REPORT

ISWA
International Solid Waste Association

Guidelines for Design and Operation of Municipal Solid Waste Landfills in Tropical Climates

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ISWA – the International Solid Waste Association
is a global, independent and non-profit making association, working in the public interest to promote and develop sustainable and professional waste management worldwide

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Report Authors:

Edi Munawar
Chemical Engineering Department
Syiah Kuala University
Jl. Tgk. Syech Abdul Rauf 7, Banda Aceh
Indonesia

Johann Fellner
Institute for Water Quality, Resources and Waste Management
Vienna University of Technology
Karlsplatz 13, 1040 Vienna
Austria

Reviewed by ISWA Working Group on Landfill

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Guidelines for Design and Operation of Municipal Solid Waste Landfills in Tropical Climates

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1. Introduction

1.1. Background

On a global scale landfilling still represents the main disposal method for municipal solid waste (MSW). In particular low and middle income countries are still almost exclusively depending on landfilling or dumping of waste, since it in particular the latter represents by far the cheapest method of waste disposal[1]. However, landfilling[2] of waste is in many countries still associated with severe negative impacts on the environment (e.g., groundwater and surface water pollution, greenhouse gas emissions) and the human health (e.g., landfill fires, landslides).

In order to avoid or minimize negative impacts associated with the operation of landfills numerous guidelines for landfill operation and management have been prepared by governmental authorities and/or international agencies during the last decades. Most of these guidelines can be accessed free of charge from all over the world (e.g., US EPA, 1998; ISWA, 2010; UNEP, 2005; Environmental Protection Agency, 2000). However, as almost all of those reports/guidelines were prepared specifically for developed countries, thereby considering their economic capacity, these guidelines might not be practical for low and middle income countries with different available budgets for waste management. In addition to the different economic capacity also the composition of the waste deposited in low and middle income countries is significantly diverse in comparison to affluent countries. Besides the composition of the deposited waste the main factor determining landfill emissions (and thus environmental pollution associated with landfilling) is quantity of water entering (infiltrating) the waste body. Water is essential for microbial biodegradation and thus for the generation of landfill gas, but also for the dissolution of pollutants and the generation of leachate. Hence, the emissions from landfills are strongly dependent on the prevailing climate.

As most low and middle income countries are geographically located in tropical and/or subtropical zones, whose climate differs again significantly from most developed countries, which are generally located in temperate zones, existing guidelines and landfill policy documents may hardly be applied to many developing countries.

In Figure 1 the Gross Domestic Product per capita GDP (expressed in US-$/cap) and the annual precipitation rate (expressed in mm/a) are given. A comparison of both maps clearly indicates that many low income countries (red, orange and yellow colours) are located around the equator and hence their climate is characterised by large quantities of rainfall.

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[1] In comparison to incineration, or mechanical biological pre-treatment

[2] Excluding sanitary landfilling

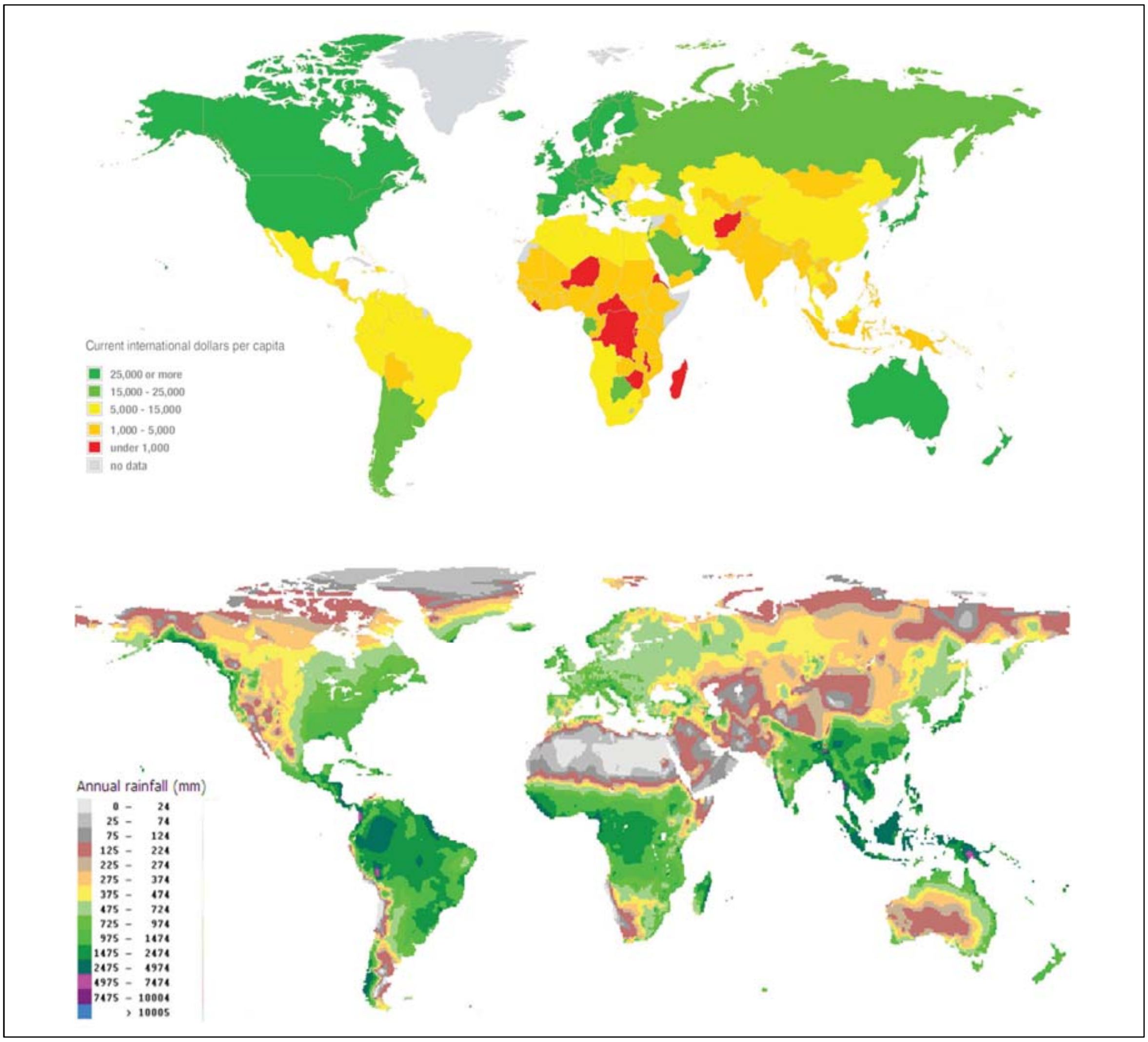

Figure 1 World map by gross domestic product (top) and by rainfall intensity (bottom) (Source: International Monetary Fund 2012 & World Climate 2012)

