STATE OF DELAWARE
UNIVERSITY OF DELAWARE
DELAWARE GEOLOGICAL SURVEY

OPEN FILE REPORT NO. 16

GEOLOGIC AND HYDROLOGIC ASPECTS OF LANDFILLS

BY
NENAD SPOLJARIC
AND
JOHN H. TALLEY

NEWARK, DELAWARE
MARCH 1982

GEOLOGIC AND HYDROLOGIC
ASPECTS OF LANDFILLS

Nenad Spoljaric and John H. Talley

INTRODUCTION

In the United States more than 3.5 billion tons of solid waste are generated annually. Of this, more than 2 billion tons are agricultural waste, such as manure and crop waste. Almost 300 million tons are generated by commercial and industrial activities and municipalities, and another 1.1 billion tons are attributed to various mining operations (Vaughan, 1969).

Increasing amounts of solid waste have had detrimental effects on environmental quality. It has become necessary to reprocess and reuse some, and to provide safe and environmentally acceptable ways of disposing of the remaining waste in properly constructed landfills.

Pollution brought about by improperly constructed landfills may be very severe. For example, the contaminants generated by the waste at the old, abandoned Army Creek Landfill, New Castle County, Delaware, were so widespread that the situation received national attention.

General and sincere concern expressed by many citizens of our State has prompted the Delaware Geological Survey to prepare this report. The report explains the functioning of a landfill, problems improperly constructed landfills may cause, and the geologic and hydrologic aspects that have to be considered in selecting a suitable disposal site for solid waste. The report does not contain discussions of other important factors, such as social impact, transportation, and specific health hazards, that must also be considered.

ACKNOWLEDGMENTS

We thank R. R. Jordan, State Geologist, our colleagues T. E. Pickett and K. D. Woodruff, and N. C. Vasuki, General Manager, Delaware Solid Waste Authority, who reviewed the original manuscript.

LAWS AND REGULATIONS

Existing laws and regulations related to waste disposal include the Resources Conservation and Recovery Act (42 USC 6901) and 7 Delaware Code, Chapters 60, 61, 64, and 74. These laws and regulations are enacted with the general purpose of preventing future contamination of water resources, ground water in particular. They represent means of protecting our environment and thus minimizing potential health hazards posed by the waste.

SOLID WASTE DISPOSAL IN DELAWARE

Much progress has been made in solid waste disposal in the State of Delaware. The Department of Natural Resources and Environmental Control (DNREC) is the regulatory agency responsible for issuing permits for the operation of new landfills. The Delaware Solid Waste Authority is mandated by the General Assembly to carry out planning and management of solid waste.

In New Castle County the Authority operates the landfill at Pigeon Point. The Delaware Reclamation Project is currently underway at Pigeon Point and when it is completed it will become the Northern Solid Waste Facility. At Sandtown, in Kent County, the Central Solid Waste Facility is in operation. This is the first lined landfill for municipal solid waste in Delaware.

Generalized criteria for the selection of landfill sites have been adopted (October 16, 1980) by the Board of Directors of the Delaware Solid Waste Authority. The development of these criteria was a very complex process because, in addition to geologic and hydrologic factors, consideration had to be given to transportation and social and other aspects.

In Delaware, we are already experiencing difficulties in selecting suitable sites for landfills. The adopted

