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Hydrogeology of a sanitary landfill, Mandan, North Dakota

Raymond D. Butler
University of North Dakota

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HYDROGEOLOGY OF A SANITARY LANDFILL,

MANDAN, NORTH DAKOTA

by

Raymond D. Butler

Bachelor of Science, University of North Dakota, 1970

A Thesis

Submitted to the Graduate Faculty

of the

University of North Dakota

in partial fulfillment of the requirements

for the degree of

Master of Science

Grand Forks, North Dakota

December

1973

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This thesis submitted by Raymond D. Butler in partial fulfillment of the requirements for the Degree of Master of Science from the University of North Dakota is hereby approved by the Faculty Advisory Committee under whom the work has been done.

Lee Clayton
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Title HYDROGEOLOGY OF A SANITARY LANDFILL, MANDAN, NORTH DAKOTA

Department Geology

Degree Master of Science

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ABSTRACT

The data from this study can be applied to much of southwestern North Dakota because the geologic and climatic conditions are similar.

The Mandan landfill is on the Heart River floodplain and next to the river on the north and steep valley wall on the south. The sanitary landfill has been used for over 20 years.

The only pre-Pleistocene unit exposed is the Cannonball Formation, which is interbedded sand, silt, and clay. Quaternary units consist of till, fluvial sand, silt, clay, and gravel, and eolian sand and silt.

A local flow system recharges on the upland next to the valley and discharges in the valley. Flow is mostly lateral and toward the river. An intermediate flow system discharges in the Missouri River valley and may receive seepage from local flow systems.

Shallow groundwater near the landfill is generally a calcium-bicarbonate type. Deeper groundwater is generally a sodium bicarbonate-sulfate type.

Shallow groundwater has been contaminated by landfill leachate. Greatest changes in groundwater occur near the center of the landfill, where there are increases in calcium, magnesium, total hardness, bicarbonate, total alkalinity, total dissolved solids, and chloride and decreases in sulfate and pH.

Leachate production is low because of lack of moisture, low temperature, and large amounts of cellulose-based refuse. Recharge rarely occurs, but some parts of the landfill receive enough moisture

from groundwater and infiltration to produce leachate. The greatest amount of decomposition (mostly anaerobic) occurs soon after burial.

CHAPTER I

INTRODUCTION

North Dakota is a state with limited groundwater and surface-water resources. These resources should be protected from pollution including pollution from sanitary landfills.

Purpose

This is a report on the hydrogeology of a sanitary landfill at Mandan, North Dakota. The purpose of the report is to provide data on the generation and movement of landfill leachates in this geologic and climatic setting. This information can be applied to landfills in much of the rest of southwestern North Dakota.

Detailed information on leachates from landfills in most of North Dakota is not available. The contamination of the small amount of available water may create social and economic problems. New industrial developments resulting from increased lignite production may create waste-disposal problems for several communities in southwestern North Dakota.

The Mandan landfill was selected for study because of its long use and because it is in a geologic and climatic setting similar to that of most of southwestern North Dakota. The landfill has been in operation for 20 years. This should be enough time for any groundwater to have migrated far enough away from the landfill to evaluate the environmental impact.

Part of the problem was to describe the geology and hydrogeology of the study area. The surficial geology was mapped on aerial photographs (scale: 1 to 4000). Information was obtained by walking the area, shoveling, hand augering, continuous-flight augering, and hydraulic rotary drilling. County soil maps and U.S. Geological Survey topographic maps were used. Well elevations were determined by the transit-stadia method.

Drilling was used to determine the subsurface geology and to install piezometers. The groundwater flow rate, direction, and quality were determined. Single and multiple piezometer installations were used to determine permeabilities, to monitor water levels, and to collect water samples.

The problem also involved determining the environmental impact of the landfill. Changes in the dynamic groundwater flow system were monitored by piezometers. Changes in water quality were determined by chemical analyses.

Location

The study area is south of the city limits of Mandan (Figures 1 and 2) in sections 34 and 35 of T.139 N., R.81 W., and in the northern half of sections 2 and 3 of T.138 N., R.81 W. The site is on the lower end of the Heart River basin where the Heart River valley joins the Missouri River valley.

Mandan has a population of about 11,100 (North Dakota Highway Department, 1972). The area is largely rural, and farming and grazing are the major industries. The landfill serves the city of Mandan and nearby area.

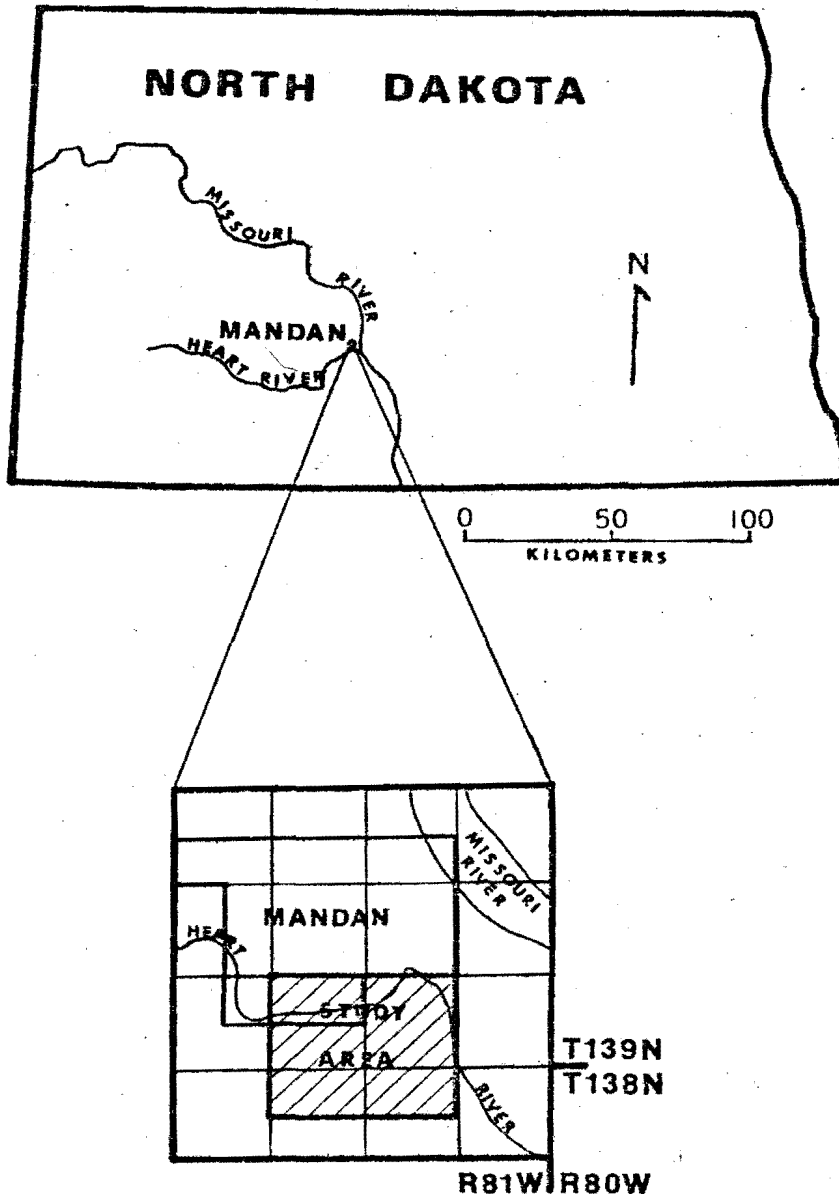


Fig. 1.—Map showing the location of the Mandan landfill study area.