1.2. Purpose of this Document

The purpose of the present document is to establish guidelines for the design and operation of landfills in tropical climates taking the limited economic capacity of many countries located in these climates into account. The document should guide landfill operators and waste management authorities to operate municipal solid waste (MSW) landfills in tropical countries as environmentally friendly as possible (considering the limited budget available).

The guidelines are organized in sections based on the sequences necessary when operating a new or expanding an existing landfill facility. Each section provides scientific background followed by technical information associated with regulatory requirements.

2. Guidelines for the design and operation of landfills in tropical climates

The main objective of landfilling is to provide a place for final storage of waste, in a way that does not impair human health and the surrounding environment. This objective can be reached by isolating the waste disposed of from the environment so that emissions from the disposal site can be collected and treated prior to their release to the environment. The other option for environmentally sound landfilling would be an intensive pre-treatment of the waste prior to disposal, so that the emissions potential of the waste (reactivity) is very low. The later concept is called final storage landfill (Baccini, 1989) and requires usually expensive pre-treatment, which will not be affordable for developing countries.

The present document should assist to reach the objective of landfilling (environmental friendly final storage of waste) under special consideration of limited financial resources and the prevailing climate presented in tropical countries. As detailed guidelines for landfill operation have recently been released by the International Solid Waste Association ISWA (in 2010), the present document tries to refer to these guidelines as far as they are applicable to specific conditions present in tropical countries.

2.1. Landfill Site Selection

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

- Neighbourhood (distances from residential area, from waterways and water bodies, and from airports)
- geological and hydrogeological conditions in the area
- seismic conditions in the area
- existence of groundwater and its current (and future) utilization
- risk of flooding, subsidence and landslides
- transport distances and existing infrastructure (e.g., access roads)
- access to intermediate and final cover material
- topography of site

Neighbourhood

Landfill sites should not be located in the immediate proximity of occupied dwellings, waterways and water bodies. A minimum distance of at least 500 m should be provided[3]. As urban settlements tend to expand very fast in many tropical countries, city developments and future land use should be anticipated when selecting a landfill site.

In case of an airport in the neighbourhood larger distances to the landfill site are recommended (potential hazard to aircrafts due to bird strike). Depending on the airport flight paths distances of more than a few kilometres may be recommended.

Besides the requirement of a minimum buffer zone between residential areas and the landfill site, distances should not be too large, as transport costs for waste increase almost linear with the distance. So sites should be located outside present and future residential areas, but close enough in order to keep transportation costs as small as possible.

Around the landfill a so called buffer zone (cultivated area – bush vegetation) for segregating the landfill from residential area should be installed. This buffer zone should prevent vector migration to residential area, absorb scattered dust driven by landfill equipment and waste collection vehicles, and reduce noise and odour nuisances of the landfill operation.

Geological and hydrogeological conditions

Information about the geological and hydrogeological conditions at the site is crucial for determining the potential risk of emissions from the landfill for the underlying soil and groundwater. In order to reduce construction costs for expensive base liner systems, landfills should be sited at locations where the subsurface layers are characterized by low hydraulic conductivity (hydraulic conductivity of less than 1×10^{-8} m/s). In the best case a subsurface layer of very low hydraulic conductivity could substitute a man-made base liner, and thereby significantly reduce landfill construction costs.

Knowledge about the groundwater flow direction is necessary in order to develop a monitoring system for the groundwater (groundwater monitoring wells up- and down-gradient of the landfill).

Information about the geological and hydrogeological conditions at the site could be obtained by geological maps (on the superficial level), or are to be investigated during the site selection process (e.g. soil borings, in situ cone penetration test).

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[3] depending on the size of the landfill, height, wind direction, … large minimum distances might be required.

Current and future utilization of water bodies in the vicinity of the landfill

In order to evaluate the suitability of the site for a landfill, comprehensive information about the current and future utilization of the groundwater or proximate water bodies is necessary. For instance if water bodies neighbouring the landfill site are used as drinking water or represent a potential source for drinking water in the future, the site can be considered as unsuitable due to the risk of groundwater contamination associated with the operation of a landfill.

Risk of flooding, subsidence and landslides

Sites are also to be classified as unsuitable if they are endangered by landslides, flooding and subsidence. Information about those risks could be gained by interviews with regional authorities or local residents. Due to large precipitation with high intensities during the rainy seasons, landslides and flooding are of significant risk in tropical countries.

Transport distances and existing infrastructure

As mentioned above, one important criterion for landfill siting is a reasonable distance of the landfill to the source of waste generation. Long transport distances of the waste increase on the one hand specific costs for waste disposal[4], on the other waste related traffic will be raised and therewith associated adverse effects and risks for inhabitants (e.g., traffic accidents, noise, and air pollution). Almost as important as short transport distances is the existing infrastructure (access roads to the landfill), as the supply and maintenance of access roads for instance may be costly for the municipality and, again, raise waste disposal costs.

Access to intermediate and final cover material

Another factor determining the overall costs of landfilling is the accessibility of cover material. Landfills are to be covered daily or at least weekly with inert material, in order to minimize windblown litter, prevent birds from scavenging, reduce risk of fire, control odours and other adverse effects (see ISWA operational guidelines for landfilling – page 7). In addition landfills have to be capped with a final cover after landfill closure.

[4] A comprehensive study carried out in Greece demonstrated that waste transportation costs could contribute between 50 and 80 % to total landfill operation costs.

