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ORIGINAL ARTICLE

A case study on anticipated leachate generation from a semi-aerobic sanitary landfill at Aruwakkalu (Puttalam District) and its impacts

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Abstract Leachate generation from sanitary landfills is regularly expected in tropical regions whenever the municipal solid wastes (MSW) attain its field capacity. However, there seems to be no studies documenting the behavior of high moisture laden MSW in sanitary landfills constructed or proposed in arid areas. Therefore, in this study prediction of leachate quantities is conducted using the water balance method with reference to a semi-aerobic sanitary landfill that would be designed to dispose 1,130 tons of pre-compacted MSW per day (in 2035) having a high moisture content of 70 % by w/w from the Metro Colombo Region which has a mean annual rainfall of 2,500 mm (but the landfill to be sited in Aruwakkalu; an arid area having a mean annual rainfall of <1,500 mm). This article also discusses the feasibility of leachate treatment (considering the expected quality) and other issues that would arise due to leachate generation. Leachate production occurs during the peak rainy seasons (October; 2nd inter-monsoonal period and November–December; north-east monsoonal period) only despite the fact that the incoming MSW has a high moisture content. Furthermore, the generated leachate is a methanogenic leachate with a low BOD_5/COD (<0.3). At higher leachate heads, leachate breakthrough time and the time of travel (TOT) for Cl^- are lower, but seepage velocities and flow rates are higher for both leachate and Cl^-. Breakthrough time and hydraulic conductivity show an inverse relationship considering groundwater contamination in Aruwakkalu having a silty-sand soil (33–93 % sand), but no proper relationship between breakthrough time and seepage velocity.

Keywords Breakthrough time · Leachate · Municipal solid wastes · Sanitary landfill · Water balance

Introduction

Metro Colombo Region (MCR) within the Colombo District (Western Province) of Sri Lanka comprises the Colombo Municipal Council (CMC) and the peripheral councils of Dehiwala-Mount Lavinia Municipal Council (MC), Kolonnawa Urban Council (UC) and Sri-Jayawardanapura Kotte MC (Fig. 1). In the MCR, urbanization and economic growth are regarded to have advanced rapidly in recent decades and this trend is expected to further continue. Such an expansion in urban population consequently will cause various problems and one of the most critical problems emerging from rapid urban expansion is the unavailability of an environmentally acceptable disposal system for municipal solid wastes (MSW).

There are several open landfills in the Colombo Metropolitan Area such as the one in Meethotamulla, Bloemendhale and Madampitiya. Presently, unsegregated MSW collected from the Kolonnawa UC and the CMC are simply dumped at Meethotamulla, resulting in intense pollution of the nearby Meethotamulla canal (which ultimately confluences the Kelani Ganga, Sri Lanka's fourth longest river), damaging the image of the beautiful landscape of the city and posing serious threats (including dengue epidemics) to public health and hygiene of the nearby citizens. The Meethotamulla dumping site is known as the largest unsanitary Landfill in the MCR with piled up waste quantities approximating more than 800 tons/day with a piled up height of more than 30 m. Continuous dumping has also resulted in several protests by the nearby residents due to the "Not In My Backyard Syndrome"

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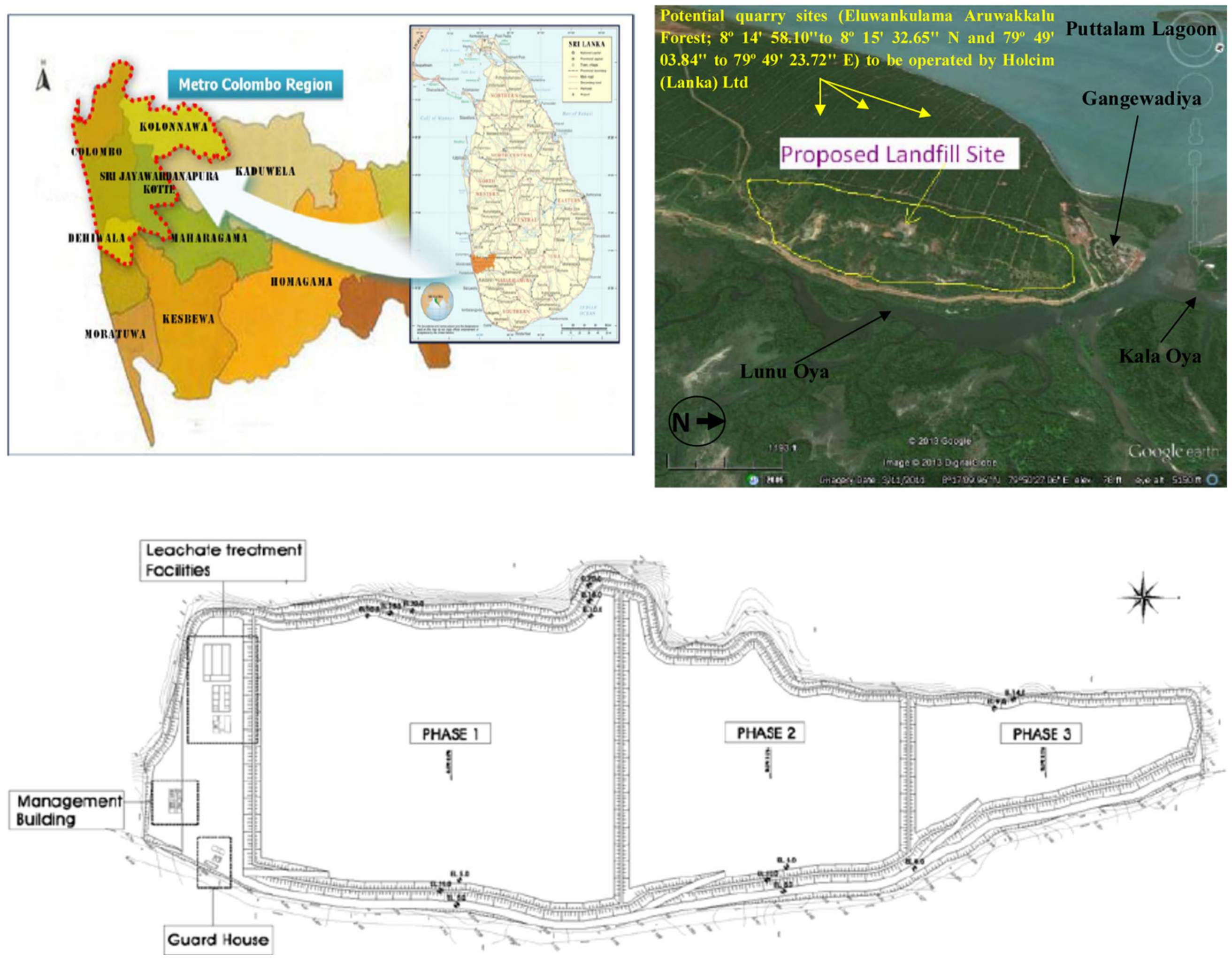

Fig. 1 MCR of Sri Lanka (*top left figure*) and a view of the sanitary landfill site having an area of 88 acres (*top right figure*)

(NIMBY) and often resulting in clashes between the Police and residents. Similar issues have prevailed from other open dumping sites in Sri Lanka. Therefore, the Ministry of Defense and Urban Development under the World Bank funded project known as the Metro Colombo Urban Development Project (MCUDP) has planned to construct and operate a semi-aerobic sanitary landfill to dispose MSW generated from the MCR. In this respect, it is planned to develop the worked out limestone quarries in Aruwakkalu (Puttalam District in the North Western Province) into a Sanitary Landfill to meet city-wide needs for at least 20 years with establishment of a waste transfer station at the Meethotamulla site and using rail transport from Colombo to the proposed landfill site at Aruwakkalu covering a distance of 170 km one-way (see "Appendix" for further details of the MCUDP including details of the proposed semi-aerobic landfill as described by DOHWA Engineering Co Ltd et al. 2014).

However, Aruwakkalu area (Puttalam District) is an arid area located within the Dry Zone of Sri Lanka receiving a mean annual rainfall of less than 1,500 mm, whereas MCR is regularly characterized by a tropical climate (receiving a mean annual rainfall of approximately 2,500 mm). Generally, the moisture content of MSW in the MCR is high reaching around 80 % by wet weight (especially during the peak rainy periods of the south-west monsoon from May–September and also during the period of December–February; north-east monsoonal season). Leachate generation in terms of quantity, quality and treatment aspects is an important criterion to be considered when designing, constructing and operating a sanitary landfill. It is expected that leachate generation would regularly occur in tropical regions whenever the MSW attains its field capacity. Some studies have shown that in arid and semi-arid areas, landfills will either not produce any significant leachate, will only produce leachate seasonally or may produce leachate only as a result of compression of an initially wet waste (e.g., Kumar et al. 2001, 2002; Aljaradi and Persson 2012; Alslaibi et al. 2013) while other reports have documented that in tropical regions or in high rainfall areas leachate generation is a regular phenomenon especially during the peak rainy seasons (e.g., Tränkler et al. 2001, 2005; Mannapperuma and Basnayake 2004; Pathirana and Basnayake 2008; Munawar and Fellner 2013). However, there seems to be no studies documenting or predicting the behavior of high moisture laden MSW in sanitary landfills constructed or proposed in arid areas. Therefore, this article presents a case study pertaining to prediction of leachate generation (in terms of quantity and quality) within a proposed semi-aerobic sanitary landfill site that would be receiving high moisture laden MSW from the MCR. This article also briefly discusses the feasibility of leachate treatment considering the expected quality and other environmental issues that are likely to emanate due to leachate generation.

