MUNICIPAL SOLID WASTE DISPOSAL
A PROBLEM IN ENVIRONMENTAL GEOLOGY

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Until a few years ago the priority given to solid waste treatment in the United States has been very low on all levels - governmental, planning, research, corporate and individual. Only when a local crisis has developed would attention turn to the problems of solid waste. Now, in the last quarter of the twentieth century, the problem is more than a rising national concern; it has suddenly coalesced into a national crisis. (1, p. 1)

The Solid Waste Act of 1965 has resulted in an enormous research activity which produced a stream of news releases, technical papers, patent disclosures, resource recovery studies, and forecasts about new methods of waste treatment. But there are as yet extremely few examples of new techniques of solid waste treatment in operation. (1) Both the Twin Cities (St. Paul/Minneapolis) and the City of Duluth in Minnesota are now in the developing stages of building solid waste processing facilities with resource recovery. In the meantime, most of the generated solid waste of these cities is still being deposited on the land, in so called sanitary landfills.

These landfills were started years ago, without regard for environmental conditions, and without the
consultation of geologists for the purpose of studying soil, groundwater, and bedrock characteristics. All too often town dumps are located on the nearest land of low economic value, and in many cases (like Duluth) this has meant filling a marsh or swamp. (1, p. 85)

In many cities the existing landfills are full, and the selection of new areas for filling becomes more and more difficult because of public objection or unsuitability of the land. In the future, thorough land use studies for the deposition of solid waste will become a necessity, for failure of a landfill site may turn out to be an expensive error.

Scope and Purpose

This paper will discuss some of the aspects of municipal solid waste disposal, particularly the physical and technical problems associated with sanitary landfills. One of its purposes is to see to what extent geologic information can be helpful in solving specific land use problems such as the location of landfill sites. Furthermore, this report is primarily a library research paper, required for graduation.
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Mr. Steve Knight
Planner
Western Lake Superior Sanitary District
HISTORICAL TRENDS OF
SOLID WASTE DISPOSAL

The garbage problem has plagued mankind throughout history. Archaeological investigations of past civilizations seem to show that some cities literally buried themselves in trash, so that they had to rebuild repeatedly on top of past garbage accumulation. (1, p. 3) In the cities of the ancient Roman Empire garbage was tossed loose into the streets and periodically picked up by sanitation men who hauled it to a convenient neighborhood dump. (2, p. 17) This practice was common throughout the Middle Ages, and as late as 1741 the streets of London (England) were "... abounding with such heaps of filth as a savage would look on with amazement." (1, p. 4) In 1792 Benjamin Franklin is said to have established the first systematic garbage pickup service for Philadelphia. According to his plan slaves had to carry loads of garbage on their heads for the Delaware River, where they waded out and deposited the garbage downstream from the city. (2, p. 23) Much of this, of course, is still practiced today, for many coastal cities dump thousands of tons of solid waste into the open ocean every day, and hundreds of sites along the Atlantic and Pacific coasts are now set aside by the U.S. Army Corps of Engineers and the U.S. Coast Guard for deposition of various kinds of wastes. (5, p. 125)
Solid household, commercial, and industrial wastes in the United States add up to some .35 billion tons per year, of which only about .19 billion tons are actually collected and disposed of by public and private collectors. The following waste classification provides insight into the absolute amount of solid waste generated each year in the United States:

Table 1

<table>
<thead>
<tr>
<th>SOLID WASTE CLASSIFICATION (in billion tons per year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Household, commercial, and industrial</td>
</tr>
<tr>
<td>Agricultural and crop residue</td>
</tr>
<tr>
<td>Animal wastes</td>
</tr>
<tr>
<td>Mineral wastes</td>
</tr>
<tr>
<td><strong>Total</strong></td>
</tr>
</tbody>
</table>


These staggering 3.5 billion tons of solid waste amount to 17.5 tons per capita per year, or about 96 pounds every day for each person living in the United States.

This paper, however, is concerned with the typical present method of packer truck municipal refuse collection and subsequent on-land deposition. A compaction-type refuse-pickup truck of typically twenty-cubic-yard compacted
capacity with a driver and two collectors empties the source containers once a week and removes the trash to an incinerator or a landfill.

Household, commercial, and industrial wastes alone (see Table 1 on page 5) generated in the United States are estimated to average 10 pounds/capita/day. Over the years, largely because of the increase in paper consumption, the uncompacted volume of solid wastes has been increasing at a faster rate than the growth in weight, a fact which will make collection in the future more difficult and costly. According to the records kept by the St. Louis County Health Department, the city of Duluth averages a monthly volume of collected urban solid waste of about 30,000 cubic yards, whereby more than two thirds of this waste is residential. All of this refuse is presently deposited on the sanitary landfill near the International Airport. It is estimated that the absolute increase of this waste volume will rise substantially, regardless of any percentage decline in the rate of population growth. See Fig. 1 for illustration.
Ideally, waste management problems should be solved on the regional level because land requirements and facilities must be planned on a time scale of several decades, sufficient to provide for foreseeable developments.(3,p.467) Individual communities would never have the resources or the experience necessary to carry out that kind of planning. In order to be effective, however, a
regional agency needs the cooperation of its constituent units, the authority to enforce standards, right of eminent domain, and the revenue sources necessary to accomplish its goals. Yet, the majority of American citizens, although concerned about the problems of solid waste disposal practices, are unwilling to provide the additional funds for necessary improvements. Consequently, national priorities should be reoriented to make the funds available to local governments and relevant agencies for the implementation of existing solid waste disposal practices. Waste management is ultimately the responsibility of government, and its ability to cope with the wastes of society will determine, to a great extent, national environmental quality.

Political difficulties begin usually at the local unit of government that is responsible for collection, because local citizenry are less willing to accept waste generated outside their community. Rail haul proposals are therefore slow in being accepted, and pipeline transport of solid wastes meets opposition from both property rights conflicts and high initial costs.

The bulk expenditures for solid waste is accounted for by the costs of collection which is a labor intensive service. As the urban expansion continues to move outward from the central city, land suitable for sanitary landfill
becomes increasingly scarce and sometimes inaccessible and, consequently, cost will rise. For large cities it is therefore indispensable to build resource recovery facilities and incineration plants which could produce usable energy and provide revenues from sale of recovered resources. Several progressive cities, including Duluth, are now in the process of building solid waste processing facilities; the one for Duluth to begin operation in 1979.

In the United States there are more than 12,000 governmentally controlled land disposal sites, 94 percent of which are unacceptable in terms of public health and environmental protection, in that they do not meet the minimum standards for sanitary landfills. Most of these land disposal sites are open dumps, and in many urban areas waste removal service is inadequate. According to Robert H. Finch, former Secretary of HEW, it was estimated that in 1968 alone at least 14,000 people suffered rat bites, and a recent study indicated a relationship between mismanaged solid waste and no less than 22 human diseases prevalent in this country. For this reason alone, sound waste management is an absolute necessity.
The United States spend annually 4.5 billion dollars for solid waste management, whereby three-fourths of these enormous costs are needed to cover collection and transportation alone. (6, p. 159) Other pertinent elements of refuse disposal management include organization, personnel, systems control, directing, cost accounting and budgeting. (4, p. 346) 85 percent of all urban solid wastes is being disposed of in open dumps, and about 5 percent in sanitary landfills. Only about 10 percent is incinerated, and the ash residues are going to the land. Thus the land is the principal recipient of solid wastes and, indeed, the decreasing availability of suitable sites for deposition in or near metropolitan areas poses a major land use problem. (6)

