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By: Roger A. Gerhardt

University of Wisconsn in-Extension
GEOLOGICAL AND NATURAL HISTORY SURVEY

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Meredith E. Ostrom, Director and State Geologist

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INTRODUCTION

The landfill method is now, and will be for some time, the principal method for disposal of solid waste in the United States. In the past landfill sites were selected primarily on the basis of economic land availability. Numerous investigations over the last several decades (see Zanoni, 1971, 1972, and 1973 for a summary of these investigations) produced concern and widespread recognition that landfills represent a possible source of ground-water contamination. These studies also revealed several important facts regarding leachate production and migration from landfill sites. (1) Landfills invariably produce a mobile liquid leachate from the infiltration of precipitation or from saturation of the refuse placed below the water table. (2) The leachate is extremely rich in dissolved materials (organic and inorganic) taken into solution from the refuse. (3) The leachate eventually becomes part of the hydrologic flow system and may be an important potential source of ground-water contamination. (4) The degree of protection offered to the ground-water resource is largely a function of each local hydrogeologic environment. (5) The dissolved materials in leachate are attenuated as they move through earth materials principally by dilution, dispersion, adsorption, ion exchange, oxidation, and filtration.

Proper selection, design, and operation of landfill sites can minimize and/or localize the ground-water contamination potential through management of the generated leachate (Farvolden and Hughes, 1969; Landon, 1969; Emrich and Landon, 1969; Kunkle, 1971; and Hughes, 1972). The leachate can be renovated or attenuated (1) under natural conditions as it moves through the underlying earth materials, (2) by collection and treatment of the leachate, or (3) by a combination collection and treatment-natural attenuation system.

The majority of landfill sites in operation today rely totally, or in part, upon natural attenuation to control the generated leachate. It therefore becomes important to determine favorable hydrogeologic conditions for natural leachate attenuation. Research conducted to date has concentrated almost exclusively on leachate movement and attenuation within the ground-water flow system. This research has shown that leachate will be attenuated by natural processes in that system (Hughes, 1972). Little direct evidence is available, however, concerning changes in leachate concentrations within the unsaturated earth materials beneath landfill sites (Lane and Parizek, 1968; Lane, 1969; and Apgar and Landmuir, 1971). Additional information concerning the physical and chemical interactions between leachate and the unsaturated earth materials is needed in order to determine which hydrogeologic characteristics of landfill sites are favorable for minimizing the potential for ground-water contamination. Such information is also pertinent in determining the optimum site location requirements for the land disposal of solid wastes.

The primary objective of this investigation was to generate data on the attenuation of leachate in the unsaturated zone beneath several landfills in Wisconsin. The study was designed to document the changes in leachate concentrations with depth and time within the unsaturated earth materials beneath the landfill sites. Secondary objectives included (1) obtaining as much relevant information as possible concerning the local hydrogeologic environments, as a framework for the interpretation of the changes in leachate concentrations within the unsaturated zone, (2) determination of the impact of leachate migration and attenuation in unsaturated earth materials upon local ground-water quality, and (3) recommendations on the need for further study.

PREVIOUS INVESTIGATIONS

In the only major published investigation of a landfill conducted in Wisconsin, Kaufmann (1970) examined the hydrogeologic environments of two existing and twenty-four prospective landfill sites in Madison, Wisconsin. The existing landfills were located in marshes in discharge areas of the Yahara River Basin and local sub-basins. The results of this study include the following: (1) The concentration of pollutants was shown to rapidly decrease with depth in areas of the landfills characterized by downward ground-water flow. (2) Areas characterized by upward or lateral flow contained groundwater equal to, or better than, background quality 20 feet below the refuse base. (3) Leachate reached background quality after traveling laterally 300 to 600 feet through silts and clays. (4) Little or no leachate attenuation was observed along the sediment-refuse interface. (5) Leachate from the landfills discharges into nearby small creeks, which empty into Lakes Mendota and Monona. (6) Mass-balance calculations indicated that the nutrient contribution to the lakes from the landfills was less than 5 percent of the total input from all sources.

Wagner (1962) originally described the design and operation of the type of soil-water sampler (pressure-vacuum or "suction" lysimeter) used in this project. This sampler consisted of a porous ceramic cup cemented to a section of plastic pipe. Water samples were recovered by applying a vacuum to a single capillary tube inserted through a single copper access tube. This method restricted sample recovery to relatively shallow depths.

The pressure-vacuum (suction) lysimeter described by Wagner (1962) was modified for use on a research project at the State College (Pennsylvania) Regional Sanitary Landfill (Lane and Parizek, 1968; Lane, 1969; and Parizek and Lane, 1970). Modification was necessary in order to collect soil-moisture samples from greater depths. This was accomplished by fitting the unit with two access tubes. One access tube is used for pressurizing and evacuating the unit and the other is used as a discharge tube for the water sample. Seventeen suction lysimeters were installed in the soil beneath the State College Regional Sanitary Landfill to study the changes in leachate quality with depth.

Results of the chemical analyses of soil-moisture/leachate samples from the State College Landfill revealed that a leachate wave front could be traced in the soil beneath the landfill trench. The leachate always appeared first at shallower depths and was more concentrated than the next deeper sampling point. For example, the highest chloride concentration at the 2 foot depth was 1,890 ppm on February 18, 1968. The highest chloride concentration at the 7 foot depth was 502 ppm on June 2, 1968. Specific conductance and chloride were shown to be the only parameters necessary to trace leachate movement. The authors concluded that severe pollution of soil water beneath a landfill can occur even though the landfill is not in direct contact with ground water.

Apgar and Langmuir (1971) continued and extended the study described above. Their conclusions included the following.

1. Quality and quantity of leachate from landfills varies markedly with different topographic settings. Leachate 2 feet below an upslope landfill cell that received only direct precipitation, had the following maximum concentrations 3 to 13 months after refuse burial: specific conductance, 8445 micromhos/cm; chloride, 1890 mg/l; BOD, 3300 mg/l; NH_3 - N, 540 mg/l; and

total iron, 225 mg/l. Upon reaching a depth of 14.5 feet (after 2.5 years or more) maximum concentrations had been reduced 80 to 99 percent.

2. In contrast, precontaminated surface and subsurface runoff from adjacent upslope cells infiltrated a downslope cell, saturating the refuse. Leachate beneath this cell, after moving downward to a depth of 36 feet in 7 years, still had a specific conductance of 6600 micromhos/cm. 600 mg/l chloride, and over 9,000 mg/l BOD.

3. Leachate beneath the landfill cells is moving downward at an approximate rate of 6 to 11 feet per year.

4. Observed mechanisms of leachate renovation in the unsaturated zone included dilution, dispersion, oxidation, chemical precipitation, cation exchange, and anion exchange.

5. Although leachate attenuation does take place, highly contaminated leachate has moved downward to depths of 50 feet or more in the soils beneath the landfill cells.

Wood (1973) describes a further modification and improvement of the suction lysimeter, allowing collection of soil water samples at any depth without loss of sample. The new procedure incorporates a check valve in the lysimeter assembly, preventing pressurization of the porous cup while gas pressure is applied to force the sample to the surface.

Remson and others (1968) and Fungaroli (1971) provided an approximate method for predicting vertical moisture movement through and out of a sanitary landfill. A moisture routing model was developed for predicting the leachate production pattern of a sanitary landfill above the water table.

The concepts of water movement in unsaturated soils under natural and calculated or modeled conditions provides a framework for understanding leachate attenuation in the unsaturated zone beneath landfill sites (Bouma and others, 1974; Bouma, 1973; Anderson and Bouma, 1973; Smith, 1967; Crosby and others, 1968, and 1971; Hill and Parlange, 1972; and Aylor and Parlange, 1973). Laboratory studies and application of unsaturated flow processes have also been applied to the problem of radioactive storage in the unsaturaged zone (Palmquist and Johnson, 1962; Corey and Horton, 1969; and Winograd, 1974).

Considerable research has been conducted on the related topics of groundwater quality and septic tank disposal systems, (Polkowski and Boyle, 1970; Bouma and others, 1972; and Dudley and Stevenson, 1973) and waste water disposal on land (Sanks and Asano, 1976; and Sopper and Kardos, 1973). These studies were valuable sources of information concerning water quality changes within the soil.

Several reports published by the Wisconsin Geological and Natural History Survey included excellent descriptions of the regional geology and physical geography of the project areas (Chamberlin, 1883; Salisbury andAtwood, 1900; Martin, 1916; Alden, 1918; Hotchkiss and Bean, 1925; and Dalziel and Dott, 1970).

Subsurface investigations and soils engineering analyses at the Portage landfill (Warzyn Engineering, Inc., 1970, 1971, and 1974) and at the Sauk County landfill (Warzyn Engineering, Inc., 1973) were quite useful for an overall understanding of the hydrogeologic environments at these sites.

METHODS OF INVESTIGATION

Site Location and Selection

Two landfill sites, one near Prairie du Sac in Sauk County, Wisconsin and the other near Reedsburg, also in Sauk County (Figure 1) were selected for study with the help of the Wisconsin Department of Natural Resources-Solid Waste Management Section. The Prairie du Sac landfill is located approximately 2.5 miles west of the City of Prairie du Sac, between County Highways PG and O, and west of Otter Creek. The Sauk County landfill is located approximately 5.5 miles east of the City of Reedsburg, south of State Highway 33.

A third landfill, near Portage in Columbia County, Wisconsin (Figure 1), was also instrumented for study. The landfill is located approximately one mile north of the City of Portage, south of County Highway X. Lack of significant data over an extended period of time forced abandonment of this landfill as one of the primary study sites. The limited data that were collected from the Portage landfill are, however, summarized in the Appendix.

The landfills included in this study were chosen for these reasons:

1. The sites were within a reasonable traveling distance of Madison.
2. The refuse had been in place long enough to be producing leachate.
3. The combination of refuse thickness and depth to the water table permitted adequate instrumentation of the unsaturated zone.
4. Permission to conduct the study was given by the owner-operator.
5. A portion of the landfill could be set aside for study without interfering with disposal operations.

Components of the Data Collection and Monitoring Network

Lysimeter Network

Leachate and soil-moisture samples were collected from the refuse and unsaturated earth materials by means of pressure-vacuum or suction lysimeters. Suction lysimeters were chosen as sampling devices because (1) previous researchers have demonstrated their efficiency and reliability in obtaining soil-moisture samples and (2) they are the only devices available that allow sample collection over extended periods of time.

The design and operation of suction lysimeters has been discussed in detail by Wagner (1962), Lane and Parizek (1968), and Parizek and Lane (1970). The suction lysimeter (Figure 2) consists of a plastic cylinder 25 inches long and 1.9 inches in diameter with a 2.5 inch porous ceramic cup attached to the bottom. When the ceramic cup is in contact with soil moisture, capillary suction causes the pores of the cup to become filled with water. Due to the small pore size

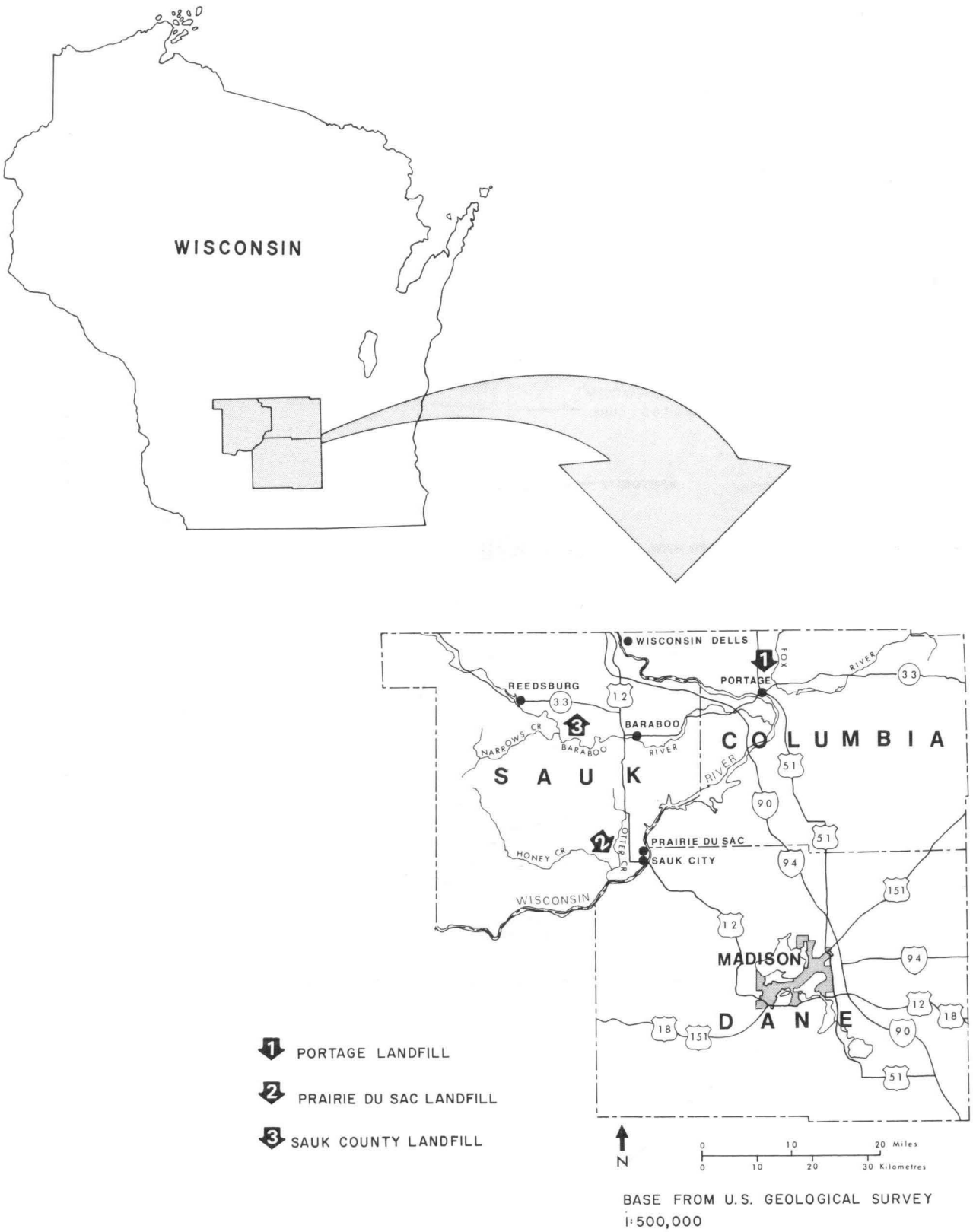
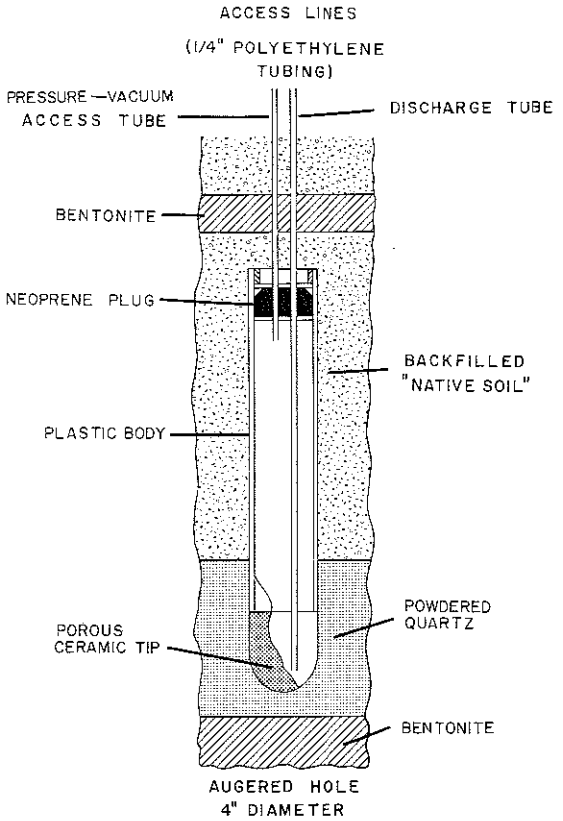


Figure 1. Location of study areas.



MODIFIED AFTER PARIZEK AND LANE (1970). NO SCALE.

Figure 2. Cross-section of a suction lysimeter and typical installation sequence.

(one micron or less), water is held tightly enough to become sealed against an air pressure of at least 15 psi. Thus, soil-moisture flow can be induced into the lysimeter by creating and maintaining a vacuum. Two access tubes (1/4-inch polyethylene tubing) inserted through separate holes in a neoprene stopper provide ports for sample discharge and for pressurization and evacuation. The capacity of a lysimeter is 1 liter of water.

Lysimeter installation (see Figure 2) was accomplished by drilling a hole to the desired depth using a truck-mounted continuous flight 4-inch auger. Pelletized bentonite was placed in the bottom of the hole (through temporary casing) to isolate the lysimeter from the soil below. A layer (approximately 6 inches thick) of powdered quartz (200 mesh) was placed on the top of the bentonite to insure good hydraulic contact between the pores of the ceramic cup and adjacent soil. The lysimeter was then positioned in the hole using $\frac{1}{2}$-inch conduit as a ramrod to force the lysimeter past protrusions in the drill hole and to seat the lysimeter firmly in the powdered quartz. The hole was then backfilled with native soil to a level slightly above the lysimeter. A second layer of pelletized bentonite was then added to further isolate the lysimeter and to guard against down-hole contamination. Intervals between lysimeters were backfilled with native soil. The base of the refuse and the surface were also sealed with bentonite.

Two lysimeter nests were installed at each landfill study site. Each nest contained from 2 to 6 lysimeter units terminating at various intervals in the unsaturated zone (including units within the refuse). Most placement holes contained multiple lysimeter units. In most cases only one or two lysimeters were placed in a single drill hole. If successively shallower installations within the same drill hole could not be properly sealed, or placed at the desired depth, additional holes were drilled to complete the instrumentation. Placement holes for each lysimeter nest were separated horizontally by 5 feet or less. A total of 6 nests containing 28 lysimeters were installed at the three study landfills. These lysimeter nests provided data on the vertical changes in leachate concentrations within the unsaturated zone.

Two single lysimeter units were installed outside the waste disposal area at the Prairie du Sac landfill during the second year of the study to provide additional data.

Soil-moisture and leachate samples for chemical analysis were collected from the lysimeters by using a portable two-way hand pump, The pressure port of the pump is attached to the lysimeter pressure-vacuum access tube. Positive air pressure is applied to force the sample out of the lysimeter, through the discharge access tube, into a 1-liter plastic sample bottle. Each sample collected was then placed in ice and transported to the laboratory for analysis. After sampling, a vacuum was placed on the lysimeter through the pressure-vacuum access tube and maintained until the next sample collection date.

Observation-Monitoring Well Network

A network of observation-monitoring wells within and adjacent to each landfill site was utilized in an effort to determine the dynamics of the ground-water flow system and the nature and extent of ground-water contamination. Thirteen wells were drilled within and adjacent to the three landfill sites and 5 existing monitoring wells were incorporated into the network. At these observation-monitoring wells, water level measurements and water quality samples were obtained.

All observation-monitoring wells completed for this study were installed by drilling 4-inch holes with a truck-mounted continuous flight auger. Each well consisted of a well screen (sand point) 24 inches long, attached to $1\frac{1}{2}$-inch galvanized pipe (plastic pipe was used for two wells at the Portage site). For each well, a hole was drilled 6 feet below the water table, the pipe and well screen were then placed in the hole, a bentonite seal was placed above the well screen, and the hole was backfilled. Additional seals were placed at the base of the refuse (where applicable) and at the surface.

Ground-water samples for chemical analysis were collected from (1) control wells located up-gradient from the landfills to establish the chemical quality of native groundwater, (2) wells located within the landfills (in association with the lysimeter nests) in order to monitor the effect of leachate migration through the unsaturated zone upon ground-water quality immediately beneath the site, and (3) wells located down-gradient and to the side of the indicated direction of ground-water flow to assist in the evaluation of the total impact of the landfills upon local ground-water quality.

Ground-water samples were collected from the wells by bailer, approximately once every three months. The samples were collected in plastic containers, iced, and transported to the laboratory for analysis.

Monthly water level measurements were also made at each well.

Soil Samples

Drive-core (split-spoon) soil samples for grain-size and chemical analyses were collected (1) during the installation of one lysimeter nest at each landfill site and (2) from a position between the two lysimeter nests at the Prairie du Sac landfill during the second year of the project. Auger samples for soil chemical analyses were collected during the installation of one background observation-monitoring well at each landfill site in order to determine the chemistry of native soils. Field observations of the earth materials penetrated during all drilling activities were made for the preparation of sediment logs.

Chemical Analyses

Leachate/Soil-Moisture and Ground-Water Samples

Table 1 lists the laboratory methods for chemical analyses performed on leachate/soil-moisture and ground-water samples. Leachate attenuation and ground-water quality determinations were based upon the relative concentrations of these chemical parameters. All analyses were made by the Water Chemistry Department, University of Wisconsin-Madison, except specific conductance which was determined in the field.

Soil Samples

Table 2 lists the laboratory methods for chemical analyses performed on soil samples. All analyses were made by the Water Chemistry Department, University of Wisconsin-Madison.

Table 1. Laboratory methods for chemical analyses performed on water samples collected from lysimeters and observation-monitoring wells.

Determination	Unit	Method
Specific Conductance	micromhos/cm @ 25°C	Conductivity bridge
Chloride (Cl)	mg/l	Mercuric nitrate titration (Standard Methods, 1971)
Alkalinity	mg/l as $CaCO_3$	Acid titration (Standard Methods, 1971)
Calcium (Ca)	mg/l	Atomic absorption (Fishman and Downs, 1966)
Magnesium (Mg)	mg/l	R[a]
Sodium (Na)	mg/l	R[a]
Potassium (K)	mg/l	R[a]
Total Iron (Total Fe)	mg/l	TPTZ colorimetric (Collins and others, 1959)
Total Organic Carbon (TOC)	mg/l C	Measurement of CO_2 using non-dispersive infrared cell (Menzel and Vacarro, 1965; Strickland and Parsons, 1968)
Total Nitrogen	micrograms/l N[1]	Steam distillation and micro-Kjeldahl techniques (Bremner, 1965; Bremner and Keeney, 1965)
$NO_3 + NO_2 - N$	micrograms/l N[1]	
$NH_4^+ - N$	micrograms/l N[1]	
Total Phosphorus (Total P)	micrograms/l P[1]	Persulfate (Standard Methods, 1971)
Dissolved Reactive Phosphorus (DRP)	micrograms/l P[1]	Colorimetric analysis (Murphy and Riley, 1962)
Zinc (Zn)	micrograms/l	Anodic stripping voltammetry (Arieland Eisner, 1963; Flato, 1972)
Lead (Pb)	micrograms/l	R[b]
Copper (Cu)	micrograms/l	R[b]
Cadmium (Cd)	micrograms/l	R[b]

1 Results for these parameters have been reported in micrograms/l because of the extreme variation in values.

R[a] Same method as for calcium

R[b] Same method as for zinc

Table 2. Laboratory methods for chemical analyses performed on soil samples.

Determination	Unit	Method
Chloride (Cl)	micrograms/gm soil	Extraction with distilled water, titration (Standard Methods, 1971)
Total Nitrogen (Total N)	micrograms N/gm soil	Micro-Kjeldahl digestion followed by steam distillation of NH_4^+ - N (Bremner, 1965)
NO_3 + NO_2 - N	micrograms N/gm soil	Steam distillation after reduction of NH_4^+ - N with Devarda alloy (Keeney and Bremner, 1966)
NH_4^+ - N	micrograms N/gm soil	Steam distillation in KCl solution (Keeney and Bremner, 1966)
Acid-extractable Phosphorus	micrograms P/gm soil	Extraction with HCl, colorimetric analysis (Murphy and Riley, 1962)
Total Phosphorus (Total P)	micrograms P/gm soil	Extraction with HCl, persulfate (Standard Methods, 1971)
Total Iron (Total Fe)	micrograms/gm soil	Extraction with ammonium acetate, TPTZ colorimetric analysis (Collins and others, 1959)
Calcium (Ca)	micrograms/gm soil	Extraction with ammonium acetate, atomic absorption (Fishman and Downs, 1966)
Magnesium (Mg)	micrograms/gm soil	R[a]
Sodium (Na)	micrograms/gm soil	R[a]
Potassium (K)	micrograms/gm soil	R[a]
Polychlorinated biphenyls (PCB)	micrograms/gm soil	Extraction by steam distillation, determined by gas chromatography (Flotard, in preparation)

R[a] Same method as for calcium

SAUK COUNTY LANDFILL

General Description

The Sauk County landfill (Figure 3) is located approximately 5.5 miles east of the City of Reedsburg, Wisconsin, south of State Highway 33, in adjoining portions of Sections 14 and 15, T.12N., R.5E. The site is situated in an east-west trending horseshore-shaped valley, which opens toward the west (Figure 4). Steep slopes with small tributary valleys descend from the north, south, and east to the main valley floor. Elevation of the area ranges from a high of 1180 feet above mean sea level in the uplands to the northeast to 940 feet above mean sea level in the main valley floor.

The total property owned by Sauk County exceeds 200 acres, with approximately 14 acres licensed for sanitary landfill purposes (roughly the area bound by the fence in Figure 4). Less than 4.5 acres has been used for solid waste disposal since landfilling began in 1973.

Landfill Operations

The Sauk County landfill, which is owned and operated by Sauk County, accepts trash, garbage, industrial and commercial refuse, demolition debris, brush, and animal carcasses collected within the county by private and municipal haulers. The disposal operation, which began in October of 1973, utilizes the cut-and-fill, or trench method of disposal (American Public Works Association, 1970). Trenches approximately 75 feet wide and 15 feet deep are excavated in an east-west direction, beginning in the northern portion of the 14 acres licensed for sanitary landfilling. Small berms are constructed around the trenches from the excavated material, which also provides daily cover material. A series of trenches in the northern one-third of the 14-acre landfill site have been filled with approximately 20 feet of refuse. Area filling will proceed over the trenches in the later stages of site development.

Instrumentation

The locations of lysimeter nests and observation-monitoring wells at the Sauk County landfill are shown in Figure 4. Figure 5 illustrates the vertical distribution of lysimeters and observation-monitoring wells at the Sauk County landfill.

Two nests of suction lysimeters (SCA and SCB) were installed at the Sauk County landfill. Nest SCA was installed beneath a landfill trench, which contained 22 feet of refuse. Lysimeters were placed in nest SCA at depths of 1, 9, 15, and 21 feet below the base of the refuse. One lysimeter unit (SCA-refuse) was placed within the refuse itself, at a depth of 13 feet below land surface. Nest SCB was installed outside the fill (refuse) area in order to provide background chemical quality of soil moisture. Lysimeters were placed in nest SCB at depths of 15, 25, 35, and 43 feet below land surface.

A network of 5 observation-monitoring wells was also established at the Sauk County landfill. Well SCW1 was drilled in association with lysimeter nest SCA. The observation-monitoring well at lysimeter nest SCB (SCW2) and the 3 remaining observation-monitoring wells (TWE, TWF, and TWG) were existing site wells (Warzyn Engineering, Inc., 1973), which were incorporated into this study. All observation-monitoring wells are relatively shallow, averaging 50 to 70 feet deep.