Fig. 2.—Aerial photograph of the Mandan landfill area looking southwest.

Topography

The landfill is on the floodplain of the Heart River (Figure 3). The south bank of the river borders the north flank of the landfill. On the south and west, a steep valley wall rises 35 m to a rolling upland.

Climate

Mandan lies on the boundary of a dry subhumid, continental climate to the east and a semiarid climate to the west. The winters are long and cold; the summers are short, hot, and dry. Climatic data for the 57 year period 1915 to 1972 and for 1972 are summarized in Table 1.

The temperature at Mandan varies considerably throughout the year. A record high of 45.5°C (114°F) and a low of -42.8°C (-45°F) has been recorded. The mean annual temperature for the 57 year period is 5°C (41°F). January has a mean daily temperature of -13.3°C (8°F) and in July it is 21.7°C (71°F). Short, hot spells occur in July and August. Normally the ground is frozen to a depth of 1 m from November to April.

The precipitation is irregular and seasonally distributed. Mean annual precipitation is 400 mm (15.9 inches) of which 70 percent occurs between April and August. During 1972 the seasonal precipitation (April to September) was about 25 mm (1 inch) less than normal. Thunderstorms are common during the warmer months.

Normally the maximum precipitation of 70 mm (3.5 inches) occurs in June. December, January, and February each receive only about 10 mm (0.4 inches) of precipitation.

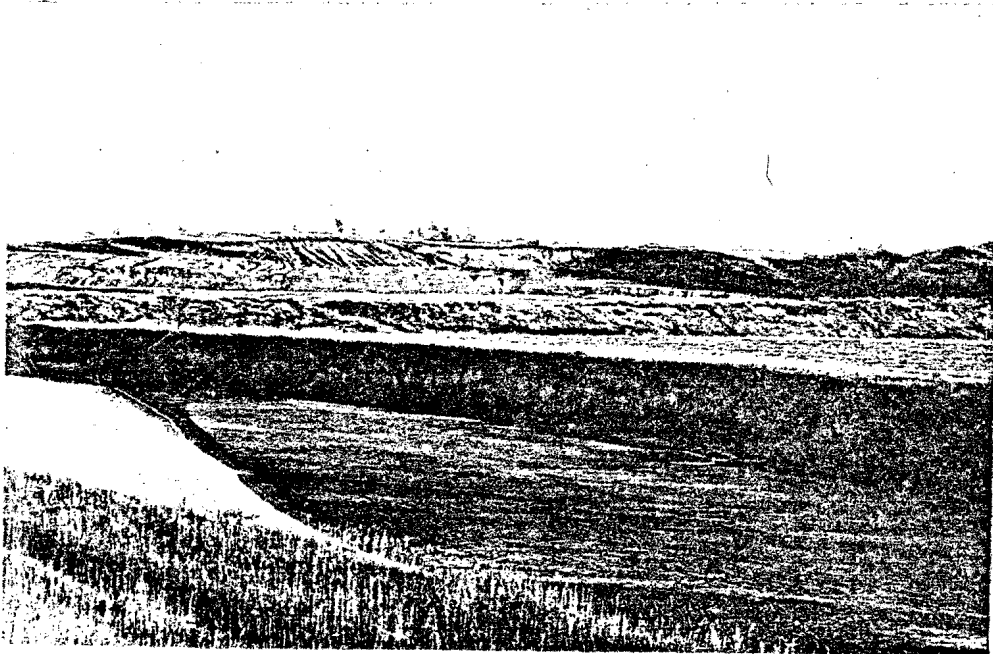


Fig. 3.—Photograph of the Mandan landfill looking southeast.

TABLE 1
CLIMATIC DATA FOR MANDAN, NORTH DAKOTA, 1915-1972*

Month	Precipitation, mm		Temperature, °C				Pan Evaporation, mm		Daily Wind Velocity, m/s	
	1915-1971 (Mean)	1972 (Total)	1915-1971 (Min.)	1915-1971 (Max.)	1915-1971 (Mean)	1972 (Mean)	1915-1971 (Mean)	1972 (Total)	1915-1971 (Mean)	1972 (Mean)
Jan	9.9	13.2	-18.9	- 7.8	-13.3	-15.6	..	..	2.2	1.8
Feb	10.2	6.6	-16.1	- 4.4	-10.6	-13.9	..	..	2.3	1.6
Mar	17.8	26.4	- 8.9	2.2	- 3.3	- 3.9	..	..	2.6	1.8
Apr	37.6	57.9	- 0.6	12.2	6.1	4.4	97.3	78.0	3.0	1.7
May	54.4	63.3	5.6	19.4	12.8	13.9	175.8	159.5	2.8	1.5
Jun	88.9	47.5	11.1	23.9	17.8	17.8	181.9	186.4	2.2	1.4
Jul	60.7	55.6	14.4	28.9	21.7	18.3	235.5	184.9	1.8	1.0
Aug	43.2	31.2	12.8	28.3	20.6	18.9	217.2	216.7	1.9	1.2
Sep	35.3	10.9	6.7	21.7	14.4	12.8	132.3	145.8	2.1	1.3
Oct	22.1	51.3	0.6	14.4	13.3	3.9	..	..	2.2	1.4
Nov	13.7		- 7.8	3.9	- 2.2		..	..	2.2	
Dec	9.7		-15.0	- 3.9	- 9.4		..	..	2.1	
Total	403.5						1040.0	971.3		

* Recorded at Northern Great Plains Research Center, Mandan, North Dakota.

Evaporation is high from April to September. Potential evaporation is about 750 mm (30 inches). The potential evaporation minus the mean annual precipitation is about 350 mm (14 inches), leaving a soil moisture deficiency most of the year. The mean seasonal evaporation of 670 mm (27 inches) for 1972 was close to the 57 year mean.

The prevailing wind is from the northwest. It averages about 2.4 m/s (5 miles an hour) from April to August. Winds are strongest during the spring and gentlest during the summer.

The growing season is about 124 days long. It starts about May 19 and ends about September 20.

Soil

Chestnut soils, regosols, and lithosols occur on the uplands. A humic gley and several types of alluvial soils occur on the bottomlands (Figure 4 and Table 2).

Most of the upland soils have good to excessive surface drainage. The permeabilities are generally fair to high. Bottomland soils range from well drained to poorly drained. The permeabilities are low to fair.

In general most of the soils are loose and friable. This makes them highly susceptible to wind and water erosion.

The upland soils are less fertile than the bottomland soils. In general the uplands are used for grazing and the bottomlands are planted with alfalfa and are grazed.

