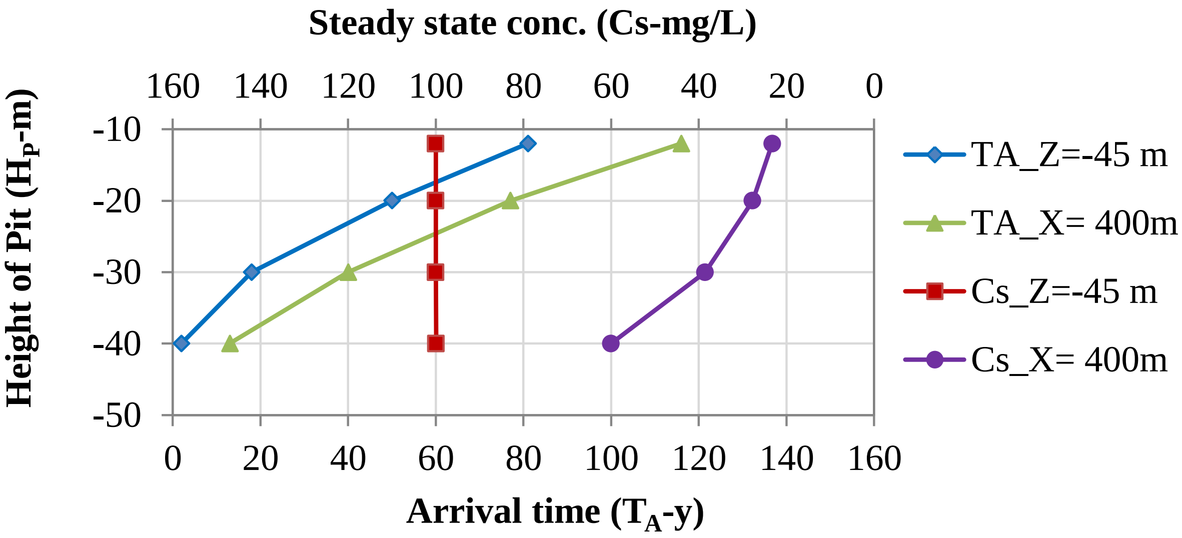

**Figure 6.14** Arrival time and steady state concentration graphs of $H_P$ variation at Dangkor landfill

### 6.4.3 Effects of Leachate Height below Ground Level at Dangkor Landfill

The height of leachate inside the dumped pit is one of the important issues for the leachate management at the landfill site, especially landfill in developing countries. The common observation during field visits is the increase of garbage height which is caused to the increase of the leachate height inside the pit, particularly the deep pit disposal, area C of Dangkor landfill as discussed in chapter 4. Figure 6.15 shows the leachate elevation inside the dumped pit together with sampling points to collect the simulation data. In the assessment of leachate height ($H_L$), the same set of basic landfill condition of input parameters was used with varying of leachate height, and the basic site information can be found in Table 6.2 for Dangkor landfill.

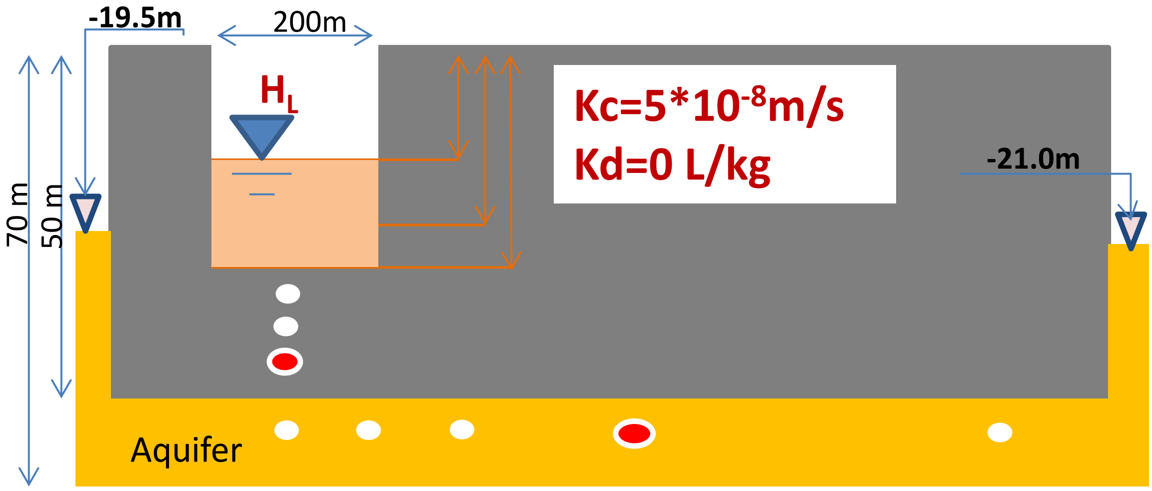

**Figure 6.15** Vertical cross-section and sampling points of $H_L$ variation at Dangkor landfill

Figure 6.16 shows the breakthrough curves of 3 different leachate heights for the clay part, which located at the point of 45 m below the ground surface. Simultaneously, the breakthrough curves of the sand part at the point of 400 m to the downstream side were shown in Figure 6.17. As of the clay part, the inclination was higher at the higher leachate height as compared to the bottom of a landfill. The leachate high at the ground surface or 0m was closed to the one with -10m below ground level, while the leachate height of -15 m was a huge difference compared to these two leachate heights. The simple conclusion is that because of the difference in hydraulic head between leachate elevation and the head in the aquifer layer. As for sand part, the incline of contamination curve was an increase in time with the difference in the steady state concentration and no big difference for the inclination of each concentration curve.