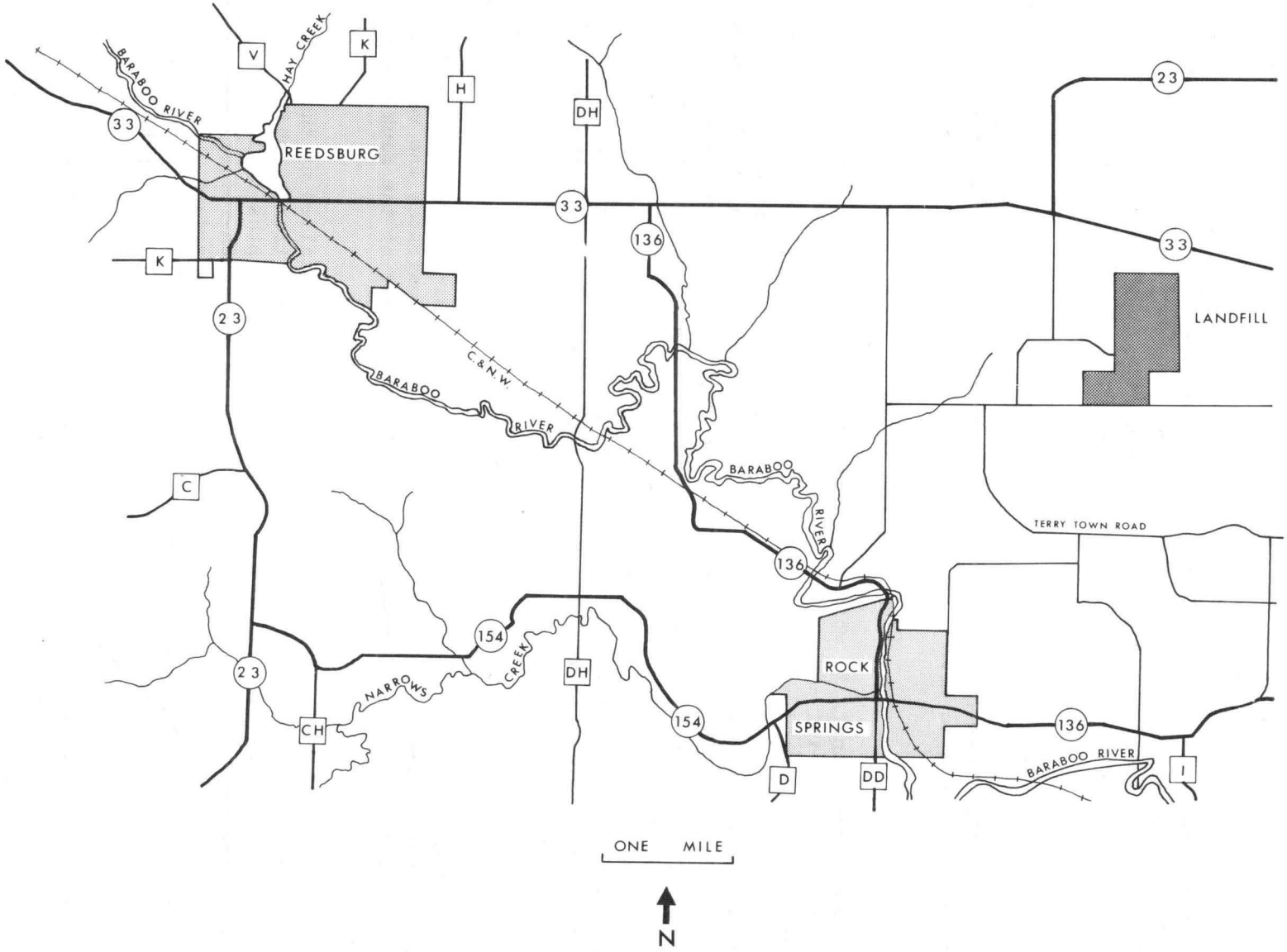


Figure 3. Location of the Sauk County landfill.

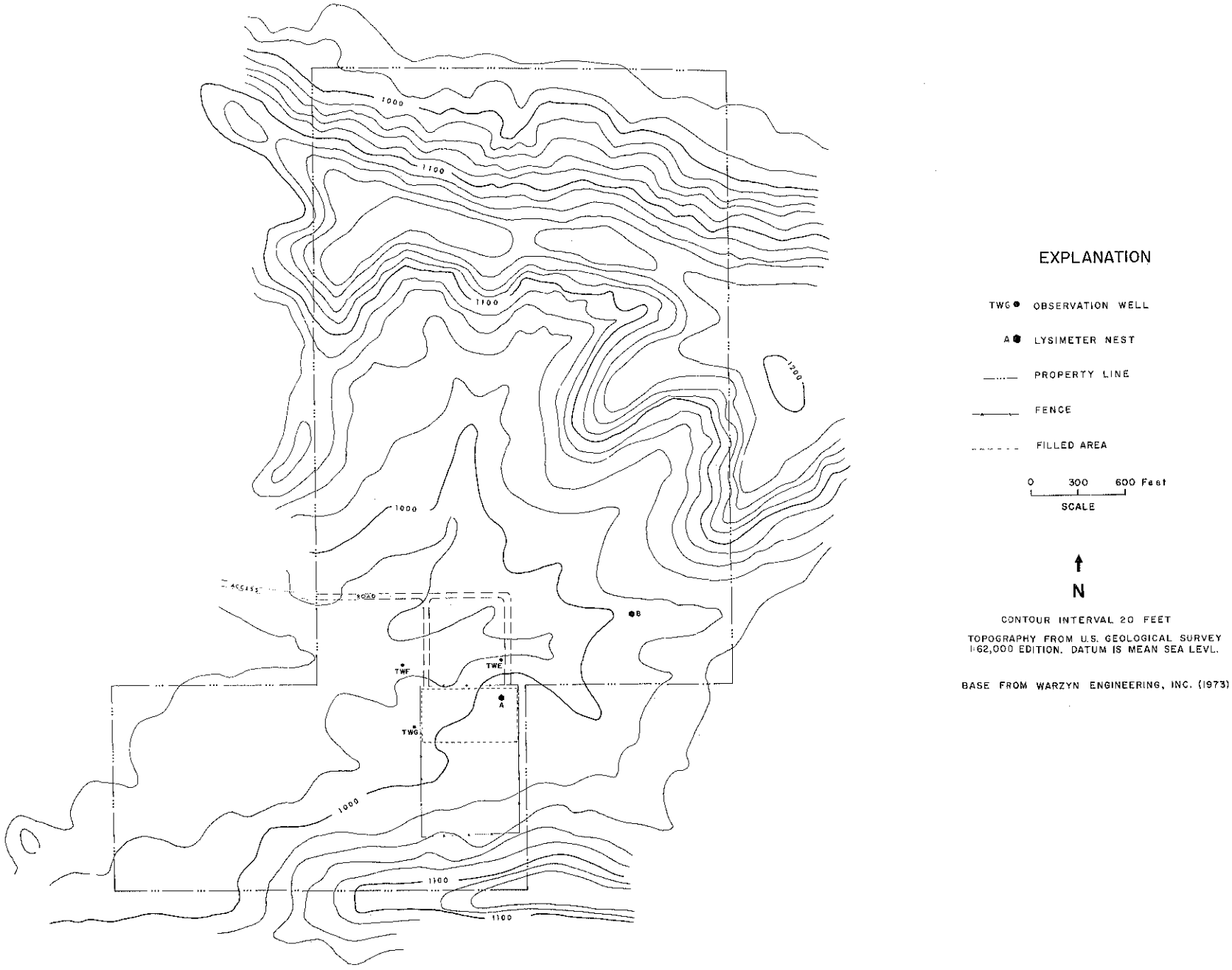


Figure 4. Instrumentation and topography at the Sauk County landfill.

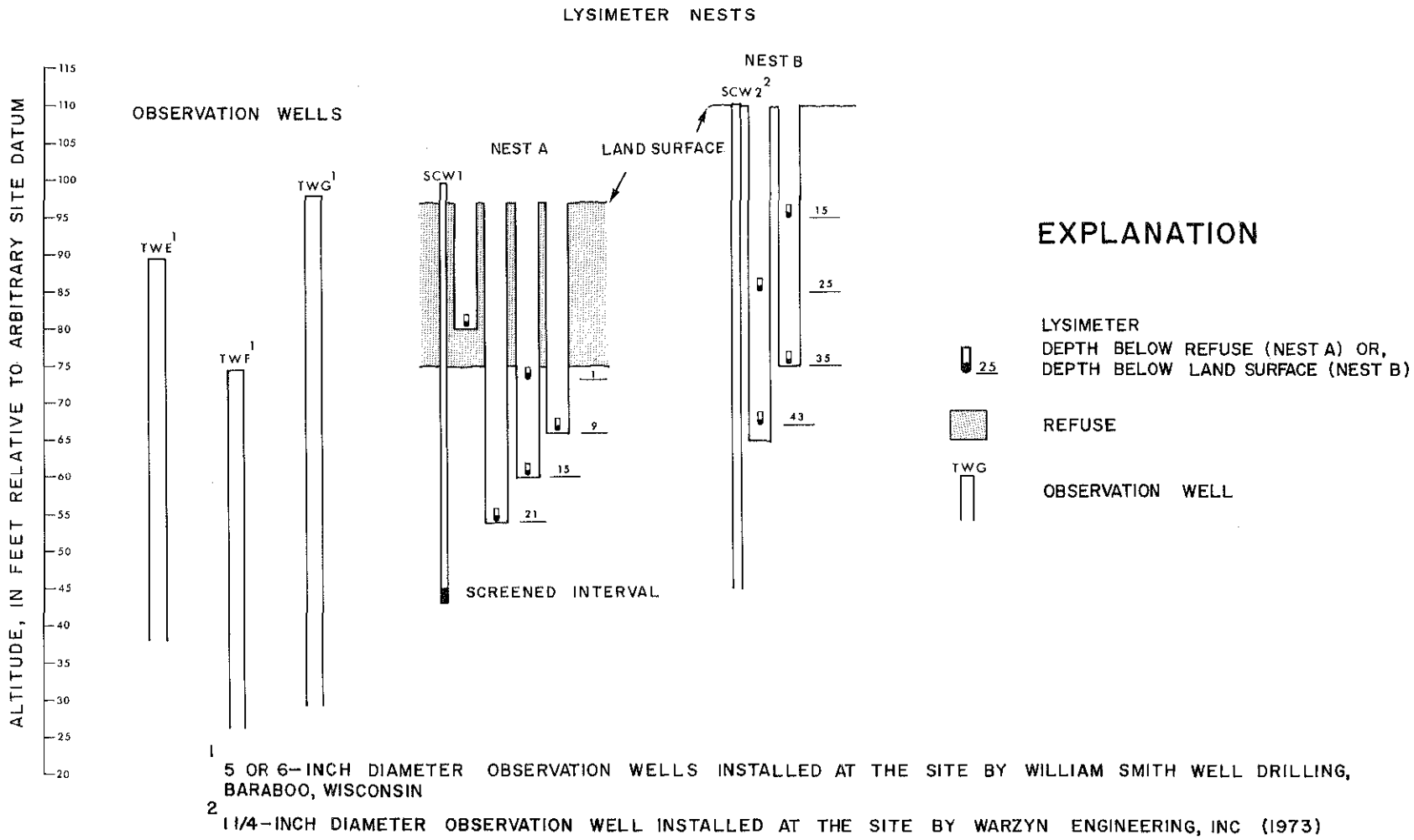


Figure 5. Vertical distribution of instrumentation at the Sauk County landfill. No horizontal scale.

An arbitrary site datum (the top of well SCW1 was assigned the value of 100.00 feet) was established to facilitate relative elevation comparisons between the various installations.

Geologic and Hydrologic Setting

The nature of the geologic materials beneath the Sauk County landfill was determined from (1) field observations of the earth materials penetrated during drilling, (2) logs of existing observation-monitoring wells, and (3) grain-size analyses of drive-core soil samples collected during lysimeter nest installations. Generalized logs are shown in Figure 6.

The sediments beneath the Sauk County landfill consist of a rather clean, uniform fine sand (Table 3). The sand apparently represents a glacial lake deposit (Salisbury and Atwood, 1900; Hotchkiss and Bean, 1925; Martin, 1916; Alden, 1918; Dalziel and Dott, 1970). The sanitary landfill is underlain by approximately 40 to 60 feet of fine sand. Thickness of the sand is variable, but it generally is thickest beneath the northern portion of the landfill site.

Table 3. Grain-size analyses of drive-core soil samples collected from beneath the Sauk County landfill. Depth of sample in feet below the base of the refuse.

	Wentworth Classification (Folk, 1965)				
	Percent by Weight				
Depth	% Gravel	% C Sand	% Med Sand	% Fine Sand	% Silt & <
3 feet	0	0.8	10.3	83.6	2.4
9 feet	0	0.8	9.2	87.6	2.4
15 feet	0	0.2	3.8	92.3	3.8
22 feet	0	0.1	3.5	94.6	1.7

The bedrock beneath the site (Warzyn Engineering, Inc., 1973) consists of the Tunnel City Group, which is a buff, dolomitic and glauconitic fine sandstone with thin dolomite beds. The next deeper bedrock unit is the Galesville Sandstone, and it is underlain by the Baraboo Quartzite Formation. The bedrock units dip at a shallow angle from the south towards the north.

Outcrops of the Oneota Formation, Trempealeau Group, Tunnel City Group, Galesville Sandstone, and Baraboo Quartzite formation surround the site on the north and south, forming a horseshoe-shaped valley (Dalziel and Dott, 1970).

Ground water occurs under water table conditions at a depth of 40 to 50 feet below land surface in the fine sand beneath the Sauk County landfill. The water table surface may be defined as that surface represented by the water level in wells. The water table is not a flat stationary surface, but changes both with time and with location. Therefore, monthly water level measurements were made at each observation-monitoring well to determine the pattern and magnitude of the water level changes.

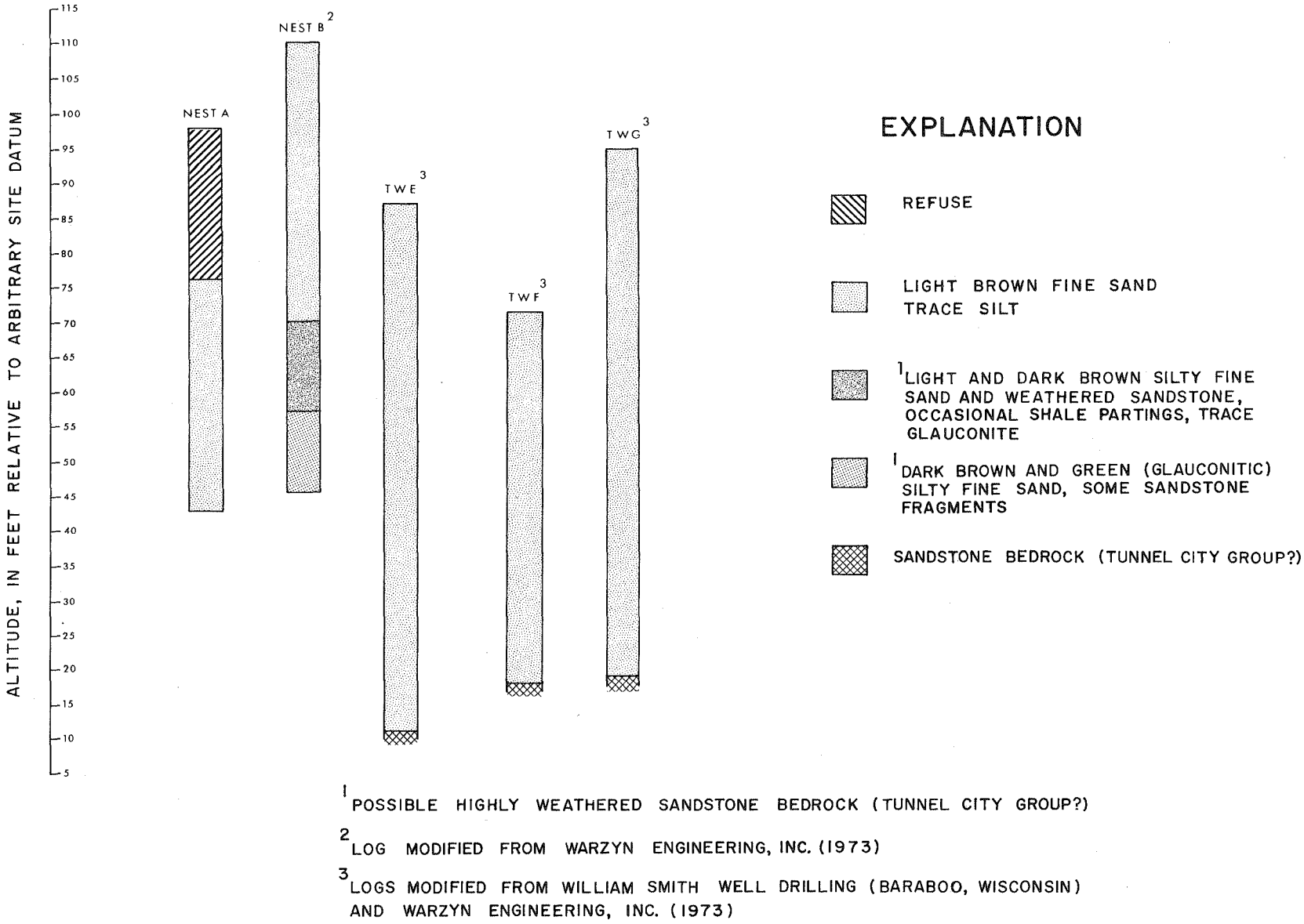


Figure 6. Generalized drill logs from the Sauk County landfill. No horizontal scale.

The hydrograph of well SCW1 (Figure 7) is representative of the fluctuations of the water table beneath the site. Water levels respond to seasonal changes in precipitation (Figure 7). Water levels declined during the late fall and winter when recharge from precipitation was low, and when precipitation stored as snow and frost could not reach the water table. Annual, or long-term, water level changes were not determined, but they are expected to be minor. The magnitude of the water level fluctuations, while not the same in all wells, has generally been between 1 and 1.5 feet.

The general pattern of ground-water movement can be determined by the shape and slope of the water table. The approximate shape of the water table surface is represented by contour lines drawn through points of equal elevation on that surface as determined from the elevation of water levels in the wells. The direction of movement is down the hydraulic gradient, from points of higher water levels to points of lower water levels, at approximately right angles to the contour lines.

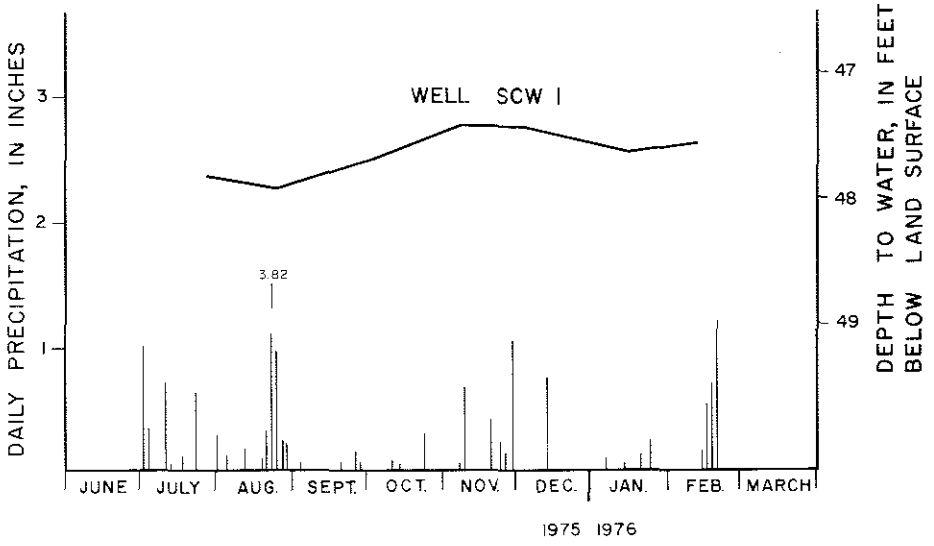


Figure 7. Changes in water level in well SCW1 and daily precipitation recorded near Reedsburg, Wisconsin. Precipitation data from National Oceanic and Atmospheric Administration (1975-1976).

The direction of ground-water movement beneath the Sauk County landfill is illustrated by the water table map (Figure 8), which was prepared from water level measurements made on November 7, 1975. Movement of ground water is generally toward the west beneath the landfill area. The average gradient of the water table was approximately 35 feet/mile. During the course of this study, little change was observed in the direction of ground-water movement, configuration of the water table, or the hydraulic gradient.

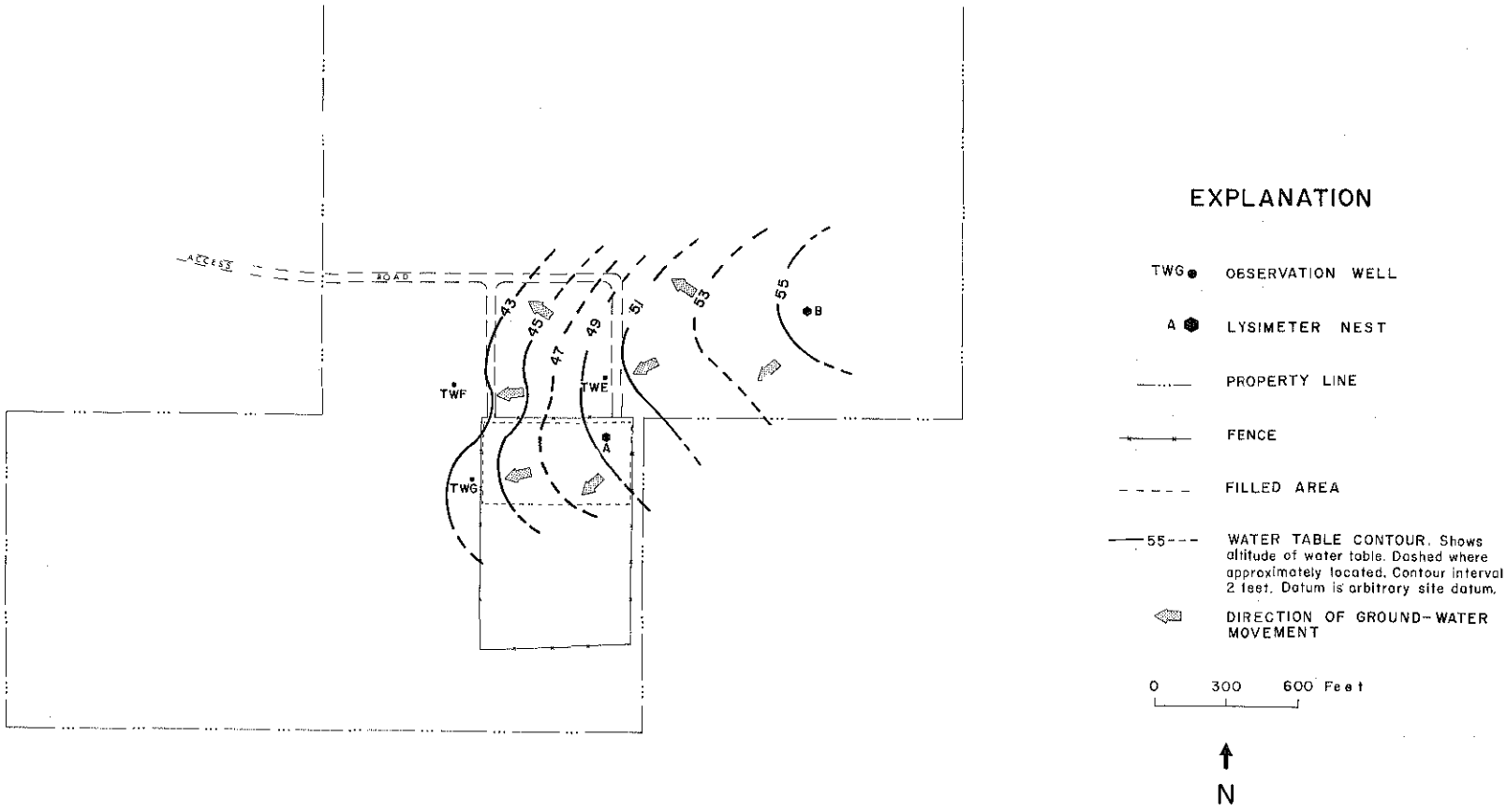


Figure 8. Map of the Sauk County landfill showing configuration of the water table--November 7, 1975.

Variations in Leachate/Soil-Moisture Quality

Background Soil-Moisture Quality

The results of the chemical analyses of soil-moisture samples from lysimeter nest SCB are shown in Table 4. Nest SCB was located outside the landfill (Figure 4) to determine the natural variations in soil-moisture quality. Sample notation refers to the lysimeter nest and the depth of the lysimeter unit below land surface. For example, SCB-15 indicates the lysimeter unit 15 feet below land surface at nest SCB. Four lysimeter units were placed at nest SCB (Figure 5), however, SCB-25 was never operational.

As shown in Table 4, observed background concentrations in the soil-moisture samples were low and did not vary significantly with depth. The uniform chemical quality of the soil moisture and the homogeneous nature of the subsoil materials (sand) suggest that chemical interactions between soil moisture and the soil material are uniform with respect to depth.

Total nitrogen, and to a lesser extent total phosphorous, concentrations decreased with depth. Organic material at or near the surface is assumed to be the major source of the phosphorous and nitrogen. Therefore, the decrease in the concentrations of phosphorous and nitrogen with depth indicates removal (by adsorption or dilution) by the sandy soil. Specific conductance, which is an indirect measure of the total dissolved solids content of the soil moisture, also showed a decrease with depth, indicating a slight overall reduction in the total dissolved solids content of the soil moisture with depth.

Most parameter concentrations decreased with time at all sampling intervals during the course of the study. The significance of these decreases is unclear because of the limited data.

Soil-Moisture/Leachate Quality

Results of the chemical analyses of soil-moisture/leachate samples collected from lysimeter nest SCA (Figure 4) are shown in Table 5. Nest SCA was placed within the landfill to sample the leachate as it moved through the underlying soil. Sample notation refers to the depth of the lysimeter unit below the base of the refuse. The lysimeter unit within the refuse is noted as such. Five lysimeters were originally placed at nest SCA (Figure 5), however, SCA-0 was never functional.

As expected, the highest leachate concentrations occurred in the samples collected from within the refuse (SCA-refuse). Lysimeter SCA-refuse was positioned within the 22 feet of refuse at nest SCA, 13 feet below land surface. Samples collected from SCA-refuse were characterized by high average concentrations of total N (181,862 μg/l), NH_4^+ - N (165,711 μg/l), alkalinity (3130 mg/l), chloride (933 mg/l), sodium (188 mg/l), potassium (479 mg/l), magnesium (149 mg/l), calcium (283 mg/l), and specific conductance (8633 μmhos/cm).

A gradual reduction of these components in the leachate within the refuse occurred during this investigation. These decreases may represent a general reduction in refuse leaching with time; more probably, the reductions reflect seasonal changes in leachate production in response to changes in precipitation. It is difficult to say with certainty which interpretation is correct.

Table 4. Results of the chemical analyses of soil-moisture samples collected from lysimeter nest SCB.

Sample	Spec. Conductance micromhos/cm 25°C	Milligrams per liter								Micrograms per liter								
		Calcium (Ca)	Magnesium (Mg)	Potassium (K)	Sodium (Na)	Chloride (Cl)	Alkalinity (as $CaCO_3$)	Total Iron (Fe)	Total Organic Carbon (as C)	Zinc (Zn)	Cadmium (Cd)	Lead (Pb)	Copper (Cu)	Total P (as P)	DRP (as P)	Total N (as N)	$NO_3 + NO_2 - N$ (as N)	$NH_4^+ - N$ (as N)
SCB-15																		
10-2-75	100	-	4.5	3.5	14.6	12	35	-	-	-	-	-	-	73	-	1122	-	-
11-7-75	90	2.7	3.2	4.3	6.8	9	34	-	-	25.19	-	41.65	11.43	111	-	503	-	-
12-3-75	70	0.16	2.8	4.6	9.7	7	27	0.13	13	-	-	-	-	6.5	-	534	-	-
2-12-76	100	0.12	2.2	4.0	2.5	6	7	2.65	29	-	-	-	-	70	-	724	-	-
SCB-35																		
10-2-75	90	2.9	4.5	5.9	14.2	11	30	-	-	-	-	-	-	43	-	98	-	-
11-7-75	70	0.04	3.4	14.9	7.4	9	19	-	-	17.07	-	59.02	9.20	133	-	866	-	-
12-3-75	50	0.16	4.0	3.1	6.0	7	22	0.18	11	10.30	1.27	29.51	16.87	2	-	-	-	-
SCB-43																		
10-2-75	60	2.2	4.0	4.6	5.4	10	28	-	-	-	-	-	-	30	-	15	-	2
11-7-75	50	0.4	2.8	4.3	4.4	8	21	-	-	7.12	-	11.90	2.09	55	-	391	-	-
12-3-75	40	3.6	4.0	3.1	1.6	8	19	0.12	10	14.00	-	11.51	2.27	2.2	-	96	-	-

Table 5. Results of the chemical analyses of soil-moisture/leachate samples collected from lysimeter nest SCA.