It has been suggested that 12 million tons of steel per year (about 10 percent of the annual production) is discarded in landfills, so that deposited solid wastes may become future sources of raw material for reuse. (6) This statement makes it clear why the construction of resource recovery facilities should no longer be delayed and why waste management needs to be reorganized on all levels.
The Nature of the Problem

Faced with the reality of disposing billions of tons of solid waste each year, source reduction of the amount and composition of solid waste at the source of generation is an important means of attaining the goal of resource conservation. In fact, source reduction represents the key to conservation of both materials and energy.(7,p.23)

Waste is also a form of pollution and it has been recognized as a public health problem of ever-expanding dimensions. Projections of present growth rates of urban populations when compared with those of per capita waste generation suggest that the present efforts for control must be substantially increased only to maintain the problematic waste levels in the urban centers.(8,p.8)

But it is not easy to convert the present production system, for it involves the economy of the whole nation. Production growth, spurred by consumption need, is the underlying cause of our present-day pollution.(3,p.455) Industry adaptations such as extension of product lifetime or recyclability of manufactured goods are long-term propositions. In the meantime, waste management must not only try to recover as much resources as possible, but also demand markets for the recyclable material. Glass, for instance, cannot be recovered to meet market specifications,
and approaches should therefore be devised whereby glass manufacture is standardized for increased recyclability. (7,p.24) At this time the available technology does not provide for fast and clean separation of mixed urban solid wastes into usable fractions, nor are there markets for such material. (6,p.166)

Very important for improved waste management is also additional data in regional meteorology, hydrology, geology, and ecology; acceptable levels of pollution for various conditions of air, land, and water use; and systems of management that include all aspects of waste disposal on a regional or sub-regional basis. (8,p.9) Also, existing institutional arrangements should be modified to fit waste management to geographic rather than political boundaries. (8)

Legislative and Institutional Problems

Legislation regarding solid waste disposal is most inadequate at all governmental levels. (8,p.16) There is no specific federal legislation in this area; therefore the agencies did not have sufficient funds to assemble and interpret data that could assist local control agencies. Only half the states have solid waste legislation, and only 16
of these have actual programs directed toward solid waste problems.\(^{(8)}\) Also, most local areas seem to lack any jurisdictional coordination to approach solid waste management on a regional basis. In some metropolitan areas, however, refuse disposal service is provided on a region-wide basis by special-purpose districts (e.g. WLSSD, Western Lake Superior Sanitary District, in Minnesota).

A fundamental weakness at the federal level is that existing legislation is directed toward pollution problems after they occur, and practically no laws are written to prevent pollution in the first place.\(^{(8, p.16)}\) Furthermore, there is a complete lack of coordination among the laws relating to pollution with respect to different government levels and the various pollution environments.

The main inadequacies in the institutional pattern with regard to pollution control are much like those of the legislative model. In general, the problems stem from the wide disparity in the powers and structures of state agencies, and the unwillingness of some states to accept responsibility where local legislation is completely lacking.\(^{(8, p.17)}\) However, the Solid Waste Disposal Act of 1965 (PL-89-272) and the Resource Recovery Act of 1970 (PL-91-512) enable the Bureau of Solid Waste Management to provide regions and municipalities with technical and financial assistance in planning and conducting solid waste
programs. This will make for better cooperation among the different levels of government and allow utilization of concepts developed at the state level. (3, p. 468)

<table>
<thead>
<tr>
<th>Name</th>
<th>Content</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Garbage</td>
<td>Wastes from the preparation, cooking, and serving of food. Market refuse, waste from the handling, storage, and sale of produce and meats.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Paper, cardboard, cartons. Wood, boxes, plastics.</td>
<td>households, institutions, and commercial concerns such as: hotels, stores, restaurants,</td>
</tr>
<tr>
<td></td>
<td>Combustible (primarily organic) Rags, cloth, bedding. Leather, rubber.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Grass, leaves, yard trimmings.</td>
<td></td>
</tr>
<tr>
<td>Rubbish</td>
<td>Metals, tin cans, metal foils. Dirt.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Noncombustible (primarily inorganic) Stones, bricks, ceramics, crockery.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Glass, bottles. Other mineral refuse.</td>
<td></td>
</tr>
<tr>
<td>Ashes</td>
<td>Residue from fires used for cooking and for heating buildings, cinders.</td>
<td></td>
</tr>
<tr>
<td>Bulky Wastes</td>
<td>Large auto parts, tires. Stoves, refrigerators, other large appliances.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Furniture, large crates. Trees, branches, palm fronds, stumps, flotage.</td>
<td></td>
</tr>
</tbody>
</table>

cont. next page
<table>
<thead>
<tr>
<th>Name</th>
<th>Content</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Street refuse</td>
<td>Street sweepings, dirt.</td>
<td>From: streets, alleys,</td>
</tr>
<tr>
<td></td>
<td>Leaves.</td>
<td>vacant lots, etc.</td>
</tr>
<tr>
<td></td>
<td>Catch basin dirt.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Contents of litter receptacles.</td>
<td></td>
</tr>
<tr>
<td>Dead animals</td>
<td>Small animals: cats, dogs, poultry, etc.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Large animals: horses, cows, etc.</td>
<td></td>
</tr>
<tr>
<td>Abandoned vehicles</td>
<td>Automobiles, trucks.</td>
<td></td>
</tr>
<tr>
<td>Construction &amp; Demolition wastes</td>
<td>Lumber, roofing, and sheathing scraps</td>
<td>From: factories, power</td>
</tr>
<tr>
<td></td>
<td>Rubble, broken concrete, plaster, etc.</td>
<td>plants, etc.</td>
</tr>
<tr>
<td></td>
<td>Conduit, pipe, wire, insulation, etc.</td>
<td></td>
</tr>
<tr>
<td>Industrial refuse</td>
<td>Solid wastes resulting from industrial processes</td>
<td>From: households,</td>
</tr>
<tr>
<td></td>
<td>and manufacturing operations, such as: food-</td>
<td>hospitals, institutions,</td>
</tr>
<tr>
<td></td>
<td>processing wastes, boiler house cinders, wood,</td>
<td>stores, industry, etc.</td>
</tr>
<tr>
<td></td>
<td>plastic and metal scraps and shavings, etc.</td>
<td></td>
</tr>
<tr>
<td>Special wastes</td>
<td>Hazardous wastes: pathological wastes, explosives</td>
<td></td>
</tr>
<tr>
<td></td>
<td>radioactive materials.</td>
<td></td>
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<tr>
<td></td>
<td>Security wastes: confidential documents, negotiable</td>
<td></td>
</tr>
<tr>
<td></td>
<td>papers, etc.</td>
<td></td>
</tr>
<tr>
<td>Animal and Agricultural wastes</td>
<td>Manures, crop residues</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Coarse screenings, grit, septic tank sludge,</td>
<td>Sewage treatment plants</td>
</tr>
<tr>
<td></td>
<td>dewatered sludge</td>
<td>septic tanks</td>
</tr>
</tbody>
</table>

Methods of Solid Waste Disposal

The disposal of the solid wastes generated by our urban environment is generally accomplished by one or more of several methods, each of which has its unique relation to the water resource of the area. The general methods of solid waste disposal are:

1. Open dumps
2. Incineration
3. Onsite disposal
4. Feeding of garbage to swine
5. Composting
6. Resource recovery methods
7. Sanitary landfill

Open dumps are by far the oldest and most prevalent method of disposing of solid wastes. In general, little effort is expended to prevent the nuisance and health hazards that frequently accompany open dumps.

Incineration is the process of reducing combustible wastes to inert residue by burning at high temperature of about 1,800°F. The residual ashes and noncombustibles generally have a volume of 5 to 25 percent of the original volume.