Both materials (those for the final cover as well as for the daily cover) should preferably be accessible in the vicinity of the landfill sites, as this would keep transportation costs of those materials to a minimum.

Topography of site

The topography of the site is to a certain extent also influences the costs for landfilling. In the best case the topography of the site could be used in conjunction with an appropriate design of the landfill to manage leachate flows without pumping, simply by gravity flow of the leachate. This of course requires differences (see Figure 2) in the altitude between the drainage layer of the landfill, leachate collection basins, leachate treatment facility and final disposal site of the leachate (e.g., receiving waters).

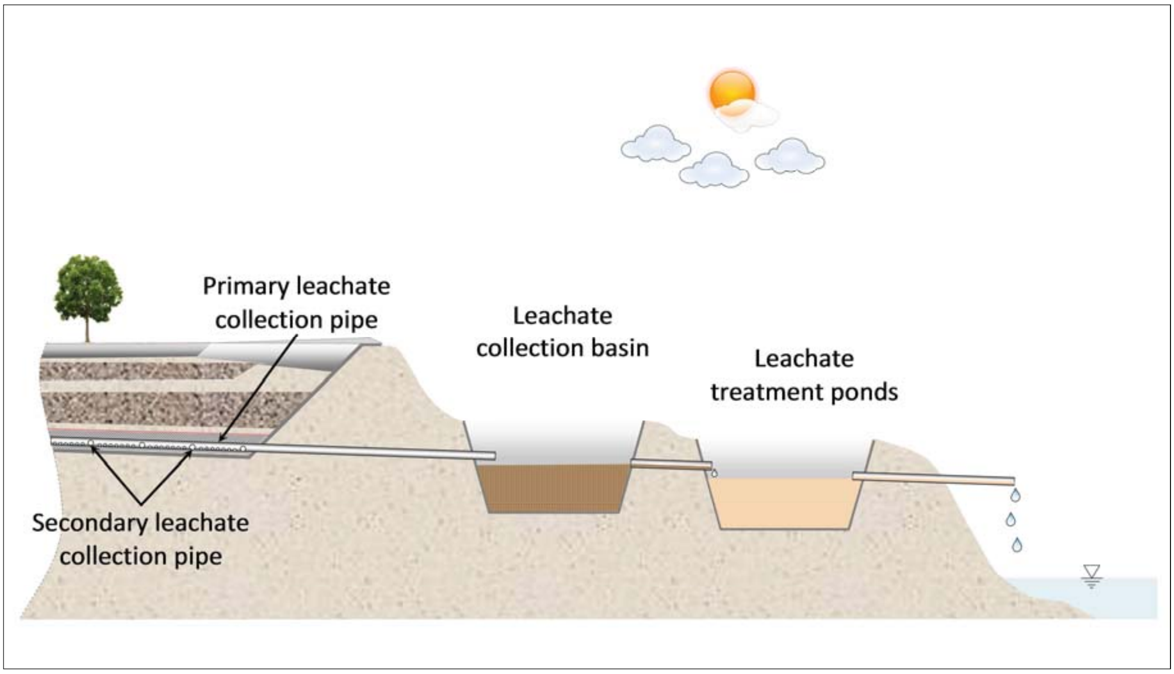

Figure 2 Gravity flow of leachate due to differences in altitude between landfill base and receiving water (schematic illustration)

2.2. Landfill Design

2.2.1. Base lining system

As indicated above leachate emissions from landfilled waste are a crucial problem in tropical countries due to the high organic content of waste on the one hand, and due to the high precipitation rates on the other. Hence adequate landfill design is urgently required.

The principles for landfill design in tropical countries[5] are isolating the waste from the surrounding environment at low costs, which should consider construction as well as operation costs. The isolation from the environment (at the base of the landfill) can be accomplished by a base lining system. In affluent countries landfill regulations often require a composite liner at the landfill base. This composite liner (see Figure 3 b) usually consists of a clay layer (of 40 to 80 cm thickness) and a high density polyethylene (HDPE) sheet (see for instance German landfill ordinance). The later in particular is expensive and hence often not affordable for landfill operations in developing countries.

Hence it is recommended to use a “single” baseliner system consisting of compacted clay layers (see Figure 3a). The clay material should preferably be accessible in the vicinity of the landfill site, in order to minimize transportation costs and traffic. Thus site selection is (as mentioned above) crucial for the overall costs of landfilling. Requirements for the compaction of the clay and the required hydraulic conductivity can be derived from international regulations on landfill construction (e.g. EU landfill directive). Typically the hydraulic conductivity of the clay should be below 1×10^{-9} m/s.

In case that the subsurface layer of the selected site is already characterized by low permeability (hydraulic conductivity $< 1 \times 10^{-9}$ m/s) a man-made base sealing may not be needed. Sometimes it might be sufficient to slightly reduce the low permeability of the existing soils, simply by loosening the upper 20 to 30 cm of the soil[6] and subsequently compaction of this layer with heavy equipment. Specific costs for the construction of base lining systems can thereby be reduce to less than 1 US-$ per m². In comparison construction costs for base lining systems in the US are reported to 20 to 30 US-$/m², whereas in the European Union costs could even be much higher, up to 70 US-$/m². The surface of the liner should be sloped with at least 2 %.

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[5] which at the same time can be classified as developing countries
[6] applying agricultural tillage

2.2.2. Drainage system

All types of base lining systems (subsurface of low permeability, clay liner or composite liner) are directly overlain by a layer of course material (e.g., gravel), the so-called leachate collection system (see Figure 3). Within the leachate collection system drainage pipes are to be installed at local low points (see Figure 4). The depth of leachate collection system should be at minimum 50 cm with a hydraulic conductivity above 10^{-3} m/s and a base slope of at least 2 %. Sufficient water drainage capacity at the landfill bottom is crucial in tropical climates as precipitation rates and thus leachate generation rates are high, especially during the wet season. Insufficient drainage of the leachate generated would cause water saturated waste zones (backwater) at the landfill bottom, which reduces the mechanical stability and thereby endangers the landfill of mechanical failure (waste slide). So landfill or waste slides have often been observed after heavy rainfall events in tropical countries. For instant, a waste slide occurred after heavy rainfall in Leuwi Gajah landfill in Bandung, Indonesia in February 2005. About 2.7 million cubic metres of waste was sliding down and hit many houses. This incident caused fatalities and property loss. 147 peoples were killed and many more injured in this disaster (Kölsch et al, 2005).

