Groundwater Contamination at Landfill Site

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Chapter 13

GROUNDWATER CONTAMINATION AT LANDFILL SITE

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Abstract

Improper design of landfill sites may cause serious problems to groundwater. Leachate, a very concentrated pollutant generated from the decomposition of waste and by precipitation, may penetrate through the waste layers and go straight to the aquifer. This chapter discusses some background on groundwater resource, its properties, and monitoring at landfill sites. Pulau Burung landfill in Penang, Malaysia was taken as the case study site where boreholes and monitoring wells were sampled and the results discussed.

Keywords: Groundwater, landfill, borehole, monitoring well, leachate.

1. Introduction

In most countries, the landfill is still the preferred method for solid waste disposal due to its low cost and maintenance. As the volume of waste produced grew, more landfill sites were built without increasing waste disposal costs. Because of their large numbers and nature of operations, landfill sites are now considered a threat to the environment, especially those that are not properly maintained and controlled. One of the threats posed by landfill sites is the production of leachate, which is generated from the decomposition of waste and by moisture that penetrates the landfill layers. Leachate is a highly polluted wastewater that contains a wide range of contaminants including organic and inorganic matters, humic and fulvic substances, and even heavy metals. The discharge of untreated leachate into a watercourse could lead to serious pollution of the water supply. This is also a prolonged problem since leachates continue to be produced for many years even after a landfill site has been closed.[24]

For some time now, there has been an increased concern regarding the contamination of groundwater by leachate infiltration. The uncontrolled infiltration of leachate from the unsaturated zone into the saturated zone (groundwater) is considered the worst environmental impact of landfills. Infiltration of leachate is a common phenomenon in an open and unlined dump site without a leachate collection system. In 1977, a study on 50 landfill sites discovered the presence of organic chemical contamination at 40 sites and infiltration by at least one hazardous chemical at 43 sites. Groundwater contamination in a landfill site depends on factors such as the composition of leachate, operation of landfill, and interaction of contaminant transport in the soil.[23]

To prevent infiltration of leachate into the groundwater, methods such as leachate collection systems, liners, and also capping are integrated into the design of a landfill site. Landfills using these types of waste disposal systems are referred to as sanitary landfills. These engineered waste disposal systems employ spreading, compacting waste, lining system, and daily soil covering. This chapter discusses how a groundwater-monitoring program can be used to effectively control the contamination of groundwater from leachate at landfill sites by focusing on the practice used by the Pulau Burung landfill site in Penang, Malaysia. For assessment and selection of groundwater monitoring at a landfill site, an understanding of the contaminant source (landfill leachate), contaminant transport (hydro geological), and receptor (groundwater) is necessary. Table 1 summarizes the aspects of a landfill site that must be considered before implementation of a groundwater monitoring network.

Table 1. Landfill Aspects for the Selection of a Groundwater Monitoring System.[1]

Landfill site	(1) Site characterization (area, waste cell structure, and depth) (2) Landfill operational system (compaction, liner, cover, and waste disposal rate) (3) Waste type and properties (composition, permeability, and density) (4) Leachate characteristics (5) Liner properties (possibility of leakage mechanism — diffuse and tear) (6) Surface run-off
Hydrogeology	(1) Groundwater system (unsaturated zone, saturated zone, and vadose zone) (2) Geology characteristic (soil type, porosity, and permeability) (3) Hydraulic (flow rate, direction, and quantity) (4) Contaminant transport (pathways and attenuation)
Rainfall	(1) Rainfall statistics (2) Catchments area (up gradient and down gradient)

2. Groundwater Resource

2.1. *Groundwater Aspects*

Generally, groundwater is the subsurface water that penetrates through pores and cracks in the soil. Several terms regarding groundwater are given in Table 2. Under normal conditions, the land surface or the unsaturated zone is sufficient for protecting the quality of groundwater below. However, due to the disruptive existence of landfill sites, the natural processes or attenuation mechanisms that convert contaminants on the surface into harmless matter are no longer effective. Because of this contaminants must be treated before they can penetrate the ground and reach the water table.

2.2. *Groundwater Flow Rate*

In an unsaturated zone, the groundwater flow is mostly gravity driven. The horizontal flow in a saturated zone depends primarily on the porosity of the soil. There are three distinct flow mechanisms:

1. *Intergranular flow*: A flow through evenly distributed and interconnected pores.
2. *Fissure flow*: A flow through fissures that occurs in the absence of pore openings (low-porosity and high-permeability conditions). This flow is less predictable, but more rapid than intergranular flow.
3. *Flow in conduit*: A flow that is channeled through a conduit. This flow is as high as a surface flow; therefore, attenuation would be insignificant but dilution might occur.

Table 2. Groundwater Terms.[2]

Terms	Explanation
Unsaturated zone	A zone that exists between the water table and the surface. This zone is only partially filled with water since it consists of an opening, pores, and crack in the soils. Water passes through this surface into the water table layer below and its movement is gravity driven.
Saturated zone	A zone in which all the pores, openings, and cracks in the soils are filled with water. Typically, it is located in the upper layer of bedrock in which water cannot penetrate.
Water table	This is the top layer of the saturated zone. It changes (rise or fall) depending on the season, rainfall, and snowmelt. The pattern of changes is usually the same throughout the year except during heavy rainfall or drought.
Aquifers	This is a water-bearing soil or rock formation that is capable of both storing and transmitting a certain amount of water.
Permeability	It is the measurement of the speed of water flowing through an opening or the pores in the soil.
Porosity	This is the measured capacity of soil to contain or hold water. Usually saturated sand contains 20% water, 25% for gravel, and 48% for clay.

The flow rate of groundwater can be calculated using the simple groundwater equation:

$$Q = K \times i/n \tag{1}$$

where Q = flow rate (m/s), K = hydraulic conductivity (m/s), i = hydraulic gradient (m/m), and n = effective porosity (dimensionless).

3. Landfill

3.1. *Operation at the Pulau Burung Landfill Site*

The Pulau Burung landfill site is situated in the Byram Forest Reserve (5° 24′ N, 100° 23′ E) and covers an area about 62.4 hectares wide. In terms of location, this site has proven to be a very valuable research site since it is located within a mangrove area and near the sea. Perimeter drains surround the landfill area. During its early operation in the 1980s, the landfill site was used merely as an open-dumping site for municipal solid waste (MSW). The waste disposal operation for the landfill site was managed by the Seberang Perai Municipal Council. In its first 10 years of operation from the early 1980s until 1990, waste was disposed without proper management and improper leachate control. During the time (1980–1990), waste disposed at the site came from Seberang Perai Selatan area and from commercial and industries areas in Seberang Perai Utara.

In 1991, the landfill site was upgraded to a Level II sanitary landfill site by implementing a semi-aerobic system. This system, also known as the Fukuoka Landfill

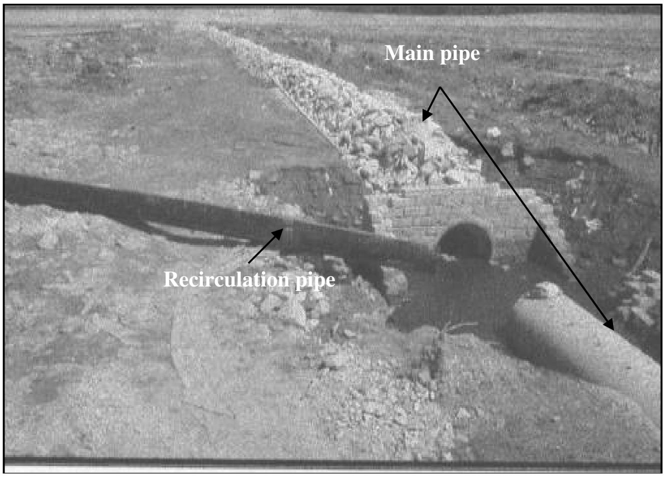

Figure 1. Constructed Main and Recirculation Pipe at Pulau Burung Landfill Site.[6]

Method, was developed by Fukuoka University in 1975. This method of land filling allows the movement of air into the waste layer through a network of horizontal pipes at the bottom of landfill site and a vertical gas vent pipe.[3] Movements of air are due to convection caused by a temperature differential between the waste layer and the atmosphere. After management of the landfill site was given to Idaman Bersih Sdn. Bhd. on August 1, 2001, it was further upgraded to a Level III sanitary landfill by implementing the recirculation of leachate into the waste layer.[4]

Presently, an average of 1,800 tons of solid wastes is being disposed of daily at this site.[5,25] It now disposes solid waste (both municipal and nonhazardous industrial wastes) from Seberang Perai Selatan, Seberang Perai Utara and Penang Island. The site is also equipped with other control systems including a leachate collection system, a gas collection system, and aeration for a leachate collection pond. Figures 1 and 2 show the construction of a horizontal leachate collection pipe at the landfill site. Two categories of waste received by the site are flammable waste and organic industrial waste. The landfill site is also of interest since it is located near the sea. A river is also nearby, and a constructed drain (perimeter drain) surrounds the landfill area. Figure 3 shows the leachate collection pond at the landfill site and Fig. 4 shows the schematic diagram of the Pulau Burung landfill site area.