Onsite disposal is a way of minimizing the waste problem at its source. Most widely used devices for onsite
disposal are incinerators and garbage grinders. Onsite incineration is used in apartment houses and institutions. Garbage grinders, on the other hand, are becoming increasingly prevalent in homes for disposal of kitchen food wastes.

Swine feed has been an accepted way of disposing of the garbage part of solid wastes from urban areas. Even as late as 1960, this method was employed in 110 American cities. The feeding of raw garbage, however, led to a widespread virus disease in the 1950's, which affected hundreds of thousands of swine. As a result, all states now require that garbage be cooked before feeding to destroy contaminating bacteria and viruses.

Composting is the biochemical decomposition of organic substances to a humuslike material. It is the partial decomposition of the moist, solid-organic matter by aerobic organisms under controlled conditions. The end product is used as soil conditioner and fertilizer.

Resource recovery methods have to be the waste disposal procedure of the future. In recent years, recovery and reuse of solid waste have shown promise, and many specific methods have been proposed. Generally speaking, however, recycled or secondary materials do not enjoy current usage, and many federal and state policies presently favor use of primary materials. New federal and state policies must be created to promote expanded recycling of recoverable
waste materials. What is most needed is the development of expanded markets which will absorb the increased tonnage of recycled materials. The National Commission on Materials Policy has stated that markets should be created for recovered materials "by encouraging the development of recycling technology, by procurement policies, and by equitable tax and transportation rate treatment for virgin and secondary materials." (7)

The operation principles of a resource recovery plant are the following: Materials recovery refers to the shredding and separation of refuse after it is dumped at a resource recovery processing center. Ferrous metals are first magnetically pulled out of the shredded refuse. Next, the process of air classification segregates the shredded light combustibles from the remaining heavier materials such as plastics, glass, nonferrous metals, leather, etc. When the light combustibles are baled and stored for burning in an incinerator or a pyrolysis chamber, the process of fuel preparation occurs. Pyrolysis is a chemical transformation proceeding in which shredded combustibles (e.g. 300 to 400 tons per day) are mixed with sewage sludge and broken down under conditions of little oxygen and high temperatures and pressure, producing combustible oils and gases. (7, p. 5)

Newsprint, corrugated and office papers of certain types are preseparated at the source of generation in order to meet
market specifications of noncontaminated paper, separated according to type.

**Sanitary landfill** consists of alternate layers of compacted refuse and soil. Each day the refuse is deposited, compacted, and covered with a layer of soil. Since this paper is specifically concerned with sanitary landfills, this type of solid waste disposal will be discussed extensively in the next section.

**SANITARY LANDFILLS**

As defined by the Minnesota Pollution Control Agency, sanitary landfill is a method of disposing of solid waste on land without creating nuisances or hazards to public health or safety. By using the principles of engineering, the solid waste is to be confined to the smallest practical area and be reduced to the smallest practical volume. Furthermore, the waste deposit has to be covered with a layer of earth at the conclusion of each day's operation. (9)

There are several sanitary landfill methods that find application. Some of these, however, must be classified as being in a research or experimental stage at present. The method selected depends on the physical con-
ditions involved and the amount and types of solid waste to be handled.

Trench and area type, and combinations thereof, are the basic landfill methods used today. They will be described in some detail at the end of this classification grouping.

Baling is a variation of basic sanitary landfill, and is used when transfer stations are involved due to long-distance hauling. Refuse will be compacted into bales in the transfer station and then transported to the final landfill site. The even surface of the bales may lead to a lower cover-material requirement, and decomposition should be very slow, which reduces poisoning hazards resulting from the buildup of methane concentrations.\(^{(1,p.87)}\) On the other hand, the uncertain rate of settling of baled landfills presents problems if the land was planned to be used for any type of construction.\(^{(1)}\)

Pulverized Refuse disposal apparently is becoming more and more popular. This method, like baling, involves a transfer station where the collection trucks deliver mixed refuse, which is shredded, compacted, and hauled to the designated landfills. The advantages of this method are volume, dust,
and insect reduction; and the rapid breakdown of
the organic constituents leads to early settling
so that the filled land can be used for other
purposes much sooner. (1,p.88)

Continuous Burial is a newer disposal method in
which special-purpose machines continuously place
the refuse, as received from collection trucks,
under the surface of the land while the top soil
is replaced as the machine advances. Depth of
burial is limited to about three feet so that the
area requirement for this type of landfill is
enormous.

A different machine of the same category is a
mobile compacter which operates directly over a
previously excavated trench, 15 feet deep. The
refuse, received directly from hauling trucks, is
compacted by the machine and extruded into the
trench. The waste deposit is covered with soil
as the compaction-burial machine advances. The
area requirement has been reduced by 75 percent by
this method. (1,p.93)

Pulverization in the Land is a method in which
comminuted refuse is tilled into the topsoil.
Soil bacteria and the available oxygen are supposed
to produce rapid decomposition of the organic
refuse, which then acts as a soil component. This process typically takes about nine to fifteen months, after which time a new load of pulverized refuse can be added and tilled in. Those inorganic components which do not rust or otherwise degrade, will remain unchanged in the soil. Here, too, special-purpose machines are needed.

Artificial aeration is a procedure carried out in special cells (70 x 70 x 15 feet) with an air distribution system. When a cell is full with refuse, it is covered with one foot of soil and supplied with air. After a few days the temperature of the waste deposit will rise up to 200°F, and after 3 months, due to decomposition, the volume is usually reduced by some 40 percent. At this point the contents of the aeration cell are bulldozed over to an adjacent fill area. Experiments with the City of Santa Clara, California, showed, however, that only "normal" municipal rubbish could effectively be aerated, whereas the volume of commercial refuse could not be significantly reduced. (1, p. 94)

Trench and area methods, as indicated before, shall now be discussed in more detail. For any landfill to qualify as a sanitary landfill the following five
requirements must be met:

1. Solid waste must be deposited in a controlled manner.
2. Solid wastes are spread in thin layers.
3. Ground cover of not less than six inches is applied daily.
4. No open burning.
5. All factors contributing to water pollution have to be eliminated.

The building block common to both methods is the cell, a day's compacted waste deposit including the continuous layer of soil. A series of adjoining cells makes up a lift (see Fig. 2).

Figure 2. Cross-section through sanitary landfill. From report (SW-65ts) U.S. Environmental Protection Agency, 1972.
The dimensions of the cell are determined by the volume of the compacted waste, and the field density of most solid waste within a cell should be at least 800 lb per cu yd. This figure may be difficult to achieve if tree branches, rubber powder, plastics, and synthetic fibers predominate because these materials tend to rebound when the compaction load is released. Such materials should be spread in thin layers (2 ft.) only, then covered with 6 inches of soil and over this, mixed solid waste should be compacted so that the overlying weight keep the elastic materials reasonably compressed. In order to prevent severe settlement problems, the height of a cell should ordinarily not exceed 8 feet, although heights up to 30 feet are reported to be common in large operations.

The trench method is an excavation procedure in which solid waste is spread and compacted in a trench. Cover material is taken from the spoil of the excavation and is compacted over the waste to form the basic cell structure (see Fig. 3). When a trench is filled up, a new trench parallel to it will be opened and the operation goes on in this fashion until the dedicated deposition area is filled. It is desirable to have cohesive soils, such as glacial till or clayey silt, in order to achieve a close spacing between the trenches; cohesive soils allow steeper walls for use in trench operations. Furthermore, it is good practice
Figure 3. Trench method sanitary landfilling.
At the end of the day, the trench is extended, and the excavated soil is used as daily cover material.

to align the trenches perpendicular to the prevailing wind in order to reduce the amount of blowing litter. Also, provisions should be made to divert surface water and to drain the bottom of the trench. The depth of the trenches is largely determined by the soil and ground water conditions, and they should be wide enough for the compacting equipment to effectively work in it.