TABLE 1. LANDFILLS IN DELAWARE

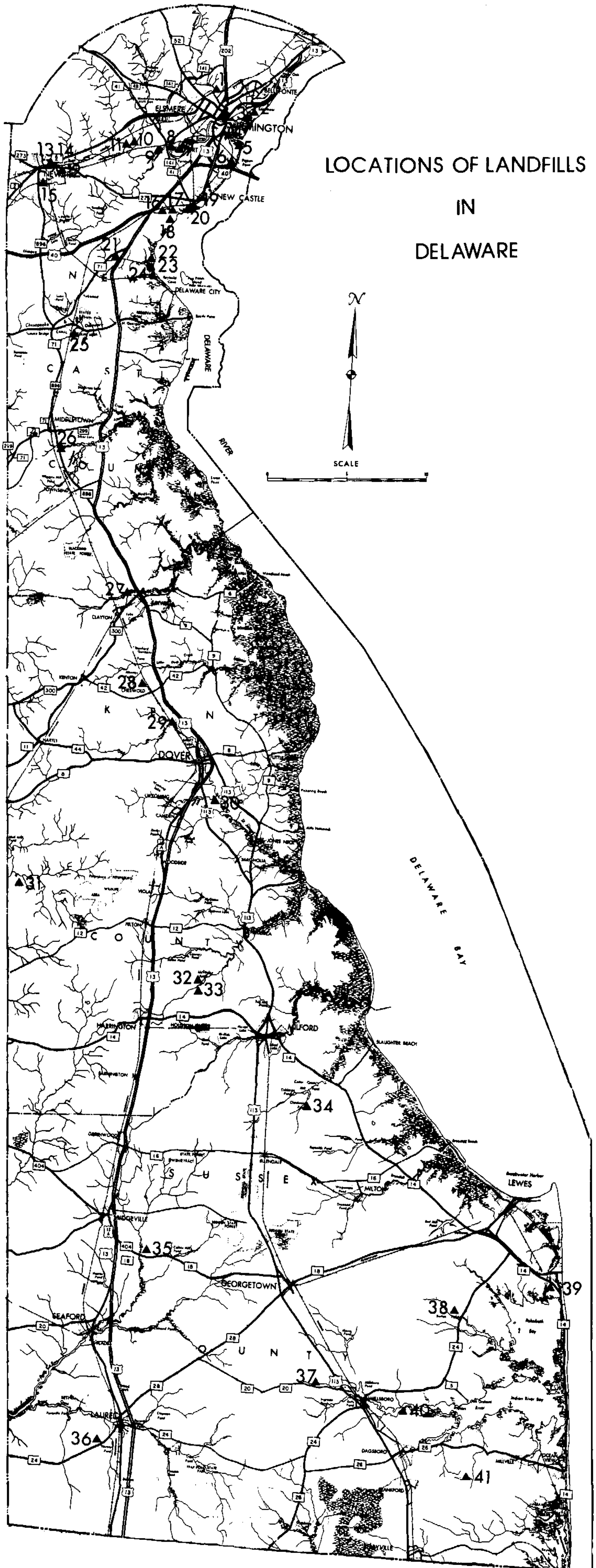
Number	Facility Designation	Size (acres)	Classification of Operation	Composition of Wastes	Period of Operation	Monitoring Wells
1	Container Corporation of America	5	Landfill	Wire, string, plastic, metal	Prior to 1968-1975	no
2	Delmarva Power and Light Co., Edgemoor	1	Landfill	Fly ash	1951-1971	no
3	E. I. DuPont - Edgemoor	17	Landfill (formerly waste lagoons)	Industrial, including sludges, coke, ore, pigment particles	1971 - open	yes
4	Delaware Contracting Co., (Formerly Pyrites Co.)	12	Landfill	Demolition and construction debris, wood, metal, ceramics, rubber	1968 - 1977	no
5	City of Wilmington, Marine Terminal	60	Landfill	Demolition and construction debris, some dredge spoils	1968 - open	no
6	Pigeon Point Landfill	177	Sanitary Landfill	Municipal, commercial, and industrial	1971 - open	yes
7	Harvey & Knotts	11.5	Landfill	Paint sludge, construction debris, other undetermined	1930's - 1978	no
8	City of Newport	10	Landfill	Municipal, some demolition & industrial	1967 - 1974	no
9	E. I. DuPont - Newport	10	Landfill	Industrial, including waste pigment batches, paper, plastics, some low-radioactive wastes	1954 - 1974	yes
10	O & T Realty	5	Landfill	Construction debris	1950 - 1973	no
11	Timko Brothers	2	Landfill	Construction debris	1959 - 1971	no
12	FMC Corporation	0.5	Landfill	Hydrolized cellulose	1968 - 1972	no
13	City of Newark	3	Sanitary Landfill	Municipal and commercial	1960's	no
14	City of Newark	3	Sanitary Landfill	Municipal and commercial	1960's	no
15	City of Newark	2	Sanitary Landfill	Municipal and commercial	1970 - 1973	yes
16	Llangollen (Army Creek)	58	"Sanitary" Landfill	Municipal, commercial, and industrial	1960 - 1968	yes
17	Delaware Sand and Gravel	25	Landfill and open dump	Commercial & industrial, including waste oils and chemicals, some municipal and sludges	1968 - 1976	yes
18	Weaver's Poleline Construction	60	Landfill	Polypropylene, construction & chemical	1965 - 1981	no
19	Abex Corporation	4	Landfill	Sand, slag, bricks, paper, wood, pallets	1900 - open	no
20	Wilmington Fibre Specialty Co.	1	Controlled burning dump	Cellulosic plastics	1969 - 1973	no
21	Tybouts Corner	50	Sanitary Landfill	Municipal, commercial, and industrial	1969 - 1971	yes
22	Delmarva Power and Light Co. - Delaware City	3	Landfill	Fly ash and sludge	1969 - open	no
23	Diamond Shamrock	3	Landfill	Waste polyvinyl chloride, ferric hydroxide, calcium chloride, calcium hydroxide	Prior to 1973-1974	yes

Table 1 (continued)

Number	Facility Designation	Size (acres)	Classification of Operation	Composition of Wastes	Period of Operation	Monitoring Wells
24	Getty Oil Company	37	Landfill	Waste-water sludge, spent catalysts, ceramic tower packing, tar-like sludges, etc.	1957 - open	yes
25	Carmen Micucio	25	Landfill	Industrial, includes wooden pallets, paper, plastic	1970 - 1980	no
26	Delaware Division of Highways, Middletown	3	Open dump	Roadside debris	1967 - open	no
27	Town of Clayton	5	Sanitary Landfill	Municipal	1968 - 1978	yes
28	Coker's Sanitation Service	50	Landfill	Semi-solid synthetic rubber processing wastes	1969 - 1981	yes
29	City of Dover	--	Landfill	Fly ash, sewage sludge, leaves, brush	Prior to 1968-Open	no
30	Wildcat Landfill	90	Landfill	Municipal, industrial, and commercial	Prior to 1968-1974	no
31	Sandtown	384	Sanitary Landfill	Municipal, industrial, and commercial	1981 - open	yes
32	All-Rite Rubbish Removal (Porter's Landfill)	6	Landfill	Plastics	? - open	no
33	Sills Landfill (Kent County)	108	Landfill	Municipal and industrial	1969 - 1980	yes
34	Anderson Crossroads (Sussex County No. 4)	51	Sanitary Landfill	Household, commercial, industrial, agricultural, and institutional	1970 - open	yes
35	Bridgeville (Sussex County No. 1)	135	Sanitary Landfill	Household, commercial, industrial, agricultural, and institutional	1969 - open	yes
36	Laurel (Sussex County No. 5)	39	Sanitary Landfill	Household, commercial, industrial, agricultural, and institutional	1970 - 1979	yes
37	Georgetown (Sussex County No. 2)	109	Sanitary Landfill	Household, commercial, industrial, agricultural, and institutional	1969 - open	yes
38	Angola (Sussex County No. 3)	53	Sanitary Landfill	Household, commercial, industrial, agricultural, and institutional	1969 - 1980	yes
39	City of Rehoboth Beach	8	Landfill	Municipal, commercial	1968 - 1976	yes
40	Delmarva Power and Light Co. - Indian River	--	Landfill	Fly ash	Prior to 1976-open	yes
41	Omar (Sussex County No. 6)	97	Sanitary Landfill	Household, commercial, industrial, agricultural, and institutional	1971 - 1980	yes

(Source: Frick, 1975; Frick and Shaffer, 1976; and Enviro-Engineers, Inc. and Bivens Assoc., Inc., 1974.)