3.2. *Landfill Type and Design*

Many types of landfills are used for the disposal of different type of wastes, whether from industries or domestic waste streams. The Pulau Burung landfill site is a co-disposal landfill site, as it accepts various wastes from residential areas and

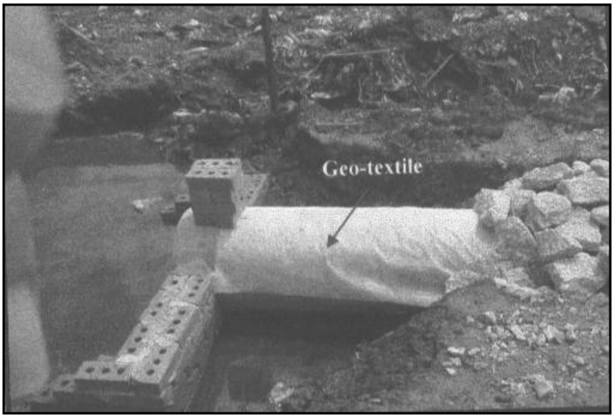

Figure 2. Geotextile are Installed to Prevent Blockage of Pipeline.[6]

Figure 3. Leachate Collection Pond (End Line of Main Leachate Pipeline).[7]

nonhazardous wastes from industries. These types of landfills play important roles in determining the groundwater-monitoring system since it affects the characterization of leachate produced, the design of the landfill layer and thus the degree of risk for contamination to the subsoil. Table 3 summarizes certain types of landfills and their descriptions.

3.3. *Landfill Design and Liner System*

Liner systems are used within containment landfills as barriers to prevent an outflow of leachate into the surrounding soil. Liners implemented by landfill operators can be either geosynthetic or natural. Most landfill operators prefer natural liners to geosynthetic ones because of their lower cost. A natural liner is compacted at the

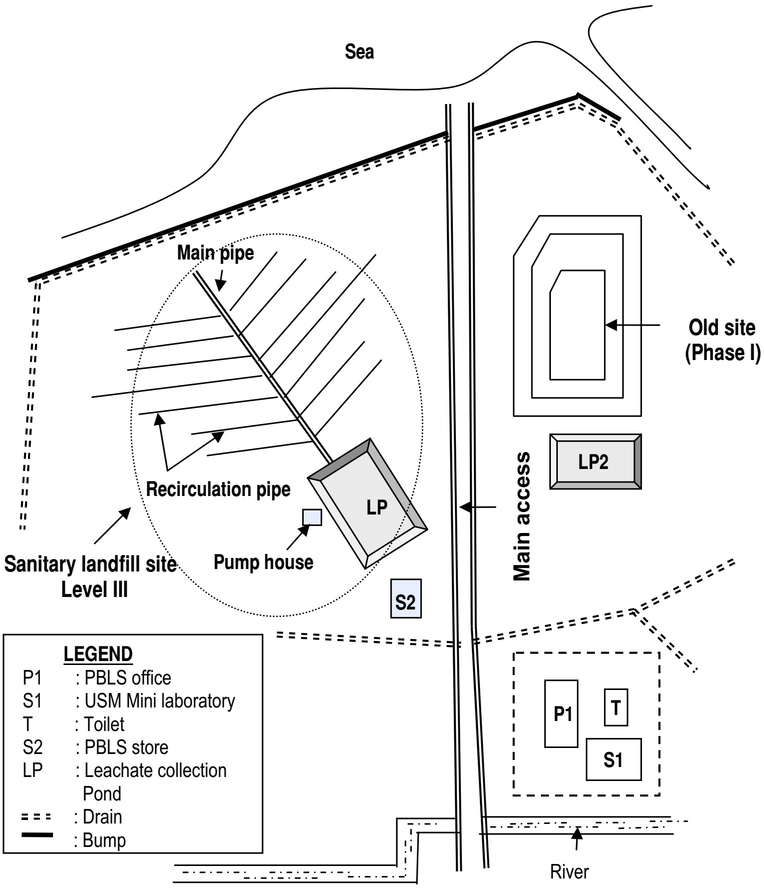

Figure 4. Schematic Diagram of Pulau Burung Landfill Site.[6]

base of the landfill, and natural soil, usually rich in clay or bentonite, is used as a liner. Bentonite is used since it is a material of low hydraulic conductivity and, thus, low permeability.[8] Bentonite is also extremely hydrophilic and attracts water between its layers, leaving little void/space. In certain cases, geosynthetic clay liners, which consist of a combination of bentonite with geotextile or geomembrane, are used, and combinations with zeolite are believed to prevent the transport of phenolic compounds.[30] Most sodium bentonites used as geosynthetic clay liner have a permeability around, and a combination with zeolite are believed to prevent phenolic compounds transport[30] 1×10^{-9} to 5×10^{-9} cm/s.[8]

Even though a liner in landfill design may be installed, infiltration of leachate into the soil is still possible with the likelihood of leachate management systems failing.[27,29,31] Infiltration of leachate may occur due to leakage in the liner design and the limitation of the liner's lifespan compared to the lifespan of leachate production,

Table 3. Type of Landfill and Description.[1]

Type of Landfill	Description
Dilute & disperse	This site does not provide any barrier between the waste and the soil surface. The leachate is allowed to seep into the soil layer and depends on natural attenuation to reduce contaminant concentration.
Bioreactor	It is designed for the purpose of maximizing the degradation rate of waste disposed at the site. This is done through the recirculation of leachate onto the waste layer.
Containment	Designed to minimize the inlet and outlet of moisture from the landfill site. Usually equipped with a leachate collection and management system.
Noninert	It can be a mono-disposal site, co-disposal site, or liquid waste site. For mono-disposal, the leachate produced will have similar characteristics as the waste type. A co-disposal site accepts both solid and liquid wastes; thus, it must be monitored and engineered to prevent contaminants due to its leachate.
Inert	This landfill site only disposes of inert wastes. Therefore, it would not produce a significant volume of leachate but there is still a risk due to surface run-off that could wash the waste away. Incoming wastes have to be controlled very well.

which extends for years after the landfill site is closed. Leachate may exit the landfill layer toward the subsoil either by diffuse or discrete leakage. Discrete leakage would be hard to monitor since it could be caused by a tear on a membrane or geosynthetic liner and would be difficult to detect. Meanwhile, diffuse leakage usually occurs if natural or mineral liners are used and it spreads on a wider scale. Therefore, the monitoring points can be separated widely within the diffuse area for detection of contamination of groundwater. Infiltration of leachate through diffuse leakage also would be less significant since attenuation of contaminants could occur while it diffuses through the liner layer. In the case of the Pulau Burung landfill site, a natural liner consisting of natural marine clay is laid at the base of the landfill site.[9,22] The main component of the natural liner consists of a low permeability clay that prevents the outflow of leachate from the landfill site and also the inflow of groundwater into the waste layer, retarding the transport of leachate solutes.[26]

3.4. *Soil Properties*

Soil properties will determine the permeability, porosity, and also the attenuation mechanism that would affect the movement of contaminants through the soil. In short, it plays a very important role in determining the movements of leachate as it seeps out from the landfill layer and the fate of contaminants as it flows down the subsoil into the groundwater below. A subsoil may consist of different types of soils

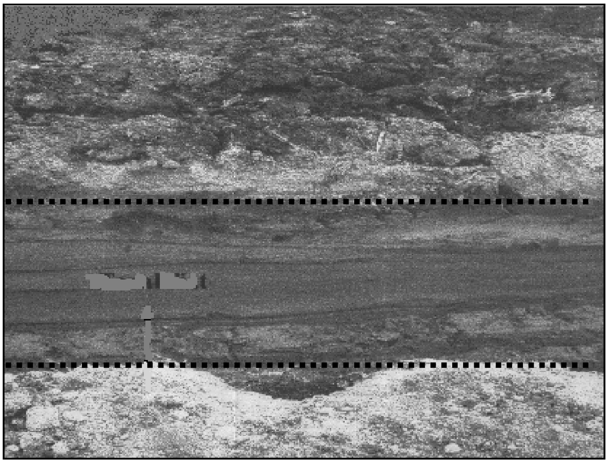

Figure 5. Soil Layer Under Leachate Collection Pond at Pulau Burung Landfill Site.[6]

and thus have different properties at each layer. An example of subsoil properties at the Pulau Burung landfill site is shown in Figs. 5 and 6. It is, however, difficult to quantify the porosity and permeability of the soil mixture. Table 4 shows the porosity and permeability of different soil types and their specific yield (ratio of the water volume to the rock volume).

