Land Disposal of Hazardous Waste

PDH: 5.0 Hours

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1. Course Overview

This course introduces an overview of hazardous waste (HW) landfill design, operation, and performance. This course covers the materials related to Landfill Operations, Site Selection, Liner & Leachate Collection Systems, Final Cover Systems, Materials, Contaminant Transport through Landfill Barriers, Landfill Stability, Subsurface Impoundments and Deep Well Injection, Closure and Post-Closure Care. This course is suggested for civil engineers, environmental engineers, and solid and hazardous waste landfill managers and operators.

2. Learning Objectives

Upon successful completion of this course, the participants will be able to:

- Explain the regulations and types of landfill for HW disposal.
- Describe the concepts of HW landfill design and its parameters.
- Discuss the materials used to construct a HW landfill.
- Interpret the HW landfill operations.
- Recognize the needs of closure and post-closure care of HW Landfill.

3. Introduction

The land disposal of hazardous waste is accomplished with spreading in open lands and landfilling in landfills. The land spreading is not widely used as it requires special precautions and sometimes hard to control the environmental pollution. The landfilling is the best option as careful design, construction, and operation of landfill can significantly be minimized/eliminated the environmental pollution. This course will mainly focus on the disposal of hazardous waste in landfill.

3.1 Definition of Hazardous Waste Landfill

Landfilling is a part of the land disposal practice of hazardous waste which may be defined as a method of hazardous waste disposal in which refuse is buried between layers of dirt so as to fill in or reclaim low-lying ground.

Landfills are necessary because:

- Other hazardous waste management technologies such as source reduction, recycling, waste minimization cannot totally eliminate the waste generated, and
- Hazardous waste treatment technologies such as incineration and biological treatment produces residues.

Why are landfills important?

Landfills contain garbage and serve to prevent contamination between the waste and the surrounding environment, especially groundwater.

What happens to the trash in a landfill?

Landfills are not designed to break down trash, merely to bury it. That is because they contain minimal amounts of oxygen and moisture, which prevents trash from breaking down rapidly. So, landfills are carefully filled, monitored, and maintained while they are active and for up to 30 years after they are closed.

What is the difference between a dump and a landfill?

A dump is an open hole in the ground where trash is buried and where animals often swarm. Dumps offer no environmental protection and are not regulated (***Figure 1***).

A landfill is a carefully designed and monitored structure that isolates trash from the surrounding environment (e.g., groundwater, air, rain). This isolation is accomplished with the use of a bottom liner and daily covering of soil.

Figure 1: An open dump (Not a landfill)

U.S. Federal regulations under **subtitle D** of RCRA define a **municipal solid waste landfill** as “a discrete area of land or an excavation that receives household waste.” Municipal solid waste landfill may be allowed to dispose household hazardous waste, but not the hazardous waste generated from the other processes. The requirements of **hazardous waste landfill**, design, operation, maintenance, closure, and permitting are covered under **subtitle C** of RCRA. The overall design of secure land disposal facilities includes:

- Control of the top to minimize air emissions and infiltration of precipitation.
- Control of the bottom to maximize the collection of leachate and minimize contaminant transport through the bottom.

3.2 Commercial Hazardous Waste Landfills

Twenty-one (21) facilities categorized as Subtitle C hazardous waste landfills and holding current USEPA identification numbers were identified in preparation of this report. Facilities are recorded on TSDF listings from the State Environmental Agencies and the USEPA Headquarters. All of the 21 facilities (***Figure 2***) are currently engaged in commercial disposal of RCRA Subtitle C hazardous waste.

Eight (8) of the twenty-one (21) operating commercial hazardous waste landfills identified hold a Toxic Substances Control Act (TSCA) permit for disposal of PCB-contaminated materials. These facilities also provide for destruction of PCB liquids via transshipment to approved PCB destruction facilities.

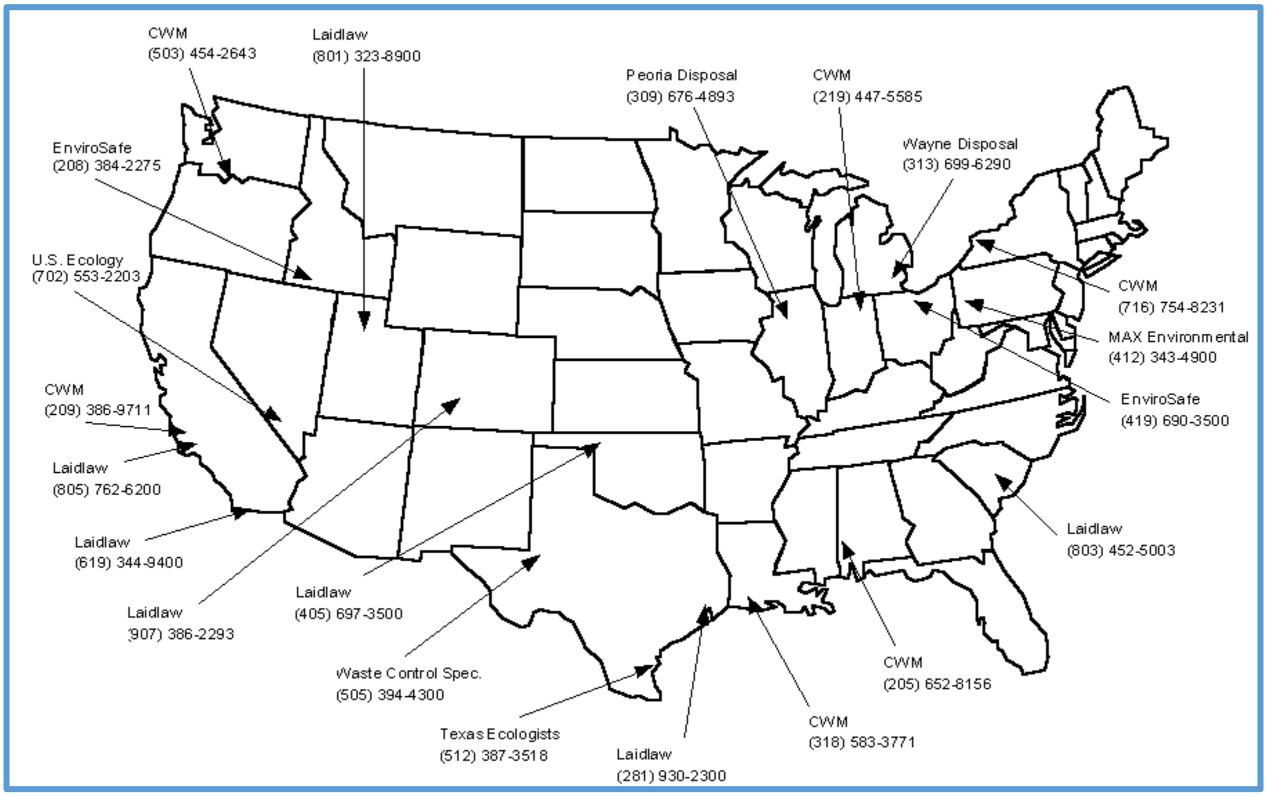

Figure 2: RCRA Subtitle C Landfills in the USA[1]

4. Site Selection

A primary objective of site selection process is to ensure that new facilities are located at intrinsically superior sites that, by virtue of their natural features and land uses setting, provide a higher degree of protection to **public health** and the **environment**. Site selection phases are shown in ***Figure 3***.

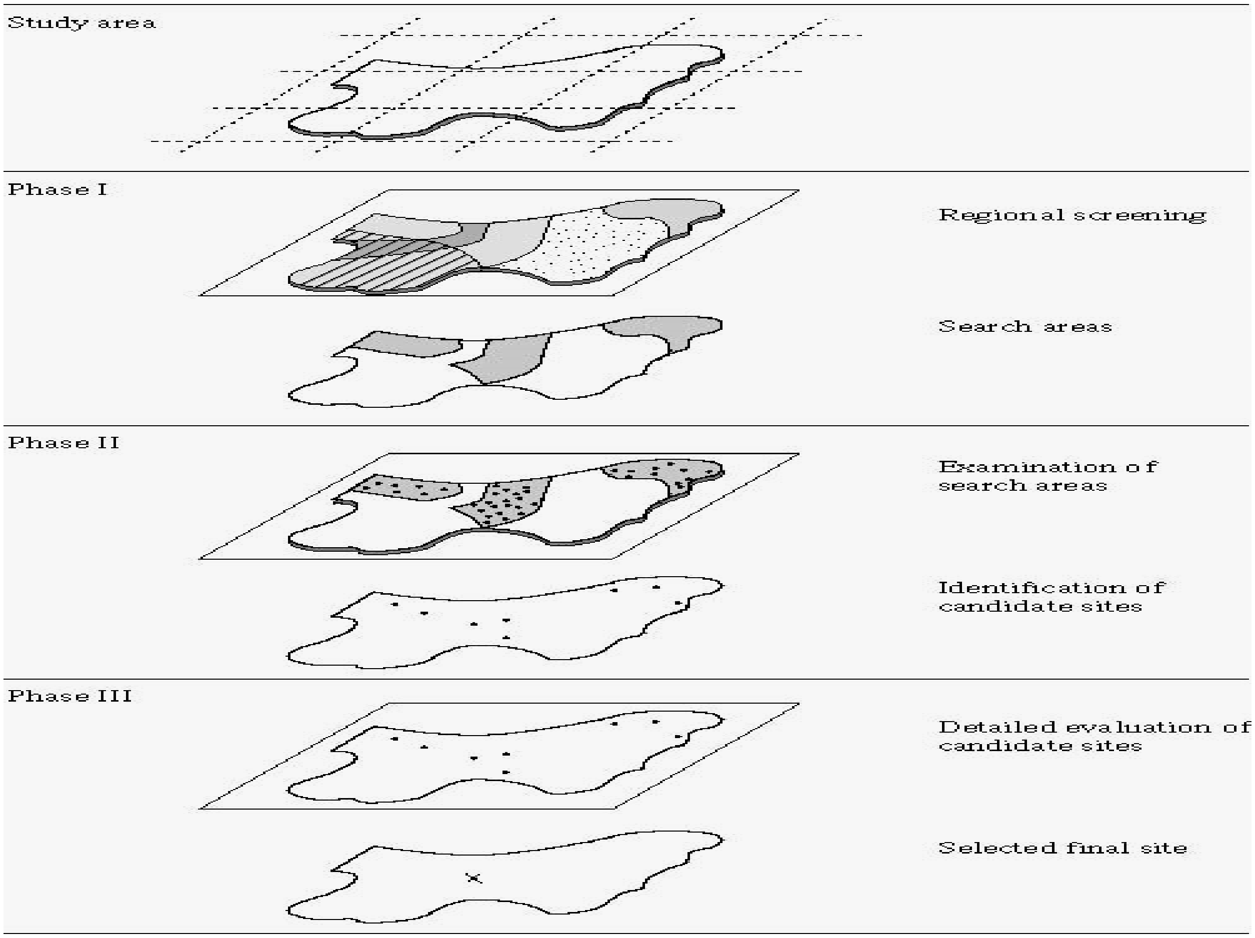

Figure 3: Phased site selection process

The 1st phase is the use of regional screening techniques to reduce a large study area, such as an entire state or region, to a manageable number of discrete search area. The 2nd phase is the evaluation of the discrete search areas in more detail and identify candidate sites within them. The candidate sites are then evaluated in even more detail at a site-specific level of analysis to provide the basis for selecting a site for landfill facility.

4.1 Public Participation

It is mandatory in the regulations that general public must be involved in the selection process of a site through public meeting and public hearing, as appropriate, for informed decision.

4.2 General Criteria for Site Selection

Potential landfill site is selected on the basis of

- Responsibility of development authorities to identify the landfill sites and hand over the sites to the concerned municipal authority for development, operation, and maintenance.
- Near the waste processing facility.
- Soil conditions and topography.
- Surface water hydrology.
- Large enough to last at least for 20-25 years.
- A buffer zone of no-development shall be maintained around the landfill site.
- Temporary storage facility for waste shall be established in each landfill site.

4.3 Criteria for Location

HW Landfills shall not be located within a certain distance of the following lakes, ponds, rivers, wetlands, flood plains, highways, habitation, critical habitat area, water supply wells, Airports, coastal zone. If it is absolutely essential to site a landfill within the restricted zone, then appropriate design measures are to be taken and prior permission from the State Pollution Control Board (SPCB)/Pollution Control Committee (PCC) should be obtained. Every state has its own Pollution Control Board (PCB) or Pollution Control Committee (PCC)[1].

a. **Lake or Pond:** No landfill shall normally be constructed within 200 m of any lake or pond. Because of concerns regarding runoff of waste contaminated water, a surface water monitoring network with approval of SPCB/PCC shall be established.

b. **River:** No landfill shall be constructed within a 100 m of a navigable river or stream.

c. **Flood Plain:** No landfill shall be constructed within a 100-year flood plain. A landfill may be built within the flood plains of secondary streams if an embankment is built along the streamside to avoid flooding of the area. However, landfills must not be built within the flood plains of major rivers unless properly designed protection embankments are constructed around the landfills.

d. **Highway:** No landfill shall be constructed within 500 m of the right of way of any state or national highway.

e. **Habitation:** A landfill site shall be at least 500 m from a notified habitated area. A zone of 500 m around a landfill boundary should be declared a no-development buffer zone after the landfill location is finalized.

f. **Public Parks:** No Landfill be constructed within 500 m of public park.

g. **Critical Habitat Area:** No landfill shall be constructed within critical habitat areas including reserved forest areas. A critical habitat area is defined as the area in which one or more endangered species live. It is sometimes difficult to identify a critical habitat area. If there is any doubt, then the SPCB/PCC shall be consulted be consulted for clarification.

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[1] CRITERIA FOR HAZARDOUS WASTE LANDFILLS, https://odocmms.nic.in/OCMMS/SPCB_DOCUMENTS/CRITERIA%20FOR%20HAZARDOUS%20WASTE%20LANDFILLS.pdf accessed June 28, 2020

h. **Wetlands:** No landfill shall be constructed within wetlands. It is often difficult to identify a wetland area. Maps may be available for some wetlands, but in many cases such maps are absent or are incorrect. If there is any doubt, then the SPCB/PCC shall be consulted for clarification.

i. **Airport:** No Landfill shall be constructed within a zone around Airports as notified by the regulatory authority or the aviation authority.

j. **Water Supply:** No landfill shall be constructed within 500 m of any water supply well.

k. **Coastal Regulation Zone:** No landfill shall be sited in a coastal regulation zone.

l. **Ground Water table level:** No landfill shall be located in areas where the ground water table will be less than 2 m below the base of the landfill.

m. Other criteria may be decided by the planners in consultation with SPCB/PCC commensurate with specific local requirements such as presence of monuments, religious structures etc.

Hazardous waste landfills should preferably be located in areas of low population density, low alternative land use value, low ground water contamination potential and at sites having high clay content in the subsoil. A HW landfill will be selected following the guidelines published by Ministry of Environment and Forest (MoEF). The step by procedure will be as follows:

i. Earmarking a' search area' taking into account the location of the waste generation units and a 'search radius' (typical 5 to 250 km). The search area will be so chosen that it minimizes the number of HW landfills in any region or state.

ii. Identification of a list of potential sites on the basis of:
  a. Availability of land
  b. Collection of preliminary data
  c. Restrictions listed in the locational criteria (Criteria for Location)

iii. Collection of preliminary data as follows:
  a. **Topographic Maps:** A topographic map will help find sites that are not on natural surface water drains or flood plains. Topographical maps may be procured from Survey of India.
  b. **Soil Maps:** These maps, primarily meant for agricultural use, will show the types of soil near the surface. They are of limited use as they do not show types of soil a few meters below the surface. They may be procured from Indian Agricultural Research Institute.
  c. **Land Use Plans:** These plans are useful in delineating areas with definite zoning restrictions. There may be restrictions on the use of agricultural land or on the use of forest land for landfill purposes. Such maps are available with the Town Planning Authority or the Municipality.
  d. **Transportation Maps:** These maps, which indicate roads and railways and locations of airports, are used to determine the transportation needs in developing a site.
  e. **Water Use Plans:** Such maps are usually not readily available. A plan indicating the following items should be developed: private and public tubewells indicating the capacity of each well, major, and minor drinking water supply line(s), water intake wells located on surface water bodies and open wells.
  f. **Flood Plain Maps:** These maps are used to delineate areas that are within a 100-year flood plain. Landfill siting must be avoided within the flood plains of major rivers.

g. **Geologic Maps:** These maps will indicate geologic features and bedrock levels. A general idea about soil type can be developed from a geological map. Such maps can be procured from Geological Survey.

h. **Aerial Photographs / Satellite Imagery:** Aerial photographs or satellite imageries may not exist for the entire search area. However, such information may prove to be extremely helpful. Surface features such as small lakes, intermittent stream beds and current land use, which may not have been identified in earlier map searches, can be easily identified using aerial photographs.

i. **Ground Water Maps:** Ground water contour maps are available in various regions which indicate the depth to ground water below the land surface as well as regional ground water flow patterns. Such maps should be collected from Ground Water Boards or Minor Irrigation Tubewell Corporations.

j. **Rainfall Data:** The monthly rainfall data for the region should be collected from the Indian Meteorological Department.

k. **Wind Map:** The predominant wind direction and velocities should be collected from the Indian Meteorological Department.

l. **Seismic Date:** The seismic activity of a region is an important input in the design of landfills. Seismic coefficients are earmarked for various seismic zones and these can be obtained from the relevant BIS code or from the Indian Meteorological Department.

m. **Site Walk Over and Establishment of Ground Truths:** A site reconnaissance will be conducted by a site walk-over as a part of the preliminary data collection. All features observed in various maps will be confirmed. Additional information pertaining to the following will be ascertained from nearby inhabitants:
   (a) flooding during monsoons.
   (b) soil type.
   (c) depth to G.W. table (as observed in open wells or tube wells).
   (d) quality of groundwater and
   (e) depth to bedrock.

n. **Preliminary Boreholes and Geophysical Investigation:** At each site, as a part of preliminary data collection, one to two boreholes will be drilled, and samples collected at every 1.5 m interval to a depth of 20 m below the ground surface. The following information will be obtained: (i) soil type and stratification; (ii) Permeability of each strata; (iii) strength and compressibility parameters (optional); (iv) ground water level and quality and (v) depth to bedrock. In addition to preliminary boreholes, geophysical investigations (electrical resistivity/seismic refraction/others) may be undertaken to assess the quality of bedrock at different sites.

iv. Selection of two best ranked sites from amongst the list of potential sites on the basis of the ranking system stipulated by MoEF.

v. Environmental Impact Assessment (**EIA**) for the two sites for the following parameters.
   (a) ground water quality.
   (b) surface water quality.
   (c) air quality – gases, dust, litter, odor.
   (d) land use alteration.
   (e) drainage alteration; soil alteration.

(f) soil erosion.
(g) ecological impacts,
(h) noise.
(i) aesthetics – visual, vermin, files.
(j) traffic alteration; and
(k) others

vi. Assessment of public perception for the two sites.
vii. Selection of Final site.
viii. The above site selection procedure shall not be applicable for location of facility within industrial areas of State Industrial Development Agencies. However, EIA requirement will apply.

4.4 Site Infrastructure

The following site infrastructure shall be provided at each HW landfill:

(a) Site Entrance and Fencing.
(b) Administrative and Site Control Offices
(c) Access Roads
(d) Waste Inspection and Sampling Facility.
(e) Equipment Workshops and Garages.
(f) Signs and Directions
(g) Water Supply
(h) Lighting
(i) Vehicle Cleaning Facility
(j) Fire Fighting Equipment Site entrance infrastructure should include:
  (a) A permanent, wide, entrance road with separate entry and exit lanes and gates.
  (b) Sufficient length/parking space inside the entrance gate till the weighbridge to prevent queuing of vehicles outside the entrance gate and onto the highway.
  (c) A properly landscaped entrance area with a green belt of 20 m containing tree plantation for good visual impact.
  (d) Proper direction signs and lighting at the entrance gate.
  (e) A perimeter fencing of at least 2 m height all around the landfill site with lockable gates to prevent unauthorized access.
  (f) Full time security guard at the site.

An accurate record of waste inputs is essential, hence good quality weighbridges shall be used. For sites receiving more than **400 tons** per day of waste, twin weigh bridges to weigh both entry and exit weights may be located on either side of an island on which a weighbridge office room is located. The weighbridge office should be elevated, and the weighbridge operators should be able to see entering vehicles as well as speak to drivers.