LOCATIONS OF LANDFILLS IN DELAWARE



NOTE:
For description of landfills see TABLE 1
(Source: Frick, 1975; Frick and Shaffer, 1976; and Enviro-Engineers, Inc. and Bivens Assoc., Inc., 1974.)

criteria will ease the selection process, but the selection of appropriate sites will, no doubt, remain a controversial subject.

The great majority of existing (or abandoned) landfills in Delaware, as well as potential future ones, are located in the Coastal Plain, the largest portion of the State (Table 1; Map 1). The sediments in the Coastal Plain are mainly composed of unconsolidated clays, sands, and gravels. Outcrops and subcrops of sandy deposits serve as major recharge zones to aquifers. Ground water occurs under water-table conditions in the outcrop and subcrop areas, and is confined farther downdip (southward) where relatively impermeable sediments separate different aquifers. All public, municipal, and industrial water supplies in Delaware south of the Chesapeake and Delaware Canal come from ground water, as does a significant portion of supplies north of the Canal.

LANDFILL DESIGN AND SITING

Landfill Siting Criteria

Proper site selection should include careful consideration of all the relevant geologic and hydrologic factors.

Subsurface geologic and hydrologic conditions should be determined in detail before a site is utilized for waste disposal. Potential pathways for contamination can and should be located and evaluated in planning; they should not be subjects of search in case problems develop. Monitoring is important in its own right, but it is not a substitute for prior knowledge of subsurface conditions.

Specific, hypothetical geologic requirements that may be used as guidelines for selecting a suitable site are shown below, classified into two major groups: (1) criteria not subject to compromise and, (2) criteria subject to judgment.

Group 1. The following requirements are considered to be absolute and not subject to compromise:

1. The base of the natural or artificial liner of the landfill must be at least 5 feet* above the seasonally high water table.

2. The base of the leachate collecting basin must be at least 3 feet above the seasonally high water-table.

3. Natural or artificially induced flow in the local water-table aquifer must be away from populated areas, existing water supply wells, and other facilities where pollution of ground water by leachate will create hazards.

4. Local topography must prevent surface water run-off from entering and collecting in the proposed site.

Group 2. The following additional criteria are subject to judgment:

1. The site is located 500 feet or more from all:

   wetlands
   undrained depressions
   carbonate terrane
   surface and subsurface fracture zones
      and faults
   areas prone to subsidence
   areas prone to sliding and slumping
   ground-water recharge zones
   surface waters

   and no corrective measures or modifications of the site are necessary, or

2. The site is located 250 to 500 feet from all:

   wetlands
   undrained depressions
   carbonate terrane
   surface and subsurface fracture zones
      and faults
   areas prone to subsidence
   areas prone to sliding and slumping

---

* A five-foot thick zone of sediment is considered adequate to provide an initial barrier between the waste and the water table.

ground-water recharge zones
surface waters

and minor corrective measures and modifications may be made to reduce the risk of pollution, or

3. The site is located 250 feet or less from one or more of the following:

   wetlands
   undrained depressions
   carbonate terrane
   surface and subsurface fracture zones and faults
   areas prone to subsidence
   areas prone to sliding and slumping
   ground-water recharge zones
   surface waters

   and major corrective measures and modifications may be necessary to reduce the risk of pollution.

In addition to the above criteria one should also consider the physical characteristics of soils at and in the proposed site. "Soils," as used here, is a term applied to all loose or moderately cohesive materials including gravel, sand, silt, and clay. The type and properties of soils will be determining factors in deciding whether or not an artificial liner is needed. The soil criteria are subdivided into three groups:

1. The compositions, textures, structures, and thicknesses of soils at the site are suitable* and ground-water pollution by movement of leachate through the soil is very unlikely.

2. The compositions, textures, structures, and thicknesses of soils at the site are marginally suitable and ground-water pollution is possible. Limited corrective measures and modification of the site may be necessary to reduce the risk of ground-water pollution through soil.

---

* Very fine soil, such as clayey soil, several feet thick, with very low permeability and porosity is an example of suitable soil.

3. The compositions, textures, structures, and thicknesses of soils at the site are unsuitable* and migration of leachate is possible. Extensive modification and corrective measures of the site may be necessary to reduce the risk of ground-water pollution through soil.

Landfill Design

A landfill can be designed to pose minimal danger to the environment.

The basic hydrologic requirements are that a landfill be constructed above the local water table, have an impermeable base (natural or artificial), incorporate a drainage system to control the flow of leachate, have means of filtering major contaminants from leachate before discharge into the environment, and incorporate venting systems for gases generated by waste (Fig. 1). Moreover, the natural or artificially induced flow of water in the local water-table aquifer should be away from areas where it may cause hazards.