Vegetation

The Heart River bottomland has a thick natural forest of cottonwood, ash, boxelder, and a field of alfalfa (Figure 2). Willows

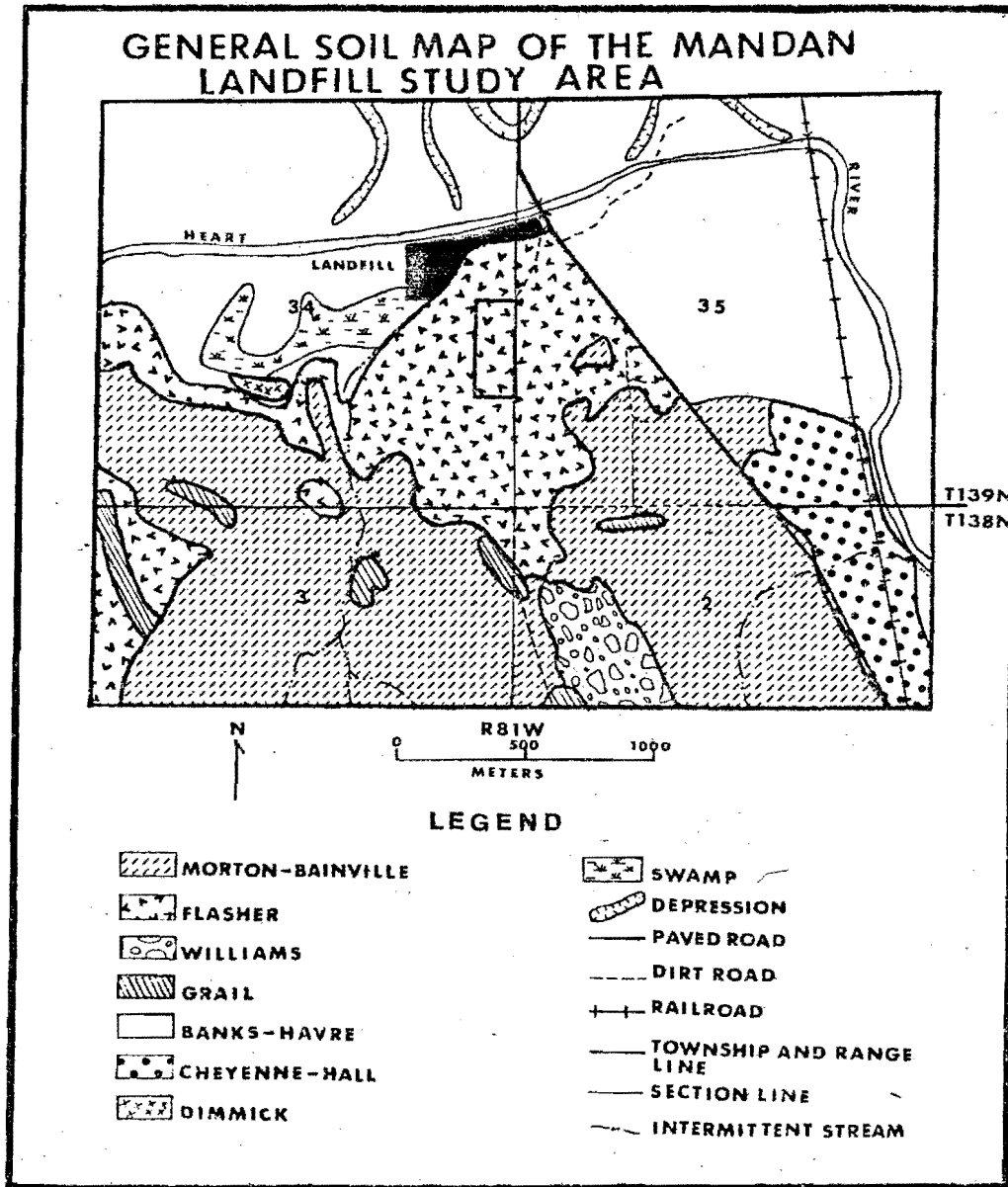


Fig. 4.—Soil map of the Mandan landfill study area, modified from the 1936 soil map of Morton County—Eastern sheet, compiled by the United States Department of Agriculture and North Dakota Agricultural Station.

TABLE 2

NAMES AND CHARACTERISTICS OF SOILS IN THE MANDAN LANDFILL STUDY AREA

Property	Williams	Morton	Bainville	Flasher	Hall
Parent Material	till, sandy clayey	silt, clay	silty, clay	sand, silt	alluvium, medium to fine
Texture	silt loam	loam	loam to clay loam	fine sandy loam to loamy fine sand	loam, silt loam
Position	ridge tops	undulating upland	rolling upland	hilly to steep broken upland	terrace
Slope	6-9%	3-8%	10-30%	15-80%	3-6%
Surface Drainage	moderately well drained	well drained	excessively drained	well to excessively drained	well drained
Other Characteristics	calcareous, fair permeability	calcareous, fair permeability	calcareous, fair permeability	fair to good permeability	fair to good permeability
Group Name (Edwards and others, 1951)	Chestnut	Chestnut	Regosol	Lithosol	Chestnut
7th Approximation Group Name (Patterson and others, 1968)	Typic Argiustoll	Typic Haploboroll	Typic Ustorthent	Entic Haplustoll	Typic Haplustoll

TABLE 2--Continued

NAMES AND CHARACTERISTICS OF SOILS IN THE MANDAN LANDFILL STUDY AREA

Property	Cheyenne	Grail	Havre	Banks	Dimmick
Parent Material	alluvium, fine to coarse	alluvium, fine	alluvium, fine	alluvium, sandy	alluvium, very fine
Texture	loam, gravelly loam	silt loam	silt loam, silty clay	loamy fine sand, silty clay	clay
Position	terrace	lower concave slopes	nearly flat bottomlands	flat bottomlands	abandoned channels, floodplain depressions
Slope	15-30%	3-9%	1-5%	0-2%	flat
Surface Drainage	excessively drained	moderately well drained	moderately well drained	fairly to poorly drained	poorly drained
Other Characteristics	high permeability	fair permeability	calcareous, organic, fair permeability	organic, fair to low permeability	organic, poor permeability
Group Name (Edwards and others, 1951)	Chestnut	Chestnut	Alluvial	Alluvial	Humic Gley
7th Approximation Group Name (Patterson and others, 1968)	Typic Haplustoll	Pachic Argiustoll	Typic Ustifluent	Typic Ustipsamment	Typic Haplaquoll

grow along the river banks. Depressions in the floodplain contain willows and marsh grasses.

The steep valley walls and gullied slopes are covered with oak, ash, elm, chokecherry, and poison ivy. Upper reaches of the gullies contain buffaloberry, buckbrush, and wild rose.

Native short and tall grasses grow on the uplands. Western wheatgrass, blue gamma, and needlegrass are common. A young forest of cottonwood grows on the northern part of the uplands.

The landfill has no vegetation on its upper surface. Sparse weeds and bushes grow on its flanks.

CHAPTER II

GEOLOGY

About 2700 m of Paleozoic^{Meissner} and Cenozoic sediment occurs in the Bismarck-Mandan area. The Cannonball Formation is the only pre-Pleistocene unit exposed. Several Quaternary formations as defined and described by Bickley (1972) and mapped by Groenewold (1972) are present. They are the Braddock, Four Bears, Coteau, Denbigh, and Oahe Formations.

Pre-Pleistocene Geology

Stratigraphic information on the Paleocene and Quaternary units was obtained by test drilling and from lithologic logs (Groenewold, 1972). Information on the Cretaceous units was obtained from the geology report of Burleigh County (Kume and Hansen, 1965) and basic-data report (Randich, 1965). The stratigraphic column of the Bismarck-Mandan area is given in Table 3.