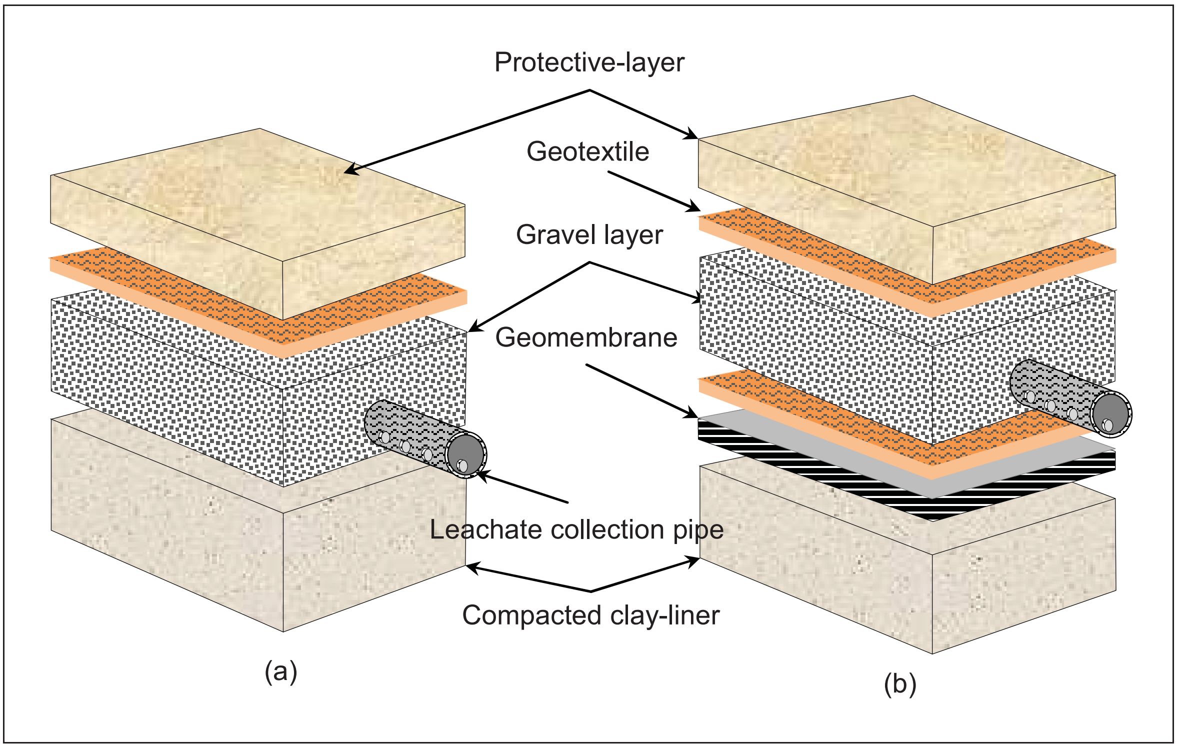

Figure 3 Schematic diagram baseline system (a) single-line system, and (b) composite lining system (as applied widely in affluent countries).

Above the drainage layer a protective layer (of shredded waste, compost, or other smaller grained waste) should be placed in order to ensure the long term functionality of the drainage layer (no waste particles can move into the drainage layer, or compaction of the first waste layers would destroy the drainage layer and the drainage pipes). The hydraulic conductivity of the protective layer should be well above 1 x 10^{-5} m/s in order to prevent the retaining of leachate in the waste mass. In addition a geotextile can be placed between the protective layer and the drainage layer. This geotextile also prevents small grained particles from migrating into the gravel layer and subsequently clogging this layer. The recommended thickness of the protective-layer is in the range of 30 to 50 cm. Above this protective layer the waste is placed and compacted.