4. Leachate

Parameters that need to be identified for landfill leachate are the leachate generation rate and the leachate concentration. Knowledge about the generation rate of leachate is important especially for designing the leachate pipes, leachate collection systems, the retention pond, leachate treatment facilities, etc. Landfill leachate is produced from a number of sources. The main sources of landfill leachate include: water produced from the decomposition of waste in the landfill layers, water squeezed out due to the waste weight, and water that passes through the waste, especially during rainfall. Landfill leachate will flow to the bottom and accumulate beneath the landfill site. Landfill leachate contains a wide range of contaminants, both organic and inorganic; some of these contaminants, such as biochemical oxygen demand (BOD), chemical oxygen demand (COD), and ammoniacal nitrogen, are highly concentrated. Table 5 provides characteristics of landfill leachate at the Pulau Burung landfill site in 2003.[11]

4.1. *Leachate Generation*

The production of landfill leachate is affected by factors such as the types of waste disposed at the site, landfill age, and amount of rainfall. These factors not only determine

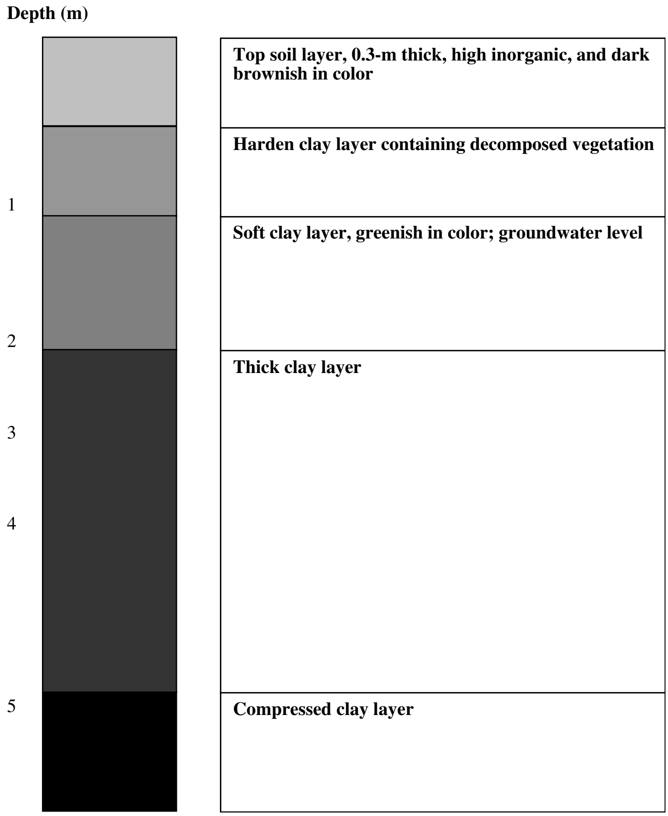

Figure 6. Diagram of Soil Layer at Pulau Burung Landfill Site.[9,10]

Table 4. Typical Porosity, Permeability, and Specific Yield of Different Type of Soils.[2]

Soil Material	Specific Yield (%)	Porosity (%)	Permeability (m/day)
Clay	1–5	45–55	1×10^{-8} to 1×10^{-4}
Sand	10–30	25–45	1×10^{-1} to 1×10^{3}
Gravel	15–30	25–35	1×10^{3} to 1×10^{5}
Sand and gravel	10–20	20–30	1×10^{1} to 1×10^{3}
Silt	5–10	35–50	1×10^{-4} to 1×10^{1}

the quantity of leachate produced but also affect its composition and quality. As the layer of waste increases on a landfill site, more moisture within the waste will be released due to the rainfall that seeps into the layers, in addition of the weight of deposited waste layer. Therefore, in humid areas such as Malaysia, the amount of leachate produced is quite high due to the high precipitation that exceeds evaporation. A study was conducted at two sanitary landfill sites in Malaysia, Ampang

Table 5. Leachate Parameter at Pulau Burung Landfill Site in 2003.[11]

Parameter	Jan	Feb	March	April	May	June	July	Aug	Sept	Oct	Nov	Average
pH	7.89	8.18	8.42	8.96	8.78	8.44	8.2	8.05	8.84	7.91	8.39	8.37
BOD_5 (mg/L)	75	98	85	66	140	181	207	548	605	1120	345	315
COD (mg/L)	1640	1700	1702	1656	1717	2338	2070	2118	2393	3450	2197	2089
Color (PtCo)	2430	2530	2940	3070	3264	3360	3680	3560	3400	6540	3630	3491
Turbidity (NTU)	174	104	67	80	100	110	114	160	150	450	170	153
SS (mg/L)	219	220	164	196	210	251	227	303	340	936	380	313
Iron (mg/L)	5.5	5.1	5.6	3.5	4	5.9	5	3.4	4.6	8.6	6.2	5.2
Ammoniacal nitrogen (mg/L)	1909	429	1017	830	626	508	820	1201	1724	1325	1104	1044.8
Oil and grease (mg/L)	7	15	10	41	3	8	9	15	13	17	18	14.2
Zinc (mg/L)	0.5	0.4	0.4	0.5	0.1	1.5	0.6	0.6	0.8	1.8	0.8	0.7
Nickel (mg/L)	0.4	0.3	0.2	0.1	0.1	0.2	0.1	0.1	0.1	0.1	0.2	0.2
Tin (mg/L)	0.1	0.1	0.1	0.1	0.1	0.2	0.1	0.2	0.1	0.1	0.2	0.1
Cadmium (mg/L)	0.04	0.04	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02

Jajar landfill site, and Pulau Burung landfill site in Penang, to quantify the actual amount of leachate generated in the field from different ages of landfill. It was found that the maximum leachate generation rate for a four-year-old landfill was about $8\,m^3 \cdot lift^{-1} \cdot ha^{-1} \cdot day^{-1}$ and named SALL4. For a 10-year-old landfill, the leachate generation rate was about $4.2\,m^3 \cdot lift^{-1} \cdot ha^{-1} \cdot day^{-1}$ and named SALL10.[12]

Some fractions of leachate are lost due to evaporation, evapotranspiration, and absorption by the waste. The evaporation of leachate depends on the factors such as the specific gravity of the leachate, ambient temperature, atmospheric pressure, wind velocity, and the difference of vapor pressure between the atmosphere and the waste surface. Evaporation also depends on the presence or the availability of the leachate to be evaporated. Evaporation rate decreases about 1% for every increase of 1% in specific gravity.[13] Evapotranspiration is the combination of evaporation and transpiration. Evaporation occurs on the soil surface while transpiration refers to the loss of water due to uptake by plants. Therefore, losses of leachate through transpiration are more significant than evaporation since transpiration processes reach deep down to the depth of plant roots.[8]

Leachate is absorbed by both the soil and the waste. The amount of leachate absorbed by soil depends on the moisture content and especially the soil's specific yield, which is shown in Table 4. Absorption of leachate by both soil and waste only occurs until the field capacity of the waste and soils has been reached. After this point, all the liquid in the waste layer will flow down as leachate. The field capacity is the maximum moisture content that can be retained by waste and soil against gravitational force. Thus, the absorption of waste depends mostly on the composition of waste and its moisture contents. The field capacity of refuse in the landfill site can be estimated if the relative percentage of each type of waste component is known. For MSW, a field capacity of 33 cm/m is considered reasonable with an initial waste moisture content of 12 cm/m.[13] Figure 7 shows the infiltration of rainfall as it moves into the waste layer.

4.2. *Leachate Composition*

4.2.1. *Waste Type*

The varying moisture content of different types of waste affects the quantity and quality of leachate. Table 6 summarizes the types of waste dumped at the Pulau Burung landfill site. Moisture inside the waste will seep downward as the waste is being compressed or due to increased weight as additional layers of waste are being dumped and compacted. As the layer of waste increases, the water that flows down will also bring contaminants along with it, as it passes through the layers of waste. Knowledge of the variation of wastes dumped at a landfill site is important

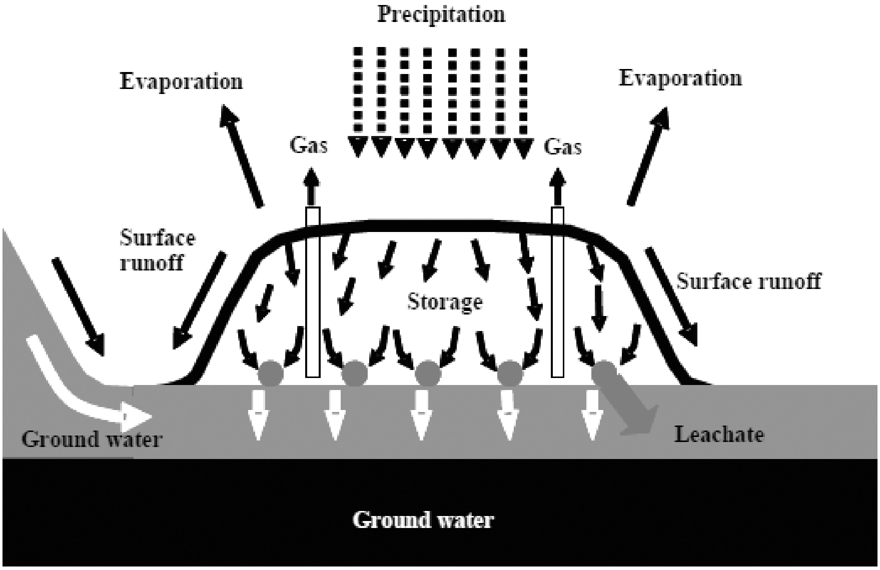

Figure 7. Hydrology at Landfill Site.[14]

Table 6. Waste Disposed at Pulau Burung Landfill Site in 2003.[7]

	Solid Wastes										
	Domestic		Garden		Construction		Industries		Other		
Month	Trips	%	Trips	%	Trips	%	Trips	%	Trips	%	Total
January	1482	19.1	66	0.9	29	0.4	5816	75.0	363	4.7	7756
February	1304	22.1	56	0.9	6	0.1	4236	71.8	301	5.1	5903
March	1405	19.3	85	1.2	35	0.5	5422	74.4	344	4.7	7291
April	1402	19.5	59	0.8	21	0.3	5335	74.4	358	5.0	7175
May	1575	21.7	119	1.6	19	0.3	5179	71.4	362	5.0	7254
June	1402	20.5	86	1.3	21	0.3	5001	73.0	343	5.0	6853
July	1462	20.0	102	1.4	13	0.2	5331	73.1	384	5.3	7292
August	1419	20.2	118	1.7	23	0.3	5097	72.5	370	5.3	7027
September	1398	19.5	79	1.1	22	0.3	5314	74.2	347	4.8	7160
October	1664	23.1	89	1.2	17	0.2	5022	69.8	399	5.5	7191
November	1651	24.8	74	1.1	16	0.2	4638	69.6	288	4.3	6667
December	—	—	—	—	—	—	—	—	—	—	—
Total	16164	20.8	933	1.2	222	0.3	56391	72.7	3859	5.0	77569

for determining the type of contamination that may occur at the site. It also provides very useful information regarding the volume of leachate generated.