Sample	Spec. Conductance micromhos/cm 25°C	Milligrams per liter								Micrograms per liter								
		Calcium (Ca)	Magnesium (Mg)	Potassium (K)	Sodium (Na)	Chloride (Cl)	Alkalinity (as $CaCO_3$)	Total Iron (Fe)	Total Organic Carbon (as C)	Zinc (Zn)	Cadmium (Cd)	Lead (Pb)	Copper (Cu)	Total P (as P)	DRP (as P)	Total N (as N)	$NO_3 + NO_2 - N$ (as N)	$NH_4^+ - N$ (as N)
SCA-refuse																		
11-7-75	9400	514	157	511	1066	1112	2563	-	1814	101.1	1.60	19.10	10.72	-	-	219,445	5	185,969
12-3-75	9800	514	171	471	489	1144	3977	477	1287	84.55	0.64	-	1.35	-	-	199,897	3416	208,749
2-12-76	6700	22	118	455	810	544	2850	316	1487	78.47	1.60	6.94	7.81	670	780	126,246	1740	102,416
SCA-1																		
10-2-75	3700	148	144	55	350	360	1182	-	-	-	-	-	-	297	-	58,600	-	-
11-7-75	5175	408	150	57	634	800	1920	-	1247	127	3.82	46.34	16.57	327	-	45,105	339	21,010
12-3-75	5300	131	149	318	531	629	2222	264	1850	18.17	2.55	6.95	19.00	87	-	76,471	4017	85,876
2-12-76	6950	20	212	225	1145	851	2620	135	1959	110.1	2.24	16.45	3.97	235	860	50,025	6119	52,860
SCA-15																		
10-2-75	1550	85	80	7.4	20	305	335	-	-	-	-	-	-	38	-	1813	-	-
11-7-75	1650	168	97	10.1	89	316	487	-	507	13.50	0.95	53.82	9.67	605	-	1744	5	88
12-3-75	2200	204	106	9.4	200	322	578	0.27	559	24.00	0.32	21.37	3.12	13	-	3637	120	1022
2-12-76	2650	10	106	5.8	324	310	535	1.50	913	22.19	0.64	6.94	8.62	80	-	2764	622	58
SCA-21																		
10-2-75	625	-	-	-	-	47	211	-	-	-	-	-	-	28	-	368	-	-
11-7-75	550	48	26	9	16	52	263	-	129	56.91	-	26.44	9.71	78	-	562	5	129
12-3-75	850	92	38	8.2	16	152	244	-	-	-	-	-	-	-	-	1107	7	1126
2-12-76	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Chemical analyses of samples from the lysimeters positioned in the subsoil (sand) beneath the refuse (SCA-1, SCA-15, and SCA-21, Table 5) show that leachate is present in the soil solution beneath the Sauk County landfill. The leachate is characterized by concentrations ranging from 2 to 100 times greater than the surrounding unaffected soil moisture, which is represented in nest SCB (Table 4).

Significant decreases in leachate component concentrations, with the exception of $NO_3 + NO_2 - N$ and the heavy metals (copper, cadmium, lead, and zinc), occurred within the first foot of soil beneath the landfill (SCA-1). For example, a comparison of lysimeter samples collected from SCA-refuse and SCA-1 on December 3, 1975, shows specific conductance, chloride, alkalinity, potassium, calcium, total N, and $NH_4^+ - N$ concentrations reduced 4500 mhos/cm (45 percent), 515 mg/l (45 percent), 1755 mg/l (44 percent), 153 mg/l (32 percent), 183 mg/l (58 percent), 123,426 μg/l (62 percent), and 122,873 μg/l, respectively in the leachate 1 foot below the base of the refuse.

$NO_3 + NO_2 - N$ concentrations in the leachate were higher in the first foot of soil beneath the landfill than in the leachate within the refuse. $NO_3 + NO_2 - N$ concentrations in samples collected from SCA-refuse and SCA-1 compare as follows:

Date	SCA-refuse	SCA-1
11-7-75	5 μg/l	939 μg/l
12-3-75	3416 μg/l	4017 μg/l
2-12-76	1740 μg/l	6119 μg/l

Higher $NO_3 + NO_2 - N$ concentrations 1 foot below the refuse may indicate that aerobic conditions exist immediately below the landfill (Apgar and Langmuir, 1971).

Consistent and systematic reductions in leachate component concentrations occurred as the leachate moved downward through the subsoil (compare SCA-1, SCA-15, and SCA-21, Table 5). Concentrations were almost always lower at the next deeper sampling point. Concentration reductions within the 20-foot soil column separating SCA-1 and SCA-21 were often quite uniform per foot of soil, as shown below:

		Reduction in Concentration per Foot of Soil	
Parameter	Sampling Date	SCA-1 to SCA-15 (14 feet)	SCA-15 to SCA-21 (6 feet)
Na	12-3-75	24 mg/l per foot	30 mg/l per foot
Ca	11-7-75	17 "	20 "
Cl	12-3-75	28 "	22 "
Spec. Cond.	10-2-75	154 μmhos/cm per foot	153 μmhos/cm per foot

Leachate renovation, or attenuation, can be expressed as the percent reduction in the average concentration of each leachate component (Table 6). While not all leachate component concentration reductions per foot of soil were as systematic as those shown above, all components did show a 4 to 5 percent reduction of the values recorded in the refuse (SCA-refuse) per foot of soil.

Table 6. Average leachate component concentrations and per cent reductions for soil-moisture/leachate samples collected from lysimeter nest SCA.

	Average Concentration				Total Reduction (%) Between SCA-refuse and SCA-21	% Reduction Per Foot Between SCA-refuse and SCA-21
	SCA-refuse	SCA-1	SCA-15	SCA-21		
Specific Conductance (micromhos/cm.)	8633	5281	2012	675	92 %	4.4 %
Calcium (mg/l)	283	176	116	70	75 %	3.6 %
Magnesium (mg/l)	148	163[a]	97	31	79 %	3.8 %
Sodium (mg/l)	788	665	158	16	98 %	4.7 %
Potassium (mg/l)	479	163	8	8	98 %	4.7 %
Chloride (mg/l)	933	660	313	83	91 %	4.3 %
Alkalinity (mg/l)	3130	1986	483	239	92 %	4.4 %
Total P (micrograms/l)	670	236	184	53	92 %	4.4 %
Total N (micrigrams/l)	181,862	57,050	2489	685	99 %	4.7 %
NH_4^+- N (micrograms/l)	165,711	53,248	389	627[a]	99 %	4.7 %
NO_3+ NO_2- N (micrograms/l)	1720	3,491[a]	249	6	99 %	4.7 %

[a] Average value exceeds value at shallower sampling interval

Upon reaching a depth of 21 feet below the base of the refuse (SCA-21), leachate component concentrations were reduced 75 to 99 percent below values recorded within the fill (SCA-refuse). This is consistent with the results reported by Apgar and Langmuir (1971) and Lane and Parizek (1968). However, leachate component concentrations in samples from SCA-21 (43 feet below land surface) were generally 2 to 10 times higher than background soil moisture samples, which are represented by the samples collected from nest SCB (Table 4).

Lysimeter samples collected from the subsoil beneath the Sauk County landfill also show a gradual increase in leachate component concentrations during the course of this study. By the February 12, 1976 sampling date many component concentrations (chloride, sodium, and specific conductance, for example) were higher in the sample collected from SCA-1 than from the sample collected from the refuse (SCA-refuse). Increasing concentrations and maximum concentrations 1 foot below the landfill may reflect a leachate front moving from the refuse into the subsoil beneath the landfill.

The changes in concentrations of zinc, copper, cadmium, and lead are more complex and less systematic with depth than those of the other leachate components (Table 5). This may reflect heavy metal contributions to the soil-moisture/ leachate by the subsoil material although this was not determined.

The consistent and systematic reductions of most leachate components with depth in the subsoil beneath the landfill are believed to reflect the homogeneous nature of the subsoil material (sand). The physical and chemical properties of a homogeneous soil (sand) should be rather consistent throughout the soil profile. In other words, the chemical contributions and the attenuation capacity of each cubic foot of soil throughout the soil profile should be nearly uniform. Unsaturated soil-moisture movement in a homogeneous soil material should be essentially vertical, with little tendency to spread laterally, except perhaps in a downslope direction in response to gravity (Bouma and others, 1974; Smith, 1967; and Palmquist and Johnson, 1962). Therefore, attenuation of any dissolved solids would directly reflect the height of the soil column separating sampling points, which is also the vertical distance through which the flow occurred. A progressive and systematic reduction in the concentration of dissolved solids in the soil moisture should occur with increased soil depth. Such a situation was observed in the subsoil beneath the Sauk County landfill. If lateral soil-moisture movement were to occur, changes in the concentrations of dissolved solids in the soil moisture would be more complex and less systematic with depth than the changes generally observed.

Soil Samples

Chemical analyses were made on uncontaminated drive-core soil samples collected at lysimeter nest SCB (Figure 4). Sample notation for the SCB soil samples indicates the sample depth below land surface. The chemical analyses (Table 7) showed little variation in parameter concentrations with respect to depth. Calcium and magnesium concentrations tended to increase with depth, indicating that these ions are being leached from the soil.

Chemical analyses were also made of leachate contaminated drive-core (split-spoon) soil samples, which were collected from directly beneath the landfill at lysimeter nest SCA (Figure 4). Sample notation for the SCA soil samples indicates sample depth below the base of the refuse. The addition of 22 feet (refuse thickness) to the SCA soil depths provides depth below land

Table 7. Chemical analyses of uncontaminated (SCB) and contaminated (SCA) drive-core soil samples collected at the Sauk County landfill.

Sample	Micrograms per gram of soil										
	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Chloride (Cl)	Total Iron (Fe)	Total N (as N)	$NO_3 + NO_2 - N$ (as N)	$NH_4^+ - N$ (as N)	Total P (as P)	Acid-extrac. P (as P)
SCA[a]											
3'	12.34	3.92	2.57	3.15	49	-	3.82	1.46	2.50	6.3	.088
9'	16.80	3.16	2.74	1.41	30	-	1.83	1.90	0.88	6.22	.056
15'	17.00	4.84	1.40	1.66	44	-	2.54	1.55	0.91	6.90	.088
21'	16.50	4.25	0.84	1.70	28	-	1.20	1.26	0.43	7.39	.088
SCB[b]											
15'	12.18	3.79	0.52	1.39	27	-	1.31	0.55	1.05	6.69	.080
25'	13.80	4.16	0.84	1.86	25	-	0.88	1.22	0.70	5.84	.088
35'	17.74	5.23	0.52	1.88	26	-	5.60	0.54	1.03	6.88	.056

[a] Sample notation indicates depth below the base of the refuse. For comparative purposes, the addition of 22 feet (refuse thickness) to the SCA soil depths provides depth below land surface, which can then be compared to the SCB soil samples.

[b] Sample notation indicates depth below land surface.

surface, which can then be compared to the SCB (background) soil samples. The chemical analyses (Table 7) showed little significant parameter concentration variations, with the exception of chloride, between the leachate-affected soils and the uncontaminated soils. Chloride concentrations in the leachate-affected soils were generally 1.5 to 2 times higher than background levels.

The behavior of calcium plus magnesium and sodium plus potassium in the contaminated soils suggests that differential ion exchange has taken place in the soil. The decrease in sodium plus potassium with depth is accompanied by an increase in calcium plus magnesium.

Analyses were made for polychlorinated biphenyls (PCB's) on two of the drive-core soil samples. Soil sample SCB-25 (uncontaminated) showed no trace of PCB. Soil sample SCA-3, which was collected 3 feet below the base of the refuse, showed 0.056×10^{-9} grams of PCB/gram soil. This limited sampling for PCB's only serves to indicate that PCB's may be present in the subsoil beneath the Sauk County landfill.

Ground-Water Quality

Variations in ground-water quality beneath the Sauk County landfill site are shown in Table 8. Well locations are shown in Figure 4. In the ground water immediately beneath the refuse (well SCW1), concentrations were generally 2 to 20 times higher than background concentrations, which are represented in the samples from wells SCW2, TWE, TWF, and TWG. The high concentrations in the sample collected from well SCW1 on July 28, 1975, are attributable to contamination introduced during drilling rather than leachate contamination. Therefore, the sample from well SCW1, collected on November 7, 1975, is the only sample considered to be representative of ground-water quality beneath the landfill.

A comparison of leachate component concentrations in the ground-water samples from well SCW1 and the deepest lysimeter unit (SCA-21, Table 5) beneath the refuse shows that the concentrations in the ground water are nearly equal to, or slightly higher than, the concentrations observed in the soil moisture. It would be reasonable to expect that leachate migration through the approximately 5 feet of soil (sand) separating lysimeter SCA-21 and the water table, plus dilution of the leachate by ground water, would result in concentration reduction in the ground water. The analysis above suggests that (1) leachate concentrations from a single vertical sampling profile (lysimeter nest) indicate concentration changes that are taking place beneath a very small portion of the landfill (refuse), (2) these changes may not necessarily reflect the total ground-water pollution potential of the landfill, and (3) even though attenuation takes place within the unsaturated zone, it may not be adequate in preventing leachate contamination of the underlying ground water (Apgar and Langmuir, 1971).

The ground-water quality data for wells TWE, TWF, and TWG (Table 8) indicate that the leachate has apparently not moved beyond the landfill area, or has attenuated within a very short distance from the active fill area (Figure 4). As shown below, high NH_4^+ - N concentrations and low NO_3 + NO_2 - N concentrations in wells TWE, TWF, and TWG, as compared to background concentrations in well SCW2, may indicate the presence of leachate in the ground water immediately outside the fill area:

Table 8. Chemical analyses of ground-water samples collected from beneath the Sauk County landfill site.

Sample	Spec. Conductance micromhos/cm 25°C	Milligrams per liter								Micrograms per liter				
		Calcium (Ca)	Magnesium (Mg)	Potassium (K)	Sodium (Na)	Chloride (Cl)	Alkalinity (as $CaCO_3$)	Total Iron (Fe)	Total Organic Carbon (as C)	Total P (as P)	DRP (as P)	Total N (as N)	$NO_3 + NO_2$ - N (as N)	NH_4^+ - N (as N)
SCW 2														
7-28-75	200	12	2	2	2.4	10	123	0.03	40	1430	70	26	-	-
11-7-75	200	170	81	21	9.6	9	122	25	31	1667	330	5	797	10
TWE														
7-28-75	175	31	23	4	5	11	83	2.62	18	670	4	291	-	-
11-7-75	125	5	18	6	2.5	9	79	18	15	144	1901	282	45	260
TWF														
7-28-75	175	35	27	4	7	13	189	0.45	12	352	12	579	-	-
11-7-75	125	6	16	4	4	11	77	11	22	44	1154	415	79	375
TWG														
7-28-75	175	31	20	4	10	12	85	0.03	12	860	8	555	-	-
11-7-75	125	7	14	4	8	11	79	14	21	111	94	380	20	413
SCW 1														
7-28-75	1900	247	88	10	108	148	992	0.23	287	1750	22	1444	-	-
11-7-75	700	-	105	7	40	49	370	35	101	311	-	-	-	-

	Sampling Date	SCW2	TWE	TWF	TWG
$NO_3 + NO_2 - N$ (g/l)	11-7-75	797	45	79	20
$NH_4^+ - N$ (g/l)	11-7-75	10	260	375	413

Further sampling is required to determine if leachate is moving with the ground water outside the fill area, or if these differences represent natural variations.

All background wells showed a decrease in concentrations in the November 7, 1975 samples. These reductions may reflect dilution by infiltrating precipitation during the fall.

Summary and Conclusions

1. Leachate was detected in the soil moisture beneath the Sauk County landfill. The leachate was characterized by concentrations that were 2 to 100 times higher than in the surrounding unaffected soil moisture.

2. Consistent and systematic reductions in leachate component concentrations occurred as the leachate moved downward through the sand soil. Concentrations were almost always lower at the next deeper sampling point.

3. Significant reductions in leachate component concentrations occurred within the first foot of soil beneath the landfill, with the exception of $NO_3 + NO_2 - N$.

4. Leachate component concentrations were reduced an average of 4 to 5 percent per foot of soil. Upon reaching a depth of 21 feet below the base of the refuse, leachate component concentrations were reduced 80 to 99 percent as compared to the concentrations recorded within the refuse.

5. The consistent and systematic reduction in leachate component concentrations with depth is believed to be the result of the homogeneous nature of the sand soil.

6. Leachate component concentrations in the soil-moisture samples collected 21 feet below the base of the refuse were generally 2 to 10 times higher than concentrations in the background soil-moisture samples.

7. In the ground water immediately beneath the landfill, concentrations were generally 2 to 20 times higher than in the background ground-water samples.

8. Even though significant leachate attenuation does take place within the unsaturated zone, it is apparently not sufficient to prevent leachate contamination of the underlying ground water. The same conclusion was reported by Apgar and Langmuir (1971).

9. Mechanisms of attenuation for the various leachate components were not determined in this study because of the limited data. However, possible mechanisms of attenuation, which were obtained from other studies, are suggested (Table 9).

Table 9. Possible mechanisms of attenuation for selected leachate components.

Parameter	Possible Mechanisms of Attenuation	References
Phosphorous	chemical precipitation adsorption fixation	Apgar and Langmuir (1971), Ferguson (1976), Spyridakis and Welch (1976), and Ellis (1973)
NO_3+ NO_2- N	dilution denitrification	Dudley and Stevenson (1973), Polkowski and Boyle (1970), Bouma and others (1972), Ellis (1973), and Spyridakis and Welch (1976)
NH_4^+- N	ion exchange nitrification adsorption	Apgar and Landmuir (1971), Dudley and Stevenson (1973), Polkowski and Boyle (1970), Bouma and others (1972), Ellis (1973), and Spyridakis and Welch (1976)
Iron	oxidation precipitation	Apgar and Langmuir (1971), and Spyridakis and Welch (1976)
Calcium Magnesium Sodium Potassium	adsorption ion exchange	Spyridakis and Welch (1976) and Ellis (1973)
Alkalinity	precipitation	Kunkle and Shade (1976)
Chloride	dilution	Apgar and Langmuir (1971) and Polkowski and Boyle (1970)
Total Organic Carbon	adsorption precipitation	Spyridakis and Welch (1976)
Zinc Lead Copper Cadmium	adsorption ion exchange precipitation	Spyridakis and Welch (1976)

PRAIRIE DU SAC LANDFILL

General Description

The Prairie du Sac landfill is located approximately 2.5 miles west of the City of Prairie du Sac, Wisconsin, between County Highways PF and O, west of Otter Creek, in the SW$\frac{1}{4}$, NE$\frac{1}{4}$, Section 5, T.9N., R.6E. (Figure 9). The site covers approximately 20 acres; however, less than 2 acres have been used since landfilling began in 1968.

The site (Figure 10) is located on the eastern margin of a broad, flat upland, which separates Honey Creek and Otter Creek. The topography of the site is gently undulating. A gentle hillslope descends eastward to the main valley of Otter Creek. Low hillslopes to the north and south descend to gently sloping tributary valleys. Elevation of the area ranges from a high of 820 feet above mean sea level in the southwest to 760 feet above mean sea level to the southeast along Otter Creek.

Landfill Operations

The Prairie du Sac landfill, a municipal sanitary landfill, utilizes the cut-and-cover, or trench, method of solid waste disposal (American Public Works Association, 1970). Trenches approximately 50 feet wide and 15 feet deep are excavated on the hilltop paralleling the eastern boundary of the site. Solid waste (trash and garbage) is dumped, spread, compacted, and covered daily with the material derived from the excavation of the trench. Since landfilling began in 1968, several trenches along the eastern border of the site have been filled, and one trench is currently in operation.

Instrumentation

The locations of lysimeter nests and observation-monitoring wells at the Prairie du Sac landfill are shown in Figure 10. Figure 11 illustrates the vertical distribution of the lysimeters and observation-monitoring wells.

Two nests of suction lysimeters (PDSA and PDSB) were installed at the Prairie du Sac landfill. Both lysimeter nests were placed within the refuse disposal area in an attempt to determine if leachate composition and attenuation varied beneath the site. Lysimeters were placed in nest PDSA at depths of 4, 13, 17, and 23 feet below the base of the refuse. One lysimeter unit (PDSA-refuse) was placed within the 17 feet of refuse at nest PDSA, 11 feet below land surface. Lysimeters were placed in nest PDSB at depths of 6, 10, 16, 22, and 37 feet below the base of the refuse (PDSB-6 and PDSB-10 were never operational). One lysimeter unit (PDSB-refuse) was placed within the 10 feet of refuse at nest PDSB, 7 feet below land surface. In addition, single lysimeter units (PDSC-34 and PDSD-34) were placed near wells PDSW1 and PDSW3 (figure 10), respectively. Both lysimeter units were placed at a depth of 34 feet below land surface.

A network of 6 observation-monitoring wells was also established at the Prairie du Sac landfill. Wells PDSW4 and PDSW6 were drilled in association with lysimeter nests PDSA and PDSB, respectively. The 4 remaining observation-monitoring wells (PDSW1, PDSW2, PDSW3, PDSW5) were installed to monitor the ground-water flow system and to provide ground-water quality samples. All observation wells were relatively shallow, averaging 60 to 80 feet deep.

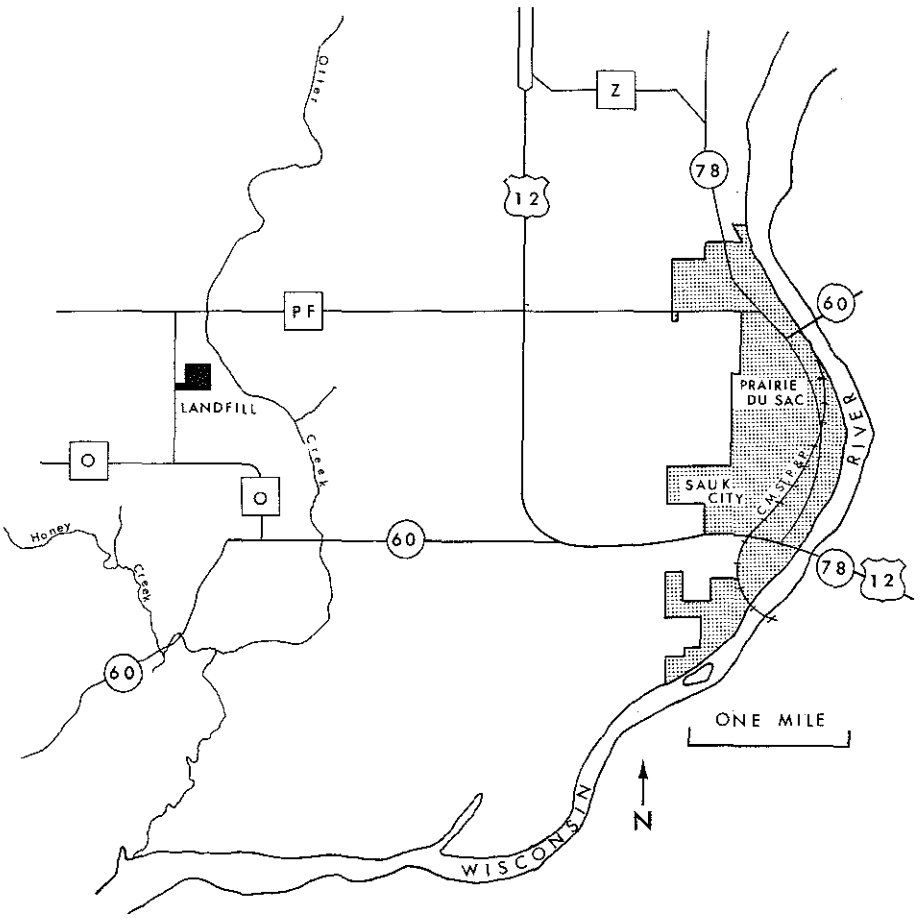


Figure 9. Location of the Prairie du Sac landfill.

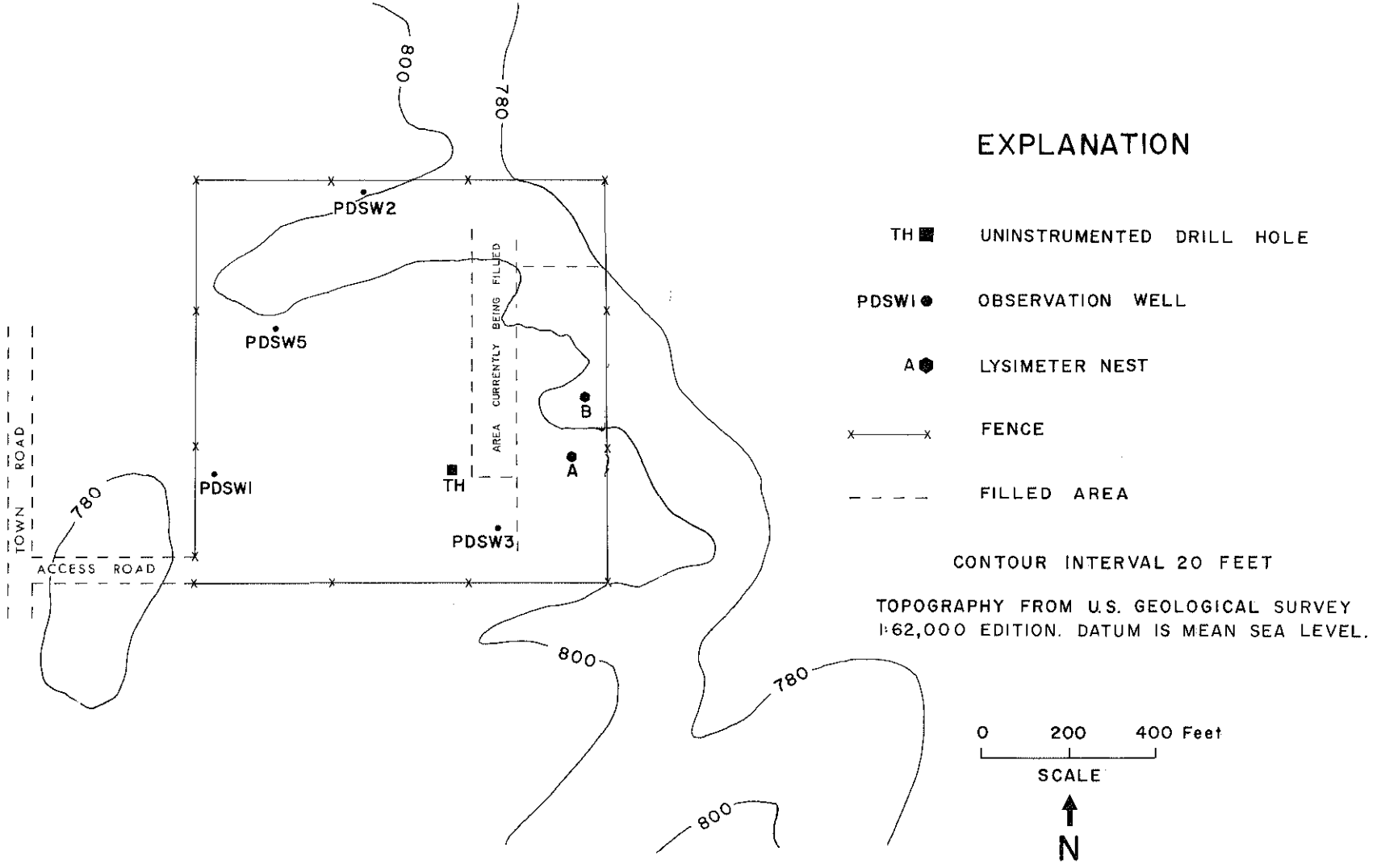


Figure 10. Instrumentation and topography at the Prairie du Sac landfill.