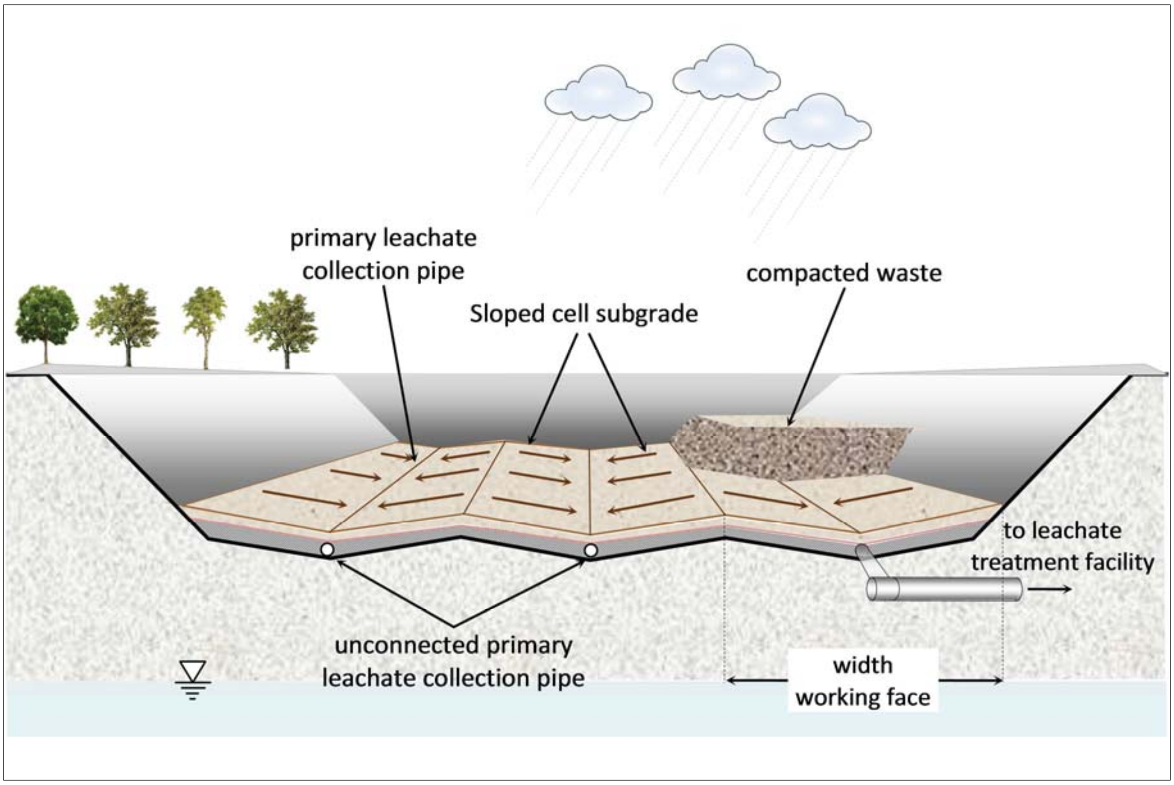

Figure 4 Schematic diagram "saw-tooth" configuration of leachate system (adapted from Qian et al, 2002).

As leachate treatment represents a major matter of expense, the landfill (also landfill extension) should be designed in a way that a minimum amount of leachate is generated. One important issue when constructing a new landfill is, that the landfill is divided into landfill cells, with separate leachate collection systems. These cells should be separated by embankments and equipped with separate leachate collection pipes that finally are connected to the main header pipe leading either to the leachate collection basin or directly to the leachate treatment facility. Figure 4 illustrate how such separation could be accomplished using the so-called "saw-tooth" configuration of the leachate collection system. In this method the landfill cells are divided into several working faces (cells). Each working face is equipped with a primary leachate collection pipe. At the commencement of landfilling operation (beginning of waste disposal), only the leachate collection pipe in the working face currently being filled with waste is connected to the leachate treatment facility. The other leachate pipes (in future working faces with no waste disposal taking place at these work faces) drain the storm water directly into the next watercourse without any treatment process.

2.2.3. Mechanical Stability

The mechanical stability of a landfill is of major concern especially in tropical countries, as several incidents of landfill slides in the past 2 decades have demonstrated. The mechanical stability of a landfill is affected by several parameters: waste composition – share of plastics[7], slope angles, degree of waste compaction, and degree of water saturation of waste layers. Although still uncertain, the later (water saturation of waste) is believed to greatly influence the mechanical stability, as by most waste slide incidents were observed after heavy rain events. For instant, the waste slide in Leuwi Gajah landfill in Bandung, Indonesia, occurred after heavy rain saturated the waste pile. Water saturation however is not the driving force for landfill slides; it is usually a steep slope of the landfill in conjunction with reduced mechanical stability (often due to water saturation) that finally leads to mechanical landfill failures. Another potential risk for the mechanical stability of landfills represents the limited interface shear strengths of certain layers such as smooth HDPE liner or geotextile. In many countries (e.g. United States) therefore landfills use textured HDPE liner with asperity height of at least 0.4 - 0.5 mm .

In general a global slope stability analysis should be performed during the design phase of the landfill using site-specific conditions. The analysis should be done under static and seismic loading conditions, if presented.

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[7] act as reinforcement within the waste pile

In order to minimize the risk of landfill slides and also the risk of erosion the slope angle should not exceed 25%. In case of huge landfills (height of more than 30 m), the maximum slope angle should be reduced or at least a benching installed (see Figure 5).

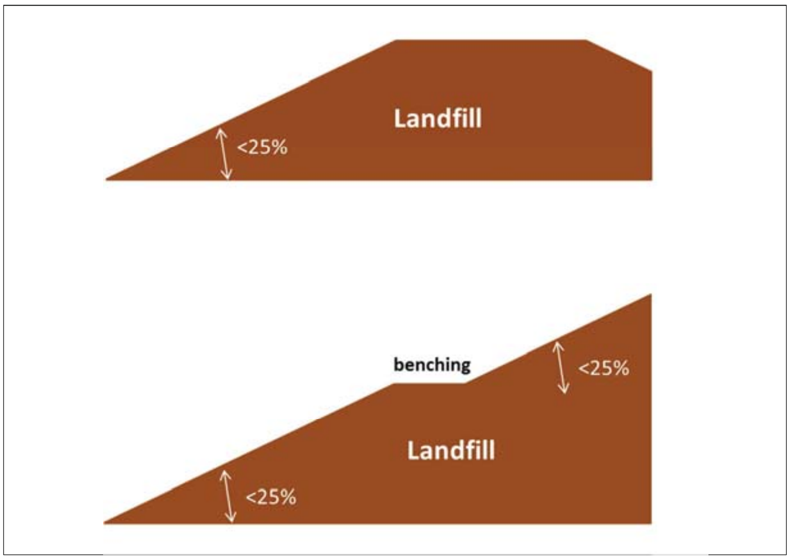

Figure 5 Landfill slope (incl. benching)

2.3. Landfill operation

Many issues concerning landfill operation are not covered (mentioned) within the present guidelines simply due to the fact that they are already described in detail in the ISWA guidelines for landfill operation (ISWA, 2010)

2.3.1. Measuring and Recordkeeping

The mass of incoming waste represents essential information for landfill operators (e.g., for determining the daily working area, estimating future construction steps, determining the necessary daily cover material, ensuring that waste layers do not exceed the planned height), but also for local waste authorities, as it provides data about the waste quantities generated and landfilled.[8]

The measurement of incoming waste mass could be done using a weighbridge facility (more costly solution) or by simply counting the number of trucks entering the landfill and estimating their waste load. As usually, if similar waste transportation trucks are used, weighing the load of a few waste trucks would be sufficient to gain a good estimate about the average waste load per truck.

[8] In many developing countries the vast majority of MSW generated is landfilled, hence data about the landfilled waste mass would allow also good estimates about the total waste generation.

Figure 6 Measuring and recordkeeping incoming waste, (a) the waste vehicle truck pass weighbridge, and (b) weighbridge operator input necessary data for recordkeeping of incoming waste.