Administrative and site control offices should include: administrative office building (permanent); site control office (portable) near the active landfill area; stores (permanent) within or near administrative office; welfare facilities – toilets, shower room, first aid room, mess room, small temporary accommodation; infrastructural services – electricity, drinking water supply, telephone, sewerage and drainage system and communication services (telephone etc.) between site control office and administrative office and weighbridge office.

5. Site Preparation

The plans and specifications of a hazardous waste landfill should require the following steps before operations begins:

- Grading the site area, constructing access roads and fences, and installation of signs, utilities.
- On-site access roads should be all-weather construction and wide enough to permit two-way truck.
- The site should have an office building with electricity, water, and sanitary services for employees and visitors.
- The site should have a building to store hand tools and equipment parts.

6. Equipment

Equipment falls into three functional categories: waste movement and compaction, earth cover transport and compaction, and support functions. Selecting the type, size, quantity, and combination of machines required to move, spread, compact and cover waste depends on:

- Waste amount and type.
- Weather conditions.
- Site and soil conditions: topography, soil moisture and difficulty of excavation.
- The distance the cover material must be transported.
- Amount and type of soil cover.
- Compaction requirements; and
- Supplemental tasks, such as maintaining roads, assisting in vehicle unloading, and moving other materials and equipment around the site

Operating landfill requires the use of heavy equipment, with the proper protective health and safety gear for the operators. Typically, bulldozers, compactors, and trucks developed for heavy construction are used for land disposal operations. Forklifts and barrel snatchers may be used to handle containerized waste. In all cases, modifications are made to accommodate health and safety requirements for the operators. Typical types of equipment that may be necessary are shown in ***Figure 4***, ***Figure 5***, and ***Figure 6***.

Figure 4: Landfill Compactor

Figure 5: Steel-wheeled compactor

Figure 6: Steel-wheeled compactor spreading waste in a working face

7. Operation

The management of hazardous waste in land disposal facilities requires the **tracking** of the waste that, the recording of the journey of the waste from **cradle-to-grave**. The main reason for the careful tracking and disposal in cells is to ensure waste **compatibility**. Many wastes may react with each other, resulting in potential for heat, combustion, and/or toxic fumes.

By **tracking** the type of waste and its location within the landfill, a waste compatibility check can be made to provide safe operating conditions for landfill operators as well as a safe long-term disposal to minimize or eliminate potentially harmful chemical reactions. The waste disposed of in a landfill are in both bulk and containerized forms. Drum waste are typically aligned and covered with other wastes, such as contaminated soils or sludges, using care not to damage the drums.

7.1 Daily/Weekly Cover

Daily / weekly cover (optional) is primarily used for prevention windblown dust, litter and odors, deterrence to scavengers, birds, reduction of infiltration (during unseasonal rain) and in improving the site's visual appearance. Soil used as daily / weekly cover shall give a pleasing uniform appearance from the site boundary. To achieve this a thickness of about a foot (0.3 m) is usually adequate and shall be adopted. Daily/weekly cover also creates a highly anisotropic environment in the landfill and as a result, seepage may exist along the relative permeable daily cover layers and through the side slopes.

7.2 Final Cover

A final landfill cover, comprising of several layers, each with a specific function shall be installed after each landfill phase reaches the full height. The final cover system shall enhance surface drainage, minimize infiltration, support vegetation to prevent erosion and control the release of landfill gases. Infiltration of water through the top of the landfill, by either direct precipitation or run-on is a major source of leachate generation at hazardous waste landfill. The final cover system minimizes and/or eliminates the leachate generation due to direct precipitation or run-on. The final cover systems also consider health and safety, aesthetics, and site usage after closure coupled with engineering requirements for permeability, compressibility, and strength.

Because the final cover is expected to remain in service for as long as the waste is present, a thorough design assesses the potential failure mechanisms both immediately after construction and throughout the service life (**30 years or more**) and provides the following:

- Controlling water movement into the landfill system to minimize leachate generation.
- Controlling animals and vectors that can introduce disease into the ecosystem.
- Protecting public from results of direct contact with waste.
- Controlling gas movement to avoid decline in air quality.
- Ensuring overall stability of the cover on the landfill slopes where slope instability could result in mass movement of contaminants into the environment.
- Controlling surface water run-off.
- Resisting erosion.
- Controlling blowing debris.
- Minimizing noxious odor; and
- Providing a more sightly appearance

In a typical final cover system, the uppermost layer, a **vegetative support layer**, consists of an organically sandy loam (topsoil) material used to support the vegetation. Vegetation provides the following important functions in the performance of the landfill cover:

- Reduce erosion
- Reduce precipitation infiltration
- Enhances evapotranspiration, returning moisture that has been absorbed into the topsoil layer into atmosphere to further reduce deeper infiltration

7.3 Waste Handling and Placement

Waste movement usually is confined to spreading the waste on the working face with compactors or dozers after loads are deposited by trucks. A waste acceptance criterion shall be formulated for each landfill site and handle waste properly. The following guidelines for waste acceptance are suggested:

(a) All waste shall be routinely accepted if the truck/tipper carries authorized documents indicating he source and type of waste. Such waste shall be routinely inspected visually at the tipping area in the landfill site.

(b) Bulk or non-containerized liquid hazardous waste or slurry-type hazardous waste containing free liquid or waste sludge, which has not been d dewatered, shall not be placed in landfills. Such waste, (usually transported in pipelines) shall be placed in Hazardous Waste Impoundments designed specifically for liquid hazardous waste.

(c) Incinerable/compostable waste or any other type of waste from which energy/material recovery is feasible, shall not be placed in HW landfills.

(d) Incompatible wastes shall not be placed in the same landfill unit. Compatible wastes will be grouped together and placed in the same landfill unit (each such unit shall have its own phase, cells etc.) Incompatible waste group shall be accommodated in separate landfill units (each such unit shall have its own phases, cells etc.).

(e) Wastes which are incompatible with the liner material shall either be containerized and placed in the landfill (enduring adequate container safety or placed in a separate landfill unit made of alternate compatible liner material).

(f) Extremely hazardous waste (e.g. radioactive waste) shall not be disposed of in HW landfills but in specially designed waste disposal units.

(g) Non-hazardous waste (e.g. municipal solid waste) shall not be deposited in HW landfills. However, such waste can be deposited in an MSW landfill unit in the vicinity of HW landfills.

(h) Residue of treated biomedical waste (e.g. incinerator ash etc.) can be deposited in HW landfills.

7.4 Compaction

Compaction is critical to extending the landfill’s life. To achieve high, in-place waste densities, a compactor may be necessary as shown in ***Figure 7***. A minimum in-place compaction density of 1,000 pounds per cubic yard is recommended. The number of passes that the machine should make to achieve optimum compaction depends on wheel pressure, waste compressibility and compaction layer thickness. Generally, three to five passes are recommended. Although additional passes will compact the waste to a greater extent, the return on the effort diminishes beyond six passes.

Each site will have different compaction results, depending on waste layer thickness. However, there will be a decrease in density above a compacted layer thickness of about 1 foot to ½ foot. The best compaction results from compacting waste in layers 1- to 2-feet thick.

The working face’s slope also affects compaction. As the slope increases, vertical compaction pressure decreases, the lower the slope, the higher the compaction. Nevertheless, the feasibility of a nearly flat working face has to be weighed against the larger area over which the waste and cover soil must be spread.

LANDFILL COMPACTORS

- But compaction of waste is important for airspace and saving volume

Figure 7: Landfill Compactor being used in working face

7.5 Leachate Collection and Control

As a consequence of precipitation while a cell is being filled and of infiltration after a cell is closed, leachate is generated in landfills through the process shown in ***Figure 8***. This necessitates the collection, treatment, and proper disposal of leachate as an integral part of any hazardous waste landfill facility.

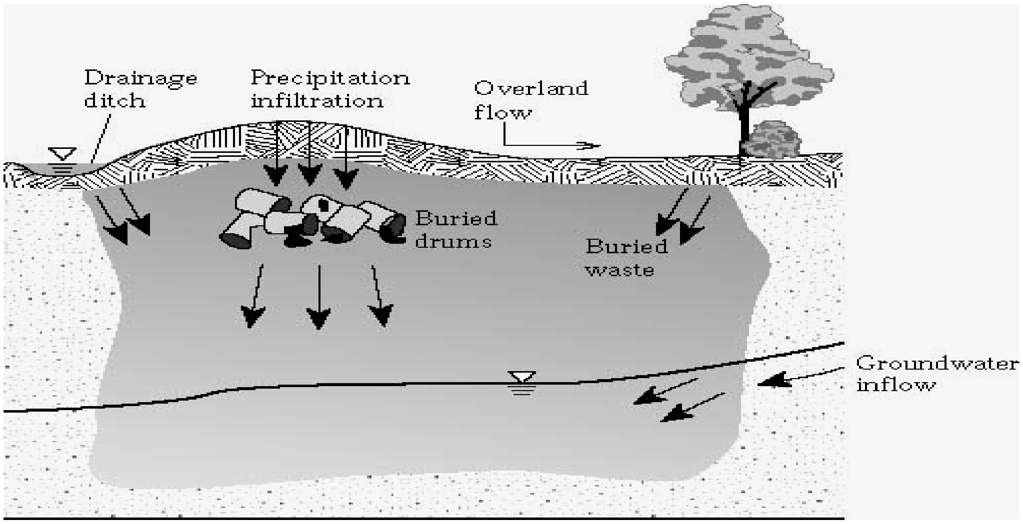

Figure 8: Sources of fluids for the generation of landfill leachate

"HELP" (Hydrologic Evaluation of Landfill Performance) model is run to estimate amount of leachate generated and head on the liner system. Based on the **HELP** model result, the leachate collection and storage systems are designed. MultiMed" Model – used to estimate the concentration of pollutants from the landfill percolation to a nearby monitoring well (***Figure 9***). This is required to meet the regulatory requirements.

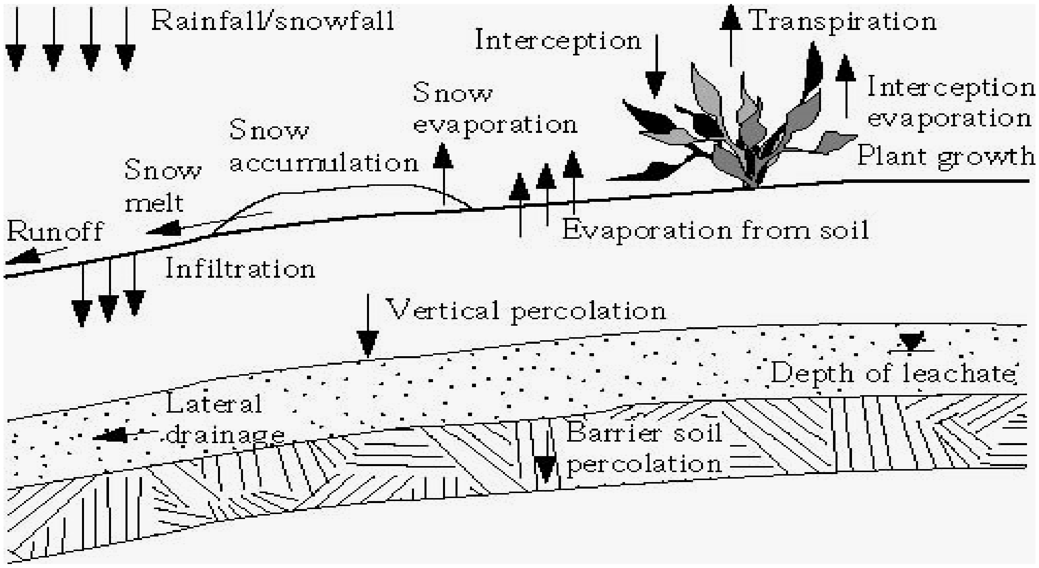

Figure 9: Water balance variables in the HELP model

7.6 Groundwater Monitoring

Landfill facilities must monitor the groundwater regularly to make sure that no contaminants are migrating from the site to the groundwater below and the around the facility. In order to do that the facility must installed a number of upgradient and downgradient monitoring wells.

7.7 Gas Monitoring and Control

Gas monitoring and control are not typically required in HW landfills as gas is rarely detected.

7.8 Run-on and Run-off Control

The facility must have options of controlling run-on to the site and create more leachate. Also, must have options of controlling run-off from the site that can migrate leachate to the surface and groundwaters.

7.9 Material Balance

A material balance shall be prepared for each material required for construction of a landfill, phase-by-phase, indicating materials required, material available and deficient material to be imported or surplus material to be exported. If a borrow area is located within the landfill site it shall not become a part of an early phase to avoid stockpiling and double handling.

7.10 Additional Controls

Good housekeeping procedures are necessary. Subtitle C requirements and many state regulations mandate operation controls. A well-planned and maintained landfill provides effective controls for access, aesthetics, wind-blown paper pickup, insects spreading, wildlife and rodents issues, littering airport nuisance by birds, odors and fires, noise due to equipment operations, road dust and tracking, scavenging, gas, leachate, adverse weather, and personal safety[2].

8. Environmental Monitoring Systems

Monitoring at a landfill site shall be carried out in four zones (a) on and within the landfill; (b) in the unsaturated subsurface zone (vadose zone) beneath and around the landfill; (c) in the groundwater (saturated) zone beneath and around the landfill and (d) in the atmosphere/local air above and around the landfill. The parameters to be monitored regulatory are:

(a) long-term movements of the landfill cover.
(b) leachate head within the landfill.
(c) leachate quality within the landfill.
(d) gas quality (optional) within the landfill.
(e) quality of pore fluid in the vadose zone.
(f) quality pore gas (optional) in the vadose zone.
(g) quality of groundwater in the saturated zones and
(h) air quality above the landfill, at the gas control facilities, at buildings on or near the landfill and along any preferential migration paths.

The indicators of leachate quality and landfill gas quality must be decided after conducting a study relating to the type of the waste, the probable composition of leachate and gas likely to be generated and the geotechnical as well as hydro-geological features of the area.

A monitoring program must specify (i) a properly selected offsite testing laboratory capable of measuring the constituents at current detection levels (ii) a methodology for acquiring and storing data; and (iii) a statistical procedure for analyses of the data.

The following instruments/equipment shall be used for monitoring:

(a) Groundwater samples for groundwater monitoring wells.
(b) Leachate samplers for leachate monitoring within the landfill and at the leachate tank.

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[2] https://www.waste360.com/mag/waste_landfill_equipment_operating accessed on August 13, 2020

(c) Vacuum lysimeters, filter tip samplers, free drainage samplers for leakage detection beneath landfill liners.
(d) Surface water samplers for collection of samples from sedimentation basin.
(e) Downhole water quality sensors for measuring conductivity, pH, DO, temperature in leachate wells, groundwater wells and sedimentation basins.
(f) Landfill gas monitors (portable) for onsite monitoring of landfill gases.
(g) Active and passive air samplers for monitoring ambient air quality.

It is recommended that the location of each type of instrument/equipment be finalized in conjunction with an expert on the basis of the topography of the area and the layout of the landfill. A **minimum of 4 sets of ground water monitoring wells (one up-gradient and three down gradient**) for sampling in each aquifer are considered desirable at each landfill site extraction systems.

9. Landfill Design

The design of the landfill has many components (***Figure 10***) including:

- site preparation
- buildings
- groundwater monitoring wells
- size
- liners
- leachate collection system
- final cover system
- gas monitoring, collection, and control system
- run-on and run-off control system.

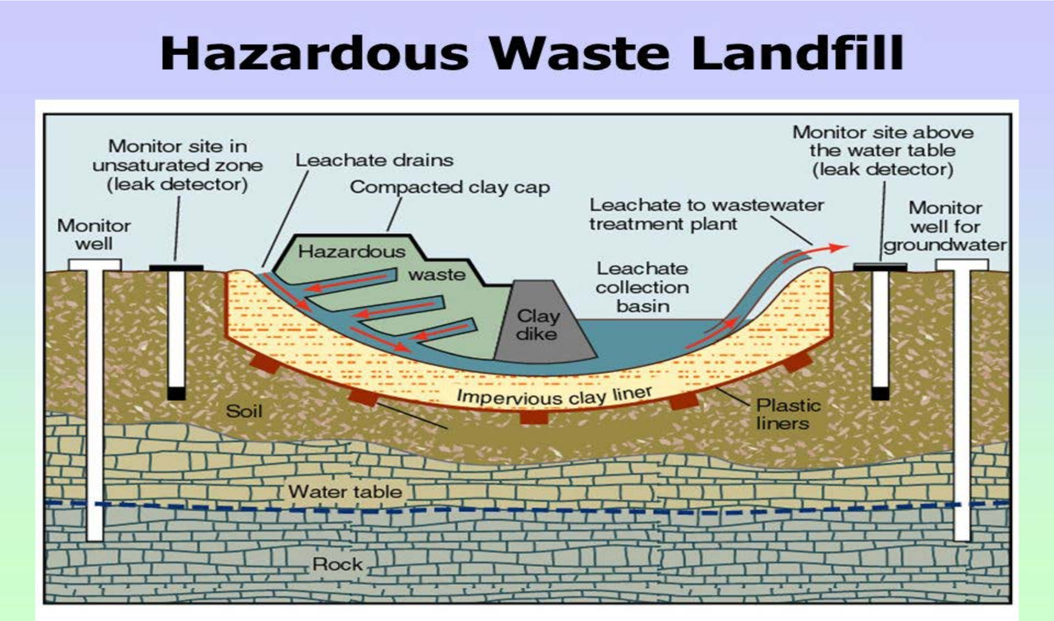


Figure 10:A schematic of HW landfill section

9.1 Landfill Groundwater Monitoring

- Groundwater monitoring for landfills is mandatory by the solid waste regulations.
- Regulations require that at least **one upgradient and three downgradient monitoring wells** shall be required within a compliance network.
- The designer may come up with a greater number of upgradient and downgradient wells depending on the hydrogeology of the site.
- Regulations require that the owners or operators of sanitary landfills must perform quarterly ground water monitoring.

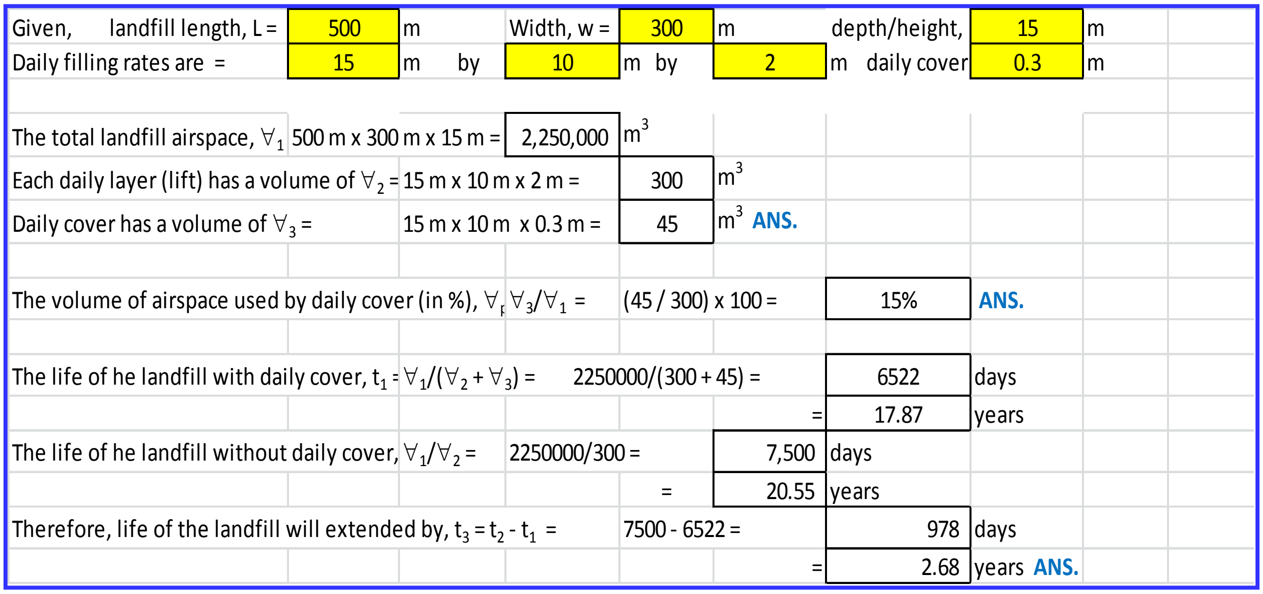
9.2 Landfill Capacity/Size and Life

The landfill capacity/size is also designated as air space or volume or service life.