The area method is simpler in that no excavation is necessary. The solid waste is simply spread on to the natural ground and covered with soil, either found on the site or hauled in (see Fig. 4). This method is used on flat or gently sloping land and also in quarries, canyons, strip mines, ravines, valleys, or other land depressions. (10) These last mentioned deposition places are, however, vigorously criticized by the environmental groups of concerned citizens.
The methods used can be varied according to the constraints of a particular site. Therefore, combinations of the area and trench methods find frequent application. One of these variations is the progressive slope or ramp method. Solid waste is spread and compacted on a slope and the cover material is excavated directly in front of the working area (see Fig. 5).
Soils and Geology

The planning of a sanitary landfill involves an analysis of the soil conditions and the study of the geologic features in and around a proposed site. Such a study may be essential in understanding how a landfill construction might affect the environment. Soil conditions surrounding the site are significant to the ultimate success of the landfill. Fine-grained soils are more useful in containing unwanted gas and water movements onside the landfill area, and soil type will ultimately determine how the landfill can be utilized once completed. (3, p. 463)

A comprehensive study identifies and describes the soils present, their variation, and their distribution. It describes the physical and chemical properties of bedrock, particularly as it may relate to the movement of water and gas, because leachate and infiltration movements are affected by the characteristics of the soil and bedrock. (10, p. 13)

Sand and gravel are in general very permeable and therefore represent a great potential for the flow of groundwater. Leachate contaminant travel originating from landfills will usually be greatest in sedimentary formations, such as sandstone, limestone, and conglomerates. Fractures and joints in sedimentary formations increase further permeability. Siltstones and shales, on the other hand, have
a very low permeability unless they have been subjected to jointing.

Leachate movement through igneous and metamorphic rocks should not categorically be discounted since these rocks, too, can be fractured and jointed and thus serve as aquifers of limited productivity. Normally, however, these rocks are known to have a very low permeability.

The availability of suitable soils for cover material is essential for any sanitary landfill operation. The many functions cover material is intended to perform at a landfill are tabulated below (Table 3).

Table 3
SUITABILITY OF GENERAL SOIL TYPES AS COVER MATERIAL *

<table>
<thead>
<tr>
<th>Function</th>
<th>Clean gravel</th>
<th>Clayey-silty gravel</th>
<th>Clean sand</th>
<th>Clayey-silty sand</th>
<th>Silt</th>
<th>Clay</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prevent rodents from burrowing or tunneling</td>
<td>G</td>
<td>F-G</td>
<td>G</td>
<td>P</td>
<td>P</td>
<td>P</td>
</tr>
<tr>
<td>Keep flies from emerging</td>
<td>P</td>
<td>F</td>
<td>P</td>
<td>G</td>
<td>G</td>
<td>E+</td>
</tr>
<tr>
<td>Minimize moisture entering fill</td>
<td>P</td>
<td>F-G</td>
<td>P</td>
<td>G-E</td>
<td>G-E</td>
<td>E+</td>
</tr>
</tbody>
</table>

cont. next page
Table 3 (cont.)

<table>
<thead>
<tr>
<th>Function</th>
<th>Clean gravel</th>
<th>Clayey-silty gravel</th>
<th>Clean sand</th>
<th>Clayey-silty sand</th>
<th>Silt</th>
<th>Clay</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimize landfill gas venting through cover</td>
<td>P</td>
<td>F-G</td>
<td>P</td>
<td>G-E</td>
<td>G-E</td>
<td>E+</td>
</tr>
<tr>
<td>Provide pleasing appearance and control blowing paper</td>
<td>E</td>
<td>E</td>
<td>E</td>
<td>E</td>
<td>E</td>
<td>E</td>
</tr>
<tr>
<td>Grow vegetation</td>
<td>P</td>
<td>G</td>
<td>P-F</td>
<td>E</td>
<td>G-E</td>
<td>F-G</td>
</tr>
<tr>
<td>Be permeable for venting decomposition gas ++</td>
<td>E</td>
<td>P</td>
<td>G</td>
<td>P</td>
<td>P</td>
<td>P</td>
</tr>
</tbody>
</table>

* E, excellent; G, good; F, fair; P, poor.
+ Except when cracks extend through the entire cover.
++ Only if well drained

After U.S. Protection Agency, "Sanitary Landfill, Design and Operation."
The cover material controls the ingress and egress of flies, discourages the entrance of food-seeking rodents, and prevents scavenging birds from feeding on the waste. When suitably compacted, many soils have a low permeability, will not shrink, and can be used to control moisture that might otherwise enter the solid waste and produce leachate (see Table 4 below).

Table 4
INfiltrATION RATES FOR BARE SOILS

<table>
<thead>
<tr>
<th>Soil type</th>
<th>Infiltration rate range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravel; sand gravel</td>
<td>1.0 - 4.0</td>
</tr>
<tr>
<td>Sand; friable silt loam</td>
<td>0.5 - 1.0</td>
</tr>
<tr>
<td>Loam</td>
<td>0.1 - 0.5</td>
</tr>
<tr>
<td>Clay</td>
<td>0.01 - 0.1</td>
</tr>
</tbody>
</table>


Another function of the cover material is to control the movement of gas. Landfill gases can be either blocked by or vented through the cover material. A permeable soil that does not retain much water can serve as a good gas vent.
On the other hand, if gases are to be prevented from venting through the cover material, a gas-impermeable soil with high moisture-holding capacity compacted at optimum conditions should be used.\(^{(10, p.15)}\) In addition to the functions just mentioned, the soil cover maintains the landfill clean and sightly and keeps the litter from being blown away. Last, and quite importantly, the cover material has in places also to serve as a road bed for collection vehicles moving to and from the operating area of the fill. In those places the material will have to be trafficable in all weather conditions, which means that clay soils would have to be avoided. And finally, soil used to cover the final lift should contain adequate nutrients and have a large moisture-storage capacity in order to grow vegetation.\(^{(10)}\)

Sanitary landfilling is a carefully engineered process of solid waste disposal, involving accurate soil analyses and appreciable excavating, hauling, spreading, and compacting of earth. Recommendations for this kind of soil manipulation are often expressed in terms of the following textural classification system (Fig. 6).
Sand - 2.0 to 0.05 mm. diameter
Silt - 0.05 to 0.002 mm. "
Clay - smaller than 0.002 mm. diameter

Figure 6. Textural classification chart.
After U.S. Department of Agriculture.
Soils that contain stones and boulders of varying sizes, as in glaciated areas, hinder compaction and should be avoided. A good practice to locate potential areas for sanitary landfills is to consult surveys prepared by the Soil Conservation Service of the U.S. Department of Agriculture. The surveys show factors like natural drainage, hazard of flooding, permeability, slope, workability, depth to bedrock and others. The SCS surveys are, however, no substitute for thorough, detailed site investigations.

In relation to land forms, flat or gently rolling land not subject to flooding is best suited for sanitary landfills. On the other hand, depressions like ravines and canyons are more efficient than flat areas since they can hold more solid waste per acre. However, they require special measures to keep surface waters from inundating the area, and permeable formations intersecting the side walls or floor of the fill have to be lined with an impervious layer of clay or other material to control the movement of fluids.

Besides natural depressions in the landscape there are man-made topographic features like strip mines, worked-out clay quarries, open pit mines, etc., which could be considered as a deposition site for solid waste. But open pit mines, abandoned limestone, sandstone, and granite quarries generally require more extensive improvements because they are either permeable or fractured. Sand and
gravel pits present a great pollution potential and gas movement and water pollution usually have to be controlled at considerable expense.