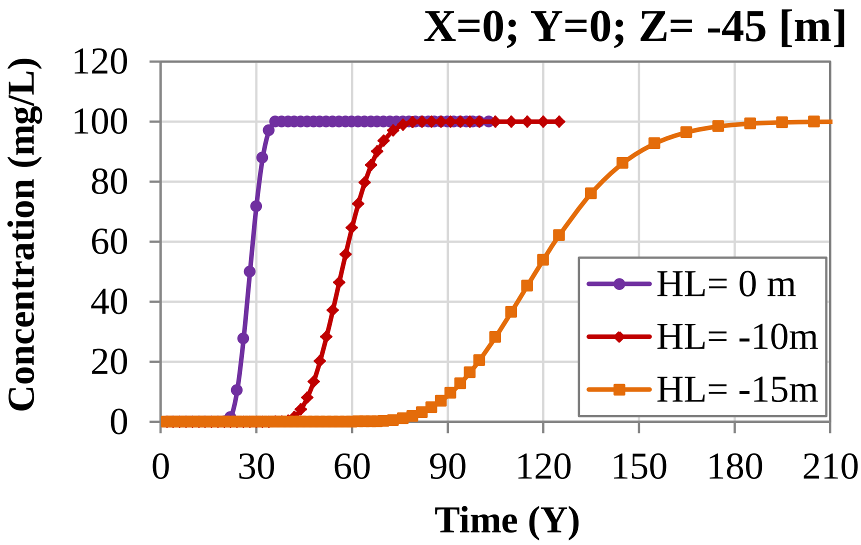

**Figure 6.16** Breakthrough curves in the clay layer of $H_L$ variation at Dangkor landfill

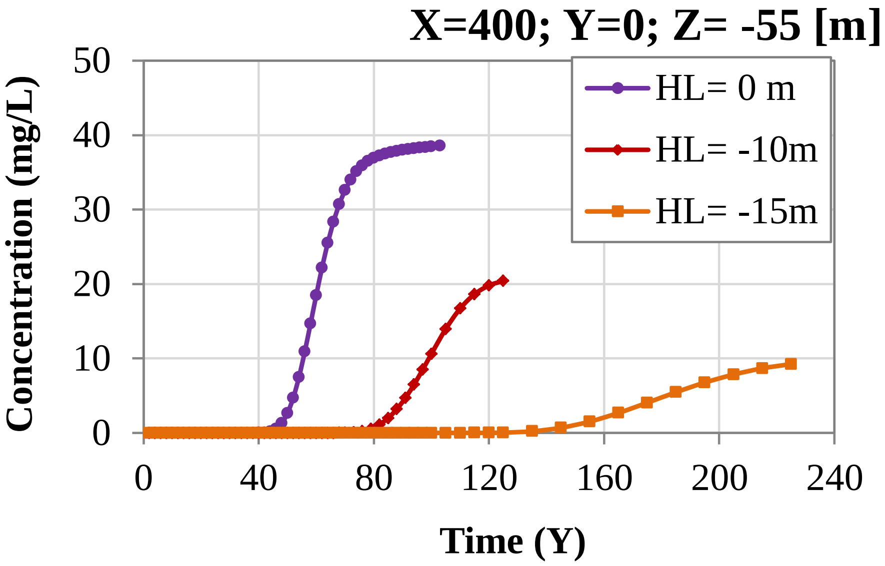

**Figure 6.17** Breakthrough curves in a sand layer of $H_L$ variation at Dangkor landfill

Figure 6.18 shows the combination of the arrival time of contamination and the steady state concentration for both parts (clay and sand). The arrival time of concentration in clay part sampling point was found the longer interval of the leachate of -15m as compared to the leachate height of 0m and -10m. At the same time, the arrival time in the sand part was also found a similar thing at the leachate height of -15m as larger interval and more significant interval compared to clay part. Also, the steady state concentrations at the equilibrium condition were largely different. It is due to the upward force from the groundwater in of the aquifer layer has some effects on it.

Based on these results of leachate height study, the best leachate management in the landfill site would be suggested to include the leachate level control inside the dumped or leachate pond, especially for deep pit disposal in Dangkor landfill. From these evidences, the groundwater can be the safest or least risky, if leachate elevation can be kept at the level of -15m from the ground level as the arrival time of leachate height of -15m is about 120 years from the starting time of landfill operation.

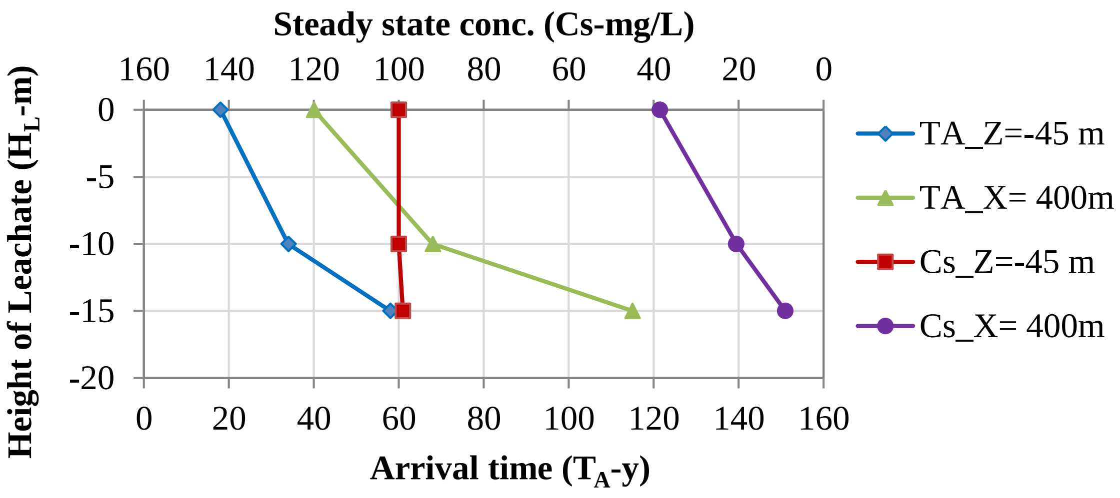

**Figure 6.18** Arrival time and steady state concentration graphs of $H_P$ variation at Dangkor landfill

### 6.4.4 Effects of Hydraulic Conductivity (Kc) at Dangkor Landfill

To evaluate the effects of hydraulic conductivity of landfill liner materials, especially for the clay part (Kc), the simulation of this study has been confirmed the lower Kc is, the longer time of traveling of contaminant to reach the certain point location. Figure 6.19 and Figure 6.20 show the breakthrough curves of contaminant inclinations in the clay and sand part of this study. In the assessment, other conditions outside of Kc, the same set of parameters which is the basic site conditions were used. In the clay part, the clear trend of different Kc from large to small was confirmed to decrease inclination of contaminant concentration with the significant large for the Kc of $5*10^{-9}$ m/s as compared to the Kc of $1*10^{-8}$ and $2*10^{-8}$ m/s. The results of Kc evaluation are similar to the previous study on the parametric study of landfill liner, Kc by Miyano 2016. For the vary Kc in sand part, the breakthrough curve at the specific high of Kc shows faster arrival time of contamination but the steady state concentration was low the lowest; it was due to the higher Kc is lead to the wider contamination plume and the wider area could lower the contaminant concentration as certain concentration with unit area.