Materials and methods

Study area

Sanitary Landfill site is located within the Wanathavillu Divisional Secretariat Division (In Sri Lanka, districts are divided into administrative sub-units known as Divisional Secretariats. These were originally based on the feudal counties) of the Puttalam District in the North Western Province and lies East of the fishing village of Gangewadiya (Fig. 1). Moreover, Lunu Oya or Lunu River (one of the tributaries of the Kala Oya) is located towards the East of the landfill area at Aruwakkalu (ultimately falling on to Kala Oya drainage basin) (Fig. 1) and it is one of the few pristine mangrove areas in Sri Lanka. Kala Oya provides the largest freshwater volume to the Puttalam Lagoon (Sri Lanka's second largest brackish water body located at 8°2′ 0 N and 790 40′ 0 E to 8°0′ 0 N and 79°52′ 0 E; 888222 N and 353067 E to 884470 N and 375100 E; 120 km north of Colombo) and it flows in at Gangewadiya (Fig. 1). Puttalam Lagoon is one of the most productive basin estuaries, being important for its finfish and shellfish fisheries (the estuary is 36,426 ha while the surrounding mangroves and salt marshes cover an extent of about 600 and 700 ha respectively) (IUCN Sri Lanka and Central Environmental Authority 2006).

However, seasonal water quality and discharge data for Lunu Oya are not available for the Project area (no gauge station within 15 km distance from the Aruwakkalu site), though this Oya contributes a low discharge to the Puttalam Lagoon during the drier spells. During the dry seasons, Lunu Oya is subjected to saline water intrusion when high tides are evident.

The soil at Aruwakkalu area is a silty-sand soil with a sand content variable in the range of 33–93 % according to sieve analysis studies and the groundwater is relatively brackish (DOHWA Engineering Co Ltd et al. 2014). Occurrence of mangrove and other halophyte species within the abandoned quarry site (when progressing towards the north of the proposed landfill) provides further evidence of the occurrence of high Cl^- in the soil and groundwater. Furthermore, the water table becomes shallow approximating the oya level when progressing from the south towards the north of the proposed landfill site as the depth of the landfill also increases from the south-north (Fig. 1).

The landfill site forms a roughly rectangular area, approximately 1.2 km (north/south) by 0.4 km wide and it has been a worked out limestone quarry which was abandoned over 20 years ago with a maximum and minimum height of 30 m (from mean sea level/MSL) and 0.5 m (from MSL), respectively.

Data collection

Data collection was simply done through intensely reviewing the feasibility reports (including geotechnical investigation reports) prepared by DOHWA Engineering Co Ltd, Resource Development Consultant (Pvt.) Ltd and Sodukwon Landfill Site Management Corporation (Design Team) along with regular discussions had with the Design Team and the Ministry of Defense and Urban Development (Project Proponent). Regular visits to the proposed landfill site were conducted along with the Design Team, Project Proponent and officials from the World Bank in order to examine the environmental characteristics of the Project Area (Aruwakkalu) and various publications too were consulted. Additionally, key informant interviews (KIIs) were held with the University of Peradeniya, villagers of the nearest Gangewadiya fishing village and employees (including security guards) attached to Holcim Lanka Pvt Limited, whose proposed limestone quarry sites (for cement production) are located in the vicinity of the landfill area (Fig. 1).

Evaluation of leachate generation, heads and breakthrough times

The water balance method (given below) was used to evaluate the seasonal variation in leachate generation

$$C = P(1 - R) - S - E \tag{1}$$

where, C is the PERC (percolation) or leachate (mm/year), P is the precipitation (mm/year), R is the runoff coefficient, S is the storage within soil or waste (mm/year), E is the evapotranspiration (mm/year).

Monthly evaporation and rainfall data for a period of 10 years (2003–2013) were obtained from the Department of Meteorology, Sri Lanka and engineering details presented in DOHWA Engineering Co Ltd et al. (2014) were considered to predict the leachate generation scenarios. From the evaporation data, potential evapotranspiration (PET) was calculated using the equation given by the International Rice Research Institute, Philippines applicable to South-east Asian regions (Kumar et al. 2001, 2002).

Additionally, PERC volumes were estimated for the peak rainy seasons (i.e., for the different phases of the landfill). In this respect, the results obtained from the water balance analysis were considered along with the total area of the different phases of the landfill. Time taken for leachate production (i.e., the time taken to reach field capacity) during the different phases of the landfill was estimated by dividing the residual liquid storage capacity available within the waste in an area of 1 m^2 (which was calculated as the product of S in Eq. 1 and the landfill cell height) by the PERC volume in 1 m^2 of the waste.

Leachate head values were calculated using the following equation given by Vesiland et al. (2002)

$$Y_{\max} = \frac{P}{2}\left(\frac{q}{K'}\right)\left[\frac{K\tan^2\alpha}{q} + 1 - \frac{K\tan\alpha}{q}\left(\tan^2\alpha + \frac{q}{K}\right)^{1/2}\right] \tag{2}$$

where, $Y_{\max}$ is the maximum leachate head (cm), P is the distance between collection (cm), q is the vertical inflow (infiltration), from a 25-year, 24-h storm (cm/day), K is the hydraulic conductivity of the leachate collection/drainage layer (cm/s), α is the liner inclination from horizontal (%).

Leachate flow rates through the soil-bentonite liner and the soil underneath the liners were calculated using the Principles of Darcy's Law as follows

$$Q = KiA \tag{3}$$

where, Q, K, i and A denote the flow rate (m^3/s), hydraulic conductivity (m/s), hydraulic gradient and cross-sectional area (m^2), respectively.

Seepage velocities (to determine the time taken to reach the soil-bentonite clay liner) were calculated using the following equation which considers advective flow (governed by Darcy's Law)

$$V_s = Ki/n_e \tag{4}$$

where, V_s, K, i and n_e denote seepage velocity (m/s), hydraulic conductivity (m/s) of the soil-bentonite clay liner, hydraulic gradient (which is the sum of the total thickness of the soil-clay liner and the leachate head divided by the total thickness of the soil-clay liner) and the effective porosity of the soil-clay liner, respectively. Note that seepage velocities were calculated with reference to the lowest and highest possible leachate heads (that were estimated by using Eq. 2) as well as a leachate head of 30 cm (which is the maximum leachate head recommended under the Resource Conservation and Recovery Act Subtitle D Regulations of the US Environmental Protection Agency and the Central Environmental Authority of Sri Lanka).

The above equation (Eq. 4) was also used to evaluate the groundwater contamination scenarios in which K and n_e denote the hydraulic conductivity of the soil layer in the landfill area and the effective porosity of the soils in the landfill area, respectively.

Retardation factor and the average velocity of Cl^- ions in the soil-bentonite clay liner were determined by using the following equation given by Shahmohammadi-kalalagh et al. (2012)

$$R = \frac{V_s}{V_{sc}} = 1 + \frac{\rho_b}{n_e}K_{SD} \tag{5}$$

where, R is the retardation factor, V_s is the seepage velocity (m/s), V_{sc} is the average velocity (m/s), ρ_b is the bulk density of soil (g/m^3), K_{SD} is the soil adsorption coefficient (m^3/g), n_e is the effective porosity.

Leachate breakthrough times (through the soil-bentonite clay liner) with reference to a leachate head of 30 cm and the lowest and highest possible leachate heads were estimated by considering the effective thickness of the soil-clay liner and the respective seepage velocities (which were calculated by using Eq. 4). Similarly, the time of travel (TOT)/breakthrough times for Cl^- (through the soil-clay liner) with reference to a leachate head of 30 cm and the lowest and highest possible leachate heads were estimated by considering the effective thickness of the soil-clay liner and the respective average velocities (V_{sc} in Eq. 5) of the Cl^- ions.

In the case of predicting the groundwater contamination scenarios, leachate breakthrough times were estimated by considering the depth to the groundwater table in the landfill area and the seepage velocities through the soils in the landfill area (which were calculated by using Eq. 4).

Results and discussion

Characteristics of the MSW received at Aruwakkalu

There is no proper evaluation in the feasibility study pertaining to the characteristics of the MCR's MSW that is received at the Meethotamulla Transfer Station, though previous reports (de Alwis 2006; Vidanaarachchi et al. 2006; Kularatne 2014a) revealed that Sri Lankan MSW contains a high moisture content of 70–80 % (on a wet mass basis) with a low calorific value (around 600–1,000 kcal/kg or 2,510,400–4,184,000 J/kg) with a bulk density of 350–400 kg/m^3 (i.e., in freshly generated wastes), 62–66 % of organic matter (biodegradable matter), 6.47–13 % of paper, 5–8 % of plastics and 2 % of glass by weight. According to Asian Institute of Technology (2004), MSW in Colombo area comprises 68.15, 11.63 and 6.69 % of short-term biodegradable (i.e., items that could degrade within 1–2 months or less), long-term biodegradable material (i.e., items that cannot easily degrade within 2–3 months) and polythene and other plastics, respectively by wet weight with 1.64 % glass, 1.85 % metal, 5.02 % wooden waste and 5.99 % paper. However, recent studies conducted by EML Consultants (2011) revealed that the average calorific value of the MSW delivered to Meethotamulla from the Colombo Municipal Council (CMC) and the Kolonnawa UC area is 15,803.57 J/g (variable in the range from 9856 to 24,000 J/g) with an average moisture content of 57.4 % (moisture content analysis was conducted during the period of May 2011—onset of the south-west monsoonal period). Furthermore, EML Consultants (2011) revealed that on an average basis the organic matter, polythene with plastic, paper (including cardboard), glass (including bottles) and the metal content is around 49.27, 21.52, 17.31, 1.81 and 1.27 %, respectively. In other words, the plastic content is significantly high indicating that the usage of plastics and polythene material has increased in the CMC area during the recent-past when compared with the data reported in previous studies (Asian Institute of Technology 2004; de Alwis 2006; Vidanaarachchi et al. 2006) possibly due to improved lifestyles/living conditions associated with improved economy in the CMC area. However, since it is planned to dispose MSW generated from Dehiwala-Mount Lavinia Municipal Council (MC) and Sri-Jayawardanapura Kotte MC too (along with MSW from the CMC and the Kolonnawa UC), the moisture content could still increase during periods of monsoon and reach as high as 80 % (often the moisture content of waste in equatorial/tropical areas is a result of surface water absorbed by waste). Colombo area situated within the Wet Zone receives rains during the period of May–September (south-west monsoon; peak rainy season) and December–February (north-east monsoon) as well as during the periods of March, April, October and November. It should be noted that on average the MSW from the MCR contains 68.4, 2.5, 9.2, 0.9, 3.5, 4.1, 6.6 and 5 % of short-term biodegradable matter, long-term biodegradable matter, polythene and other plastics, metal waste, wooden waste, glass, paper and other wastes, respectively (DOHWA Engineering Co Ltd et al. 2014).