Although marshes and tidal lands have little real estate value, they should under no circumstances be used as landfill sites, for they possess immense ecological value as nesting and feeding grounds for wildlife. Besides, they are commonly a direct link to our groundwater systems.

**Hydrologic Implications**

The possibility of ground and surface water pollution in the area of a landfill must carefully be considered at all stages of a fill operation. Even after completion of a waste deposition project, water surveillance monitoring data should be collected for several years, because leachate is a strong pollutant and may remain so for more than a decade after the landfill is completed. Water pollution is caused by refuse leaching, which occurs only when the following conditions exist:

(1) Landfill location in or adjacent to an aquifer.

(2) Supersaturation within the fill caused by the flow of ground water into the fill from percolation
of precipitation and surface water runoff, by water of decomposition, or by an artificial source.

(3) Leachate must be produced and must be capable of entering an aquifer or body of surface water such as a stream or lake.

After a site is filled and reclaimed, the surface sources of water for leaching are rainfall, runoff, and irrigation; subsurface sources are high ground water levels and possible breaks of water mains and sewers. If leaching of a landfill does occur and is not corrected or controlled, the water in the vicinity of the fill can become polluted to the point where it is unfit for human and animal consumption or for industrial and irrigation uses. (4)

In the humid areas of the United States, leachate will be generated from solid waste disposal in a relatively short period of time. In the semi-arid and arid west and southwest, generation of leachate may be delayed for many decades. Initial leachate generation will be dependent on time of emplacement and moisture content; the generation will then be seasonal in response to climatic conditions. (13)

In sanitary landfills, the rate of infiltration is governed by the permeability and infiltration capacity of the soil used as cover material. Part of the water which enters the refuse deposits is absorbed by the porous com-
ponents such as cardboards and paper, and the remaining water percolates downward to the soil zone or even the water table. During the vertical percolation process the water leaches both organic and inorganic constituents from the refuse and, upon entering the water table, the leachate becomes part of and moves with the ground water flow system (see Fig. 7).

![Diagram of leachate movement](image)

Figure 7. (Adapted from W.J. Schneider). Generalized movement of leachate through ground water.

The movement of leachate from a waste disposal site is governed by the physical environment. Since chemical contaminants are in solution, they tend to travel faster than the biological ones, which are easily filtered out from the percolating leachate by sandy or silty soils. The chemical contaminants, however, are carried into the water table and begin to move according to the hydraulics of the specific ground water flow system. Therefore, the pollution
potential of a given system depends largely upon the mobility of the contaminants, their accessibility to the ground water reservoir, and the hydraulic characteristics of that reservoir. (11, p. F7) The configuration of the water table generally reflects the topography, and the leachate flows downgradient under the influence of gravity from uplands to stream valleys, where it discharges as base flow to the stream system.

When dipping confined aquifers crop out in upland areas, they are exposed to recharge and could easily be contaminated by leachate, given the right hydrogeologic conditions. But pollution potential is highest where the water table is at or near land surface, so that waste deposits are in continual contact with the water. Continual contact of waste with water produces extremely strong leachate highly contaminated with both biological and chemical pollutants. Under favorable hydrogeologic conditions, such as permeable materials and steep hydraulic gradients, the leachate may travel rapidly through the ground water system and pollute extensive areas. (11) The following sketches illustrate the hydrologic effects of solid waste disposal in different geologic environments. (See figures 8 through 15)

Leachate
Figures 10 to 12. Different effects on groundwater resources of solid waste disposal sites:

(10) in a permeable environment;
(11) in a permeable environment, underlain by a fractured-rock aquifer;
(12) in a relatively impermeable environment.

Figures 13 to 15. Different effects on groundwater resources of solid waste disposal sites:

(13) in a permeable environment;
(14) in a semi-permeable environment;
(15) in impermeable clay, where leachate follows the contact between clay and the more permeable stratum.


Leachate
Leachate management must be considered as a basic element in the design and location of a sanitary landfill. Most of the ground water and surface pollution problems from landfills have developed because no consideration has been given to what will happen to the leachate once it is generated. In many cases sanitary landfills are designed without an awareness that leachate will even be generated (Emrich, 1970). When a sanitary landfill is conscientiously designed, there are two choices in the management of the generated leachate.

1. The pollutional characteristics of the leachate can be attenuated or renovated as it moves through the underlying earth material before being discharged to the surface or into the ground water.

2. Leachate is collected before it reaches either the surface or the ground water and is treated and eventually discharged to a body of surface water.

The majority of sanitary landfills are designed today on the basis of the first choice. Therefore, sufficient distance of travel through the unsaturated earth materials above the ground water is necessary. Present good design criteria to prevent ground water pollution call for one foot of suitable earth material below the landfill for every foot of refuse. The underlying earth materials may
be deeply weathered rocks (saprolite) or thick soils. This material should be well to moderately well drained. If permeability is high, there will be rapid downward movement of the leachate and insufficient renovation causing ground water pollution. On the other hand, if permeability is low, leachate will pond in the bottom of the refuse deposit and then move laterally, discharging to the surface.

Today there are many sites that are suitable only if the leachate is collected and treated. Sites, in major metropolitan areas, that would be suitable for natural renovation are either in high demand for other uses or no longer available. Leachate collection landfills must be hydraulically isolated from nearby surface and ground water. This can be accomplished through the use of natural or man-made impermeable barriers at the bottom and sides of the landfill. The barriers must be graded so that the leachate drains to collection points. On natural barriers such as dense shale or plastic clays, drain tiles may be set in place to expedite leachate drainage.

A typical man-made barrier would be an asphalt liner mixed with butyl rubber, placed on top of a soil cement. This asphalt liner is then covered with several feet of sand to convey the leachate to a central collection point where it will be pumped to treatment facilities. Ordinary treatment consists of liming the leachate, raising the pH,
reduction of BOD, and precipitation of the heavy metals and iron. The treated leachate is then released into sewage treatment facilities or discharged directly into surface waters.\(^{(13)}\) The quality of surface water upstream and downstream must be known at all times, and geocriteria should include location, flow, and flood frequency of all surface waters in the vicinity of a fill.

**Site selection** for solid waste disposal requires full consideration of the geocriteria like soils, geology, hydrology, and topographic position, because all of these parameters are interrelated. \(^{(11, p. F9)}\) To date, with few exceptions, these considerations have been on a local scale, dealing primarily with the hydrological characteristics of the immediate site.\(^{(11, p. F9)}\) In addition to local factors, water resources must also be considered as regional resources in their relation to solid waste disposal. Planners need adequate regional information in order to weigh all available alternatives and insure that final site selections are compatible with comprehensive regional planning goals and environmental protection concepts.

The solid waste disposal problem is one of the most urgent tasks for most city and county governments. In fact, it is such an important issue that state and federal legislation is needed to solve the problem. The selection of suitable sites for solid waste disposal has to be a
veritable regional planning endeavor which emphasizes the protection and preservation of natural resources such as land, air, and water.