- To estimate the size of a landfill, generation rate of waste, population estimate, and number of years of operation are necessary.
- In other words, if the landfill area is known, the volume between the base grade and final elevation can be estimated by using computer software that are commercially available.
- If the volume of the landfill and the density of waste are known, based on the daily throughput of waste (volume//day of ton/day), the landfill life can be estimated.

Example 1: Calculate how much daily cover will be needed and how much total volume (air space) will be used by the daily cover during the life of the hazardous waste landfill. How much longer the landfill can be used if daily cover were not employed. The landfill is 500 m by 300 m in an average plan and 15 m high. Daily fitting rates are 15 m by 10 m by 2 m and daily cover is 0.3 m.

Solutions:



Given, landfill length, L =	500	m	Width, w =	300	m	depth/height,		15	m	
Daily filling rates are =	15	m by	10	m by	2	m daily cover		0.3	m	

The total landfill airspace, $\forall_1$ 500 m x 300 m x 15 m = 2,250,000 m^3

Each daily layer (lift) has a volume of $\forall_2$ = 15 m x 10 m x 2 m = 300 m^3

Daily cover has a volume of $\forall_3$ = 15 m x 10 m x 0.3 m = 45 m^3 **ANS.**

The volume of airspace used by daily cover (in %), $\forall_r$ $\forall_3/\forall_1$ = (45 / 300) x 100 = 15% **ANS.**

The life of he landfill with daily cover, $t_1 = \forall_1/(\forall_2 + \forall_3)$ = 2250000/(300 + 45) = 6522 days

= 17.87 years

The life of he landfill without daily cover, $\forall_1/\forall_2$ = 2250000/300 = 7,500 days

= 20.55 years

Therefore, life of the landfill will extended by, $t_3 = t_2 - t_1$ = 7500 - 6522 = 978 days

= 2.68 years **ANS.**

9.3 Landfill Liner System

A landfill's major purpose and one of its biggest challenges is to contain the trash so that the trash does not cause problems in the environment. The **bottom liner prevents the trash from coming in contact with the outside soil, particularly the groundwater**. In MSW landfills, the liner is usually some type of durable, puncture-resistant synthetic plastic (polyethylene, linear low-density polyethylene, polyvinylchloride - **LLDPE**, high-density polyethylene, polyvinylchloride - **HDPE**). It is usually 30-100 mils thick (1 mil = 1/1000 inch). The plastic liner may be also be combined with compacted clay soils as an additional liner. The plastic liner may also be surrounded on either side by a fabric mat (**geotextile mat**) that will help to keep the plastic liner from tearing or puncturing from the nearby rock and gravel layers. **RCRA Subtitle C** requires that solid waste landfills must have a bottom composite double liner system that consists of (from top to down - ***Figure 11***):

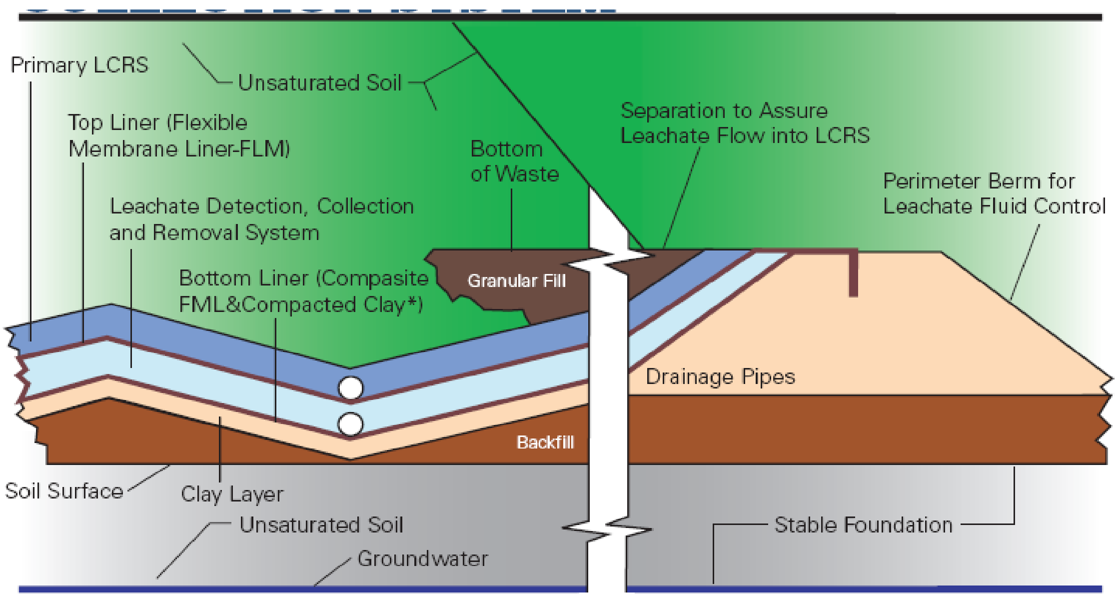
a) A primary leachate collection layer of thickness 30 cm (12-inch) or more and coefficient of permeability in excess of 10^{-2} cm/sec (10^{-4} m/sec).

b) A primary composite liner comprising of a HDPE geomembrane of thickness 1.5 mm (60-mil) or more.

c) A secondary leachate collection layer (also called leak detection layer) of thickness 30 cm (12-inch) or more and coefficient of permeability in excess of 10^{-3} cm/sec (10^{-5} m/sec).

d) A secondary composite liner comprising of a HDPE geomembrane of thickness 1.5 mm(60-mil) or more.

e) A compacted clay (or compacted amended soil) layer of thickness 91 cm (36-inch) or more having a coefficient of permeability of 10^{-7} cm/sec (10^{-9} m/sec) or less.



* The compacted clay layer is to be a minimum of 3 ft in thickness and have a hydraulic conductivity less than 1×10^{-7} cm/sec

Figure 11: A typical double liner with leachate collection system

Example 2: Estimate the volumetric flowrate through a compacted clay liner at a landfill measuring 3.0 ha. The liner thickness is 1 m (3 ft) and the saturated hydraulic conductivity is 1.0×10^{-7} cm/s. Assume 0.33 m (1 ft) water ponded on the liner.

Solutions:

Given, ***A*** =	3	ha =	30000	m^2
k =	1.00E-07	cm/s	1E-09	m/s
Liner thickness, ***T*** =	1	m =	3.281	ft
Water/Leachate depth on liner, ***H*** =	0.33	m =	1.08	ft
Using Darcy's flow equation,	$Q = kAi$			
Where, ***i*** =	$\frac{H + T}{T}$	=	$\frac{0.33 + 1}{1}$	
		=	**1.3300**	
Q **=**	0.000000001 m/s x 30000 m^2 x 1.33			
=	3.99E-05	m^3/s		
=	**3.45**	**m^3/day ANS.**		

9.4 Landfill Leachate Collection System

The leachate collection system shall be designed and placed:

- To prevent causing failure of the liner.
- To filter and prevent migration of fines to the drainage layer from above; and
- So that no more than one-foot head of leachate may accumulate over the liner at its lowest point excluding manifold trenches and sumps.

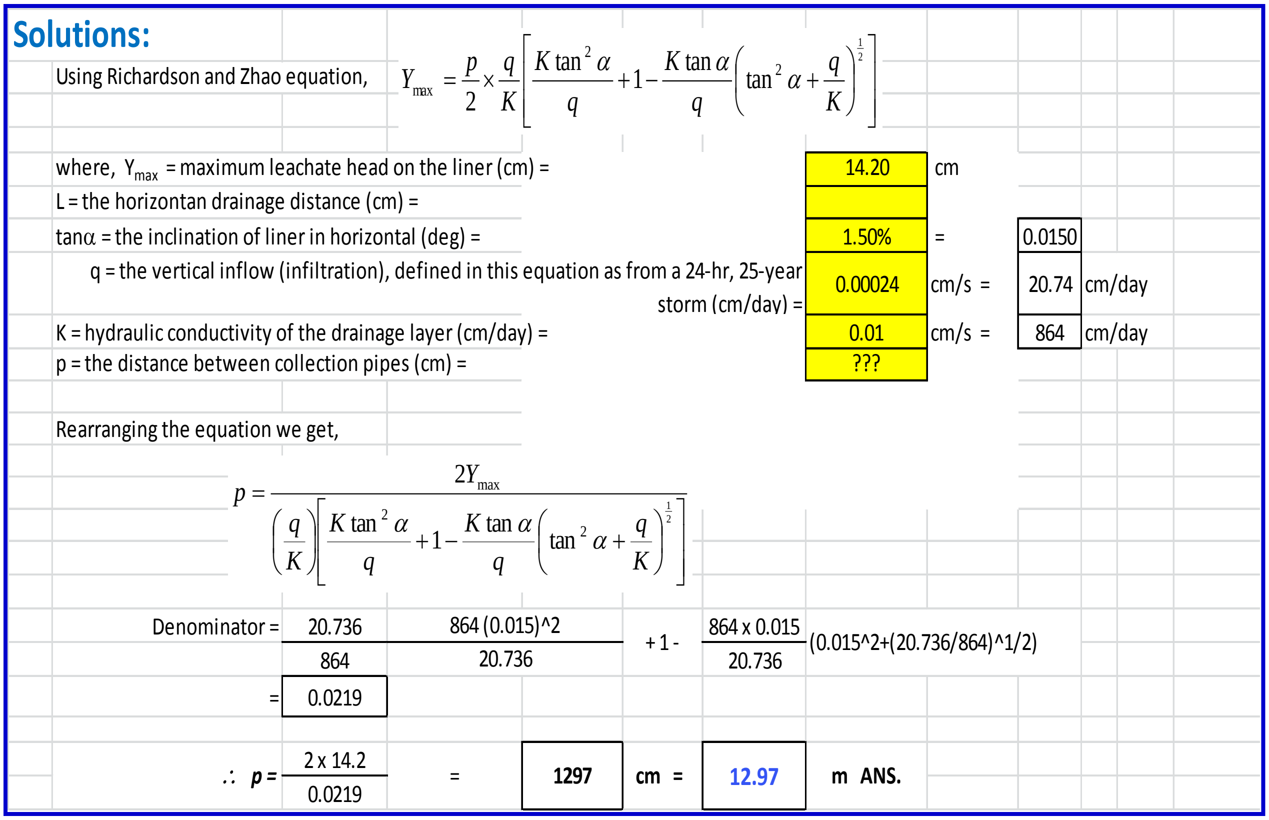
The tanks or impoundments used for storage of leachate shall have a flow equalization and surge capacity at least equal to the maximum expected production of leachate from **HELP Model** run for any **seven-day** period for the life of the facility. The storage tanks and impoundments shall be aerated as necessary to prevent and control odors. Leachate storage impoundments/pond (***Figure 12***) shall be equipped with a liner system that shall provide equal or greater protection of human health and the environment than that provided by the liner of the cells producing the leachate. At a minimum, a synthetic component will be required.

Figure 12: A leachate collection pond is designed to catch the contaminants that can get into water that goes through the trash in a landfill

Example 3: Determine the spacing between pipes in a leachate collection system by using granular drainage material and the following properties. Assume that most conservative design all storm water from 24-hr, 25-year storms enter the leachate collection system.

Design storm (24-hr, 25-year) = 8.2 inch = 0.00024 cm/s
Hydraulic conductivity of the granular material = 10^{-2} cm/s
Drainage slope = 1.5%
Maximum leachate depth on liner = 14.2 cm

Example 3: - Solutions



Solutions:

Using Richardson and Zhao equation, $Y_{max} = \frac{p}{2} \times \frac{q}{K}\left[\frac{K\tan^2\alpha}{q} + 1 - \frac{K\tan\alpha}{q}\left(\tan^2\alpha + \frac{q}{K}\right)^{\frac{1}{2}}\right]$

where, Y_{max} = maximum leachate head on the liner (cm) = 14.20 cm

L = the horizontan drainage distance (cm) =

tanα = the inclination of liner in horizontal (deg) = 1.50% = 0.0150

q = the vertical inflow (infiltration), defined in this equation as from a 24-hr, 25-year storm (cm/day) = 0.00024 cm/s = 20.74 cm/day

K = hydraulic conductivity of the drainage layer (cm/day) = 0.01 cm/s = 864 cm/day

p = the distance between collection pipes (cm) = ???

Rearranging the equation we get,

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

Denominator = $\frac{20.736}{864}\left[\frac{864\,(0.015)\text{^}2}{20.736} + 1 - \frac{864 \text{ x } 0.015}{20.736}(0.015\text{^}2+(20.736/864)\text{^}1/2)\right]$

= 0.0219

∴ $p = \frac{2 \text{ x } 14.2}{0.0219}$ = 1297 cm = 12.97 m ANS.

9.5 Landfill Final Cover System

Owner or operator of all sanitary landfills shall install a final cover system that is designed to achieve the performance requirements of the regulations. The final cover system shall be designed and constructed are from top surface downwards to the waste (***Figure 13*** and ***Figure 14***):

(a) A surface soil layer of local topsoil which supports self-sustaining vegetation, and which has a thickness not less than 60 cm (24-inch).

(b) A drainage layer of thickness 30 cm (12-inch) or more having a coefficient of permeability in excess of 10^{-2} cm/sec (10^{-4} m/sec).

(c) Single composite barrier comprising of

  i. A HDPE geomembrane of thickness 1.5 mm (60-mil) or more and

  ii. A compacted clay (or compacted amended soil) layer of thickness 60 cm (24-inch) or more having a coefficient of permeability of 10^{-7} cm/sec (10^{-9} m/sec) or less. At locations where availability of clay is limited, amended soil will be constituted by mixing of clay to locally available soil to achieve the desired permeability.

(d) A regulatory layer (optional) of thickness 30 cm (12-inch) having coefficient of permeability greater than 10^{-2} cm/sec (10^{-4} m/sec). Such a layer shall be provided whenever there is requirement of (i) gas collection or (ii) transition filter between waste and soil.

The drainage layer shall be replaced by the local topsoil, if the coefficient of permeability of the local topsoil is greater than 10^{-4} cm/sec. In such a case the total thickness of the surface soil layer (of topsoil) will be 91 cm (36-inch). In dry arid regions, where self-sustaining vegetation is not possible, special erosion control measures shall be adopted for the stability for the cover soil layer. The cover materials listed above can be substituted by equivalent materials if the following is satisfied:

(a) the use of such components has been demonstrated over a 10-year period in different HW landfills and approved by a regulatory agency or SPCB/PCC.

(b) the design, construction and quality control specifications of such materials have been approved by a regulatory agency or SPCB/PCC and are available for implementation.

Finished side slopes shall be stable and be configured to adequately control erosion and runoff. Slopes of 33% (3H : 1V) will be allowed provided that adequate runoff controls are established. Steeper slopes may be considered if supported by necessary stability calculations and appropriate erosion and runoff control features.

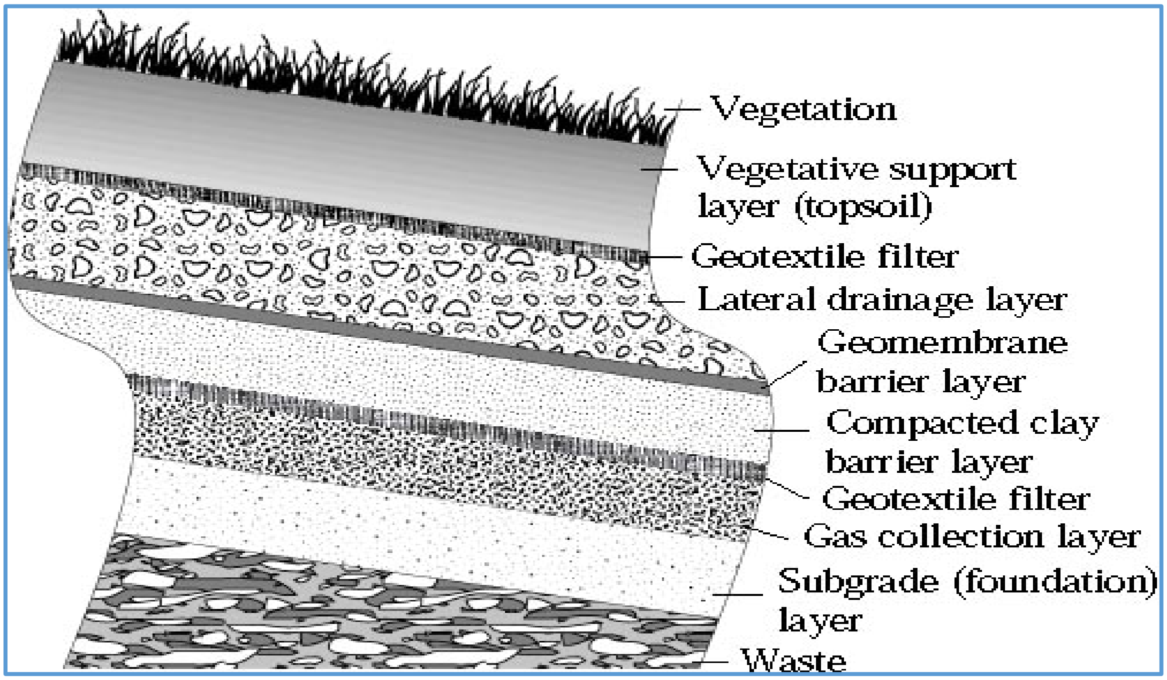


Figure 13: Typical detail final cover systems

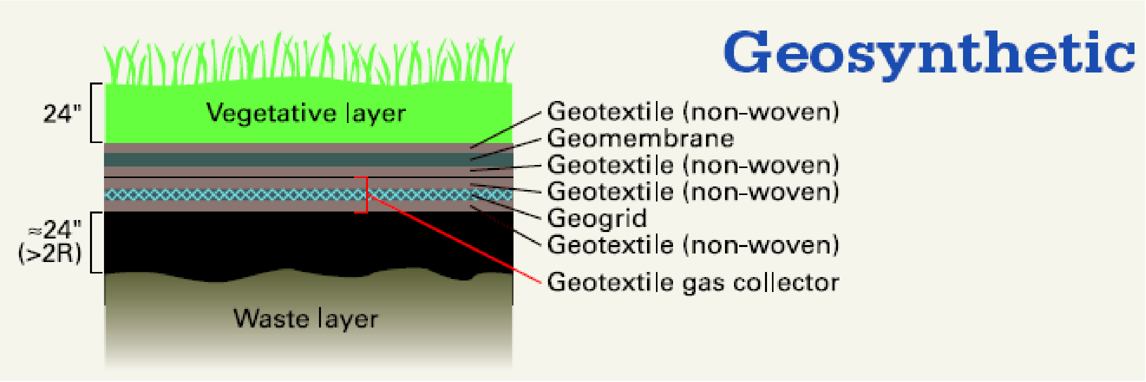
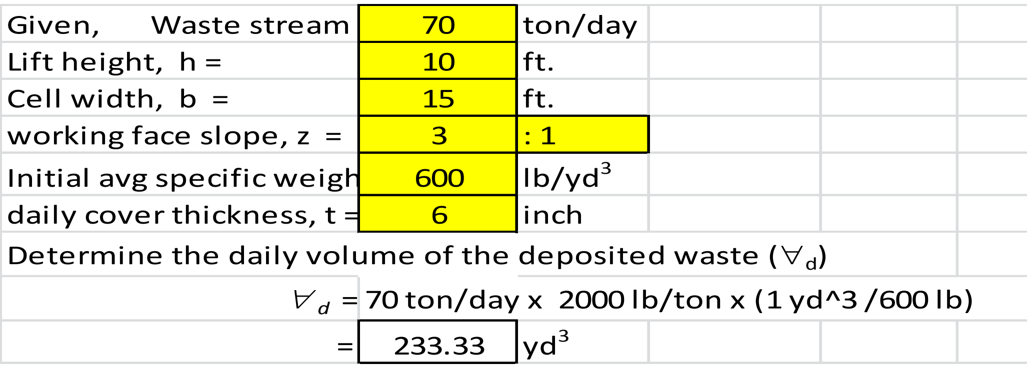


Figure 14: Typical alternate final cover systems

Example 4: Determine the ratio of waste to cover materials (soil – volume basis) as a function of initial compacted specific weight for a solid waste stream of 70 tons per day to be placed in 10 ft lifts with a cell width of 15 ft. The slope of the working face is 3:1. Assume the waste is compacted initially to an average specific weight of 600 lb/yd^3. Daily cover thickness is 6 inches.