Therefore, by taking into consideration that the maximum possible moisture content of the fresh waste is around 80 % by wet weight with a bulk density of 350 kg/m^3 and that 70 % of the moisture would be retained in the compacted waste (on a weight mass basis), around 113 m^3/day of moisture would be lost as primary leachate during compaction (taking into consideration that the moisture loss is 10 % during compaction; see "Appendix"). As a result of compaction of high moisture containing 1,130 tons of MSW from Colombo to 1,040 tons per day (maximum carrying capacity of a container is 20 tons and there are a total of 52 containers or 26 containers per train) while the bulk density increases to 750 kg/m^3 (see "Appendix"), it is expected that in 2035 the Aruwakkalu landfill site would be receiving 1,386.7 m^3 of waste per day containing 728 m^3 of water or 52.5 % moisture by volume (525 mm/m of waste). Any water losses due to evaporation and leaks from the containers are negligible. Also any primary leachate collected would be getting re-introduced to the already dropped garbage in the cells when raising or tilting the containers to release the MSW (along with the collected leachate).

Leachate generation and its treatment

Secondary leachate (balance of initial moisture content of the MSW, water generated due to biochemical reactions and rainwater percolation through the landfill) generation occurs when the compacted refuse attains its field capacity (Kumar et al. 2001, 2002; Vesiland et al. 2002; Mannapperuma and Basnayake 2004). Some studies have shown that compacted waste has a field capacity of 20–35 % by volume (Kumar et al. 2001; Vesiland et al. 2002), though lysimeter studies conducted by the University of Peradeniya in heavy rainfall areas of Sri Lanka revealed that the field capacity of compacted MSW would be around 55.0 % (Mannapperuma and Basnayake 2004). Taking into consideration of the rainfall and evaporation patterns (Table 1) in Puttalam/Project area and the maximum probable field capacity of compacted waste, the leachate generate rates estimated by the water balance method are presented in Table 2. It is noted that leachate generation occurs in October (2nd inter-monsoonal period) and during the first 2 months of the north-east monsoonal period (November and December), which is the peak rainy season in drier/arid areas of Sri Lanka.

The negative values of Infiltration (I)-PET represent potential moisture deficiency where infiltration fails to supply the water needed for vegetation. Actual loss due to evapotranspiration during the wet months is equal to PET as the soil is at its storage capacity and there is more than adequate moisture available (Kumar et al. 2001, 2002).

Table 2 also shows the PERC/leachate volume expected during the period of October, November and December during the different phases of the landfill and the time taken for leachate generation noting that 18 % of the precipitation becomes percolation. Peak PERC quantity is expected

Table 1 Monthly total rainfall and evaporation patterns at Puttalam (in mm) from 2003 to 2012

Year	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	Average
Rainfall patterns											
January	121.7	35.3	57.7	70.5	73.2	27.8	27.5	3.2	140	0	55.7
February	31.4	1.3	29	78.4	31.4	136.7	0.9	6.6	72.7	65.4	45.4
March	127.4	94.6	81.6	139.8	17.1	189.4	147.2	3.5	16.5	156.3	97.3
April	241.2	54.4	223.4	22.2	135	198.7	110.1	74.4	169.2	85	131.4
May	53.4	232.8	11.6	31.9	0.8	1.9	6	7.1	0	0	34.6
June	31.4	20.4	11.7	0.1	22.3	0.4	6.1	9.8	0.7	0	10.3
July	22	0.5	6.8	0	24.2	17.4	10.2	1.8	0	2.6	8.6
August	36.1	0.6	0	0	12.8	87.8	51.3	52.5	1.2	6.6	24.9
September	4.8	141.9	0	48.4	116.2	0.8	0.7	98.9	0	58.3	47
October	174.1	383.3	130.4	512.7	206.2	555.2	99.2	71.1	169.3	453.7	275.5
November	176.6	301	266.7	392.8	127.7	403.3	248.9	281.4	20.7	116.5	233.6
December	47.1	260.5	75.4	88.6	140.1	72.9	194.7	325.4	112.3	345.2	166.2
Total	1,067.2	1,526.6	894.3	1,385.4	907	1,692.3	902.8	935.7	702.6	1,289.6	1,130.4
Evaporation patterns											
January	77.66	121.72	96.98	86.49	106.01	100.42	88.16	101.31	61.49	108.14	94.84
February	93.90	154.79	121.37	107.89	118.03	117.51	111.69	123.73	78.49	111.80	113.92
March	131.37	164.61	138.01	112.51	160.28	107.38	124.27	160.51	127.08	142.84	136.89
April	121.90	146.34	73.24	134.30	133.80	124.95	110.05	137.95	120.24	124.79	122.76
May	135.94	130.13	133.06	160.72	163.27	171.25	180.14	139.60	148.20	164.31	152.66
June	139.26	149.94	148.59	129.02	147.07	153.57	158.76	157.73	155.49	158.24	149.77
July	144.80	154.00	150.50	158.83	165.11	164.95	157.85	161.58	160.74	174.79	159.31
August	156.30	178.76	177.71	182.45	178.87	165.57	152.59	144.59	140.06	183.97	166.09
September	177.39	146.05	160.44	138.89	157.86	134.39	157.88	132.56	170.36	172.64	154.85
October	112.54	116.56	139.44	107.05	124.02	93.50	141.88	119.89	136.11	110.57	120.15
November	75.01	75.73	74.35	87.92	107.40	67.35	71.25	72.66	75.14	82.92	78.97
December	98.36	82.03	80.99	88.34	84.44	75.22	65.45	50.40	78.88	64.83	76.89
Total	1,464.43	1,620.66	1,494.68	1,494.41	1,646.16	1,476.06	1,519.97	1,502.51	1,452.28	1,599.24	1,527.1

Note that the nearest weather station is at Eluwankulama

(Source: Department of Meteorology, Sri Lanka)

during the period of November. It is evident that the time taken for leachate production from a cell with a height of 60 m is 7.2 years at the rate of 26,645.9 m^3/year during Phase I (which has a total area around 127,755 m^2 and a cell height of 60 m with 10 years lifespan; to be commenced in 2016). However, in actual situations due to chanelling (fingering) effects as a result of variable pore sizes, moisture content does not remain constant in cells and the actual field capacity may be slightly lower than the theoretical field capacity (due to non-homogeneities in the waste), the leachate would be produced well before the theoretical times shown in Table 2.

LandGem modeling studies have revealed that peak landfill gas (LFG) generation peaks 1 year after closure of the landfill with a 75 % collection efficiency in 2035 (DOHWA Engineering Co Ltd et al. 2014; Fig. 2). Therefore, it is likely that methanogenesis effectively occurs during this period and thereafter; hence the leachate generated is a methanogenic leachate which will have a quality similar to what is reported from several opening dumping sites in Sri Lanka (Table 3) with pH between 6.02 and 8.6, high levels of NH_4^+–N varying between 6 and 4,095 mg/L, Cl^- levels between 320 and 723 mg/L and electrical conductivity levels between 3.2 and 31.4 mS/cm. Leachate quality predicted and described in the feasibility study is not very accurate since biochemical oxygen demand (BOD_5) values are higher than the chemical oxygen demand (COD) values. As shown in Table 3, the $BOD_5/COD < 0.3$ reflecting that the leachate is not fully amenable for biological treatment or the presence of high concentrations of recalcitrant organic materials that is partially stable and biologically resistant to further biodegradation (Garg 1999; Aziz et al. 2007, 2010; Kim and Lee 2009; Vilar et al. 2010; Adlan et al. 2011;

Table 2 Estimation of leachate generation as per the water balance method, PERC volume expected during the rainy periods and the time taken for leachate production during the different phases of the landfill

Leachate generation patterns

Parameter	January	February	March	April	May	June	July	August	September	October	November	December	Annual total
Average pan evaporation (mm)	94.84	113.92	136.89	122.76	152.66	149.77	159.31	166.09	154.85	120.15	78.97	76.89	1,527.1
Adjustment factor	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93	–
PET (mm)	88.2	105.9	127.3	114.2	141.9	139.3	148.2	154.5	144.0	111.7	73.4	71.5	1,426.1
Runoff coefficient	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	–
Runoff *R* (mm)	11.14	9.08	19.47	26.27	6.91	2.06	1.71	4.98	9.4	55.1	46.71	33.24	226.07
Infiltration *I* (mm)	44.55	36.3	77.87	105.09	27.64	8.23	6.84	19.91	37.6	220.4	186.85	132.98	904.26
I-PET	−43.65	−69.6	−49.43	−9.11	−114.26	−131.07	−141.36	−134.59	−106.4	108.7	113.45	61.48	−515.84
PERC (mm)	–	–	–	–	–	–	–	–	–	83.7	88.41	36.46	208.57

PERC volume during the peak rainy periods and time frame for leachate generation

Phase of the landfill	PERC quantity			PERC volume in 1 m^2 of waste (m^3/year)	Residual liquid storage capacity in 1 m^2 of waste (m^3)	Time taken for leachate production/time taken to reach field capacity (years)	Rate of leachate production (m^3/year)
	October	November	December				
Phase I	10,693 m^3 (356.4 m^3/day)	11,294.8 m^3 (376.5 m^3/day)	4,657.9 m^3 (155.3 m^3/day)	0.2086	1.5	7.2	26,645.9
Phase II	7,538.2 m^3 (251.3 m^3/day)	7,962.5 m^3 (265.4 m^3/day)	3,283.7 m^3 (109.5 m^3/day)	0.2086	1.5	7.2	18,784.4
Phase III	3,720.3 m^3 (124 m^3/day)	3,929.6 m^3 (131 m^3/day)	1,620.6 m^3 (54.0 m^3/day)	0.2086	1.13	5.4	9,270.5