4.2.2. *Landfill Age*

As a landfill ages, the waste in the landfill layer will degrade and result in different by-products. Phases of a degradation process inside the landfill layer are aerobic, anaerobic, methanogenic, fermentation, etc. These processes are influenced by microorganism activity between the waste layers as well as the availability of oxygen. In the early stage, decomposition of waste in landfill layer occurs under aerobic conditions since oxygen is still present within the compacted waste layers. However, this condition only lasts for a few days or weeks. This stage produces heat as high as 80–90°C and a complex solution within a neutral pH value. Not much is contributed to the leachate composition at this point, but the high temperature generation is very important in enhancing the waste decomposition. Once the oxygen has been fully utilized within the waste layer, decomposition occurs anaerobically. Leachate production during this stage will contain high concentrations of ammonia, metals and soluble degradable organics, and is very acidic. After several months or years, leachate will be produced under methanogenic conditions. Leachate will be in a slightly alkaline or neutral condition with much lower contaminant concentrations but still high in ammonia. Once biodegradation is nearly completed, aerobic conditions prevail. Table 7 shows the typical composition of leachate at different ages of landfill.

4.2.3. *Rainfall Statistics*

Rainfall is the means by which outside water infiltrates the landfill system and causes the amount of landfill leachate to increase. Even though the infiltration of rainfall into the landfill increases the quantity of leachate, it also changes the concentration of leachate through dilution processes. Table 8 shows the rainfall statistics for the Butterworth station located about 30 km from Pulau Burung landfill site. An example of the effect caused by rainfall on the leachate quality (color and COD) at Pulau Burung landfill site is shown in Fig. 8.

4.3. *Infiltration of Leachate*

Leachate will flow downward to the bottom of the landfill and if no liner is present, will continue to seep downward until it reaches the water table. The availability of a liner in a landfill will minimize or attenuate the flow, and leachate collection pipes will direct the flow to a designated area (leachate collection pond) prior to treatment before discharge. However, there have been few studies on the possibility of failure of an a liner system to prevent the infiltration of landfill leachate into the groundwater.

Table 7. Typical Data on the Composition of Leachate From New and Matured Landfill.[15]

	Value, mg/L		
	New Landfill (Less than 2 Years)		Mature Landfill (Greater than 10 Years)
Constituents	Typical	Range	
BOD_5	10,000	2,000–30,000	100–200
TOC	6,000	1,500–20,000	80–160
COD	18,000	3,000–60,000	100–500
Total suspended solids	500	200–2,000	100–400
Organic nitrogen	200	10–800	80–120
Ammonia nitrogen	200	10–800	20–40
Nitrate	25	5–40	5–10
Total phosphorus	30	5–100	5–10
Ortho phosphorus	20	4–80	4–8
Alkalinity as $CaCO_3$	3,000	1,000–10,000	200–1,000
pH	6	4.5–7.5	6.6–7.5
Total hardness as $CaCO_3$	3,500	300–10,000	200–500
Calcium	1,000	200–3,000	100–400
Magnesium	250	50–1,500	50–200
Potassium	300	200–1,000	50–400
Sodium	500	200–2,500	100–200
Chloride	500	200–3,000	100–400
Sulfate	300	50–1,000	20–50
Total iron	60	50–1,200	20–200

Even in an engineered landfill site, there are still possibilities of leakage due to design faults or limitations, or the exceeding of a liner's lifetime. Therefore, an acceptable leakage limit typically considers the physical and attenuation properties of the lining system.

4.4. *Attenuation of Leachate*

Contaminant transport at a landfill site involves numerous movements and changes, such as the passing of contaminants through the liner to the groundwater flow and the discharge of groundwater to surface water. These changes are due to the attenuation properties[28] of either the lining system or the soil type at the site. Attenuation causes a decrease in contaminant concentration as it undergoes physical, chemical, and biological processes such as sorption and desorption, precipitation and dissolution, advection/ dispersion, dilution, and degradation. Figure 9 shows an example of the attenuation of leachate as it infiltrates into the groundwater system, and Table 9 summarizes the parameters affected by these attenuation processes.

Table 8. Rainfall Statistic at Butterworth Station.[7]

	August 2003	September 2003	October 2003	November 2003
Days	Rain (mm/day)	Rain (mm/day)	Rain (mm/day)	Rain (mm/day)
1	31.1	9.1	89.8	1.2
2	44.3	13.7	82.4	2
3	20.9		113.6	8.4
4	T		123.7	4.1
5			82.5	T
6			5.7	1.1
7		82.8	3.9	1.2
8		70.5	9.9	27.6
9	0.2	5.2	T	5.2
10	T	T	0.2	22.3
11		4.9	T	18.1
12	4.9	8.6	0.2	4.1
13	15.3	23.5	10.5	
14	46	22.4	16.1	
15	38	0.1		32.4
16	13.6		8.6	1.5
17	6.5		2.3	
18		34.2	7.3	0.6
19		21.9	22.8	14.6
20		1.3	60.6	5.8
21		0.2	7.8	
22			3.7	2.6
23	34.8	6.9		6.5
24		0.8	9.9	T
25		6	0.1	22.1
26		0.2		20.4
27	38.2	12.8		
28	0.3	0.4		34.1
29	20.9		2.2	
30	17.2		6.9	
31	1.7		3.1	
Total	333.9	325.5	675.4	235.9

4.4.1. *Adsorption*

One of the major attenuation processes[29] occur within the subsurface soil and involves the interaction of contaminant toward the soil surface due to either physical attraction (physical adsorption) or chemical bond (chemisorption). Both interactions are almost the same as they are the processes by which dissolved contaminants are prevented from entering the aqueous phase, and they will be referred to here simply as the adsorption process. The process occurs at the surface of a certain solid matter

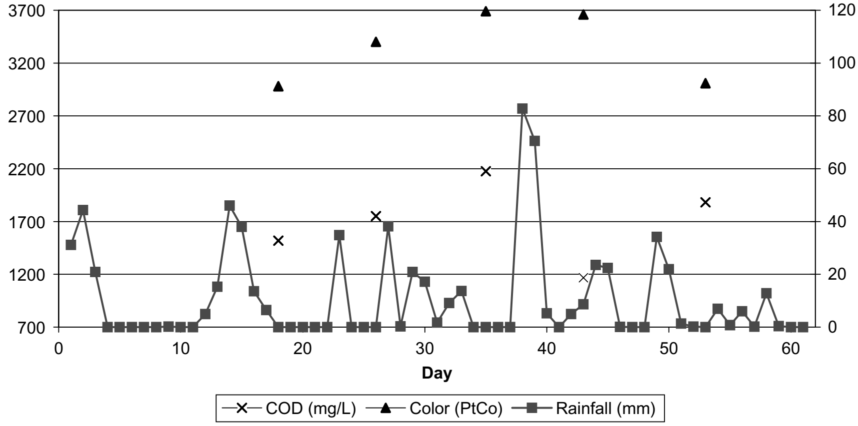

Figure 8. Relationship of Rainfall (August–September 2003) for COD and Color in Leachate.[7]

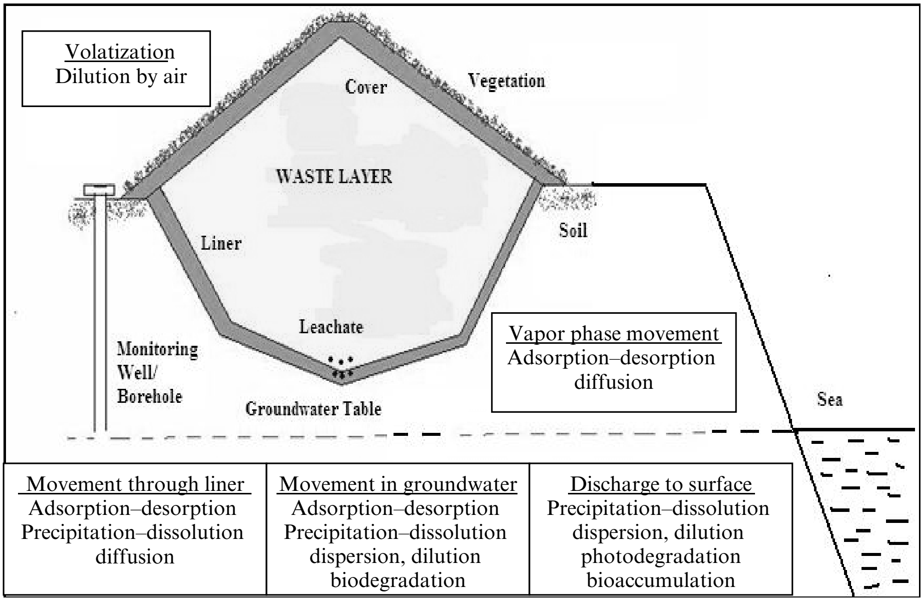

Figure 9. The Attenuation of Leachate.[16]

and the aqueous layer with which it comes in contact. This process is also sometimes referred to as an adsorption-exchange. Adsorption is known to cause a decrease in leachate TDS value, while the exchange only changes the type of ion in the leachate but does not reduce the value of TDS.[1,17] The adsorption process is induced by a chemical process where the charged ions of contaminants are attracted to the surface or into the solid interior. The processes are either complete or partially reversible.