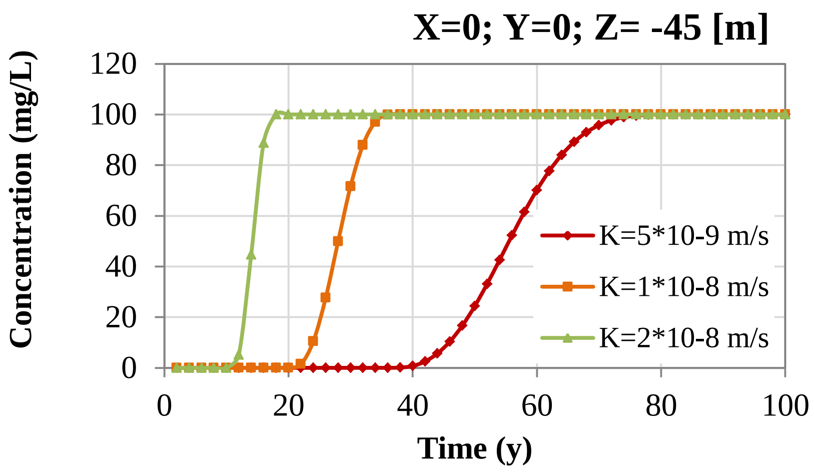

**Figure 6.19** Breakthrough curves in clay layer of Kc variation at Dangkor landfill

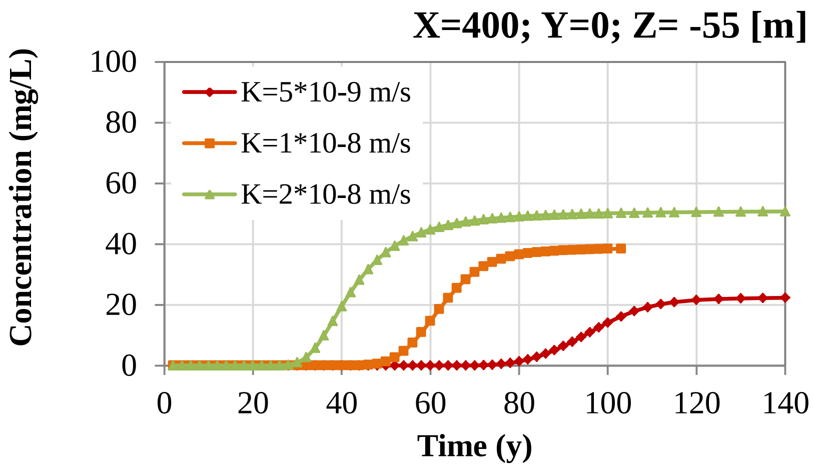

**Figure 6.20** Breakthrough curves in a sand layer of Kc variation at Dangkor landfill

Figure 6.21 shows the arrival time and steady state concentration of contaminant as for variable Kc. Results show the faster arrival time of contaminant as higher Kc. Also, for the steady state concentration was increased with the increase of Kc. However, with the current site conditions, if Kc is larger than the 5*10-8 m/s, the upward contamination plume will occur. It is due to the large velocity in clay part with the low velocity in the aquifer.

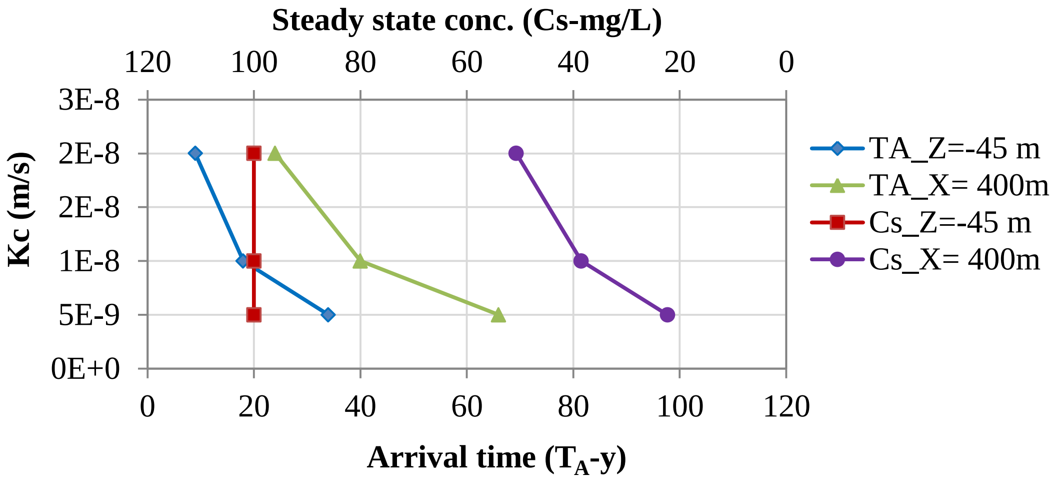

**Figure 6.21** Arrival time and steady state concentration graphs of Kc variation at Dangkor landfill

### 6.4.5 Effects of Partition Coefficient ($K_d$) at Dangkor Landfill

In the evaluation, the effects of the variable partition coefficient (Kd) for contaminant transport in underground condition, four Kd values (0; 0.001; 0.005 and 0.01 L/kg) were selected and simulated in the basic landfill site condition. The same sampling points to previous sections were collected to observe and discuss its behaviors. Figure 6.22 and Figure 6.23 show the breakthrough curves of contaminant concentration inclination for different Kd. For both clay and sand parts, the results confirm as small Kd or Kd close to zero has faster and higher incline of contaminant concentration, while larger Kd made lower incline. Kd is very important parameters to retain and slow down the movement of a contaminant in underground condition, especially in the clay layer as a liner before contaminant reaching the aquifer. It is the key factor affecting the retardation factor (Rd), which helped in retarding the transportation. However, the partitioning coefficient depends on the kind and specific heavy metal, as well as the characteristic of the clay or liner materials.