In the areas where the physical characteristics of the underlying soils are not suitable as a landfill liner, artificial liners are used. There are many types of natural and artificial materials that can be used: bentonite and other clay sealants, asphaltic liners (asphalt, concrete and soil cement), soil sealant (lime), sprayable liquid rubber, and synthetic polymeric liners (butyl rubber and polyethylene), and some others.

In selecting the right kind of liner one has to consider the composition and type of waste. Some waste may contain chemical components that could damage or weaken the liner. One should also consider whether or not the liner can be punctured easily, and how thick it has to be for a given amount and type of refuse.

Every landfill should have several monitoring wells strategically located so that any possible leak of leachate can be detected. Early detection is extremely important so that the necessary remedial measures can be taken and damage to the environment, particularly to ground water, minimized.

---

* Sandy soil with high porosity and permeability is an example of unsuitable soil.

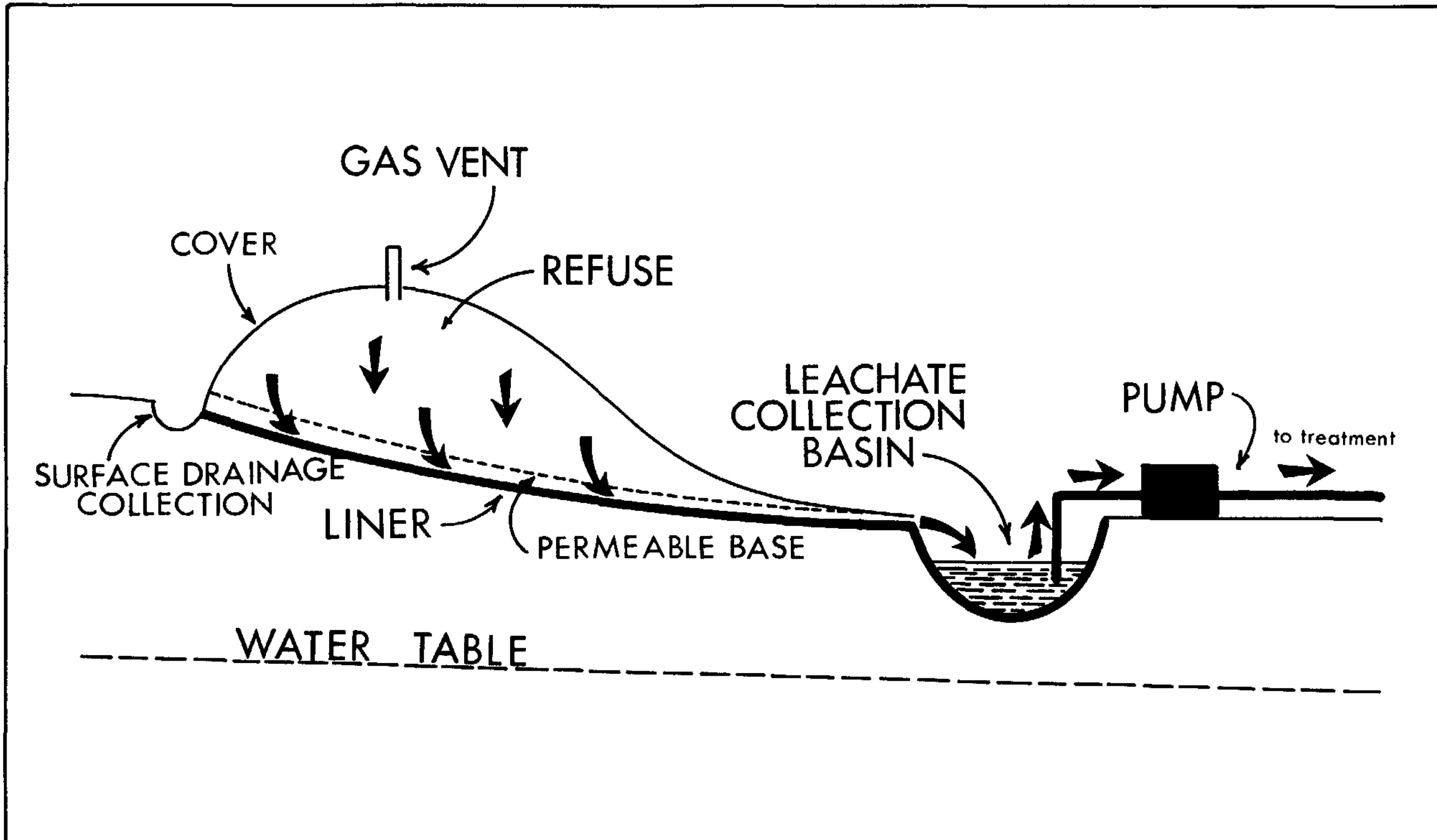


Figure 1. Schematic diagram of a landfill with useful terminology. Arrows indicate leachate flow paths.

MODERN METHODS OF TREATMENT AND
DISPOSAL OF SOLID WASTE

Composition of Solid Waste

The composition of refuse (solid waste) is highly variable and dependent upon many factors such as geographic location and the type of refuse (industrial or community).

Some of the most common constituents of refuse are: paper, food waste, wood, plastics, rubber, paints, oils, metals, glass, ceramics, and leather (more detailed composition is shown in Table 2). Some components of the waste are very dangerous or toxic. Other toxic compounds may develop during the decomposition of the waste, for example: methane, hydrogen sulfide, various organic compounds, chloride, sulfate, and some major and heavy metals.