Table 9. Attenuation Processes and Affected Parameters.[13]

Attenuation Processes	Parameters Affected
Precipitation/dissolution	Al, As, Ba, Br, Cd, Ca, Cr, Cu, Fe, Pb, Mg, Mn, Hg, Ni, K, Se, SiO_2, $SO_{4\ 2-}$, Zn
Sorption/desorption	As, Ba, Br, Cd, Cr, Cu, Fe, Pb, Hg, Ni, Zn
Complexation	Ba, Ca, Cr, Cu
Ion exchange	NH_3, Ba, Ca, Cr, Cu, F^-, Fe, Pb, Mg, Mn, K, Se, Na, $SO_{4\ 2-}$, Zn
Filtration	COD (minor)
Dilution	Cl, VOC
Degradation	NH_3, COD, Fe, NO_{3-}, VOC

Common adsorbents in the soil are sand, clay, organic matter, humic substance, and also hydrous metal oxides.[18]

4.4.2. *Complexation*

Complexation occurs between complexing agents and metal ions to form complex matter (soluble or insoluble). The formation of complexes will affect the dispersion of contaminants in the groundwater body. Typical complexing agents are sulfide, sulfate, chloride, and bicarbonate species. The complexation process depends on pH, DO, metal, and anion concentration.[18]

4.4.3. *Precipitation/Dissolution*

In this process, contaminants either enter the aqueous phase or form a solid phase. It is the same phase as a complexation process where complexing agents react with ions of metals to form soluble or insoluble complexes. These processes are affected by the factors such as the pH value, temperature, pressure, type, and concentration of complexing agents and also the oxidation agents.[18] This process affects the extent of trace metal contamination in the groundwater and also the mobility of the metals in the leachate contaminated groundwater plume.

4.4.4. *Advection/Dispersion*

Advection/dispersion occurs because of the motion or flow of groundwater. This motion enhances the spreading of contaminants into the groundwater and influences the extent of the contamination zone. Dispersion spreads the contaminants to a larger area in the groundwater whereas the advective transport of contaminant only affects a certain point in a groundwater aquifer. The dispersion of contaminants in the groundwater is similar to the dispersion of gases in the atmosphere. It is also affected by the groundwater velocity. Many researchers also believe that the dispersitivity also depends on the scale of area being studied.

4.4.5. *Dilution*

Dilution of the concentration of contaminant is accomplished through contact with existing water bodies or the addition of water. This process does not chemically alter the leachate composition. Dilution occurs as soon as the leachate-concentrated liquid comes into contact with other water sources. In this case, the water source is formed either from rainfall that seeps into the ground or from the existence of groundwater in the soil. Dilution reduces the concentration of contaminant that is present in the highly-polluted leachate. Hardness, chloride, nitrate, and sulfate that are not attenuated by soil will be reduced by the dilution process.[13] This process is influenced by a difference of density between leachate and groundwater, groundwater velocity, diffusion/dispersion coefficient, soil strata, leachate entry velocity, and the landfill area.[13]

4.4.6. *Filtration*

Filtration involves the physical entrapment of suspended solids and settleable solids in leachate. The efficiency of the process depends on leachate hydraulic gravity and soil pore size. However, the change in leachate properties due to this process is quite insignificant.

4.4.7. *Degradation (Biodegradation, Hydrolysis, and Oxidation-redox)*

Biodegradation is a process in which organic compounds are oxidized by microorganisms. Active microbial populations are present in the subsurface layer. Biodegradation is limited by numerous factors including the concentration of the contaminants, pH, presence of toxicants, adsorption, temperature, as well as the lack of oxygen and other nutrients such as phosphorus and nitrogen. Hydrolysis involves the breakdown of mineral by H^+ and OH^- that are present in the groundwater. This process is influenced by the pH, type and concentration of cations, oxidation-redox state, and temperature. The hydrolysis process is enhanced at a high temperature, low pH, low oxidation-redox state, and with low organic contents. Most highly charged trace metals are strongly hydrolyzed in aqueous phase. Oxidation is a process that involves the transfer of electrons between atoms. This brings out the reaction of combination and separation of ions or molecules. Redox potential indicates the oxidation state of multivalent metal ion in the aqueous environment.

5. Monitoring Well/Borehole

Groundwater contamination can be detected by using either groundwater monitoring well/borehole (direct method/sampling) or a geophysical technique (indirect method/nonsampling).[32] Geophysical techniques operate by imposing stress on the subsurface, measuring the response toward the imposed stress, and using the data to assess the nature of the groundwater body. Some examples of the geophysical method involve the use of heat conduction, magnetism, shock waves, and electricity. However, numerous studies have found that the detection of groundwater contamination using this method can be very difficult since the data can be affected by a number of factors such as contaminant type, soil type, soil porosity, soil moisture, moisture profile, and clay content.

For routine monitoring purposes, usually the groundwater-monitoring method is used. This is the same method applied at the Pulau Burung landfill site. A monitoring well or borehole is constructed at the landfill site. The diameter of a monitoring well is much larger than that of the borehole. The construction of a monitoring well is accomplished through digging, while a borehole can be constructed just by drilling. For groundwater monitoring, usually a series or network of monitoring points is constructed within the landfill site. In the case of Pulau Burung landfill site, a monitoring well was positioned at both leachate collection ponds, in the middle of the landfill and at site boundaries where the contaminated groundwater will exit the gradients. The monitoring points of the five boreholes at Pulau Burung landfill site are shown in Fig. 10.

5.1. *Type of Monitoring Well/Borehole*

Many types of monitoring wells/boreholes are used to retrieve groundwater samples. The most common type is through the construction of a conventional borehole at the monitoring point. Other monitoring types derived for sampling are either a combination of borehole and piezometer installation or other multilevel sampling devices.

5.1.1. *Open and Fully Screened Boreholes*

The uncased boreholes or fully screened boreholes have been used to sample groundwater for many years. Open/uncased boreholes are used at sites with stable soil while fully screened boreholes are used for unconsolidated soil types.[15] A fully screened method is applied for the sampling of groundwater at the Pulau Burung landfill site. The sample is obtained by pumping it from a depth or a number of samples taken from the boreholes. This method provides a depth-averaged sample of groundwater since the pumping would force the water from the surrounding groundwater to enter