According to DOHWA Engineering Co Ltd, it has been proposed to have a final grassed capping (slope of 1:2 rather than 1:1.5) using a silty-sand soil (similar to the type of soil occurring within the proposed landfill site as per the sieve analysis studies conducted by DOHWA Engineering Co Ltd et al. 2014) though quantities and sources have not been identified. Soil within the landfill site has a sand content of 31.7–93 % (DOHWA Engineering Co Ltd et al. 2014). Sandy soils with steep slopes (>7 %) would have *R* values around 0.15–0.20 (Vesiland et al. 2002)

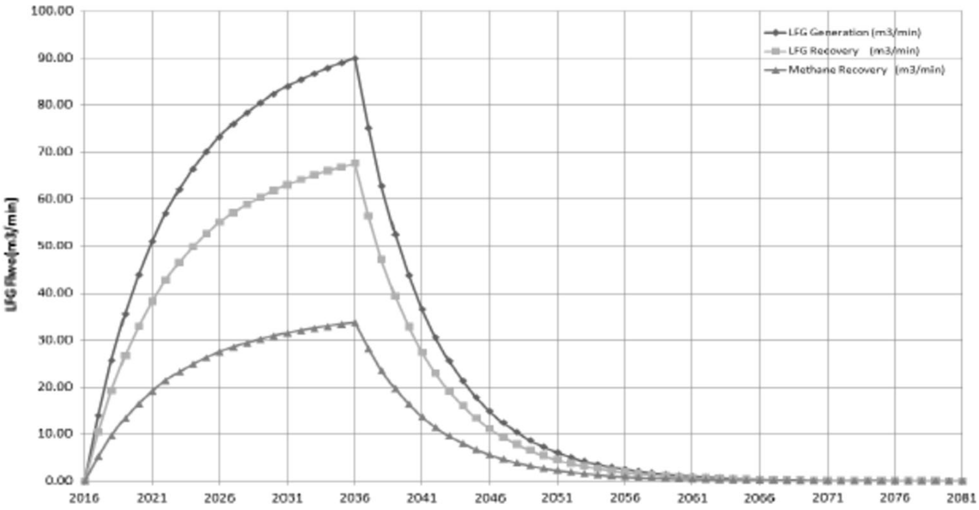

Fig. 2 Predicted LFG generation (Source: DOHWA Engineering Co Ltd et al. 2014)

Al-Hamadani et al. 2011; Zainol et al. 2012). It should be noted that heavy metal levels will be significant too, but may vary depending on the initial concentrations in the compacted waste (depending on types of hazardous waste generated from various areas of the MCR).

It has been proposed to treat the leachate such that the treated effluent would contain a pH of 5.5–9, $BOD_5 < 100$ mg/L, $COD < 250$ mg/L and NH_4^+–$N < 50$ mg/L (i.e., the tolerance limits for industrial and domestic wastewaters discharged into marine coastal waters under the National Environmental Act No. 47 of 1980 and its amendments; Extraordinary Gazette No. 1534/18 dated 1st February 2008). Nevertheless, Lunu Oya is not located within the Coastal Zone which is defined under the Coast Conservation and Coastal Resource Management Department enacted Coast Conservation and Coastal Resource Management Act No. 57 of 1981 as “the area lying within a limit of 300 m landward of the Mean High water Line and a limit of 2 km seaward of the mean Low Water Line and in the case of rivers, streams lagoons or any other body of water connected to the sea either permanently or periodically, the landward boundary shall extend to a limit of 2 km measured perpendicular to the straight base line drawn between the natural entrance points identified by the mean low water line thereof and shall include waters of such rivers, streams, and lagoons or any other body of water so connected to the sea”. Since Lunu Oya is an inland water body, there is a necessity for any treated effluent to have a pH of 6–8.5, $BOD_5 < 30$ mg/L, $COD < 250$ mg/L and NH_4^+–$N < 50$ mg/L (i.e., the tolerance limits for industrial and domestic wastewaters discharged into inland surface waters under the Provincial Environmental (protection and quality) Regulation No. 01 of 2010 of the North Western Provincial Environmental Statute No. 12 of 1990 (Extraordinary Gazette No. 1685/11 dated 21st December 2010). It should be noted that in the North Western Province (i.e., Puttalam and Kurunegala Districts) Provincial Environmental Authority is the main government body that will have the responsibilities regarding the use of lands, environmental management and conservation of natural resources, etc. under the North Western Provincial Environmental Statute No. 12 of 1990.

However, disposal to the Lunu Oya is not a good solution due to its almost stagnant nature. Furthermore, the proposed effluent treatment plant is likely to fail, with no mechanism to remove colloidals, COD and heavy metals, etc. and considering the values presented in Table 3, the BOD_5/COD is very low (<0.3) indicating the presence of high concentrations of recalcitrant or non-biodegradable organics (Garg 1999; Aziz et al. 2007, 2010; Kim and Lee 2009; Vilar et al. 2010; Adlan et al. 2011; Al-Hamadani et al. 2011; Zainol et al. 2012). Heavy metals could denature the suspended bacterial biomass in the biological reactor upsetting the denitrification and nitrification reactions. Moreover, metals strongly compete against organic compounds for active sites on bioflocs, thus hampering organic adsorption and degradation (Lawrence et al. 2004). Also the proposed denitrification and nitrification reactor will not be practical and expensive too since an external carbon source would be necessary to complete the denitrification, especially when the organic compounds present in the leachate are not fully biodegradable (Vilar et al. 2010).

Furthermore, the treatment plant design does not accurately consider the effluents attributed to the washing of the containers, sewage generated by the workforce and washwaters derived from the tractor-trailer tire washing facility (see below).

- Total blackwater and greywater amount from the 15 fulltime workforce is around 1.8 m^3/day (considering

Table 3 Methanogenic leachate quality reported from various dumping sites in Sri Lanka

Parameter	Reported values	Dumping site	Remarks
pH	6.8–8	Senanayake (Sri-Jayawardanapura Kotte MC), Buthgamuwa (Sri-Jayawardanapura Kotte MC), Karadiyana (Moratuwa MC + Kesbewa Pradeshiya Sabah) and Maharagama (Maharagama UC) – all in Colombo District (Western Province)	Esakku et al. (2005); Pathirana and Basnayake (2008)
	8–8.5	Gohagoda (Kandy District/Central Province)	Mayakaduwa et al. (2012)
	6.02–8.57	Gohagoda (Kandy District/Central Province)	Mayakaduwa et al. (2013)
	7.45–8.37	Gohagoda (Kandy District/Central Province)	Wijesekara et al. (2012a, b)
	8–8.6	Gohagoda (Kandy District/Central Province)	Wijesekara et al. (2014a, b); values presented are annual average values
BOD_5 (mg/L)	1,000–4,000	Senanayake (Sri-Jayawardanapura Kotte MC), Buthgamuwa (Sri-Jayawardanapura Kotte MC), Karadiyana (Moratuwa MC + Kesbewa Pradeshiya Sabah) and Maharagama (Maharagama UC) – Colombo District/Western Province	Esakku et al. (2005); Pathirana and Basnayake (2008)
	1,485	Gohagoda (Kandy District/Central Province)	Mayakaduwa et al. (2012)
	380	Gohagoda (Kandy District/Central Province)	Wijesekara et al. (2012a, b)
	270	Gohagoda (Kandy District/Central Province)	Wijesekara et al. (2014a)
	3,590 (maximum)	Gohagoda (Kandy District/Central Province)	Wijesekara et al. (2014b)
			Normally, BOD_5 is variable in the range of 97–1,770 mg/L (Jones et al. 2006)
COD (mg/L)	10,000–20,000	Senanayake (Sri-Jayawardanapura Kotte MC), Buthgamuwa (Sri-Jayawardanapura Kotte MC), Karadiyana (Moratuwa MC + Kesbewa Pradeshiya Sabah) and Maharagama (Maharagama UC) – Colombo District/Western Province	Esakku et al. (2005); Pathirana and Basnayake (2008)
	1,500–7,000	Gohagoda (Kandy District/Central Province)	Mayakaduwa et al. (2012)
	1,835	Gohagoda (Kandy District/Central Province)	Wijesekara et al. (2012a, b)
	3,000–7,000	Gohagoda (Kandy District/Central Province)	Wijesekara et al. (2014a, b); values presented are annual average values
			Normally, COD values are variable in the range of 622–8,000 mg/L (Jones et al. 2006)
TDS (mg/L)	200–1,500	Senanayake (Sri-Jayawardanapura Kotte MC), Karadiyana (Moratuwa MC + Kesbewa Pradeshiya Sabah) and Maharagama (Maharagama UC) – Colombo District/Western Province	Esakku et al. (2005)
			Values are lower than what is reported by Jones et al. (2006)
Electrical conductivity (mS/cm)	3.2–31.4	Gohagoda (Kandy District/Central Province)	Wijesekara et al. (2014a, b). Values are lower than what is reported by Jones et al. (2006) due to dilution and flushing of organics and inorganic matter by river water (Wijesekara et al. 2014a, b)
TSS (mg/L)	8,000–26,000	Gohagoda (Kandy District/Central Province)	Mayakaduwa et al. (2012)
	322–14,418	Gohagoda (Kandy District/Central Province)	Wijesekara et al. (2014b); values presented are annual average values
NO_3^- (mg/L)	1–765	Gohagoda (Kandy District/Central Province)	Mayakaduwa et al. (2012); Wijesekara et al. (2012a, b)
	30–780	Gohagoda (Kandy District/Central Province)	Wijesekara et al. (2014b); values presented are annual average values
NO_2^- (mg/L)	0.1–410	Gohagoda (Kandy District/Central Province)	Wijesekara et al. (2014b); values presented are annual average values