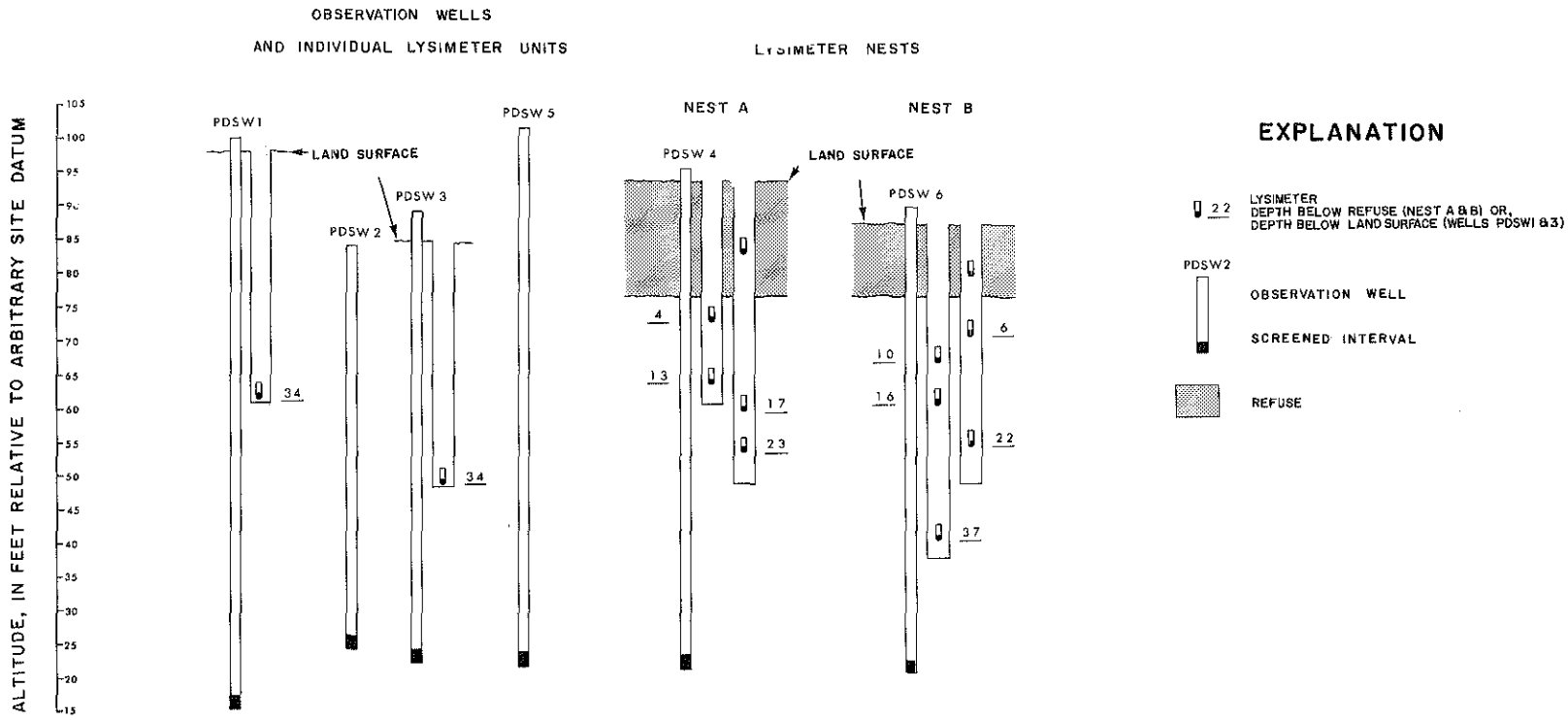


Figure 11. Vertical distribution of instrumentation at the Prairie du Sac landfill. No horizontal scale.

An arbitrary site datum (the top of well PDSW1 was assigned the value of 100.00 feet) was established to facilitate relative elevation comparisons between the various installations.

Geologic and Hydrologic Setting

The nature of the geologic materials beneath the Prairie du Sac landfill was determined from field observations of the earth materials penetrated during drilling and from grain-size analyses of two sets of drive-core (split-spoon) soil samples (SS1 and SS2) collected from beneath the refuse. Split-spoon soil sample set no. 1 was collected during the installation of lysimeter nest PDSA and set no. 2 was collected at a position midway between lysimeter nests PDSA and PDSB (Figure 10). Generalized logs are shown in Figure 12.

The subsoil beneath the Prairie du Sac landfill consists of sands and gravels (Table 10 and Figure 12) of glacial outwash deposits (Alden, 1918; Salisbury and Atwood, 1900; Martin, 1916; and Dalziel and Dott, 1970). Outwash is stratified detritus (chiefly sand and gravel) removed or "washed out" from a glacier by meltwater streams and deposited in front or beyond the terminal moraine or the margin of the active glacier (American Geological Institute, 1972, p. 505). Generally the material becomes coarser with depth. The gravel deposits encountered in all the drill holes appear to be of limited areal extent.

Ground water occurs under water table conditions at a depth of 50 to 70 feet below land surface in the sands and gravels beneath the Prairie du Sac landfill. The water table may be defined as that surface represented by the water levels in wells. The water table is not a flat, stationary surface, but changes with both time and location. Therefore, monthly water level measurements were made at each observation-monitoring well to determine the pattern and magnitude of the water level changes.

The hydrograph of well PDSW4 (Figure 13) is representative of the fluctuations of the water table beneath the site. Water levels respond to seasonal changes in precipitation (Figure 13). Water levels declined during the late fall and winter when recharge from precipitation was low and when precipitation stored as snow and frost could not reach the water table. Water levels rose in the spring because of recharge from spring rains and snowmelt. Water levels declined during the summer, as most rainfall during this season is lost by evaporation, transpiration, and retention as soil moisture, and is now available for recharge. Water levels in the fall of 1975 did not return to the levels recorded during the fall of 1974 because there was less rainfall in the fall of 1975. The magnitude of the water level fluctuations, while not the same in all wells, has generally been between 1 and 2 feet.

The general pattern of ground-water movement can be determined by the shape and slope of the water table. The approximate shape of the water table surface can be represented by contour lines drawn through points of equal elevation on that surface as determined from the elevation of water levels in the wells. The direction of movement is down the hydraulic gradient, from points of higher water levels to points of lower water levels, at approximately right angles to the contour lines.

Table 10. Grain-size analyses of drive-core soil samples collected from beneath the Prairie du Sac landfill. Depth of sample in feet below the base of the refuse.

Wentworth Classification (Folk, 1965)

SET #1	Percent by Weight				
Depth	% Gravel	% C Sand	% Med Sand	% Fine Sand	% Silt &
1	2.9	36.9	45.9	12.4	1.8
7	0.4	3.1	72	24.3	0.2
11	0.4	3.2	70.9	25.2	0.3
17	65.1	21.8	10.2	2.7	0.2
SET #2					
1	4.2	33.6	34.9	29.2	1.8
5	0.2	48.9	44.9	4.8	1.2
9	0	29.9	62.9	6.4	0.9
14	0.2	3.1	71.7	23.4	1.6
19	22.2	23.5	39.5	13.1	1.8

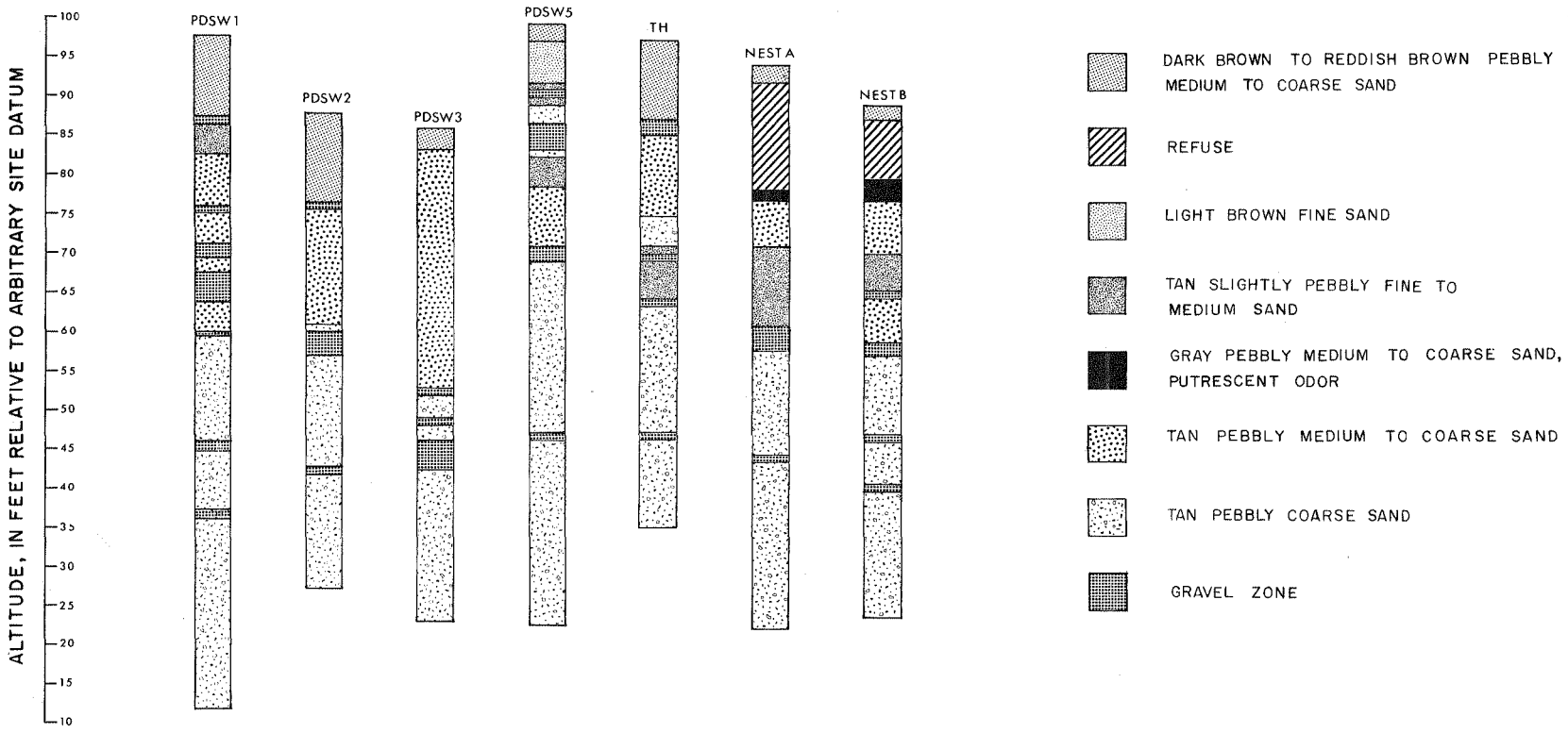


Figure 12. Generalized drill logs from the Prairie du Sac landfill. No horizontal scale.

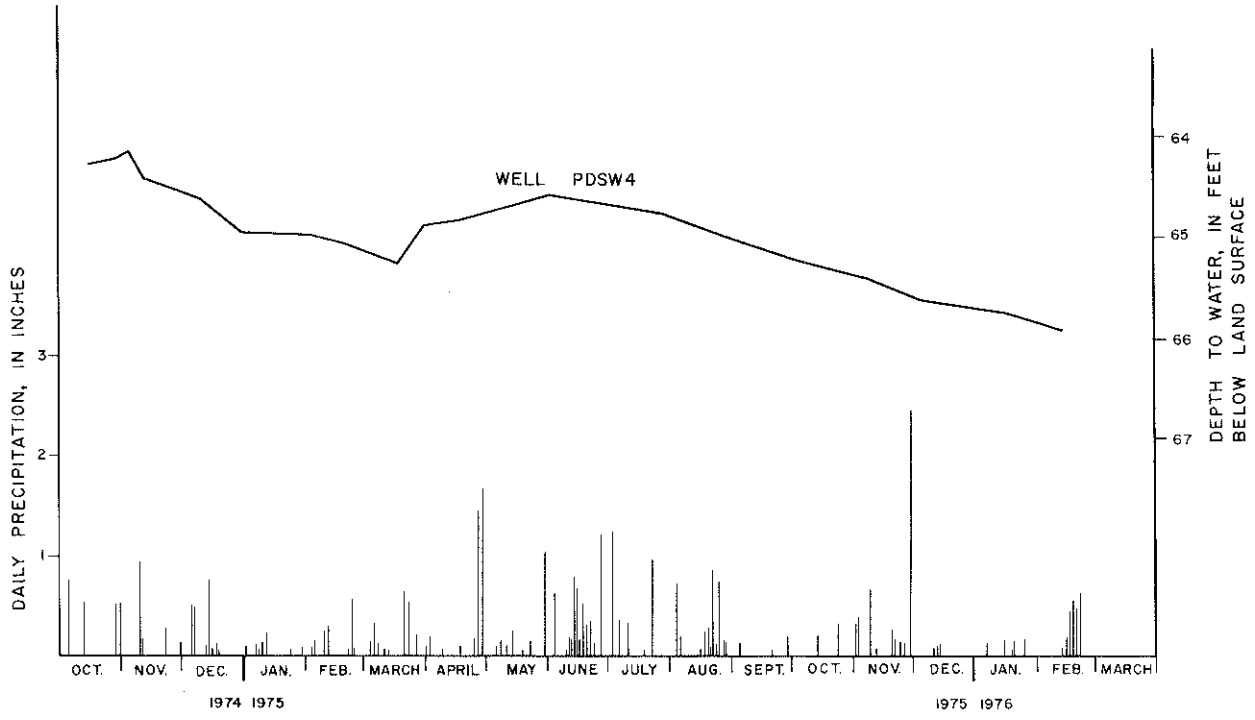


Figure 13. Changes in water level in well PDSW4 and daily precipitation recorded near Prairie du Sac, Wisconsin. Precipitation data from National Oceanic and Atmospheric Administration (1974-1976).

The direction of ground-water movement beneath the Prairie du Sac landfill is illustrated by the water table map (Figure 14), which was prepared from water level measurements made on December 10, 1974. Movement of ground water is generally toward the southwest beneath the landfill area. The average gradient of the water table was approximately 8.5 feet/mile. During the course of this study, little change was observed in the direction of ground-water movement, configuration of the water table, or the hydraulic gradient.

Results

Soil-Moisture/Leachate Samples

Introduction. Changes in leachate component concentrations with time for each sampling depth at lysimeter nests PDSA and PDSB are shown in Figures 15 and 16, respectively. Sample notation refers to the depth of the lysimeter unit below the base of the refuse. The lysimeter units positioned within the refuse material are noted as such. The prefix PDSA or PDSB identifies the lysimeter units placed in nest A and nest B, respectively.

The concentration-time plots show a complex pattern of leachate component concentration changes with depth in the sands and gravels beneath the Prairie du Sac landfill. It is apparent from the accumulated data that a single leaching-attenuation pattern does not exist beneath the landfill. This is illustrated by the behavior, through time and at various depths, of the leachate components in the samples collected from each lysimeter nest and from a comparison of the concentrations observed at each nest.

Lysimeter Nest PDSA. Plots of the various leachate component concentrations (Figure 15) show that the leachate samples collected from within the refuse material (PDSA-refuse) generally contained the lowest concentrations of any of the lysimeter samples collected from nest PDSA. Soil-moisture/leachate samples collected from lysimeter PDSA-4, which was positioned 4 feet below the base of the refuse, generally showed higher concentrations than those observed within the refuse (PDSA-refuse). For example, average concentrations for selected leachate components for samples from PDSA-refuse compare with samples from PDSA-4 as follows:

Parameter	PDSA-refuse	PDSA-4
Specific Conductance (μmhos/cm)	1233	2206
Chloride (mg/l)	44	161
Sodium (mg/l)	71	133
Potassium (mg/l)	68	93
Magnesium (mg/l)	56	92
Alkalinity (mg/l, as $CaCO_3$)	744	1107
Total nitrogen (μg/l)	17,200	54,200
Total P (μg/l)	198	276

These increases occurred despite leachate migration through the 4 feet of soil (sand) that separates lysimeter PDSA-4 and the base of the refuse. This suggests that leachate samples from lysimeter PDSA-refuse may not be representative of the chemical quality of the leachate being produced within the refuse material.

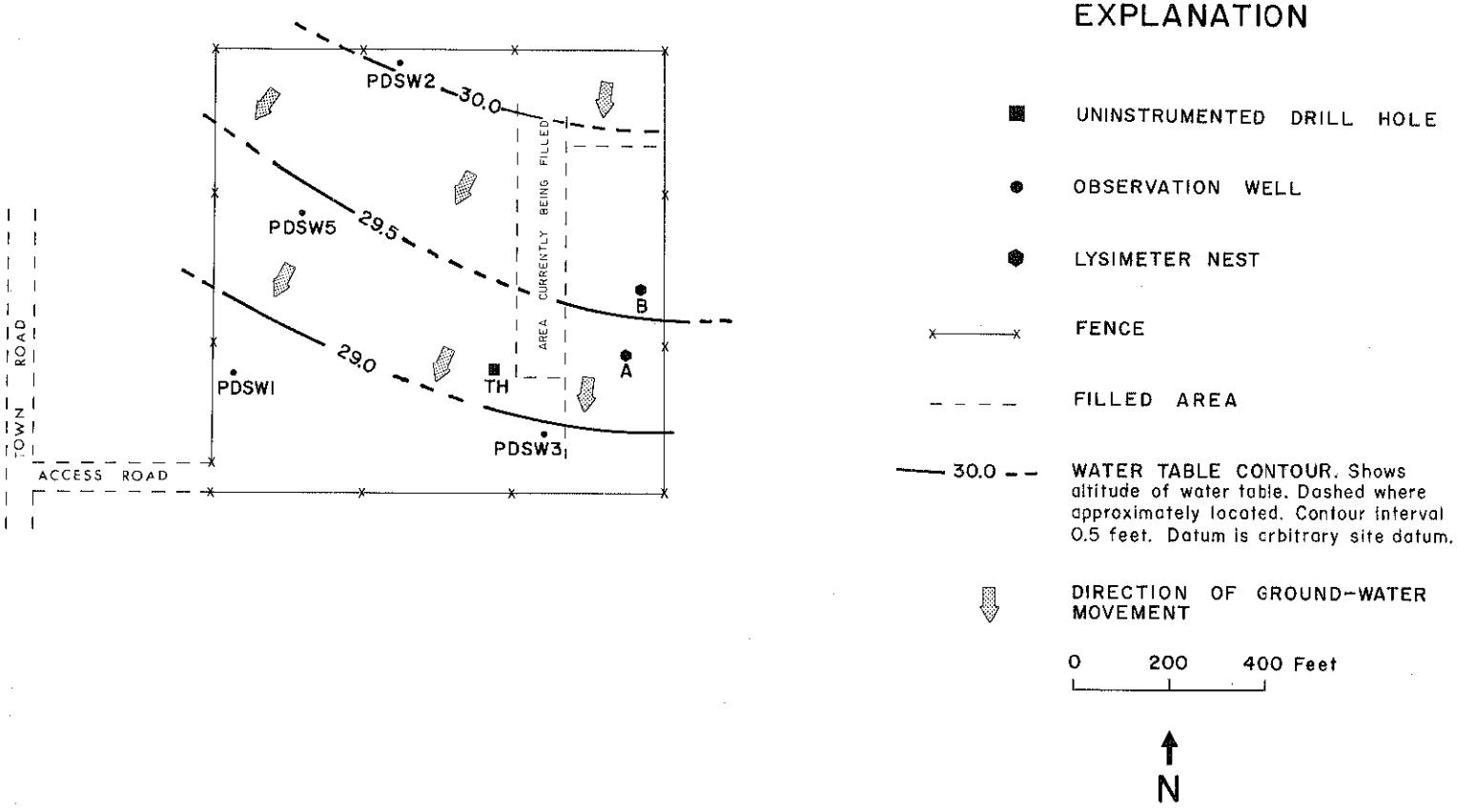


Figure 14. Map of the Prairie du Sac landfill showing configuration of the eater table--December 10, 1974.

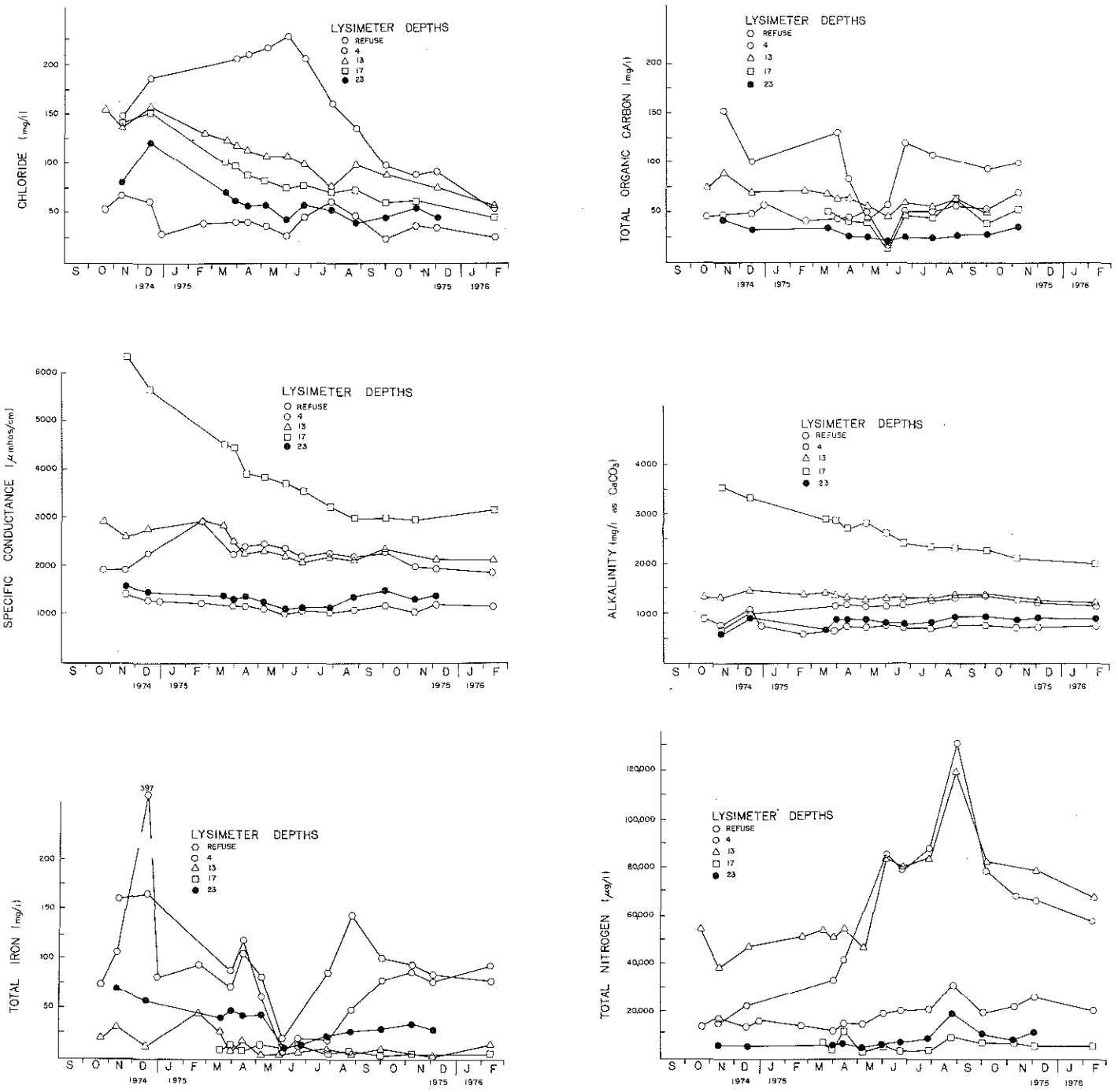


Figure 15. Changes in leachate component concentrations with time in soil-moisture/ leachate samples from lysimeter nest PDSA. Sample notation refers to the depth of the lysimeter unit below the base of the refuse. The lysimeter unit placed within the refuse material is noted as such.

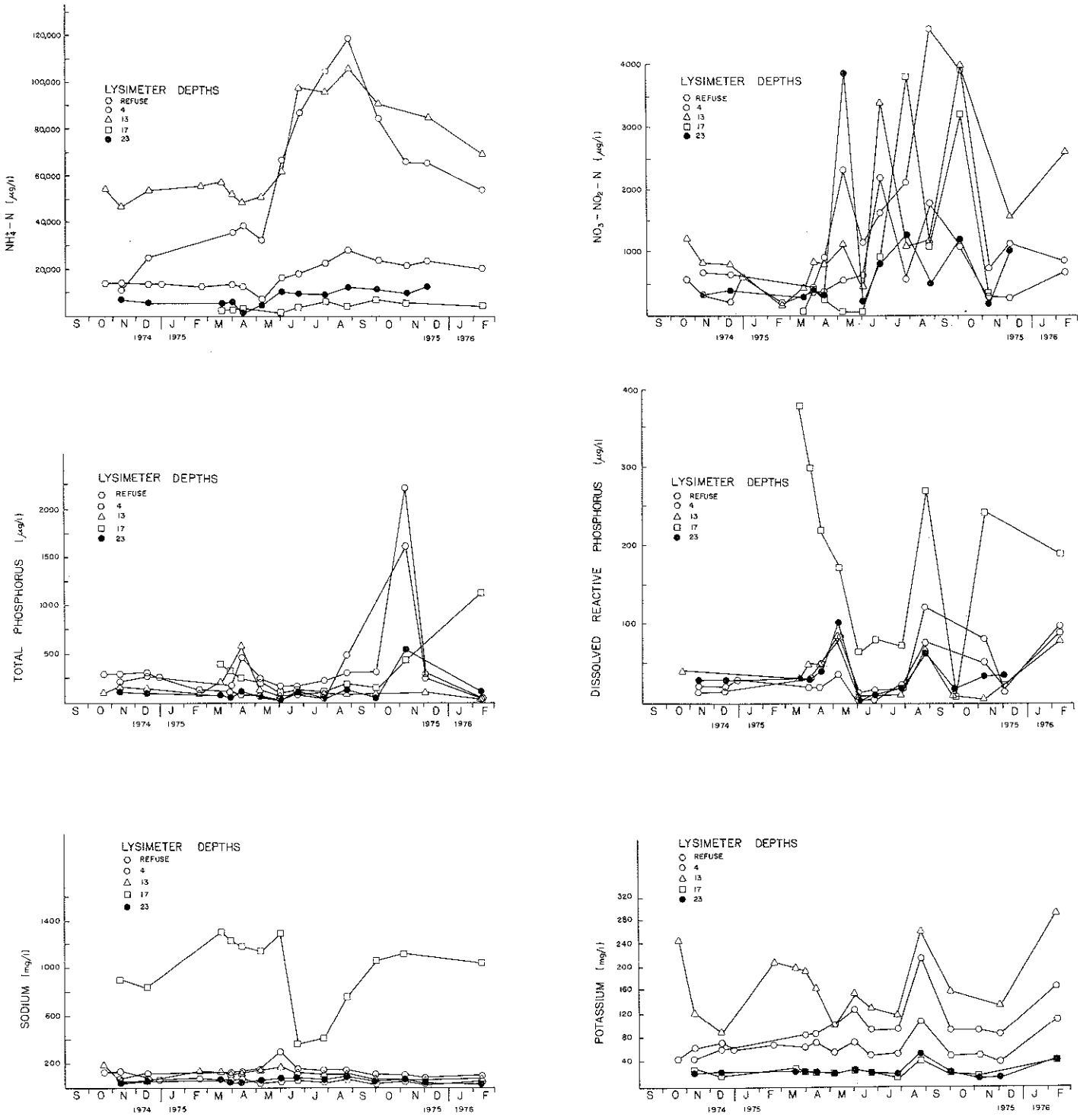
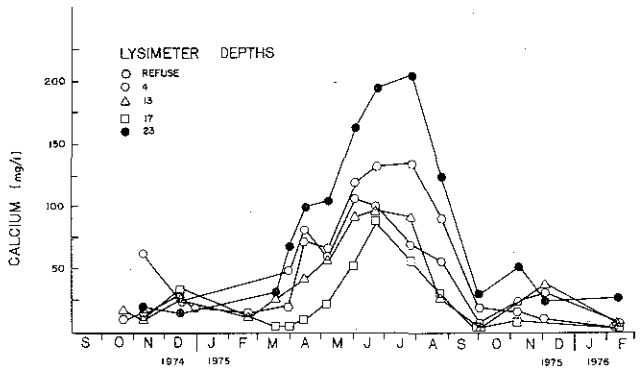
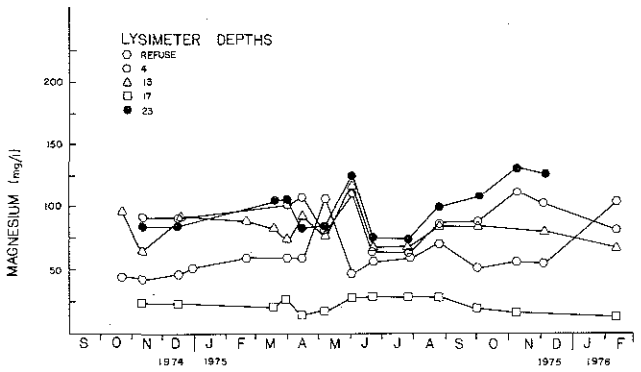
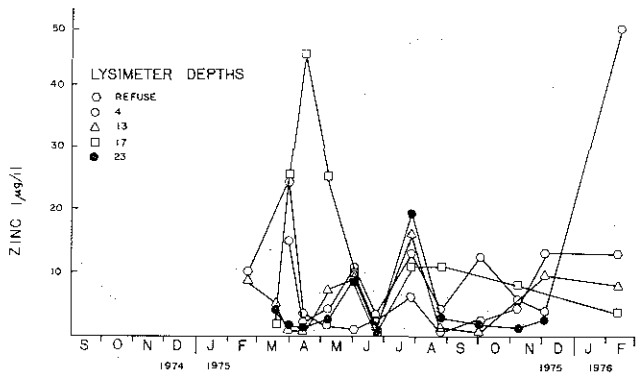
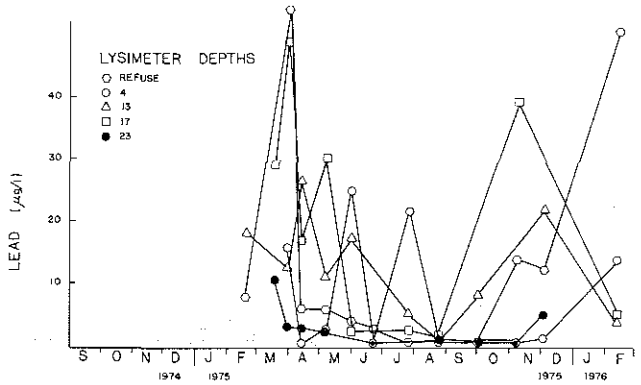


Figure 15. (Continued).