Disposal of Solid Waste

The actual disposal of solid waste in a landfill is commonly done by spreading and compacting the waste in layers within a confined area called a cell. After a certain amount of waste has been accumulated in the cell, it is covered daily with a thin layer of soil and compacted. A horizontal series of cells make up a lift (Fig. 2).

The dimensions of cells depend on the amount and kind of waste; they are usually several feet thick.

Landfill operations may also employ such techniques as grinding, milling, or shredding of refuse, and the addition of sewage sludge.

Refuse is shredded in order to make sites more acceptable to the public, increase the density of refuse in pounds per cubic yard of landfill space, promote decomposition of refuse, and reduce the amount of cover material needed.

In addition, reusable components of solid waste, such as glass and metal, may be separated from the rest of the waste and returned to appropriate plants for recycling.

Organic wastes suitable as sources of energy may also be separated and, after proper treatment, used as fuel. Interest in the conversion of organic waste to energy is a recent development. This concept is attractive for two

TABLE 2. Composition of Solid Waste

Component	Paper	Garden	Metal	Glass	Food	PRLT[b]	Fines[c]	ARD[d]	Diapers	Wood	Composite
COD[e]	0.804	0.815	0.492	0.011	0.754	2.14	0.935	0.040	0.720	0.503	0.520
TKN*	0.028	0.171	0.022	0.140	3.09	1.25	0.131	0.119	0.138	0.228	0.247
Total Phosphate	0.048	3.14	2.79	0.049	10.4	1.40	1.97	4.48	2.65	0.103	2.32
Lipids	2.47	3.04	0.420	1.54	13.8	5.02	4.85	1.52	2.26	1.00	2.84
Ash	92.0	36.5	4.85	2.25	41.6	182	49.5	19.6	96.0	77.9	25.8
Crude Fiber	21.7	16.6	0.235	0.040	10.5	21.5	6.39	5.85	13.7	20.8	11.3
Total Carbon	58.0	14.4	4.80	0.750	19.5	15.8	16.4	13.4	44.5	51.0	24.8
Inorganic Carbon	4.30	4.66	3.40	0.220	2.58	5.75	4.30	7.80	0.740	0.380	3.08
Organic Carbon	53.7	9.74	1.40	0.530	17.0	10.1	12.1	5.60	43.8	50.7	21.8
Sugar as Sucrose	< 0.1	1.71	<0.1	<0.1	6.08	<0.1	1.18	<0.1	<0.1	<0.1	3.50
Starch	3.40	7.42	<0.1	<0.1	8.57	3.42	7.20	6.40	<0.1	0.78	16.2
Asbestos	NA[f]	NA	NA	NA	NA	NA	NA	NA	NA	NA	<1[g]
Arsenic[h]	<0.1	NA	<0.1	10.2	NA	NA	1.2	3.6	<0.1	<0.1	80
Selenium[h]	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	<0.1
Mercury[h]	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	5.0
Lead[h]	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	15.0
Beryllium[h]	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	<0.1
Cadmium[h]	0.36	NA	20.9	2.7	NA	1.8[i]	4.2	4.5	0.25	1.6	2.4
Iron[h]	375	330	6.25[a]	3220	505	444	0.392[a]	0.340	99.0	0.378	0.782[a]
Zinc[h]	50.0	106	175	9.75	59.0	118	322	181	343	59.4	127
Chromium[h]	8.2	1.1	15.3	1.1	1.3	2.0	13.1	10.1	0.5	1.1	10.7
Manganese[h]	13.1	194	870	15.7	12.2	12.1	115	177	5.90	50.0	90.5
Potassium[h]	11.2	0.135[a]	1.00	2.70	0.162[a]	98.7	135	555	750	90.0	475
Magnesium[h]	160	4175	80.5	472	377	289	1.02[a]	2.63[a]	279	253	0.225[a]
Calcium[h]	77.5	0.830[a]	<0.25	16.2	0.465[a]	912	2.11[a]	4.08[a]	360	590	0.437[a]
Sodium[h]	9.70	185	37.0	60.0	804	143	400	0.209[a]	0.110[a]	572	950
Copper[h]	4.5	9.34	0.221[a]	2.54	8.58	12.4	35.8	32.6	4.14	38.2	31.6
Nickel[h]	15.7	15.7	115	19.0	12.5	32.0	33.2	10.1	3.36	27.0	10.1
Moisture	56.7	156.4	8.80	2.00	216.5	57.04	123	30.79	133	21.43	
Moisture[j]	35.20	56.91	6.18	1.65	70.07	49.27	49.36	18.52	66.28	17.10	
Composition	42.6	10.7	12.2	12.2	3.6	8.7	2.9	3.2	1.3	2.6	
Composition[j]	41.62	15.77	8.21	7.83	7.56	10.91	3.58	3.36	2.47	1.99	

[a]Percent by dry weight unless otherwise specified.

[b]Plastics, rubber, leather, and textiles.

(Source: Fuller, (ed.), 1976).

[c]<25.4 mm (1.0 in.).

[d]Ash, rocks, and dirt.

[e]g COD/g sample.

[f]Not analyzed.

[g]Fibers per gram.

[h]Parts per million by weight.

[i]Plastics, rubber, and leather not analyzed.

[j]Percent wet weight.