The Dakota Group (early Cretaceous) is the oldest stratigraphic unit considered in this report. It occurs at a depth of 933 m to 1066 m in Burleigh County. It is a massive marine sandstone ranging in thickness from 37 to 100 m.

The Pierre Formation (late Cretaceous) consists of dark-gray marine shale about 335 m thick in Burleigh County. The upper part of the Pierre is often fractured and contains some sandy lenses (Randich, 1965). The top of the Pierre in the study area is at a depth of 373 m.

TABLE 3

STRATIGRAPHIC COLUMN OF THE BISMARCK-MANDAN AREA

AGE	UNIT NAME		DOMINANT LITHOLOGY
Pleistocene	Coleharbor Group	Oahe Fm.	Fine sand, coarse silt
		Denbigh Fm.	Well-sorted, medium sand
		Coteau Fm.	Organic, poorly sorted, sandy, clayey silt; gravel, sand, clay
		Four Bears Fm.	Non-organic gravel, sand, silt, and clay
		Braddock Fm.	Slightly bouldery, cobbly, pebbly, sandy, silty, clay
Paleocene	Tongue River Fm.		Sand, silt, clay, sandstone, siltstone, shale, limestone, lignite
	Cannonball Fm.		Sand, sandstone, silt, clay, shale
	Ludlow Fm.		Sandstone, shale, lignite
Cretaceous	Hell Creek Fm.		Sandstone, clay, mudstone, lignite
	Colorado Group	Fox Hills Fm.	Sand, sandstone, siltstone, shale
		Pierre Fm.	Shale, sandy shale
		Niobrara	Calcareous shale
		Carlile Fm.	Shale
	Montana Group	Greenhorn Fm.	Calcareous shale
		Belle Fourche Fm.	Shale
		Mowry Fm.	Shale
	Dakota Group	Newcastle Fm.	Sandstone
		Skull Creek Fm.	Shale
		Fall River Fm.	Sandstone and shale
		Lakota Fm.	Sandstone and shale
		Swift Fm.	Shale, sandstone, siltstone
Jurassic	Rierdon Fm.		Siltstone
	Piper Fm.		Limestone and shale
	Alaska Bench Fm.		Dolomite
Pennsylvanian	Tyler Fm.		Sandstone and shale
	Amsden Fm.		Limestone, shale, sandstone
	Mississippian	Big Snowy Group	Undifferentiated	Limestone and shale
Madison Group		Undifferentiated	Limestone and evaporites

TABLE 3--Continued

STRATIGRAPHIC COLUMN OF THE BISMARCK-MANDAN AREA

AGE	UNIT NAME	DOMINANT LITHOLOGY	
Devonian	Birdbear Fm.	Limestone	
	Duperow Fm.	Limestone	
	Souris Bay Fm.	Dolomite and limestone	
	Dawson Bay Fm.	Dolomite and limestone	
Silurian	Interlake Fm.	Dolomite	
	Stonewall Fm.	Limestone and dolomite	
Ordovician	Stony Mountain Fm.	Limestone	
	Red River Fm.	Limestone and dolomite	
	Winnepeg Group	Undifferentiated	Sandstone, shale siltstone
Cambro-Ordovician	Deadwood Fm.	Sandstone, shale, limestone	
Precambrian		Granite	

The Fox Hills Formation (late Cretaceous) consists of marine sandstone about 85 m thick in the study area. It also contains several intervals of interbedded sandstone and shale. In southern Morton County, the Fox Hills is light-gray sand, banded sandstone and shale, and concretionary buff sand (Laird, 1942). The top of the Fox Hills is at 458 m in the study area. The contact with the Hell Creek Formation is sharp.

The Hell Creek Formation (late Cretaceous) is continental in origin and consists of interbedded gray sandstone, mudstone, siltstone, carbonaceous shale, and thin lignite beds. Individual beds are thin and show much lateral variation (Groenewold, 1972). The Hell Creek is about 87 m thick southeast of the study area. Contact with the Ludlow Formation is gradational.

The Ludlow Formation (Paleocene) is continental in origin and consists of yellow-brown sandstone, green-black shale, and thin lignite beds (about 0.3 m thick). It is generally less than 4 m thick in the study area (Groenewold, 1972) and thickens to the west. The upper contact with the Cannonball Formation is conformable and gradational and consists of lignitic shale grading into interbedded silt and sand. The Ludlow-Cannonball contact may be present at an elevation 528 m in a well location in T.139 N., R.81 W., sec. 34, NE $\frac{1}{4}$, SE $\frac{1}{4}$, NE $\frac{1}{4}$.

The Cannonball Formation (Paleocene) is about 90 m thick in the study area. It consists of two members. The upper member consists of alternating sand and silt, and the lower member consists of laminated clay and silt.

The lower member is homogenous, dark-gray, silty clay about 30 m thick. Several thin shale layers are present.

The upper member is interbedded sand, silt, and clay about 60 m thick. Individual layers of sediment range in thickness from 0.01 m to 1 m. The sand is fine-grained, gray-brown, friable, glauconitic, and noncalcareous. The clay is silty, medium to dark-gray, noncalcareous, and locally stiff. The upper member locally contains layers of shale, carbonate-cemented sandstone, and concretionary limestone. The carbonate-cemented sandstone ranges in thickness from 0.01 m to 0.5 m and is locally discontinuous.

Excellent exposures of the Cannonball Formation occur in the area. Landfill operations have exposed a section about 12 m thick. The exposure contains conspicuous beds of sediment that are laterally continuous over short distances. Differences in lithology cause light and dark tones in the beds of sediment. There are alternating layers of buff colored sand and dark-gray silt and clay. The layers range in thickness from 0.01 m to 0.4 m with an average thickness of a few hundredths of a meter.

Weathered parts of the Cannonball are yellow-brown because of limonite stain. The sediment has a cracked, blocky texture and is very friable and noncalcareous.

The fresh, unoxidized sediment consists of dark-gray to gray beds which are very compact when wet. Individual sand layers are buff colored and have thin dune and ripple cross-bedding. Clay layers are partly indurated and are locally mottled.

A discontinuous bed of carbonate sandstone occurs in several exposures in the region at an elevation of about 558 m. It is about 0.6 m thick and has thin dune cross-bedding. This bed seems

to be regionally persistent. Laird (1942) reported a concretionary sandstone bed forming a topographic bench in southern Morton County. Hall (1958) also noted a concretionary layer about the same elevation in the area.

The Cannonball Formation is mostly offshore and nearshore sediment in the study area.

Pleistocene Geology

Quaternary stratigraphic units present in the study area are the Braddock, Four Bears, Coteau, Denbigh, and Oahe Formations (Bickley, 1972). They consist of alluvial, colluvial, and eolian sediment. Figure 5 is a map of the surficial geology of the area.

The Braddock Formation is olive-drab glacial till. It consists of bouldery, cobbly, pebbly, sandy, silty, clay and reaches a maximum thickness of 1 m on the upland area. Much of this unit has been removed by erosion leaving scattered granitic boulders over parts of the upland. The Braddock may be Wisconsinan in age.