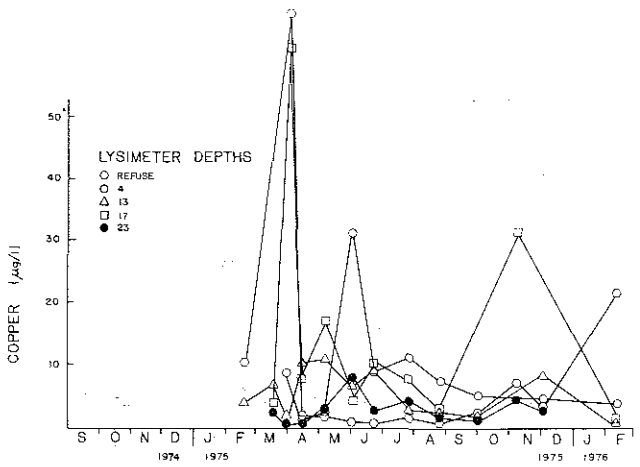


Figure 15. (Continued).

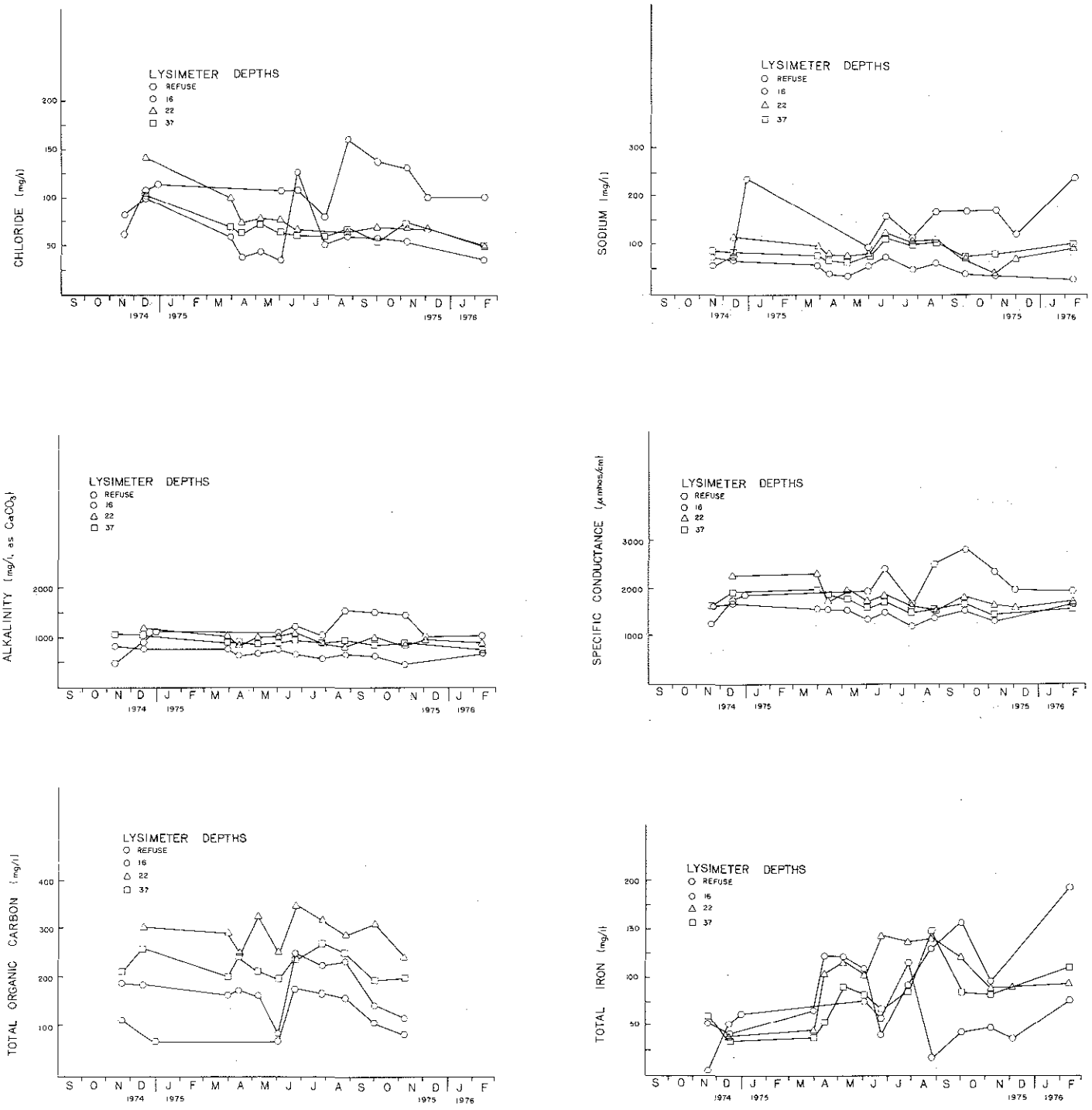
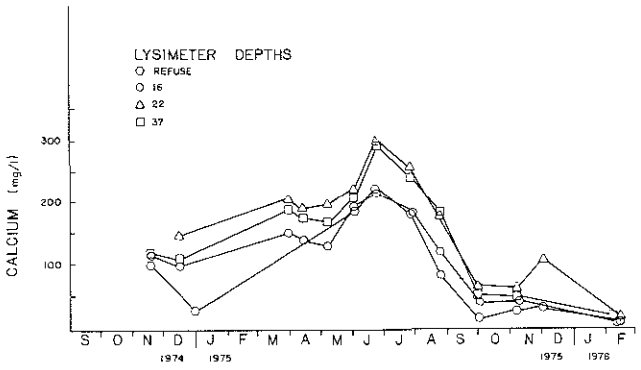
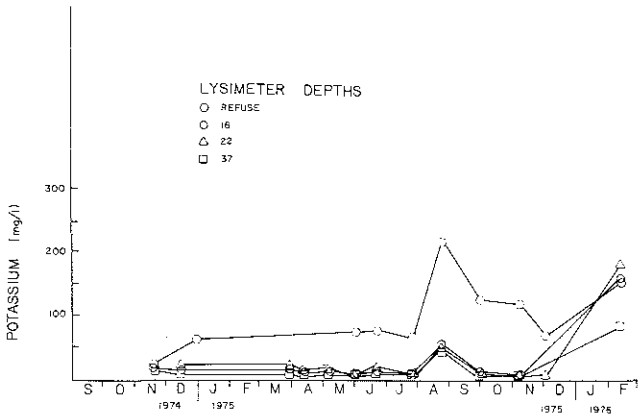
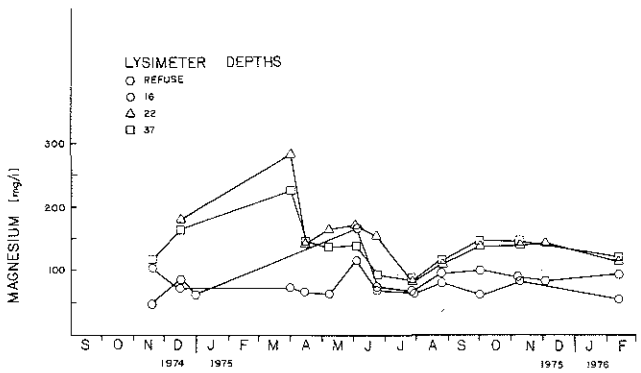
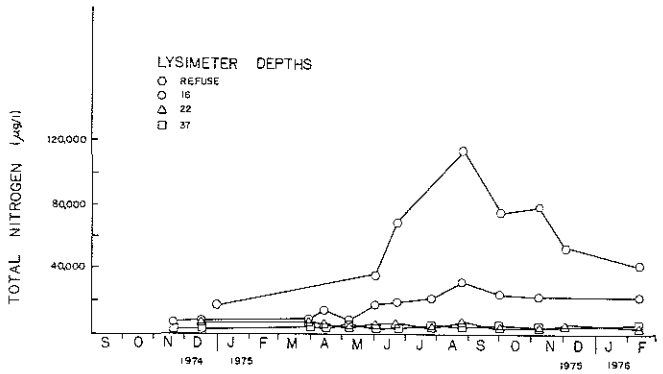


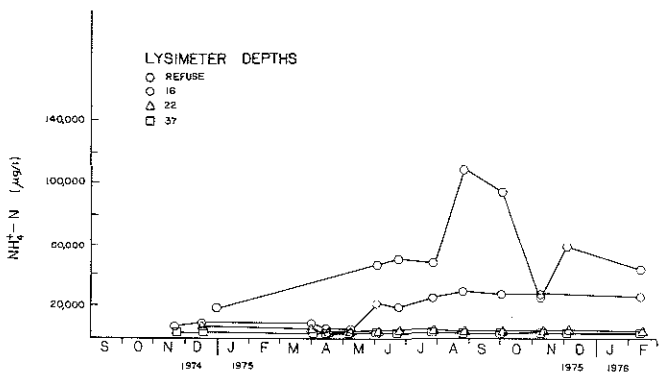
Figure 16. Changes in leachate component concentrations with time in soil-moisture/ leachate samples from lysimeter nest PDSB. Sample notation refers to the depth of the lysimeter unit below the base of the refuse. The lysimeter placed within the refuse material is noted as such.

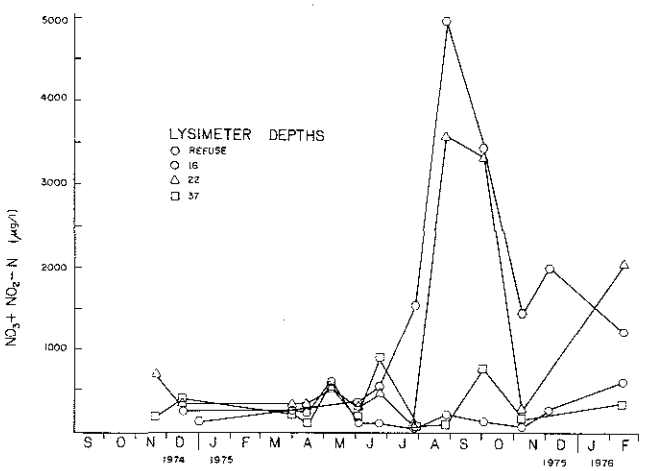












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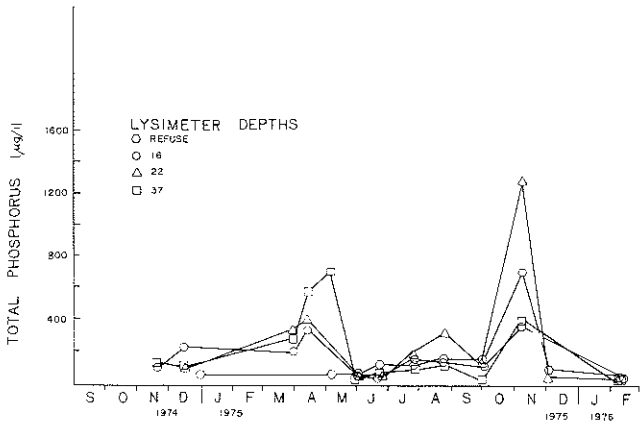
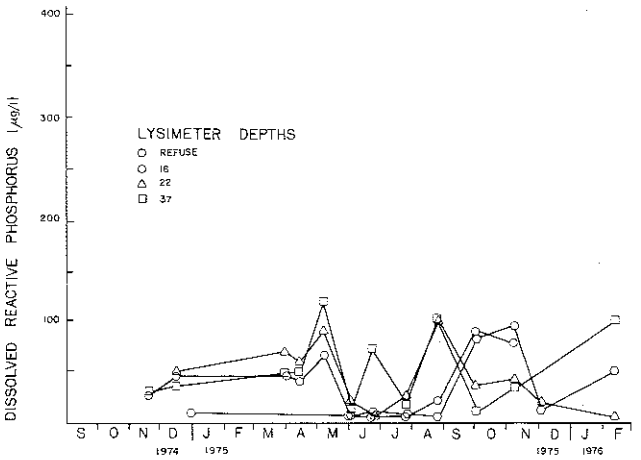
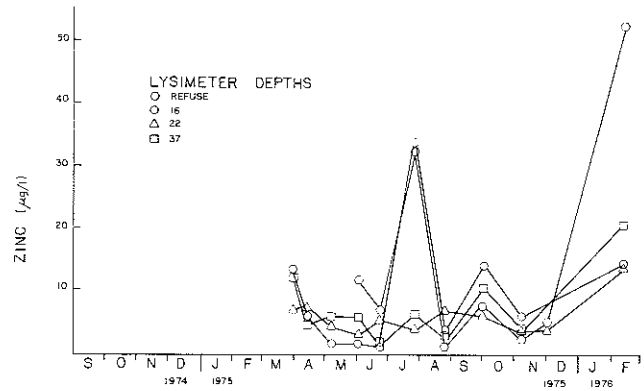
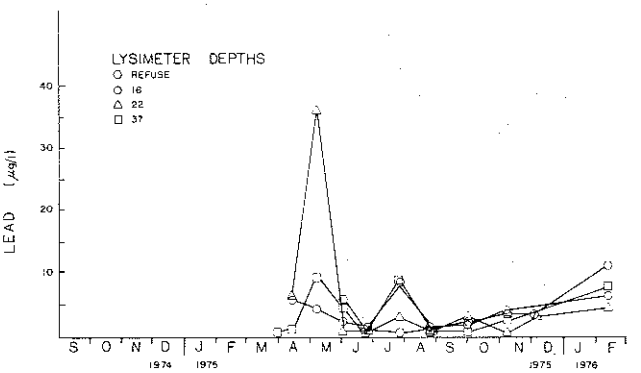








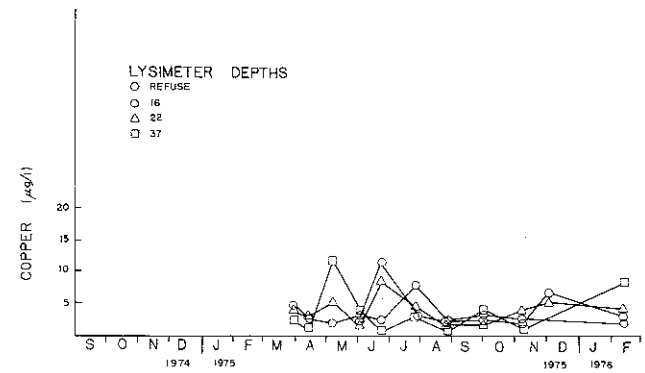


Figure 16. (Continued).

The concentration-time plots of the various leachate components for samples from lysimeters PDSA-4, PDSA-13, PDSA-17, and PDSA-23 (Figure 15) illustrate the leaching patterns developed in the sands and gravels beneath the refuse at lysimeter nest PDSA.

Chloride and total organic carbon (Figure 15) were the only two leachate components that showed a systematic decrease in concentration with depth. Upon reaching a depth of 23 feet below the base of the refuse (PDSA-23), average chloride and total organic carbon concentrations remained fairly stable, but did decrease sharply at all sampling depths during the spring of 1975.

The behavior of the remaining leachate components is more complex than that of chloride or total organic carbon. Concentration changes were variable and less systematic with respect to depth. In fact, leachate component concentrations were frequently observed to increase with depth in the subsoil beneath the Prairie du Sac landfill.

Specific conductance and alkalinity concentration-time plots display the same general trends (Figure 15). Alkalinity and specific conductance increased with depth, reaching maximum values 17 feet below the base of the refuse (PDSA-17). Concentrations then decreased between the 17-foot interval and the 23-foot interval (PDSA-23). Alkalinity and specific conductance values remained fairly stable through time at all sampling intervals, with the exception of the 17-foot interval, where a general decrease in specific conductance and alkalinity was observed.

Total iron concentrations (Figure 15) decreased with depth, reaching minimum values at the 17-foot interval (PDSA-17). Concentrations increased between the 17-foot interval and the 23-foot interval (PDSA-23). A significant reduction in total iron values occurred in the samples collected from all lysimeters at nest PDSA on June 2, 1975.

Total nitrogen concentrations (Figure 15) showed high values in the subsoil immediately beneath the refuse (PDSA-4 and PDSA-13). Average total nitrogen concentrations in samples from lysimeters PDSA-4 and PDSA-13 were 54.2 mg/l and 64.5 mg/l, respectively. This compares to an average total nitrogen concentration of 17.2 mg/l in samples from the refuse material (PDSA-refuse), and average concentrations for samples from PDSA-17 and PDSA-23 of 5.9 mg/l and 7.5 mg/l, respectively. Total nitrogen concentrations in the samples from lysimeters PDSA-4 and PDSA-13 showed a general increase during the study. Concentrations at the other sampling depths remained fairly stable. NH_4^+ - N concentrations showed the same general trends as total nitrogen. $NO_3 + NO_2$ - N concentrations at all sampling depths were extremely variable and fluctuated greatly among the samples collected from each interval, $NO_3 + NO_2$ - N concentrations generally increased at all depths following the spring of 1975.

Total phosphorus concentrations (Figure 15) were generally low at all sampling depths and showed little variation with time. High total phosphorus concentrations were observed, however, in the samples from all depths on November 2, 1975. Dissolved reactive phosphorus (DRP) concentrations were generally low and showed similar values at all sampling depths, with the exception of the PDSA-17 samples, which showed high concentrations. Dissolved reactive phosphorus concentrations were reduced at all sampling depths in the samples collected in June and July of 1975, and concentrations increased at all sampling depths in the October 2, 1975, samples.

Sodium concentrations were low and stable through time at all sampling depths except PDSA-17, which recorded very high sodium concentrations. The average sodium concentration in the samples from PDSA-17 was 1001 mg/l. All other sampling depths showed average sodium concentrations of 70-150 mg/l. Sodium concentrations in the June 23, 1975, sample collected from PDSA-17 showed a sharp decrease. Concentrations then increased through the summer to concentration levels recorded prior to June 23, 1975. Concentrations at all other sampling depths remained stable during this period.

Potassium concentrations increased with depth, reaching maximum concentrations 13 feet below the base of the refuse (PDSA-13). Concentrations then decreased at the 17-foot interval (PDSA-17) and remained low at the 23-foot interval (PDSA-23). Many of the fluctuations in potassium concentrations occurred simultaneously at all sampling depths.

Calcium concentrations decreased with depth, reaching minimum values in the samples collected from PDSA-17. Samples from PDSA-23 showed the highest calcium concentrations recorded at nest PDSA. Concentrations at all sampling depths increased during the spring and early summer of 1975, reaching maximum values in July or August. Concentrations then declined through the summer and remained at these lower concentrations for the remainder of the study. The pattern of calcium concentration changes with time suggests that these changes are seasonal.

Changes in magnesium concentrations with depth were similar to the changes observed in calcium. However, magnesium did not show the major concentration peaks that were observed for calcium. All sampling depths showed fairly stable magnesium concentrations through time.

Concentrations of heavy metals (zinc, copper, and lead) were generally quite variable. However, concentrations were generally highest in the PDSA-17 samples. For example, average zinc, lead, and copper concentrations for samples from lysimeter PDSA-17 were 15.8 μg/l, 21.7 μg/l, and 16.6 μg/l, respectively. Analyses were also made for cadmium; however, concentrations were below detectable limits in most samples.

Lysimeter Nest PDSB. Changes in leachate component concentrations with time for each sampling depth at lysimeter nest PDSB are shown in Figure 16. Sample notation refers to the depth of the lysimeter unit below the base of the refuse. The prefix PDSB identifies lysimeter units placed in nest PDSB. The lysimeter unit placed within the refuse material is noted as such.

The concentration-time plots for nest PDSB show that the pattern of leachate component concentrations that developed within the refuse and subsoil beneath the landfill at lysimeter nest PDSB differs from the patterns observed at nest PDSA.

Chloride, sodium, alkalinity, and specific conductance profiles display the same general trends (Figure 16). The highest values for these components were recorded in the samples collected from within the refuse material (PDSB-refuse). Concentrations decreased at the 16-foot interval (PDSB-16), then increased at the 22-foot (PDSB-22) and 37-foot (PDSB-37) intervals. The concentrations of these four parameters were generally higher in the leachate samples collected from the refuse at nest PDSB, and lower in the subsoil, than concentrations for the same

parameters in the samples from nest PDSA. Concentration peaks at the 17-foot interval in nest PDSA for sodium, alkalinity, and specific conductance and at the 13-foot interval (nest PDSA) for chloride were not observed at similar depths in the subsoil at nest PDSB. Concentrations of these four parameters remained stable with time at all sampling depths at nest PDSB.

The lowest total organic carbon, total iron, and calcium concentrations at nest PDSB (Figure 16) were recorded within the refuse material (PDSB-refuse). Total organic carbon and total iron concentrations increased with depth, reaching maximum concentrations at the 22-foot interval. Concentrations were reduced slightly at the 37-foot interval. Total organic carbon concentrations in the samples from nest PDSA were generally lower (20 to 70 mg/l) than concentrations observed at nest PDSB (25 to 150 mg/l). A reduction in total organic carbon in all lysimeter samples from nest PDSB occurred in the samples collected on June 2, 1975. These reductions were not as pronounced as those observed in the PDSA samples on the same date. Total iron concentrations were generally lower within the refuse material and higher in the subsoil for PDSB samples than for PDSA samples. The major reduction in total iron concentrations in the June 2, 1975 samples from nest PDSA was not as pronounced in the samples at nest PDSB. Total iron concentrations at all sampling depths at nest PDSB increased during the course of the study. Changes in calcium concentrations with time in the samples from nest PDSB were similar to the changes observed at nest PDSA, although average concentrations for nest PDSB (90 to 160 mg/l) were generally higher than concentrations for nest PDSA (30 to 75 mg/l).

Potassium concentrations were highest in the samples collected from within the refuse material (PDSB-refuse). Concentrations were reduced within the subsoil, and all sampling intervals beneath the refuse showed low, stable concentrations. Concentrations of potassium in the subsoil were generally lower at nest PDSB than at nest PDSA. The concentration peak for potassium, which was observed in the samples from PDSA-17, was not observed at a similar depth at nest PDSB. Similar concentration-time changes for potassium were observed in the samples from both nests.

Magnesium concentrations generally increased with depth in the subsoil at nest PDSB. Changes in magnesium concentrations with time in the PDSB samples were similar to the changes observed in the PDSA samples, however, concentrations were generally higher in the lysimeter samples from nest PDSA.

Total nitrogen and NH_4^+ - N concentrations showed high concentrations within the refuse material and in the subsoil immediately beneath the landfill to a depth of 16 feet (PDSB-16). Low, stable concentrations were observed in the samples from lysimeters PDSB-22 and PDSB-37. Total nitrogen and NH_4^+ - N concentrations within the refuse (PDSB-refuse) and in samples from PDSB-16 increased during the course of the study. NO_3 + NO_2 - N concentrations were variable and less systematic with respect to depth than either total N or NH_4^+ - N. NO_3 + NO_2 - N concentrations were higher within the refuse material and lower in the subsoil at nest PDSB than for samples from nest PDSA.

Total phosphorus concentrations for all sampling depths at nest PDSB were generally low and stable. The concentration peak for total phosphorus in the PDSB samples collected on November 2, 1975, was also observed in the PDSA samples for the same date. Dissolved reactive phosphorus concentrations in the PDSB samples were generally low, but tended to increase with depth in the subsoil beneath the landfill.

Heavy metal concentrations (zinc, lead, and copper) in the PDSB samples were variable and did not show any systematic changes with respect to time or depth. Analyses were made for cadmium, however concentrations were generally below the limits of detection.

Soil Samples

Chemical analyses were made on uncontaminated, or background, auger soil samples collected during the drilling of well PDSW5 (Figure 10). Sample notation for the PDSW5 soil samples indicates the sample depth below land surface. The chemical analyses (Table 11) showed little variation in parameter concentrations with depth. Noticeable, however, are the high concentrations at the 4- and 8-foot intervals. This suggests that many of the chemical parameters are being leached from the near-surface soil.

Chemical analyses were also made on auger soil samples collected from drill hole TH (Figure 10), which was an uninstrumented test hole drilled just outside the active fill area. Originally the TH soil samples were collected to provide data on the chemical quality of background soil. However, the chemical analyses (Table 12) indicated that the TH soils may have been affected by landfill leachate. (Sample notation for the TH soil samples indicates the depth of the sample below land surface.)

High chloride concentrations in the TH soil samples at the 24- to 38-foot intervals suggest that lateral movement of landfill leachate may have occurred. Since chloride is practically unaffected by reactions in the soil (Apgar and Langmuir, 1971), it is generally considered a good tracer of leachate movement. The topographic position of the TH drill hole (Figure 10) and its position relative to the fill area argue against surface contamination as the source of the high chloride values.

Calcium, magnesium, and NH_4^+ - N concentrations tended to be higher in the TH soil samples than in the PDSW5 (background) samples. NO_3 + NO_2 - N and acid-extractable phosphorus concentrations were generally lower in the TH soil samples than in the background soil samples. The lower NO_3 + NO_2 - N and higher NH_4^+ - N concentrations in the TH soil samples, as compared to the values observed in the PDSW5 (background) soil samples, suggest that anaerobic (reducing) conditions exist in the subsoil outside the landfill area. (Polkowski and Boyle, 1970)

Two sets of split-spoon (drive-core) soil samples were collected from beneath the refuse for chemical analyses. Split-spoon soil sample set No. 1 was collected during the installation of lysimeter nest PDSA (Figure 10) in September of 1974. Split-spoon soil sample set No. 2 was collected in May of 1975, at a point midway between lysimeter nests PDSA and PDSB (Figure 10). Sample notation for both split-spoon soil sample sets indicates the depth of the sample below the base of the refuse. The addition of 17 feet and 10 feet (refuse thickness) to the sample depths for split-spoon sample sets No. 1 and No. 2, respectively, provides depth below land surface, which can then be compared to the depths for the background (PDSW5 soil samples) soil samples.

A comparison of the chemical analyses for split-spoon soil sample sets No. 1 and No. 2 (Table 13) shows that all parameter concentrations, with the exception of chloride, total N, and NO_3 + NO_2 - N, were significantly lower in

Table 11. Chemical analyses of uncontaminated auger soil samples collected at the Prairie du Sac landfill.

Sample	Micrograms per gram of soil										
	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Chloride (Cl)	Total Iron (Fe)	Total N (as N)	$NO_3 + NO_2$ - N (as N)	NH_4^+ - N (as N)	Total P (as P)	Acid-extract. P (as P)
PDSW5-soil[a]											
4'	100	17	7.8	11.6	40.5	0.21	4.13	1.53	1.60	28.6	8.3
8'	2100	1120	8.8	19.0	61.4	0.41	2.97	2.27	0.02	6.2	22.0
12'	5260	1860	12.0	12.0	45.6	0.83	2.47	2.03	0.70	27.2	15.0
18'	3600	1480	8.6	10.0	27.8	1.15	3.67	1.53	0.83	11.0	20.0
24'	4360	1340	7.2	12.0	27.3	1.17	1.83	1.80	0.80	21.6	18.7
28'	3620	1060	7.2	10.0	60.2	0.75	3.20	1.37	0.87	16.2	16.6
34'	4160	1440	10.0	13.0	47.3	4.66	1.82	2.00	0.70	28.8	26.2
38'	4880	1480	12.4	12.0	49.3	1.87	0.92	1.83	0.23	5.6	15.8
44'	5360	1440	9.2	12.0	49.1	1.86	2.27	1.23	0.67	12.8	28.4
48'	5120	1060	6.4	12.0	30.9	0.73	3.25	1.27	0.03	16.6	18.4
54'	4160	1180	9.4	14.0	46.3	1.16	0.26	1.70	0.27	9.4	14.4
58'	4960	1080	7.8	12.0	38.5	0.72	0.18	2.80	0.47	15.4	11.6
64'	5720	1180	12.0	13.0	52.9	1.59	0.64	-	-	22.6	18.2

[a] Sample notation indicates depth below land surface

Table 12. Chemical analyses of auger soil samples collected from test drill hole TH.