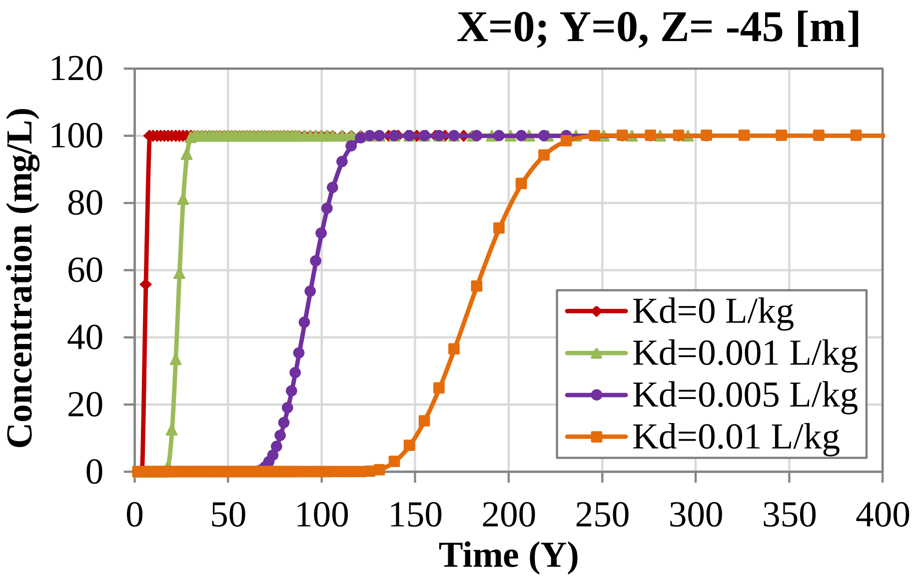

**Figure 6.22** Breakthrough curves in clay layer of $K_d$ variation at Dangkor landfill

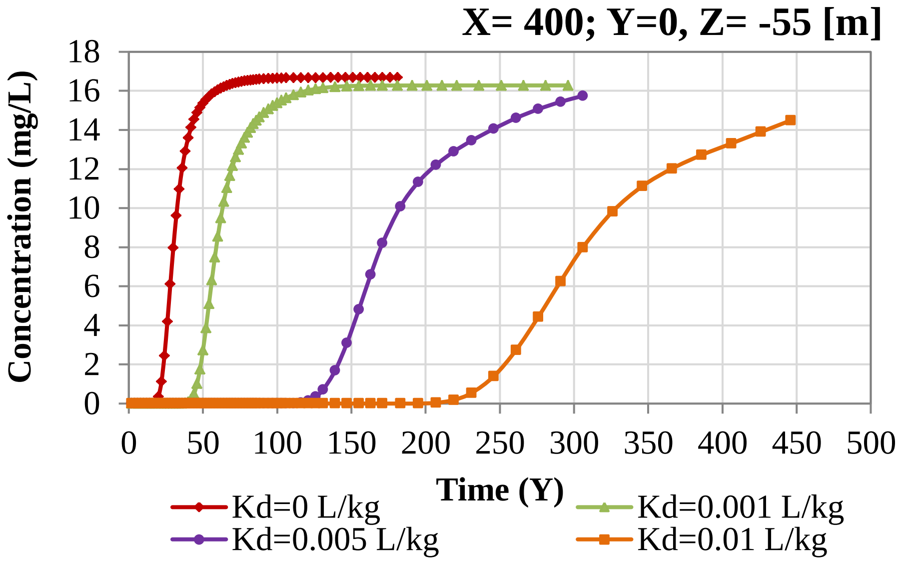

**Figure 6.23** Breakthrough curves in a sand layer of $K_d$ variation at Dangkor landfill

Figure 6.24 shows the arrival time and steady state concentration of contaminant of all selected Kd values. The arrival time was increased with the increase of Kd value same for both clay and sand layers. However, changing of Kd value was not much affected by the steady state concentration at the equilibrium condition. The increase of Kd value is very high effective in retarding arrival time of contaminant, while the reduction of steady state concentration should address or combine with other condition or parameters.

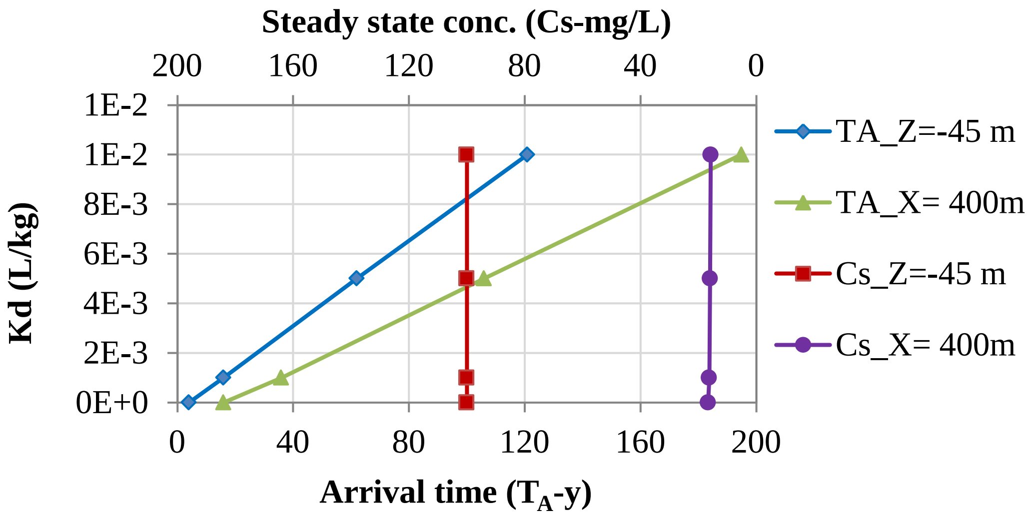

**Figure 6.24** Arrival time and steady state concentration graphs of $K_d$ variation at Dangkor landfill

### 6.4.6 Effects of Leachate Height above Ground Level at Nonthaburi Landfill

The risks regarding the leachate height have been described in the Dangkor landfill, in Cambodia as for leachate lower than the ground level case. The other possible rise up above the ground level of leachate in the dumped pits is due to the height of the garbage over the ground surface together with the cover soil for some landfill, especially in Nonthaburi landfill. The other basic condition of the Nonthaburi landfill shows in Table 6.3. While the hydraulic gradient and hydraulic conductivity at the sand layer were set similar to the Dangkor landfill case, and as well as, the hydraulic gradient of the clay part was also similar. However, the elevation, the layer thickness and hydraulic conductivity and some other parameters were different.

In this landfill case, the sampling points were collected at the same location (horizontal distance) as for sand part (0, 100, 200, 400 and 800 m), while in the vertical direction inside the clay part as shorter distance compared to the Dangnkor landfill case, the sample location was selected at the position of 16, 18 and 20 m. The sampling points and the model ground layer can be seen in Figure 6. 25.

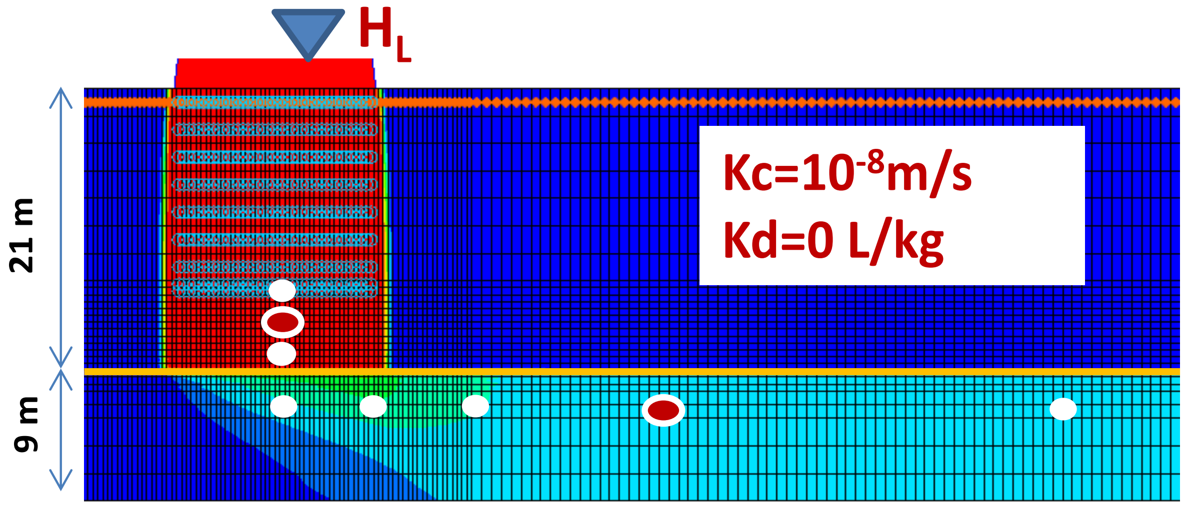

**Figure 6.25** Vertical plume of contaminant transport with sampling points at Nonthaburi landfill

Figure 6.26 shows the breakthrough curves of different leachate height at the central part with the depth of -18 m along the Z axis (clay part). Other cases, the higher leachate level leads, the higher inclination of contaminant concentration. The degree between leachate height of 7 and 3m above ground level was quite similar but significantly lower for the leachate height of 0 m (same as a ground level). However, the breakthrough curves in the sand part at the distance of 400m downstream side was not found large differences of inclination among those leachate heights see Figure 6.27.

