Investigation on Shortening of Post Closure Duration in a Hazardous Waste Landfill

by

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16321

Progress Report submitted to the

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CERTIFICATION OF APPROVAL

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Approved by,

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UNIVERSITI TEKNOLOGI PETRONAS
TRONOH, PERAK
January 2016

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

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ABSTRACT

Secured Landfill or Hazardous Waste landfill is an engineered structure that is fully equipped with standards regulated components necessary to prevent any waste contaminants from polluting the environment and harming human health. As the landfill reaches its service life, the landfill is required to be closed and subjected to 30 years of post-closure care. An extensive post closure care period demands significant funding and resources to cover the cost of landfill aftercare. Aside from financial issue, post-closure care of hazardous waste landfill is emphasized to ensure maximum protection towards the environment and human health. In this case, reduction in post closure care period is believed to be a solution to the problem. Thus, this study aims to determine the completion criteria of post-closure care and investigates on the reduction of post closure care period in a hazardous waste landfill. The completion of the landfill post closure care was assessed based on three approaches which were impact/risk assessment approach, performance based approach and target values approach. The impact/risk assessment approach evaluates potential hazardous risks associated with the landfill as for this study are the water infiltration rate and water distribution in the landfill. The effect of these two factors was analysed through the leachate generation model. The performance based system was used to evaluate the landfill performance after its closure by studying different performance of landfill containment system. The target value approach was a stage whereby the desirable state of the landfill must be achieved in order to terminate the post closure care procedure. In this study, the tolerable pollutants concentration within the landfill was the target value to be achieved in order to complete the post-closure care. Finally, the post-closure care period was determined at which it can be reduced to 3 years. Also, an economic analysis is conducted to verify the advantage of reducing the post-closure care period. As a result, the post-closure care period of hazardous waste landfill can achieve a period of less than 30 years and was calculated to be more feasible than the cost of 30 years of post-closure care.

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CHAPTER 1: INTRODUCTION

1.0 BACKGROUND STUDY

Solid and hazardous waste has become a major environmental problem in Malaysia for a very long time. Hazardous waste, in general, is a type of waste that poses harm to the environment and human health. The wastes are usually generated from sources such as electronic devices and toxic chemicals which can be found in household materials and industrial productions. Statistics showed that rapid growth of solid and hazardous waste generation in the country is so alarming that it has become a constant struggle to cater to its waste management. The situation is then countered by an enforcement of The Environmental Quality Act 1974 where regulations on hazardous waste were introduced. Therefore, secured landfill is still the ultimate choice for solid and hazardous waste disposal (Scharff, van Zomeren et al. 2011).

Secured landfill or Hazardous Waste landfill is a carefully engineered concept whereby a structure is built into or on top of the ground for allocation of waste to prevent contamination between the hazardous waste and the surrounding environment, also to prevent serious hazards to human's health. An engineered hazardous waste landfill facility design includes a combination of natural protection and engineered systems that work together to contain or control the waste (Canadian Council of Minister of the Environment 2006). Generally, landfill is made up of few components in order to comply with certain design criteria to ensure landfilling practices can guarantee a safe environmental solution to waste generation and hazardous waste treatment. These components consist of a durable and puncture resistant liner system, an integrated leachate collection network system within the landfill, storm water drainage, landfill gas collection system and groundwater monitoring station (Freudenrich, 2000).

As the landfill has reached its life span, it is subjected to a landfill closure. It is a requirement by Department of Environment for the landfill owners to produce a detailed safe closure plan for their secured landfill before they proceed with the post-closure care (UNEP, 1995). After landfill closure, the monitoring and maintenance work for the landfill is continued. This process is known as the post closure care of the landfill. The monitoring and maintenance of liners, final covers, leachate collection systems, leak detection system and gas collection system at the landfill site ensures the protection of environment and human's health from any form of hazardous constituents that may be released from the landfill. The common post closure care period is 30 years but the duration can be reduced or extended with the permission of the authority (Environmental Protection Agency, 2012).

Post closure care of a secured landfill demands an extensive period of time due to the critical procedure need to be taken to safely ensure the landfill emissions no longer pose potential threat towards the surroundings. Surely, the post closure care will require a significant amount of funding to assure the continuity of the aftercare, not to mention the resources to handle the process for the next 30 years per se. On a side note, shortening the period of post closure care in a hazardous waste landfill might just be the solution to the problem of aftercare funding and resources provision. It may also be the environmental solution needed to the safety issue commonly raised by the society on landfill emission to the surroundings.

1.1 PROBLEM STATEMENT

As a part of the environmental regulations enforced on all landfill operators or owners, the post closure care of the landfill is crucial as to avoid any contamination coming from the landfill that may have an adverse effect on the environment and human health. The aftercare period of the landfill is dependent to the landfill emission which in most cases, the aftercare period takes up to 30 years until the landfill is assured to be secured from any threat to the environment or humans after completing the procedure (Laner, Fellner et al. 2012). In order to cater to the post closure care of the secured landfill, significant amount of funding and resources are important to support the process until the completion of the aftercare. The extensive period for the post closure care raised up two concerns on the funding of the aftercare. First of all, the funding accrual mechanism for the landfill aftercare presently may not consider the potential excess of post closure care period; second, proper management of the aftercare funding is crucial to enable appropriate protection of the environment, human health, financial health of landfill operators and to avoid funds for the emergence of landfill being exhausted (Morris, Crest et al. 2012). Therefore, the landfill is expected to reach its functional stability in a fast pace to ensure the funding for the aftercare completion is within the time frame (Scharff, van Zomeren et al. 2011)

Aside from the funding issue, running a hazardous waste landfill facility has always been a risky operation. The waste disposal in the landfill resulted in an increasing awareness to negative health effects for the residences living nearby the sites (Vrijheid 2000). In addition, the landfill emission is pointed out as the main reason for the health concern. Given the allowable landfill emission can only be determined after the completion of landfill aftercare, the landfill operator or owner will have to face this issue for a long time before it can be solved. Essentially, time is the main factor to the problems of the post closure care of the secured landfill. In order to counter the problems, the reduction of the landfill post closure care period is believed to be a cost-effective strategy as well as an environmental solution to health effect awareness raised by the community nearby the landfill site.

1.2 OBJECTIVE AND SCOPE OF STUDY

The post closure care of the landfill is defined as the time at which the authorities approve the end of regulated aftercare and release the owner or operator from responsibility for the site since the landfill is unlikely to present threats to the environment and human health. The procedure for landfill aftercare involves the landfill emissions monitoring systems and receiving systems, maintenance and control of landfill facilities and site surveillance. These criteria are utilized to evaluate the aftercare but in terms of aftercare and aftercare completion evaluation, different suggestions arose (Laner, Fellner et al. 2012). In order to complete the landfill post closure care period, a guideline enables the landfill owner or operator to evaluate the completion of the landfill aftercare. Based on the guidelines or the criteria of the aftercare completion, the shortening of post closure care period in a hazardous waste landfill can be investigated.

The investigation on the reduction of the landfill post closure care period will be based on the monitoring of three (3) main components of a secured landfill which are leachate monitoring, groundwater monitoring and the monitoring of the performance of the landfill final cover. The monitoring of gas collection in hazardous waste landfill is excluded. This is because hazardous waste management in Malaysia mostly practice treatment process like incineration before the waste is being landfilled. Therefore, minimum gas is generated from the waste as they are solid material of non-biological origin.

From the issues discussed, the objectives of this investigation comprises of these two:

1. To estimate hazardous waste landfill post closure care completion using the site-specific criteria derivation.
2. To investigate the shortening of post closure care duration in a hazardous waste landfill.

1.3 STUDY AREA

The site specific hazardous waste landfill is located in Bukit Nenas, Negeri Sembilan, about 15 kilometre from major town of Sepang due northwest and 16 kilometre from Seremban due northeast of the site area. The hazardous waste landfill has been operating for 18 years from 1997 to 2015. It consists of 6 cells in total with a waste capacity of 1.6 million tonnes over 45 acres to contain all the disposed hazardous waste. The landfill accepted a daily waste intake of 300 metric tonnes per day including slags from the incineration facility, solidified waste from the solidification facility and external wastes that fulfil the direct landfill acceptance criteria. It is surrounded by residential areas within 2km to 5 km radius which also connected to several river branches. The hazardous waste landfill is currently undergoing an expansion development whereby a new hazardous waste landfill will be constructed on top of the existing landfill. The objective of this expansion development is to provide a bigger volume capacity to cater to the increasing waste intake.

CHAPTER 2: LITERATURE REVIEW

2.1 POST CLOSURE CARE OF A HAZARDOUS WASTE LANDFILL AND ITS COMPLETION

With the increasing amount of hazardous waste generation around the world, landfill has become a dominant solution to hazardous waste disposal. According to The World Counts (2015), more than 400 million tonnes of hazardous waste is produced each year globally. The handling of hazardous waste is so meticulous that the end solution to treating the waste is by disposing them to the landfill. This fact resulted in hundreds of thousands of waste containment sites operated around the world. Eventually, all these landfills will reach their estimated service life and the closures of the landfills are necessary. Aside from the closure of the landfill, the landfill owner or operator is obligated to continue monitoring and maintaining of the landfill to protect against any hazardous release from the landfill to the environment (USEPA, 2014). This procedure is known as the post closure care period.

Strategies for the management of closed landfill are required to inure cost effective protection of the environment and human health. The post closure care activities will include leachate management, groundwater monitoring, and inspection and maintenance of the final cover. The aftercare of a closed landfill will go through several typical process which are the monitoring of landfill emissions and receiving systems, maintenance and control of landfill facilities and site surveillance (Laner, Fellner et al. 2012). These are the common criteria needed to evaluate the landfill aftercare.