Sample	Micrograms per gram of soil										
	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Chloride (Cl)	Total Iron (Fe)	Total N (as N)	$NO_3 + NO_2$ - N (as N)	NH_4^+ - N (as N)	Total P (as P)	Acid-extract. P (as P)
TH-soil[a]											
4'	108	86	5.8	10.4	4.0	0.10	8.86	0.30	1.20	40	3.7
12'	4320	1740	10.0	9.6	2.0	0.70	2.40	0.60	2.10	19.8	7.3
24'	5120	1720	8.2	8.0	116	1.32	2.30	0.60	2.10	4.2	7.0
28'	5180	1900	6.8	6.0	170	1.59	1.84	0.80	1.10	16.8	7.7
34'	5160	1680	7.0	8.8	111	1.02	2.06	0.60	1.20	7.4	7.0
38'	5880	1600	6.2	8.8	341	1.55	2.00	0.40	0.90	14	8.0
44'	6560	1860	9.4	22.0	49.6	1.18	2.55	0.20	0.40	6.6	10.6
48'	5360	1620	7.8	9.6	29.7	1.32	2.12	0.50	0.30	31.8	6.2
54'	3620	1140	5.2	5.6	7.9	0.95	2.20	0.20	0.30	12.8	5.7
58'	4420	1500	6.4	10.8	11.3	1.38	2.01	0.30	0.40	13.6	3.5

[a] Sample notation indicates sample depth below land surface.

Table 13. Chemical analyses of drive core soil samples collected from beneath the refuse at the Prairie du Sac landfill.

Sample	Micrograms per gram of soil										
	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Chloride (Cl)	Total Iron (Fe)	Total N (as N)	$NO_3 + NO_2 - N$ (as N)	$NH_4^+ - N$ (as N)	Total P (as P)	Acid-extract. P (as P)
Split-spoon soil sample #1[a]											
1'	2380	1360	9.2	40.8	22.8	6.73	10.72	0.02	6.0	14.5	6.2
7'	1880	880	21.4	58.0	19.4	6.84	8.91	1.00	7.4	11.7	5.1
11'	2040	860	12.6	29.6	17.3	3.60	6.76	0.30	7.3	7.1	3.9
17'	8320	1400	11.0	14.4	-	-	-	-	-	-	-
Split-spoon soil sample #2[a]											
1'	214.2	56.9	5.7	30.2	134	-	11.35	0.62	3.40	6.1	0.2
5'	336.1	55.2	10.6	26.1	22	-	8.36	0.36	3.18	2.9	0.4
9'	393	55.7	10.2	25.4	48	-	12.58	0.74	1.80	4.4	0.2
14'	335.7	59.0	9.5	9.2	20	-	3.03	0.68	0.26	5.3	0.1
19'	418.7	68.5	13.0	12.6	36	-	11.96	0.47	0.92	4.2	0.4

[a] Sample notation indicates depth below the base of the refuse. For comparative purposes, the addition of 17 feet or 10 feet (refuse thickness) to the soil depths for soil sample sets No. 1 and No 2, respectively, provides depth below land surface, which can then be compared to the PDSW5 and TH soil sample depths.

the second set of split-spoon soil samples. As most of the parameters that showed increases are cations, it appears that the soil-moisture/leachate has removed some of these ions from the soil during the period separating collection of the two sample sets. The increases in chloride and the nitrogen species over the same period may reflect increased infiltration through the landfill. The increased infiltration may also account for the removal of the ions from the soil.

A comparison of the concentrations in split-spoon soil sample set No. 1 (Table 13) with background soils (PDSW5 soils, Table 11) shows that concentrations of calcium, sodium, potassium, total iron, total N, and NH_4^+ - N were generally higher beneath the landfill. Low concentrations beneath the landfill were observed for magnesium, chloride, NO_3 + NO_2 - N, total P, and acid-extractable P. The lower chloride values beneath the landfill, as compared to higher values outside the active fill area (PDSW5 soil samples), may indicate lateral movement of landfill leachate. The lower concentrations of total P and acid-extractable P beneath the landfill are consistent with the results reported by Apgar and Langmuir (1971).

Analyses were made for polychlorinated biphenyls (PCB's) on the second set of split-spoon soil samples. PCB's were detected at all sampling depths beneath the refuse, as shown below.

Depth Below Refuse, in feet	PCB Concentration
1	0.022×10^{-9} grams/gram of soil
9	0.068×10^{-9} grams/gram of soil
14	0.029×10^{-9} grams/gram of soil
19	0.093×10^{-9} grams/gram of soil

This limited sampling for PCB's only serves to indicate the presence, in low concentrations, of PCB's in the subsoil beneath the Prairie du Sac landfill.

Ground-Water Quality

The chemical quality of uncontaminated, or background, ground water was determined by sampling wells PDSW1, PDSW2, and PDSW5 (Figure 10). The results of the chemical analyses and mean concentration values are presented in Table 14. The analyses for wells PDSW1, PDSW2, and PDSW5 are similar and believed to be representative of background ground-water quality in the vicinity of the Prairie du Sac landfill.

The chemical quality of ground water immediately beneath the refuse was determined by sampling wells PDSW4 and PDSW6 (Figure 10), which were placed at lysimeter nests PDSA and PDSB, respectively. In the ground water immediately beneath the refuse, concentrations were generally 2 to 5 times higher than background concentrations (Table 14). In general, concentrations in the samples from wells PDSW4 and PDSW6 were similar, except for lower concentrations of NO_3 + NO_2 - N in samples from well PDSW6.

A comparison of leachate component concentrations in the ground-water samples from wells PDSW4 and PDSW6 and in the deepest lysimeter units beneath the refuse (PDSA-21, Figure 15, and PDSB-37, Figure 16), shows that concentrations in the ground water were generally 2 to 6 times lower than concentrations observed in the soil-moisture/leachate. Total iron concentrations were generally between

Table 14. Chemical analyses of ground-water samples collected from beneath the Prairie du Sac landfill.

Sample	Spec. Conductance micromhos/cm 25°C	Milligrams per liter								Micrograms per liter				
		Calcium (Ca)	Magnesium (Mg)	Potassium (K)	Sodium (Na)	Chloride (Cl)	Alkalinity (as $CaCO_3$)	Total Iron (Fe)	Total Organic Carbon (as C)	Total P (as P)	DRP (as P)	Total N (as N)	$NO_3 + NO_2$ - N (as N)	NH_4^+ - N (as N)
PDSW1														
9-25-74	-	24	11	0.6	7.3	7.8	99	0.02	2.3	352	4	151	139	66
10-28-74	150	22	12	0.6	3.3	1.6	88	0.14	0.9	22	16	120	58	65
12-30-74	125	15	12	0.6	3.3	7.3	76	-	0.8	14	2	141	39	21
5-7-75	125	9	12	3.4	4.0	11.0	85	0.23	2.9	230	5	191	36	109
7-28-75	150	24	21	2.9	8.3	11.0	72	0.03	29.0	870	6	254	17	73
11-7-75	100	8	16	3.9	6.3	9.4	64	0.44	13.0	144	5	102	79	62
average	130	17	14	2.0	5.4	8.0	81	0.17	8.2	272	6.3	160	61	66
PDSW2														
9-25-74	-	25	16	0.7	1.6	1.7	109	0.09	4.5	176	6	164	163	96
10-28-74	175	27	13	0.6	2.8	2.1	118	0.08	1.1	22	4	123	91	68
12-30-74	200	32	12	0.6	1.8	7.7	105	0.05	2.6	64	8	128	52	22
5-7-75	175	16	13	4.6	3.6	10.4	104	0.38	0.6	47	4	259	109	185
7-28-75	125	27	20	2.9	7.0	10.6	72	0.01	13.0	288	4	10	105	108
11-7-75	175	13	22	3.9	9.1	9.5	73	0.55	23.0	55	7	40	2	25
average	170	23	16	2.2	4.3	7.0	97	0.19	7.5	109	7	121	87	84
PDSW3														
9-25-74	-	37	50	0.6	9.2	35.5	389	0.11	12.0	134	4	397	52	5
10-28-74	925	16	69	1.4	16.6	40.3	309	0.16	1.8	24	8	65	10	7
12-30-74	925	18	70	0.6	19.6	39.5	612	-	2.7	16	7	378	14	3
5-7-75	850	96	55	3.4	12.4	32.1	551	0.27	6.9	28	24	177	113	63
7-28-75	750	143	63	2.3	31.0	30.3	461	0.01	34.0	124	6	62	7	6

Table 14. (Continued).

Sample	Spec. Conductance micromhos/cm 25°C	Milligrams per liter								Micrograms per liter				
		Calcium (Ca)	Magnesium (Mg)	Potassium (K)	Sodium (Na)	Chloride (Cl)	Alkalinity (as $CaCO_3$)	Total Iron (Fe)	Total Organic Carbon (as C)	Total P (as P)	DRP (as P)	Total N (as N)	$NO_3^+ NO_2^-$ N (as N)	NH_4^+ - N (as N)
PDSW3 (cont.)														
11-7-75	625	28	44	0.4	17.8	21.8	361	0.76	28.0	44	14	76	89	59
average	815	56	58	1.4	17.8	33.2	445	0.26	14.1	62	11	192	47	24
PDSW4														
9-25-74	-	38	34	0.4	3.0	7.9	225	0.17	-	18	6	667	964	435
10-28-74	950	76	32	1.8	2.0	8.1	334	0.17	-	14	6	276	364	254
12-30-74	475	73	28	2.6	1.4	10.0	331	-	1.3	56	20	254	1132	39
5-7-75	475	59	32	4.0	14.8	14.0	299	1.42	1.4	42	14	448	78	229
7-28-75	525	123	48	4.1	14.0	15.0	324	0.01	7.0	120	6	585	1050	342
11-7-75	375	35	41	5.9	12.3	13.0	229	0.30	22.0	211	22	1154	5	1363
average	560	64	36	2.8	10.7	11.0	290	0.41	7.9	77	12	545	470	291
PDSW5														
9-25-74	-	-	-	-	-	-	-	-	-	-	-	-	-	-
10-28-74	175	28	11	1.9	5.2	2.1	70	0.10	1.3	115	4	99	91	68
12-30-74	150	28	14	0.6	3.4	7.4	112	0.02	4.5	126	2	94	76	61
5-7-75	125	9	12	2.6	4.1	9.5	77	0.22	1.6	70	5	336	216	181
7-28-75	125	21	22	2.7	6.4	11.2	57	0.05	17.0	300	2	10	47	81
11-7-75	125	9	19	5.8	6.6	8.3	70	0.18	19.0	44	7	108	7	23
average	140	19	16	2.7	5.1	7.7	77	0.11	8.7	131	4	129	87	83

Table 14. (Continued).

Sample	Spec. Conductance micromhos/cm 25°C	Milligrams per liter								Micrograms per liter				
		Calcium (Ca)	Magnesium (Mg)	Potassium (K)	Sodium (Na)	Chloride (Cl)	Alkalinity (as $CaCO_3$)	Total Iron (Fe)	Total Organic Carbon (as C)	Total P (as P)	DRP (as P)	Total N (as N)	$NO_3 + NO_2$ - N (as N)	NH_4^+ - N (as N)
PDSW6														
9-25-74	-	-	-	-	-	-	-	-	-	-	-	-	-	-
10-28-74	500	32	27	5.3	4.8	5.7	176	0.18	-	202	10	655	234	761
12-30-74	625	52	31	3.3	2.8	12.0	295	-	-	30	6	510	53	562
5-7-75	475	52	34	5.1	6.7	12.5	271	0.21	1.2	97	10	748	34	462
7-28-75	550	121	54	4.2	12.9	13.0	339	0.00	15.0	176	6	567	16	445
11-7-75	625	38	48	5.1	13.3	12.8	384	0.51	22.0	44	13	672	3	427
average	555	59	39	4.6	8.1	11.2	293	0.23	12.8	110	9	630	68	531

100 and 300 times lower in the ground-water samples. These reductions are believed to have resulted from (1) continued soil-moisture/leachate movement through the 20-25 feet of subsoil that separates the deepest lysimeter units and the water table and (2) dilution by ground water, which probably accounts for most of the concentration reductions.

Ground-water samples from well PDSW3 (Table 14) showed the highest concentrations for specific conductance (815 μmhos/cm), magnesium (58 mg/l), sodium (8.1 mg/l), total organic carbon (14.1 mg/l), chloride (33.2 mg/l), and alkalinity (445 mg/l), and the lowest concentrations for NH_4^+ - N (24 μg/l), NO_3 + NO_2 - N (47 μg/l), potassium (1.4 mg/l), and total P (62 μg/l) of any of the ground-water samples collected at the Prairie du Sac landfill. Well PDSW3 is located down gradient from the fill area (Figure 14); thus it is in a position to intercept a significant portion of the leachate-affected ground water leaving the site.

Discussion of Results

Factors Controlling Soil-Moisture/Leachate Quality

Introduction. An examination of soil-moisture/leachate quality from the two lysimeter nests (PDSA and PDSB) at the Prairie du Sac landfill, as shown in Figures 15 and 16, and the graphs of average leachate component concentrations for each lysimeter sampling depth at nests PDSA and PDSB (Figure 17) brings out several apparently anomalous conditions:

1. The chemical quality of the leachates within the refuse material at lysimeter nests PDSA and PDSB differed considerably.

2. Leachate component concentrations generally did not vary systematically, with respect to depth, in the subsoil beneath the Prairie du Sac landfill. In many cases, leachate component concentrations were observed to increase with depth.

3. The patterns of leachate component concentration changes that developed in the subsoil beneath the Prairie du Sac landfill often differed greatly at the two lysimeter nests.

The observed changes in leachate component concentrations in the subsoil beneath the Prairie du Sac landfill are difficult to interpret because of the large number of interdependent variables affecting the results. However, the concentrations of the leachate, or any leachate component, at depth in the unsaturated zone beneath the landfill will depend upon the interaction of several factors:

1. The chemical quality of the leachate being produced within the refuse material.

2. Chemical interaction between the subsoil material and soil-moisture/leachate.

3. Unsaturated soil-moisture/leachate movement.

4. Mobility and depth of penetration of the various leachate components.

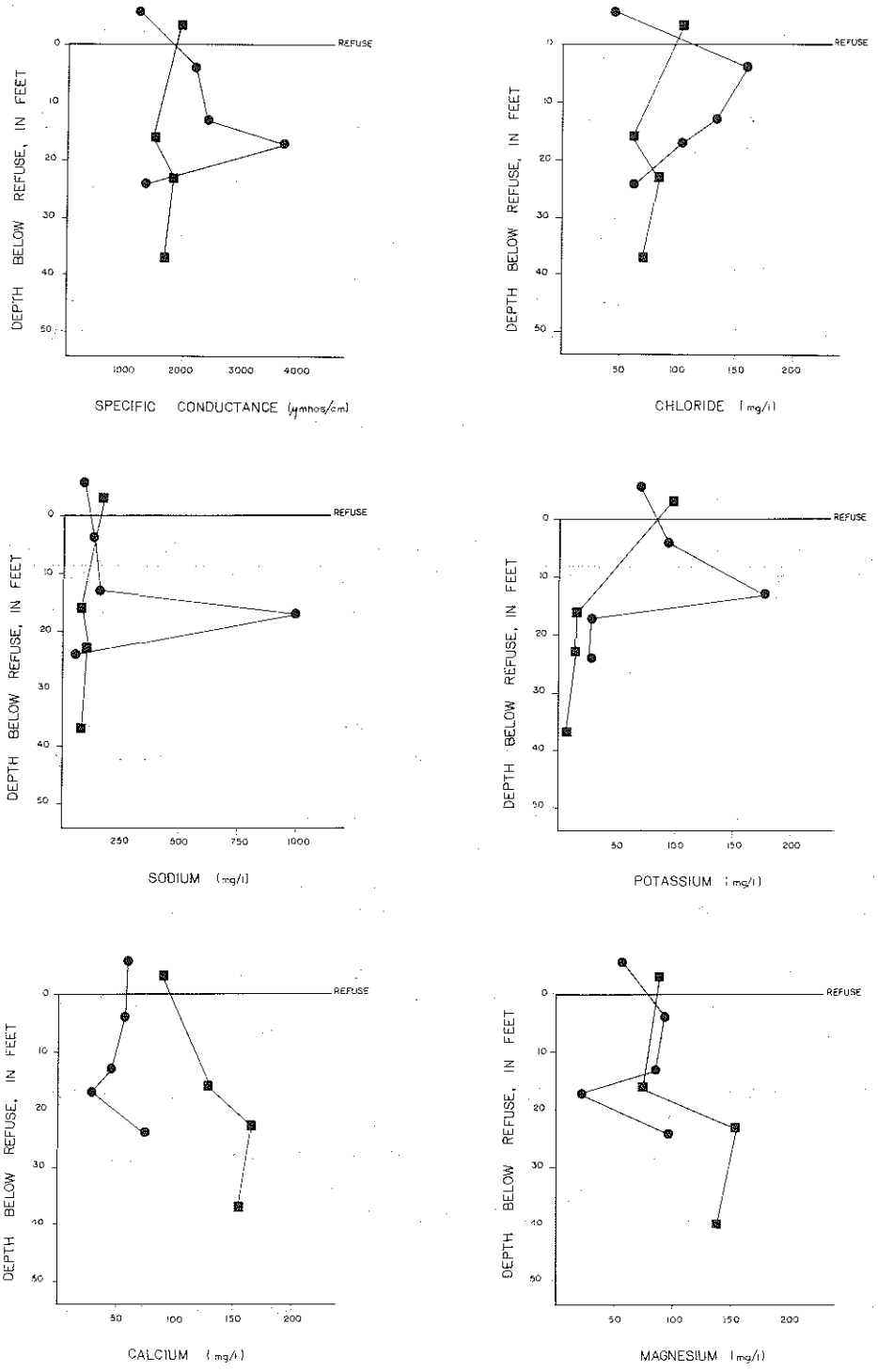


Figure 17. Average leachate component concentrations for lysimeter samples collected from nest PDSA (circles) and nest PDSB (squares). The base of the refuse is also shown on each graph.

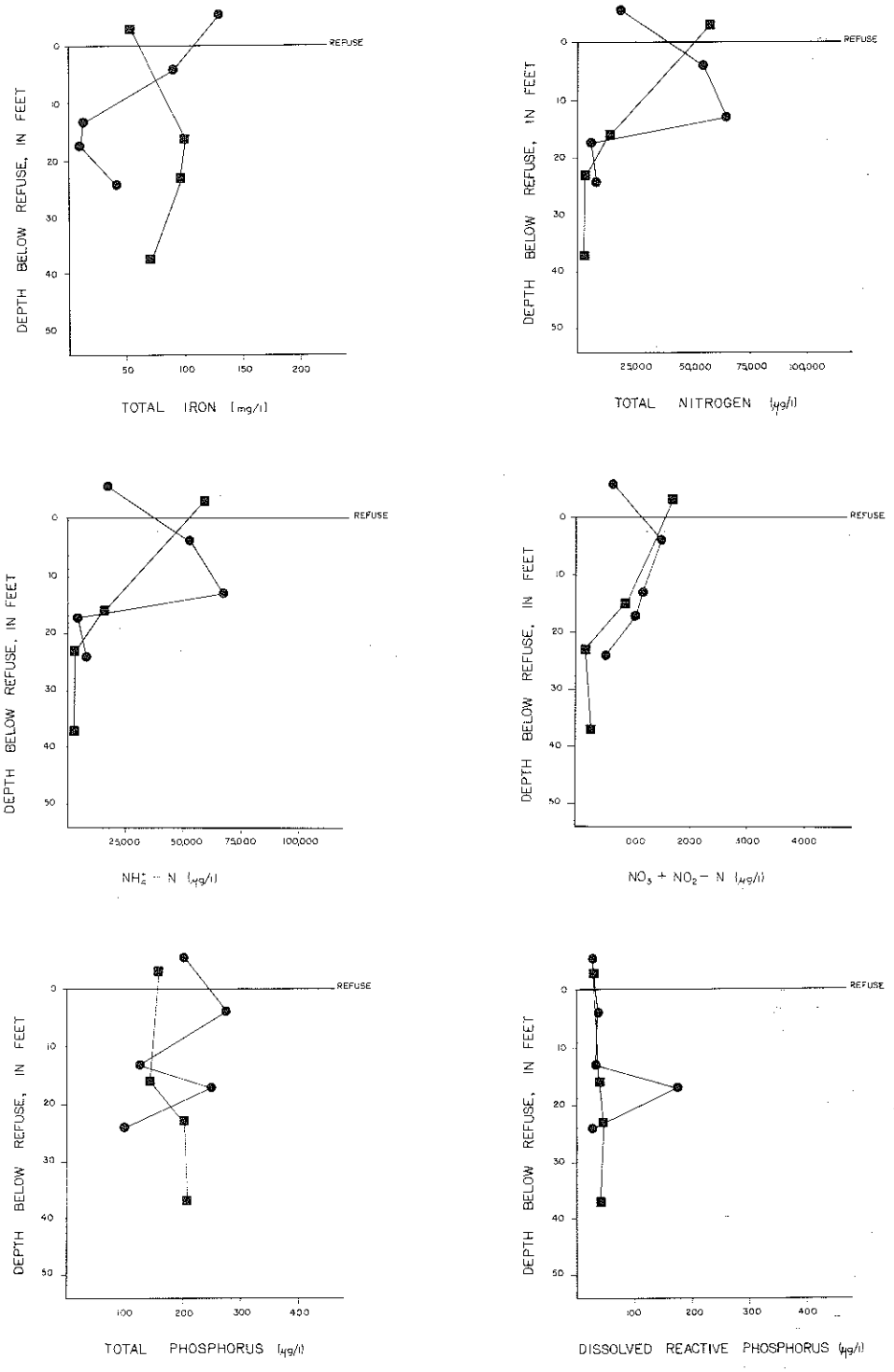
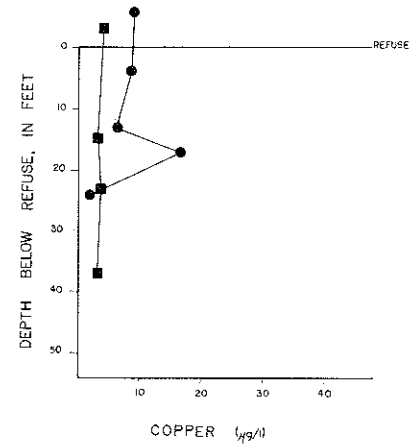
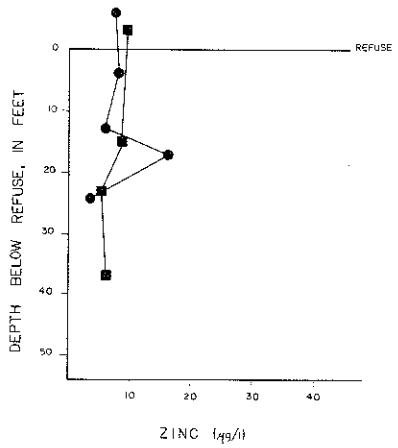
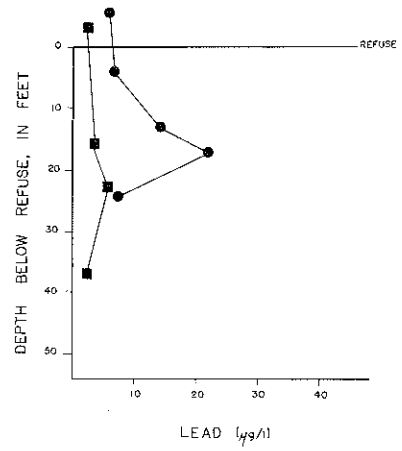
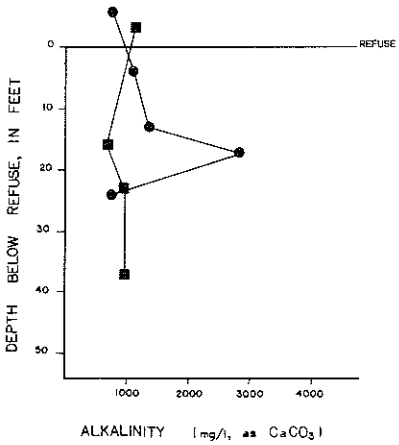


Figure 17. (Continued).









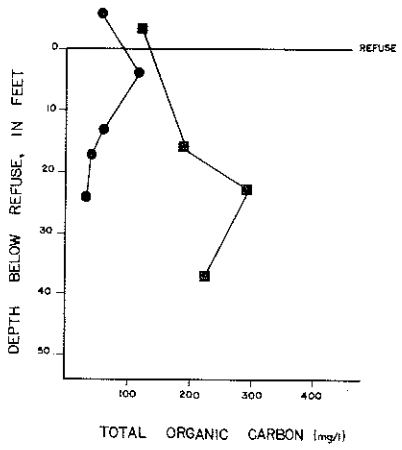


Figure 17. (Continued).

Refuse Leachates. A comparison of the average parameter concentrations for leachate samples collected from the refuse material at lysimeter nests PDSA (PDSA-refuse) and PDSB (PDSB-refuse) is given in Table 15. The data show that parameter concentrations in the refuse leachate at nest PDSB generally were from 30 to 70 percent higher than concentrations in the refuse leachate at nest PDSA. Higher concentrations occurred in the refuse leachate at nest PDSB despite the fact that the refuse there is only 10 feet thick, as compared to the 17 feet of refuse at nest PDSA. The higher parameter concentrations in the refuse leachate at nest PDSB may reflect differences in the composition of the refuse material, or lysimeter position (Figure 11). Lysimeter PDSB-refuse wasposition near the base of the refuse column. This suggests that leachate concentrations are highest near the base of the fill where infiltrating precipitation has been in contact with the entire refuse column. In contrast, lysimeter PDSA-refuse was positioned near the middle of the refuse column. Apparently lysimeter PDSA-refuse intercepted only leachate produced in the upper portions of the refuse column, and therefore concentrations are lower.

The different patterns of leachate component concentration changes that developed in the subsoil at lysimeter nests PDSA and PDSB (Figure 17) may be attributable, in part, to different component concentrations in the leachates being produced within the refuse material.

Interactions Between the Subsoil and Soil-Moisture/Leachate. As soil-moisture/leachate moves through the unsaturated zone beneath the landfill, the subsoil materials may affect leachate component concentrations in two ways: (1) leachate components may be preferentially retained by the soil material or (2) the soil-moisture/leachate may selectively remove ions from the subsoil material. Therefore, soil/moisture/leachate samples collected from the lysimeters reflect not only landfill leachate component concentration changes but also chemical interactions between the leachate and the subsoil material. Such interactions could be expected to vary as the nature of the subsoil material changes. Several lines of evidence from the data collected suggest that soil-moisture/leachate interactions with the subsoil material have modified apparent concentrations in the lysimeter samples.

Concentration-time plots for calcium and magnesium generally showed a negative correlation (with time and depth) with sodium and potassium, for lysimeter samples collected from nest PDSA (Figure 15). This suggests that differential ion exchange has occurred in the subsoil as the relative concentrations of these ion pairs change. The same trends were not observed in the lysimeter samples from nest PDSB (Figure 16). This may be related in part to the differences in subsoil stratigraphy at the two nests (Figure 12).

A comparison of the chemical analyses for the two split-spoon soil sample sets (Table 13) show that most parameter concentrations were significantly lower in the second set, suggesting that the soil-moisture/leachate removed many of these constituents from the soil during the 8 months separating collection of the two sample sets. (Split-spoon soil sample set No. 1 was collected in September, 1974, and set No. 2 was collected in May, 1975). These decreases may have resulted from increased soil-moisture/leachate movement through the subsoil in response to the spring recharge period. However, most parameter concentrations in the lysimeter samples, with the exception of calcium and magnesium, did not show a corresponding increase following the apparent removal of these ions from the subsoil material. Dilution by the increased volume of water moving through the subsoil during the spring recharge period may have reduced any concentration increases in the soil moisture that could be attributable to subsoil leaching.

Table 15. Average parameter concentrations in the refuse leachates at lysimeter nests PDSA (PDSA-refuse) and PDSB (PDSB-refuse).

Parameter	PDSA-refuse	PDSB-refuse
Specific conductance (μmhos/cm)	1233	1983
Chloride (mg/l)	44	105
Sodium "	71	160
Potassium "	68	97
Calcium "	59	89
Magnesium "	56	88
Total iron "	131	52
Total organic carbon (mg/l)	49	120
Alkalinity (mg/l as $CaCO_3$)	744	1120
Total N (mg/l)	17.2	58.5
NO_3+ NO_2- N (mg/l)	0.64	1.69
NH_4^+- N "	16.4	58.3
Total P (μg/l)	198	161
DRP "	24	25
Zinc "	7.2	9.5
Copper "	9.1	3.2
Lead "	5.6	2.2

The frequency of lysimeter sampling (approximately bimonthly) and the fact that the lysimeter units collect soil moisture continually between sample collection dates may have resulted in the incorporation of any concentration peaks in the soil moisture (if they occurred), with less concentrated leachate within the lysimeter units.