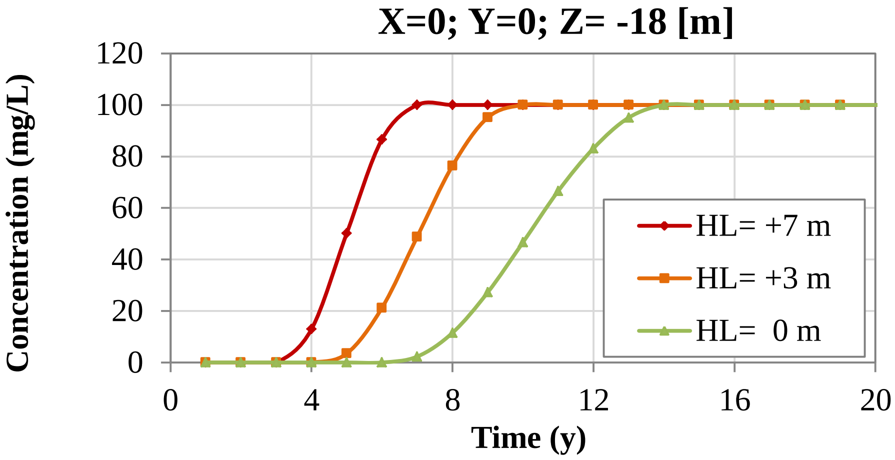

**Figure 6.26** Breakthrough curves in clay layer of $H_L$ variation (above ground level) at Nonthaburi landfill

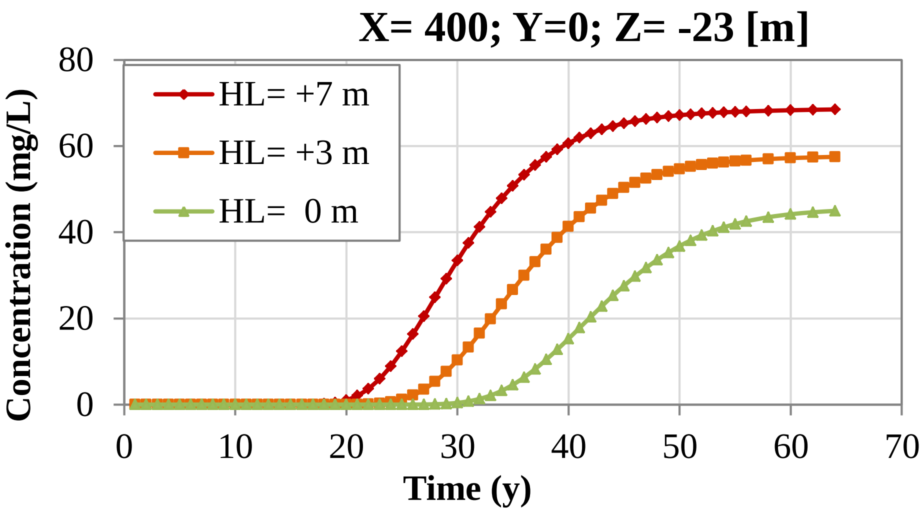

**Figure 6.27** Breakthrough curves in the clay layer of $H_L$ variation (above ground level) at Nonthaburi landfill

It can be confirmed from Figure 6.28 that no significant differences among the leachate height above ground levels regarding the arrival times as compare to the leachate heights below ground level as illustrated in the Dangkor landfill case. However, even though the slight difference of the different leachate heights for both in the clay and sand parts, but the clear difference of steady state concentration in equilibrium were confirmed at the aquifer layer (sand part). The higher leachate level is, the faster the arrival time of contaminant and also the higher of steady state of contaminant concentration as a consequence and similar trends to the Dangkor landfill case.

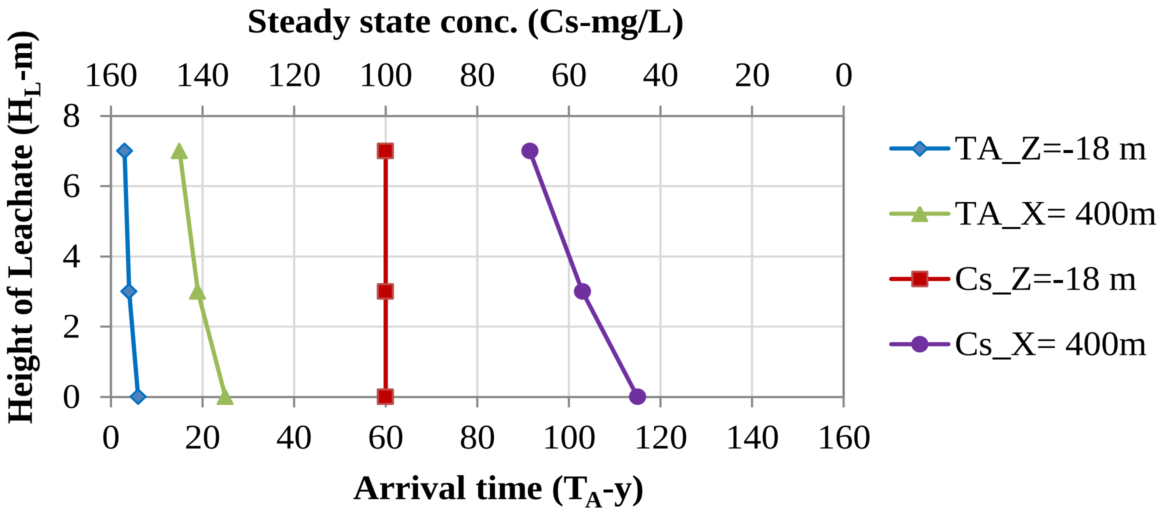

**Figure 6.28** Arrival time and steady state concentration graphs of $H_L$ variation at Nonthaburi landfill

### 6.4.7 Effects of Pit Height and Hydraulic Conductivity at Nonthaburi Landfill

The effects of pit height ($H_P$) at the Nonthaburi landfill was also confirmed with the similar results to the Dangkor case but different level, as shown in Figure 6.29. In this condition, the depth of -18 m was the most dangerous to the groundwater, due to the clay layer thickness was only 3 m left, according to the geo-survey report, KRUNGTHEP GROTECHNIQUE Co., Ltd **(2013)**. And the trends were similar for both clay and sand parts at of arrival time of contaminant. However, the significant delay of the arrival time of contaminant can be found of the depth of -10 m, which is the longest arrival time, as well as the lowest steady state contaminant concentration as for sand part.