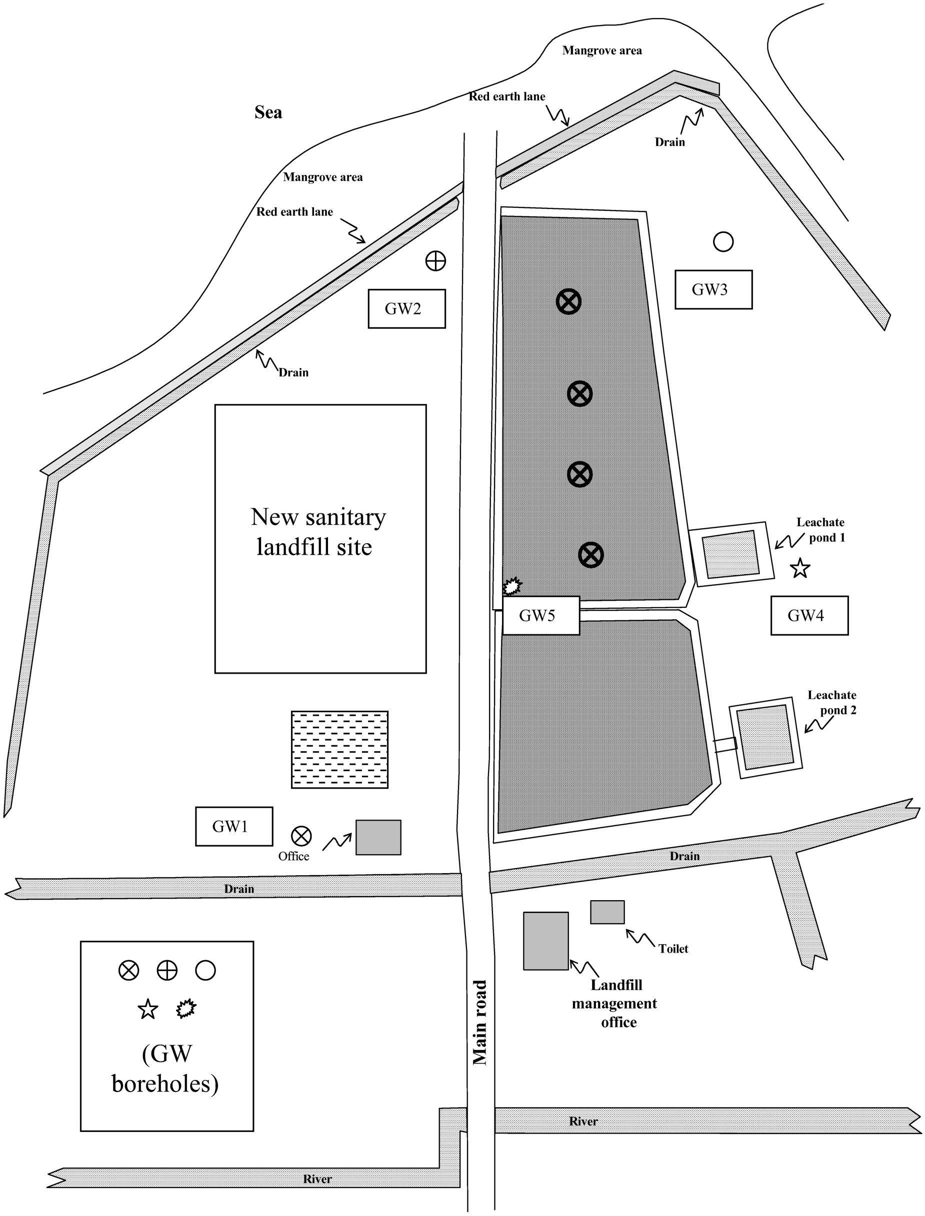

Figure 10. The Monitoring Points of the Five Boreholes at Pulau Burung Landfill Site.[9]

the casing of the borehole. However, prepumping or purging to remove the stagnant water in the borehole casing is necessary as the step will draw the fresh groundwater from the surrounding aquifer to be taken as samples. Sampling without prepumping or purging would result in an error of the sampling procedure and will be discussed

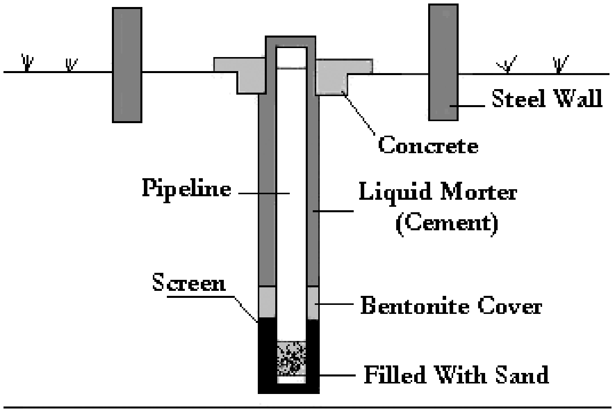

Figure 11. Schematic Design of an Open Borehole at Pulau Burung Landfill Site.[9]

further in this chapter. Figure 11 shows an example of a fully screened borehole built at Pulau Burung landfill site.

5.1.2. *Straddle Packer and Multipacker Boreholes*

This method is similar to the open or fully screened boreholes. The difference is that this method uses packers to restrict the vertical movement of water during the sampling. Using packers ensures that the pumping would only suck groundwater from a certain section of an aquifer since it is being isolated by the packer.[19] However, the difficulty in using this method is normally caused by the irregularity of the borehole wall and results in operational problems. Research by Barczewski and Marschall (1989) concluded that this method would give the same depth-averaged samples as the open or fully screened borehole method.

5.1.3. *Short-screened Boreholes and Piezometers*

With this method, a series of short-screened boreholes, with 1–2-m-long screens are set on different depths and separated by low-permeability bentonite seal. One or a bundle of nested piezometers can be placed within the borehole for abstraction of groundwater sample. This method is quite effective since it only requires the use of small diameter pump and only a small amount of stagnant groundwater within the screen needs to be excreted. In order to obtain a representative sample, purging of at least 2–3 borehole volumes is recommended.[20] It is a cost-effective method for determining the variability of groundwater quality at different depths. However, it is necessary to reduce the rate of pumping for low-permeability soil since it could damage the pump if the boreholes are emptied during the sampling.

5.1.4. *Multilevel Boreholes and Lysimeter*

This method is designed to simplify the sampling procedure by eliminating the need to remove stagnant water and reducing the screen length and tube diameter. This sampling method usually uses gas lift or suction to remove water from the sampling device to obtain the sample.

5.2. *Coordination, Number, and Depth of a Borehole*

The coordination of monitoring wells is determined by assessing the risk of contamination at the landfill site. Selection of the monitoring position is made by determining the pathway in which contamination would likely to occur; it should be as close as possible to the leachate source. The number of wells chosen also depends on the risk assessment of the landfill site. Usually, at least three monitoring wells are required in which one is located on the upper gradient of the landfill site and the other two at the lower gradient. Figure 12 shows the groundwater-monitoring wells based on the upper gradient and lower gradient flows at landfill site.

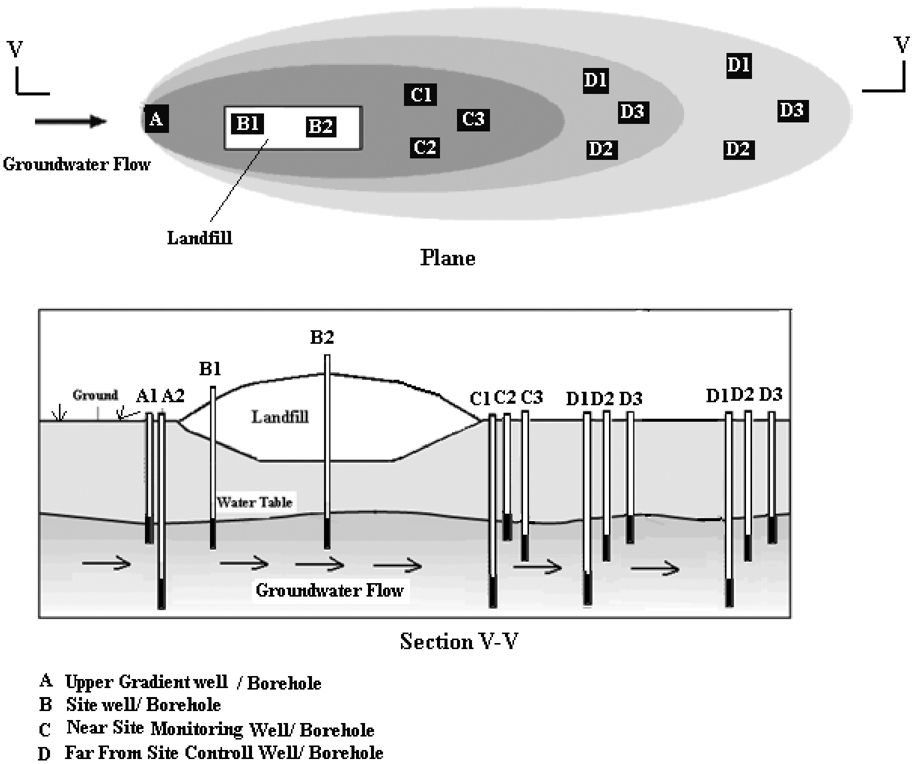

Figure 12. Groundwater-monitoring Well Based on the Upper-gradient and Lower-gradient Flows.[10]

In the case of the Pulau Burung landfill site, monitoring is selected based on the location where infiltration of leachate is likely to occur. Additional monitoring wells are also installed at the boundaries of the landfill site to provide baseline data for future extension of the landfill area. These additional wells also help determine the risk of natural water resource pollution surrounding the area. The numbers of additional wells constructed is also determined by the type of liner used at the site. At least one additional monitoring well is required per 100 m width of landfill site for a landfill site with a natural liner and per 50 m width for an artificial liner. This ratio is due to the probability of leakages by diffusion for landfill site with natural liner, and leakages through hole or tears for the artificial liner. If leachate contamination is discovered, other monitoring wells are usually needed, including a well outside the landfill area. The depth of a monitoring well/borehole depends on the regional water table and the coordination of monitoring point in the landfill site, which is either on natural ground or on the waste layer as shown in Fig. 12.