The aftercare completion on the other hand, is the moment at which the responsibility for the remaining risk of a landfill is transferred from the operator to society, meaning the organization that is willing to accept the remaining risk and emission potential. Previous research studied on the post closure care and its completion is analysed and the regulatory approaches for the completion of landfill aftercare are reviewed. Based on the research done by (Laner, Scharff et al., 2011) three approaches are categorized as:

1. Impact/risk assessment approach evaluates the site-specific condition to determine the impact/risk associated with the completion of the post closure care and landfill end use.
2. Performance based approach evaluates the landfill performance by assessing the ability of the landfill components to function effectively in providing maximum protection to the environment and human health.
3. Target values approach which is defined as the completion criteria need to meet in order to terminate the post-closure care.

Impact/risk assessment approach evaluates any form of risk associated with the landfill as long as the landfill represents a hazard and has the ability to harm the environment and human health. Besides that, this approach is also part of the procedure to determine the completion of landfill post closure care. The impact/risk assessment evaluates all the risks that are associated to the site-specific landfill until an acceptable level of risk for the landfill site is defined which leads to the end of the aftercare (Pivato, 2003). An acceptable risk is agreed when the landfill achieved its functional stability whereby it no longer poses threat to the environment and human health. This condition must be assessed with the consideration of leachate concentration, performance of the containment system, the effect of contaminants to groundwater and other relevant factors.

The impact/risk assessment approach is followed by the performance based system which aims to assess the landfill performance with respect to the landfill post-closure care procedure (Morris, Barlaz, 2010). This method must be site-specific to ensure the reliability of the performance data and providing the appropriate guidelines to progressively reducing the post-closure care period. In general, the performance based system analyses the concentration trend in leachate from landfill closure to post-closure care, the effect of the performance of containment system, the pollutants migration to the groundwater and groundwater pollution. Through these analyses, the performance of the landfill after its post-closure care can be estimated.

(Laner, Crest et al. 2012) suggested that the evaluation of the landfill aftercare completion is best to be approached with performance-based procedure by combining target values approach and risk assessment method. The target values approach focuses on achieving the desirable state of the landfill whereby the post-closure care could then be terminated. This approach fulfils the overall completion criteria of a landfill post-closure care by considering the quality of the containment system and the tolerable pollutants concentration level produced from the landfill. Leachate and landfill gas must be controlled and treated to a level that is acceptable for the environment (R. Stegmann 2003). Therefore, the method to reduce landfill contaminants generation is rigorously discussed in this method to achieve the reduction of post-closure care period.

These approaches are incorporated into the derivation of the aftercare completion criteria as a guideline to ensure the evaluation of the landfill aftercare completion considers all aspects associated with the environmental impact on the landfill. The procedure is then developed to derive the site-specific criteria for the landfill aftercare completion (Laner, Fellner et al, 2012) as described below.

- Characterization of the landfill environment system

  Evaluate the collected data and information on the condition of the landfill, the barrier system and the deposited waste and associated pollutants discharge.

- Emission parameters and scenario analysis

  Establish the pollutants parameters to be fitted into the model in order to estimate the future discharge. The pollutants generation model is adapted into various scenarios to investigate performance of the entire landfill.

- Transport pathways and pollutant migration

  The estimation of future pollutants discharge from the scenario analysis will provide input to pollutant migration modelling.

- Environmental compatibility and completion criteria

  Concentration obtained from the migration pathway will be compared to a certain level of compliance to determine the minimum level of landfill discharge allowed.

- Monitoring and surveillance

  Establish the observation on the performance of the landfill in accordance to the estimated landfill discharge.

2.2 SITE-SPECIFIC CRITERIA DERIVATION

2.2.1 LEACHATE GENERATION MODEL

A mathematical formulation developed to calculate the concentration of the leachate substances was found by Belevi and Baccini (1989). The model formulation was modified and taking into account the water flow heterogeneity and the leachate release mechanism occurring within the landfill (Laner et al., 2011). The formula is adapted into a leachate generation model to estimate the concentrations of established leachate substances. The result presented in the leachate generation model shows the substance concentrations in the leachate decrease exponentially with the increase of liquid-to-solid ratio of the deposited waste (Laner, Fellner et al, 2012). The liquid-to-solid ratio, L/S is defined as the amount of water in litres that passed through 1 kg of waste dry matter (Beaven and Knox, 1999). The model formulation requires site-specific data in order to estimate the generation of leachate in the landfill during post-closure care. The information needed include the concentration of leachate substances after landfill closure, the mobilizable fraction of each substance, heterogeneity of water flow in landfill, the annual water infiltration rate at site and the amount of waste disposed in the site-specific landfill.

On a side note, the described leachate generation model formulation assumes constant water flow patterns within the landfilled waste and leachate release mechanisms. In the next approach, the scenario of containment system performance is assessed and incorporated into model formulation to investigate the effect of a change in the landfill's water flow pattern to the leachate generation.

2.2.2 CONTAINMENT SYSTEM

The purpose of landfill containment system is to reduce the potential of water infiltrating into the landfill and percolating through the groundwater, distance the contact between the waste and environment and to control the emission of landfill gas (Hauser, Barron et al, 2001). Considering the primary requirements of the landfill containment system, the most important aspect of barrier performance are proper design, construction of the system and several other factors (Bonaparte et al., 2002). Besides that, long-term performance of the containment system must be taken into consideration as a precaution of future landfill discharge. According to Inyang (2004), the long-term performance of the landfill containment system depends on the stresses applied on it. It is estimated that long-term performance of different barrier components assuming there is no maintenance and repair taking place may extend the landfill performance from several decades for leachate drainage systems to geologic time for low-permeability mineral liners (Rowe, 2005). When the site-specific landfill lacks of data to evaluate the long-term performance of containment systems, a set of scenarios is used to define the effect of different containment system performance levels on landfill discharge. The barrier performance levels are estimated based on an evaluation of the actual system design and function derived from experts' evaluation. The different containment system performances levels are combined with the established leachate generation model to estimate the future landfill discharge and its effect to the environment. However, the reliability of the performance of containment system is still uncertain due to insufficient information data. The study of the containment system performance level intends to show the effect of different barrier performance on the landfill discharge. The landfill performance eventually still relies on the future condition of the landfill.

2.2.3 POLLUTANTS MIGRATION

The results from the combination between the scenario of containment system performance and the leachate generation model are used as inputs to the pollutant migration to the groundwater. The migration of leachate from the landfill percolating through the subsurface is emphasized. The pollutant migration pathway is a major contribution to the long-term pollution within the landfill (Kjeldsen et al., 2002). The study of pollutant migration aims to understand the ability of natural environment to mitigate the impact of leachate discharge to groundwater. The natural environment mentioned is regarded as natural attenuation process whereby the nature ability to reduce the toxicity and concentration of pollutants in the groundwater through naturally occurring physical, chemical or biological process.

Based on the pollutant migration, pollutant concentrations are calculated at each relevant Points of Compliance (PoCs) as showed in the example of schematic diagram in Figure 2.1. The leachate discharge from the landfill is taken as the source of contaminants and used to assess the concentration of pollutants at each environmental medium. As different performance of containment system result in different leachate generation rate, the pollutant concentration is calculated using a mass balance approach whereby the maximum leachate concentration equals the concentration entering the groundwater.

The estimated maximum concentrations along the migration pathway are used to derive the attenuation factors (AFs). The AF is defined as the ratio of the maximum concentration at the source to the maximum concentration at each respective points of compliance (AF $=C_{max,cource}/C_{max,PoC}$).

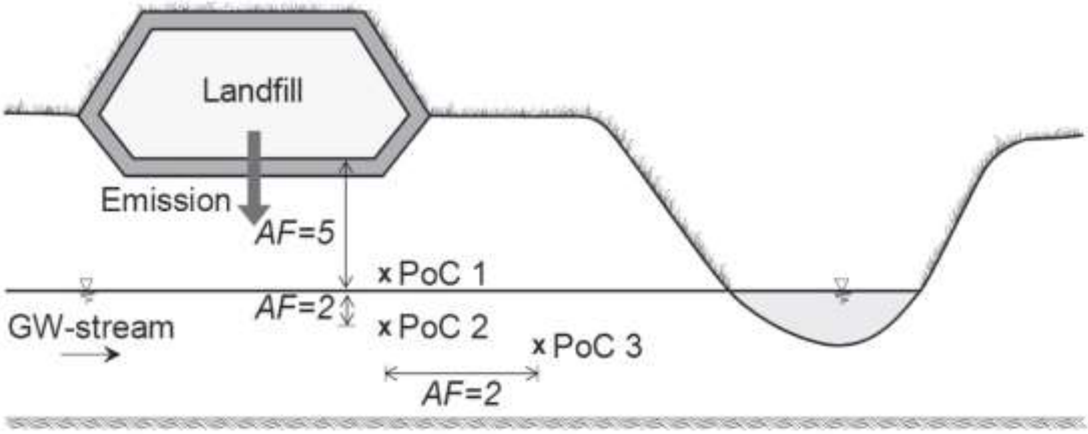

Figure 2.1: Examples of Subsurface Migration Pathway with Scenario- and Substance-Specific Attenuation Factors (AF) between the Different Points of Compliance (Laner, 2011)

2.2.4 POST-CLOSURE CARE COMPLETION CRITERIA

The attenuation factors (AF) calculated from the pollutant migration pathways are applied to the maximum concentration at each point of compliance to be compared with the standard leachate discharge limit. After considering the leachate generation in the landfill, performance of the containment system and leachate migration from the landfill to the groundwater, the comparison of the maximum concentration at certain point of compliance with the standards limit will determine the tolerable landfill discharge level and predict the post-closure care period required until the landfill achieve its functional stability.