Finally, the slight differences in the nature of the subsoil materials in the split-spoon soil sample sets (Table 10) may have contributed to the different chemical concentrations in the two sample sets.

Leachate component concentrations were often observed to increase with depth in the subsoil beneath the landfill (Figure 17). For example, in lysimeter samples from nest PDSA, sodium, potassium, alkalinity, specific conductance, copper, lead, zinc, total N, NH_4^+ - N, and DRP concentrations were observed to increase with depth. Calcium, magnesium, total iron, and total organic carbon concentrations increased with depth in the lysimeter samples from nest PDSB. These increases suggest chemical contributions from the subsoil material to the soil-moisture/leachate.

The patterns of leachate component concentration changes with depth (Figure 17) also suggest chemical interactions between the soil-moisture/leachate and the subsoil material. In the lysimeter samples from nest PDSA, maximum concentrations for sodium, lead, copper, DRP, alkalinity, and specific conductance, and minimum concentrations for calcium, magnesium, NH_4^+ - N, total N, and total iron, occurred in the samples collected from lysimeter PDSA-17. Lysimeter PDSA-17 was placed within a 4-foot gravel layer (Figure 11). The high and low concentrations observed in the PDSA-17 samples may indicate a chemical contribution from the gravel and/or selective removal of some chemical constituents by the gravel. Similar maximum and minimum concentration patterns were not observed in the PDSB lysimeter samples. At lysimeter nest PDSB several thin layers of gravel occurred; however, no lysimeter units were placed within these gravel layers. Finally, if the concentration peaks and depressions for PDSA-17 samples (Figure 17) are ignored, the patterns of leachate component concentration changes for lysimeter nests PDSA and PDSB become very similar. This suggests that the gravel layer at nest PDSA has, in some way, affected soil-moisture/leachate concentrations.

The concentration peaks for potassium, NH_4^+ - N, and total N in lysimeter samples from PDSA-13 (Figure 17) may have resulted from a chemical contribution from the subsoil, although such a relationship was not clear from the data.

Unsaturated Soil-Moisture/Leachate Movement. The principles of water movement through unsaturated earth materials have been discussed in detail by Bouma (1973), Bouma and others (1974), Corey and Horton (1969), Crosby and others (1968 and 1971), Hill and Parlange (1972), Alyor and Parlange (1973), Palmquist and Johnson (1962), Smith (1967), and Winograd (1974). In an unsaturated soil, there is not enough water to keep all pores filled during the downward movement of water. Water occurs only in the finer pores and not in the larger ones because the total amount of available water is insufficient to fill all the pores. The smaller pores can "pull strongest" (exert stronger capillary forces) and thus get filled, thereby excluding the larger ones. In the case of a fine material overlying a coarse material, movement of water into the coarse bed can occur only when the rate of water application exceeds the capacity of the fine material to disperse the water laterally by capillarity.

Water will not move into the coarser material until the finer material approaches saturation, at which time gravitational forces exceed capillary forces and drainage into the coarser material occurs.

The apparent contradictions (increases) in leachate component concentrations with depth may have resulted, in part, from the modification (by the gravel layers) of soil-moisture/leachate movement through the unsaturated earth materials beneath the Prairie du Sac landfill.

Lysimeter PDSA-17, which was placed in the gravel layer at nest PDSA, and the lysimeter (PDSA-13) placed in the sand just above the gravel layer (Figures 11 and 12) generally showed the highest concentrations at nest PDSA (Figure 17). This relationship suggests that when the subsoil system is unsaturated the gravel layer may act as a partial impeding layer to the downward movement of soil-moisture/leachate. Such a situation would promote the lateral flow of soil-moisture/leachate in the sands above the gravel. Lateral flow and retention of significant portions of the soil-moisture/leachate in the sand above the gravel may be responsible for the high concentrations observed in the sand layer for several reasons:

1. The sand layer has become chemically saturated with respect to ion exchange capacity and other attenuation processes and is therefore no longer effective in reducing leachate concentrations.

2. The pH of the sand layer has been altered as a result of leachate contact, affecting the solubilities of the various chemical parameters.

3. Physical retention of leachate within the sand layer would result in lower relative concentrations in the deeper subsoil horizons, since only a small portion of the leachate actually penetrates to these depths or is diluted by uncontaminated soil-moisture.

Two additional lines of evidence seem to support the contention that lateral flow of landfill leachate has occurred in the sands above the gravel layer. First, high chloride concentrations were observed in the TH soil samples from the 24- to 38-foot intervals (Table 12). The TH soil samples were collected just outside the active fill area (Figure 10). The zone in which the high chloride concentrations occurred included the gravel layer and the sands immediately above the gravel layer. The high chloride values in this zone would seem to indicate that landfill leachate has moved laterally beyond the fill area, generally in the horizons above, and including, the gravel layer. Second, a single lysimeter unit (PDSD-34) was installed near well PDSW3 (Figure 10), 34 feet below land surface, at the top of a gravel layer encountered at this depth. Lysimeter PDSD-34 was sampled in order to determine if soil-moisture quality at the sand-gravel contact downslope from the fill area had been affected by the lateral movement of landfill leachate. For comparative purposes, an additional lysimeter unit (PDSC-34) was placed at a sand-gravel contact (34 feet below land surface) near well PDSW1 (Figure 10) to provide background soil-moisture quality. It should be noted that these gravel layers probably do not represent a single continuous deposit. Nevertheless, a comparison of soil-moisture quality from the lysimeters should indicate the possible presence of landfill leachate. As shown in Table 16, concentrations in the PDSD-34 samples were generally higher than background concentrations (PDSC-34) in a similar

Table 16. Results of the chemical analyses of soil-moisture samples collected from lysimeters PDSC-34 and PDSD-34.

Sample	Spec. Conductance micromhos/cm 25°C	Milligrams per liter							Micrograms per liter				
		Calcium (Ca)	Magnesium (Mg)	Potassium (K)	Sodium (Na)	Alkalinity (as $CaCO_3$)	Total iron (Fe)	Chloride (Cl)	Total P (as P)	DRP (as P)	Total N (as N)	$NO_3 + NO_2 - N$ (as N)	$NH_4^+ - N$ (as N)
PDSC-34													
10-2-75	300	-	-	-	-	187	-	15	86	-	142	-	-
11-7-75	275	16.8	24.6	2.0	8.1	177	-	17	233	-	899	136	5
12-3-75	250	-	-	-	-	-	-	-	-	-	-	-	-
PDSD-34													
10-2-75	800	-	-	-	-	534	-	18	44	-	1044	-	-
11-7-75	900	15.1	70.0	3.5	14.6	598	-	24	133	-	1634	258	47
12-3-75	850	11.2	87.0	2.7	12.0	365	0.16	13	13	-	192	-	-
2-12-76	1025	2.2	81.0	11.5	4.7	696	1.70	9	180	70	592	1448	486

horizon. The higher concentrations in the PDSD-34 samples suggest that landfill leachate has moved laterally beyond the boundary of the fill area in the sands above the gravel layer.

According to the theory of unsaturated soil-moisture movement, the lysimeters placed within the gravel layers should not consistently yield a sample because soil-moisture would be prevented from entering the coarse material. The fact that we were able to extract small sample volumes from these lysimeters suggests that much of the soil-moisture was derived from the sand-gravel contacts rather than from the gravel layer itself. The addition of the powdered quartz during installation also created an artificial medium for soil-moisture movement to the lysimeters from the sand above the gravel layers. These gravel layers would probably always transmit some soil-moisture because (1) the gravels were not well sorted, (2) an equalibrium flow rate through the gravels would ultimately be established for a given moisture content, and (3) the gravels appear to be discontinuous and soil-moisture flow around the gravel layers could occur. The generally low, stable concentrations observed in the samples collected from below the gravel layer beneath the fill (PDSA-23) apparently reflect attenuation and/or dilution of soil-moisture/leachate that has moved downward through, or around, the gravel layer.

During the spring recharge period the subsoil system may approach saturation. Such a situation would result in the movement of soil-moisture/leachate into and through the gravel layer beneath the landfill. Dilution by the increased amount of water moving through the subsoil would likely result in reduced leachate component concentrations, especially in the gravel and overlying sands. The decreases in specific conductance, NH_4^+ - N, DRP, total organic carbon, total iron, sodium, potassium, chloride, and alkalinity in samples collected during the spring of 1975, especially in the PDSA-13 and PDSA-17 samples, may have resulted from this "flushing action." The complex variations observed for NO_3 + NO_2 - N and total iron concentrations at nest PDSA (Figure 15) may indicate that the subsoil system oscillated between aerobic (unsaturated) and anaerobic (saturated) conditions.

The patterns of leachate component concentration changes that have been discussed for lysimeter nest PDSA were generally not observed in the PDSB samples (Figure 17). This is believed to be the result of (1) lysimeter positions, (2) differences in subsoil stratigraphy, and (3) the fact that the gravel layers at nest PDSB (Figure 12) were much thinner and did not produce the same effects upon soil-moisture movement.

Mobility and Depth of Penetration of the Various Leachate Components. The maximum leachate component concentrations at the various sampling depths, especially in the PDSA samples (Figure 17) may represent the maximum depth to which a given component has moved, or they may represent a slug of leachate moving through the subsoil. The fact that the peak concentrations occurred at different depths may reflect the relative mobilities of the various components. The high NH_4^+ - N and total N concentrations in the subsoil immediately beneath the refuse (Figure 17), for example, may represent (1) a slug of leachate, (2) the depth to which these components have moved, or (3) the presence of reducing conditions beneath the refuse. Several lines of evidence, however, indicate that other factors must be responsible for the concentration peaks observed for most of the leachate components:

1. Concentration peaks for individual leachate components at the various sampling depths have remained fairly constant during the study. If these concentration peaks represented leaching fronts or the depth of penetration, then concentrations should show a gradual reduction as the front/component moved downward through the subsoil. Also, concentrations should increase with time at the next deeper sampling point as the leachate moved downward. This was not observed.

2. The same concentration peaks at similar depths were not observed in the PDSB samples.

3. Changes in concentrations often occurred simultaneously at all sampling depths, which argues against a leachate front moving through the subsoil.

Leachate Attenuation and Ground-Water Pollution Potential

The extent of leachate attenuation in the unsaturated zone beneath the Prairie du Sac landfill cannot be evaluated because of the complexities of the chemical data and the many possible variables affecting the results. However, in the groundwater immediately beneath the landfill and in the down-gradient direction, concentrations were generally from 2 to 6 times higher than in background ground water. Clearly the landfill has affected ground-water quality in the immediate vicinity of the landfill. The extent of ground-water impairment outside the landfill property was not determined.

Summary and Conclusions

1. A complex pattern of leachate component concentration changes has developed in the unsaturated sands and gravels beneath the Prairie du Sac landfill. The concentrations of individual leachate components were often observed to increase with depth, reaching maximum concentrations within the subsoil rather than within the refuse material.

2. The observed concentrations of the leachate, or any leachate component, at depth in the unsaturated sands and gravels beneath the landfill apparently have resulted from the interaction of several factors: (a) the chemical quality of the leachate being produced within the refuse material; (b) chemical interactions between the subsoil material and the soil-moisture/leachate; (c) unsaturated soil-moisture/leachate movement; and (d) possibly the mobility and depth of penetration of the various leachate components.

3. The extent of leachate attenuation in the unsaturated sands and gravels beneath the Prairie du Sac landfill could not be evaluated because of the many possible variables affecting the results.

4. In the ground water immediately beneath the refuse and in the down-gradient direction, concentrations were generally from 2 to 6 times higher than in background ground-water samples.

PROBLEMS ASSOCIATED WITH THE USE OF PRESSURE-VACUUM LYSIMETERS

The use of pressure-vacuum (suction) lysimeters as sampling devices proved to be a reliable and efficient method for obtaining soil-moisture/leachate samples from the unsaturated zone. However, the operation of these devices did pose several problems:

1. As noted by Apgar and Langmuir (1971), the small pore diameter of the ceramic cup (one micron or less) may exclude bacteria and perhaps other particulates from the sample. This must be considered when decisions are made concerning the choice of chemical parameters to be analyzed for in the samples. The ceramic material comprising the cup, and sample collection by exerting a gas pressure on the lysimeter unit, may also alter the chemistry of the soil moisture. These effects were not determined in this study.

2. The pressure-vacuum lysimeter continually collects soil moisture between sampling dates. This results in an integrated sample over the collection period. Minor, or short duration, changes in soil-moisture chemistry may be lost due to this averaging effect. The longer the time separating sample collections, the greater this effect will be. A compromise period must be established that allows enough sampling time to provide the needed sample volume and at the same time is short enough to allow observations of soil-moisture chemical changes in the detail called for by a project.

3. Water frozen in the sample discharge access tubes prevented sample collection during the winter months. Apparently enough soil-moisture remains in the discharge tube following sample collection to freeze and prevent subsequent sampling. This problem appears to occur only after temperatures drop to well below freezing. The line remains frozen until temperatures return to well above freezing. Insulation of housing units that protected the tubing at the surface did not prevent freezing. Apparently heat must be added to the housing unit to prevent freezing. This problem must also be considered in contemplating a study using pressure-vacuum lysimeters. If the planned study will be of short duration, it may be advantageous to avoid sampling during the winter months. If this is not possible, careful consideration should be given to the construction of a heated housing unit for the surface-exposed lysimeter tubing.

CONCLUSIONS AND RECOMMENDATIONS

Although insufficient data are available to make positive statements concerning the attenuation of leachate in the unsaturated zone, several general observations can be made:

1. The observed concentrations of the leachates, or any leachate component, at depth in the unsaturated earth materials beneath the landfills apparently have resulted from the interaction of several factors: (a) the chemical quality of the leachates being produced within the refuse material; (b) chemical interactions between the subsoil materials and the soil-moisture/leachate; (c) unsaturated soil-moisture/leachate movement; and (d) the mobility and depth of penetration of the various leachate components.

2. At the Sauk County landfill, changes in leachate concentrations varied systematically with respect to depth. This apparently was a direct consequence of the uniform nature of the fine sands beneath the landfill. A much more complicated and less systematic pattern of leachate concentration changes was observed in the subsoil beneath the Prairie du Sac landfill. This apparently results from the layered nature of the sands and gravels beneath the site. As the nature of the subsoil materials changes, so do the relative effects of the factors that affect leachate concentrations.

3. Whether satisfactory leachate attenuation within the unsaturated zone is obtained at either site is uncertain.

4. Because the results of this study should be considered preliminary, the data that were collected only apply to the landfills studied. The observed results of this study are also expected to change as leaching from the landfills continues.

It was hoped that the results from this investigation could be used for improving current landfill site requirements--in particular, for the establishment of optimum distance requirements for landfills placed above the water table in a variety of soil types. Many questions remain to be answered before sound regulations can be established. Absolute regulations and requirements specifying a separation distance between landfills and the water table may never be obtainable. The capacity of the unsaturated zone to attenuate leachate depends upon a variety of factors that will vary greatly from one environment to another. However, with additional information a more quantitative evaluation of the capacity of the unsaturated zone to attenuate leachate over an extended period of time can be made. Therefore, the following recommendations are suggested for future studies:

1. The attenuation of landfill leachate in the unsaturated zone should be examined beneath landfills placed within soil types that differ from those of this study.

2. A longer period is needed to evaluate properly the changes in leachate production and attenuation with time. Both processes are expected to change markedly during the life of a landfill. Of critical importance is to determine at what point the subsoil system becomes chemically saturated and the attenuation processes are no longer effective. Such an approach would be enhanced if the study began at a landfill prior to the disposal of any waste material.

3. Unsaturated hydraulic conductivity should be determined on all distinctively different subsoil horizons. This could be accomplished by installing a series of tensionmeters beneath the landfill to determine the soil-moisture/leachate flow paths. Tensiometers should also be placed horizontally away from the actual disposal area to determine the possibilities of lateral soil-moisture/leachate movement. The rate of water (leachate) movement through the subsoil system could also be determined.

4. Soil sampling of all distinctively different subsoil horizons for chemical analyses should be made. This should include background soils as well as several soil sample sets collected at different times from beneath the refuse. This would help determine to what extent soil-moisture/leachate interactions with the subsoil material have affected the observed soil-moisture/leachate chemical quality.

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APPENDIX

PORTAGE LANDFILL

Introduction

Recovery of soil-moisture/leachate samples from the eight lysimeters originally installed at a landfill site near Portage, Wisconsin, was sporadic and inconsistent. Lack of significant data over the period from October, 1974, to October, 1975, forced abandonment of this landfill as a primary study site. As the data that were collected represented widely scattered points in time and location (depth), no conclusions can be made concerning leachate attenuation in the unsaturated zone beneath the landfill. The data that were collected, however, are summarized to provide some understanding of the impact of solid waste disposal in this particular environment upon local ground-water quality.

General Description

The Portage landfill (Figure A1) is located approximately one mile north of the City of Portage, Wisconsin, south of County Highway X, in the SW$\frac{1}{4}$, NE$\frac{1}{4}$, Section 29, T.13N., R.9E. The site covers approximately 40 acres, however less than 4 acres have been used since landfilling began in 1971.

The site (Figure A2) is located on the northeast hillslope of a glacial drumlin. A drumlin is a low, smoothly rounded elongate and oval hill, mound, or ridge of compact glacial till, built under the margin of the ice and shaped by its flow, or carved out of an older moraine by readvancing ice. Its longer axis is parallel to the direction of movement of the ice (American Geological Institute, 1972, p. 213). The drumlin is situated at the west edge of a marsh bordering the left-bank floodplain of the Fox River. Elevation of the area ranges from 790 feet above sea level in the marsh to a high of 880 feet above mean sea level at the crest of the drumlin to the southwest.

Landfill Operations

The Portage landfill utilizes the trench, or cut-and-cover, method of solid waste disposal (American Public Works Association, 1970). Trenches are constructed in an east-west direction parallel to the northeast hillslope. The trenches are formed by partial excavation and subsequent construction of earth walls to form the trench sides. Material used as cover, in trench construction, and as a liner for the bottom of the trenches is obtained at the site. Solid waste is dumped from the top of the trenches, compacted, and covered. Since landfilling began, 6 trenches have been constructed and filled. Only one trench is in current operation.

Instrumentation

The location of lysimeter nests and observation-monitoring wells at the Portage landfill is shown in Figure A2. Figure A3 illustrates the vertical distribution of lysimeters and observation-monitoring wells.

Two nests of suction lysimeters (PA and PB) were installed at the Portage landfill. Both nests were placed within the refuse disposal area in an attempt to determine if leachate composition and attenuation varied beneath the landfill. Lysimeters were placed in nest PA at depths of 7, 12, 18, and 25 feet below the base of the refuse, which was 13 feet thick at nest PA. One lysimeter unit (PA-refuse) was placed within the refuse material at a depth of 10 feet below land surface. (Lysimeters PA-18 and PA-25 were never operational). Lysimeters

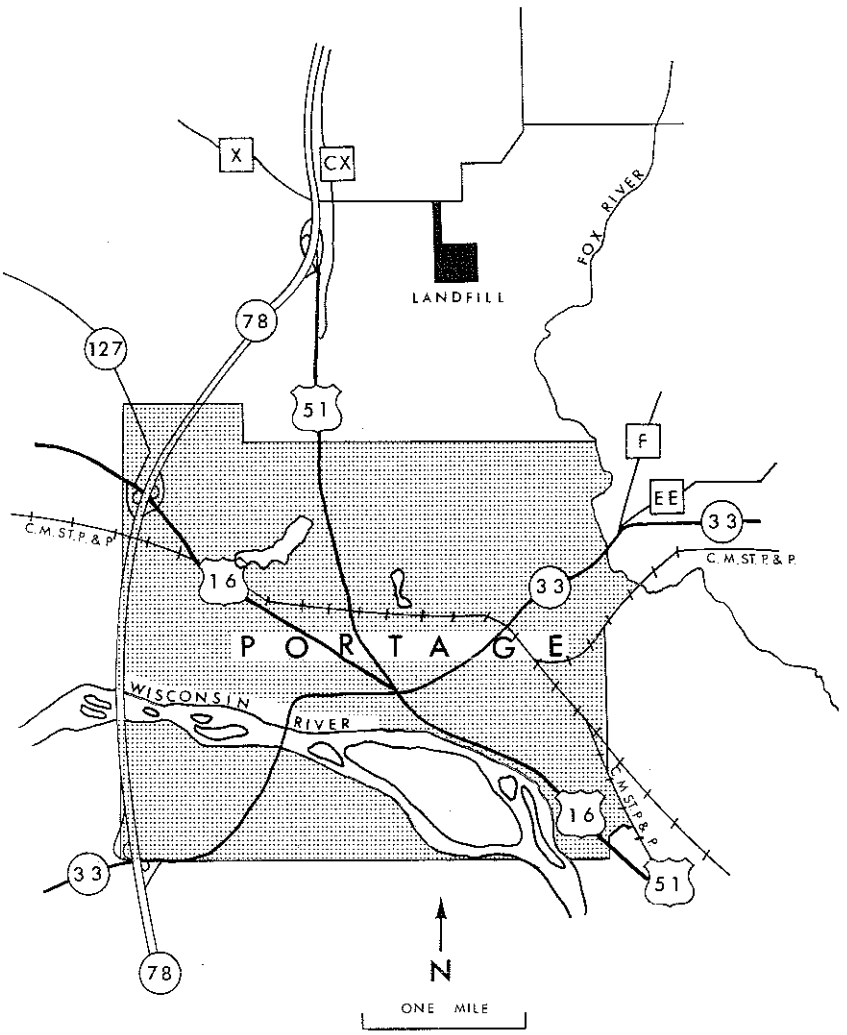


Figure A1. Location of the Portage landfill.

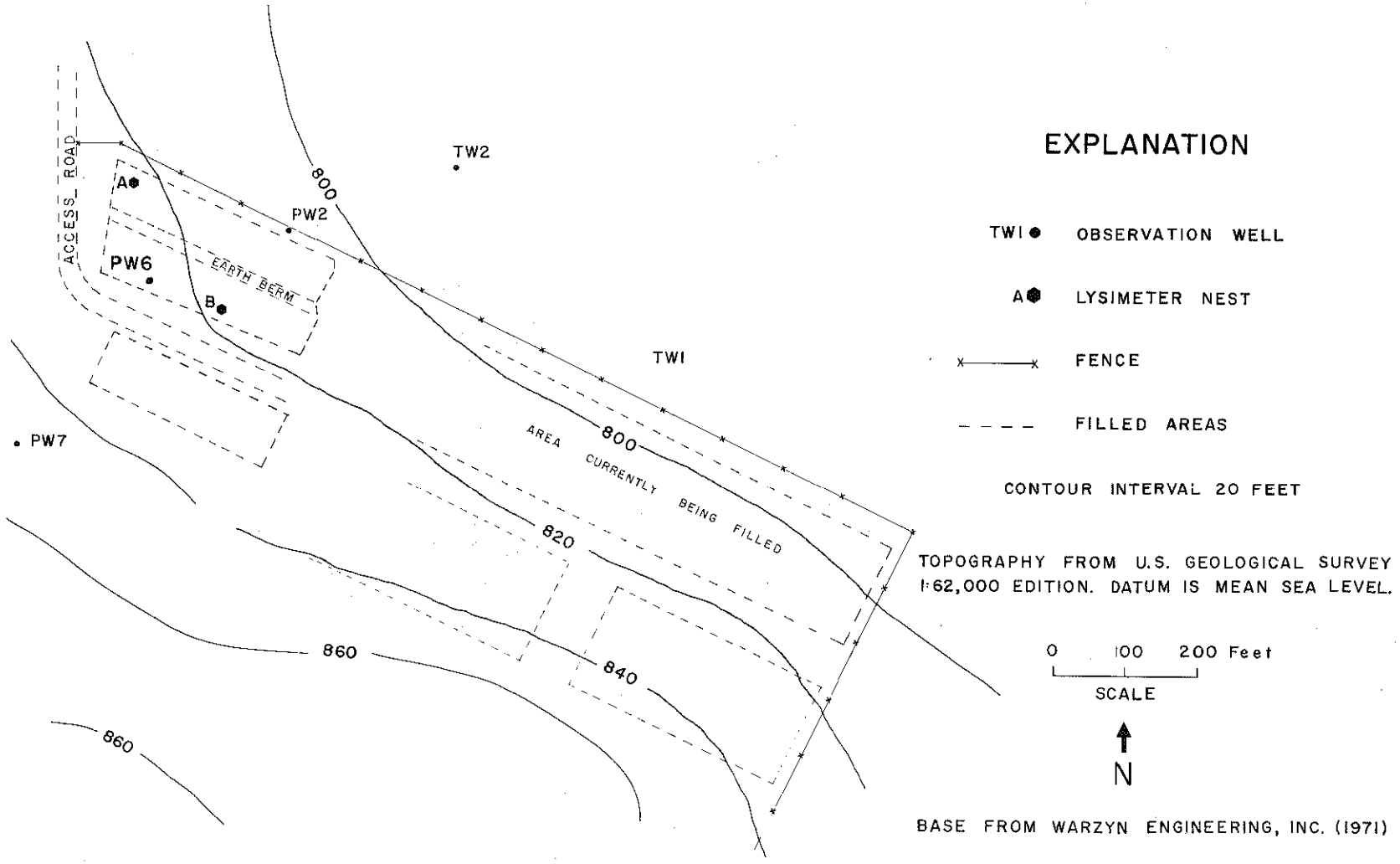
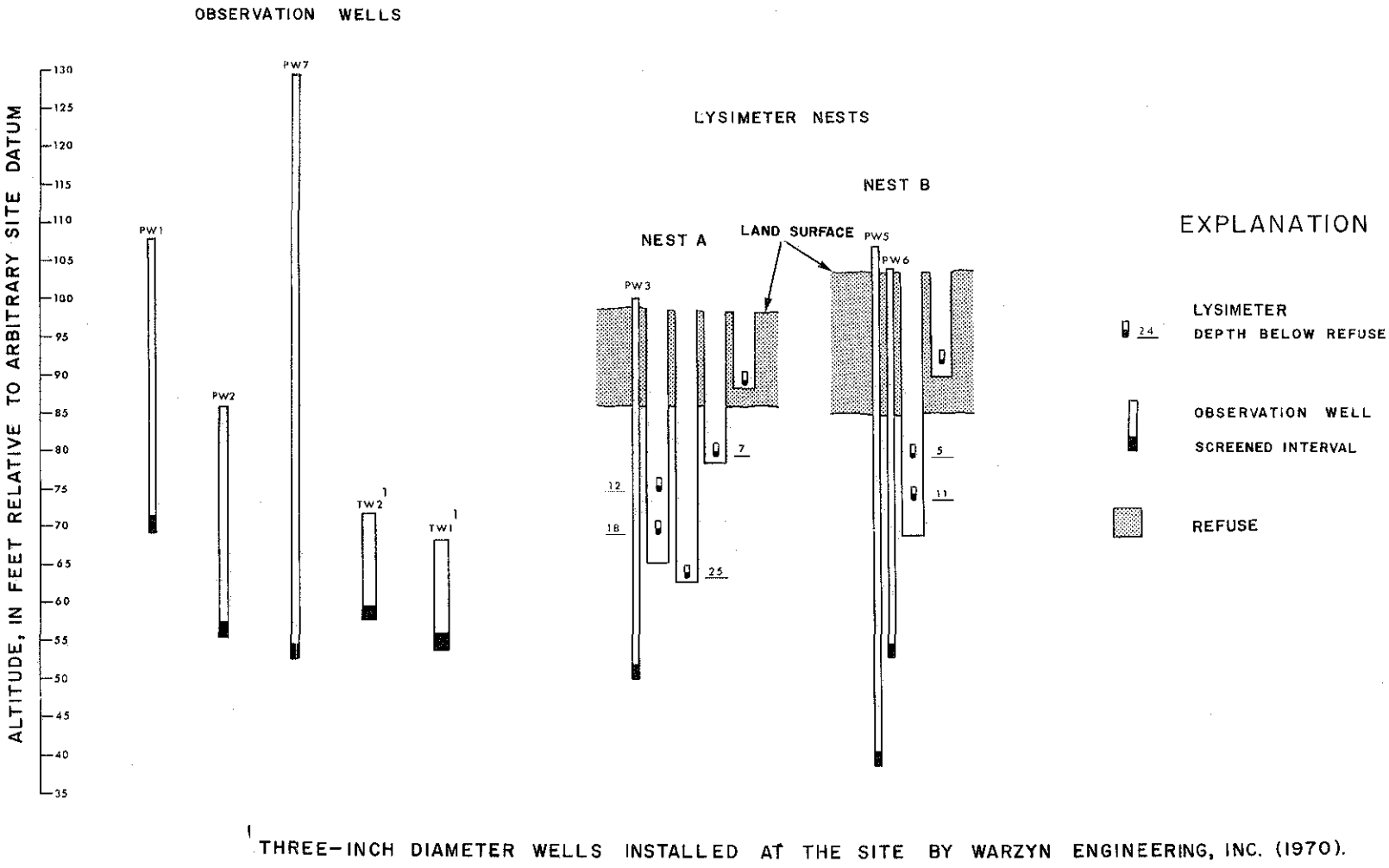


Figure A2. Instrumentation and topography at the Portage landfill.