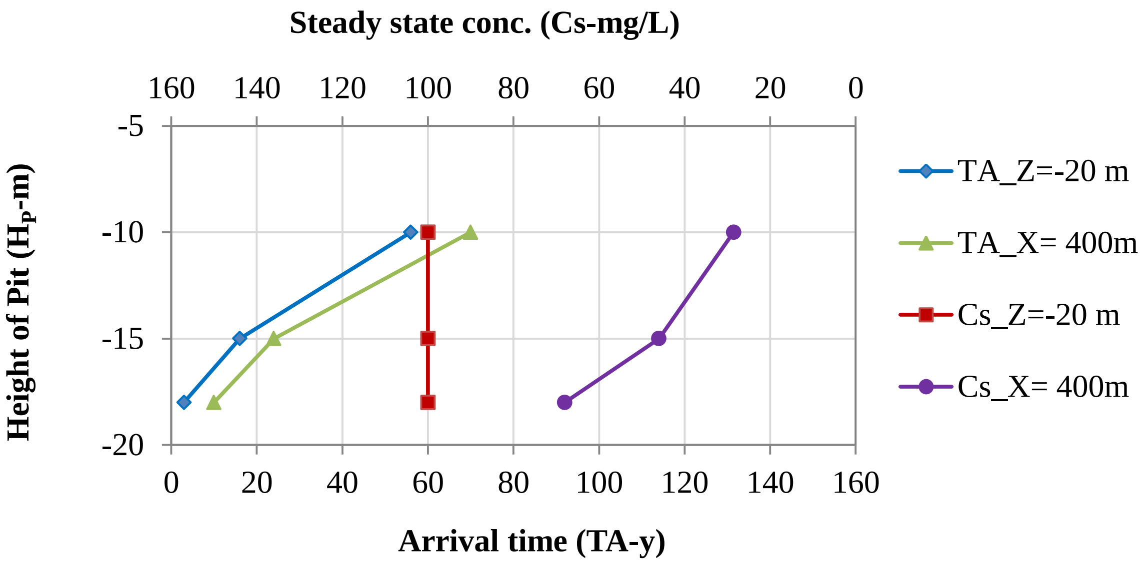

**Figure 6.29** Arrival time and steady state concentration graphs of $H_P$ variation at Nonthaburi landfill

As for the effects regarding the hydraulic conductivity (Kc) as shown in Figure 6.30, the significant longer arrival of contaminant can be found at the Kc of $1*10^{-9}$ m/s, while slight differences can be found for Kc of $1*10^{-8}$ and $5*10^{-9}$ m/s, especially in the sand part. According to this simulation results, the groundwater will be safe if the hydraulic conductivity as low as of the study by Miyano (2016) found the Kc about $10^{-9}$ to $10^{-10}$ m/s. With this landfill condition the large difference of the Kc of $1*10^{-9}$ m/s, not only the longer arrival time of contaminant but also the smaller steady-state contaminant concentration at the equilibrium condition. The arrival time showed above the 80 years' time, while the equilibrium concentration was about 15 mg/L after the very long time is steady state. This results could be confirmed by the study of Tsanis (2006) with the study found the groundwater flow is most sensitive to the changes in the hydraulic conductivity and to a lesser extent to changes in infiltration and leachate infiltration flow.

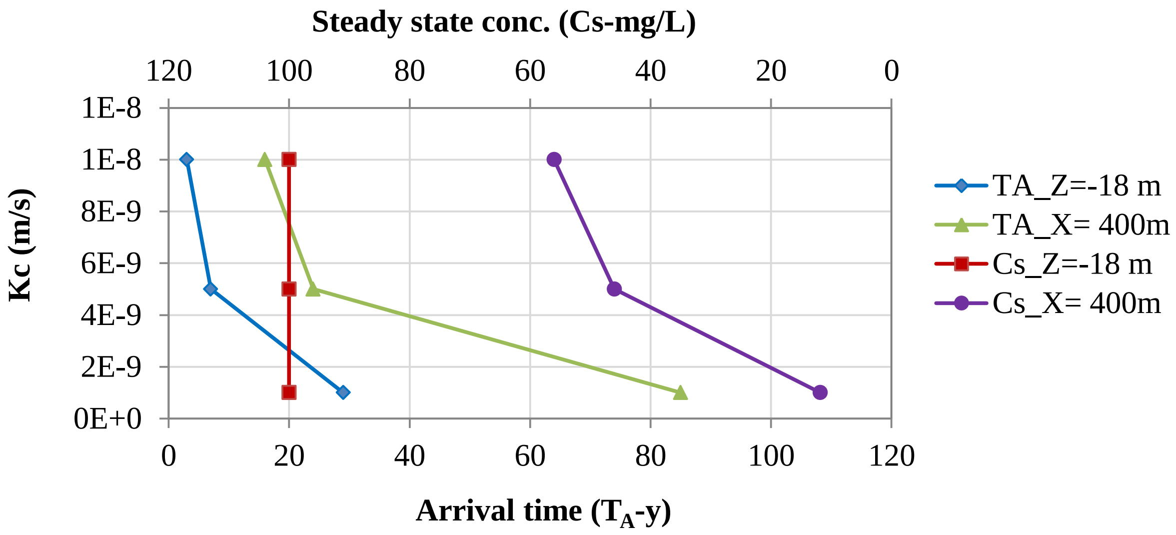

**Figure 6.30** Arrival time and steady state concentration graphs of Kc variation at Nonthaburi landfill

### 6.5 Model Concerns and limitations

From the simulation experiment before using the GMS software, some of the basic key observation can be pointed out as following issues:

- GMS: MODFLOW and MT3D can provide convenient input of parameters and boundary conditions and good visualization options for the output to interpret results better.
- The effective use of the software (or any modeling software) can only be done if the user well understands the theory.
- The selection of input parameters can produce significantly different results. Hence, the input parameters should be selected with scrutiny to model real-world and theoretical problems properly.
- Results should always be double-checked and analyzed carefully.
- Model grid and mesh size (Coarser and finer)

  - The finer mesh gives the higher concentration as compared to coarser mesh
  - The software gives the average value in the grid size
  - The smallest size allowable is 16.67 cm.
- Boundary and contaminant point source location
  - Make sure to provide enough distance between the contaminant source and model edge to avoid the flow over the borders, and the upward flow of the contaminant plume.
  - Specify head need to be set to define the flow direction
- The unit should be consistent (some units have given by the software)
- Time step
  - Smaller time step gives a smoother graph and higher accuracy
  - A sudden change in time step should not be used, to avoid the effect of artificial oscillation as results of overshoot and undershoot.

## 6.6 Conclusions

The simulation studies of two representative sites have been conducted with the current site conditions and several possible changes in both site condition, and also the natural clay barrier has been assessed. Groundwater and contaminant transports in underground condition highly depend on the several landfill site conditions, such as groundwater level, relative pit depth (pit height), clay barrier layer thickness, leachate height and other geological condition, i.e. hydraulic conductivity (Kc) and partitioning coefficient (Kd). Moreover, some of the key conclusions from this chapter can be drawn as follows:

- The depth of the pit or pit height is very sensitive to the groundwater and contaminant transport in underground condition. The deeper pit high could cause the faster of the arrival time of contaminant and higher steady-state contaminant concentration. It can suggest the pith height of the current landfill conditions should not lower than the depth of 30m and 15m below ground surface as for Dangkor and Nonthaburi case, respectively. The shallower pit height will be the significant reduction risks to the groundwater contamination from the landfill leachate

- The leachate height significantly affects the contaminant transport processes in underground conditions. Therefore the control of leachate levels inside the pits by proper drainage could reduce of the risk to the groundwater.

- The soil permeability, presented as hydraulic conductivity is one of the most sensitive to the groundwater flow and contaminant movement in the underground conditions. The higher hydraulic conductivity is the higher risk to the groundwater.
- The partitioning coefficient of the clay layer is one of the powerful factors controlling the movement of the contaminant of the clay layer. The higher partition coefficient can be retarded and slow drown the contaminant movement.

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# Chapter 7

# Conclusions and Recommendations

This chapter emphasizes the key findings and conclusion of the study, such as the main characteristics of leachate, sediment, groundwater and surface water as well as the potential risks to the surrounding environments. In the end, the chapter explains the possible solutions and the recommendation to the local authorities where the study landfills located.