2.3 CRITICAL ANALYSIS LITERATURE

A group of scientists agree that the completion of landfill post-closure care is acceptable when the landfill achieves its functional stability where it is unlikely to cause any harm to the environment and human health, no extreme risk will be imposed on the landfill and sufficient financial provision towards the landfill aftercare (Scharff, 2009). The completion criteria of post-closure care for Municipal Solid Waste (MSW) landfill has been derived based on several researches. There are projects that have been conducted to experiment the sustainability of the landfill. One of which the pilot experiment which uses the Monolith approach for hazardous waste. The Monolith approach uses the method of solidification as alternative of waste stabilization in the hazardous waste landfill. This method immobilizes the contaminants with minerals and binding agent (Scharff, 2010). This method produced results with lasting low levels of landfill discharge, leaving the only alternative of contaminants reduction mechanism is solubility control and flushing of mobile salts. However, the Monolith experiment is conducted with no regard of landfill containment system which later on the researchers realized the solidified contaminants cell is badly affected by the weathering process and wash-out of salts.

In this study, the landfill performance of the study site considers the performance of the containment system and its effect on the landfill discharge. Given that the landfill owner practices the solidification approach as pre-treatment of waste before disposing into the landfill, the factor that differentiates the landfill performance with past research is the usage of good performance containment system on the hazardous waste landfill.

CHAPTER 3: METHODOLOGY

3.1 CHARACTERIZATION OF THE LANDFILL AND THE SURROUNDING

General data and information on the condition of the secured landfill and the site is critical to assist on the evaluation of the criteria. The climatic condition on site helped to determine the average infiltration of water into the waste. The geology of the site is important to learn the potential of the landfill condition affecting the nearby area. The rate of waste disposal is also necessary information to evaluate the aftercare completion procedure (Laner 2011).

The hazardous waste landfill has been operating for 18 years from 1997 to 2015. It consists of 6 cells in total with a waste capacity of 1.6 million tonnes over 45 acres to contain all the disposed hazardous waste. It is surrounded by residential areas within 2km to 5 km radius which also connected to several river branches. The height of waste deposition in this landfill starts from Reduced Level (RL) 26 meter to RL 61 meter which has a total of 35 meter height. The average annual precipitation at the site is 2500 mm/yr. The groundwater level lies between 3m to 5m below the landfill base. The thickness of the aquifer is 1m with a hydraulic conductivity of1.42×10^{-5}.

The closure liners of the landfill should be of low hydraulic conductivity to minimize long term infiltration of rain water and leachate generation. The estimation for rate of rainfall infiltrating through the containment system would be ranging from 0.5% to 0.8%. The final cover consists of non-woven geo-textile (600 g/m^2), smooth geo-membrane HDPE about 1mm thick, non-woven geo-textile (600 g/m^2), 100mm thick of 25mm single size aggregate, 300mm thick of well compacted earth fill, close turf and network of subsoil pipe of 100mm diameter perforated double wall HDPE corrugated pipe wrapped around with geo-textile 250 g/m^2 tied with steel wire at every 250mm length, installed at 50m centre to centre grids with 300mm by 300mm drainage strip with 25mm single size aggregate.

Figure 3.1: Network of Subsoil Pipe Installed during the Final Cover Layering

3.2 LEACHATE GENERATION MODEL

The leachate monitoring data received for the estimation of leachate generation in the hazardous waste landfill dated back from January 2015 until December 2015. The closure of the landfill was executed on March 2015. The mobilizable fraction of leachate substances was a result of leaching test conducted on hazardous waste in the secured landfill (Scharff, van Zomeren et al, 2010). The information data was retrieved through literature. The heterogeneity of water flow was calculated as the quotient of total volume of waste body with total volume of water flow through the landfill contributing to the leachate generation. Using all the data acquired, the estimation of the concentration of leachate substances were calculated using the formula illustrated below.

$$c(t) = c_{0,leach} \cdot e^{-\left(\frac{C_{0,leach}}{m_{0,leach}} \cdot \Delta \frac{L}{S} \cdot h\right) \cdot t}$$

Where:

$c(t)$ = substance concentration at time t (mg/L)

t = time after intensive reactor (years)

$c_{0,leach}$ = substance concentration readily leachable after the intensive reactor phase (mg/L)

$m_{0,leach}$ = leachable fraction of mobilizable substances (mg / kg DM)

h = heterogeneity factor of water flow

$\Delta \frac{L}{S}$ = change in the deposited waste L/S ratio per year (L/ kg DM .year)

The model formulation developed by Belevi and Baccini (1989) to predict the future leachate generation of the secured landfill was established by using the concentration of the leachate substance as a function of liquid-to-solid ratio, L/S.

3.3 SCENARIO ANALYSIS ON THE PERFORMANCE OF THE BARRIER SYSTEM

Landfill discharge was predicted based on the formulated leachate generation model. Besides that, the containment system performance of the landfill was also based on the leachate generation model. Assuming that there is no abrupt change in the pollutant release mechanism and the re-distribution of the water flow in the landfill for the next decades, the estimation of leachate generation was continued by concentrating on the scenario whereby the performance of the containment system is concerned. The scenario analysis investigates three levels of performance given when the barrier system functions at its best level, when there is gradual decrease in barrier system performance and when the barrier is ineffective.

The scenario of the containment system performance was labelled as Status Quo, Scenario A and Scenario B. Status Quo is a scenario whereby the containment system shows constant performance at the top and bottom barrier of the landfill throughout the service period. Assumptions were made that 0.5% of the annual precipitation infiltrates into the waste body, 99% of leachate generation remained within the landfill and collected via the leachate collection system whereas 1% is released to the subsurface. Another scenario of the Status Quo, Status Quo*, is when the top barrier functions consistently throughout the modelling period while the bottom barrier is assumed ineffective. Scenario A represents the performance of the containment system gradually decreasing at the top and bottom barrier of the landfill throughout the service period. An evaluation was conducted to observe the future performance of the containment system by following a procedure that focuses on the best and worst service level of the system. This evaluation was conducted by a team of experts to create list of factors related to the performance of the containment system through three service period of post-closure care (Laner, 2011). Some of the factors to be considered in the evaluation are the current performance of the system, the construction and design of the barriers (Bonaparte et al., 2002).

Another scenario can be derived from Scenario A, Scenario A*, is when the bottom barrier appears ineffective. Lastly, Scenario B indicates the worst case scenario of the containment system performance. Assumption made was that 25% of the annual precipitation infiltrates into the waste body and all the leachate generation is released to the subsurface. Both the top and bottom barriers were concluded to be ineffective.

3.4 TRANSPORT PATHWAYS AND POLLUTANT MIGRATION

Several soil types were identified at the landfill based on the site investigation report. The types of soil included are boulders, cobbles, gravels, sand, silt and clay. The distance between the landfill base and the maximum groundwater level is between 3m to 5m. The soil layer consists of clay, silt, sand and gravel. The thickness of the aquifer is 1 meter with hydraulic conductivity of $1.42\ x\ 10^{-5}$ and the groundwater flow direction is from northwest to southeast of the landfill. According to the Annual Environmental Management Report of the site specific landfill, the pollutant migration is as illustrated in Figure 3.2. The schematic diagram of the landfill pollutant migration pathway is demonstrated in Figure 3.3.

Figure 3.2: The Pollutant Migration in the Landfill

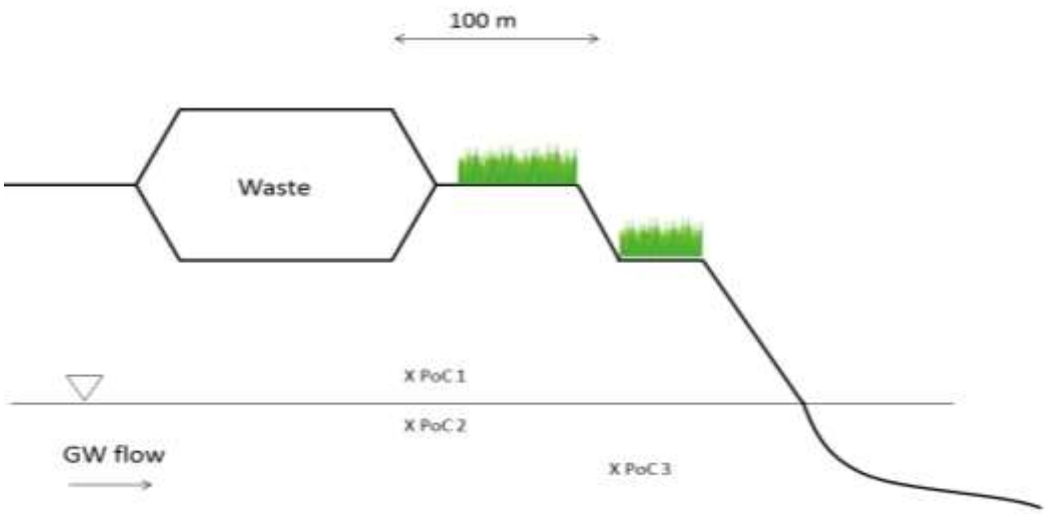

Figure 3.3: A Schematic of the Pollutant Pathway in Site Specific Landfill

The leachate generated in the landfill will first percolate through the unsaturated zone and pass through Point of Compliance (PoC) 1 which is situated above the groundwater level and below the landfill base. PoC 2 is located in the groundwater plume with additional contamination from the mixing of leachate and groundwater flow and PoC 3 is located 100m downstream of PoC 2. The pollutants concentration at all points of compliance were determined and compared with each other to calculate the attenuation factor from one point to another. The attenuation factor is an estimation of pollutants concentration reduction when being transported through the ground. The attenuation factor is a quotient of maximum pollutant concentration at source to pollutant concentration at each point of compliance.

$$AF = (\frac{C_{max,source}}{C_{max,PoC}})$$

The pollutants concentration at PoC1 was taken as the maximum leachate concentration released to the landfill subsurface. As the pollutants migrate from PoC1 to PoC2, the leachate concentrations reduced to a certain dilution factor as a result of mixture between leachate and groundwater. The dilution factor was calculated as below:

Dilution factor = [Leachate flow rate (m^3/yr) + Groundwater flow in the mixing zone (m^3/yr)] / Leachate flow rate (m^3/yr)

The concentrations at PoC3 were calculated using the maximum leachate concentration at source.

$$C_{PcC3} = C_o/(AF_1 * AF_2)$$

C_{PcC3} = Concentration at Point of Compliance 3

AF_1 = Attenuation Factor at Point of Compliance 1

AF_2 = Attenuation Factor at Point of Compliance 2

3.5 DETERMINATION OF COMPLETION CRITERIA

The attenuation factor, AF obtained was applied to the maximum concentration at each respective point of compliance. The result was then compared with the Ministry of Health raw water quality standards to produce tolerable pollutants concentration for each scenario as completion criteria of landfill post-closure care.