Table 3 continued

Parameter	Reported values	Dumping site	Remarks
NH_4^+–N (mg/L)	6–4,095	Gohagoda (Kandy District/Central Province)	Wijesekara et al. (2014b); values presented are annual average values. During heavy rainfalls levels were around 3,000 mg/L
PO_4^{3-} (mg/L)	2.1–258.3	Gohagoda (Kandy District/Central Province)	Mayakaduwa et al. (2012); Wijesekara et al. (2012a, b). Levels >5 mg/L for effluents disposed to inland waters (Extraordinary Gazette No. 1685/11 dated 21st December 2010)
	5–260	Gohagoda (Kandy District/Central Province)	Wijesekara et al. (2014b); values are annual average values
Cl^- (mg/L)	320	Gohagoda (Kandy District/Central Province)	Wijesekara et al. (2014a)
	723	Gohagoda (Kandy District/Central Province)	Wijesekara et al. (2014b)
			Jones et al. (2006) have reported Cl^- levels in the range of 570–4,710 mg/L
Fe (mg/L)	0.6–9.5	Gohagoda (Kandy District/Central Province)	Mayakaduwa et al. (2012). Values exceed 3 mg/L (with reference to disposal of effluents to inland waters as per Extraordinary Gazette No. 1685/11 dated 21st December 2010) and the US NPDES limit of 1.6 mg/L (Jayaweera et al. 2008)
	1.49–317	Gohagoda (Kandy District/Central Province)	Wijesekara et al. (2014b); values are annual average values. Values exceed 3 mg/L (with reference to disposal of effluents to inland waters as per Extraordinary Gazette No. 1685/11 dated 21st December 2010) and the US National Pollutant Discharge Elimination System (NPDES) limit of 1.6 mg/L (Jayaweera et al. 2008)
Mn (mg/L)	0.1–1.4	Gohagoda (Kandy District/Central Province)	Mayakaduwa et al. (2012). Values >1.1 mg/L: effluent limits to inland waters under US NPDES (Kularatne et al. 2009); no limits enacted in the Sri Lankan legislation for Mn
	0.155–32	Gohagoda (Kandy District/Central Province)	Wijesekara et al. (2014b); values are annual average values. Values >1.1 mg/L: effluent limits to inland waters under US NPDES (Kularatne et al. 2009); no limits enacted in the Sri Lankan legislation for Mn
Pb (mg/L)	0.005–0.04	Senanayake (Sri-Jayawardanapura Kotte MC) and Maharagama (Maharagama UC) – Colombo District/Western Province	Esakku et al. (2005)[a]
	0.05–0.25	Buthgamuwa (Sri-Jayawardanapura Kotte MC) and Karadiyana (Moratuwa MC + Kesbewa Pradeshiya Sabah) – Colombo District/Western Province	Esakku et al. (2005). Pb values exceed 0.1 mg/L for inland surface waters (Extraordinary Gazette No. 1685/11 dated 21st December 2010)
	0.24–0.794	Gohagoda (Kandy District/Central Province)	Mahakaduwa et al. (2013). Pb values exceed 0.1 mg/L for inland surface waters (Extraordinary Gazette No. 1685/11 dated 21st December 2010)
	0–0.36	Gohagoda (Kandy District/Central Province)	Mahakaduwa et al. (2012). Pb values exceed 0.1 mg/L for inland surface waters (Extraordinary Gazette No. 1685/11 dated 2^{1st} December 2010)
	0.217	Gohagoda (Kandy District/Central Province)	Wijesekara et al. (2012a, b). Pb values exceed 0.1 mg/L for inland surface waters (Extraordinary Gazette No. 1685/11 dated 21st December 2010)
	0.015–0.416	Gohagoda (Kandy District/Central Province)	Wijesekara et al. (2014b); values are annual average values. Pb values exceed 0.1 mg/L for inland surface waters (Extraordinary Gazette No. 1685/11 dated 21st December 2010)

Table 3 continued

Parameter	Reported values	Dumping site	Remarks
Cu (mg/L)	0.005–0.04	Senanayake (Sri-Jayawardanapura Kotte MC) and Maharagama (Maharagama UC) – Colombo District/Western Province	Esakku et al. (2005); Pathirana and Basnayake (2008)[a]
	0.05–0.25	Buthgamuwa (Sri-Jayawardanapura Kotte MC) and Karadiyana (Moratuwa MC + Kesbewa Pradeshiya Sabah) – Colombo District/Western Province	Esakku et al. (2005); Pathirana and Basnayake (2008)[a]
	0.135	Gohagoda (Kandy District/Central Province)	Wijesekara et al. (2012a, b)[a]
	0.048–0.443	Gohagoda (Kandy District/Central Province)	Wijesekara et al. (2014b)[a]; values are annual average values
Zn (mg/L)	0.005–0.04	Senanayake (Sri-Jayawardanapura Kotte MC) and Maharagama (Maharagama UC) – Colombo District/Western Province	Esakku et al. (2005); Pathirana and Basnayake (2008)[a]
	0.05–0.25	Buthgamuwa (Sri-Jayawardanapura Kotte MC) and Karadiyana (Moratuwa MC + Kesbewa Pradeshiya Sabah) – Colombo District/Western Province	Esakku et al. (2005); Pathirana and Basnayake (2008)[a]
	0.371	Gohagoda (Kandy District/Central Province)	Wijesekara et al. (2012a, b)[a]
Ni (mg/L)	0.005–0.04	Senanayake (Sri-Jayawardanapura Kotte MC) and Maharagama (Maharagama UC) – Colombo District/Western Province	Esakku et al. (2005); Pathirana and Basnayake (2008)[a]
	0.05–0.25	Buthgamuwa (Sri-Jayawardanapura Kotte MC) and Karadiyana (Moratuwa MC + Kesbewa Pradeshiya Sabah) – Colombo District/Western Province	Esakku et al. (2005); Pathirana and Basnayake (2008)[a]
	0.207	Gohagoda (Kandy District/Central Province)	Wijesekara et al. (2012a, b)[a]
Cr (mg/L)	0.014–0.627[b]	Gohagoda (Kandy District/Central Province)	Mahakaduwa et al. (2013). Levels >0.5 (total Cr) mg/L for inland surface waters (Extraordinary Gazette No. 1685/11 dated 21st December 2010)
	0.02–0.17[b]	Gohagoda (Kandy District/Central Province)	Mahakaduwa et al. (2012). Levels <0.5 (total Cr) mg/L for inland surface waters (Extraordinary Gazette No. 1685/11 dated 21st December 2010)
	0.061	Gohagoda (Kandy District/Central Province)	Wijesekara et al. (2012a, b). Levels <0.5 (total Cr) mg/L for inland surface waters (Extraordinary Gazette No. 1685/11 dated 21st December 2010)
	0.021–0.323[b]	Gohagoda (Kandy District/Central Province)	Wijesekara et al. (2014b); values are annual average values. Levels <0.5 (total Cr) mg/L for inland surface waters (Extraordinary Gazette No. 1685/11 dated 21st December 2010)
Cd (mg/L)	0.092	Gohagoda (Kandy District/Central Province)	Wijesekara et al. (2012a, b). Levels are slightly <0.1 mg/L for inland surface waters (Extraordinary Gazette No. 1685/11 dated 21st December 2010)
	0.004–0.062	Gohagoda (Kandy District/Central Province)	Wijesekara et al. (2014b); values are annual average values
As (mg/L)	0.002	Gohagoda (Kandy District/Central Province)	Wijesekara et al. (2014a). Levels are <0.2 mg/L for inland surface waters (Extraordinary Gazette No. 1685/11 dated 21st December 2010)

[a] Values are lower than 3, 2, 0.1 and 3 mg/L for Cu, Zn, Pb and Ni, respectively: effluent limits for inland surface waters (Extraordinary Gazette No. 1685/11 dated 21st December 2010)

[b] Values are higher than 0.1 mg/L for Cr^{6+}: effluent limits for inland surface waters (Extraordinary Gazette No. 1685/11 dated 21st December 2010)

that the potable water requirement is 150 L per person per day with 80 % of it ending up in the sewer system).

- Tire washing effluent quantities would be around 1.2 m^3/day (considering that the water requirement would be 40 L per vehicle tire washing and that there would be at least 30 tractors during the period of 2035).
- Effluent quantities from container washings would be around 52 m^3/day (considering that 1,000 L of water is needed to wash one container; a total of 52 containers would be transferring a total of 1,040 tons of compacted waste per day in 2035).

Moreover, details pertaining to the quality of the effluent expected from the container and tire washing activities are not furnished in the feasibility report, though there will be a significant load of total suspended solids (TSS) rather than having high levels of BOD_5 and COD (because in the case of the containers, any primary leachate collected would be getting re-introduced back to the garbage when the containers would be tilted by the tractor trailers to dispose the waste + leachate to the cells). Although there will be some dilution of the leachate by other effluent streams, the BOD_5/COD of the total influent to the treatment plant would be still lower than 0.3 when evaluating the final influent BOD_5 and COD levels through a mass balance analysis. Taking into consideration of the sewage component (sewage in Sri Lanka would comprise 220–500 BOD_5 mg/L and 500–1,000 COD mg/L) and the leachate quantity (methanogenic leachate contains 1,000–4,000 BOD_5 mg/L and 10,000–20,000 COD mg/L) alone which are the predominant effluent streams with high BOD_5 and COD levels (period of November shows peak leachate generation with a quantity of 800 m^3/day as a safety factor), mass balance analysis revealed that the expected BOD_5/COD ratio would be around 0.1–0.2. Several reports have shown that biological treatment plants are not ideal to treat stabilized landfill leachates (i.e., leachates having less biodegradable matter), but physico-chemical treatment processes are very effective in reducing pollutants from the stabilized leachates (Ahn et al. 2002; Renou et al. 2008; Vilar et al. 2010; Yilmaz et al. 2010; Zainol et al. 2012).