The Four Bears Formation occurs as an elevated terrace deposit 15 m above the floodplain on the south side of the Heart River valley. An excellent exposure occurs near the landfill. It consists of a northwest-southeast trending channel deposit buried by sand and silt of the Oahe Formation. The channel is incised 16 m into the Cannonball Formation to the top of a carbonate-cemented sandstone bed. The deposit is 25 m thick and consists of two facies. The lower facies is buff-colored sand with flat-bedding, tabular-bedding, and cross-bedding. Organic fragments occur on bedding surfaces in parts of the deposit. Coal pebbles, clay pebbles, and gastropod fragments are also abundant

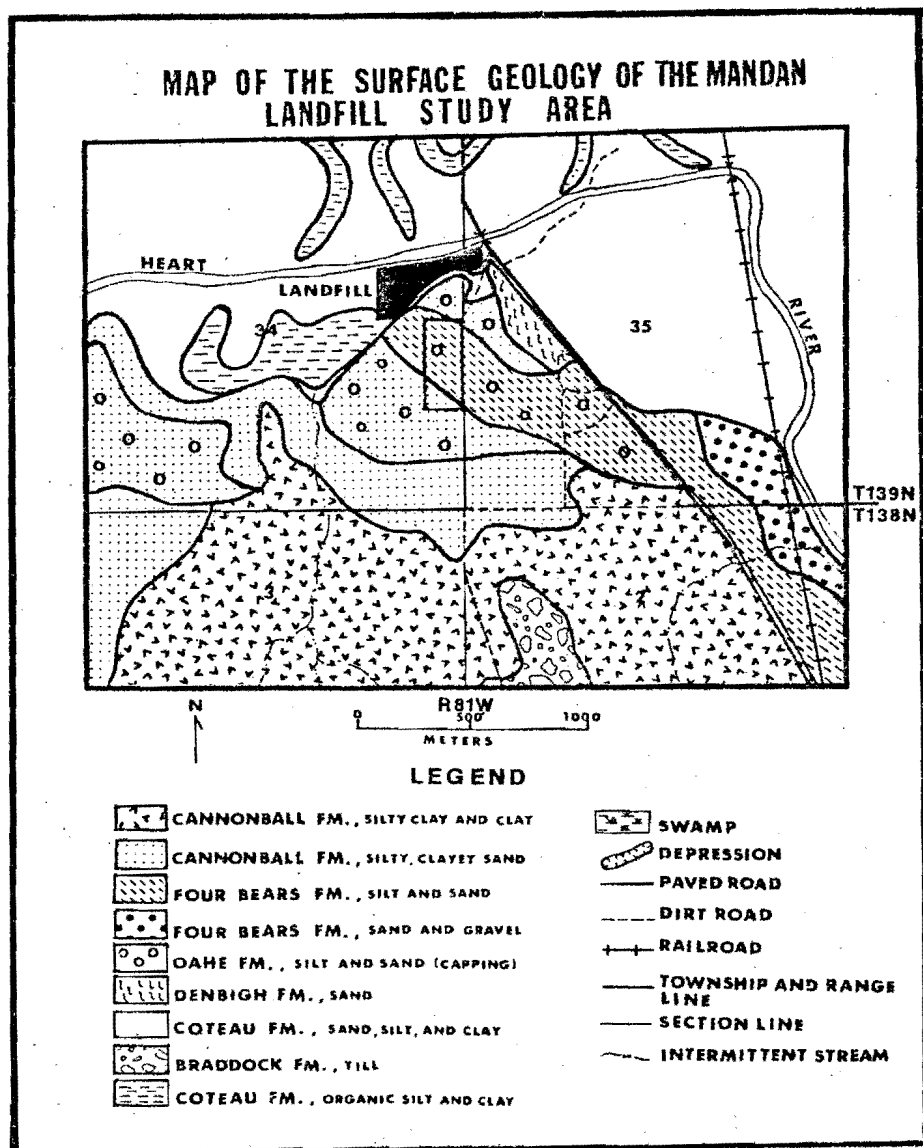


Fig. 5.—Map of the surficial geology of the Mandan landfill area.

in the lower part of this sand. The upper facies is gray, laminated silt.

The contact of the Four Bears with the Cannonball Formation is sharp. The elevation of this contact varies considerably.

The Four Bears Formation was deposited during a drainage diversion of the Heart River. It is Wisconsinan in age.

The Coteau Formation is mostly a thick alluvial deposit filling the Heart River valley. Minor amounts of colluvial and marsh deposits also occur.

The Coteau Formation has a maximum thickness of 30 m in the study area. It consists of blue-gray silt as much as 3 m thick at the base of the valley alluvium. The clay grades upward to sand and silt. Lenses of gravel as much as 3 m thick occur in this sandy unit. The lenses are laterally continuous for 300 m and consist of fine to medium gravel with lignite and gastropod fragments. About 10 m of gray silt overlie the sandy unit.

Colluvial deposits of the Coteau Formation occur at the base of slopes. They consist of gray, dirty, organic, silty clay ranging in thickness from 0.0 m to 0.3 m.

Poorly drained depressions on the floodplain contain marshy deposits of the Coteau Formation consisting of black, organic clay. The deposits range in thickness from 0.0 m to 0.2 m.

Most of the Coteau Formation was deposited as the Heart River meandered across its valley and deposited coarse sediment in point bars and fine sediment on natural levees and floodbasins. The Coteau Formation is Holocene in age.

The Denbigh Formation is light-tan, loose, well-sorted, medium-grained sand. It is 3 m thick over the Four Bears Formation in the northern part of the study area. The Denbigh Formation is wind-blown sand that is Holocene in age.

The Oahe Formation is the uppermost Quaternary unit in the study area. It forms a thin capping of buff to gray, loose silt and sand as much as 1 m thick. The Oahe thins away from the river. It is wind-blown silt and sand and is Holocene in age.

History

Before the Pleistocene the area consisted of an undulating to rolling upland. The pre-glacial path of the Heart River may have been to the east across Burleigh County. Evidence for a pre-glacial Heart River is inconclusive (Randich, 1973).

A glacial advance caused deposition of ground moraine and outwash. Drainage through part of the valley now occupied by the Heart River was forced to flow west. A fluvial terrace was formed by the west-flowing river on the south side of the valley. This terrace is about 15 m above the present floodplain.

A diversion of the Missouri River caused the Missouri to flow south. The Heart River drainage was captured and flowed south. The Missouri River cut a deep trench into Tertiary and Cretaceous sediment as it formed a wide valley.

Since then the Heart River has, at sometime, downcut into the Cannonball Formation. As much as 30 m of clay, silt, sand, and gravel fills the valley. The meandering river has formed a valley about 1500 m wide. Several cutoff meanders occur to the north and east of

the landfill. They contain colluvium and marshy deposits.

Eolian sand and silt has been deposited on the uplands. As much as 1 m of silt caps the uplands. The sand may be as much as 2 m thick.

Erosion has removed much of the glacial till and created an integrated drainage. Many minor streams dissect the uplands and valley wall.

The channel of the Heart River has been modified for flood control. Several meanders were cutoff by a dike.

The river is actively downcutting and has steep banks. The river is attempting to regain its former course in a cutoff meander. It has eroded sediment very near the dike. The present channel is about 5 m below the floodplain and is about 10 to 12 m wide from bank to bank.