The release rate of leachate at the definitive points of compliance reflects the level of natural protection assigned to the site specific landfill and the estimated duration for the leachate to comply with the leachate completion criteria, indicating the termination of post-closure care.

3.6 ECONOMIC ANAYSIS

A hypothetical economic analysis was deduced based on the cost of the post closure care activities. The cost for landfill post closure care covered the cost for site security maintenance, landfill cover maintenance, maintenance of the mechanical system for leachate extraction, leachate monitoring and treatment, maintenance of groundwater monitoring wells and groundwater monitoring along with analysis and report, (Morris and Barlaz, 2011). The cost estimation was made based on a few assumptions. The cost of post-closure care was calculated for each scenario based on the performance of the containment system and the duration of the post- closure care of each scenario. Finally, the cost of each scenario was compared with the cost of 30 years post-closure care to identify the benefit of reduced post-closure care.

CHAPTER 4: RESULTS AND DISCUSSION

4.1 LEACHATE GENERATION

The formulation of the generation models as for all leachate substances are given in Table 4.1 below along with the substances concentration. The leachate monitoring data received for the estimation of leachate generation in the hazardous waste landfill provides the concentration of leachate substances. The mobilizable fraction of leachate substances was retrieved through literature. The heterogeneity of water flow was calculated as the quotient of total volume of waste body with total volume of water flow through the landfill contributing to the leachate generation. The liquid-to-solid ratio, L/S was calculated by dividing the amount of water in litres that passed through the landfill with the weight of dry matter in the landfill. The model was formulated with the assumption that the landfill has a constant release mechanism with consistent water flow regime and negligible post-biodegradation process (Belevi and Baccini, 1989).

Table 4.1: Model Formulation and Concentration of Leachate Substances to Estimate the Leachate Generation

Biological Oxygen Demand (BOD)	
BOD Leachate Concentration, $c_{0,leach}$(mg/L)	313.25
BOD Mobilizable Fraction, $m_{0,leach}$ (mg/kg)	895
Chemical Oxygen Demand (COD)	
COD Leachate Concentration, $c_{0,leach}$ (mg/L)	1689.25
COD Mobilizable Fraction, $m_{0,leach}$ (mg/kg)	2307
Ammoniacal Nitrogen ($NH_3 - NO_2$)	
$NH_3 - NO_2$ Leachate Concentration, $c_{0,leach}$ (mg/L)	847.5
$NH_3 - NO_2$ Mobilizable Fraction, $m_{0,leach}$ (mg/kg)	893
Mercury (Hg)	
Hg Leachate Concentration, $c_{0,leach}$ (mg/L)	<0.01
Hg Mobilizable Fraction, $m_{0,leach}$ (mg/kg)	0.5
Cadmium (Cd)	
Cd Leachate Concentration, $c_{0,leach}$ (mg/L)	0.0775
Cd Mobilizable Fraction, $m_{0,leach}$ (mg/kg)	3

Hexa Chromium [Cr(IV)]	
Cr(IV) Leachate Concentration, $c_{0,leach}$ (mg/L)	0.175
Cr(IV) Mobilizable Fraction, $m_{0,leach}$ (mg/kg)	400
Arsenic (As)	
As Leachate Concentration, $c_{0,leach}$ (mg/L)	1.55
As Mobilizable Fraction, $m_{0,leach}$ (mg/kg)	6
Lead (Pb)	
Pb Leachate Concentration, $c_{0,leach}$ (mg/L)	11.36
Pb Mobilizable Fraction, $m_{0,leach}$ (mg/kg)	25
Tri Chromium [Cr(III)]	
Cr(III) Leachate Concentration, $c_{0,leach}$ (mg/L)	36.84
Cr(III) Mobilizable Fraction, $m_{0,leach}$ (mg/kg)	300
Copper (Cu)	
Cu Leachate Concentration, $c_{0,leach}$ (mg/L)	8.85
Cu Mobilizable Fraction, $m_{0,leach}$ (mg/kg)	80
Manganese (Mn)	
Mn Leachate Concentration, $c_{0,leach}$ (mg/L)	10.05
Mn Mobilizable Fraction, $m_{0,leach}$ (mg/kg)	22.5
Nickel (Ni)	
Ni Leachate Concentration, $c_{0,leach}$ (mg/L)	0.77
Ni Mobilizable Fraction, $m_{0,leach}$ (mg/kg)	20
Zinc (Zn)	
Zn Leachate Concentration, $c_{0,leach}$ (mg/L)	0.975
Zn Mobilizable Fraction, $m_{0,leach}$ (mg/kg)	90
Iron (Fe)	
Fe Leachate Concentration, $c_{0,leach}$ (mg/L)	0.18
Fe Mobilizable Fraction, $m_{0,leach}$ (mg/kg)	6.95

The average annual change of L/S ratio was calculated by dividing the amount of water passed through the landfill before closure, in litres, with the total dry mass of waste deposited at site, in kg, resulting in change of L/S ratio of 0.26 L/kg annually. The concentration of BOD was estimated at 223.7 mg/L, COD was at 835.2 mg/L and $NH_3 - N$when L/S ratio is 0.26 L/kg. The concentration trend is shown in Figure 4.1. The concentration levels show further declination as they reached L/S ratio of 3.0 L/kg implying that after approximately 11 years, the BOD and COD concentration will reduce to a constant level within the regulatory standards.

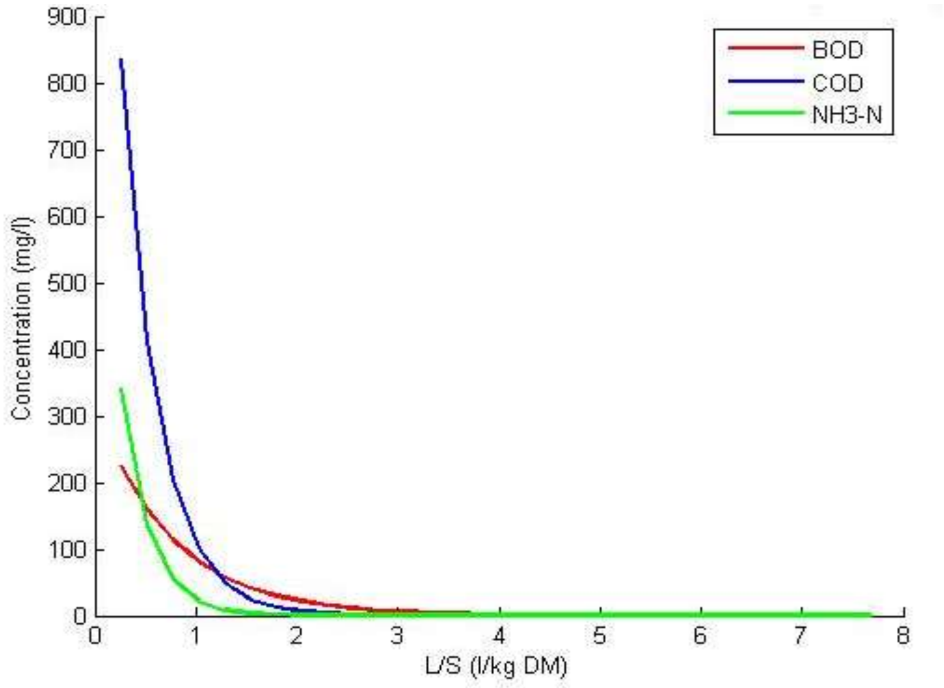

Figure 4.1: Estimation of Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD) and Ammonia Nitrogen ($NH_3 - N$) Concentration Level as a Function of Liquid-to-Solid Ratio, L/S

Based on the concentration trend graph of heavy metals showed in Figure 4.2, the concentration of Lead, Chromium (III), Copper and Manganese were found to be 7.3 mg/L, 6.5 mg/L, 8 mg/L and 6.5 mg/L. The concentrations of the rest of heavy metals indicated in the model formulation were very low which was below 1.2 mg/L. The result showed the leachate concentration undergoes an exponential decrease after landfill closure (Gibbons et al., 2007).