Information about the waste mass landfilled might also be important for financial accounting (for determining the deposit fee), for instance if one landfill serves several municipalities, landfill costs must be divided according to the waste amounts delivered from each municipality.

Modern weighbridge facilities (see Figure 6) are usually equipped with recordkeeping devices, which allow the weighbridge staff to record the waste mass, the origin of the waste, the truck ID, arrival time, etc.

2.3.2. Unloading of the waste

Unloading of incoming waste should be carried out in small working areas ("working face"). The working face should be only as large as necessary to allow adequate truck movement and unloading space, as well as efficient operation of landfill equipment.[9]

To keep the size of working area as small as possible is important due to the following reasons: the size of the working face determines the amount of daily cover material required (which might be costly) and it also strongly influences the leachate generation rate, as at the working face the largest part of incoming rainwater becomes leachate (low evaporation rate and little runoff, which however is almost as polluted as leachate). In addition small working faces hinder unwanted scavenging by humans and animals.

[9] For detailed information see ISWA operational guidelines for landfills (ISWA, 2010).

Although there is no special technique required for unloading waste, unloading the first layer of waste (directly above the protective layer) need to be done carefully (under the control of trained stuff) in order to avoid any damage of the leachate collection system and the base liner due to excessive load (as results of landfill equipment, waste trucks or the waste itself). In particular attention must be given to the following points when unloading the first layer of waste:

1) Access road

   The access road to the working face must be constructed to ensure that waste trucks and landfill vehicles will drive over hard-surfaced ramps thereby avoiding excessive load for the leachate collection system.

2) Manoeuvring space

   The end of the access road must be constructed relatively wide to allow waste trucks and landfill vehicles to turn around.

3) Unloading point

   The first waste truck must unload the waste directly at the end of the access road and the waste must be disposed horizontally.

4) Bulky and hard waste

   Any bulky and hard waste must be removed from the waste that will be landfilled as first layer directly above the protective layer. This is again to avoid any puncture pressure on the liner/leachate collection system.

5) Minimum thickness of first waste layer

   Preferably the first layer of waste should be deposited without compaction (thickness of about 120 cm).

2.3.3. Waste Compaction

Waste compaction is essential at every landfill, simply due to is positive effect regarding the saving of landfill space. In addition compacted waste has a range of other benefits such as better mechanical stability, less odour release, higher gas generation rates (due to anaerobic conditions prevailing), reduced risk of landfill fires, etc. In addition good waste compaction[10] can also reduce leachate generation rates (by increased surface runoff) as different research studies indicate.

The compaction can be conducted by bulldozers or special waste compactors (very heavy equipment). The latter are more effective, but also more expensive and hence often not affordable for landfill operators in developing countries in tropical

[10] difficult to achieve in developing countries, as investment costs and also operational costs for compactors are often beyond the finical resources of landfill operators

climates. Most effective waste compaction can be reached by spreading the waste in 30 to 40 cm thick layers with subsequent compaction by repeated passages of the available waste compaction equipment. The overall effectiveness of compaction depends on the size of the compactor, number of passes and the characteristics of the waste landfilled. In general more compaction passes will only slightly increase the waste density, but significantly increase fuel consumption of the compactor. Hence, the number of compaction passes need to be optimized in conjunction with fuel consumption of the compactor (operational costs).

2.3.4. Daily cover application

Daily cover application is essential and required in every landfill operation. Daily cover application will minimize negative effects of landfill operation such as odours nuisance, waste blowing, and vector populations. It might also avoid landfill fires, minimize contamination of surface runoff, and improve aesthetics of landfill operation. The availability of soil or other inert matter as cover material is already of importance for the site selection of the landfill (see chapter for site selection).

Figure 7 Application of unutilized compost as regular cover in Gampong Jawa Landfill, Banda Aceh, Indonesia.

In practice landfill operators often face difficulties regarding the availability of suitable cover material, which frequently leads to landfill operation without daily or weekly coverage of the waste. Instead of transporting soil or other inert material to landfill over longer distances (which is expensive), unutilized compost or demolition waste could be used as alternative daily cover material. Figure 7 presented the application of unutilized compost as regular cover material at Gampong Jawa landfill in Banda Aceh, Indonesia. This can be considered as “best available practice” to operate landfills, especially for sites with insufficient soil cover material or lack of financial resources.

2.3.5. Leachate and leachate treatment

Due to high amounts of precipitation large quantities of leachate (liquid discharge from solid waste) from landfills in tropical climates are to be expected. Annual leachate generation rates of more than 1,000 litres per m² are frequently observed in tropical countries. Quality of leachate from landfills in tropical countries is comparable to those generated in most affluent countries. It is mainly characterized by high contents of organic pollutants, ammonium and easy soluble salts. Pollutant´s concentration increase usually during the dry season (less dilution of leachate by rainwater) and decreases during the wet season.

The leachate treatment method widely applied in many tropical countries is the multi-stage treatment in different leachate ponds. Thereby the collected leachate is first treated anaerobically, then aerobically (aeration of pond), followed by a maturation pond[11] from which the “treated” leachate is finally discharged into the sewer or the next watercourse. This treatment method is quite inexpensive[12], but also its effectiveness is limited. Although it is practiced at many sites no monitoring about the quality of inflow and/or outflow is conducted. Hence, a crucial recommendation regarding any leachate treatment facility would be to monitor its effectiveness with respect to pollutant removal (using some indicator substances such as COD or ammonia).

In order to avoid expensive[13] pumping of the leachate the altitude of the landfill base and the leachate treatment ponds should be arranged in a way that leachate flow is driven by gravity (see Figure 2). This is of particular importance for landfills in tropical climates as huge amounts of leachate have to be managed. Besides a clever arrangement of leachate treatment facilities (in order to avoid pumping of leachate) special

[11] Instead of the maturation pond a constructed wetland could be used as final treatment step
[12] Investment costs as wells as operational costs.
[13] Due to large quantities

interest must be given to the sizing of leachate treatment ponds, as they will receive large quantities of water within short time periods.