5.3. *Construction of a Well/Borehole*

A well or borehole can be constructed either during landfilling or retrofitted after landfilling. Both methods of monitoring design have their own advantages and disadvantages as summarized in Table 10. Drilling of a borehole for groundwater sampling must be done with precautions in order to avoid contamination or damage to the liner system, especially in the case of a monitoring point located on the waste

Table 10. Monitoring Design on Landfill Site.[1]

Type of Monitoring Installation	Advantages	Disadvantages
Retrofitted	Made vertically Monitoring well with higher density can be built where required Easier selection for design and sealing	Difficult due to risk of puncture Unpredictable drilling problem Potentially hazardous during drilling stage Usually required large or more specialize drilling rig for over 30 m deep
Built	Monitoring from base of landfill drainage layer Install on site Obtain monitoring data during landfill operational	Prune to damage during landfill operation Design might be effected or disintegrated by chemical Required additional foundation system for maintaining vertically and prevent puncture No capping and restoration

Table 11. Type of Drilling Method for Construction of Borehole.[1]

Drilling Rig	Advantage	Disadvantage
Rotary rig	Inexpensive; Quick and easy cleaning; Lining can be put directly into the hollow; Required no drilling liquid; Allow continuous sampling in consolidated material	Cannot drill through hard rock; Depth and water strike cannot be easily identified using solid stem auger; Solid stem auger cannot be used on loose ground; Hollow stem auger cannot drill through presence of boulder; Installation of annular fill and seal cannot be done in easily collapsed ground
Cable rig	Inexpensive; Easy to clean and to identify changes in water; Use little amount of drilling fluid; Possible to obtain undisturbed bulk sample; Required temporary casing for installation of lining but with more accuracy	Cannot drill through hard rock; Slow; Can damage the side of borehole
Other rotary rig	Could be inexpensive and fast in unconcealed material; Continuous sampling can be made in consolidated material; Can be use for drilling in all formation type	Can be expensive; May required drilling fluid and possibility of contaminant due to circulating fluid; Can damage the side of borehole; Sampling can be slow at great depth; In unconsolidated formation, only installation of narrow diameter lining permitted

layer. Common drilling methods on the waste layer include continuous flight augers, hollow stem augers, single flight augers, large diameter single-tube barrel, and cable percussion (shell and auger). For natural ground drilling, common drilling methods are auger (hollow stem augers, continuous flight, or single flight), cable percussion (shell and auger), and conventional rotary. Table 11 summarizes the different methods of drilling and their advantage and disadvantages.

5.3.1. *Contamination During Drilling*

Drilling of a borehole must also be done properly in order to avoid contamination of groundwater during the process and to avoid damage to the constructed borehole. Contamination may originate either from the addition of drilling fluid or contaminated drilling equipment. The addition of drilling fluid or water is unavoidable; therefore, water from a known quality source is normally used and the characterization of the added water can be provided as a reference for the groundwater data. Meanwhile, to prevent contamination due to contaminated drilling equipment, decontamination of the equipment is necessary after each drilling exercise, especially if drilling is done in a contaminated ground. Decontamination of drilling parts is done by pressure-washing, rinsing, or steam cleaning.

5.4. *Borehole Maintenance and Cleaning*

A borehole must be maintained in order to prevent silt accumulation and blockage by other objects. Therefore, the cleaning of a well/borehole is required to remove silt and other material from the lining, gravel pack, and strata. Cleaning is done by surging and pumping the borehole for a certain period. The volume of water used for cleaning should exceed the normal borehole volume (pre pumping or purging) to achieve adequate cleaning. A lesser volume may be used if a geotextile wrap is used for the borehole design. Maintenance is not only needed for active boreholes but also for abandoned and damaged boreholes. These boreholes must be sealed and capped with either cement or bentonite to prevent contamination of groundwater through the borehole passage.

6. Sampling and Measurement

6.1. *Measurements*

Measurements taken at a landfill site should include physical measurements, principle chemical composition, minor chemical composition, and biological measurement. For example, physical measurements would include landfill site runoff, vegetation presence, rainfall measurement, surface water flow rate, both leachate and groundwater level, and the base of a monitoring point level. Table 12 lists the parameters for these types of measurements. As in the case of sampling for other water sources, sampling at wells/boreholes can be done either as a discrete or spot sample, or composite or continuous sample. Discrete or spot samples are taken at a single point, whereas composite samples are taken from a number of monitoring points or at different time intervals. Data recorded by data loggers and electronic instrumentation are called continuous samples.

6.2. *Sampling and Measurement Devices*

6.2.1. *Level Measurement*

Level measurement is used to measure the water level inside a borehole. The most common device used is an electric tape, which uses a probe submerged in the water

Table 12. Parameter for Physical, Chemical, and Biological Measurements.[1]

Measurements	Parameters
Physical	Water balance (rainfall and meteorological data and volume changes in landfill site); Observation (surface run off, vermin, vegetation, and other contaminants source); Groundwater and leachate level
Principle chemical composition	pH, temperature, EC, DO, Eh, TSS, TDS, NH_3-N, TON, VFA, TOC, BOD, COD, Ca, Mg, Na, K, total alkalinity, SO_4, Cl, Fe, Mn
Minor chemical composition	Trace metals, inorganic (Cd, Cr, Cu, Ni, Pb, Zn, orthophosphate, As, Ba, B, CN, F, Hg, dissolved methane), and organic (phenols, mineral oils, pesticide, polychlorinated biphenyl, and chlorinated solvents) contaminants
Biological	Coliform bacteria, chlorophyll a, toxicity test, macroinvertebrate community

to form an electrical circuit. Inaccurate results from the device may occur in different conductivity waters (high or low) and in different environments. To overcome these errors, a sensitivity switch can be used and regularly calibrated for the dipping purpose. Other devices used for this measurement are the float device or pressure transducer, which are used for remote or continuous monitoring, together with a data logger or chart recorder. A pressure transducer operates on the pressure of the groundwater level and further depths would result in much higher pressure. Therefore, a range of depth must be determined and calibrated to obtain accurate and reliable data.

6.2.2. *Sampling Apparatus*

At the Pulau Burung landfill site, groundwater samplings were obtained through the use of a suction pump called the Masterflex Composite Sampler. Examples of sampling done at the landfill site are shown in Figs. 13 and 14. Besides the suction pump, many types of sampling devices are used for the groundwater borehole as summarized in Table 13.

6.3. *Sampling Procedures*

Before groundwater abstracted from a borehole can be analyzed, prepumping or purging of stagnant water within the borehole is necessary. This is because the stagnant water that remains in the borehole no longer has the same characteristics as the surrounding water (groundwater). The stagnant water might have undergone significant chemical changes due to long contact with atmospheric pressure degassing, contamination, and biological processes. Usually three borehole volumes (internal radius of borehole × height of water column in borehole) are purged before sampling is done. However, purging also creates some problems since a large volume of water

Figure 13. Abstraction of Groundwater Sample at GW2 Point.[9]

Figure 14. Abstraction of Groundwater Sample at GW5 Point.[10]

needs to be discarded and will also draw fine matters that introduce high suspended solids into the sample. Filtration of a sample can be done to resolve the problem of suspended solids. Filtration may be conducted during sampling or in the laboratory.

While samples are typically analyzed in the laboratory, some parameters must be measured on site such as pH, temperature, electrical conductivity, dissolved oxygen, and redox potential. These parameters must be determined on site since

Table 13. Various Sampling Devices.[1,2]

Equipment	Advantage	Disadvantage
Bailer	Easy to operate and portable; Low cost; Dedicated or disposable	Slow purging due to low abstraction; Sampling the top of water column; Bailing cable can cause cross-contamination due to movement and agitation if used vigorously
Discrete depth sampler	Easy to operate and portable; Low cost; Sampling different depth by sequential sampling	Slow purging due to low abstraction; Failure in closure due to presence of suspended solid; Causes agitation and thus causes pressure change
Inertial	Can be used for purging; Can operate to up to 60 m depth and in silty condition; Low-cost dedicated system; Simple maintenance; Available in lightweight and portable	Causes agitation; Will entrain the suspended solid in the sample
Suction (peristaltic)	Tubing can be installed in the hole; Avoid cross-contamination by the used of inertial pump as priming mechanism	Suction can degas sample; Causes agitation and thus causes pressure change; Only operates up to the depth of 7.6 m or less; May cause cross-contamination thus requiring priming
Electric submersible	Easy to operate and can be used for purging even for low flow purging; Operates deeper than 75 m using pump with diameter more than or equal to 50 mm	Causes agitation and thus causes pressure change; Heavy and requires vehicle for transport; Capability reduced in higher temperatures and presence of suspended solids
Bladder	Can be used for low purging; Operates at any depth; Small disturbance to sample	Slow purging due to low abstraction; Expensive;
Gas lift	Operates at any depth	Requires compressor or tank; Degassed and pressure change of sample due to usage of gas

Table 14. Recommended Storage and Preservation of Groundwater Sample.[21]

Parameter	Recommended Container	Max Holding Time	Preservation Required
Temperature	Polyethylene, glass	Analyze immediately	None
pH	Polyethylene, glass	Analyze immediately	None
Alkalinity	Polyethylene, glass	48 h	4°C
BOD	Polyethylene, glass	24 h	4°C
COD	Polyethylene, glass	48 h; 28 days if acidified	4°C; acidify with H_2SO_4 to pH <2, 4°C
VOC	Glass, teflon	14 days	4°C; acidify with HCl to pH <2, 4°C
TDS	Polyethylene, glass	7 days	4°C
Ammonia	Polyethylene, glass	7 days; 28 days if acidified	4°C; acidify with H_2SO_4 to pH <2, 4°C
Nitrate	Polyethylene, glass	48 h	4°C
Heavy metals (include iron and manganese)	Polyethylene, glass	6 months except 28 days for Hg	Acidify with HNO_3 to pH <2, 4°C (for dissolved metal, filter before acidify)
Calcium, magnesium, sodium, potassium, fluoride, sulfate, chloride, hardness	Polyethylene, glass	28 days	4°C

significant changes of groundwater may occur as soon as it comes in contact with the atmosphere. To prevent contamination of a sample, it is advisable to analyze the sample within 24 h, under limited exposure to sunlight, stored at low temperatures, and without agitation of the sample. For lab analysis, an appropriate container is needed. Certain analyses of parameters will also require the preservation of a sample as summarized in Table 14.