Example 4: - Solutions

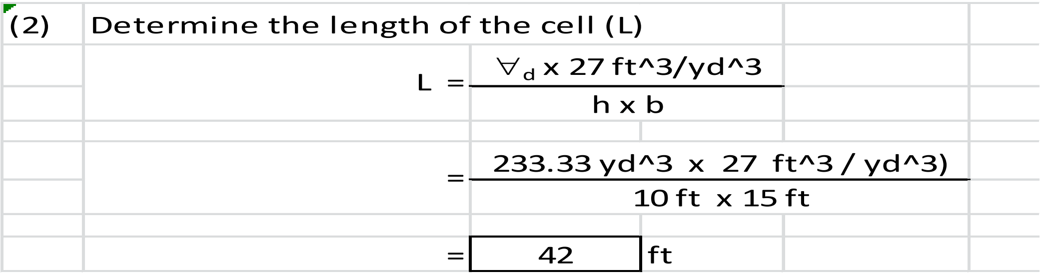


Given, Waste stream	70	ton/day
Lift height, h =	10	ft.
Cell width, b =	15	ft.
working face slope, z =	3	: 1
Initial avg specific weigh	600	lb/yd^3
daily cover thickness, t =	6	inch

Determine the daily volume of the deposited waste ($\forall_d$)

$\forall_d$ = 70 ton/day x 2000 lb/ton x (1 yd^3 /600 lb)

= $\boxed{233.33}$ yd^3



(2) Determine the length of the cell (L)

$$L = \frac{\forall_d \text{ x } 27 \text{ ft^3/yd^3}}{\text{h x b}}$$

$$= \frac{\text{233.33 yd^3 x 27 ft^3 / yd^3)}}{\text{10 ft x 15 ft}}$$

= $\boxed{42}$ ft

(3) Determine Cell surface area, SA

(a) for the top of the cell

$SA_T = L \times b$

$= 42\ ft \times 15\ ft$

$= \boxed{630}\ ft^2$

(b) for the face of the cell

$SA_F = L \times SQRT[h^2 + (z \times h)^2]$

$= 42\ ft \times SQRT[10\text{^}2 + (3 \times 10)\text{^}2]$

$= \boxed{1328.2}\ ft^2$

(c) for the side of the cell

$SA_S = b \times SQRT[h^2 + (z \times h)^2]$

$= 15\ ft \times SQRT[10\text{^}2 + (3 \times 10)\text{^}2]$

$= \boxed{474.34}\ ft^2$

(4) Determine the volume for daily cover ($\forall_c$)

$\forall_c = t\ inch \times (1\ ft/\ 12\ inch) \times (SA_T + SA_F + SA_S)\ ft^2$

$= 6\ inch \times (1\ ft/12\ inch) \times (630 + 1328.16 + 474.34)\ ft\text{^}2$

$= \boxed{1216.25}\ ft^3$

(5) Determine the ratio of waste to cover soil

$$R_{W:C} = \frac{\forall_d \times 27\ ft\text{^}3/yd\text{^}3}{\forall_c}$$

$$= \frac{233.33\ yd\text{^}3 \times 27\ ft\text{^}3/yd\text{^}3}{1216.25\ ft\text{^}3}$$

$= \boxed{5.18 : 1}$ **ANS.**

9.6 Landfill Gas Monitoring, Collection, and Control Systems

Gas monitoring, collection, and control systems are not typically used in HW landfills as gas is rarely detected. This is attributed to the fact that most waste are received in stabilized or solid form and there are no putrescible materials present as would be found in a convention conventional municipal solid waste landfill. As the long-term effects of gas generation are not known and costs are minimal, USEPA recommends installation of gas collection systems. In the Subtitle C landfill, the gas collection system is typically installed directly below the low permeability clay cap (Figure 13).

9.7 Landfill Run-on and Run-off Control System

Run-on Control System: As much water as possible should be diverted off the landfill to minimize operational problems and leachate formation. A run-on control system should prevent liquid from flowing onto the active portion of the landfill during the peak discharge from a 25-

year storm event. The run-on system also should collect and redirect surface waters entering the landfill boundaries (***Figure 15*** and ***Figure 16***).

Run-off Control System: A run-off control system must be able to manage at least the volume of water that results from a **24-hour, 25-year** storm over the active portion of the landfill (Figures 14 and 15). The run-off system should collect and control any water that may have contacted any waste materials and must comply with Clean Water Act (CWA) point and nonpoint source requirements.

Figure 15: This storm drainage pipe empties into a drainage ditch. Controls both run-on and run-off

Figure 16: **Drainage ditches run along the base of a landfill. Controls both run-on and run-off**

9.8 Landfill Stability

A landfill can fail to meet the performance requirements for a number of reasons pertaining to stability. Failure mechanisms for cover systems include total and differential settlements that may exceed the tolerance of the cover system. Landfill must be stable during construction, operations, and many years after the final closure. Stability often termed as **slope stability** as the probability failing the slope is high if not designed properly.

Slope stability can be mathematically defined in a number of different ways such as by **rotational force equilibrium**, **rotational moment equilibrium**, or **sliding wedge force equilibrium**. The slope stability analysis necessitates the hypothesis of failure surface, the determination of driving and resisting forces, and the definition of a **factor of safety (FS)** employing these force systems. The location that produces the lowest **FS** is termed as **critical failure surface** (***Figure 17*** through ***Figure 21***). Several software (PCSTABL, GEOSLOPE, etc.) are available to perform the slope stability analysis.

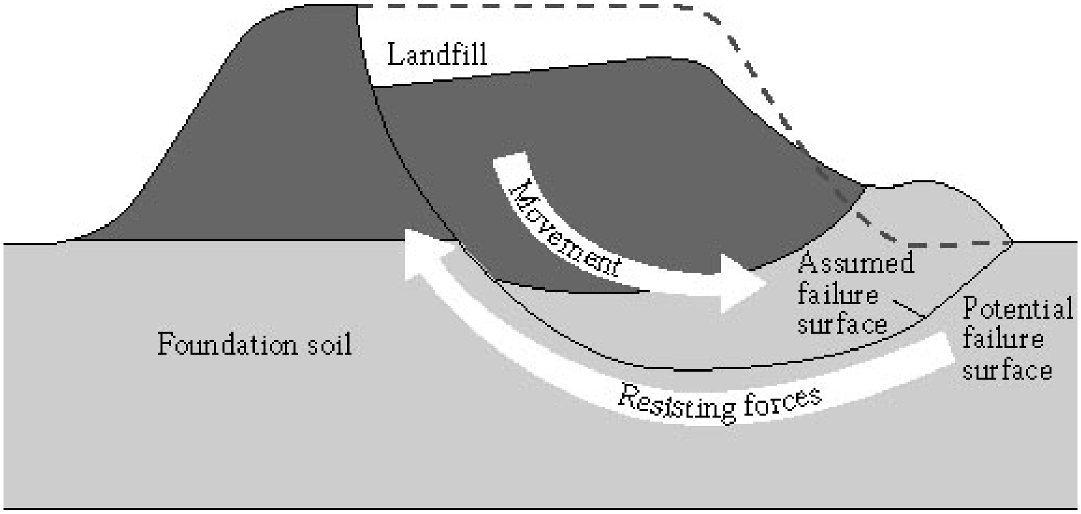


Figure 17: Schematic of landfill stability

================== DATA SUMMARY ====================

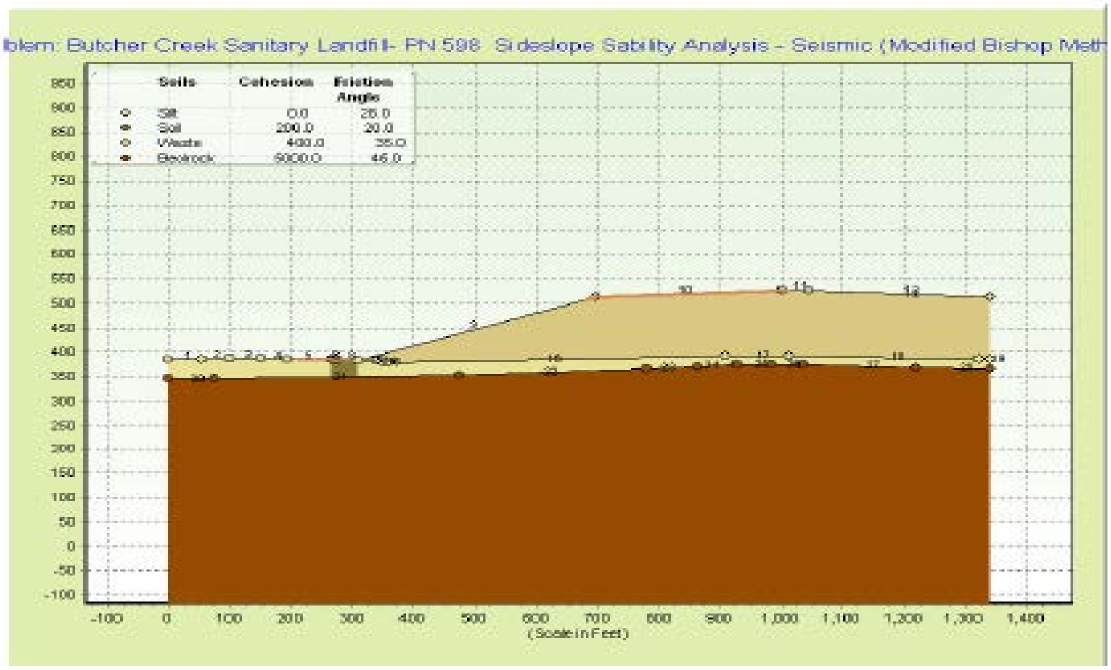
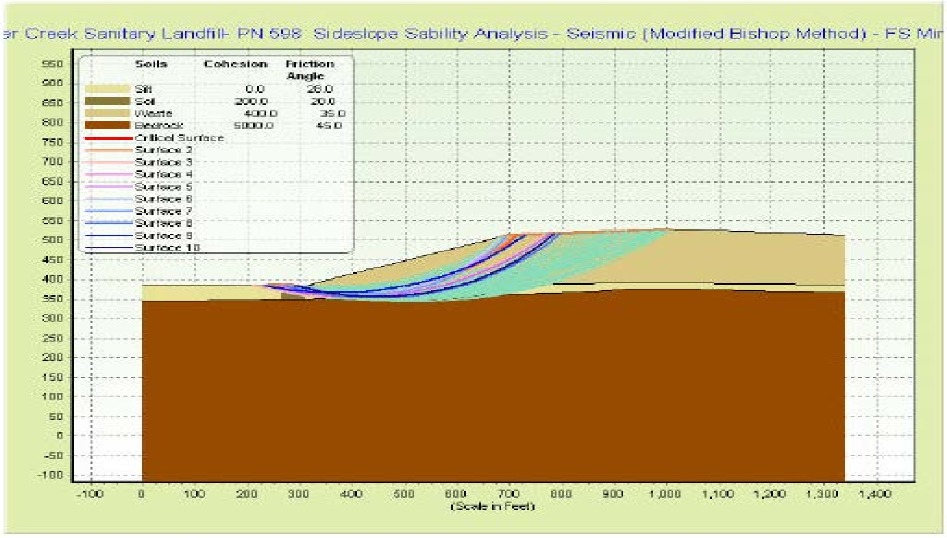
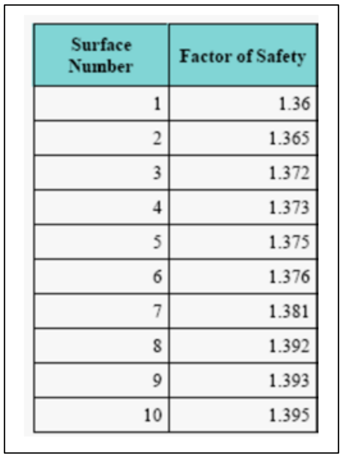


Figure 18: Landfill slope stability analysis by PCSTABL

=============== All Surfaces Generated =============





Surface Number	Factor of Safety
1	1.36
2	1.365
3	1.372
4	1.373
5	1.375
6	1.376
7	1.381
8	1.392
9	1.393
10	1.395

Figure 19: List of FS for several failure surfaces of Landfill slope stability analysis by PCSTABL

============ Factor of Safety Histogram ===========

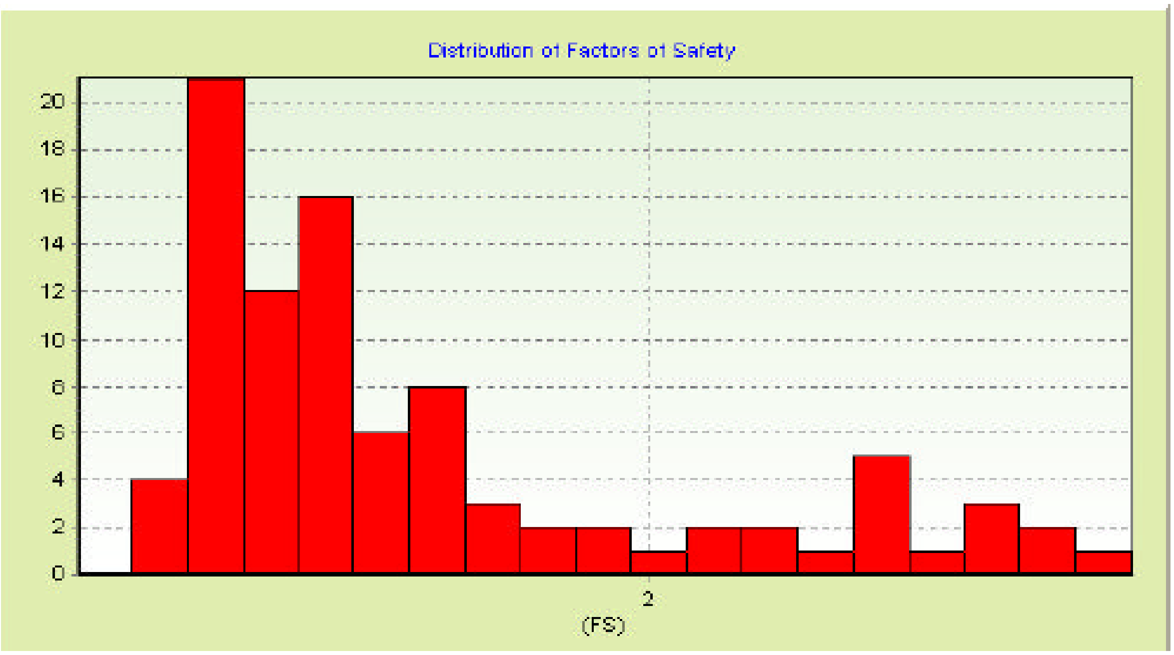


Figure 20: Distribution of FS of Landfill slope stability analysis by PCSTABL

Figure 21: Typical slope failure

9.9 Landfill Construction Quality Assurance (CQA) and Quality Control (QC)

A construction quality assurance and quality control program is required for all landfill units mentioned above. The program shall ensure that the constructed unit meets or exceeds all design criteria and specifications in the permit. The program shall be developed and implemented under the direction of a CQA officer who is a registered professional engineer. The CQA program shall address the following physical components, where applicable:

(a) Foundations.
(b) Low-hydraulic conductivity soil liners.
(c) Synthetic membrane liners.
(d) Leachate collection and removal systems.
(e) Gas management components; and
(f) Final cover systems.

9.10 Software Used in Landfill Design

Several software is used when a landfill is designed, and these are:

1. **HELP Model** – to estimate the leachate amount, head on the liner system, and the percolation of leachate through the liner system.

2. **PCSTABL and/or GEOSLOPE –** used to make sure that the side slopes the cells and/or the final covers are stable under normal and seismic conditions.

3. **MultiMed Model** – used to estimate the concentration of pollutants from the landfill percolation to a nearby monitoring well. This is required to meet the regulatory requirements.

4. **LandGEM** – used to estimate the amount of gas generated from the solid waste decomposition process.

9.11 Landfill Leachate Estimate

Leachate is defined as liquid that has percolated through solid waste and has extracted dissolved or suspended materials from it. USEPA **HELP** (**Hydrologic Evaluation of Landfill Performance**) model is used to estimate the amount of leachate generated in a landfill. The estimate helps in designing the leachate storage facility as well as hauling and treatment facility.

Leachate Characteristics: The major parameters that are used to characterize leachate include BOD_5, *COD*, *TOC*, *pH*, and *Total Alkalinity*. Parameters are evaluated by tracking concentration versus time and comparing to drinking water standards.

Other than HELP model, hypothetical water balance can be used to estimate the amount of leachate a landfill will generate:

The equation is $\boldsymbol{L = P - R_{on} + U - E - R_{off}}$

where, L = leachate amount, P = precipitation, R_{on} = run-on surface water, U = underflow of groundwater into the landfill cell, E = evapotranspiration, and R_{off} = run-off surface water.

- If the landfill (LF) is designed and operate properly, then there should not be any run-on into the LF that is $R_{on} = 0$.
- Additionally, most of the time a landfill is constructed above the groundwater table and possessing an impermeable liner will give $U = 0$.
- Therefore, the equation can be simplified as $\boldsymbol{L = P - E - R_{off}}$

Example 5: Estimate the annual volume of leachate generated per hectare (or acre) for a landfill in the USA. The climate is temperate, annual average rainfall is 1.07 m/year (42 inch/year) and evapotranspiration is estimated to be at 55%. The waste is covered with soil and run-off from the site is 10%. There is no run-on of surface water, similarly there is no underflow groundwater into the cell.

Example 5: - Solutions

For these calculations, it is necessary to convert depth of rainfall (precipitation) into volume.

P = 1.07 m /year = 1.07 ha m /year / ha

$$\therefore \mathbf{L = P - E - R_{off}} = 1.07 \text{ ha m} - (0.55 \times 1.07 \text{ ha m}) - (0.1 \times 1.07 \text{ ha m})$$

$$= 0.3745 \text{ ha m} \times (10{,}000 \text{ m}^2/\text{ ha})$$

$$= 3{,}745 \text{ m}^3 \times (1000 \text{ L}/ 1 \text{ m}^3) = 3.745 \times 10^6 \text{ L}$$

= **989,432 gal**. **ANS.**

Leachate Estimation by EPA HELP Model:

Hydrologic
Evaluation of
Landfill
Performance

HELP

What does the model do?

- Estimate the amount of leachate generated by a landfill to assist in the evaluation of liner, leachate collection system, storage capacity and cap designs.
- Estimate the percolation through the liner that is used to MultiMED Model as an input to assess the groundwater contamination for alternate liner design.
- The model is basically a device to estimate the water balance for a landfill.

What does not the model do:

- HELP model is not a tool for estimating the amount of stormwater runoff from a landfill.

Data input:

Weather Data	soil/waste layer characteristics	Landfill parameters
✓ Evaporation ✓ Precipitation ✓ Temperature ✓ Solar radiation	✓ Porosity ✓ Field capacity ✓ Wilting point ✓ Saturated hydraulic conductivity ✓ Soil Conservation Service (SCS) runoff curve number for antecedent moisture condition II.	✓ landfill design (liners, leachate collection & removal systems [LCRS], waste, cap) ✓ vegetation and shading ✓ leachate recirculation

Wilting point: *When soil-water content becomes so low that the surface tension of soil-water interface exceeds the osmotic pressure of the roots, water will no longer enter the roots.*

Note: leachate amount is calculated usually on the basis of 1-acre area

Model uses input to account for:

- ✓ surface storage of water

- ✓ snowmelt
- ✓ runoff, infiltration
- ✓ evapotranspiration, vegetative growth
- ✓ soil/waste moisture storage
- ✓ lateral drainage, leachate recirculation
- ✓ unsaturated vertical drainage.

Data output from HELP Model:

- ✓ leakage through the liners
- ✓ head on the liner
- ✓ volume of leachate generated.