Decomposition and Gas Movement Control

The process of natural decomposition in solid waste is accompanied by the spontaneous production of gas. The quantity generated in a landfill and its composition depend on the types of solid waste that are decomposing. Organic wastes produce most of the gas, and its rate of production is governed solely by the level at which microbial decomposition takes place within a landfill. When decomposition is completed, gas production ceases. It was found that theoretically, if decomposition is carried to completion, each pound of solid waste with 25 percent inert matter can produce more than 6.0 cu ft of gas.\(^{(10, p.7)}\)

The major constituents of landfill decomposition gas are methane (CH\(_4\)) and carbon dioxide (CO\(_2\)). Other gases frequently present are nitrogen (N\(_2\)), oxygen (O\(_2\)), hydrogen (H\(_2\)), and hydrogen sulfide (H\(_2\)S) which has a very repugnant odor. Landfills which contain large amounts of sulfate, for instance, in the form of
gypsum board (CaSO$_4$•2H$_2$O), will usually produce a lot of hydrogen sulfide. However, oxygen-containing groundwater and atmospheric oxygen diffusing into a landfill will oxidize hydrogen sulfide to tasteless and odorless sulfur and sulfates. (4,p.128)

As long as aerobic synthesis prevails, like during the early stages of decomposition, very little methane is produced. On the other hand, if essentially anaerobic conditions (absence of oxygen) exist in a landfill, the decomposition of organic matter results in the formation of major methane and nitrogen, varying with the types of waste. Most of the nitrogen seems to be generated during the first few months of decomposition whereas methane increases with time, reaching the level of carbon dioxide. The table below illustrates the gas proportions at different time intervals.
Table 5
LANDFILL GAS COMPOSITION

<table>
<thead>
<tr>
<th>Time interval since start of cell completion (months)</th>
<th>Average percent by volume</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N₂</td>
<td>CO₂</td>
<td>CH₄</td>
</tr>
<tr>
<td>0 - 3</td>
<td>5.2</td>
<td>88</td>
<td>5</td>
</tr>
<tr>
<td>3 - 6</td>
<td>3.8</td>
<td>76</td>
<td>21</td>
</tr>
<tr>
<td>6 - 12</td>
<td>0.4</td>
<td>65</td>
<td>29</td>
</tr>
<tr>
<td>12 - 18</td>
<td>1.1</td>
<td>52</td>
<td>40</td>
</tr>
<tr>
<td>18 - 24</td>
<td>0.4</td>
<td>53</td>
<td>47</td>
</tr>
<tr>
<td>24 - 30</td>
<td>0.2</td>
<td>52</td>
<td>48</td>
</tr>
<tr>
<td>30 - 36</td>
<td>1.3</td>
<td>46</td>
<td>51</td>
</tr>
<tr>
<td>36 - 42</td>
<td>0.9</td>
<td>50</td>
<td>47</td>
</tr>
<tr>
<td>42 - 48</td>
<td>0.4</td>
<td>51</td>
<td>48</td>
</tr>
</tbody>
</table>

Source: Reference 10

The relationships between time and multiple gas generation as presented in Table 3 are confirmed in the following graph which plots the results of an anaerobic landfill simulation.
Both carbon dioxide and methane are important to consider when evaluating the effect a landfill may have on the environment. When carbon dioxide dissolves, it can form carbonic acid (H$_2$CO$_3$) which causes mineralization of the groundwater.\(^{(10)}\) Methane, on the other hand, is explosive when present in air between 5 and 15 percent.\(^{(10)}\) If methane vents into the atmosphere (its specific gravity
is less than that of air) it may accumulate in buildings or other enclosed spaces on or near a sanitary landfill.

The potential movement of decomposition gas is an essential element in landfill site selection, particularly if enclosed structures are going to be built on or adjacent to the site, or if the fill is to be located near existing developed areas. Soil conditions surrounding the landfill have an important influence on the movement of gas. Clays are most favorable, whereas dry soils do not significantly impair the flow of gas. Thus well-drained soils act as a vent to flow, and if the cover material of a landfill represents a barrier, the gases will migrate laterally until they find a way to diffuse into the atmosphere. Besides emergence in nearby buildings, methane gas from landfills has been found to accumulate in explosive concentrations in sewer lines. Gas from landfills can also kill vegetation by excluding oxygen from the root zone. If the natural soil, hydrologic, and geologic conditions do not provide control of gas movement, then sound engineering principles must be applied. The two basic methods of gas control are those of permeable vents and impermeable barriers, both of which shall be shortly discussed in the following paragraphs.
Permeable methods. Lateral gas movement can be prevented by building gravel vents or gravel-filled trenches in and around the landfill. It is important that the filter material is — under all circumstances — more permeable than the surrounding soil and, furthermore, it should be graded in order to avoid infiltration and clogging by adjacent soil carried in by water. To make sure that all lateral gas flow is intercepted, the trenches should be deeper than the fill and, if possible, they should be drained naturally by using field tile at the bottom. The top of gravel trenches should always be free of soil and vegetation in order to ensure proper venting. The sketch below illustrates the basic idea.

Figure 17. Gravel-filled trenches to control lateral gas movement. After reference 10.
Another method of this type uses a network of perforated pipes with vertical vents inserted through a relatively impermeable top cover (see Fig. 18). The gas collecting pipe system is placed in shallow gravel trenches within or on top of the waste material. The sizes and spacings required depend upon the rate of gas production. Unless the gas is collected or burned off, the vertical vents should never be located near buildings.

Figure 18. Gas venting via pipe systems.
After reference 10.
A similar method which could be mentioned at this point is the use of pumped exhaust wells in which pipe vents are attached to a suction pump that creates differential driving pressure for gas movement.

**Impermeable methods.** The opposite from the venting methods just described is to control gas movement by material less permeable to it than the surrounding soils. An impermeable barrier can be used to contain the gas and vent it through the top cover. This barrier is most commonly built of compacted clay. It is important though that the material be kept moist in order to avoid shrinking and cracking. The clay can either be placed at the bottom of the fill as a liner, or be installed as a curtain wall to block underground gas flow (see Fig. 19). The clay layer should have a thickness of 18 to 48 inches, depending upon clay type, waste, and site conditions. Furthermore, the liner should be constructed as the fill progresses, for prolonged exposure to air could dry it out and result in shrinking and cracking of the clay. If not suitable soil for the construction of impermeable liners is available, synthetic membranes are often used for gas flow barriers.
Figure 19. Clay barriers to block underground gas flow. After reference 10.

THE LANDFILL SITE SELECTION STUDY FOR WASHINGTON COUNTY, MINNESOTA

The following is a summary of a specific site selection study conducted in the state of Minnesota. The purpose for interjecting this summary report here is to study and review some of the advanced methodologies used in land management information today.

Together with the Center for Urban and Regional Affairs (CURA) of the University of Minnesota, the State
Planning Agency, other state governmental branches, several University departments, and other institutions, the Minnesota Land Management Information System (MIMIS) has compiled a landfill site selection study by means of a computer locational analysis.

The primary goal of the project was to improve the quality of land use decisions in both the public and private sector. This objective was achieved by building a data bank of information on physical resources, relative accessibility to market of these resources, and information on current land use, zoning, and ownership patterns.

The basic criteria to be satisfied in the selection of a site for a landfill operation in any county of the state are the mandatory requirements stipulated in the rules and regulations (SW 1 to 12) of the Minnesota Pollution Control Agency (MPCA). These requirements are partly locational and partly site-related in emphasis. The setback standards, for example, are inherently locational problems; surficial geology of a site or its vegetation cover and topography, on the other hand, are referred to by the MPCA as site problems. But even these site-related problems have a locational dimension, because sites of prohibitive geology or topography are identified and eliminated through locational analysis long
before site-specific engineering investigation takes place, thus avoiding the costs of premature site analysis.