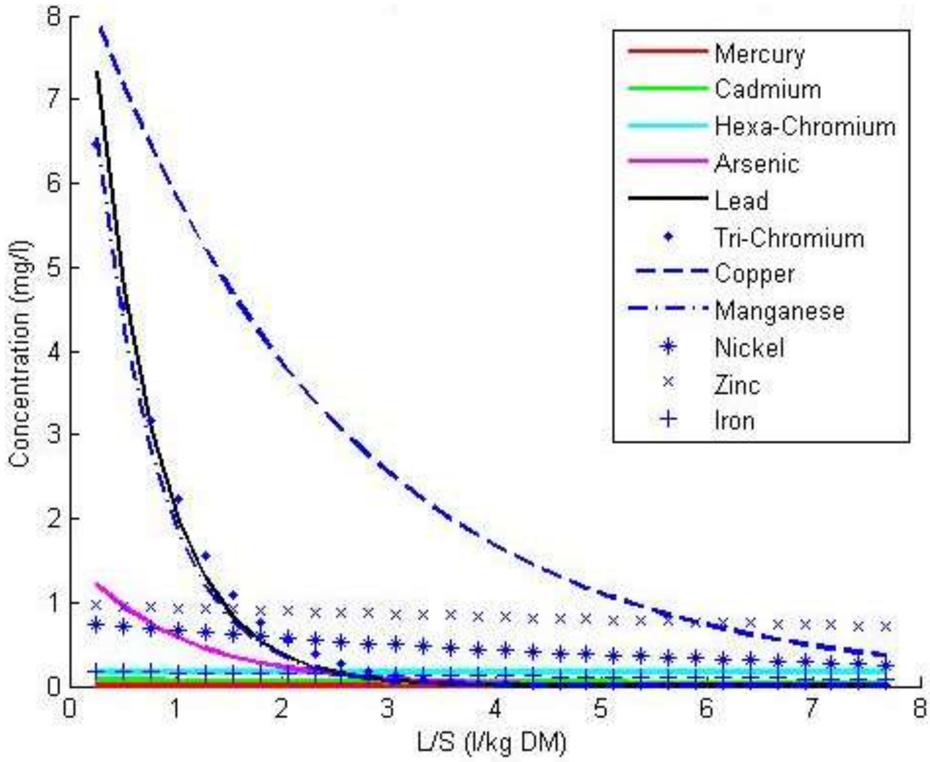

Figure 4.2: Estimation of Heavy Metals Substances Concentration Level as a Function of Liquid-to-Solid Ratio.

4.2 SCENARIO ANALYSIS OF THE PERFORMANCE OF THE CONTAINMENT SYSTEM

4.2.1 STATUS QUO

The Status Quo is the scenario of which the containment system is regarded as at its best performance at the site. The technical barriers performed at consistent efficiency with a constant substance release mechanism and water flow pattern. The top barrier system allows 0.5% of annual precipitation infiltration rate into the waste body and the barrier efficiency of landfill base is 1% of leachate generation. The leachate generation model for the Status Quo is based on the formulated model as tabulated in Table 4.1 and illustrated in Figure 4.1 and Figure 4.2.The leachate concentration of BOD and COD decreases steadily due to the high barrier efficiency that allows little infiltration into the waste body (Laner, 2011). The leachate concentration that is released to the subsurface has a slight lower value compared to the leachate generated within the landfill due to the difference in barrier efficiency between top barrier of the landfill and the bottom barrier. The scenario of Status Quo* is another situation of the Status Quo where it is assumed that the bottom barrier of the landfill is completely ineffective therefore it exudes the same leachate release rate as the Status Quo.

4.2.2 SCENARIO A

Scenario A investigates the effect of gradual decrease in containment system performance and barrier deterioration that will affect the landfill discharge. The site condition on substance release mechanism and water flow pattern remained constant. However, the efficiency of the landfill technical barrier gradually decreases and affecting the water infiltration rate into the landfill and leachate release rate to the landfill subsurface. In this scenario, the rate of leachate percolating through the subsurface was more emphasized. Due to the gradual decrease in cover performance, the leachate release rate was predicted to vary throughout the post-closure care period.

An evaluation of the future performance of the containment system followed a procedure that focuses on the best and worst service level of the system. The estimation of future barrier performance was evaluated based on three service period, 0-10 years, 11-20 years and 21-30 years. This evaluation was first initiated by a team of experts to identify several important factors related to the performance of the containment system and the effect of the performance on the leachate release rate to the subsurface. Each factor was evaluated its importance to the performance of both the top barrier and the base barrier system, and weighting factor was calculated by the team of experts for each factor. For the study of the site-specific landfill, scores were given to each factor with the observation of the site containment system performance. Using the scores given and the weighting factor provided, the leachate generation rate for Scenario A containment system was then calculated for both top barrier and bottom barrier of the landfill as shown in Table 4.2 and Table 4.3.

Table 4.2: The Evaluation Result of the Containment System Performance on Leachate Generation for Top Barrier of the Landfill

Factors - top cover	**Evaluation Score** *(1-3)*	**Weighting Factors** *0-10 years*	*10-20 years*	*20-30 years*
Barrier performance at time of evaluation	2	0.36	0.08	0.065
Construction quality program	2	0.76	0.88	0.24
Re-cultivation layer (cover)	1	0.17	0.24	0.244
Heat production within waste	1	0.09	0.06	0.04
Climate	1	0.08	0.12	0.487
Typical vegetation and projection after use	1	0.09	0.48	0.487
Relief	1	0.08	0.1	0.12
Expected settlements	2	0.76	0.18	0.13
Lining control systems (direct monitoring)	1	0.03	0.02	0.017
Drainage system	2	0.1	0.09	0.08
	Evaluation Results	2.52	2.25	1.91
	Leachate Generation Rate [mm/year]	92.1	125.4	114.2

Table 4.3: The Evaluation Result of the Containment System Performance on Leachate Generation for Bottom Barrier of the Landfill

Factors - bottom lining system	**Evaluation Score**	**Weighting Factors**		
	(1-3)	*0-10 years*	*10-20 years*	*20-30 years*
Barrier performance at time of evaluation	2	0.44	0.08	0.07
Construction quality program	1	0.46	0.49	0.44
Distance to groundwater	1	0.08	0.08	0.09
Heat production within waste	1	0.09	0.06	0.05
Climate	1	0.07	0.08	0.09
Overburden pressure	2	0.08	0.08	0.08
Leachate quality	1	0.08	0.08	0.08
Monitoring (e.g. groundwater monitoring)	1	0.08	0.07	0.07
Stability of foundation	1	0.1	0.44	0.46
Drainage system	2	0.92	0.22	0.2
Landfill geometry (heap vs cavity)	2	0.08	0.43	0.48
	Evaluation Result	2.48	2.11	2.11
	Leachate percolating through landfill base [mm/year]	1.61	1.9	2.2

The leachate concentration decreases steadily for the first 10 years of the post-closure care period before drastically decreased at the second service period until the third service period of post-closure care in Figure 4.3. The estimation of barrier deterioration was roughly between three service periods. Thus, it is assumed that the containment system is at its best performance during the first service period before gradually losing efficiency. BOD concentration was reduced from 275.2 mg/l to 85.8 mg/l, COD concentration declines from 1288.3 mg/l to 112.5 mg/l and $NH_3 - N$ concentration was decreased from 596.5 mg/L to 25.3 mg/L within 10 years of post-closure care. After completing the first service period, the concentration of BOD reduced from 85.8 mg/L to 42.6 mg/L, COD declined from 112.5 mg/L to 26 mg/L and $NH_3 - N$ decreased from 25.3 mg/L to 3.8 mg/L as reaching the 11^{th} year of post-closure care period. The drastic declination indicates the barrier performance level determined at each service period is gradually decreasing (Laner, 2011).

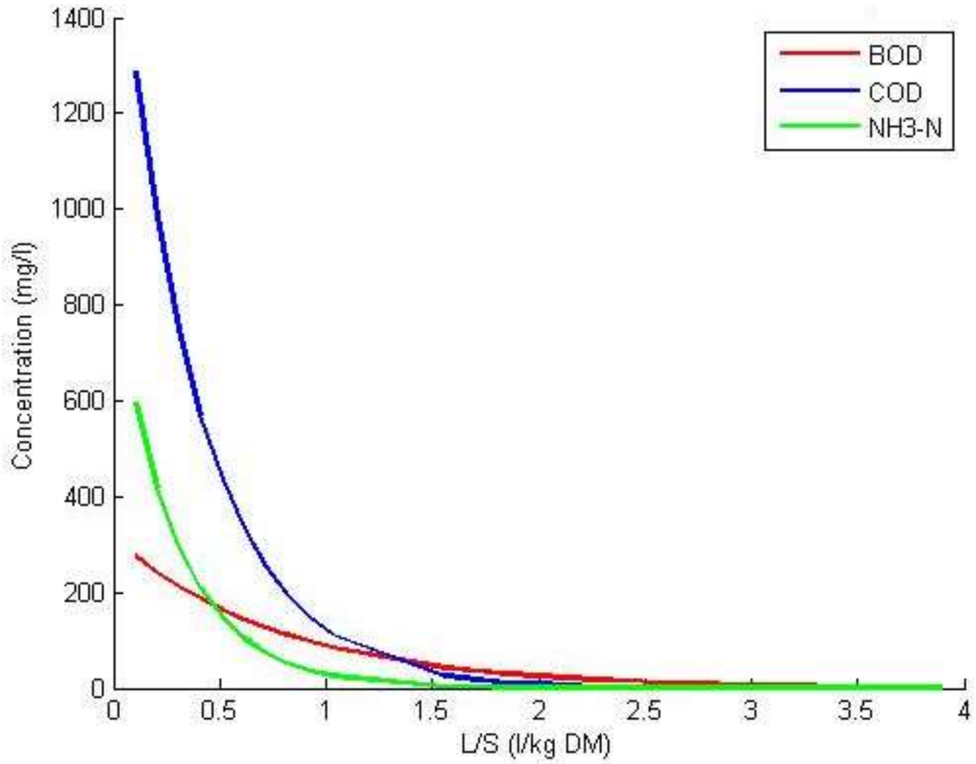

Figure 4.3: Scenario A of Leachate Generation of Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD) and Ammonia Nitrogen ($NH_3 - N$) Concentration

Figure 4.4 depicts the leachate concentration at three respective service periods. The most noticeable concentration of heavy metals substances are Lead, Chromium (III), Copper and Manganese. The declination in concentration of these heavy metals was very apparent. Lead concentration was decreased from 9.6 mg/L to 2.11 mg/L, Chromium (III) was reduced from 8 mg/L to 2.4 mg/L, Copper was declined from 8.5 mg/L to 5.9 mg/L and Manganese was decreased from 8.5 mg/L to 1.9 mg/L within 10 years of post-closure care. The performance of the containment system was clearly worsened when going to its second service period. This is due to the result showing that the concentrations of the heavy metals further reduced rapidly. The concentration of Lead was further decreased from 2.11 mg/L to 0.8 mg/L, Chromium (III) was reduced from 2.4 mg/L to 1.1 mg/L, Copper was decreased from 5.9 mg/L to 4.7 mg/L and Manganese concentration was reduced from 1.9 mg/L to 0.8 mg/L. The other heavy metals substances posed very low concentrations which were deemed tolerable and within standards limit. However, the concentration levels increased slightly at the third service period due to the decreasing efficiency of top lining system of the landfill that allows higher water infiltration rate into the landfill (Laner, 2011).