## 7.1 General Conclusions

The major conclusions drawn from above chapters in this study are the combination of field investigation, in-situ measurement, and laboratory measurement and simulation study To visualize the flow of pollutants through the soil in a broader sense, the transportation of contaminants through the soil as landfill liner was modeled using software "groundwater modeling system-GMS). GMS software in combining with the landfill site conditions from common landfill practiced in the Indochina peninsular region, in order to identify the future potential risk to the surrounding groundwater. The detailed conclusions can be summarized as follows:

### Landfill Site Characterization

- Complicated MSW composition since no proper waste separation at the source and landfill site
- Waste composition is the organic waste majority
- The common dumping method is a trench or excavated method
- Deep pit disposal for MSW has been used as common landfill practice in the region.
- A low permeable geological barrier as natural clay liner, Kc=$10^{-(8-9)}$ m/s by Oedometer test
- Leachate drainage and treatment systems were not applied and improper leachate management
- Uncontrolled release of fresh leachate to the surrounding environment due to the poor landfill management

### Landfill Leachate Characterization

- Most of basic parameters for all the leachate samples show high concentration compared to industrial effluent standard of Thailand.

- No significant seasonal variation was observed for the heavy metal (HM) concentration in the fresh leachate with covered areas but slight change for the leachate from opened space landfill areas. It is due to the covering soil can protect leachate from the dilution by the rainwater.

- Relatively high HM concentrations were observed in the leachate; dissolved liquid part concentrations were over the groundwater standard, and total concentrations are several times higher than the industrial effluent standard of Thailand.

- Total HM concentrations of leachate are much larger than HM concentrations dissolved in the liquid part of leachates, due to the major HMs adsorption in the suspended solid contains in the leachate.

- The major portion of the HMs in leachate is partitioned in the suspended solid.

- No significant seasonal difference of HM contents in the suspended solids but higher suspended solids concentration in the dry season than the wet season was confirmed.

### Influential Factors to Leachate Quality

The main impact factors found in this study were based on the landfill site conditions, discussed as follows:

- Precipitation was caused by significant dilution of the leachate contamination, which is one of the main factors changing the leachate quality. On the other hands, leachate quantity is very much affected by the rainwater but it is not deeply studied in this research.
- Soil cover can protect the water percolation into the waste layer; the leachate quantity can be reduced with the increase of contamination level for some period of time before stabilizing of the leachate.
- Waste thickness (waste height) is the function of the waste volume since the waste height is the height of unit area. Increasing of waste height is the main factor of

contaminant concentration increase, due to the waste is the main source of pollutions.

- Waste fire in the deep pit is one of the important factors reducing the contamination level of the leachate inside the pit. It is due to the charcoal from the waste material burn can adsorb the existing heavy metals and accelerating the solid sedimentation, as well as the fire can reduce the huge amount of the waste inside the pit.

### Landfill Sediment Characterization

- Leachate sediment contained high fine particle which is considered as the major absorbents of HMs in this study case.
- No significant seasonal difference of HM content in sediment has been confirmed.
- HM contents in the sediment were higher than suspended solid of the leachate, which is due to the longtime adsorption and accumulation of HMs in the sediment. The future risk of the sediments could be suggested, especially at LDP of Nonthaburi landfill site.
- HM contents in the sediment are lower than the soil standard limit of Japan

### Groundwater Characterization

- The contaminated landfill leachates have not influenced groundwater of nearby landfills for all study sites. It is due to the low permeable geological condition surrounding the dumped pit areas.
- Evidence of contaminant expansion can be seen as the case of nearest observation well (OSW1) of Nonthaburi landfill; it can be confirmed the future risk of nearby groundwater especially the deep pit disposal which reduces the natural barrier layer thickness.
- Most of the existing heavy metals as background value contained in the groundwater are lower and in between the environmental and effluent standard.
- No significant seasonal difference of HM concentrations in the groundwater due to the low contaminant concentration without the influence from the leachate.

### Surface Water Characterization (Particular case of Dangkor landfill)

- The landfill leachates influenced surface water at the Dangkor landfill areas, it is due to the uncontrolled release of fresh leachate to the surrounding areas especially to the nearby natural creek.
- Significant seasonal variation of surface water quality has been confirmed as a higher concentration in the dry seasons than wet seasons, which can be clear evidence of surface water contamination by the uncontrolled release of fresh leachate to surrounding areas and water body.
- Most of basic parameters and assessed HM concentration were higher than the effluent and groundwater-surface water standard limit.

### Future groundwater risks

- Groundwater and contaminants transportation processes are highly depended on the landfill site conditions as key factors listed as follows:
    - Groundwater level (aquifer hydraulic gradient)
    - Pit depth (lower natural barrier layer thickness)
    - Leachate height (vertical hydraulic gradient)
    - Geological conditions (hydraulic conductivity, Kc and partitioning coefficient, Kd).
- The deep dumped pit in the landfill could cause large percolation of contaminants and the greater risk to the aquifer/groundwater.
- The pit depth greater than 20 m are in the high risk of groundwater contamination of the current landfill condition, other controlling factors need to be applied in order to reduce the future risks, such as leachate elevation or leachate height.
- The leachate height was significantly affected by the contaminant transportation process in underground conditions. Therefore the control of leachate levels inside the pits by proper drainage could reduce of the risk to the groundwater. Keeping the leachate level inside the pit lower than the ground surface of 15 m, as for the 30m pit depth will be secured the groundwater from the landfill pollution
- The soil permeability and chemical sorption on the clay layer is the important parameters controlling the fluctuations of groundwater and contaminants.

## 7.2 Summary of Investigation Flow and Results

In addition, to wrap up the entire flows of this study, Figure 7.1 shows the general chart of leachate production, including the surrounding environments which affected by the leachate as commonly found in the previous studies and literature. Figure 7.2 shows the whole flowchart of the related leachate production, problems and the results obtained from this study. Initially, the chart consisted of 3 main parts; the primary sources of leachate production, the landfill site conditions, and management affected the leachate production and the final impact of leachate on surrounding environments. The text box orientated in a different color as the new issue found in this study, the confirmation of previous studies and literature have been done, the main source of leachate production and the further need of detailed study in the future (Figure 7.2).