The required capacity of a single leachate treatment pond can be determined simply by using the following formula, which considers the maximum daily precipitation rate, the ratio between leachate and rainfall, the surface area of the landfill and the required residence time of the leachate in the pond:

$$v = \frac{P_{max} \cdot r \cdot A \cdot t_{ops}}{1000} \cdot 0.5$$

where:

v : Volume of leachate treatment pound [m^3]

p_{max} : maximum precipitation rate [mm/day] for a design storm over a period of t_{ops}

r : ratio between leachate amount and rainfall [-]

A : catchment area (surface area of the landfill) [m^2]

t_{ops} : optimum residence time of leachate in the treatment ponds [day]

1000 : conversion factor from [mm] to [m]

0.5 : factor considering that only part (50 %) of the infiltrating rainwater is directly discharged as leachate

2.3.6. Landfill Gas Management

Landfill gas (LFG) is produced by the anaerobic degradation of organic material present in solid waste. It is mainly composed of methane and carbon dioxide. In addition it may contain low contents of hydrogen sulphide (H_2S), volatile organic compounds (VOCs), ammonia, hydrogen gas, and carbon monoxide. Management of landfill gas, in particular methane, is of importance due to its explosion risk[14] and its high greenhouse gas potential. Moreover some trace components of landfill gas represent a potential lethal hazard. Hydrogen sulphide for instance is at low concentrations (<2 ppm[15]) only a nuisance, but at higher concentrations (> 200 ppm) it cannot be smelled anymore, and at concentrations above 1000 ppm H_2S is lethal within a few minutes. Hence landfill gas collection and management is not only essential to prevent the release of major compounds such as methane, but also important due to trace components.

Besides the mitigation of health and environmental hazards gas collection enables to utilize the landfill gas as fuel in order to generate heat or electricity.

[14] at certain mixtures with ambient air

[15] ppb …parts per million

In tropical climates municipal solid waste landfill usually contains high fractions of organic matter which decompose to a large extent to CH_4 and CO_2. Degradation rates of organic matter at landfills in tropical countries are reported to be higher than in temperate climates (e.g. European Union), simply due to the fact that the moisture content of the waste (and water exchange rate) is higher and ambient temperatures are higher (Wang et al., 2012). Both have positive impacts on the microbial activities and thus on the generation of landfill gas.

Currently different options are applied to minimize gas emissions from landfills in developing and tropical countries. One rather expensive method is to capture and utilize the gas as fuel in a gas engine to generate electricity. Another less expensive option is to pipe the gas into a nearby facility (industrial plant) and utilize its energy content. This option however requires a "consumer" of landfill gas nearby the site. As both options require high technology and significant capital investment, they are typically carried out in collaboration with developed countries under the frame work of clean development mechanism (CDM)[16]. Only in some threshold countries which established feed in tariffs electricity projects are carried out without CDM.

A second option is flaring landfill gas (convert CH_4 to CO_2) without energy recovery. Although this option does not require high technology or high investment costs, it is seldom applied as it increases landfill operation costs without generating financial revenues (exception: it is applied within the CDM framework). The third option for reducing landfill gas emissions is to install a methane oxidation layer[17] to convert CH_4 to CO_2 by methanogenic bacteria. As for the second management option, no financial revenues can be generated by the landfill operator when installing a methane oxidation layer; it "only" reduces the environmental impact of landfill gas. Nevertheless investment costs and also operational costs are much lower for the third option in comparison to option one or two. In addition the methane oxidation layer could also reduce the amount of rainwater infiltrating into the landfill and thereby decrease leachate generation rates.

In general it is recommended that national authorities should consider incentives for landfill operators to reduce landfill gas emissions, as they represent a major source of greenhouse gas emissions (up to 5 % of total greenhouse gas emissions in developing countries).

[16] a mechanism within the Kyoto protocol
[17] preferably made of compost

2.3.7. Monitoring of landfill emissions

In order to evaluate the potential impact of landfill emissions on the environment, information about the amount and the composition of the two major emissions leachate and landfill gas are required. An extensive literature review demonstrated that there is almost no data about full scale landfills in tropical climates available, most information about landfill behaviour under tropical conditions has been derived from small scale experiments. Hence monitoring of landfill emissions would not only allow evaluating the significance and the environmental impact of those emissions, but it would also generate important knowhow about the behaviour of full scale landfills in developing countries. Besides the emissions of the landfill also potentially affected environmental media (such as groundwater or neighbouring surface water) should be monitored.

Minimum requirement regarding the monitoring of leachate, ground- and surface water as well as landfill gas should already be specified in the operational permission of the landfill.

A. Monitoring of leachate and water quality

The leachate quality should be analysed at least twice[18] a year, whereby indicative parameters such as electrical conductivity, pH, chemical oxygen demand COD, ammonia or chloride content should be analysed. Besides the analysis of the raw[19] leachate, the effluent of the leachate treatment facility should also be monitored in order to evaluate its efficiency regarding pollutant removal and at best to adapt the treatment method. The effluent should be analysed for the same parameters as that of the raw leachate.

In order to evaluate the functionality of the base liner groundwater samples have to be taken upstream and downstream the landfill (at least once a year). Parameters for the groundwater analysed should again be in accordance with parameters of the leachate analysis. In case the effluent of the leachate treatment is discharged into surface waters, these surface waters (upstream and downstream the sewage disposal) need to be analysed.

B. Monitoring of landfill gas

Landfill gas is characterized by a distinctive and unpleasant odour which is often a main reason for the neighbourhood to complain about the landfill site. Even more problematic however is the fact that landfill gas can cause an explosion hazard, when methane concentrations are above 5% by volume but less than 15% in atmospheric air. In

[18] In the rainy season and in the dry season
[19] untreated

order to evaluate the explosion risk methane concentrations inside buildings at the landfill or in the close neighbourhood should be monitored regularly (at intervals of 3 months).

If monitoring results indicate an explosion risk (methane levels close to or above 5 %), measures (ventilation, evacuation, etc.) must be undertaken in consultation with the competent authority.

Apart from the explosion risk, landfill gas also contains a wide range of volatile organic compounds that are classified as hazardous air pollutants. Therefore, samples must be taken at various positions at the landfill site to measure the content of volatile organic compounds. Sampling can be taken directly at gas wells or using techniques which satisfies the competent authority. The volatile organic compound compositions in landfill gas must then be subjected to occupational and environmental health risk assessments.