Frequencies of sampling can be determined using the groundwater flow rate calculated using Eq. (1). From the flow rate, distance and travel time of contaminants are calculated using:

$$t = s/Q, \tag{2}$$

where, $t =$ travel time (s) and $s =$ distance (m).

This equation takes into account the flow rate of groundwater; thus, it can only be used to determine the minimum groundwater frequencies since movement of contaminants also influenced by other factors such as different flows between soil pores and attenuation mechanisms.

6.4. *Sampling Error*

Sampling error must be prevented in order to obtain an accurate representative data. Certain factors must be considered especially during the sampling of groundwater. These factors include the sampling procedure and the selection of sampling devices. Table 15 summarizes the factors that affect the quality of groundwater sample and the affected parameter.

Table 15. Error in Sampling and Affected Parameter.[1]

Process	Contaminant Affected	Causes	Prevention
Inappropriate sampling	Alkalinity, BOD, COD, DO, TOC, VOC, NH_3-N, metal, phosphate, organic compound, and dissolved gases	Still water in the well are not purged before sampling	Appropriate selection of purging procedure
Pressure change	Alkalinity, DO, VOC, NH_3-N, and dissolved gases	Sampling method — movement of equipment causes small pressure change	Reduce or eliminate movement part of equipment during sampling
	DO, VOC, and dissolved gases	Change of pressure — underground to ambient pressure	Sustain pressure if possible
Temperature change	DO, VOC and dissolved gases	Sample storage	Do analysis immediately
Aeration/ oxidation	DO, VOC, NH_3-N, trace metal, and dissolved gases	Contact with air causes release of gases and volatile compounds and the precipitation of metals	Reduce contact with air and use air-tight sampling bottle
Adsorption/ dissolution of metals	Trace metals	Silt in water sample — problem with some trace metals such as zinc, iron, and manganese	Prevent suction of silt together with water sample
Cross-contamination	DO, VOC, trace metals, trace organic compounds, and dissolved gases	Sample equipment and handling	Equipment for leachate and water samples should be separated
Adsorption/ desorption of organics	BOD, COD, TOC, and trace organic compounds	Material in sampling equipment and borehole	Selection of appropriate tube, filter and design

7. Data Assessment

7.1. *Record*

7.1.1. *Baseline/Background Data*

In order to determine whether or not there is significant contamination in the groundwater data, another set of data is required for comparison with the data taken during or after landfilling is completed. This set of data is called baseline data or background data. There are two ways for determining baseline data for groundwater in landfill site. These are:

1. *Historical Data*: Groundwater data that has been taken on the site before the landfill started its operation.
2. *Upper Gradient Data*: Groundwater data that has been taken on the same groundwater body as the one in the landfill site but on the upper gradient of the site. This gives groundwater data that is not influenced by leachate infiltration.

However, it should be emphasized that even baseline data itself may have variations since it is still affected by other factors besides landfill, such as seasonal factors like rainfall. A set of data is required, so that the total variability of the baseline data is used for the comparisons. In the case of the Pulau Burung landfill site, it began its operation as a dumping site; therefore, it did not have any historical baseline data for comparison with the current data. However, for further expansion of the landfill site, necessary steps have been taken to install two boreholes at the potential sites to indicate the baseline data for future use.

7.1.2. *Borehole Log*

Log data for borehole installations at the landfill site are kept as records for safety and maintenance. Information that is included in the log data are well number, well location (grid point), date of installation, type of well, type and diameter of well casing, mean sea elevation of the top well casing, ground surface near well, depth of the well, top of the screen, and material and length of well screen.

7.2. *Data Analysis*

Current data and the baseline data are compared to determine whether or not the contamination of leachate occurs at the landfill site. In the case of Pulau Burung, two sets of data were compared from research done by Yusof[9] and Izham.[10] The comparison showed very significant changes in groundwater parameters during the

Table 16. Average Value of Parameter Sampled at Monitoring Wells, GW1 to GW5.[9,10]

	(01/10/2001–23/10/2003)				
Parameter	GW1	GW2	GW3	GW4	GW5
COD (mg/L)	153	116	655	585	541
pH	8.19	7.08	6.67	6.7	7.28
Turbidity (NTU)	96	12	13	109	190
SS (mg/L)	104	20	51	63	115
Color (PtCo)	376	599	301	199	330
Manganese (mg/L)	1.20	0.40	0.20	0.70	1.71
Lead (mg/L)	0.88	0.77	0.77	0.64	0.80
Mercury (mg/L)	0.01	0.01	0.01	0.01	0.01
Copper (mg/L)	0.22	0.19	0.26	0.21	0.51
Total chromium (mg/L)	0.10	0.10	0.12	0.11	0.09
Phosphate (mg/L)	0.3	0.3	0.3	0.7	1.3
Sulfate(mg/L)	18.7	4.2	0.7	0.9	2.1
Nitrate (mg/L)	5.7	2.5	1.8	3.6	7.9
BOD (mg/L)	23	19	160	120	135
Temperature (°C)	25	25	31	30	31

one-year time frame as shown in Table 16. An increase in certain parameters was discovered especially for BOD, COD, turbidity and SS.

7.3. *Data Representation*

As data are recorded for a number of monitoring points at certain time intervals, it would be effective to portray such data in a graphical format such as a time series chart or spatial plot. An example of groundwater-monitoring data obtained from Pulau Burung landfill site over time is shown in Figs. 15 and 16.

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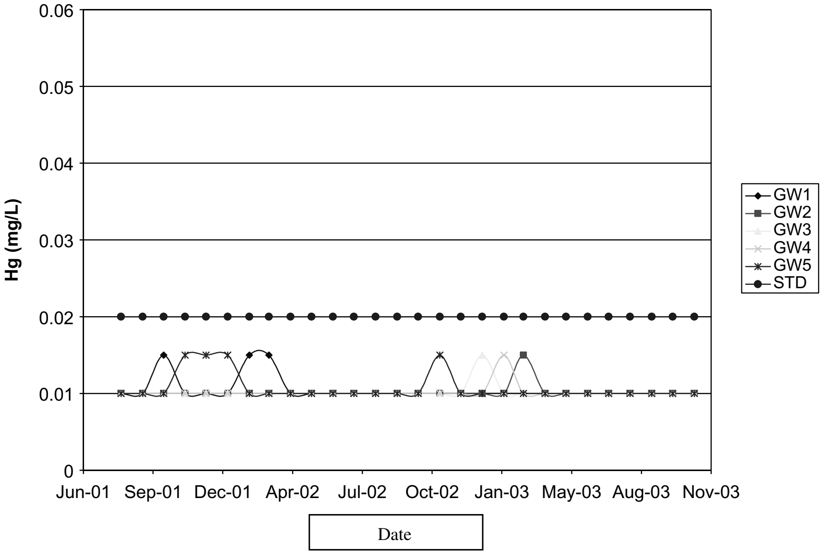

Figure 15. Time Series Graph for Hg (August 8, 2001–November 5, 2003).[10]

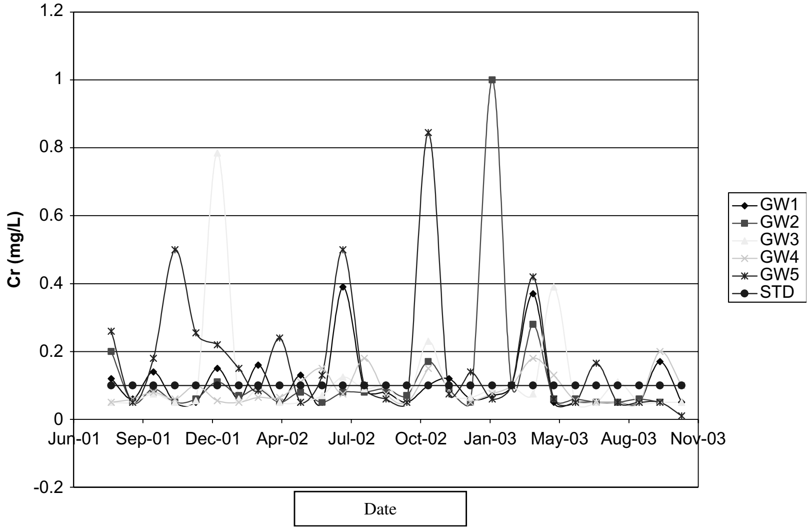

Figure 16. Time Series Graph for Total Cr (August 8, 2001–November 5, 2003).[18]

Nomenclature

BOD Biochemical oxygen demand, mg/L
COD Chemical oxygen demand, mg/L
DO Dissolved oxygen, mg/L

EC	Electrical conductivity, μS/cm
Eh	Redox potential, mV
i	Hydraulic gradient, m/m
K	Hydraulic conductivity, m/s
n	Effective porosity, dimensionless
NH_4-N	Ammoniacal nitrogen, mg/L
PBLS	Pulau Burung landfill site
Q	Flow rate, m/s
s	Distance, m
SO_4	Sulfate, mg/L
t	Time, s
TDS	Total dissolved solids, mg/L
TOC	Total organic carbon, mg/L
TON	Total oxidized nitrogen, mg/L
TSS	Total suspended solids, mg/L

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