* TKN - Total Kjeldahl (nitrogen)

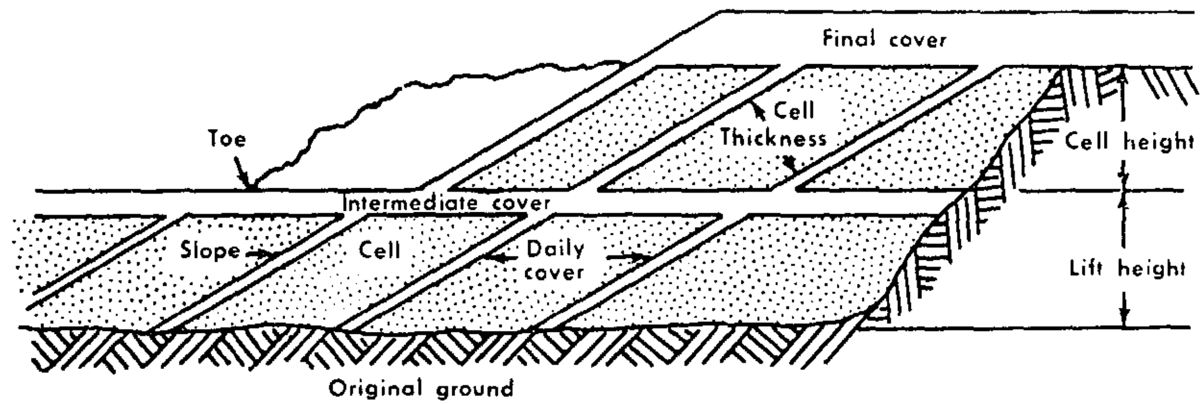


Figure 2. Cross-section of an active landfill showing method of waste disposal in cells. (Source: Brunner and Keller, 1972).

reasons: (1) some components found in solid waste can be effectively utilized as a new energy source, and (2) solid waste disposal problems can be partially alleviated by the conversion of waste into energy.

The estimated total annual amount of usable organic waste in the United States is about 1.5 billion tons. If this were to be utilized as an energy source, it would be equivalent to about 1.4 million barrels of oil or about 9 trillion cubic feet of gas (Garofalo and Martin, 1977).

Decomposition of Waste

Natural decomposition of organic waste is carried out by bacteria and other micro-organisms which use waste as food. The initial decomposition is aerobic (uses oxygen) but soon thereafter becomes anaerobic (does not use oxygen).

Different types of waste decompose at different rates. For example: food wastes, composed of sugars and proteins, are rapidly decomposed. On the other hand, wood and paper decompose slowly. The rate of decomposition is also dependent upon the presence or absence of oxygen, age of the landfill, degree of compaction of the waste, temperature, and moisture content.

Various organic and inorganic substances can be leached out by either ground water or rain water. Leachate is a liquid high in dissolved solids and in chemical and biological oxygen demand (Table 3). Landfills in wet climates generate leachate by water entering the waste, percolating through it, and picking up many soluble materials and products of chemical and biological reactions. Water can enter a landfill from precipitation, springs, surface runoff, ground water, or flooding. Modern landfills are designed and constructed to avoid the intrusion of water. Delaware's regulations do not permit the construction of landfills below the water table.

As the landfill grows older, the composition of leachate becomes more complex and concentrated, and attains a very unpleasant odor.

Landfills in which refuse is deposited in or near the water table are likely to contribute many undesirable organic chemicals to ground water. Even those landfills that do not receive appreciable quantities of solid wastes from industrial

TABLE 3. Composition of Initial Leachate* from Municipal Solid Waste

Component	Study A		Study B	
	Low	High	Low	High
pH	6.0	6.5	3.7	8.5
Hardness, $CaCO_3$	890	7,600	200	550
Alkalinity, $CaCO_3$	730	9,500		
Ca	240	2,330		
Mg	64	410		
Na	85	1,700	127	3,800
K	28	1,700		
Fe (total)	6.5	220	0.12	1,640
Ferrous iron	8.7+	8.7+		
Chloride	96	2,350	47	2,340
Sulfate	84	730	20	375
Phosphate	0.3	29	2.0	130
Organic-N	2.4	465	8.0	482
NH_4-N	0.22	480	2.1	177
BOD	21,700	30,300		
COD			809	50,715
Zn			0.03	129
Ni			0.15	0.81
Suspended solids			13	26,500

* Average composition, mg per liter of first 1.3 liters of leachate per cubic foot of a compacted, representative, municipal solid waste.

\+ One determination.

(Source: Brunner and Keller, 1972).

operations may pollute ground water with industrial organic compounds by leaching such substances from finished products manufactured for domestic and commercial use.

Potential also exists for long-term pollution of ground water by organic chemicals from older landfills in contact with the water table. Such pollution could persist for many years after landfills are closed.

In addition to leachate, decomposition of waste generates gases, primarily carbon dioxide, methane, and hydrogen sulfide. Methane is particularly dangerous because it forms a flammable mixture with the air (5% - 15% concentration). To prevent significant build-up of gases in landfills, special venting pipes are installed to provide a release and dispersion of gases (especially methane) in the atmosphere.

LEACHATE

Pollution of Ground Water by Leachate

Modern landfills are designed to contain and control the flow of leachate. Commonly, leachate is directed to flow into a catchment basin and from there is pumped either to a treatment plant or through a set of filters before being discharged into the environment, usually to a river (Fig. 1).

Problems develop when leachate escapes from the controlled system in newly constructed landfills, or directly into the environment from the older, improperly constructed, landfills (Fig. 3A).

In most failures leachate seeps through the base of a landfill into the underlying sediments. Many sediments contain minerals that have the capacity either to absorb (and adsorb) many contaminants from leachate, or to exchange (ion exchange) them for the elements found in their composition. Fine sediments, clays in particular, have the ability to do both. In addition, these clays have low permeabilities, thus the flow of leachate through them occurs only at a very slow rate. The absorption (and adsorption) and ion exchange are very complex processes and depend on many variables.