3. Final Cover Application

After the landfill or a single landfill cell has reached its final capacity the waste need to be covered first by an intermediate cover layer, which is insensitive to settlements of the landfill surface. The functions of this intermediate cover layer (e.g. 50 cm of soil or compost) are:

- prevention of erosion by wind and water
- reduction of water infiltration, and gas emissions (at least partial oxidation of methane generated)
- promote vegetation, and
- aesthetic issues.

The reduction of water infiltration rates can be accomplished by a cover material of high water retention capacity (e.g. compost material), by profiling the surface (establishing a relatively large slope of 5 to 10 %) and/or intensive vegetation.

After 5 to 20 years (depending on the settlement development) the intermediate cover could/should be replaced and overlain by a top sealing system (e.g., clay liner of 50 cm and soil layer > 50 cm), which further reduces the amount of water infiltrating into the waste. Again a sufficient surface slope (>5 %) as well as dense vegetation cover[20] are recommended for the final capping of the landfill.

[20] In order to prevent erosion

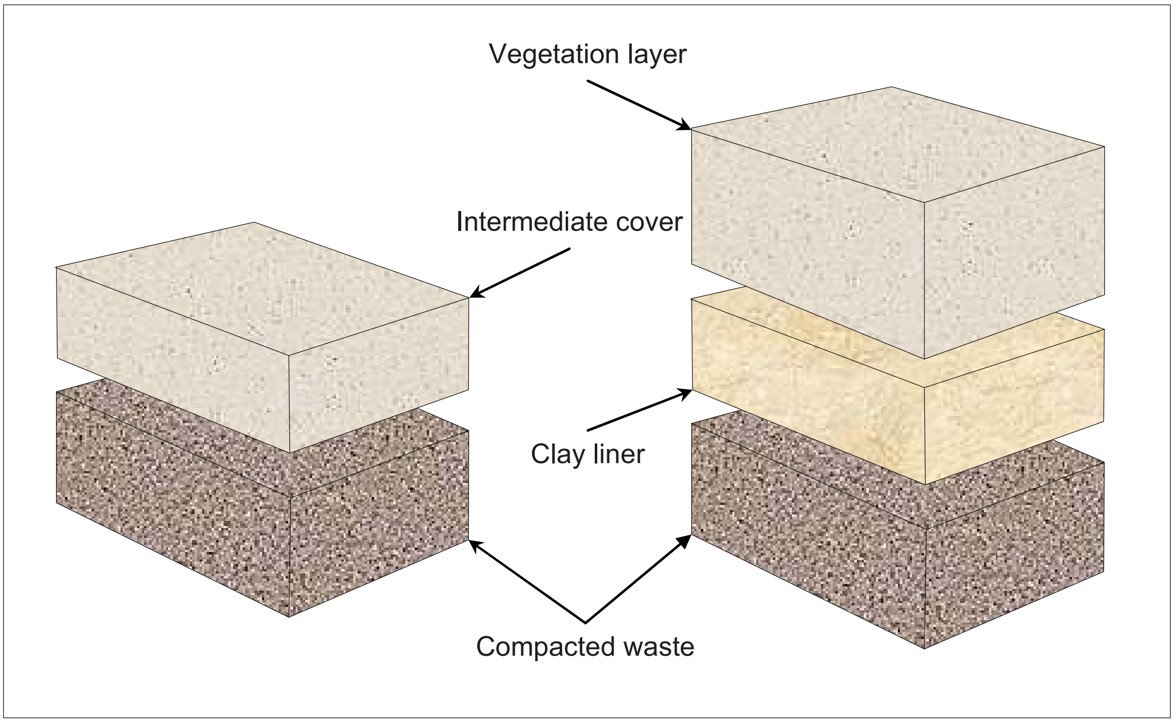

Figure 8 schematic diagrams cross sectional cover system, intermediate cover (left) and final cover systems (right) – in case that the intermediate cover material is not removed (and reused), the final cover (clay liner & vegetation layer) is placed above the intermediated cover.

4. Post-Closure Care

After closure landfills are to be managed and controlled in order to avoid adverse effects on humans and the environment. This post-closure care[21] has to be prolonged as long as landfill emissions represent a hazard to human health and the environment. Based on numerous investigations at MSW landfills in temperate climates the duration of this post-closure care is estimated to be in the range of several decades to centuries. In particular leachate emissions stay on an environmentally incompatible level for long time periods. Due to the fact that the so called liquid to solid ratio (gives the amount of water in litres that has passed through 1 kg of dry solid waste) is largely determining the duration of the landfill aftercare, in tropical climates necessary aftercare periods are likely to be much shorter than in temperate climates. For instance the liquid to solid (L/S) ratio of a landfill with an average height of 20 m, a waste density[22] of 800 kg/m³ and an annual leachate generation rate of 1,000 mm/a reaches a value of 5 litre/kg waste (which is considered to be required to reduce the emission potential to an acceptable level and thus terminate landfill aftercare) already after around 50 years. For comparison, a similiar

[21] or landfill aftercare

[22] water content of 40 % (this high value indicates a bioreactor landfill environment based on studies of the US EPA, however due to the high content of organic matter in the waste as well as the high precipitation rates a water content of 40% is realistic)

landfill in a temperate climate zone (annual leachate generation of 200 mm/a) would need 250 years to reach the same L/S ratio.

Hence, post-closure care of landfills and especially its duration is less critical in tropical climates in comparison to most affluent countries. Nevertheless, regular monitoring and maintenance after landfill closure are required to ensure that the closed landfill does not cause any risk for the environment. Post-closure monitoring should likewise to the operational phase focusing on water[23] and gas monitoring. In addition the status of different landfill elements should also be observed, such as final cover integrity, drainage system, vegetation, slope stability, etc.

5. References

Landfill operator and readers of this document should note that the present guidelines are based on the reference list below. Some references are not cited within the document, but have been added as further reading. Those who are interested in reading more and going to the sources of information for landfill design, operation and management in tropical countries will find this list useful.

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[23] leachate and groundwater

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