The approach MLMIS took in solving the problem of site search was to test every 40-acre parcel of Washington County against location criteria parameters. After identification of the information variables necessary to the computer locational search for suitable landfill sites, the variables were organized into four discreet steps of analysis. Steps 1 and 2 were designed to select out those 40-acre parcels which would be prohibited as landfill sites by the standards of the MPCA regulations. Steps 3 and 4 deal with environmental factors and problems of cost and land use. The variables in step 1 are grouped under such headings as urban development, shoreline proximity, unacceptable surficial geology, floodplains, wetlands, and others. Step 2 organizes the variables into groups of so called "flexible prohibitions" like low density residential character, proximity to airports, parks, or highways. The variables organized into step 3 of the analysis identify parcels prohibited for reasons of environmental factors such as intermittent streams, geology and soil limitations, vegetation, etc. Some of the factors in step 4 are the different classes of wells, haul distance from I-694, and accessibility.
At the end of each step of analysis a computerized summary map was produced, displaying the prohibited parcels and the remaining possible sites. Thus each map shows a phase in the process of elimination. The final, comprehensive map, then, shows those sites that have survived the computer locational search. In the case of the Washington County search, only three sites could stand the test. However, this site selection technique does not make specific recommendations as to the suitability of the three potential sites for a landfill. According to the Minnesota Department of Health representative of the site selection group, "there are serious questions concerning environmental health, groundwater quality protection, landfill design technology, and economics which could dictate that no area of Washington County is suitable for a landfill." As yet there are no fail-safe landfills known which would positively protect the quality of groundwater. Despite the high reliability of computer searches, poor choices can still result when basic information (e.g. geology or hydrology) is inadequate or erroneous. Nevertheless, the MLMIS-study demonstrates the usefulness of a computerized land-use analysis for selecting best use of land from available information.
THE DULUTH SANITARY LANDFILL

In 1958 the City of Duluth started to operate a "modified" sanitary landfill on city owned property in section 31, T51N, R14W, near the municipal airport. Three years later, the Duluth Disposal Company (DDC) was taken under contract to operate the landfill for the city. In the fall of 1965, Duluth Disposal Company purchased the site of the present landfill to begin their own "modified" landfill and, at the same time, the City landfill was discontinued. Since 1972 DDC has a Minnesota Pollution Control Agency sanitary landfill permit, and the site has been operated since that time using a combination of the ramp and area fill methods. The following map defines the geographic location of the landfill and outlines the bedrock geology of the immediate area.
Figure 20. Location map showing the landfill in relation to the city and general bedrock geology.

From reference 17.
Investigation

The writer of this paper has made an effort to look into the Duluth landfill operation and, specifically, to see how well or to what extent this operation conforms to the physical aspects of sanitary landfill principles.

Initial Engineering Analysis: In 1971, Willard Peterson, a consulting engineer from Duluth, analysed the landfill site for Duluth Disposal Company by drilling a series of test holes and designing a scheme for progressive waste deposition. The sketches of the next three pages summarize Mr. Peterson's work.
Figure 21. Existing conditions as of Nov. 1971.

Information by St. Louis County Health Department, after a blueprint by W. Peterson, P.E., Duluth.
Surface Elevations

1426
sandy clay loam with rocks & boulders
12'
14'
water
15'

1417.7

1418.1
firm grey clay
5'
sand
8'
surface water entered hole. W.T. could not be determined.
15'

1423.1

1409
gravel
4'
6'
water

1410
elev. varies
5'
6'
water

5

6
7

An attempt to draw a fence diagram failed because the test holes are too closely spaced. The diagram would have been cumbersome.

Figure 22. Test holes under existing conditions in Nov. 1971.

Information by St. Louis County Health Department, after a blueprint by W. Peterson, P.E., Duluth.
Figure 23. Development plan of Duluth Sanitary Landfill for the years 1 through 11.

Information by St. Louis County Health Department, reduced from a blueprint by W. Peterson, P.E., Duluth.
Geology: The landfill area is right at the contact between the two major gabbroic units, namely the older, anorthositic gabbro (a coarse-grained feldspathic rock) and the younger, layered series gabbro (a finer-grained olivine gabbro characterized by banding). More accurately, the landfill lies over the layered gabbro (see Fig. 24) which, at this location, has large blocks of anorthositic gabbro inclusions. These inclusions are to be found in the layered series more than a mile from the contact, which dips steeply and follows widely spaced joints in the anorthositic gabbro. (17, p. 6) The bedrock under the landfill is covered by glacial ground moraine (Schwartz, 1949) 30 to 60 feet thick.
Figure 24. Duluth Sanitary Landfill in relation to Miller Creek and the contact of the two bedrock units in the area.

Information obtained from reference 17.
Soils: In June, 1976, Lakehead Testing Laboratory, Incorporated performed a series of soil tests for WLSSD on the site of the Duluth landfill. At the same time they installed six groundwater monitoring wells. These monitoring wells were installed at the same locations at which the soil test holes were drilled (see Fig. 25 and 26).

The logs of the borings indicate that the soil profile consists of essentially two strata. These are first the surficial fills and solid wastes which vary from less than 2 feet at boring #4 to 27 feet at boring #5. The second stratum penetrated is an alluvial or glacial outwash soil consisting of clayey silts, silts, and silty sand. It has also been reported that numerous small pockets of sand and gravel (possibly Kames) are scattered on the site. Furthermore, there were cobbles and boulders found in the poorly sorted till. Soil permeability and available water capacity were found to be low. In general, the soils are classified as poorly drained, having a seasonal high water table which could pond at the surface.
Figure 25. Test Borings/Monitoring Wells
Information by WLSSD.
Figure 26. Water Table Observation Well Diagram showing Garbage / Soil interface.

Information from Lakehead Testing Laboratory boring logs, released by WLSSD.
Drainage: The drainage system in the area is poorly developed, and the land surrounding the site is generally low and swampy, especially north and west of the landfill (see Fig. 29). The drainage divide between the Miller Creek and Wild Rice Lake Watersheds crosses the northern portion of the site. Most of the surface runoff water from the fill area ends up in Miller Creek which crosses the site in the southeastern corner (see Fig. 27 on the next page).

Groundwater: The test borings (see Fig. 25 and 26) indicated that the groundwater table is up into the waste deposits in a large portion of the landfill. According to the groundwater elevation in the monitoring wells, the groundwater south of the drainage divide flows toward Miller Creek (see Fig. 28). Some of the groundwater emerging from the landfill is surfacing and flowing into Miller Creek.

The area surrounding the landfill is not suitable for any development of large scale groundwater supplies, for most of the groundwater is flowing away from the site, thus carrying leachate contaminants with it. The zone of influence for the landfill is shown on the map of Figure 29.
Figure 27. Drainage Patterns of Duluth Sanitary Landfill.

Information by WLSSD.
Figure 28. Groundwater flows in the fill area.

Information by WLSSD.
Figure 29. Duluth Disposal Landfill zone of influence.

Information by WLSSD.

Scale

1 Mile

N

70
The groundwater quality on and around the site had been monitored on a monthly basis since May 1976. During the winter months, however, monitoring was not possible because of freezing water or lack of water. In addition, there were seven surface water monitoring stations established from which water quality was analysed. The map in Figure 30 shows the location of the different monitoring stations. Generally the groundwater is of low quality as a result of entering leachate. Table 6 summarizes the results of the groundwater monitoring program.