Flow in the Heart River varies during the year. Spring runoff usually causes flooding. Thunderstorms also cause high flows. Normal summer flow is about $3.6 \text{ m}^3/\text{s}$ (120 cubic feet a second). Discharge is controlled in part by Heart Butte Dam at Lake Tschida in western Morton County.

CHAPTER III

GENERAL INFORMATION ON THE MANDAN LANDFILL

The purpose of this chapter is to give general information on landfills and landfill terminology and to give data on the Mandan landfill.

Terminology

The terminology relating to landfills as used in this report needs to be defined.

Sanitary Landfill.--According to the American Society of Civil Engineers (1959, p.1) a sanitary landfill is

. . . a method of disposing of refuse on land without creating nuisances or hazards to public health or safety by utilizing the principles of engineering to confine the refuse to the smallest practical area, to reduce it to the smallest practical volume, and to cover it with a layer of earth at the conclusion of each day's operation or at such more frequent intervals as may be necessary.

Refuse.--Refuse refers to all solid wastes such as putrescible and nonputrescible material including garbage, rubbish, ashes, street cleanings, dead animals, abandoned vehicles and machinery, construction and demolition waste (North Dakota State Department of Health, 1970).

Garbage.--Garbage consists of putrescible animal and vegetable wastes from handling, preparation, and consumption of food, including wastes from markets, storage facilities, handling and sale of

produce and other food products (North Dakota State Department of Health, 1970).

Rubbish.--Rubbish consists of nonputrescible solid waste that is combustible or noncombustible. It includes paper, rags, cartons, furniture, rubber, plastics, yard trimmings, leaves, glass, cans, dust, metal furniture, and crockery (North Dakota State Department of Health, 1970).

Cell.--A cell is a layer of refuse surrounded by earth. The fill is of some convenient width and it is lengthened as needed. Refuse is placed at one end, covered with earth, and compacted.

Leachate.--Leachate is a liquid leached from decomposing refuse and containing organic or inorganic contaminants.

History

The present landfill site became a sanitary landfill about 1950 after a study was made to determine the feasibility of operating a sanitary landfill in a cold northern climate (Van Derwerker, 1952). The site of the 1950 study was on the uplands south of the present site.

Refuse in the present site was initially placed in a trench excavated down to the water table in alluvial sediment. When the trench was filled, a combined ramp and area method of filling was used. Refuse was placed at the foot of a slope (length:height = 3:1), pushed up the slope, compacted about 20 to 30 percent of original volume, and covered with a layer of earth about 0.3 m thick. Earth used for fill was taken from an outcrop of the Cannonball Formation and stockpiled along the sides of the cell.

Additional refuse cells are constructed by the progressive slope (ramp) method until a complete layer of refuse about 4 m thick has formed (Figure 6). A final cover of 0.6 m of earth is added.

A map of the history of filling of the Mandan landfill is given in Figure 7. A core of garbage consisting of about everything except trees, branches, auto bodies, and demolition concrete was formed. A perimeter of rubbish consisting mostly trees, auto bodies, and large appliances was built to provide a windbreak around the core.

In general it takes about 6 years to complete a 12 m layer of refuse. In 1952 the daily production of refuse in Mandan was about 1.4 kg (3 pounds) for each person. Today the daily output for each person is about 1.8 kg (4 pounds).

The present dimensions of the landfill are as follows:

Length = 800 m

Width = 500 m

Thickness = 15 m

Surface area = $4 \times 10^5 \text{ m}^2$

Volume = $6 \times 10^6 \text{ m}^3$.

The landfill is about 15 m above the floodplain on the south, west, and north sides. The east side borders the sloping valley wall.

The flanks are nearly vertical and surface runoff is rapid. The flanks are exposed to flooding of the Heart River.

The upper surface of the landfill has about 1 percent slope toward the Heart River. Differential settlement has caused several large oval-shaped depressions to form. These depressions fill with rain and runoff which may remain as much as a week after a storm.



Fig. 6.—Photograph of the method of filling of the Mandan landfill.

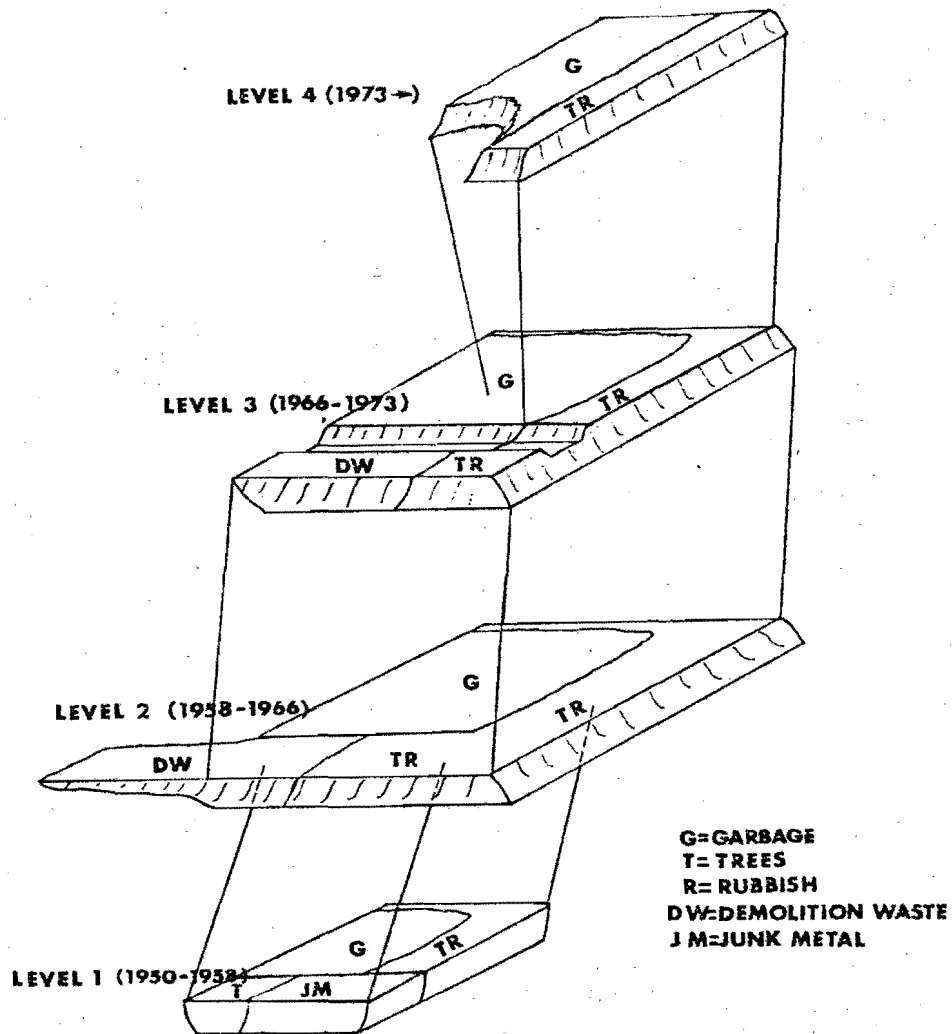


Fig. 7.—Diagram showing the history of filling of the Mandan landfill, 1950 to 1973.

CHAPTER IV

GROUNDWATER THEORY

Introduction

Groundwater theory developed from several important early papers (Meinzer, 1923a, 1923b; Hubbert, 1940). Hubbert (1940) presented the physical laws of steady-state groundwater flow mathematically.