Therefore, releasing the effluent from the treatment plant to the Lunu Oya would result in intense pollution especially during the drier spells when discharge is very low due to high evapotranspiration and the leachate pollution would even spread to upstream areas (up to the zone of saline water intrusion) during the high tides. High levels of nutrients would lead to cultural eutrophication considering the almost stagnant nature of the Lunu Oya and the high NH_3/NH_4^+ levels (from the hydrolysis and acidogenesis of nitrogen containing fractions of the waste) would be extremely toxic to the aquatic biota, especially fish. The heavy metals too would be toxic to the biota and high levels of Fe may also impart significant acidity (especially during drier spells) due to abiotic oxidation of Fe^{2+} and subsequent hydrolysis of Fe^{3+} (Jayaweera et al. 2008). The reduced, total organic carbon (TOC) rich mangrove sediments would become a crucial sink for the heavy metals due to adsorption and sulfate reducing bacteria (SRB) mediated dissimilatory SO_4^{2-} reduction mechanisms; however, ingestion of contaminated sediments/detritus matter by bottom dwelling fauna would ultimately result in bioaccumulation in higher trophic level faunal species such as Birds of Prey which are found in plenty due to the close proximity of the landfill site to the Wilpattu National Park (about 1.5 km to the boundary of the park, which is located towards the East of the landfill site), one of Sri Lanka's Ramsar wetlands. Also during high tidal events when there is saline water intrusion, there could be desorption of sediment adsorbed metals due to intense competition between Na^+ ions and metal ions for adsorption sites, resulting in an increased likelihood of the bioavailability of desorbed metals to fish, etc. in the long run considering that the Project area experiences a drier climate (e.g., Guhathakurta and Kaviraj 2004; Kularatne 2014b).

Leachate generation and groundwater contamination scenarios

Table 4 shows the maximum possible saturated depth (leachate head) over the high-density polyethylene (HDPE) liner which is calculated by using the method proposed by Vesiland et al. (2002) (Eq. 2). Taking into consideration of the design of the leachate collection layer (refer to "Appendix"; Fig. 4), possibilities that the HDPE liner is subjected to puncture is low since the free liquid depth would be <30 cm (which is the maximum leachate head recommended under the Resource Conservation and Recovery Act Subtitle D Regulations of the US Environmental Protection Agency and the Central Environmental Authority of Sri Lanka too) in many cases. However, operation of the nearby potential quarry sites (i.e., the Eluwankulama Forest; Fig. 1) for limestone extraction by

Table 4 Anticipated leachate head in the liner system according to the design of the leachate collection layer

Pipe spacing P (m)	Slope (%)	Y_{max} leachate head (cm)
20	2	2.1
20	4	1.8
25	2	2.6
25	4	2.2
50	2	5.3
50	4	4.5

Holcim (Lanka) Ltd (for cement production) could pose a danger to the single composite liner. This is because higher peak particle velocities due to the usage of detonators and charging drilled holes with ammonium nitrate/fuel oil and dynamite may rupture the HDPE liner and perhaps the soil-bentonite layer too, ultimately leading to groundwater contamination. Furthermore, the groundwater table becomes shallow from the south-north direction of the landfill (from 6.95 to 0.05 m; from Phase I to Phase III of the site during drier spells) when depth increases (see Fig. 1; Table 5). Therefore, a rise in the groundwater table (as there is a hydraulic gradient from the oya towards the land as per the stakeholders consulted) in Phase III and certain sections of Phase II of the site during the peak rainy seasons may also cause high pressure on the single composite liner layer, to result in possible ruptures. Table 5 shows the possible leachate flow and the breakthrough time for the leachate to penetrate the soil-bentonite layer once the HDPE layer is damaged (considering that contaminants especially Cl^- do not show significant retardation and are transported by advective flow). It is evident that the leachate breakthrough time and even the time of travel (TOT) for Cl^- are less at higher leachate heads, but seepage velocities and flow rates are higher for both leachate as a whole and the Cl^- ions. Since Cl^- ions are conservative contaminants with a zero soil adsorption coefficient, Cl^- ions exhibit a retardation factor of 1 considering the equation suggested by Shahmohammadi-kalalagh et al. (2012) (Eq. 5) and hence the average velocity of the Cl^- ion migration will be equivalent to the seepage velocity of the leachate.

Table 5 also shows the time taken for groundwater contamination considering a maximum effective porosity of 35 % for coarse sand and gravel mixed soils (Weiner 2000), variable groundwater table within the Project Site and the hydraulic conductivities ranging from 1.08×10^{-6} to 2.68×10^{-5} m/s. It is noted that the time taken to reach the groundwater table is less in areas where the hydraulic conductivity is high. In other words, there is an inverse relationship between breakthrough time and hydraulic conductivity, but breakthrough time shows no proper relationship to the seepage velocity.

Opportunities to minimize environmental pollution

Groundwater contamination prevention and monitoring

The deeper sections of Phases II and III of the landfill (where the groundwater table is shallow; refer to Table 5) require considerable filling after evaluation of the maximum possible rise in the groundwater table during the rainy seasons. Placement of a double composite liner system (comprising the same HDPE and soil-bentonite layer) is beneficial and as recommended by the Central Environmental Authority (2005) for Class D landfills (i.e., those landfills which receive more than 200 tons of MSW per day), soil-bentonite mixture must be with a high concentration of bentonite (more than 5 % by weight) with the thickness >60 cm and hydraulic conductivity $<5 \times 10^{-10}$ cm/s.

A “No Quarrying” buffer zone of at least 1,000 m would be useful to be established with Holcim (Lanka) Ltd from the boundary of the landfill towards the potential quarry sites at the Eluwankulama Forest to prevent any rupturing of the liner systems due to rock blasting activities.

In addition to wells provided within the landfill site, there would be a necessity to have a cluster of wells to evaluate groundwater quality at multiple depths. In this respect, the direction of the hydraulic gradient (which is not well identified) requires detailed investigation and these well clusters should be placed up-gradient from the landfill to evaluate the background groundwater quality as well as immediately down-gradient from the landfill to determine the influence of the landfill on groundwater. Groundwater monitoring is essential for a period of at least 20 years since closure of the landfill. The measured parameters should be assessed with reference to World Health Organization (WHO) or Sri Lankan drinking water SLS 1983: 614 Standards (Parts 1 and 2 for Human Consumption) every quarterly (which is the stipulated frequency under RCRA Subtitle D Regulations of the USEPA) and depending on serious public complaints received during the operation of the landfill and closure of the landfill.

Leachate treatment

The treated leachate with any other treated effluent is not recommended to be disposed to the Lunu Oya considering its almost stagnant nature. Instead recycling the pumped out raw leachate (as a source of water and nutrients) back to the landfill cells would enhance biodegradation (example, El-Fadel et al. 1997; Hernández-Berriel et al. 2010) as water is a scare resource in Aruwakkalu. Furthermore, leachate recirculation to the landfill site would suppress dust since this area often experiences high winds with speeds of around 7–8 m/s (Elliot et al. 2003; Fernando and Sonnadara 2007).

Conclusions

This case study concludes that leachate production occurs during the peak rainy seasons only despite the fact that the incoming waste regularly has high moisture content and the generated leachate is a methanogenic leachate with a low

Table 5 Estimated seepage velocities, flow rates and breakthrough time for different leachate heads through the soil-bentonite layer and the groundwater contamination times

Clay liner

Leachate head $Y_{\max}$ (cm)	Seepage velocity of the leachate (cm/s)	Leachate breakthrough time (years)	Leachate flow rate (m^3/s)	Average velocity of Cl^- ions (cm/s)	Time of travel (TOT) for Cl^- ions (years)	Remarks
1.8	2.12×10^{-7}	4	1.06×10^{-9}	2.12×10^{-7}	4	Flow rates were calculated using the Principles of Darcy's Law (Eq. 3) considering an area of 1 m^2 and seepage velocity was calculated using the equation $V_s = Ki/n_e$ (Eq. 4) where V_s, K, i and n_e denote seepage velocity, hydraulic conductivity, hydraulic gradient and effective porosity, respectively Since flow takes place through pore spaces, the seepage velocity will be higher than the Darcy velocity. Effective thickness of the clay layer would be around 0.27 m since the top 10 % is usually ineffective due to desiccation cracks, etc. Total porosity is equivalent to effective porosity (0.5 for clay) Equation 5 has been used to estimate the average velocity of Cl^- ions
5.3	2.36×10^{-7}	3.6	1.18×10^{-9}	2.36×10^{-7}	3.6	
30	4×10^{-7}	2.1	2×10^{-9}	4×10^{-7}	2.1	

Groundwater contamination scenarios

Groundwater level (m)	Hydraulic conductivity of the soil (m/s)	Seepage velocity (m/s)	Breakthrough time (h)	Flow rate (m^3/s)	Landfill phase	Remarks
6.85	2.68×10^{-5}	5.24×10^{-4}	3.6	1.84×10^{-4}	Phase I area	Flow rates were calculated using the Principles of Darcy's Law considering an area of 1 m^2 (Eq. 3) and seepage velocity was calculated using the equation $V_s = Ki/n_e$ (Eq. 4) where V_s, K, i and n_e denote seepage velocity, hydraulic conductivity, hydraulic gradient (1 m horizontal distance of the groundwater table) and effective porosity, respectively Note that groundwater levels and hydraulic conductivity values were extracted from DOHWA Engineering Co Ltd et al. (2014)
3.3	1.08×10^{-6}	1.02×10^{-5}	90	3.56×10^{-6}	Phase I area	
5.20	1.38×10^{-5}	2.05×10^{-4}	7	7.18×10^{-5}	Phase II area	
0.05	1.20×10^{-5}	1.71×10^{-6}	8.1	6×10^{-7}	Phase II area	
0.05	8.99×10^{-6}	1.28×10^{-6}	10.8	4.495×10^{-7}	Phase III area	

BOD_5/COD (<0.3). Furthermore, at higher leachate heads, leachate breakthrough time and the TOT for Cl^- are lower, but seepage velocities and flow rates are higher for both leachate as a whole and the Cl^- ions. An inverse relationship occurs between breakthrough time and hydraulic conductivity considering groundwater contamination scenarios in areas having a silty-sand soil, but there is no proper relationship between breakthrough time and the seepage velocity.