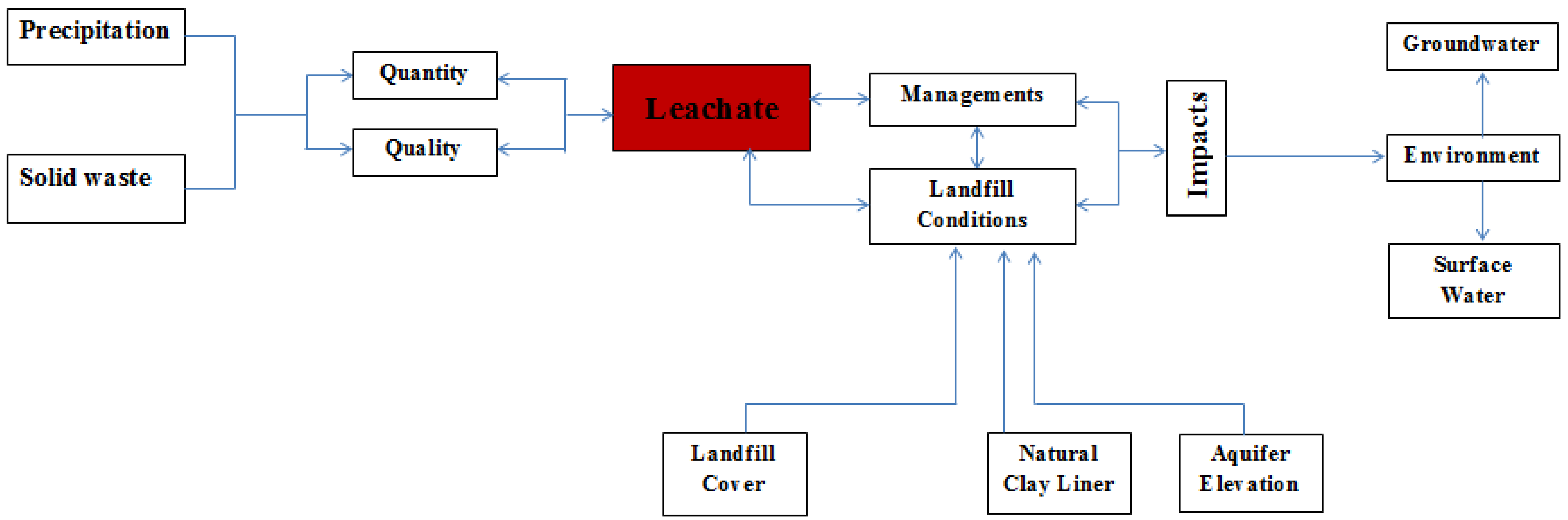

**Figure 7.1** General chart for leachate production and its effects to the surrounding environments

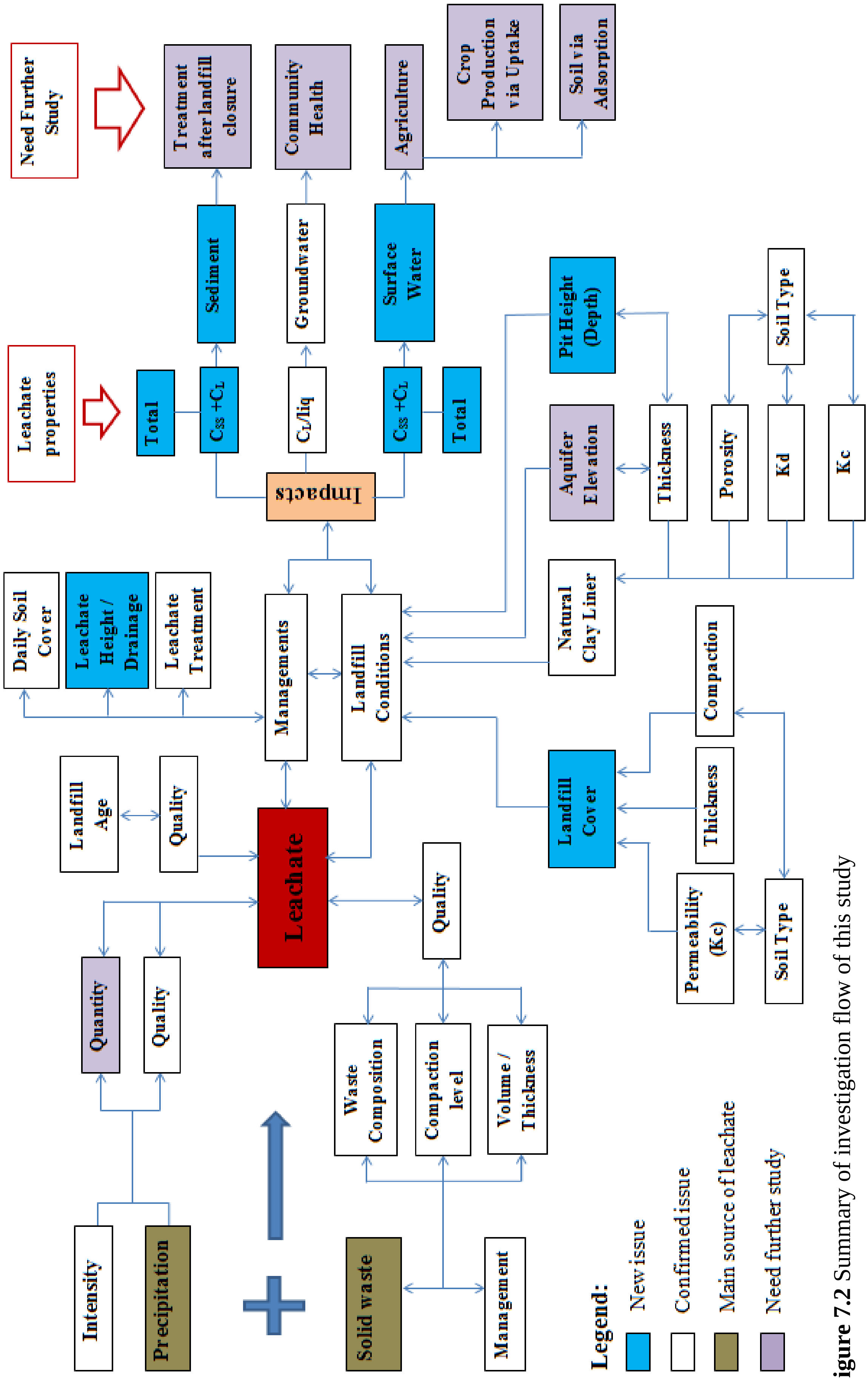

**Figure 7.2** Summary of investigation flow of this study

## 7.3 Recommendations

The recommendation from this study finding could be separated into two groups of considerations:

### To local landfill authority/government

Outside of solid waste management at the sources (effective 3R practices), some concerns base on the results of this study are pointing as follows:

1. Uncontrolled release of leachate from the landfills should be solved (stop), to mitigate the risk to the surrounding surface water and agriculture areas.
2. The major contaminants are partitioning in the suspended solids, the filtering of leachate as pre-treatment before releasing to nearby areas and creeks will be highly reduction of contaminants.
3. Sand filter or sand bed technique would be appropriate in these landfills due to the simple in operation and management, and low technical support is needed.
4. The longer monitoring of the leachate and groundwater quality is needed, due to the possible risks from deep pits and leachate height are found in this study, as well as the evidence of contaminant plum expansion was found, especially at Nonthaburi landfill.
5. Since the high HM contents were found in the landfill sediment, the treatment of the sediment after the closure is needed, due to the huge volume of sediment at the bottom of leachate pond will be exited and continuous of expanding contamination to surrounding area and groundwater in the future.

### To researchers/future recommended study

1. In the simulation of the current study, many parameters are assumed as representative of the site conditions. Therefore, a more advanced study on the site geologies is recommended for the better and accurate results of prediction.
2. This study has not been investigated the leachate quantity and sediment volume from the real site. Therefore, the related study on these issues will be helpful in the planning of leachate and sediment treatment and remediation.

3. All of the landfill sites in this study are surrounded by the agriculture and paddy fields; therefore the further investigation of agricultural soil contamination of nearby areas will be useful to provide the future risk consideration for both landfill planning, and the action need to be done after constructing a landfill to reduce the consequent risks.

4. The study on the rice production contamination of the surrounding paddy fields will also be good indicator or evidence to prove as the risk to the human and community health.