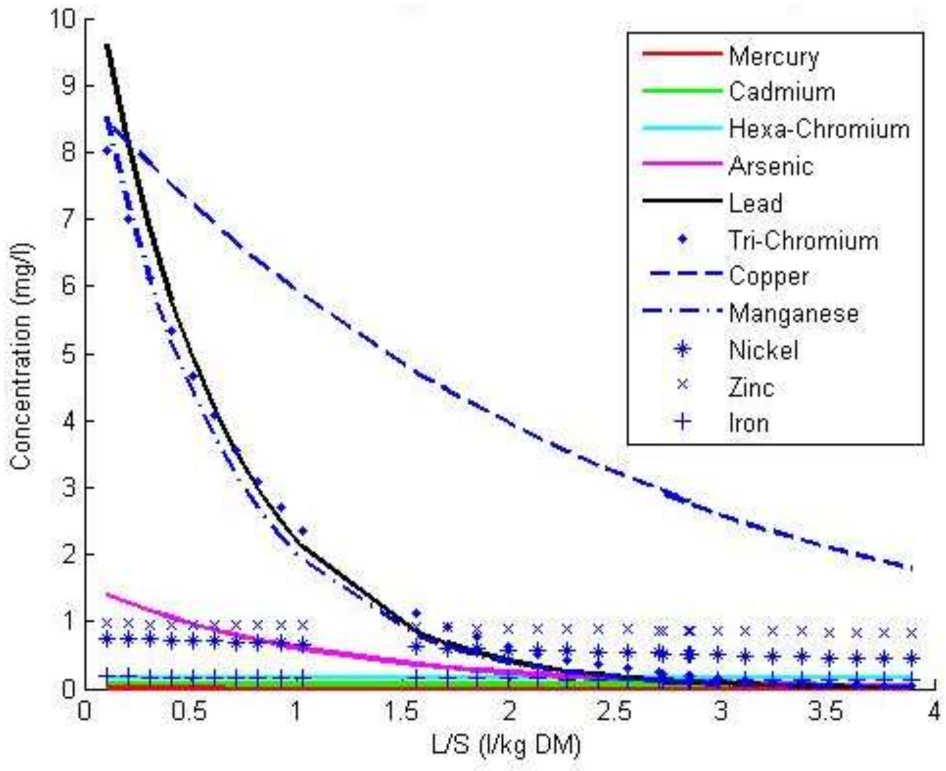

Figure 4.4: Scenario A of Leachate Generation of Heavy Metals Substances Concentration

4.2.3 SCENARIO B

Scenario B justifies the performance of the containment system when it is completely ineffective and its effect on the landfill discharge. The top barrier system is assumed to allow water infiltration of 25% from the annual precipitation and all the generated leachate will be released to the subsurface hence reflecting the worst performance of the bottom barrier system of the landfill. As a result, Figure 4.5 illustrates the rapid declination in BOD, COD and $NH_3 - N$ concentration. BOD concentration was reduced from 60 mg/l to 0.003 mg/l within 7, COD concentration was decreased from 52.7 mg/l to 0.0016 mg/l and $NH_3 - N$ was declined from 9.5 mg/L to 0.0012 mg/L within 4 years of post-closure care before all the values became negligible afterwards. The rapid declination in leachate concentration is caused by significant level of water infiltration rate into the waste body and subsequent wash-out of mobilizable substances (Scharff, van Zomeren, 2010).

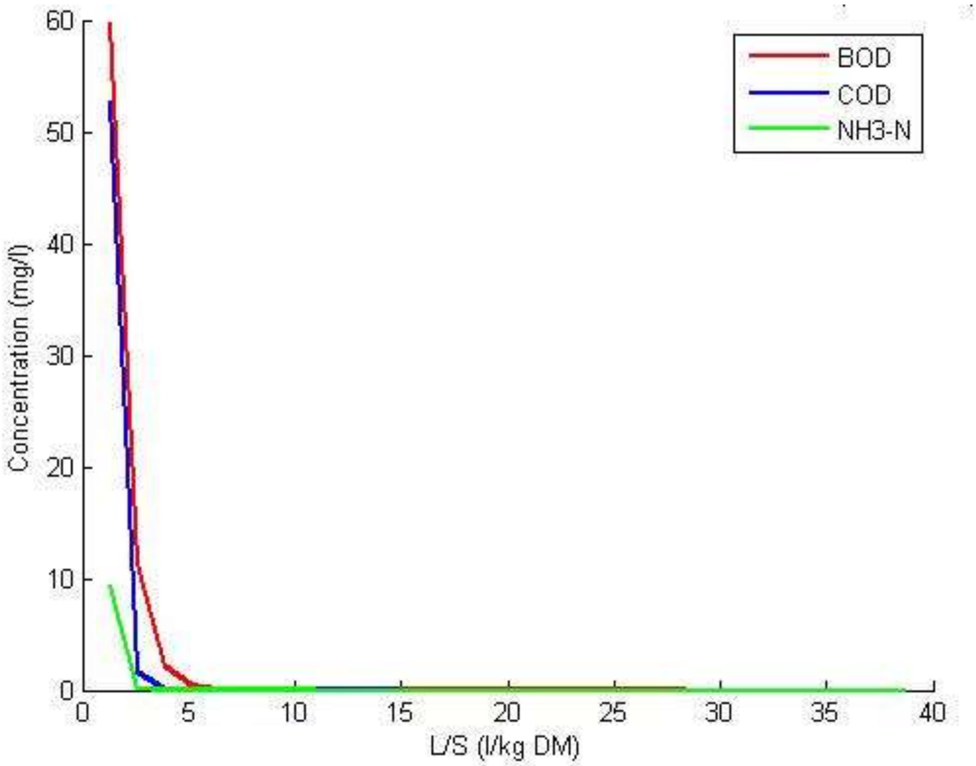

Figure 4.5: Scenario B of Leachate Generation of Biochemical Oxygen Demand (BOD) and Chemical Oxygen Demand (COD)

Figure 4.6 illustrates the reduction heavy metals substances concentrations in leachate in an accelerated time. The leachate substances identified were Lead, Chromium (III), Copper and Manganese as their values were more than then standard limits. Lead concentration was decreased from 1.3 mg/L to 0.0021 mg/L within 4 years, Chromium (III) was reduced from 1.6 mg/L to 0.0015 mg/L within 5 years, Copper was declined from 5.2 mg/L to 0.0012 mg/L within 17 years and Manganese was decreased from 1.2 mg/L to 0.0021 mg/L within 4 years of post-closure care. The values achieved by these substances afterwards were insignificant and within the standard limits. All the generated leachate was released to the subsurface within the post-closure care period due to ineffective bottom barrier system. Therefore, the leachate concentration percolating through landfill base contain the same value as of the leachate generation in the landfill.

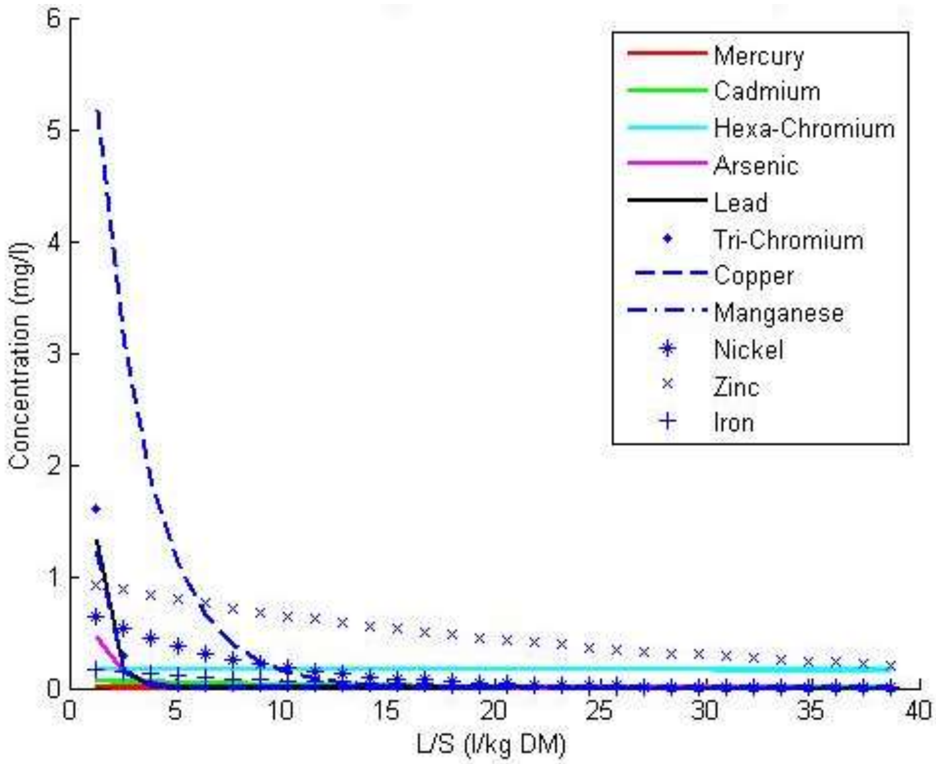

Figure 4.6: Scenario B of Leachate Generation of Tri Chromium (CrIII), Copper (Cu) and Manganese (Mn)

The final outcomes of the investigation on the performance of the containment system showed that different cover performance significantly affect the water infiltration rate into the landfill as well as the percolation rate of leachate through the subsurface. As observed from the result of Status Quo, the leachate release rate was more controlled and the declination of leachate substances concentration was steady. The result of the model formulation supports the fact that Status Quo performs at its best condition. As for Scenario A in which the containment system is facing gradual barrier deterioration throughout the post-closure care period, the result of leachate generation model showed that the concentration of the substances decreased steadily at the first service period followed by rapid declination when going into the second service period of post-closure care. The period basis rapid declination proves that the containment system gradually downgraded its performance within certain time throughout the post-closure care period. In the case of Scenario B, the rapid declination in leachate substances concentration depicts that the containment system performance was deemed ineffective from the start of post-closure care which results in the percolation rate of leachate through the subsurface is almost 100% and leachate substances concentration was reduced to stable limits within few years of post-closure care period.