The proposed biological treatment plant (without having any mechanisms to remove colloidals, high COD levels and heavy metals) for leachate remediation is likely to fail resulting in significant pollution of the Lunu Oya which is a pristine area with almost stagnant waters. Hence, recirculation of the pumped out leachate as a source of water and nutrients back to the landfill would be a suitable option in drier regions such as Aruwakkalu to enhance biodegradation.

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Appendix: brief description of the MCUDP

MSW transferring to the Landfill Site and Unloading Operations at the Landfill Site

It has been proposed to construct a transfer station site at Meethotamulla (located north of the Colombo city center) adjoining the currently operated dumping site simply by demolishing the existing windrow composting facility. After compaction the MSW would be transported by rail (using 2 trains per day) to the landfill site covering a total distance of 170 km.

Without any landfill pre-treatment, it has been planned to install a "Compactor cum Loader" under the dumping pad (which would be designed to have a day's capacity of MSW or 1,130 tons in 2035 as a maximum) with the inlet hoppers opened to the surface of the dumping pad to facilitate easy loading of MSW. Three mini tractor shovels with pneumatic wheels would be operating to load the compactors by pushing the MSW into the hopper holes. The compactors would press the delivered MSW (increasing the bulk density to 750 kg/m^3 from 350 kg/m^3 with a 10 % moisture loss) and transfer them to a total of 52 steel containers (each container having a waste carrying capacity of 20 tons with the interior coated with an epoxy coating) per day that will be placed on tractor trailers. Accordingly, three compactors are to load 12 containers per hour, hence approximately 2.5 h is needed to load 26 containers for one train. Tractors would be deployed to tow the loaded containers along a tractor lane to the appropriate loading point under a Transfer Crane, which would lift the container and place it on the rail wagon. Unloading of the empty containers from the rail wagon and placing them on the tractor trailers also to be done by the Transfer Crane (there shall be 2 Transfer Cranes to ensure fast and uninterrupted transfer operations).

At the Aruwakkalu landfill site, there will be an unloading transfer station about 400 m from the landfill edge. A transfer crane shall transfer the MSW loaded containers from the rail wagon to the bed of tipping trailers. Also it shall transfer the empty containers from the tipping trailers back to the rail wagons. About 30 tractors would be deployed to tow the tipping trailers to the sanitary landfill. The back door of the containers would be opened and then the tipper bed would be tilted along with the containers to unload the MSW to the landfill cells. Then the tractors shall take the empty containers to a washing bay and then take the containers back to the transfer station. A total of 15 fulltime workers would be stationed to operate the landfill and the transfer station.

Engineering details of the landfill

The proposed landfill is a semi-aerobic landfill (Fukuoka Method) in which leachate is collected in a leachate collection pond through perforated pipes packed with small crushed stones and partial air gets supplied through the collection pipeline on the slope and gas extraction well (Fig. 3).

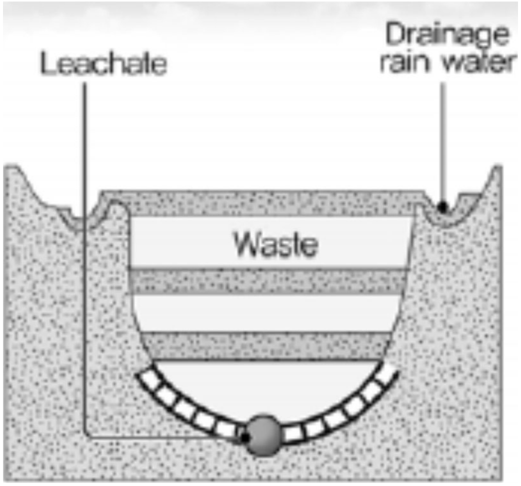

Fig. 3 Sanitary landfill method (Source: DOHWA Engineering Co Ltd et al. 2014)

It has been planned to open the landfill in 2015 (when there will be 1,010 tons/day from a population of 1,085,700) and end the operations in 2035 (when there will be 1,130 tons/day from an estimated population of 1,254,900). The landfill will be operated in three phases as follows (as landfilling cells and the cells within a phase are separated by inter-cell bunds) and the total lifespan has been designed for 20 years.

- Phase I: total area around 127,755 m^2 and a cell height of 60 m with 10 years lifespan (to be commenced in 2016).
- Phase II: total area around 90,063 m^2 and a cell height of 60 m with 7 years lifespan (to be commenced later).
- Phase III: total area around 44,448 m^2 and a cell height of 45 m with 2 years lifespan (to be commenced later).

It has been planned to introduce a single composite lining system comprising a soil-bentonite clay layer (having a hydraulic conductivity/permeability coefficient $\leq 1 \times 10^{-7}$ cm/s) and then fortify this liner with a HDPE sheet (Fig. 4). The leachate collection and drainage installation plan has the following criteria (Fig. 4).

Leachate collection/drainage layer

- Thickness: 30 cm minimum
- Hydraulic conductivity/permeability coefficient: 10^{-3} cm/s or more.
- Particle sizes of collection/drainage layer: 10/13, 16/32 mm.
- Bottom ground floor slope: 2–4 %.

Leachate collection/drainage pipes (porosity type)

- Minimum diameter of collection/drainage pipes—15 cm or more per US Environmental Protection Agency (USEPA).
- Pipe hole diameter of collection/drainage pipes: 1 cm or larger and smaller than the minimum diameter of collection/drainage pipes.
- Distance between holes: Collection pipe diameter; 1:1–1.5:1.
- Spacing distance between collection/drainage pipes: 15–40 m (50 m maximum).

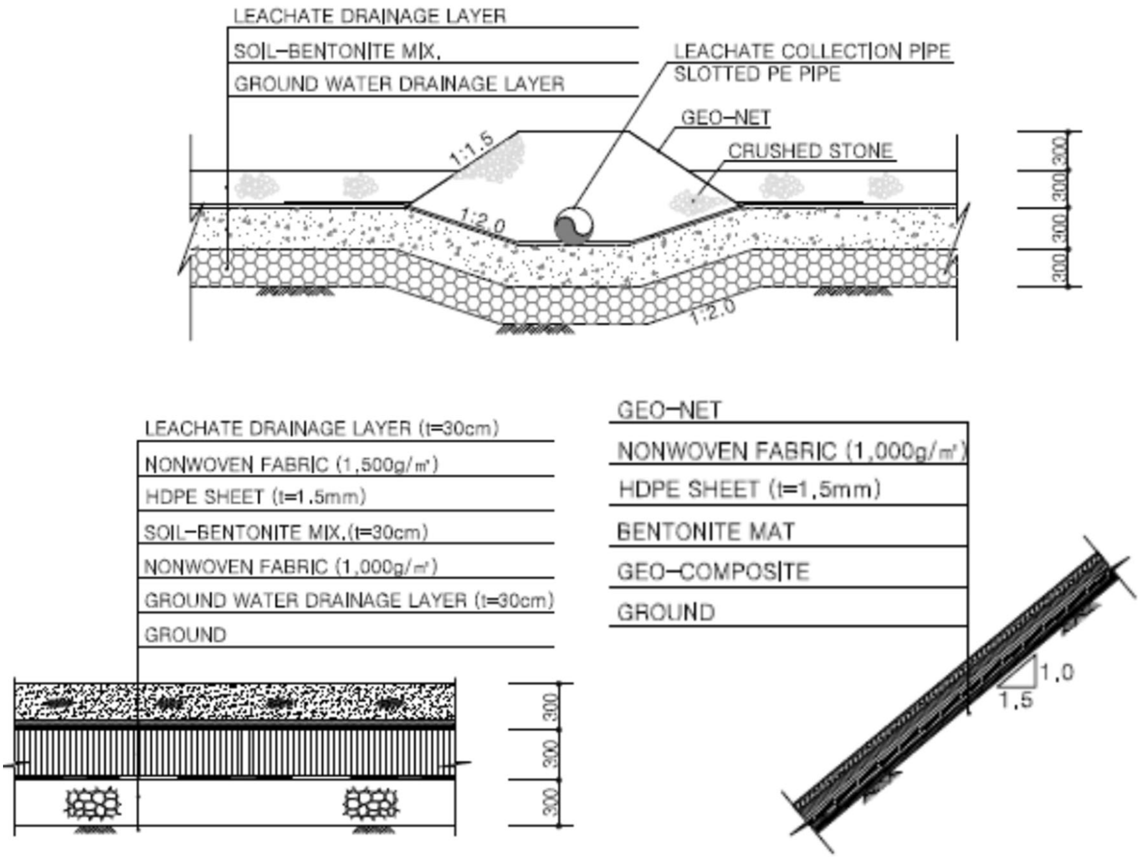

Fig. 4 Leachate collection and drainage installation plan (Source: DOHWA Engineering Co Ltd et al. 2014)

Leachate treatment, disposal and the quality of the treated effluent

As per the details given in the Feasibility study conducted by DOHWA Engineering Co Ltd et al. (2014), 198 m^3 of leachate per day is expected in the period of 2035 and leachate volume (Q) was calculated using the equation $Q = 1/1{,}000\ (C1 \times A1 \times C2 \times A2) \times I$ where I, C and A denote rainfall intensity (mm/day), leachate factor (used as 0.5 in the feasibility) × landfill area (127,755 m^2), respectively. Giving an allowance of 10 %, the leachate treatment plant has been designed to 220 m^3/day. Additionally, untreated leachate would comprise 2,000, 4,000, 500, 1,200 and 6 mg/L of COD, BOD_5, TSS, NH_4^+–N and TP, respectively. However, detailed engineering details of the collection system and the effluent treatment plant especially the reactor sizes (except for the equalization or regulation tank which has a capacity of 5,400 m^3 and a hydraulic retention time of 7 days), types and dosages of chemicals to be used and specifications of the electromechanical units that will be installed, methods of sludge dehydration, etc.) are not furnished in the feasibility report, though it is planned to design, construct and commission possibly a batch type effluent treatment plant that will comprise biological treatment (Fig. 5). Details of the biological treatment system are as follows: Under the anoxic conditions, firstly, the leachate nitrate (NO_3^-) comes into contact actively with the denitrified microorganisms and it reduces nitrate to nitrite (NO_2^-) and nitrite to nitrogen gas (N_2), respectively, and then emit it to the atmosphere, which help to remove nitric oxide (denitrification) from the leachate. Under the aerobic conditions, the leachate organic gets oxidized and ammonia goes through a nitrogen oxidization process changing to nitrite and nitrate in turn. By utilizing the aeration facility, the reactor performs aeration so as to bring the dissolved oxygen (DO) to 1–3 mg/L for the purpose of providing the aerobic conditions.