In the early 1960s a theoretical background of groundwater flow was presented to complement field studies (Toth, 1962, 1963). Groundwater flow patterns were derived mathematically by solving standard boundary value problems.

Several studies have expanded groundwater theory into usable mathematical models of various flow systems. The flow models had areas ranging from thousands of square kilometers to a few square kilometers or less (Meyboom, 1963, 1966, 1967a, 1967b; Williams, 1968; Freeze, 1969; Hitchon, 1969a, 1969b).

Early work in groundwater chemistry by Chebotarev (1955) established a sequence of chemical facies for groundwater flow systems. The results of several thousand water sample analyses were used to show the changes. Brown (1963) used groundwater chemistry in a groundwater study. Back (1960) and Charron (1965) used groundwater chemistry to determine flow directions. Meyboom (1966) and Toth (1968) used water chemistry as a secondary indicator of various flow systems.

There have been several flow models developed for parts of the Great Plains that used groundwater chemistry. Hamilton (1970) developed a groundwater flow model for the Little Missouri River Basin in western North Dakota. Hagmaier (1971) developed a model for uranium deposition in the Powder River Basin in Wyoming. Schulte (1972) used water chemistry as a flow system indicator in a flow model of Spiritwood Lake area in central North Dakota.

Terminology

The terms as they are used in this report are defined below. These terms are in common usage in groundwater studies.

Flow-System Terminology

Flow System.--The flow system as defined by Toth (1963, p.4806) is

. . . a set of flow lines in which any two flow lines adjacent at one point of the flow region remain adjacent through the whole region; they can be intersected anywhere by an uninterrupted surface across which flow takes place in one direction.

Topography and length of flow path can be used to define three types of flow systems: local, intermediate, and regional.

Local Flow System.--Flow in a local flow system is from a small topographic high to an adjacent low. The length of flow path in a local flow system ranges from a few hundred meters or less up to a thousand meters.

Intermediate Flow System.--Flow in an intermediate flow system is from a regional topographic high to a regional low. The length of flow path in an intermediate flow system ranges from a thousand meters up to several thousand meters.

Regional Flow System.—Flow in a regional flow system is from a large regional topographic high to a regional low. The length of flow path in a regional flow system ranges from a few thousand meters to several tens of thousands of meters.

Groundwater flow is three dimensional and can be resolved into flow components and resultants. The flow vectors are mutually perpendicular.

Longitudinal Component.—The longitudinal component parallels a river or divide. It is called underflow.

Vertical Component.—The vertical component is along a line extended to the center of the earth. It may be up or down.

Lateral Component.—The lateral component is normal to the plane of the longitudinal and vertical components. It may be called lateral flow.

The three components can be resolved into a total flow vector, a horizontal component, and a flow resultant.

Total Flow Vector.—The total flow vector is the direction of flow in three dimensional space. It is the vector sum of the horizontal flow component and the flow resultant.

Horizontal Flow Component.—The horizontal flow component is the direction of flow in a plane normal to the vertical.

Flow Resultant.—The flow resultant is the direction of flow in a plane parallel to the vertical. An approximation is obtained by constructing a cross-section across the flow field. The cross-section

may be constructed by contouring values of potential in a plane of the section. Flow resultants are drawn at right angles to lines of equal potential. It is assumed that the sediment is homogenous and isotropic.

Corrections must be made for anisotropic conditions. Iso-potential lines and flow resultants are refracted at permeability interfaces according to the tangent law (Hubbert, 1940, p. 943). The flow resultant must also be corrected for distortion in a vertically exaggerated section (van Everdinger, 1963).

Static Head.---The static head is the height above a standard datum of the surface of a column of water (or other liquid) that can be supported by the static pressure at a given point. It is the sum of elevation head and pressure head. Head, when used alone, is understood to mean static head (Lohman and others, 1972).

Total Head.---The total head of a liquid at a given point is the sum of elevation head, pressure head, and velocity head. It is equal to the static head plus velocity head of the fluid (Lohman and others, 1972).

Water Table.---The water table is an imaginary plane in an unconfined aquifer at which pore pressure equals atmospheric pressure. The configuration of the water table is a subdued replica of the topography.

Recharge.---Recharge is the addition of water to the groundwater flow system through the unsaturated zone to the water table. A recharge area occurs where there is downward movement of groundwater away from the water table.

Discharge.--Discharge is the loss of water from the groundwater flow system by evapotranspiration, stream baseflow, springs, and seepage areas. A discharge area occurs where there is upward movement of groundwater toward the water table.

Water-Chemistry Terminology

Parts Per Million.--Parts per million is the concentration of dissolved matter, by weight, in a million parts of solution by weight.

Equivalents Per Million.--Equivalents per million is the normality of a solution multiplied by 1000.

Hydrochemical Facies.--A hydrochemical facies is a body of water in a groundwater flow system differing from other bodies of water by its chemical characteristics. The hydrochemical facies classification of Back (1960) is used in this report. Equivalents per million of cations and anions in solution are used to compute percentage values.

As used by Hamilton (1970, p.9) a facies term alone

. . . indicates that the ion content of the water is composed of at least 90 percent of that member (for example, bicarbonate water indicates that the anions are composed of at least 90 percent bicarbonate). Double anion terms (for example bicarbonate-sulfate) describe water that is composed of at least 50 percent but less than 90 percent of the first named member (bicarbonate); the second member is greater than 10 but less than 50 percent of the total anions. A calcium-magnesium facies indicates that the cations are composed of at least 90 percent calcium and magnesium. But, a calcium-sodium facies represents water in which the calcium and magnesium comprise at least 50 percent of the total cations.

Groundwater Flow

The following is a brief description of groundwater concepts.

Groundwater flow theory fundamentals are based on the Bernoulli Theorem, Darcy's Law, the Continuity Equation, and the Laplace Equation.

Bernoulli Theorem

Hydraulic potential is produced by topography and operated by gravity. The elevation, pressure, and velocity at a point along a flow line is expressed in the equation for hydraulic potential

$$\phi = gZ + \frac{P - P_o}{\rho} + \frac{V^2}{2}, \quad (1)$$

where ϕ = hydraulic potential at point P,

g = gravitational acceleration,

Z = elevation of point P above a datum,

P = pressure at point P, and

ρ = density of water.

The fluid is assumed to be incompressible and flow is frictionless.

The velocity head, $\frac{V^2}{2g}$, is negligible in groundwater flow. The potentials have units of energy per unit mass.

Dividing equation 1 by gravitational acceleration, g , yields

$$\frac{\phi}{g} = Z + \frac{P - P_o}{\gamma} + \frac{V^2}{2g}, \quad (2)$$

where γ is the weight density of water. The terms are in units of energy per unit weight.

In equation 2, $\frac{\phi}{g}$, the hydraulic head, is the height (h) above a datum that a fluid will rise in a piezometer placed at point P.

Hydraulic head (h) is in units of energy per unit weight of water.

Equation 2 can therefore be written

$$h = Z + \frac{P - P_o}{\gamma}, \quad (3)$$

which states that the hydraulic head, or total head, is the sum of the elevation head and the pressure head.