THREE-INCH DIAMETER WELLS INSTALLED AT THE SITE BY WARZYN ENGINEERING, INC. (1970).

Figure A3. Vertical distribution of instrumentation at the Portage landfill. No horizontal scale.

were placed in next PB at depths of 5 and 11 feet below the base of the refuse, which was 17 feet thick at nest PB. One lysimeter unit (PB-refuse) was placed within the refuse material, at a depth of 12 feet below land surface.

A network of 7 observation-monitoring wells was also established at the Portage landfill. Wells PW3 and PW6 were drilled to the top of the water table in association with lysimeter nests PA and PB, respectively. In addition, at nest PB a deeper well (PW5) was installed 17 feet below the completion depth of well PW6. Two additional wells (PW2 and PW7) were installed, and two existing site wells (TW1 and TW2) were incorporated into the study (Warzyn Engineering, Inc., 1970 and 1973).

An arbitrary site datum (the top of well PW3 was assigned the value of 100.00 feet) was established to facilitate relative elevation comparisons between installations.

Geologic and Hydrologic Setting

The nature of the geologic materials at the Portage landfill was determined from (1) field observations of the earth materials penetrated during drilling, (2) logs of existing wells (Warzyn Engineering, Inc., 1970), and (3) inspection of drive-core (split-spoon) soil samples collected from beneath the landfill. Generalized logs are shown in Figure A4.

The subsoil beneath the landfill consists of a heterogeneous mixture of silty, gravelly sand (till). The gravel appears to occur in isolated lenses of limited areal extent and disseminated throughout the subsoil profile. Large cobbles and boulders were observed on the surface over much of the area. Beneath the landfill trenches, which commonly contain 15 feet of refuse, a 1- to 2-foot dense, compacted layer of silty, clayey sand was encountered. This material serves as a liner and has a low reported permeability of 0.5×10^{-4} cm/second (Warzyn Engineering, Inc., 1974).

Ground water occurs under water table conditions at a depth of 45 to 50 feet below land surface in the till beneath the Portage landfill. The water table may be defined as that surface represented by the water levels in wells. The water table is not a flat, stationary surface, but changes with both time and location. Therefore, monthly water level measurements were made at each observation-monitoring well to determine the pattern and magnitude of the water level changes.

The hydrograph of well PW6 (Figure A5) is representative of the fluctuations of the water table beneath the site. Water levels declined during late fall and winter when recharge from precipitation was low, and when precipitation was stored as snow and frost and could not reach the water table. Water levels rose during the spring in response to increased recharge from spring rains and snowmelt. The amplitude of the water level fluctuations, while not the same in all wells, has generally been between 0.5 and 1.0 feet.

Water level data from the two vertically spaced wells (PW5 and PW6) at lysimeter nest PB (Figure A5) show that a vertical component of ground-water flow has apparently developed beneath the landfill. This is indicated by the higher water levels in the shallower (Pw6) of the two wells. This suggests that the landfill is in an area of ground-water recharge.

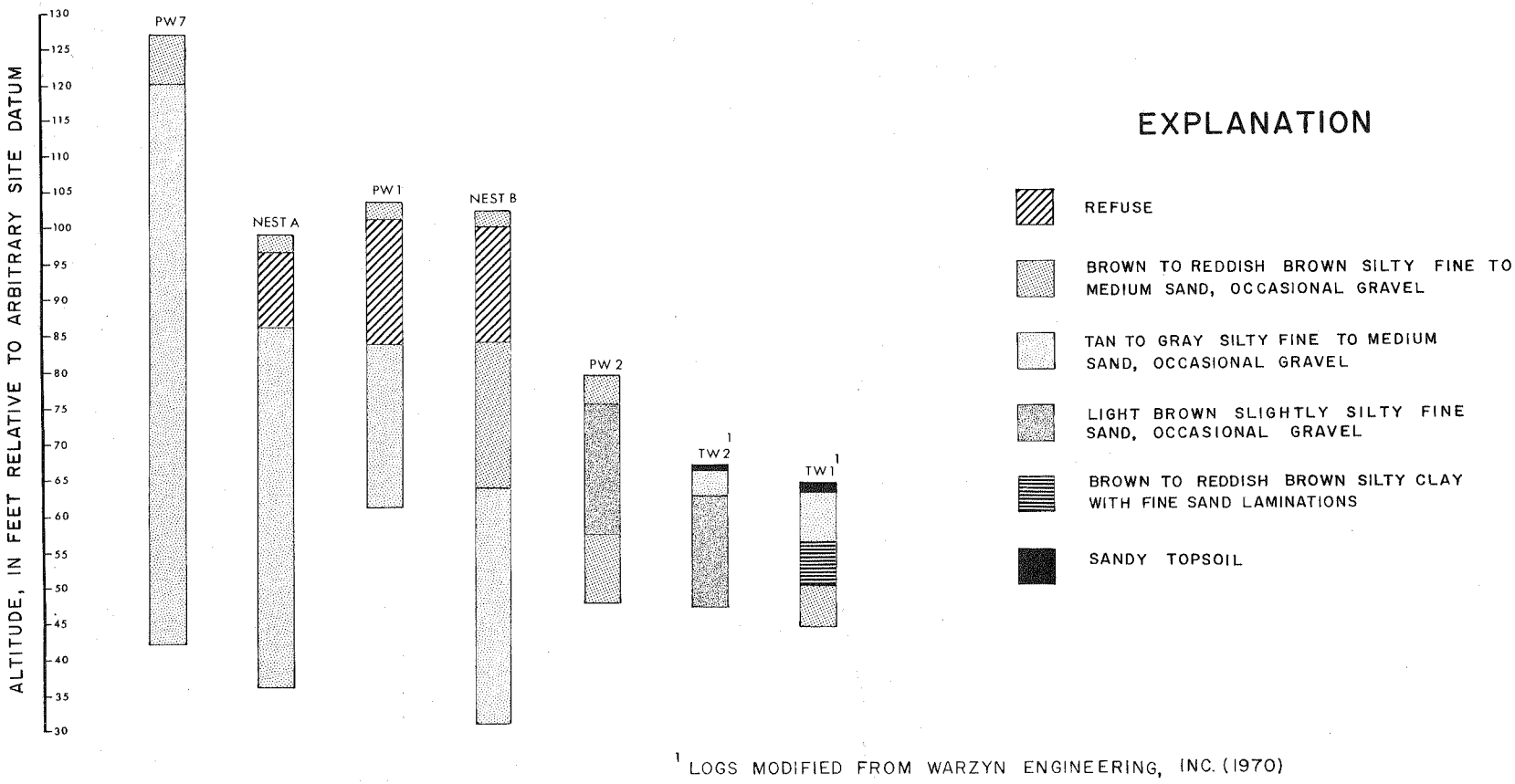


Figure A4. Generalized drill logs from the Portage landfill. No horizontal scale.

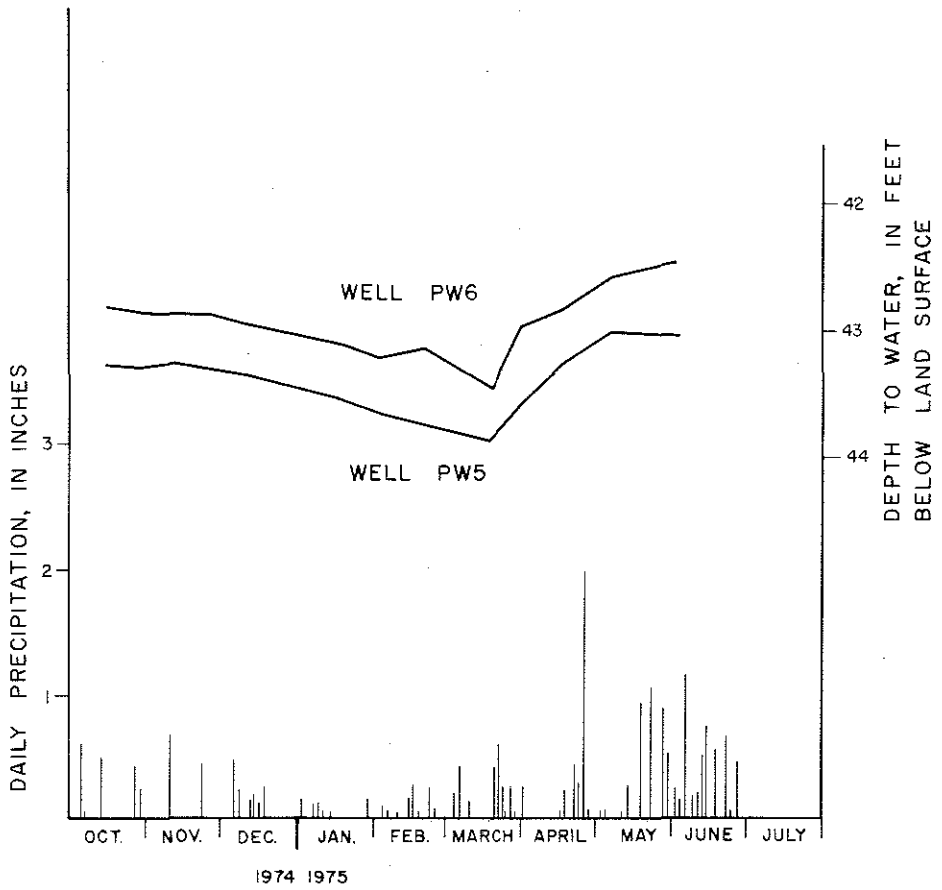


Figure A5. Changes in water levels in wells PW5 and PW6, and daily precipitation recorded near Portage, Wisconsin. Precipitation data from National Oceanic and Atmospheric Administration (1974-1975).

The general pattern of ground-water movement can be determined by the shape and slope of the water table. The approximate shape of the water-table surface can be represented by contour lines drawn through points of equal elevation on that surface as determined from the elevation of water levels in the wells. The direction of movement is down the hydraulic gradient, from points of higher water levels to points of lower water levels, at approximately right angles to the contour lines.

The direction of ground-water movement beneath the Portage landfill is illustrated by the water table map (Figure A6), which was prepared from water level measurements made on December 10, 1974. Movement of ground-water is generally toward the east-southeast. The average gradient of the water table was approximately 17.90 feet per mile. During the course of this study, little change was observed in the direction of ground-water movement, configuration of the water table, or the hydraulic gradient.

Variations in Soil-Moisture/Leachate Quality

Results of the chemical analyses of soil-moisture/leachate samples collected from lysimeter nests PA and PB are shown in Table A1. Sample notation refers to the lysimeter nest and to the depth of the lysimeter unit below the base of the refuse. The lysimeter units placed within the refuse material are noted as such.

Because of the limited data, only general observations can be made concerning soil-moisture/leachate quality:

1. The chemical quality of the leachates within the refuse material varies. For example, average specific conductance values for leachate samples from lysimeters PA-refuse and PB-refuse were 1480 μmhox/cm and 16,963 μmhos/cm, respectively. These differences probably reflect differences in the composition of the refuse material at the two nests.

2. Soil-moisture/leachate quality apparently improves with increased depth in the subsoil at nest PB. For example, average specific conductance was 4910 μmhos/cm in samples from lysimeter PB-5, and 3200 μmhos/cm in the samples from lysimeter PB-11. Similar reductions were observed for chloride.

3. All lysimeter samples collected at the Portage landfill generally showed reductions in leachate component concentrations during the course of this study. These changes may be seasonal, or they may reflect decreased leaching from the refuse.

Soil Samples

Table A2 shows the results of the chemical analyses of uncontaminated soil samples (PW7 soil) collected near well PW7 (Figure A2). The chemical analyses show high concentrations in the 8- to 18-foot interval and low concentrations at the 4-foot interval. This suggests that chemical constituents are being leached from the near-surface zone and precipitated at depth. Although concentrations at all sampling depths were similar, most parameters showed a slight decrease with depth, with the exception of the apparent chemical buildup at the 8- to 18-foot intervals.

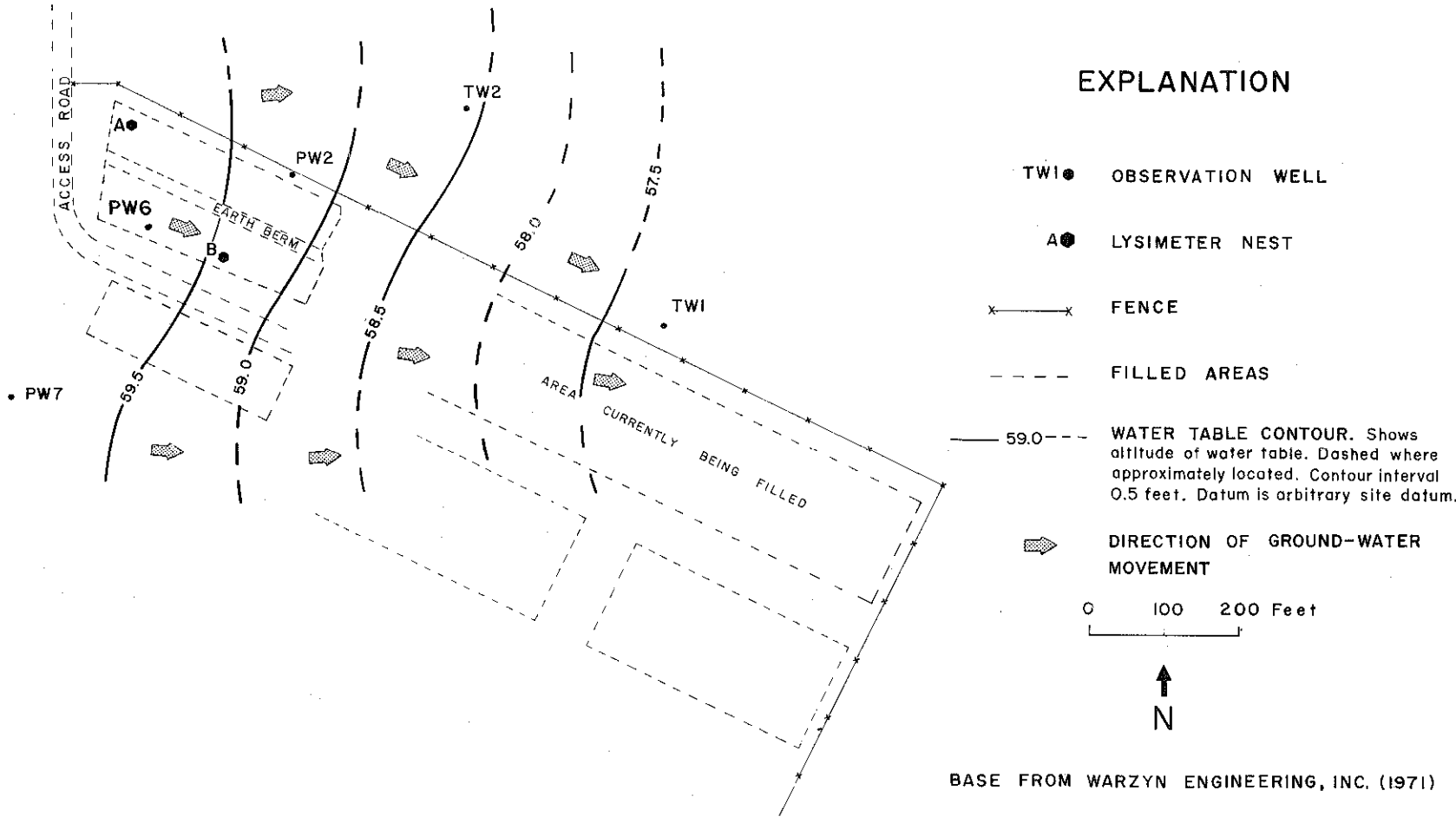


Figure A6. Map of the Portage landfill showing configuration of the water table--December 10, 1974.

Table A1. Results of the chemical analyses of soil-moisture/leachate samples collected from lysimeter samples from lysimeter nests PA and PB.

Sample	Spec. Conductance micromhos/cm 25°C	Milligrams per liter								Micrograms per liter								
		Calcium (Ca)	Magnesium (Mg)	Potassium (K)	Sodium (Na)	Chloride (Cl)	Alkalinity (as $CaCO_3$)	Total Iron (Fe)	Total Organic Carbon (as C)	Zinc (Zn)	Cadmium (Cd)	Lead (Pb)	Copper (Cu)	Total P (as P)	DRP (as P)	Total N (as N)	$NO_3 + NO_2 - N$ (as N)	$NH_4 - N$ (as N)
PA-refuse																		
11-4-74	1900	122	111	4	27	160	487	-	-	-	-	-	-	71	-	635	233	736
11-18-74	1700	128	160	0.7	3	137	430	-	-	-	-	-	-	-	-	-	-	-
12-2-74	1550	29	125	3.9	19	99	460	-	-	-	-	-	-	66	-	435	653	699
12-30-74	1200	107	25	6.5	13	100	682	-	-	-	-	-	-	63	28	210	121	142
5-7-75	1050	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
PA-18																		
12-2-74	1500	43	165	2.4	12	33	-	-	-	-	-	-	-	-	-	-	-	-
12-30-74	1150	66	32	4.1	9	60	620	-	-	-	-	-	-	-	-	280	280	-
6-2-75	1700	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
PA-25																		
10-21-74	1750	13	134	2.8	14	220	729	-	-	-	-	-	-	41	34	10	255	13
PB-refuse																		
12-30-74	20000	-	-	-	-	1532	-	-	-	-	-	-	-	-	-	-	-	-
4-17-75	20000	-	-	-	-	-	8810	-	-	-	-	-	-	-	50	139,992	-	-
5-7-75	15250	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
6-2-75	12800	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
PB-5																		
10-21-74	6300	19	70	14	851	133	2801	-	-	-	-	-	-	-	-	-	-	-
11-4-74	5275	12	54	13	640	159	2421	-	-	-	-	-	-	704	-	1477	2240	306
11-18-74	4750	8	55	11	602	119	2302	-	-	-	-	-	-	-	-	-	-	-
12-2-74	4725	14	75	10	1075	117	2329	-	-	-	-	-	-	195	252	1067	63	10
5-7-75	3500	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Table A1. (Continued).

Sample	Spec. Conductance micromhos/cm 25°C	Milligrams per liter								Micrograms per liter								
		Calcium (Ca)	Magnesium (Mg)	Potassium (K)	Sodium (Na)	Chloride (Cl)	Alkalinity (as $CaCO_3$)	Total Iron (Fe)	Total Organic Carbon (as C)	Zinc (Zn)	Cadmium (Cd)	Lead (Pb)	Copper (Cu)	Total P (as P)	DRP (as P)	Total N (as N)	$NO_3 + NO_2$ - N (as N)	NH_4^+ - N (as N)
PB-11																		
10-21-74	3400	160	314	11	80	125	1340	-	-	-	-	-	-	-	-	-	-	-
11-18-74	3000	88	94	8	35	-	1077	-	-	-	-	-	-	-	-	-	-	-

Table A2. Chemical analyses of uncontaminated (PW7) auger soil samples and contaminated drive-core soil samples collected at the Portage landfill.

Sample	Micrograms per gram of soil										
	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Chloride (Cl)	Total Iron (Fe)	Total N (as N)	$NO_3 + NO_2 - N$ (as N)	$NH_4^+ - N$ (as N)	Total P (as P)	Acid-extrac. P (as P)
PW 7 (soil)[a]											
4'	60	22	0.50	1.5	27.3	0.027	196	0.92	0.49	844	191
8'	420	219	0.36	1	52.4	0.380	24	0.03	0.03	1449	1197
13'	462	105	0.72	2.4	70.3	0.845	28	1.00	1.08	1658	1562
18'	568	218	0.71	1.5	79.1	0.251	13	1.34	0.49	1033	879
23'	537	180	0.81	1.4	77.2	0.906	22	1.04	0.68	1449	958
28'	567	197	0.92	1.5	54.4	0.624	7	0.74	1.53	932	499
33'	397	111	0.86	1.5	53.6	1.022	17	1.04	1.52	895	484
38'	492	148	0.40	1.3	49.3	0.966	5	0.25	0.08	856	295
43'	516	323	0.69	1.6	53.2	1.005	4	0.31	0.12	1159	282
48'	445	131	0.42	1.0	49.6	1.468	3	0.25	0.55	756	378
PA[b]											
3'	485	170	0.60	1.0	-	-	6.8	-	-	-	-
7'	400	151	0.49	0.7	-	-	2.9	-	-	-	-
12'	405	107	0.68	1.7	-	-	5.1	-	-	-	-
17'	433	125	0.41	0.7	-	-	3.6	-	-	-	-

[a] Sample notation indicates depth below land surface.

[b] Sample notation indicates depth below the base of the refuse. For comparative purposes, the addition of 13 feet (refuse thickness) to the PA soil depths provides depth below land surface, which can then be compared to the PW7 soil samples.

Also shown in Table A2 are the results of the limited chemical analyses of split-spoon soil samples collected during the installation of lysimeter nest PA (Figure A2). Sample notation for the PA soil samples indicates the sample depth below the base of the refuse. The addition of 13 feet (refuse thickness) provides depth below land surface. Because of the limited data, no conclusions can be drawn.

Ground-Water Quality

Variations in ground-water quality beneath the Portage landfill are shown in Table A3. Well locations are shown in Figure A2. Landfill leachate apparently has had a variable effect on ground-water quality immediately beneath the fill (refuse) area (wells PW5 and PW6). A comparison of the ground-water quality immediately beneath the fill area (well PW6) with background ground-water quality (well PW7) shows that some chemical parameters increased while others decreased or remained unchanged. Noticeable are the reduced concentrations of sodium, potassium, and $NO_3 + NO_2 - N$, and the increased concentrations of total N and $NH_4^+ - N$ in the ground water beneath the landfill.

A comparison of depth versus ground-water quality for wells PW6 (shallow) and PW5 (deep), which were completed beneath the landfill, shows that concentrations generally increased with depth, with the exception of alkalinity, DRP, total N, and specific conductance. The inconsistent pattern of ground-water quality changes with depth may be the result of dispersion and dilution of leachate within the ground-water flow system.

Concentrations in the samples from well PW2 were generally only slightly above background concentrations. This well is poorly located considering the indicated directions of ground-water flow. Well PW2 probably only intercepts a small portion of the leachate-affected ground water discharging from the landfill area.

Ground-water quality north of the landfill area along the marsh (wells TW1 and TW2) apparently has not been affected by landfill leachate. Samples from wells TW1 and TW2 showed concentrations equal to, or better than, background ground-water quality (well PW7). Noticeable however, are the high concentrations of $NO_3 + NO_2 - N$. The high $NO_3 + NO_2 - N$ concentrations in samples from these wells may indicate (1) possible contamination by leachate from the operating landfill trench (Figure A2) or (2) contamination by surface runoff from the landfill. Therefore, it is difficult to interpret the water-quality data from these wells in terms of leachate attenuation or renovation with increased flow distance from the landfill.

Failure of the Lysimeter Network

Recovery of soil-moisture/leachate samples from the 8 lysimeters installed beneath the Portage landfill was sporadic and inconsistent at best during the first 6 months of this project. It was hoped that the situation would correct itself, especially during the spring of 1975, in response to increased moisture from the spring recharge period. Continued data collection through this period and extending into October of 1975, however, failed to yield a single lysimeter sample.

Table A3. Chemical analyses of ground-water samples collected from beneath the Portage landfill.

Sample	Spec. Conductance micromhos/cm 25°C	Milligrams per liter								Micrograms per liter				
		Calcium (Ca)	Magnesium (Mg)	Potassium (K)	Sodium (Na)	Chloride (Cl)	Alkalinity (as $CaCO_3$)	Total Iron (Fe)	Total Organic Carbon (as C)	Total P (as P)	DRP (as P)	Total N (as N)	$NO_3 + NO_2 - N$ (as N)	$NH_4 - N$ (as N)
PW 3														
9-25-74	-	74	30	0.45	0.65	6	386	-	-	448	12	1886	30	2517
10-28-74	725	56	47	0.72	2.56	6	370	-	-	84	6	1007	26	1695
12-30-74	500	32	43	4.3	3.60	12	279	-	-	45	6	959	84	898
5-7-75	300	-	-	-	-	-	-	-	-	-	-	1357	219	544
PW 6														
10-28-74	925	72	36	0.50	1.10	8	428	-	-	285	24	1412	56	1498
11-18-74	850	73	44	1.48	2.48	14	428	-	-	280	4	1639	9	1059
12-30-74	725	67	41	1.60	2.40	12	411	-	-	110	6	978	227	558
5-7-75	575	-	-	-	-	-	-	-	-	-	-	-	-	-
PW 5														
10-28-74	725	72	66	1.60	3.20	7	439	-	-	228	24	1016	26	752
12-30-74	625	54	51	3.00	2.40	11	395	-	-	70	8	998	25	516
5-7-74	450	-	-	-	-	-	-	-	-	-	-	-	-	-
PW 2														
9-25-74	-	51	39	1.12	2.03	7	575	-	-	794	4	287	55	169
10-28-74	550	52	38	0.70	2.30	7	307	-	-	45	2	47	26	52
12-30-74	500	52	34	2.20	2	12	300	-	-	25	2	149	50	21
5-7-75	400	-	-	-	-	-	-	-	-	-	-	63	98	172
TW 1														
9-25-74	-	34	9	0.30	0.52	4	176	-	-	62	2	217	264	30
10-28-74	375	38	21	1.48	2.24	4	191	-	-	12	4	136	169	37
12-30-74	350	38	19	1.80	1.12	9	192	-	-	54	4	9	600	435

Table A3. (Continued).

Sample	Spec. Conductance micromhos/cm 25°C	Milligrams per liter								Micrograms per liter				
		Calcium (Ca)	Magnesium (Mg)	Potassium (K)	Sodium (Na)	Chloride (Cl)	Alkalinity (as $CaCO_3$)	Total Iron (Fe)	Total Organic Carbon (as C)	Total P (as P)	DRP (as P)	Total N (as N)	NO_3^{-1} NO_2^{-} N (as N)	NH_4^{+} - N (as N)
TW 1 (con't)														
5-7-75	300	-	-	-	-	-	-	-	-	-	-	14	211	99
TW 2														
9-25-74	-	49	30	0.54	1.87	4	282	-	-	43	8	98	817	20
10-28-74	475	48	31	1.60	1.60	4	269	-	-	14	6	56	637	58
12-30-74	475	53	32	1.88	1.32	11	289	-	-	20	6	9	601	42
5-7-75	400	-	-	-	-	-	-	-	-	-	-	196	800	48
PW 7														
10-28-74	650	61	42	1.92	2.96	6	321	-	-	23	20	30	143	13
12-30-74	575	63	37	3.60	4.80	14	285	-	-	119	18	129	115	88
5-7-75	500	-	-	-	-	-	-	-	-	-	-	148	4	72

It appears that the clay cover and clay liner enclosing the landfill trench significantly retards infiltration into the refuse and leachate movement out of the refuse into the subsoil below. The base of the trench was constructed with a 2 percent slope, with the intent of diverting leachate to a sump-pump system for collection and removal. While the sump-pump system has never been operational, 3 feet of saturated refuse was encountered above the trench liner. The subsoil beneath the trench was unsaturated. Lysimeter collection difficulties were also encountered beneath another landfill (not included in this project) that had a thick, impermeable clay cover. These conditions seem to support the contention that very little moisture moves into or out of the refuse in landfills with thick impermeable cover or trench liners, at least during the early stages of refuse decomposition and leachate production. Installation difficulties, the short history of the Portage landfill site, or moisture conditions unique to the monitoring period may also have been responsible for failure of the lysimeter network. Nevertheless, the potential problems associated with lined (or covered) landfill sites should be given careful consideration whenever the installation of lysimeters is contemplated.

Finally, it has been suggested that lysimeters be used as a method for determining the effectiveness of landfill trench liners. If a lysimeter unit placed immediately beneath a lined landfill trench fails over an extended period of time to collect a soil-moisture/leachate sample, then it is assumed that the liner has prevented significant leachate infiltration into the subsoil. However, lack of a sample from a lysimeter unit may also reflect unique subsoil moisture conditions, malfunction of the lysimeter, or improper installation. It is therefore suggested that in projects of this nature, a series of tensiometers be installed in addition to the lysimeters. The tensiometers would provide more definitive data on the actual moisture conditions in the subsoil.