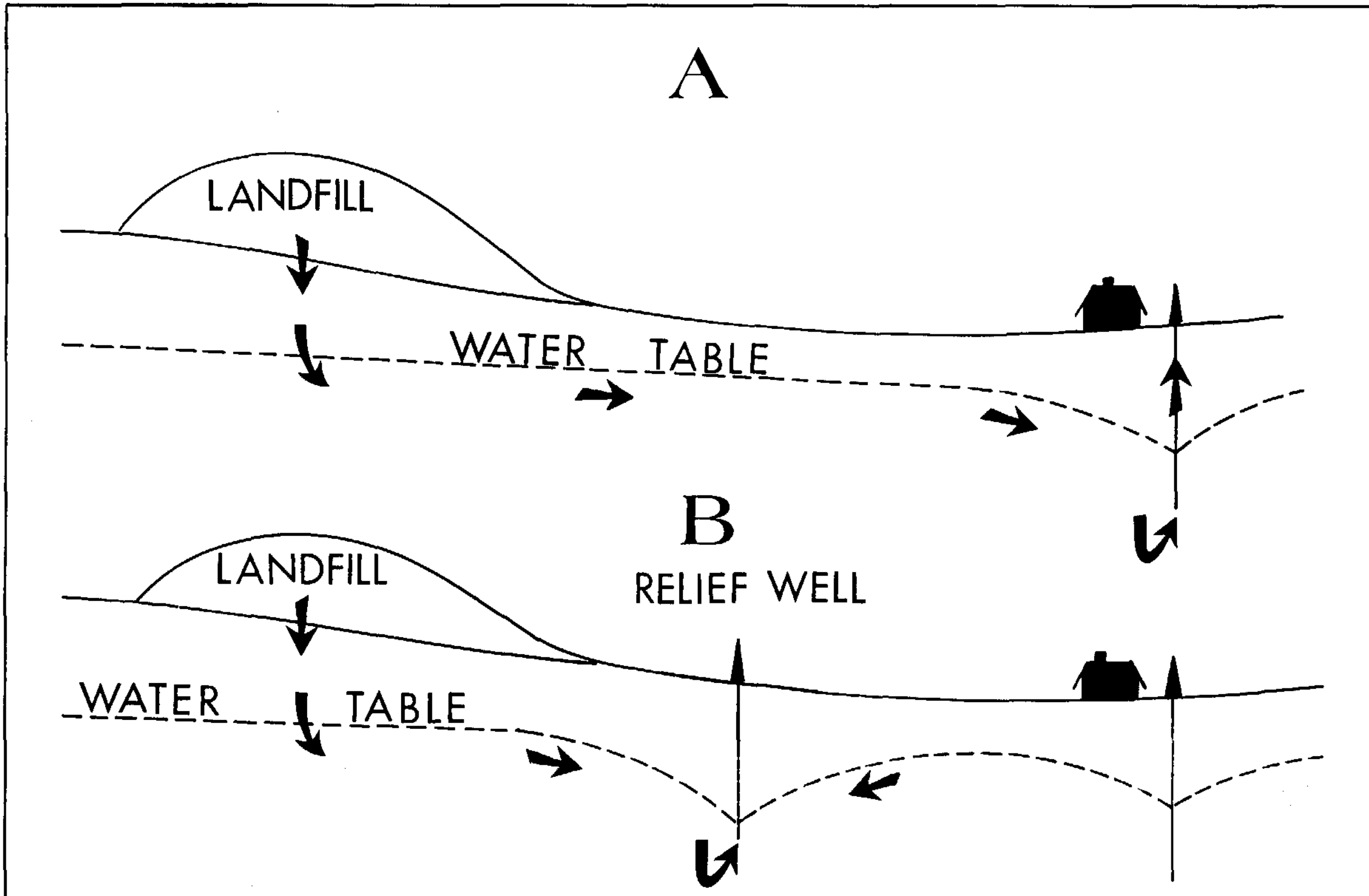


Figure 3. Schematic diagram of water pollution by leachate (A). Leachate diversion from water-supply well by installing a relief well between the landfill and the supply well (B).

Continuous percolation of leachate into the ground below and around landfills eventually leads to the sediment becoming saturated with pollutants from leachate. Thus the sediments become unable to continue to filter out a variety of components from leachate. Leachate then begins to spread farther and farther from the landfill, traveling both through the ground above the water table and via ground water below the water table. When this situation is reached, leachate poses a direct hazard. Leachate reaching surface water, although undesirable, is usually dispersed and diluted; the dilution and dispersion of leachate in the ground water, however, is a very slow process.

Contamination of ground water may escape detection for months, even years. Once ground-water pollution is detected, the damage to the water has been done and it may take a long time before the water quality can be restored utilizing limited methods currently available.

Corrective Measures

The contamination of ground water by leachate in the vicinity of a properly designed landfill usually indicates a leak through a faulty liner. If there are monitoring wells around the landfill, the contamination will be detected by chemical analyses of water samples taken from the wells at pre-specified time intervals.

In some existing landfills only the lower part of the unconsolidated sediments is tapped by monitoring wells, even though other overlying, less permeable water-bearing zones may be present. Under such conditions a portion of ground-water pollution derived from the refuse may flow undetected through the overlying beds.

A similar situation may occur in areas underlain by only one primary water-bearing zone if too few monitoring wells are installed, or if the wells installed tap only the uppermost part of the zone of saturation.