4.3 ATTENUATION FACTOR

The attenuation factor is a quotient of maximum pollutant concentration at source to pollutant concentration at each point of compliance. Attenuation factor calculates the concentration reduction of pollutant that migrates from its source to the landfill subsurface. It was derived from the pollutant migration pathway and it was estimated for all scenarios of leachate generation. The derivation of attenuation factor for the all leachate substances is presented in Table 4.4, Table 4.5 and Table 4.6.

Based on the transport pathway, there were 3 points of compliance (PoC) which were PoC1 (above groundwater), PoC2 (below groundwater which is the mixing zone of leachate and groundwater and PoC3 (the groundwater 100m downstream of the landfill. The pollutants concentration at all points of compliance were determined and compared with each other to calculate the attenuation factor from one point to another. The outcome of the derivation was based on the influence of leachate generation from landfill and not the total pollutant concentration in the groundwater. From the results showed in Table 4.4, Table 4.5 and Table 4.6, the attenuation factor at PoC1 was estimated to be 25, at PoC2 was less than 1 for heavy metals and at PoC3 was 1 except for BOD and COD. The attenuation factor derived in Status Quo* and Scenario A* showed the same range value which was 1 due to the reason of 99% leachate generation was released to PoC1 which then affected the rest of the points of compliance. The attenuation factor acts as a natural treatment filter that reduces the concentration of the leachate substances (Stegmann, 2004).

Table 4.4: Calculation of Attenuation Factor Based on Maximum Leachate Concentration Released to the Subsurface For Status Quo and Status Quo*

SCENARIO	PARAMETER	C,max	LEACHATE RELEASE RATE(mm/yr)	AF,PoC1	C,PoC1 (mg/L)	AF,PoC2	C,PoC2 (mg/L)	AF,PoC3	C,PoC3 (mg/L)
Status Quo	BOD	223.7000	12.5000	20.0000	11.1850	2.2995	97.2827	45.9897	4.8641
	COD	835.1711	12.5000	20.0000	41.7586	5.9359	140.6971	118.7190	7.0349
	Hg	0.0098	12.5000	25.0000	0.0004	0.2518	0.0016	0.6089	0.0026
	Pb	7.3000	12.5000	25.0000	0.2920	0.5903	0.4946	0.9428	0.5246
	Cu	7.9525	12.5000	25.0000	0.3181	0.6744	0.4717	0.9792	0.4817
	Ni	0.7400	12.5000	25.0000	0.0296	0.5689	0.0520	0.8388	0.0620
	Zn	0.9600	12.5000	25.0000	0.0384	0.2485	0.1545	0.6071	0.2545
	Cd	0.0760	12.5000	25.0000	0.0030	0.7042	0.0043	1.0000	0.0043
	Cr(III)	8.9400	12.5000	25.0000	0.3576	0.7042	0.5078	1.0000	0.5078
	Cr(IV)	0.1750	12.5000	25.0000	0.0070	0.7042	0.0099	1.0000	0.0099
	As	1.2100	12.5000	25.0000	0.0484	0.7042	0.0687	1.0000	0.0687
	Mn	6.5400	12.5000	25.0000	0.2616	0.7042	0.3715	1.0000	0.3715
	Fe	0.1760	12.5000	25.0000	0.0070	0.7042	0.0100	1.0000	0.0100
	NH3-N	340.1000	12.5000	25.0000	13.6040	0.7042	19.3177	1.0000	19.3177
Satus Quo*	BOD	223.7000	12.5000	1.0101	221.4630	2.1151	105.7609	2.1365	104.7033
	COD	835.1711	12.5000	1.0101	826.8194	4.8458	172.3501	4.8947	170.6266
	Hg	0.0098	12.5000	1.0101	0.0097	0.6566	0.0148	0.9366	0.0158
	Pb	7.3000	12.5000	1.0101	7.2270	0.6988	10.3423	0.9971	10.3723
	Cu	7.9525	12.5000	1.0101	7.8730	0.7030	11.1996	0.9991	11.2096
	Ni	0.7400	12.5000	1.0101	0.7326	0.6975	1.0503	0.9906	1.0603
	Zn	0.9600	12.5000	1.0101	0.9504	0.6556	1.4496	0.9355	1.5496
	Cd	0.0760	12.5000	1.0101	0.0752	0.7042	0.1068	1.0000	0.1068
	Cr(III)	8.9400	12.5000	1.0101	8.8506	0.7042	12.5679	1.0000	12.5679
	Cr(IV)	0.1750	12.5000	1.0101	0.1733	0.7042	0.2460	1.0000	0.2460
	As	1.2100	12.5000	1.0101	1.1979	0.7042	1.7010	1.0000	1.7010
	Mn	6.5400	12.5000	1.0101	6.4746	0.7042	9.1939	1.0000	9.1939
	Fe	0.1760	12.5000	1.0101	0.1742	0.7042	0.2474	1.0000	0.2474
	NH3-N	340.1000	12.5000	1.0101	336.6990	0.7042	478.1126	1.0000	478.1126

Table 4.5: Calculation of Attenuation Factor Based on Maximum Leachate Concentration Released to the Subsurface For Scenario A and Scenario A*

SCENARIO	PARAMETER	C,max	LEACHATE RELEASE RATE(mm/yr)	AF,PoC1	C,PoC1 (mg/L)	AF,PoC2	C,PoC2 (mg/L)	AF,PoC3	C,PoC3 (mg/L)
Scenario A	BOD	275.2	92.1	20.0	13.8	18.9	14.6	377.4	0.7
	COD	1288.3	92.1	20.0	64.4	18.9	68.3	377.4	3.4
	Hg	0.0099	92.1	25.0	0.0004	0.9434	0.0	1.0	0.0004
	Pb	9.602	92.1	25.0	0.3841	0.9434	0.4	1.0	0.4071
	Cu	8.5	92.1	25.0	0.3396	0.9434	0.4	1.0	0.3600
	Ni	0.7591	92.1	25.0	0.0304	0.9434	0.0	1.0	0.0322
	Zn	0.9711	92.1	25.0	0.0388	0.9434	0.0	1.0	0.0412
	Cd	0.0768	92.1	25.0	0.0031	0.9434	0.0	1.0	0.0033
	Cr(III)	9.106	92.1	25.0	0.3642	0.9434	0.4	1.0	0.3861
	Cr(IV)	0.175	92.1	25.0	0.0070	0.9434	0.0	1.0	0.0074
	As	1.4087	92.1	25.0	0.0563	0.9434	0.1	1.0	0.0597
	Mn	8.5191	92.1	25.0	0.3408	0.9434	0.4	1.0	0.3612
	Fe	0.1783	92.1	25.0	0.0071	0.9434	0.0	1.0	0.0076
	NH3-N	596.583	92.1	25.0	23.8633	0.9434	25.3	1.0	25.2951
Scenario A*	BOD	2.752	92.1	1.0	2.7	1.0	2.9	1.0	2.9
	COD	12.883	92.1	1.0	12.8	1.0	13.5	1.0	13.4
	Hg	0.000099	92.1	1.0	0.0	0.9434	0.0	1.0	0.0001
	Pb	0.09602	92.1	1.0	0.1	0.9434	0.1	1.0	0.1008
	Cu	0.084905	92.1	1.0	0.1	0.9434	0.1	1.0	0.0891
	Ni	0.007591	92.1	1.0	0.0	0.9434	0.0	1.0	0.0080
	Zn	0.009711	92.1	1.0	0.0	0.9434	0.0	1.0	0.0102
	Cd	0.000768	92.1	1.0	0.0	0.9434	0.0	1.0	0.0008
	Cr(III)	0.09106	92.1	1.0	0.1	0.9434	0.1	1.0	0.0956
	Cr(IV)	0.00175	92.1	1.0	0.0	0.9434	0.0	1.0	0.0018
	As	0.014087	92.1	1.0	0.0	0.9434	0.0	1.0	0.0148
	Mn	0.085191	92.1	1.0	0.1	0.9434	0.1	1.0	0.0894
	Fe	0.001783	92.1	1.0	0.0	0.9434	0.0	1.0	0.0019
	NH3-N	5.96583	92.1	1.0	5.9	0.9434	6.3	1.0	6.2605

Table 4.6: Calculation of Attenuation Factor Based on Maximum Leachate Concentration Released to the Subsurface For Scenario B