- Major function: To remove organics and nitrogen.
- Hydraulic retention time (HRT): 220 m^3/day, over 5 days.
- Operational method: Anoxic and aerobic conditions
- Mixed liquor suspended solids (MLSS): over 4,000 mg/L.
- Emergency (low loads due to flow fluctuations etc.): To operate a single line only.

Figure 6 shows the location where the treatment plant would be constructed and operated as well as the locations proposed to install groundwater monitoring wells. The dehydrated sludge would be landfilled within the landfill site itself.

In addition, as per the feasibility study (DOHWA Engineering Co Ltd et al. 2014), the interior of the 52 containers will be washed using five automatically operated high pressure guns (i.e., at least 1,000 L of water would be required to wash one container) and these washwaters along with the sewage generated by the workforce will be directed to the leachate treatment plant.

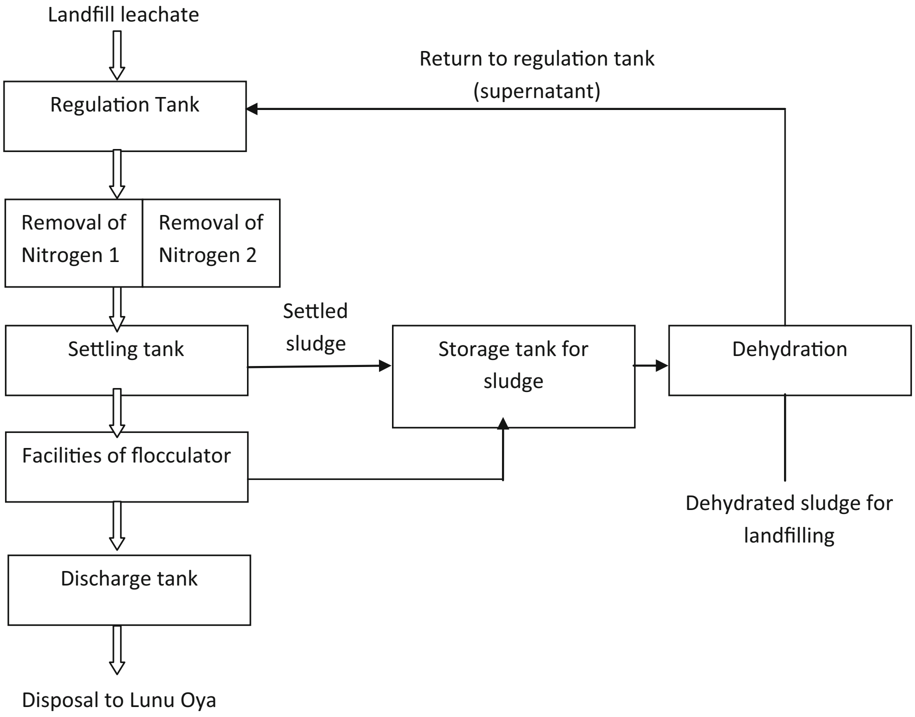

Fig. 5 Proposed effluent treatment plant at the sanitary landfill facility (Source: DOHWA Engineering Co Ltd et al. 2014)

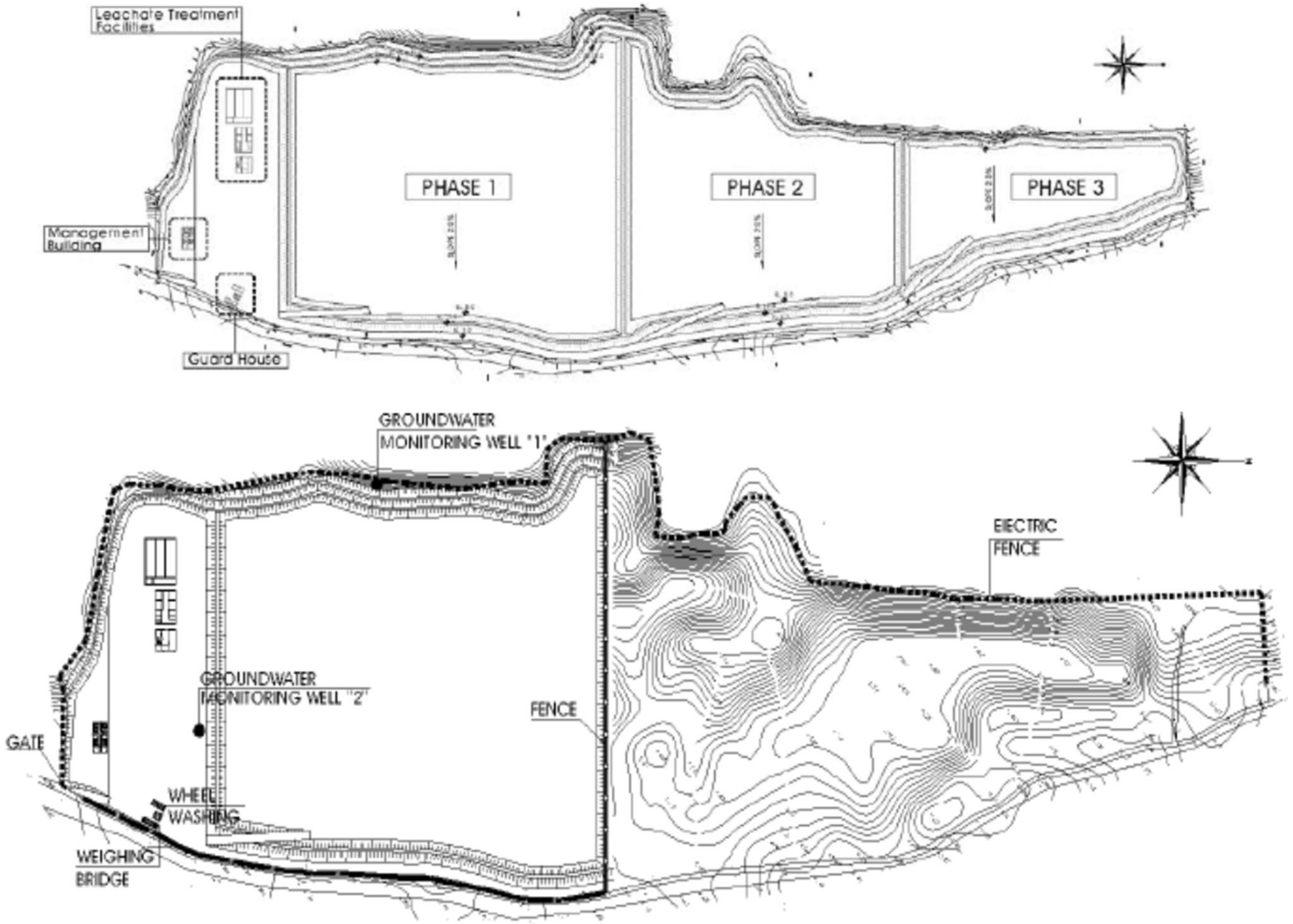

Fig. 6 Sanitary landfill layout plan showing the location of the treatment plant, different phases planned and groundwater monitoring wells (Source: DOHWA Engineering Co Ltd et al. 2014)

Furthermore, washwaters from cleaning of the wheels of the tractors towing the tipping trailers would be directed to the treatment plant (i.e., 40 L of water would be required to wash one tractor). The number of vehicles passing the cleaning machine is around 30 taking into consideration of the entry amount of MSW (1,130 tons/day in 2035) and the capacity of a transporting vehicle. However, details pertaining to the quality of the effluent expected from the container and tire washing activities are not furnished in the feasibility report.

As per the feasibility study (DOHWA Engineering Co Ltd et al. 2014), treated effluent would be used to supply make up water (i.e., 10 L × 30 tractors with trailers = 300 L/day) and the rest of the treated effluent would be disposed to the Lunu Oya. The effluent would be treated to conform to the tolerance limits for industrial and domestic wastewaters discharged into marine coastal waters (standards are pH of 5.5–9, $BOD_5 < 100$ mg/L, $COD < 250$ mg/L and $NH_4{}^+$–$N < 50$ mg/L) under the National Environmental Act No. 47 of 1980 and its amendments (Extraordinary Gazette No. 1534/18 dated 1st February 2008).

Groundwater monitoring plans

In accordance to the feasibility report, groundwater inspection compatible with configuration of the Sanitary Landfill site and topographical conditions will be put in place for periodic observation of groundwater in order to check whether there is any pollution and also to preclude any environmental and public health problems that could arise. To check for pollution of groundwater by leachate, appropriate spots at upper and lower streams will be identified for installation of wells in order to test groundwater pollution.

Figure 6 shows the locations proposed to install groundwater monitoring wells. Note that two wells will be installed during phase I and one well per phase II and III (exact locations where groundwater wells would be installed in phases II and III are not given).

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