Uses of HELP model data:

- ✓ evaluate effectiveness of LCRS **(<12” head**) - pipe spacing; hydraulic conductivity of drainage material; slope of the liner
- ✓ develop design capacity of leachate storage units (7 days)
- ✓ evaluate performance of alternate caps
- ✓ used (w/Multimed) to evaluate alternate liners

Input data - climatology:

- certain data are needed to perform the water balance evaporative zone depth, leaf area index.
- these parameters act with other variables (precipitation, temperature, solar radiation) to determine evapotranspiration

Input data – precipitation:

- default data in model is for 5-year period only
- other option is synthetic data generation
- data for synthetic record are provided in the model for certain areas of USA.
- consider stations in adjoining states – e.g., Greensboro, Knoxville, Washington DC, etc.
- synthetic data generation allows for periods greater than **5** years
- synthetic data may be used from cities in model, or other data may be input; monthly averages for other cities may be entered, NOAA data can be imported, etc.
- synthetic data generation statistically manipulates mean monthly precipitation data for a period of record to produce a realistic rainfall record (dry years and wet years)
- run synthetic data for at least **20** years
- select monthly output = results will be provided for monthly precipitation rates each year, annual averages, average for all years, peak day
- for a bottom liner, assume **0%** runoff, for a cap assume **100%** runoff

Input data – temperature:

- location and duration selected should match precipitation data
- data can be manually entered

Input data - solar radiation:

- location and duration should match precipitation data

Input data – Liner layers:

- vertical percolation layer
- lateral drainage layer
- barrier soil layer
- geomembrane liner

Vertical percolation layer:

- vertical drainage patterns - downward due to gravity; upward due to evapotranspiration
- downward movement depends on the characteristics of the material, number/type of waste layers
- vegetative support layers, protective cover soils and waste are examples
- to run model, consider the thickness of the layer, characteristics of the material
- to evaluate a bottom liner, use 1 lift of appropriate waste material (120 inches) - assume well compacted MSW for sanitary landfill (SLF); MSW with channeling for construction demolition debris (CDD); appropriate type of industrial waste for industrial landfill (ILF).

Lateral drainage layer:

- layer directly above a liner/barrier soil to promote flow into the leachate collection system (LCS)
- for model, consider thickness of the layer and characteristics of the material
- material may be sand/aggregate or geosynthetic
- for bottom liners, usually use **18 inches** of sand or gravel
- must input slope and slope length (maximum flow distance to LCS)

Barrier soil layer:

- functions to restrict vertical drainage
- hydraulic conductivity (*k*) significantly less than vertical percolation layer or lateral drainage layer
- assume that soil is saturated when installed
- flow is assumed to be only vertical
- driving force is head on the layer
- must input the thickness of the layer, type of material

- model menu has ***$1.0x10^{-7}$*** cm/sec soil or it can be changed manually.

Geomembrane (GM):

- virtually impermeable synthetic membrane
- percolation/drainage due to flaws in manufacturing and installation
- model considers flaws in manufacturing and installation, quality of installation
- ‘reasonable’ values generally assumed to be 1 manufacturing hole/acre; 5 installation holes/acre; good quality installation

QUESTION - are these assumption conservatives? They are industry practices. Individual can assume different numbers with justifications.

Model software is user friendly:

- Prompts user when additional information is needed.
- Contains menus with values normally used.
- Allows input of additional data.
- Has good “Help” function
- Carefully review any data other than default values in menus in model

Modeling a composite liner system:

- Layer 1 = waste = vertical percolation layer (assume 10 feet or 120 inches)
- Layer 2 = LCS drainage layer = lateral drainage layer (input slope on the liner, greatest flow distance)
- Layer 3 = geosynthetic liner = geomembrane layer (select thickness[in inches], type of material)
- Layer 4 = compacted clay or amended soil = barrier soil layer (assign thickness, in inches)
- Evaluation performed for 1 acre
- Assume bare soil, no leaf cover, no runoff

HELP Model results that affect landfill design:

- head on the liner
- leakage through the liner
- leachate collected from the lateral drainage layer

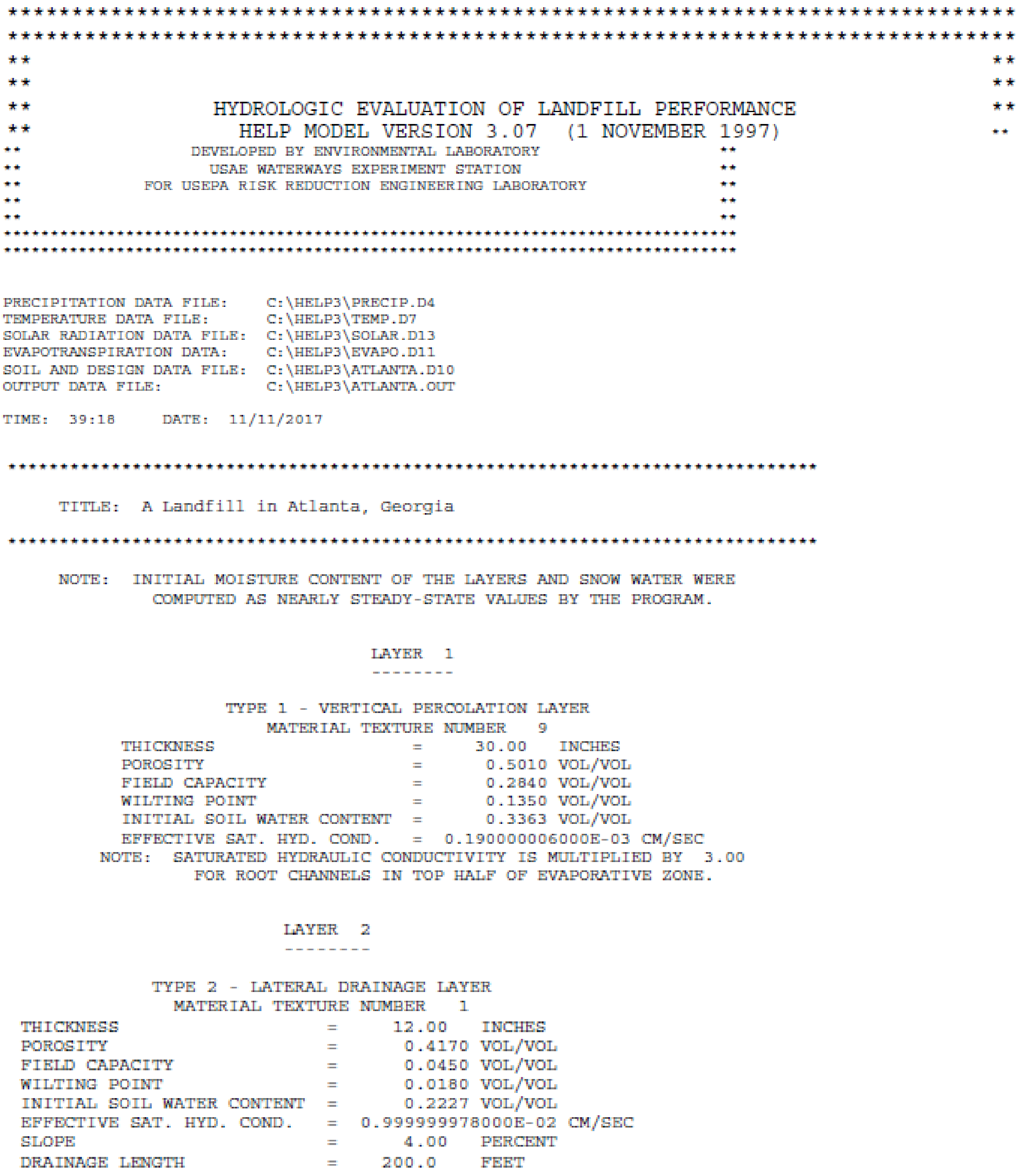
Head on the liner:

- model result used to assess the effectiveness of the LCS design = spacing of pipes, permeability of the drainage material
- maximum buildup of head < 12 inches
- model provides the maximum head for 1 day for the period, also the location of the greatest buildup

Leakage through the liner:

- results are used to assess the performance of the liner system for alternate liner design or the performance of an alternate cap design
- results are influenced by the materials, QA/QC during installation of geomembrane (GM), head on the liner
- for bottom liners, the data are used to evaluate effects on groundwater and liner performance
- for caps, data are used to demonstrate equivalency of alternate cap design to regulatory cap
- look at average annual data, also maximum year data

Print out from Computer HELP Model Run



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**                                                                          **
**                                                                          **
**              HYDROLOGIC EVALUATION OF LANDFILL PERFORMANCE               **
**                HELP MODEL VERSION 3.07  (1 NOVEMBER 1997)                **
**              DEVELOPED BY ENVIRONMENTAL LABORATORY                       **
**                USAE WATERWAYS EXPERIMENT STATION                         **
**           FOR USEPA RISK REDUCTION ENGINEERING LABORATORY                **
**                                                                          **
**                                                                          **
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PRECIPITATION DATA FILE:     C:\HELP3\PRECIP.D4
TEMPERATURE DATA FILE:       C:\HELP3\TEMP.D7
SOLAR RADIATION DATA FILE:   C:\HELP3\SOLAR.D13
EVAPOTRANSPIRATION DATA:     C:\HELP3\EVAPO.D11
SOIL AND DESIGN DATA FILE:   C:\HELP3\ATLANTA.D10
OUTPUT DATA FILE:            C:\HELP3\ATLANTA.OUT

TIME:  39:18     DATE:  11/11/2017


******************************************************************************

     TITLE:  A Landfill in Atlanta, Georgia

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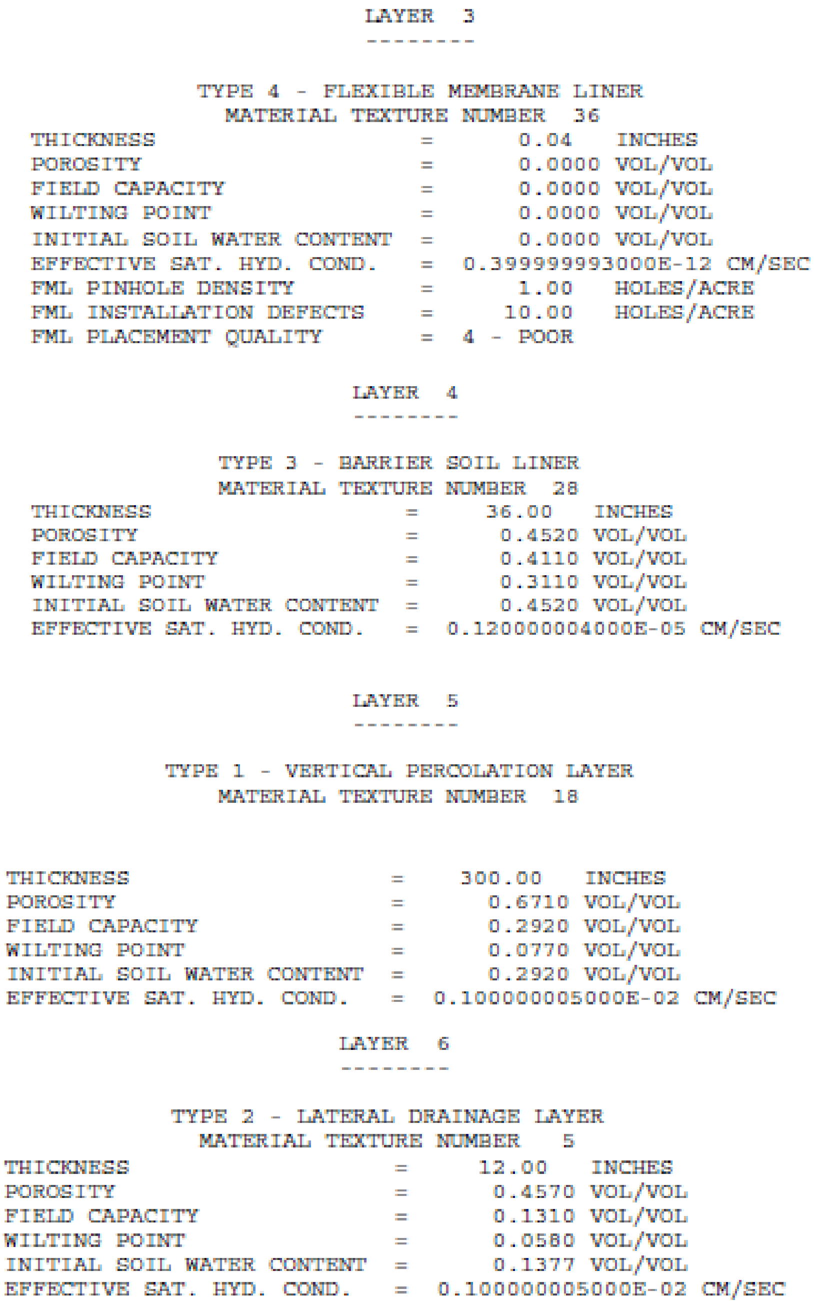
     NOTE:  INITIAL MOISTURE CONTENT OF THE LAYERS AND SNOW WATER WERE
            COMPUTED AS NEARLY STEADY-STATE VALUES BY THE PROGRAM.


                                 LAYER  1
                                 --------

                     TYPE 1 - VERTICAL PERCOLATION LAYER
                        MATERIAL TEXTURE NUMBER   9
           THICKNESS                    =    30.00    INCHES
           POROSITY                     =     0.5010 VOL/VOL
           FIELD CAPACITY               =     0.2840 VOL/VOL
           WILTING POINT                =     0.1350 VOL/VOL
           INITIAL SOIL WATER CONTENT   =     0.3363 VOL/VOL
           EFFECTIVE SAT. HYD. COND.    =  0.190000006000E-03 CM/SEC
         NOTE:  SATURATED HYDRAULIC CONDUCTIVITY IS MULTIPLIED BY  3.00
                FOR ROOT CHANNELS IN TOP HALF OF EVAPORATIVE ZONE.


                                 LAYER  2
                                 --------

                     TYPE 2 - LATERAL DRAINAGE LAYER
                       MATERIAL TEXTURE NUMBER   1
           THICKNESS                    =    12.00    INCHES
           POROSITY                     =     0.4170 VOL/VOL
           FIELD CAPACITY               =     0.0450 VOL/VOL
           WILTING POINT                =     0.0180 VOL/VOL
           INITIAL SOIL WATER CONTENT   =     0.2227 VOL/VOL
           EFFECTIVE SAT. HYD. COND.    =  0.999999978000E-02 CM/SEC
           SLOPE                        =     4.00    PERCENT
           DRAINAGE LENGTH              =   200.0     FEET
```



```
                             LAYER  3
                             --------

                TYPE 4 - FLEXIBLE MEMBRANE LINER
                  MATERIAL TEXTURE NUMBER  36
  THICKNESS                      =       0.04    INCHES
  POROSITY                       =       0.0000 VOL/VOL
  FIELD CAPACITY                 =       0.0000 VOL/VOL
  WILTING POINT                  =       0.0000 VOL/VOL
  INITIAL SOIL WATER CONTENT     =       0.0000 VOL/VOL
  EFFECTIVE SAT. HYD. COND.      =   0.399999993000E-12 CM/SEC
  FML PINHOLE DENSITY            =       1.00    HOLES/ACRE
  FML INSTALLATION DEFECTS       =      10.00    HOLES/ACRE
  FML PLACEMENT QUALITY          =   4 - POOR

                            LAYER  4
                            --------

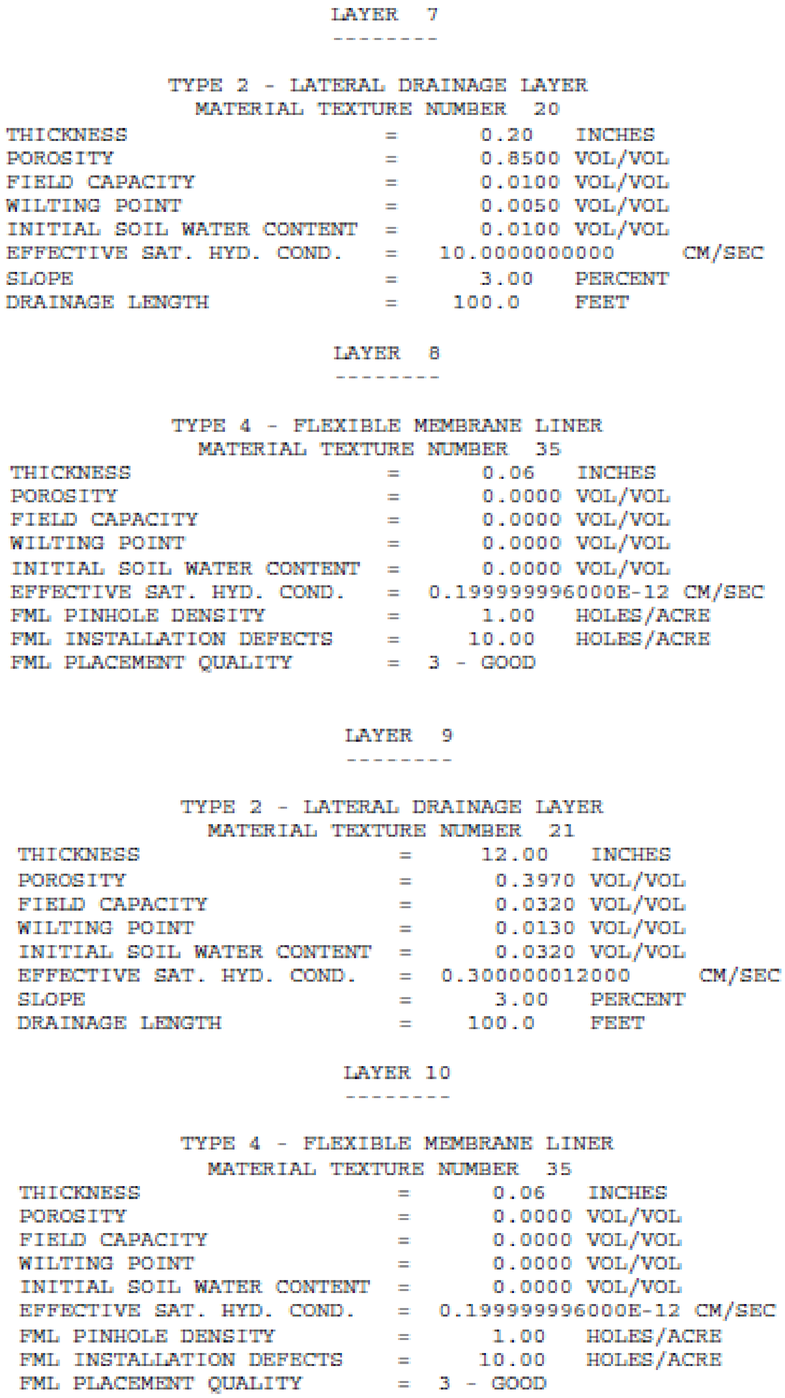
                 TYPE 3 - BARRIER SOIL LINER
                 MATERIAL TEXTURE NUMBER  28
  THICKNESS                     =      36.00    INCHES
  POROSITY                      =       0.4520 VOL/VOL
  FIELD CAPACITY                =       0.4110 VOL/VOL
  WILTING POINT                 =       0.3110 VOL/VOL
  INITIAL SOIL WATER CONTENT    =       0.4520 VOL/VOL
  EFFECTIVE SAT. HYD. COND.     =   0.120000004000E-05 CM/SEC


                            LAYER  5
                            --------

             TYPE 1 - VERTICAL PERCOLATION LAYER
                 MATERIAL TEXTURE NUMBER  18


THICKNESS                     =     300.00    INCHES
POROSITY                      =       0.6710 VOL/VOL
FIELD CAPACITY                =       0.2920 VOL/VOL
WILTING POINT                 =       0.0770 VOL/VOL
INITIAL SOIL WATER CONTENT    =       0.2920 VOL/VOL
EFFECTIVE SAT. HYD. COND.     =   0.100000005000E-02 CM/SEC
                           LAYER  6
                           --------

             TYPE 2 - LATERAL DRAINAGE LAYER
               MATERIAL TEXTURE NUMBER   5
THICKNESS                     =      12.00    INCHES
POROSITY                      =       0.4570 VOL/VOL
FIELD CAPACITY                =       0.1310 VOL/VOL
WILTING POINT                 =       0.0580 VOL/VOL
INITIAL SOIL WATER CONTENT    =       0.1377 VOL/VOL
EFFECTIVE SAT. HYD. COND.     =   0.100000005000E-02 CM/SEC
```



```
                        LAYER  7
                        --------

            TYPE 2 - LATERAL DRAINAGE LAYER
              MATERIAL TEXTURE NUMBER  20
THICKNESS                  =      0.20    INCHES
POROSITY                   =      0.8500 VOL/VOL
FIELD CAPACITY             =      0.0100 VOL/VOL
WILTING POINT              =      0.0050 VOL/VOL
INITIAL SOIL WATER CONTENT =      0.0100 VOL/VOL
EFFECTIVE SAT. HYD. COND.  =   10.0000000000      CM/SEC
SLOPE                      =      3.00    PERCENT
DRAINAGE LENGTH            =    100.0     FEET