SCENARIO	PARAMETER	C,max	LEACHATE RELEASE RATE(mm/yr)	AF,PoC1	C,PoC1 (mg/L)	AF,PoC2	C,PoC2 (mg/L)	AF,PoC3	C,PoC3 (mg/L)
Scenario B	BOD	59.7042	625	20.0	2.9852	19.8	3.0	396.7	0.1505
	COD	52.6785	625	20.0	2.6339	19.8	2.6560	396.7	0.1328
	Hg	0.0091	625	25.0	0.0004	0.9917	0.0004	1.0	0.0004
	Pb	1.3206	625	25.0	0.0528	0.9917	0.0533	1.0	0.0533
	Cu	5.2395	625	25.0	0.2096	0.9917	0.2113	1.0	0.2113
	Ni	0.6417	625	25.0	0.0257	0.9917	0.0259	1.0	0.0259
	Zn	0.9262	625	25.0	0.0370	0.9917	0.0374	1.0	0.0374
	Cd	0.0686	625	25.0	0.0027	0.9917	0.0028	1.0	0.0028
	Cr(III)	7.9637	625	25.0	0.3185	0.9917	0.3212	1.0	0.3212
	Cr(IV)	0.1746	625	25.0	0.0070	0.9917	0.0070	1.0	0.0070
	As	0.456	625	25.0	0.0182	0.9917	0.0184	1.0	0.0184
	Mn	1.2119	625	25.0	0.0485	0.9917	0.0489	1.0	0.0489
	Fe	0.1592	625	25.0	0.0064	0.9917	0.0064	1.0	0.0064
	NH3-N	9.465	625	25.0	0.3786	0.9917	0.3818	1.0	0.3818

4.4 COMPLETION CRITERIA

The completion criteria was derived by data gathered from the leachate generation model, scenario analysis, pollutant migration and attenuation factor calculation. Table 4.7 shows the allowable substance concentration level in leachate. The result showed all the tolerable concentrations level for each scenario. The pollutants concentration limit based on national recommended raw water quality standards (Ministry of Health, 2010) was applied to PoC2 and multiplied with the attenuation factor from each points of compliance (upon arriving to PoC2) to produce the tolerable pollutants concentration for each scenario as a completion criteria of landfill post-closure care. The concentration levels tabulated in Table 4.7 can be established as the compliance criteria if taking several water quality standards as its basis (Hjelmar et al., 2001).

Table 4.7: Allowable Substance Concentration in Leachate at Source in Compliance with the Limit Values at PoC2

PARAMETER	COMPLIANCE CRITERIA AT PoC 2 (mg/L)	STATUS QUO	STATUS QUO*	SCENARIO A	SCENARIO A*	SCENARIO B
BOD	6.0	275.9381	12.8191	2264.1509	5.7753	2380.0079
COD	10.000	1187.1898	48.9473	3773.5849	9.6255	3966.6799
Hg	0.001	0.0063	0.0007	0.0236	0.0010	0.0248
Pb	0.050	0.7379	0.0353	1.1792	0.0476	1.2396
Cu	1.000	16.8592	0.7101	23.5849	0.9529	24.7917
Ni	0.020	0.2844	0.0141	0.4717	0.0191	0.4958
Zn	3.000	18.6374	1.9868	70.7547	2.8588	74.3752
Cd	0.003	0.0528	0.0021	0.0708	0.0029	0.0744
Cr(III)	0.050	0.8803	0.0356	1.1792	0.0476	1.2396
Cr(IV)	0.050	0.8803	0.0356	1.1792	0.0476	1.2396
As	0.010	0.1761	0.0071	0.2358	0.0095	0.2479
Mn	0.200	3.5211	0.1423	4.7170	0.1906	4.9583
Fe	1.000	17.6056	0.7113	23.5849	0.9529	24.7917
NH3-N	1.500	26.4085	1.0670	35.3774	1.4294	37.1876

Using the data from the leachate generation model for Status Quo, Scenario A and Scenario B, the leachate concentration for each substance was evaluated and compared with the compliance criteria from Table 4.7 to predict the duration of post-closure care required. The estimation of post-closure care duration was identified when the landfill discharge was considered to be at tolerable level after taken into account the leachate generation in the landfill, scenario of containment system performance and the groundwater natural attenuation process towards the leachate substances. The post-closure care duration estimated for each scenario of containment system performance is showed in Table 4.8. The maximum post-closure care duration for the scenario of constant performance and decrease performance of barrier system were estimated at 27 years. Meanwhile, the inefficiency in containment system performance achieved the shortest post-closure care duration which was 14 years. However, ineffective barrier system indicates unregulated flushing of contaminants into the groundwater which will further harming the environment (Laner, Crest et al., 2012). Thus, landfill owner are not encouraged to neglect the use of containment system.

Table 4.8: The Estimation of Post-Closure Care Duration for Each Scenario

PARAMETER	POST-CLOSURE CARE DURATION BASED ON		
	CONSTANT BARRIER PERFORMANCE	DECREASE OF BARRIER PERFORMANCE	INTENSIVE WATER INFILTRATION THROUGH THE BARRIER
BOD	1	1	1
COD	1	1	1
Hg	24	1	1
Pb	7	11	2
Cu	1	1	1
Ni	27	27	14
Zn	1	1	1
Cd	16	10	1
Cr(III)	7	12	2
Cr(IV)	1	1	1
As	9	15	2
Mn	3	5	1
Fe	1	1	1
NH3-N	4	10	1

4.5 ECONOMIC ANALYSIS

The cost estimation for landfill post-closure care was broken down into the following categories:

1. Site security maintenance
2. Cover maintenance
3. Leachate management system
4. Groundwater management system
5. Leachate monitoring
6. Groundwater monitoring
7. Surface water monitoring
8. Statistics and reports

The cost for each category was obtained by survey conducted to investigate on the normal price of which Malaysia's landfill owners usually negotiate with the contractor with the consideration of the site-specific landfill. The frequency of cover maintenance for each scenario was considered according to the containment system performance. The cost for each category in post-closure care is as shown in Table 4.9.

Table 4.9: The Cost Estimation for Post-Closure Care

CATEGORY	COST BASIS	COST ($)	COST (RM)	UNITS	VALUE
Site Security Maintenance	Annual	30.00	121.20	m	34
Cover Maintenance	Annual	1,100.00	4,444.00	ha	0.0165
Leachate Collection System Cleanout	Annual	500.00	2,020.00	ha	0.55
Leachate Pump Replacement	Annual	4,000.00	16,160.00	each	2
Groundwater Well Maintenace and Replacement	Annual	140.00	565.60	wells	7
Groundwater Monitoring	Annual	2,000.00	8,080.00	events	3
Groundwater Analytical	Annual	75.00	303.00	wells*events	21
Surface Water Monitoring	Annual	1,500.00	6,060.00	events	3
Surface Water Analytical	Annual	120.00	484.80	events	3
Leachate Monitoring	Annual	2,500.00	10,100.00	events	3
Statistics and Reporting	Annual	8,000.00	32,320.00	each	1

Based on the cost outlined in Table 4.9, the cost of post-closure care for each containment system scenario was calculated in Table 4.10. The cost of 30 years of post-closure care was also included to assist in making comparison between the cost of 30 years of post-closure care period and post-closure care period of less than 30 years.

Table 4.10: The Total Cost of Post-Closure Care for Each Scenario

CATEGORY	COST (RM/year)	CONSTANT BARRIER (RM)	DETERORIATE BARRIER (RM)	INTENSIVE INFILTRATION (RM)	30 YEARS POST-CLOSURE CARE
Site Security Maintenance	4,120.80	111,261.60	111,261.60	57,691.20	123,624.00
Cover Maintenance	73.33	1,979.80	9,312.40	35,245.36	2,199.78
Leachate Collection System Cleanout	1,111.00	29,997.00	29,997.00	15,554.00	33,330.00
Leachate Pump Replacement	32,320.00	872,640.00	872,640.00	452,480.00	969,600.00
Groundwater Well Maintenace and Replacement	3,959.20	106,898.40	106,898.40	55,428.80	118,776.00
Groundwater Monitoring	24,240.00	654,480.00	654,480.00	339,360.00	727,200.00
Groundwater Analytical	6,363.00	171,801.00	171,801.00	89,082.00	190,890.00
Surface Water Monitoring	18,180.00	490,860.00	490,860.00	254,520.00	545,400.00
Surface Water Analytical	1,454.40	39,268.80	39,268.80	20,361.60	43,632.00
Leachate Monitoring	30,300.00	818,100.00	818,100.00	424,200.00	909,000.00
Statistics and Reporting	32,320.00	872,640.00	872,640.00	452,480.00	969,600.00
TOTAL		**4,169,926.60**	**4,177,259.20**	**2,196,402.96**	**4,633,251.78**

CHAPTER 5: CONCLUSION

As the landfill has reached its life span, it is subjected to a landfill closure followed by the monitoring and maintenance work for the landfill. This process is known as the post closure care of the landfill. The monitoring and maintenance of the overall landfill components ensures the protection of environment and human's health from any form of hazardous constituents that may be released from the landfill. The common post closure care period is 30 years. Post closure care of a secured landfill demands an extensive period of time due to the critical procedure need to be taken to safely ensure the landfill emissions no longer pose potential threat towards the surroundings. Surely, the post closure care will require a significant amount of funding to assure the continuity of the aftercare, not to mention the resources to handle the process for the next 30 years per se.

This research is to investigate the shortening the period of post closure care in a hazardous waste landfill. The investigation on the reduction of the landfill post closure care period will be based on the monitoring of three (3) main components of a secured landfill which are leachate monitoring, groundwater monitoring and the monitoring of the performance of the landfill final cover. The site-specific criteria for the completion of the landfill post closure care were derived using future landfill discharge estimation procedure. The evaluation of post closure care duration was then applied to an economic analysis to observe and compare the benefits of having post-closure care duration less than 30 years.

The investigation on the shortening of post-closure care duration for the site-specific landfill shows the landfill can achieve a maximum of 27 years post-closure care. The shortening of 3 years in post-closure care reduces its cost to RM 463,325 compared to the cost of 30 years post-closure care.

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