Table 6
DULUTH DISPOSAL GROUNDWATER MONITORING SURVEY
(May 1976 through December 1976)

<table>
<thead>
<tr>
<th>Test Parameter</th>
<th>Range in ppm</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>7.3 – 11.4</td>
</tr>
<tr>
<td>Alkalinity (CaCO₃)</td>
<td>124 – 3,520</td>
</tr>
<tr>
<td>BOD₅</td>
<td>7.0 – 193</td>
</tr>
<tr>
<td>COD</td>
<td>60 – 2,160</td>
</tr>
<tr>
<td>Total Phosphorus</td>
<td>0.01 – 0.045</td>
</tr>
<tr>
<td>Total Kjeldahl - N</td>
<td>1.54 – 599.2</td>
</tr>
<tr>
<td>Ammonia - N</td>
<td>0.24 – 549.9</td>
</tr>
<tr>
<td>Nitrate - N</td>
<td>0.01 – 0.12</td>
</tr>
</tbody>
</table>

continued on next page
Table 6 (cont.)
DULUTH DISPOSAL GROUNDWATER MONITORING SURVEY

<table>
<thead>
<tr>
<th>Test Parameter</th>
<th>Range in ppm</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>7.3 - 11.4</td>
</tr>
<tr>
<td>Chloride (Cl)</td>
<td>4.0 - 112</td>
</tr>
<tr>
<td>Sulfate (SO₄)</td>
<td>11 - 62</td>
</tr>
<tr>
<td>Hardness (CaCO₃)</td>
<td>60 - 808</td>
</tr>
<tr>
<td>Total Solids</td>
<td>268 - 5,447</td>
</tr>
<tr>
<td>Suspended Solids</td>
<td>2 - 1,254</td>
</tr>
<tr>
<td>Dissolved Solids</td>
<td>266 - 5,035</td>
</tr>
</tbody>
</table>

Information furnished by Western Lake Superior Sanitary District

The following graphs (Fig. 31) represent an attempt by the author to show monthly fluctuations in the degree of surface water contamination in Miller Creek, both upstream and downstream from the landfill. As already mentioned, available information indicates that contaminated groundwater from the landfill is surfacing and flowing into the creek, thereby contributing to the obvious drop in Miller Creek water quality downstream of the fill site. Indeed this condition is clearly demonstrated by the graphs in Figure 31 for the five test parameters required by the Minnesota Pollution Control Agency. As to heavy metals, it was reported by WLSSD.
Figure 30. Groundwater and surface water monitoring stations in and around the Duluth Sanitary Landfill.

Information by WLSSD.

- Groundwater monitoring wells
- Surface water monitoring stations
Figure 31. Contamination fluctuations in Miller Creek, above (M-1) and below (M-2) the landfill.

Compiled from water surveillance monitoring data by Western Lake Superior Sanitary District.
that in 1976 only Iron and Manganese reached violating levels.

In June 1977, the writer of this paper took two water samples from Miller Creek, one above and one below the landfill, and ran a set of analyses on five MPCA-required test parameters. The tests were run as suggested in "Standard Methods for the Examination of Water and Wastewater" (Reference 19) and were performed in the Lake Superior Basin Studies Center Analytical Laboratory of the UMD under the guidance of authorized personnel. The following tests were executed:

Chloride content and conductivity.
Chemical oxygen demand (COD).
Total dissolved solids (TDS).
Carbonate alkalinity as ppm of CaCO₃.
Hydrogen potential (pH).

A nitrate test was about to be done when the laboratory ran out of the necessary reagents; the preparation of these reagents would have taken too much time, so the test was dropped. In Table 7, contamination levels of this analysis are compared with those found by WLSSD one year ago.
Table 7

TEST COMPARISON FOR SURFACE WATER IN MILLER CREEK

<table>
<thead>
<tr>
<th>Parameters</th>
<th>1976*</th>
<th>1977</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M-1</td>
<td>M-2</td>
</tr>
<tr>
<td>Chloride (Cl)</td>
<td>3.50</td>
<td>19.00</td>
</tr>
<tr>
<td>COD</td>
<td>12.00</td>
<td>208.00</td>
</tr>
<tr>
<td>TDS</td>
<td>131</td>
<td>924</td>
</tr>
<tr>
<td>Alkalinity (CaCO₃)</td>
<td>100</td>
<td>740</td>
</tr>
<tr>
<td>pH</td>
<td>7.8</td>
<td>7.2</td>
</tr>
<tr>
<td>conductivity in μS/cm</td>
<td></td>
<td>195</td>
</tr>
</tbody>
</table>

*Information by WLSSD

M-1 Miller Creek above landfill
M-2 Miller Creek below landfill

Clearly, it has been confirmed that water contamination below the landfill is much higher than above. The only puzzle is posed by COD with an unexpected low reading at M-2 (1977). After calculations had been rechecked for possible errors, an explanation might be found in the fact that the water samples were taken at a high flow rate (rainy day) which could conceivably dilute or flush out the organics content in the water, thereby reducing the chemical oxygen demand (COD).
WLSSD found that the environmental problems caused by the Duluth Sanitary Landfill could be minimized by installing a leachate barrier and leachate collection system, which would prevent the leachate from entering and contaminating Miller Creek.\(^{(16)}\) Also, the grading plan should be so revised that a reduced amount of water would enter the site, thus minimizing runoff problems. The idea is sketched out on the following page (Fig. 32).

Conclusion

From all the information gathered, it is apparent that the location of the Duluth Sanitary Landfill is not ideal. In fact, it violates three basic requirements from the MPCA rules and regulations, namely SW6(1)(d), (f) and (g) which say that sanitary landfill sites are prohibited within wetlands, locations considered hazardous because of the proximity to airports, and areas which are unsuitable because of reasons of geology, hydrology, etc.\(^{(20)}\)

The whole area in which the landfill is located has a wetland character because it is swampy (see Fig. 29). Critical groundwater levels had been encountered during the initial engineering analysis done in 1971 (see Fig. 22), shortly before MPCA granted DDC the permit for operation.
Figure 32. Proposed Improvements.

By WLSSD
of a sanitary landfill. Again, the MPCA regulations state clearly in SW6(2)(b) that "solid waste shall not be deposited in such a manner that material or leachings therefrom may cause pollution of underground or surface water."(20,p.6) Furthermore, there is a five foot separation proposed between the lowest portion of the landfill and the high water table elevation. Yet the test borings revealed that the groundwater stands right up into the garbage (see Fig. 26).

The bedrock under the fill has never been studied, and there was no information available concerning fractures in the layered gabbro. Fractured bedrock under or near a landfill, however, could be a significant factor in municipal groundwater management, for if leachate reaches fractured rock it can travel fast and might end up in wells. The clayey-silty-sandy soils at the Duluth landfill have a relatively strong filtering capacity and groundwater contamination away from the fill could be minimal were it not for the high water levels. Nevertheless, no evidence of contamination was encountered in monitored private wells in the area surrounding the landfill.(16) The pollution of Miller Creek, however, is severe and the proposed landfill improvement by means of a clay barrier and collection pond (see Fig. 32) is commendable.
A major problem with the landfill is its proximity to the Duluth International Airport. Seagulls attracted to the landfill apparently present a hazard to air traffic safety, and the Federal Aviation Administration (FAA) at one time threatened to close the Airport. Presently the problem is under control through a bird poisoning program.

Finally, Mr. J. Kurtz, supervising sanitarian from the St. Louis County Health Department, complained that the fill was not truly a "sanitary" landfill in that a gas movement monitoring program was lacking, and that the compaction and daily covering of the waste deposits leaves much to be desired.
FINAL REMARKS

The placing of a landfill is a very important land allocation problem which all urbanizing areas increasingly will encounter. In the future it will be more and more difficult to find suitable sites, because the populations of modern metropolitan centers create enormous locational problems for regional waste disposal. In high-density areas of the region cost and lack of space usually make it impossible to locate a waste site. In the low-density sectors, on the other hand, waste transportation costs are higher, environmental degradation is imminent, and citizen opposition is strong against the use of local community land as a dumping place for refuse generated elsewhere. Thus the problems of locating a landfill are environmental and political in nature and present a real challenge in regional land use planning.
REFERENCES


14) Robinette, Alan and Asmussen, Dennis, 1975. "A Landfill Site Selection Study for Washington County and Ramsey County, Minnesota." Center for Urban and Regional Affairs (CURA) of the University of Minnesota.