                        LAYER  8
                        --------

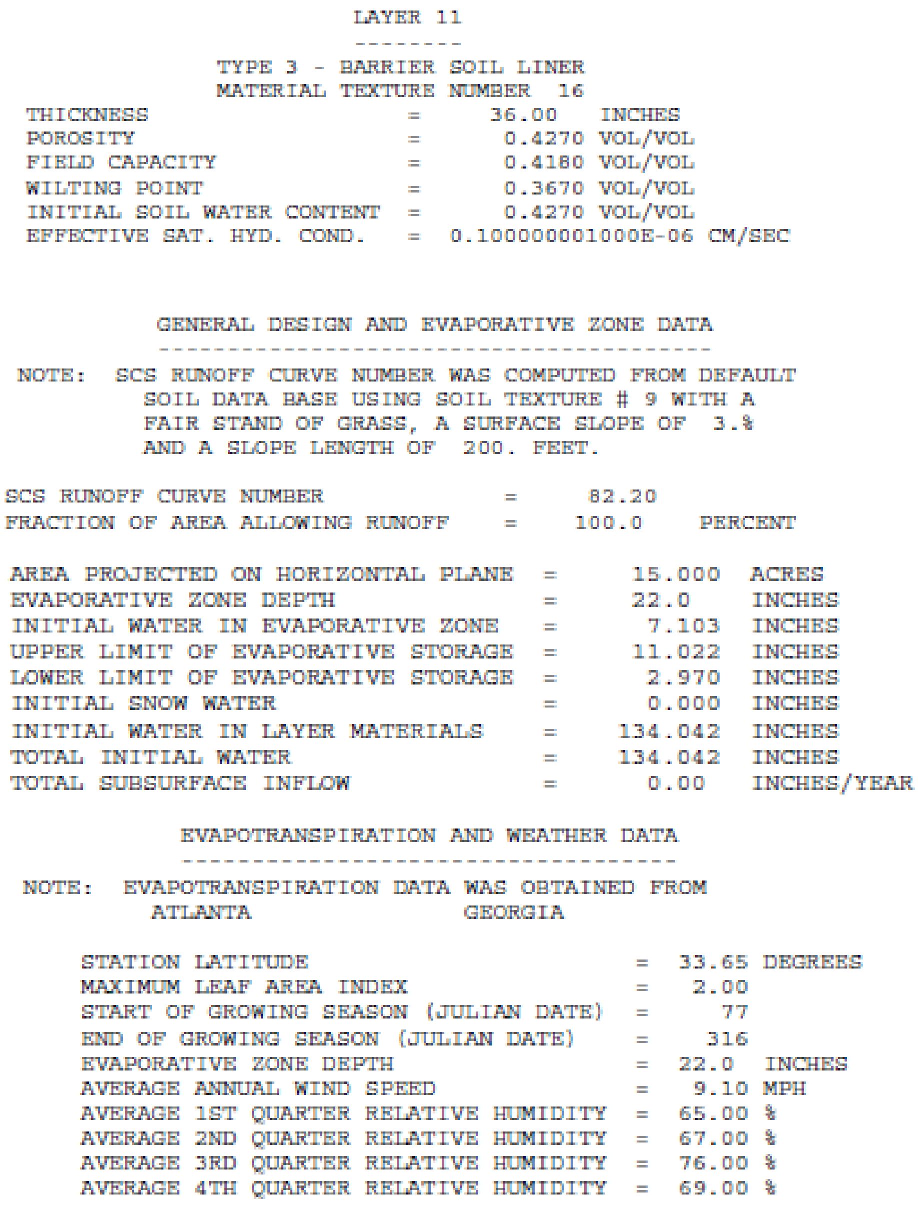
            TYPE 4 - FLEXIBLE MEMBRANE LINER
              MATERIAL TEXTURE NUMBER  35
THICKNESS                  =      0.06    INCHES
POROSITY                   =      0.0000 VOL/VOL
FIELD CAPACITY             =      0.0000 VOL/VOL
WILTING POINT              =      0.0000 VOL/VOL
INITIAL SOIL WATER CONTENT =      0.0000 VOL/VOL
EFFECTIVE SAT. HYD. COND.  = 0.199999996000E-12 CM/SEC
FML PINHOLE DENSITY        =      1.00    HOLES/ACRE
FML INSTALLATION DEFECTS   =     10.00    HOLES/ACRE
FML PLACEMENT QUALITY      = 3 - GOOD


                        LAYER  9
                        --------

            TYPE 2 - LATERAL DRAINAGE LAYER
              MATERIAL TEXTURE NUMBER  21
THICKNESS                  =     12.00    INCHES
POROSITY                   =      0.3970 VOL/VOL
FIELD CAPACITY             =      0.0320 VOL/VOL
WILTING POINT              =      0.0130 VOL/VOL
INITIAL SOIL WATER CONTENT =      0.0320 VOL/VOL
EFFECTIVE SAT. HYD. COND.  = 0.300000012000      CM/SEC
SLOPE                      =      3.00    PERCENT
DRAINAGE LENGTH            =    100.0     FEET

                        LAYER 10
                        --------

            TYPE 4 - FLEXIBLE MEMBRANE LINER
              MATERIAL TEXTURE NUMBER  35
THICKNESS                  =      0.06    INCHES
POROSITY                   =      0.0000 VOL/VOL
FIELD CAPACITY             =      0.0000 VOL/VOL
WILTING POINT              =      0.0000 VOL/VOL
INITIAL SOIL WATER CONTENT =      0.0000 VOL/VOL
EFFECTIVE SAT. HYD. COND.  = 0.199999996000E-12 CM/SEC
FML PINHOLE DENSITY        =      1.00    HOLES/ACRE
FML INSTALLATION DEFECTS   =     10.00    HOLES/ACRE
FML PLACEMENT QUALITY      = 3 - GOOD
```



```
                          LAYER 11
                          --------
                TYPE 3 - BARRIER SOIL LINER
                MATERIAL TEXTURE NUMBER  16
  THICKNESS                   =     36.00   INCHES
  POROSITY                    =      0.4270 VOL/VOL
  FIELD CAPACITY              =      0.4180 VOL/VOL
  WILTING POINT               =      0.3670 VOL/VOL
  INITIAL SOIL WATER CONTENT  =      0.4270 VOL/VOL
  EFFECTIVE SAT. HYD. COND.   =  0.100000001000E-06 CM/SEC

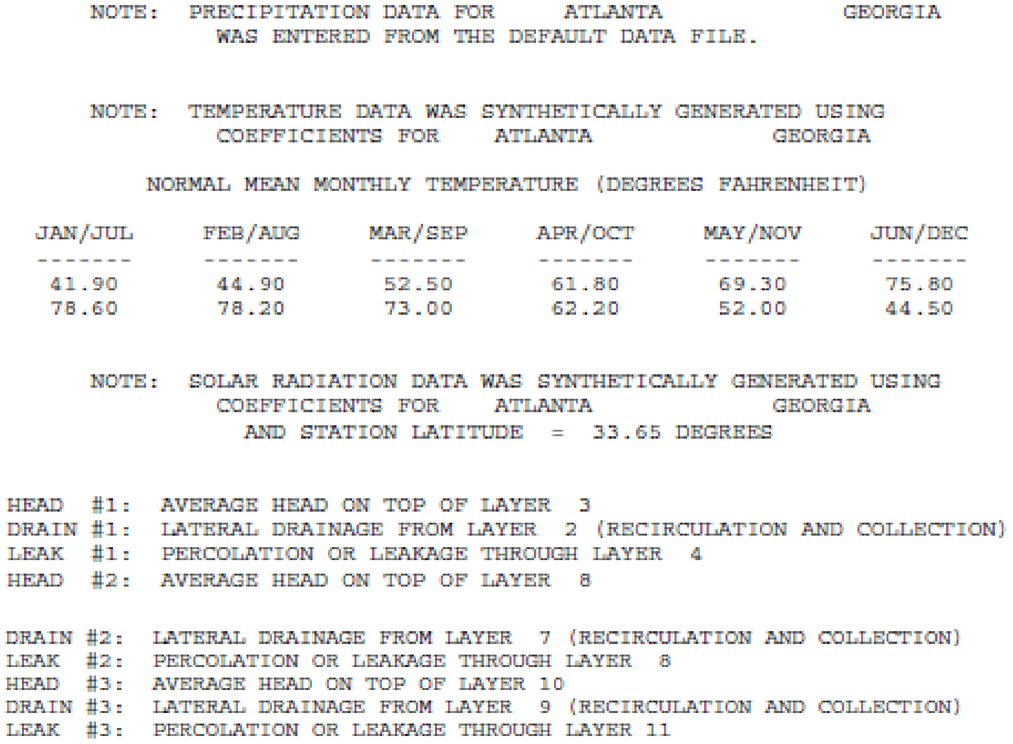

           GENERAL DESIGN AND EVAPORATIVE ZONE DATA
           ----------------------------------------
 NOTE:  SCS RUNOFF CURVE NUMBER WAS COMPUTED FROM DEFAULT
          SOIL DATA BASE USING SOIL TEXTURE # 9 WITH A
          FAIR STAND OF GRASS, A SURFACE SLOPE OF  3.%
          AND A SLOPE LENGTH OF  200. FEET.

 SCS RUNOFF CURVE NUMBER             =     82.20
 FRACTION OF AREA ALLOWING RUNOFF    =    100.0    PERCENT

 AREA PROJECTED ON HORIZONTAL PLANE  =     15.000  ACRES
 EVAPORATIVE ZONE DEPTH              =     22.0    INCHES
 INITIAL WATER IN EVAPORATIVE ZONE   =      7.103  INCHES
 UPPER LIMIT OF EVAPORATIVE STORAGE  =     11.022  INCHES
 LOWER LIMIT OF EVAPORATIVE STORAGE  =      2.970  INCHES
 INITIAL SNOW WATER                  =      0.000  INCHES
 INITIAL WATER IN LAYER MATERIALS    =    134.042  INCHES
 TOTAL INITIAL WATER                 =    134.042  INCHES
 TOTAL SUBSURFACE INFLOW             =      0.00   INCHES/YEAR

             EVAPOTRANSPIRATION AND WEATHER DATA
             -----------------------------------
 NOTE:  EVAPOTRANSPIRATION DATA WAS OBTAINED FROM
          ATLANTA               GEORGIA

      STATION LATITUDE                       =  33.65 DEGREES
      MAXIMUM LEAF AREA INDEX                =   2.00
      START OF GROWING SEASON (JULIAN DATE)  =     77
      END OF GROWING SEASON (JULIAN DATE)    =    316
      EVAPORATIVE ZONE DEPTH                 =  22.0  INCHES
      AVERAGE ANNUAL WIND SPEED              =   9.10 MPH
      AVERAGE 1ST QUARTER RELATIVE HUMIDITY  =  65.00 %
      AVERAGE 2ND QUARTER RELATIVE HUMIDITY  =  67.00 %
      AVERAGE 3RD QUARTER RELATIVE HUMIDITY  =  76.00 %
      AVERAGE 4TH QUARTER RELATIVE HUMIDITY  =  69.00 %
```



```
      NOTE:  PRECIPITATION DATA FOR     ATLANTA             GEORGIA
               WAS ENTERED FROM THE DEFAULT DATA FILE.


      NOTE:  TEMPERATURE DATA WAS SYNTHETICALLY GENERATED USING
               COEFFICIENTS FOR    ATLANTA             GEORGIA

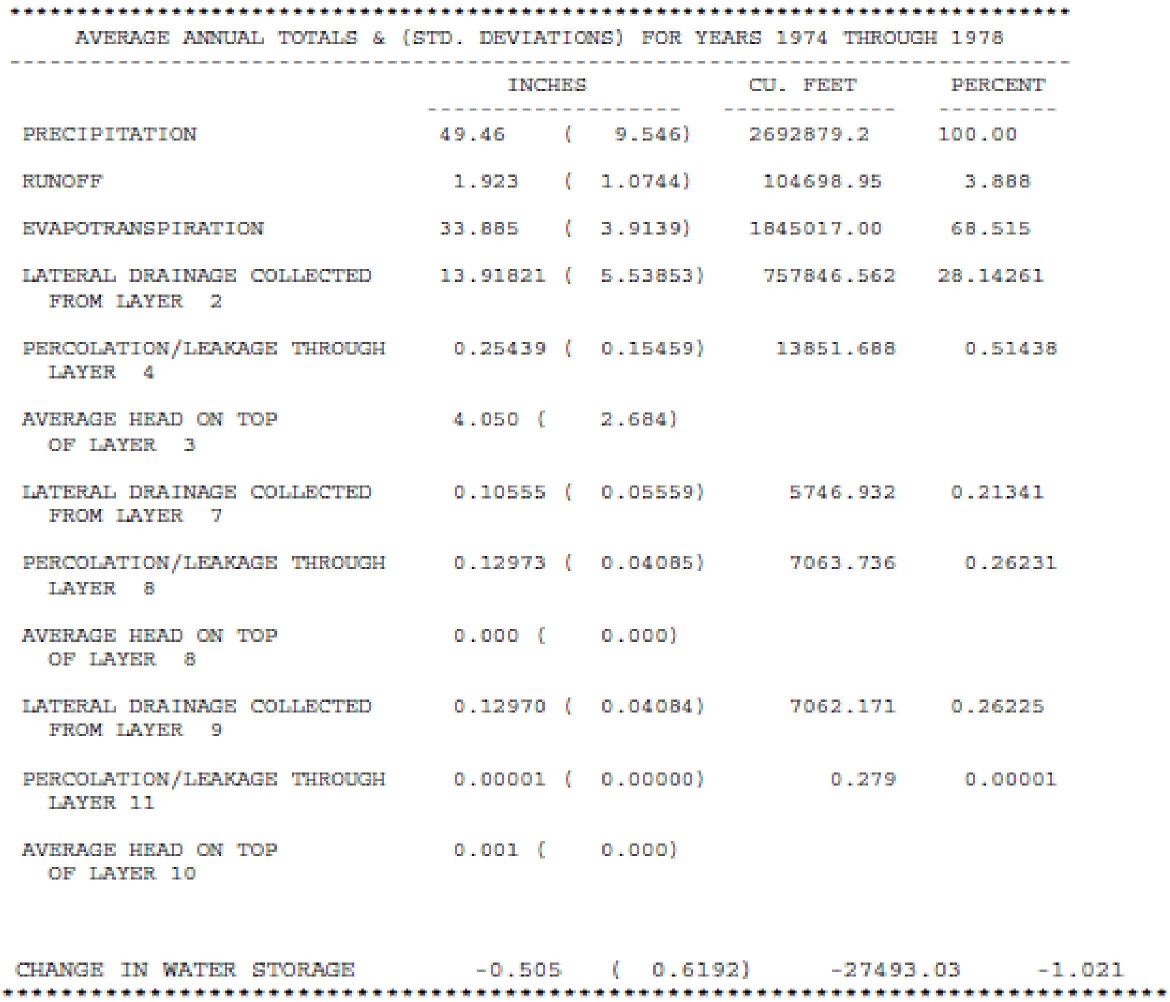
          NORMAL MEAN MONTHLY TEMPERATURE (DEGREES FAHRENHEIT)

  JAN/JUL     FEB/AUG     MAR/SEP     APR/OCT     MAY/NOV     JUN/DEC
  -------     -------     -------     -------     -------     -------
   41.90       44.90       52.50       61.80       69.30       75.80
   78.60       78.20       73.00       62.20       52.00       44.50


      NOTE:  SOLAR RADIATION DATA WAS SYNTHETICALLY GENERATED USING
               COEFFICIENTS FOR    ATLANTA             GEORGIA
                 AND STATION LATITUDE  =  33.65 DEGREES


HEAD  #1:  AVERAGE HEAD ON TOP OF LAYER  3
DRAIN #1:  LATERAL DRAINAGE FROM LAYER  2 (RECIRCULATION AND COLLECTION)
LEAK  #1:  PERCOLATION OR LEAKAGE THROUGH LAYER  4
HEAD  #2:  AVERAGE HEAD ON TOP OF LAYER  8

DRAIN #2:  LATERAL DRAINAGE FROM LAYER  7 (RECIRCULATION AND COLLECTION)
LEAK  #2:  PERCOLATION OR LEAKAGE THROUGH LAYER  8
HEAD  #3:  AVERAGE HEAD ON TOP OF LAYER 10
DRAIN #3:  LATERAL DRAINAGE FROM LAYER  9 (RECIRCULATION AND COLLECTION)
LEAK  #3:  PERCOLATION OR LEAKAGE THROUGH LAYER 11
```



```
*******************************************************************************
     AVERAGE ANNUAL TOTALS & (STD. DEVIATIONS) FOR YEARS 1974 THROUGH 1978
-------------------------------------------------------------------------------
                                    INCHES             CU. FEET       PERCENT
                              -------------------   -------------   ---------
 PRECIPITATION                49.46     (   9.546)   2692879.2      100.00

 RUNOFF                        1.923    (  1.0744)    104698.95       3.888

 EVAPOTRANSPIRATION           33.885    (  3.9139)   1845017.00      68.515

 LATERAL DRAINAGE COLLECTED   13.91821 (  5.53853)    757846.562   28.14261
   FROM LAYER  2

 PERCOLATION/LEAKAGE THROUGH   0.25439 (  0.15459)     13851.688     0.51438
   LAYER  4

 AVERAGE HEAD ON TOP           4.050 (    2.684)
   OF LAYER  3

 LATERAL DRAINAGE COLLECTED    0.10555 (  0.05559)      5746.932    0.21341
   FROM LAYER  7

 PERCOLATION/LEAKAGE THROUGH   0.12973 (  0.04085)      7063.736     0.26231
   LAYER  8

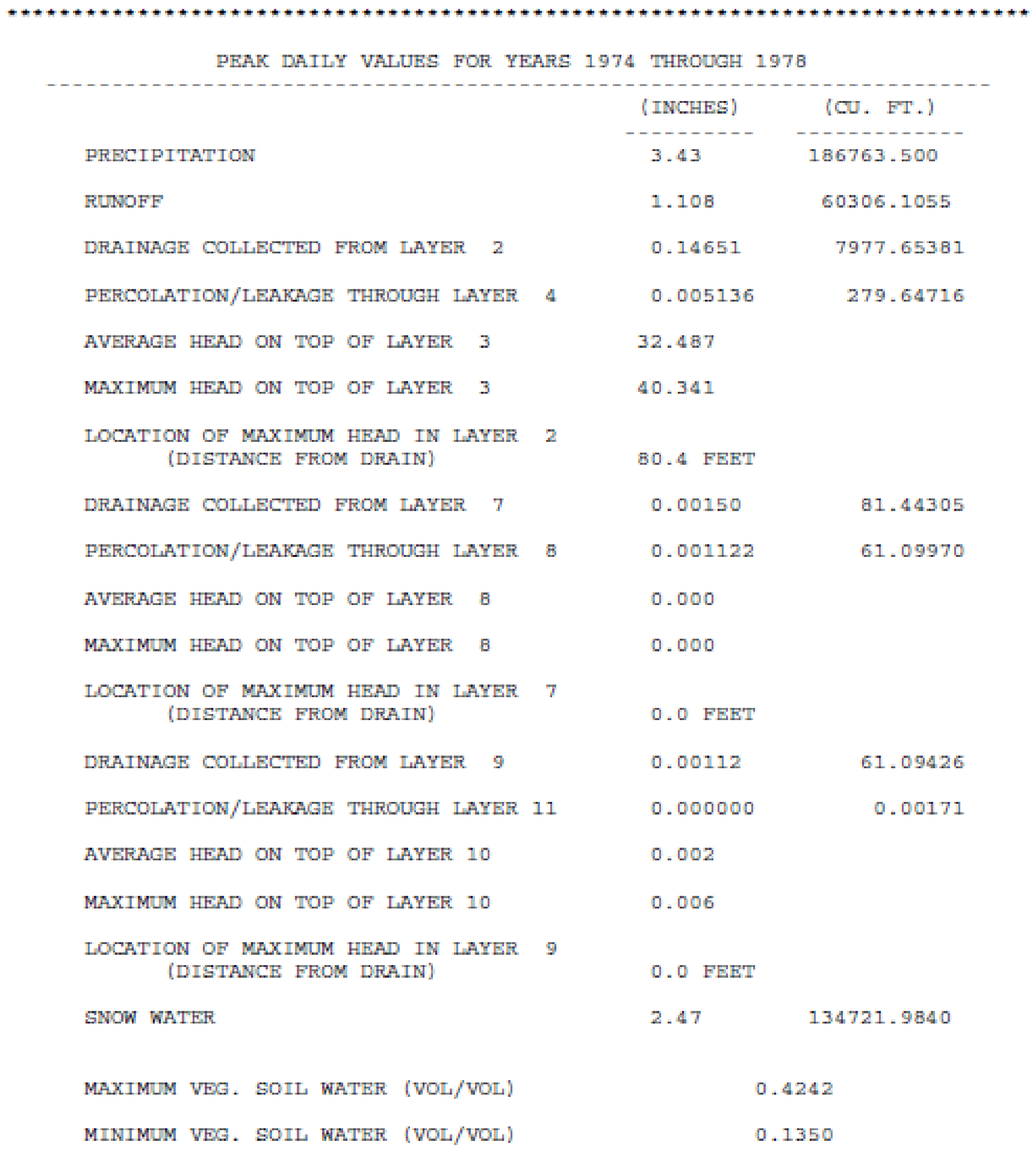
 AVERAGE HEAD ON TOP           0.000 (    0.000)
   OF LAYER  8