Accurate evaluation of overall pollutant buildup, migration patterns, and flow rates within and beneath the site and surrounding area requires several strategically located stations for samples to be collected and analyzed. The number of sampling points required is primarily controlled by the expected variability of each parameter and the degree of monitoring accuracy required. Sampling-point distribution and monitoring procedures are dictated by geologic, hydrologic, and chemical conditions likely to be encountered. Each water-bearing unit below the landfill may have to be monitored.

If there are no monitoring wells around the landfill (older, improperly designed, landfills) leachate contamination will most likely be detected by ground-water users. The most common signs that water is contaminated are unpleasant odor and taste. At this stage the available remedial measures are quite limited and it usually takes a long time (months, years, or even decades) before acceptable water quality is restored. The most important first step is to reverse the ground-water flow direction away from the user's well. This is achieved by drilling and constructing a well between the landfill and the user's well (Fig. 3B). Pumping water from the newly drilled well eventually reverses the flow and may restore the quality of water in the user's well. The actual length of time it takes to restore acceptable water quality depends on factors such as: distance to the landfill, degree of contamination, and rate of pumping. Of course, ground water is consumed by this process.

An example of this type of contamination and the effectiveness of the described remedial procedure is demonstrated at the Army Creek Landfill near Llangollen (New Castle County Areawide Waste Treatment Management Program, 1977). Here the remedial procedure is still in effect and will continue for an unforseeable time in the future.

Another possible remedial measure is to remove the source of contamination, i.e., to remove the refuse from the landfill, and allow natural purification to restore water quality. Natural purification may take years and thus is not a quick solution of the problem. In the case of a large landfill, the removal of refuse may not be an acceptable or economically feasible solution.

CONCLUSIONS

Despite high rate of recovery of solid waste for reuse or conversion to energy, there are still residues that must be disposed in landfills. There will be a need for landfills until means are found to reuse all of the waste.

Thus the long-term solution to waste disposal in general is to proceed with the development of more efficient and economical means of reusing and recycling as much waste as possible. Simply disposing of waste in landfills is, no matter how well they may be designed, not a solution to this problem.

In Delaware the most modern methods of recycling and disposal of waste will be or are already being employed. The landfills constructed utilizing these methods will probably not pose serious environmental hazards in the future. However, there are numerous old landfills in the State (Table 1) that were improperly designed and may continue to cause serious problems. These should be carefully studied so that the danger they may pose can be alleviated or avoided.

Selected Bibliography

Brunner, D. R. and Keller, D. J., 1972, Sanitary landfill design and operation: U. S. Environmental Protection Agency, 59 p.

Chian, E. S. K. and DeWalle, F. B., 1975, Compilation of methodology for measuring pollution parameters of landfill leachate: U. S. Environmental Protection Agency, 163 p. (EPA-600/3-75-011).

Enviro-Engineers Incorporated and Bivens Associates, Incorporated, 1974, State plan for solid waste management, State of Delaware, Volume 1 and 2: Department of Natural Resources and Environmental Control, State of Delaware, 379 p.

Frick, D. R., 1975, The relation of solid waste disposal to water quality: New Castle County Areawide Waste Treatment Program (208), 35 p.

Frick, D. R. and Shaffer, L., 1976, Assessment of the availability, utilization, and contamination of water resources in New Castle County, Delaware: Office of Water and Sewer Management, Department of Public Works, New Castle County, Delaware, 215 p.

Fuller, W. H., (ed.), 1976, Residual management by land disposal - Proceedings of the hazardous waste research symposium: Tucson, Arizona, 270 p. (EPA-600/9-76-015).

Garofalo, D. and Martin, K. R., 1977, Regional energy availability from conversion of solid waste: Photogrammetric Engineering and Remote Sensing, v. 43, no. 6, p. 727-738.

Genetelli, E. J. and Cirello, J., (eds.), 1976, Gas and leachate from landfills: Formation, collection, and treatment: Research Symposium, New Brunswick, New Jersey: U. S. Environmental Protection Agency, 189 p. (EPA-600/9-76-004).

Griffin, R. A., Cartwright, K., Shimp, N. F., Steele, J. D., Ruch, R. R., White, W. A., Hughes, G. M., and Gilkeson, R. H., 1976, Attenuation of pollutants in municipal landfill leachate by clay minerals, Part 1: Illinois State Geol. Survey, Environmental Geology Notes No. 78, 34 p.

Griffin, R. A., Frost, R. R., Au, A. K., Robinson, D. G., and Shimp, N. F., 1977, Attenuation of pollutants in municipal landfill leachate by clay minerals, Part 2: Illinois State Geol. Survey Environmental Geology Notes No. 79, 47 p.

Hughes, G. M., Landon, R. A., and Farvolden, R. N., 1971, Hydrogeology of solid waste disposal sites in northeastern Illinois: U. S. Environmental Protection Agency, 154 p.

Lindorff, D. E. and Cartwright, K., 1977, Groundwater contamination: Problems and remedial actions: Illinois State Geol. Survey Environmental Geology Notes No. 81, 58 p.

New Castle County Areawide Waste Treatment Management Program, 1977, Preparatory paper for Army Creek (Llangollen) landfill roundtable, November 17-18, 1977 (Abstract).

U. S. Environmental Protection Agency, 1978, Municipal sludge landfills: Process design manual.

U. S. Environmental Protection Agency, 1978, Sludge treatment and disposal: Sludge Disposal, 155 p. (EPA-625/4-78-012).

U. S. Environmental Protection Agency, 1980, Onsite wastewater treatment and disposal systems, 391 p.

Vaughan, R. D., 1969, Solid waste management: The Federal role: U. S. Department of Health, Education and Welfare, Bureau of Solid Waste Management, 22 p.