 LATERAL DRAINAGE COLLECTED    0.12970 (  0.04084)      7062.171    0.26225
   FROM LAYER  9

 PERCOLATION/LEAKAGE THROUGH   0.00001 (  0.00000)         0.279     0.00001
   LAYER 11

 AVERAGE HEAD ON TOP           0.001 (    0.000)
   OF LAYER 10


 CHANGE IN WATER STORAGE        -0.505    (  0.6192)     -27493.03     -1.021
*******************************************************************************
```



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              PEAK DAILY VALUES FOR YEARS 1974 THROUGH 1978
   ------------------------------------------------------------------------
                                                (INCHES)      (CU. FT.)
                                               ----------    -------------
      PRECIPITATION                              3.43        186763.500

      RUNOFF                                     1.108        60306.1055

      DRAINAGE COLLECTED FROM LAYER  2           0.14651       7977.65381

      PERCOLATION/LEAKAGE THROUGH LAYER  4       0.005136       279.64716

      AVERAGE HEAD ON TOP OF LAYER  3           32.487

      MAXIMUM HEAD ON TOP OF LAYER  3           40.341

      LOCATION OF MAXIMUM HEAD IN LAYER  2
            (DISTANCE FROM DRAIN)               80.4 FEET

      DRAINAGE COLLECTED FROM LAYER  7           0.00150         81.44305

      PERCOLATION/LEAKAGE THROUGH LAYER  8       0.001122        61.09970

      AVERAGE HEAD ON TOP OF LAYER  8            0.000

      MAXIMUM HEAD ON TOP OF LAYER  8            0.000

      LOCATION OF MAXIMUM HEAD IN LAYER  7
            (DISTANCE FROM DRAIN)                0.0 FEET

      DRAINAGE COLLECTED FROM LAYER  9           0.00112         61.09426

      PERCOLATION/LEAKAGE THROUGH LAYER 11       0.000000         0.00171

      AVERAGE HEAD ON TOP OF LAYER 10            0.002

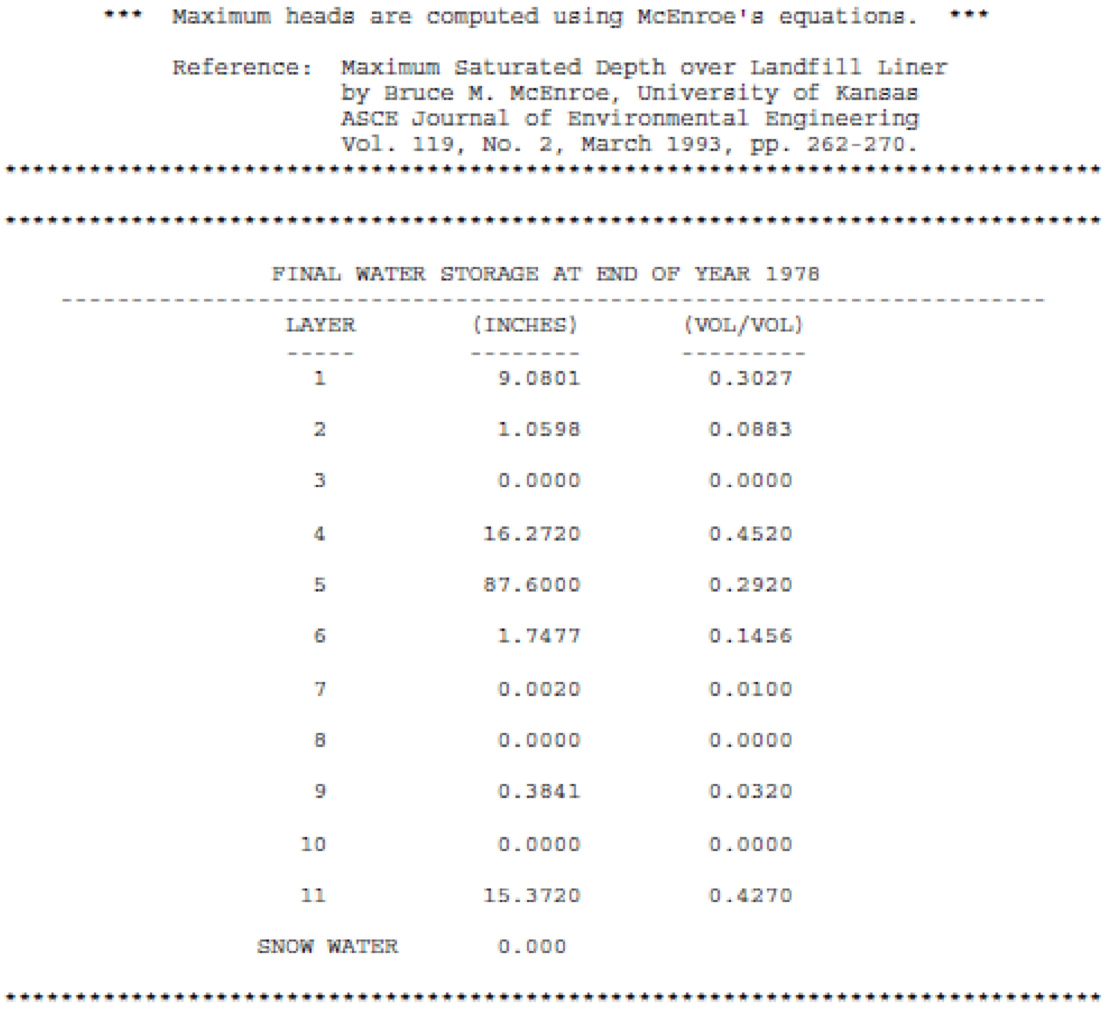
      MAXIMUM HEAD ON TOP OF LAYER 10            0.006

      LOCATION OF MAXIMUM HEAD IN LAYER  9
            (DISTANCE FROM DRAIN)                0.0 FEET

      SNOW WATER                                 2.47        134721.9840


      MAXIMUM VEG. SOIL WATER (VOL/VOL)                  0.4242

      MINIMUM VEG. SOIL WATER (VOL/VOL)                  0.1350
```



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        ***  Maximum heads are computed using McEnroe's equations.  ***

             Reference:  Maximum Saturated Depth over Landfill Liner
                         by Bruce M. McEnroe, University of Kansas
                         ASCE Journal of Environmental Engineering
                         Vol. 119, No. 2, March 1993, pp. 262-270.
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                  FINAL WATER STORAGE AT END OF YEAR 1978
    ----------------------------------------------------------------------
                   LAYER        (INCHES)       (VOL/VOL)
                   -----        --------       ---------
                     1            9.0801         0.3027

                     2            1.0598         0.0883

                     3            0.0000         0.0000

                     4           16.2720         0.4520

                     5           87.6000         0.2920

                     6            1.7477         0.1456

                     7            0.0020         0.0100

                     8            0.0000         0.0000

                     9            0.3841         0.0320

                    10            0.0000         0.0000

                    11           15.3720         0.4270

                 SNOW WATER       0.000

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```

9.12 Surface Water, Groundwater, and Soil Contamination by Leachate

If the side slopes of the landfill are not compacted and maintained properly, leachate may leak through the wastes and finds its way to go to the nearby surface streams. That is how the surface water will be contaminated by leachate. If the bottom liners of the landfill are not designed and constructed properly, the leachate may leak through the liners and finds its way to go to the groundwater and the soil (***Figure 22***). The dissolved contaminants will be in groundwater and the suspended and ionized contaminants will be stuck with soil by adsorption and ion exchange mechanisms.

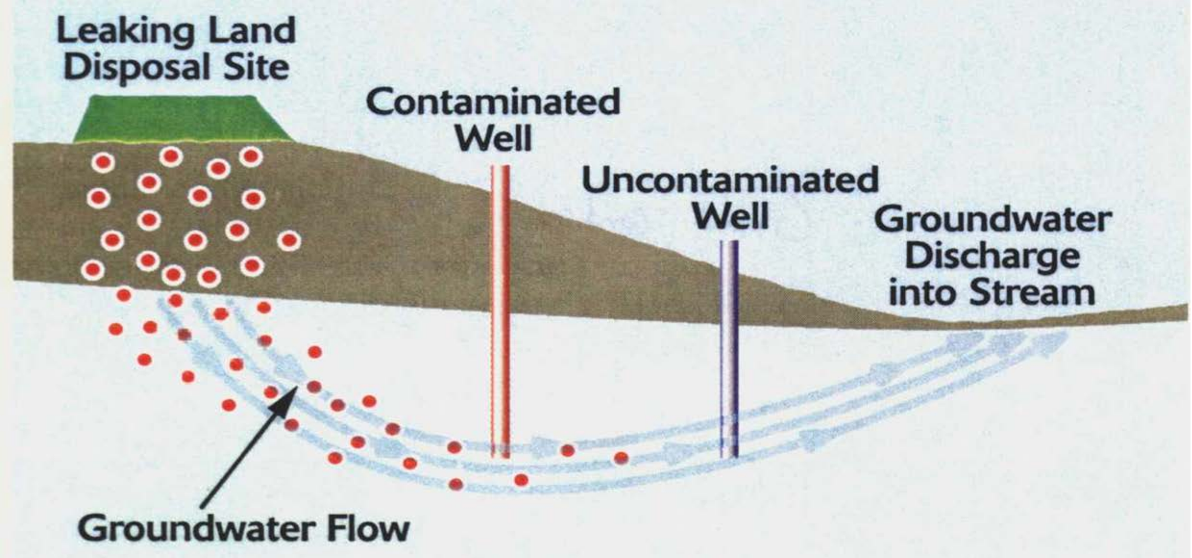


Figure 22: Soil and groundwater contamination by leachate

10.Materials Used in Landfill Construction

The materials used in HW landfill constructions are: Geomembrane, Geotextile, Compacted Clay, and Geocomposite Clay Liner (GCL)

10.1 Geomembrane

Geomembrane is an engineered polymeric material (a **geosynthetic**) that is fabricated to be virtually impermeable.

a. **Types:**

  - **HDPE** (High-density polyethylene) – Minimum 60 mil (***60/1,000-inch thickness***)
  - **PVC** (Polyvinyl chloride)
  - **LDPE** (Low-density polyethylene) – Minimum 30 mil

b. **Physical properties:**

  i. Thickness, density, water & solvent vapor transmission

c. **Mechanical properties:**

  - Tensile behavior, tear resistance, impact resistance, puncture resistance, frictional characteristics, and stress cracking

d. **Chemical properties:**

  i. Swelling resistance, chemical compatibility, ozone resistance, UV light resistance

e. **Biological properties:**

i. Resistance to animals, fungi, and bacteria.

f. **Thermal properties:**

i. Warm & cold temperature behavior, thermal expansion

10.2 Geotextile

A geotextile is a geosynthetic which is fabricated to be permeable and has two categories of hydraulic properties:

- **Filtration** – removal of suspended solids (SS) from the flowing liquid
- **Drainage** – the transportation of liquids across the plane of the fabric.

Darcy's law can be used to estimate flow rates within geotextiles to study their drainage characteristics and to design the drainage systems using geotextiles and geocomposite.

The properties of geotextile for consideration of endurance include:

- UV light stability
- Abrasion resistance
- Chemical stability
- Thermal stability
- Creep resistance

10.3 Compacted Clay

Compacted clay is widely used as a barrier layer in liner and final cover systems. This soils typically consist of natural clay, silty clays, sandy clays, and clayey silts. The properties/tests of soil that need to be evaluated/performed at a minimum are:

- Classification (ASTM D2487) – USCS and AASHTO (***Figure 23*** and ***Figure 24***)
- Grain Size distribution with hydrometer analysis (ASTM D422) (***Figure 25***)
- Atterberg Limits (ASTM D4318) – Plastic Limit (PL), Liquid Limit (LL), and Plasticity Index (PI)
- Moisture Content (ASTM D2216) – Optimum MC
- Density (ASTM D1556: Sand-cone Method; ASTM D2922: Nuclear Probe Method)
- Specific Gravity (ASTM D854)
- Standard Proctor Density (ASTM D698) (***Figure 26*** and ***Figure 27***)
- Permeability (ASTM D5084) – *In-situ* (Boutwell) and *ex-situ* (*Shelby tube)*

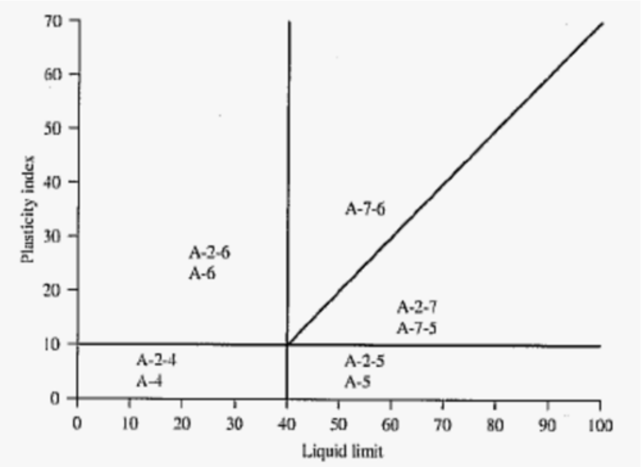


Figure 23: AASHTO Soil Classification System

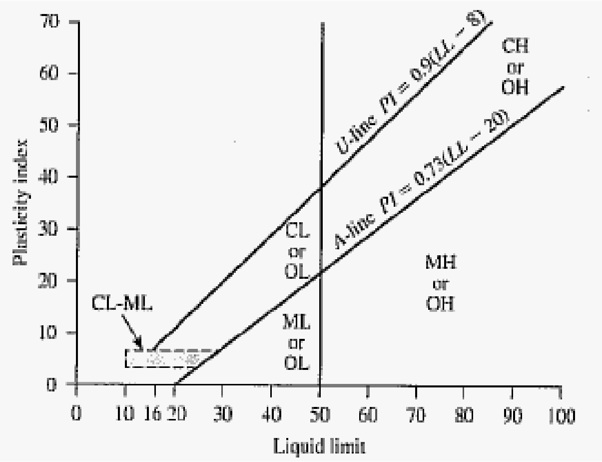


Figure 24: Unified Soil Classification System (USCS)

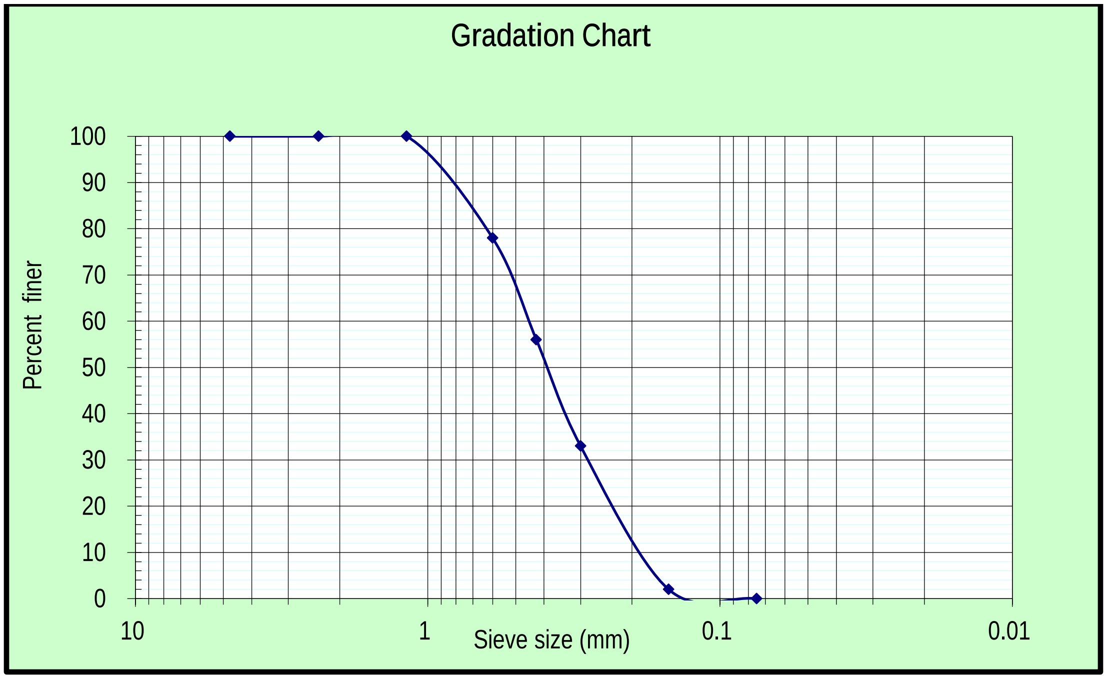


Figure 25: Grain size distribution curve for soil

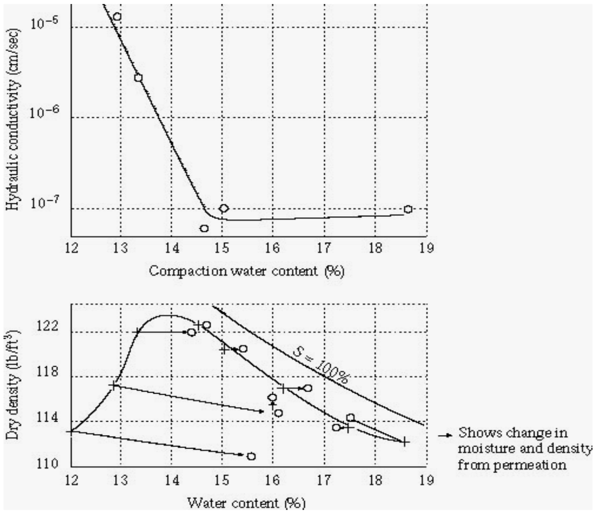


Figure 26: Influence of compaction moisture content on the hydraulic conductivity of compacted clay

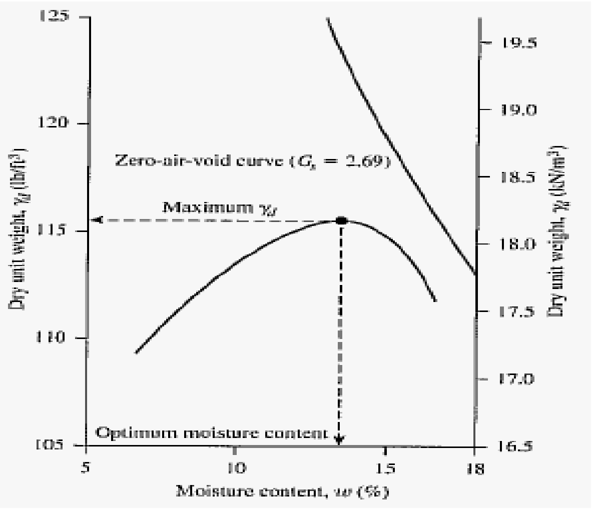


Figure 27: Standard proctor compaction test results

10.4 Geosynthetic Clay Liners (GCL)

- **GCLs** are a manufactured product combining geosynthetics with bentonite.
- **GCLs** are about 5 -10 mm thick, the hydraulic conductivity is quite low (generally < *$5.0x10^{-9}$ cm/s*) because of bentonite.
- Design concerns relate to slope stability and, for use in liners, chemical compatibility of bentonite and leachate.
- **GCLs** are preferred over compacted clay for landfill cover systems assuming slope stability is adequate.

11. Contaminants Transport Through Landfill Liner

Contaminant transport through barriers includes contaminants carried with migrating fluid because of hydraulic gradients (**advection**) and molecular diffusion in response to chemical concentration gradients. As better liner with **geomembrane and compacted clay** of lower and lower effective hydraulic conductivities, are being built in the landfill, ***molecular diffusion*** *becomes the controlling mechanisms of contaminant transport.*

11.1 Molecular Diffusion

Molecular diffusion occurs two ways:

1. **liquid phase diffusion –** through a saturated barrier
2. **gas phase diffusion** – after partitioning from the liquid phase.

The molecular diffusion rates are characterized by **Fick's 2nd law** describing one-dimensional diffusion of solutes in soil as:

$$\partial c / \partial t = (D^* / R)\left(\partial^2 c / \partial x^2 \right)$$

where, c = concentration of a solute (mg/cm^3); t = time (s).

D^* = effective diffusion coefficient (cm^2/s)

R = dimensionless retardation factor

x = direction of diffusion (cm)

According to **Fick's law**, the driving force (or gradient) for molecular diffusion is the chemical potential. The effective diffusion coefficient attempts to include real-world subsurface conditions including the tortuosity of the flow, temperature variations, and reactions occurring in the surface.

The apparent diffusion coefficient is defined as D^*/R and includes retardation effects such as those due to adsorption. Retardation factor, R is a function of the bulk density ρ, porosity η, and distribution coefficient K_d as:

$$R = 1 + (\rho / \eta) K_d$$

An increasing retardation factor results in a decreasing initial rate of diffusive transport. That is, more is adsorbed or otherwise retarded, and the breakthrough is delayed.

11.2 Transport through Geomembrane

Geomembrane are manufactured as solid homogenous nonporous materials. As such, they are not porous media materials, and cannot be permeated by liquids in the traditional sense. However, geomembranes contain interstitial spaces between the large polymer molecules through which small molecules or gas can diffuse. Thus, geomembranes, even perfectly constructed, i.e. free of defects or holes, permit dissolved constituents of the contained fluids and gases to escape. Such transport of contaminants through geomembrane is on a molecular basis by diffusion process and **involves 3 steps**:

- The solution or adsorption of the permeant into the upstream surface of the geomembrane (partitioning of molecule from leachate to gas)
- Diffusion of contaminants through the geomembrane
- Volatilization or desorption of the contaminant at the downstream surface of the geomembrane.

11.3 Advective Transport through Compacted Clay

The advective flow through clay liners depends on the hydraulic conductivity, gradient, and liner dimensions (***Figure 28***). Neglecting retardation, an analysis of the advective flow can be made using **Darcy's law (*Figure 29*)** as follows and the concentration of the contaminants in the leachate:

$$q = kiA$$

where, q = flow rate through compacted clay (cm^3/s)

k = hydraulic conductivity (cm/s)

i = hydraulic gradient (cm/cm) = $(h_1-h_2)/l$

A = flow x-sectional area perpendicular to the direction of flow (cm^2)

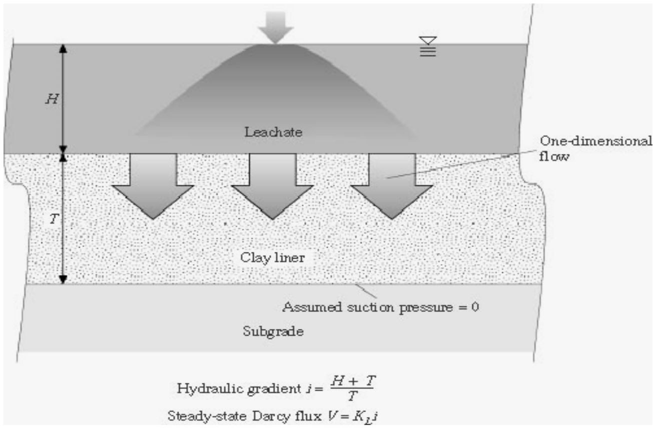


Figure 28: Schematic of advective flow and transport

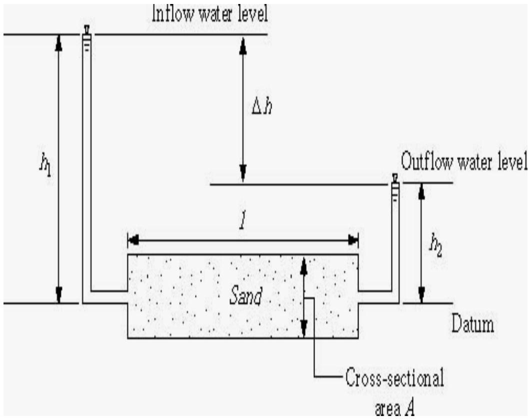


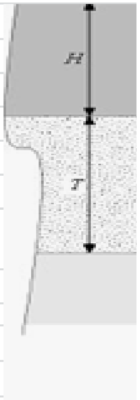
Figure 29: Darcy's experiment

Example 6: A landfill, 300 m by 500 m in plan was constructed with a single clay liner 1 m thick having a permeability of 5×10^{-7} cm/s. The average leachate head is 0.5 m. An analysis of leachate indicates a concentration ***C*** of carbon tetrachloride at 10 mg/L, among other contaminants. What is the annual steady-state flow and advective contaminant transport rate from this landfill? How much drinking water per year could be contaminated to the drinking water standard of 0.005 mg/L.?

Example 6: - Solutions

Given parameters

H =	0.50	m		
T =	1	m		
k =	5.00E-07	cm/s =	5.00E-10	m/s
landfill length, L =	500	m		
Width, W =	300	m		
Concentration of carbon tetrachloride, C =	10	mg/L		
Drinking water standard =	0.005	mg/L		



Calculate the hydraulic gradient (from the Figure)

$$i = \frac{H+T}{T}$$

$$= \frac{0.5 + 1}{1} = 1.50 \text{ m/m}$$

Calculate the Darcy flux (v) (from the Figure)

v = ki = 7.50E-10 m/s

Calculate the flow for the entire landfill on an annual basis

Q = vAt = 0.0000000075 m/s x 500 m x 300 m x 31536000 s/year 1 year = 31536000 s

= **3.55E+04** m^3/year **ANS.**

Calculate the loading L to the subsurface environment

L = Q x C = 35478 m^3/year x 10 mg/L x 1000 L/ 1 m^3

= 3.55E+08 mg/year = **354.78** kg/year **ANS.**

Calculate the quantity of contaminated groundwater, ∀w:

∀w = (354780000 mg/year)/ 0.005 mg/L **7.10E+10** L/year **ANS.**

About 71 billion liters of water will be contaminated per year from about 355 kg of contaminants.

12.Surface Impoundments and Deep Well Injection

Hazardous wastes sometimes are placed on land-based facilities including surface impoundments such as **pits, pond**, and **lagoons (*Figure 30*)**, for treatment or storage. After the treatment or storage, the waste has to be transported to hazardous waste disposal facility for final disposal. Liquid hazardous wastes are disposed of in deep injection wells. The injection wells must be properly sited, constructed, and operated.

The fate of contaminants after disposal in deep injection wells in not clear, although the combination of favorable chemical reactions and dilution afford protection to groundwater and surface water supplies. The injected wastes undergo chemical reactions both between waste constituents and between waste constituents and the formation materials. Reactions include carbonate dissolution in limestone and dolomite, sand dissolution, clay dissolution, hydrolysis, and coprecipitation. The fate of contaminants is predicted by modeling neutralization, hydrolysis, and precipitation reactions using reaction rates and equilibrium constants from the literature for solid-liquid equilibria for aqueous electrolyte solutions.

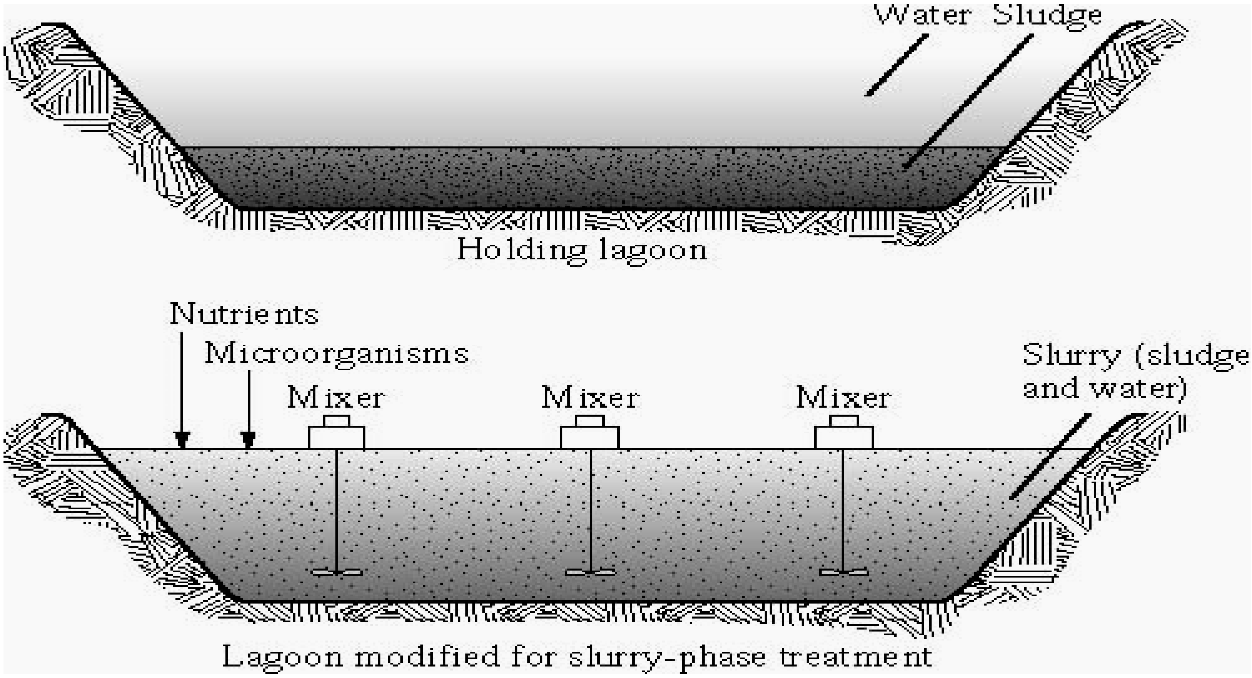


Figure 30: In-situ Lagoon systems

13.Closure and Post-Closure Care

The closure of a hazardous waste disposal facility should minimize or eliminate to the extent necessary to protect human health and the environment, post-closure escape of hazardous waste, hazardous constituents, leachate, contaminated run-off, or hazardous waste decomposition products to the groundwater or surface waters or to the atmosphere.

With successful closure of a landfill and construction of the final cover system, monitoring of the system is required.

- Monitoring of the system includes measurement of the leachate head within landfill to preclude bathtub effect.
- Another major closure consideration is maintenance of the cover integrity.
- Monitoring of groundwater and subsurface environment is a necessary component of the final closure and post-closure care.
- Air monitoring may also be required. Air emission can be monitored at the site boundaries to ensure limited risk to the public health and the environment.
- By regulations, hazardous waste disposal facility must monitor the groundwater, gas, and the integrity of the final cover system at least for a period **30 years**, called **post-closure care period**.
- Post-closure care period may be decreased or increased based on the monitoring results.
- Completed landfills may be used for recreational purposes such as parks, play-grounds, or golf courses. Parking and storage areas or botanical gardens are other final uses (***Figure 31***).

Figure 31: Grass and other plants cover at the completed landfill

14.Summary

In this course land disposal of hazardous waste primarily hazardous waste landfill (Subtitle C Landfill) was discussed and understood the processes and the needs of HW Landfills. This course introduces an overview of hazardous waste (HW) landfill design, operation, and performance. This course covered the materials related to Landfill Operations, Site Selection, Liner & Leachate Collection Systems, Final Cover Systems, Materials, Contaminant Transport through Landfill Barriers, Landfill Stability, Subsurface Impoundments and Deep Well Injection, Closure and Post-Closure Care. Several problems were solved as well as HELP Model run results were reviewed to understand the extent of HW landfill design and related issues.

15. References

1. Personal work experience and open sources from internet.
2. Other references are shown as footnotes.

+++++++++++++++ **The End** ++++++++++++++

Any questions please contact the instructor at makarim@juno.com

QUIZ for Land Disposal of Hazardous Waste

1. Hazardous waste landfills are necessary because other hazardous waste management technologies such as source reduction, recycling, waste minimization cannot totally eliminate the waste generated, and hazardous waste treatment technologies such as incineration and biological treatment produces residues.
a. True
b. False

2. The requirements of hazardous waste landfill, design, operation, maintenance, closure, and permitting are covered ______________ of RCRA.
a. Subtitle C
b. Subtitle D
c. Subtitle I
d. Subtitle J

3. The overall design of secure land disposal facilities includes: (i) Control of the top to maximize air emissions and infiltration of precipitation and (ii) Control of the bottom to minimize the collection of leachate and minimize contaminant transport through the bottom.
a. True
b. False

4. Operational considerations for subtitle C landfill may include covering the waste at the end of the operation day with _______________ thick soil which is termed as daily cover.
a. 6-inch
b. 12-inch
c. 18-inch
d. 24-inch
e. 36-inch

5. Typically, bulldozers, compactors, and trucks developed for heavy construction are used for land disposal operations.
a. True
b. False

6. ____________________ is run to estimate amount of leachate generated and head on the liner system.
a. HELP model
b. Multimedia model
c. LandGEM
d. PCSTABLE model

7. A liner with __________ effectiveness will prevent chemical constituents from migrating across the liner system into the environment, because no liner is _____________effective, leachate collection is required.
a. 50%
b. 65%
c. 85%
d. 100%

8. Public participation is NOT mandatory in the regulations that general public must be involved in the selection process of a site through public meeting and public hearing, as appropriate, for informed decision.
a. True
b. False

9. ____________________ is run to estimate amount of gas generated in the landfill.
a. HELP model
b. Multimedia model
c. LandGEM
d. PCSTABLE model

10. The bottom liner system for a Subtitle C landfill consists of
a. single liner
b. double liner
c. triple liner
d. just soil liner

11. The thickness of clay component of a Subtitle C landfill is
a. 12-inch (1 ft)
b. 24-inch (2 ft)
c. 36-inch (3 ft)
d. 48-inch (4 ft)

12. The required maximum permeability of clay component of a Subtitle C landfill is
a. 1.0×10^{-5} cm/s
b. 1.0×10^{-7} cm/s
c. 1.0×10^{-10} cm/s
d. 1.0×10^{-13} cm/s

13. The minimum thickness of HDPE (High-density polyethylene) that can be used in Subtitle C landfill liner system is:
a. 40-mil
b. 30-mil
c. 60-mil
d. 80-mil

14. The slope stability analysis necessitates the hypothesis of failure surface, the determination of driving and resisting forces, and the definition of a _____ ____ _____ employing these force systems.
a. cradle to grave (CG)
b. factor of safety (FS)
c. all of the above
d. none of the above

15. GCLs are about 5 - 10 mm thick, the hydraulic conductivity is quite low and generally <________________ because of bentonite.
a. 5.0 x 10^{-9} cm/s
b. 9.0 x 10^{-9} cm/s
c. 5.0 x 10^{-13} cm/s
d. 7.0 x 10^{-9} cm/s

16. As better liner with geomembrane and compacted clay of lower and lower effective hydraulic conductivities, are being built in the landfill, ________________ becomes the controlling mechanisms of contaminant transport.
a. molecular advection
b. molecular convection
c. molecular diffusion
d. hydraulic gradient

17. According to **Fick's law**, the driving force (or gradient) for molecular diffusion is the ____________.
a. chemical potential
b. electrical potential
c. hydraulic potential
d. all of the above
e. none of the above

18. Slope stability can be mathematically defined in a number of different ways such as by rotational force equilibrium, rotational moment equilibrium, or sliding wedge force equilibrium. The location that produces the lowest factor of safety (FS) is termed as __________ _________ __________.
a. critical failure surface
b. 6th failure surface
c. 10th failure surface
d. all of the above
e. none of the above

19. By regulations, hazardous waste disposal facility must monitor the groundwater, gas, and the integrity of the final cover system at least for a period of ____________________, called post-closure care period.
a. 10 years
b. 20 years
c. 30 years
d. 50 years

20. ____________________ is run to find the failure surfaces in slope stability analysis.
a. HELP model
b. Multimedia model
c. LandGEM
d. PCSTABLE model

21. Landfill must be stable during construction, operations, and many years after the final closure. Stability often termed as ________ __________ as the probability failing the slope is high if not designed properly.
a. construction stability
b. slope stability
c. operational stability
d. closure stability
e. none of the above

22. A geotextile is a geosynthetic which is fabricated to be permeable and has two categories of hydraulic properties such as _________________ and _______________________.
a. filtration and drainage
b. permeability and drainage
c. all of the above
d. none of the above

23. Infiltration of water through the top of the landfill, by either direct precipitation or run-on is a major source of _________________ generation at hazardous waste landfill.
a. gas
b. leachate
c. fire
d. none of the above

24. In order to monitor the quality of ground water around a Subtitle C landfill facility, the facility must installed a number of _________________ and ________________ monitoring wells.
a. deep and shallow
b. upgradient and downgradient
c. north and south
d. east and west

25. The management of hazardous waste in land disposal facilities requires the tracking of the waste that, the recording of the journey of the waste from ____________________.
a. state-to-state
b. cradle-to-grave
c. county-to-county
d. country-to-country

26. The final cover system minimizes and/or eliminates the leachate generation due to direct precipitation or run-on.
a. True
b. False

27. Subtitle C Landfill must be stable during construction, operations, and many years after the final closure. Stability often termed as _______ ________ as the probability failing the slope is high if not designed properly.
a. slope stability
b. property stability
c. leachate stability
d. land stability

28. The requirements of **hazardous waste landfill** design, operation, maintenance, closure, and permitting are covered in __________ of RCRA.
a. Subtitle C
b. Subtitle D
c. Subtitle I
d. Subtitle J

29. No landfill shall be located in areas where the ground water table will be less than 2 m below the base of the landfill.
a. 2 m
b. 4 m
c. 5 m
d. 10 m

30. No landfill shall be constructed within 500 m of any water supply well.
a. 100 m
b. 500 m
c. 600 m
d. 700 m

31. No landfill shall be constructed within a 100-year flood plain. A landfill may be built within the flood plains of secondary streams if an embankment is built along the streamside to avoid flooding of the area. However, landfills must not be built within the flood plains of major rivers unless properly designed protection embankments are constructed around the landfills.
a. 25-year
b. 50-year
c. 100-year
d. 500-year

32. No landfill shall be constructed within a 100 m of a navigable river or stream.
a. 10 m
b. 20 m
c. 50 m
d. 100 m

33. No landfill shall normally be constructed within _______ of any lake or pond. Because of concerns regarding runoff of waste contaminated water, a surface water monitoring network with approval of SPCB/PCC shall be established.
a. 200 m
b. 300 m
c. 400 m
d. 500 m

34. A landfill site shall be at least ________ from a notified habitated area. A zone of ________ around a landfill boundary should be declared a no-development buffer zone after the landfill location is finalized.
a. 100 m
b. 500 m
c. 600 m
d. 700 m

35. A properly landscaped entrance area with a green belt of ________ containing tree plantation for good visual impact is required for a Subtitle C landfill.
a. 10 m
b. 15 m
c. 20 m
d. 25 m

36. For sites receiving more than _______ tons per day of waste, twin weigh bridges to weigh both entry and exit weights may be located on either side of an island on which a weighbridge office room is located.
a. 200
b. 300
c. 350
d. 400

37. Soil used as daily / weekly cover shall give a pleasing uniform appearance from the site boundary of subtitle C landfill. To achieve this a thickness of about a foot (0.3 m) is usually adequate and shall be adopted.
a. 0.3 m (12-inch)
b. 0.6 m (24-inch)
c. 0.9 m (36-inch)
d. 1 m (40-inch)

38. A **minimum of ____ sets of ground water monitoring wells (______ up-gradient and ______ down gradient**) for sampling in each aquifer are considered desirable at each landfill site extraction systems.
a. 3, 1, 2
b. 4, 1, 3
c. 5, 2, 3
d. 6, 2, 4

39. By regulations, hazardous waste disposal facility must monitor the groundwater, gas, and the integrity of the final cover system at least for a period _____________, called post-closure care period.
a. 10 years
b. 20 years
c. 30 years
d. 40 years

40. Slope stability can be mathematically defined in a number of different ways such as by rotational force equilibrium, rotational moment equilibrium, or sliding wedge force equilibrium.
a. True
b. False