Darcy's Law

Darcy's Law relates the rate of flow through a porous medium to the permeability and hydraulic gradient. For flow in the x direction, the velocity is

$$V_x = -K_x \frac{dh}{dx}, \quad (4)$$

where V_x = seepage velocity in the x direction,

K_x = permeability in x direction, and

$\frac{dh}{dx} = i$ = change in head in x direction.

Equation 5 can be expressed as a rate of flow through a porous medium:

$$Q = K i A, \quad (5)$$

where Q = rate of flow, in cubic meters a second,

K = field permeability, in meters a second,

i = hydraulic gradient, in meters per meter, and

A = cross-sectional area of flow, in meters squared.

Continuity and Laplace Equations

The Continuity Equation is an expression of the law of conservation of mass:

$$\frac{d(V_x)}{dx} + \frac{d(V_y)}{dy} + \frac{d(V_z)}{dz} = -F \frac{d(\rho)}{dt}, \quad (6)$$

where V_x , V_y , V_z = velocity in x, y, and z directions,

ρ = density of fluid, and

t = time.

The Continuity Equation shows that the difference between the mass entering and leaving a system is equal to the mass stored in the system.

Assuming a constant density, equation 6 becomes

$$\frac{dV_x}{dx} + \frac{dV_y}{dy} + \frac{dV_z}{dz} = -F \frac{d\rho}{dt} . \quad (7)$$

For steady state conditions the right hand side of equation 7 becomes zero, and the Continuity Equation becomes

$$\frac{dV_x}{dx} + \frac{dV_y}{dy} + \frac{dV_z}{dz} = 0 . \quad (8)$$

The Continuity Equation in this form is combined with equation 4, Darcy's Law, to obtain the Laplace Equation:

$$\frac{d^2 \phi}{dx^2} + \frac{d^2 \phi}{dy^2} + \frac{d^2 \phi}{dz^2} = 0 . \quad (9)$$

This equation can be used to express the distribution of hydraulic potential in three-dimensional space.

Groundwater Flow Models

Present-day groundwater flow models are based on flow models developed by Toth (1962, 1963) and Meyboom (1963). Toth developed a mathematical framework for isotropic, homogenous material and ideal boundary conditions. Meyboom utilized field observations to develop a flow model for the semiarid western Canadian prairie.

A theoretical model of groundwater flow by Toth (1962, 1963) described three types of flow systems: local, intermediate, and regional. Superimposition of smaller flow systems on larger ones was a characteristic of the model (Figure 8). Complicated problems such as heterogeneity, anisotropy, water-table irregularity, and stratigraphic pinchouts were treated with detailed mathematical and digital computer techniques. Three-dimensional modeling was also attempted.

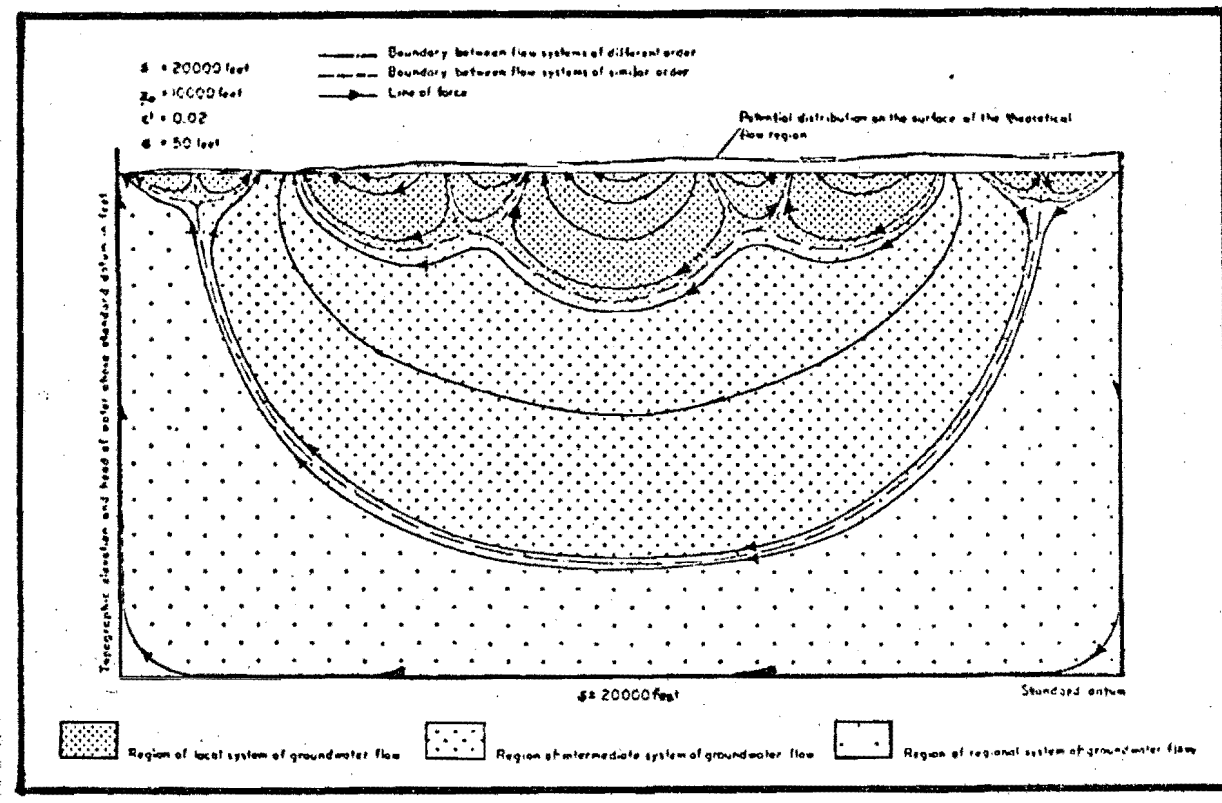


Fig. 8.—Theoretical flow pattern and boundaries between different flow systems (from Toth, 1963, p. 4807).

Groundwater flow in Saskatchewan, Canada was modeled into the Prairie Profile (Figure 9) by Meyboom (1963). By definition the Prairie Profile

. . . consists of a central topographic high bounded at either side by an area of lower elevation. Geologically the profile is made up of two layers of different permeability, the upper layer having the lower permeability. Through the profile is a steady flow of groundwater from the area of recharge to the area of discharge. The ratio of permeabilities is such that groundwater flow is essentially downward through the material of low permeability and lateral and upward through the more permeable layer. The potential distribution is governed by the differential equation of Laplace.

Groundwater flow in the Mandan landfill has some of these characteristics. One half of an asymmetric Prairie Profile is developed at the landfill site.

The models of Toth and Meyboom conflict on whether or not unconfined groundwater flow systems can cross major topographic divides and large river valleys. Toth (1963) indicates that they cannot cross these features while Meyboom (1963) indicates large-scale flow systems can cross these features.

Application of computer techniques to groundwater flow description and modeling was researched by Freeze and Witherspoon (1966, 1967, 1968) and Freeze (1969). A three-dimensional groundwater flow model for nonsteady, heterogenous, anisotropic conditions was developed with the aid of a computer.

Groundwater Chemistry

Groundwater chemistry may be used to indicate the type of groundwater flow. Chebotarev (1955) developed a hydrochemical model for groundwater flow. Meyboom (1966), Toth (1968), Charron (1965), and

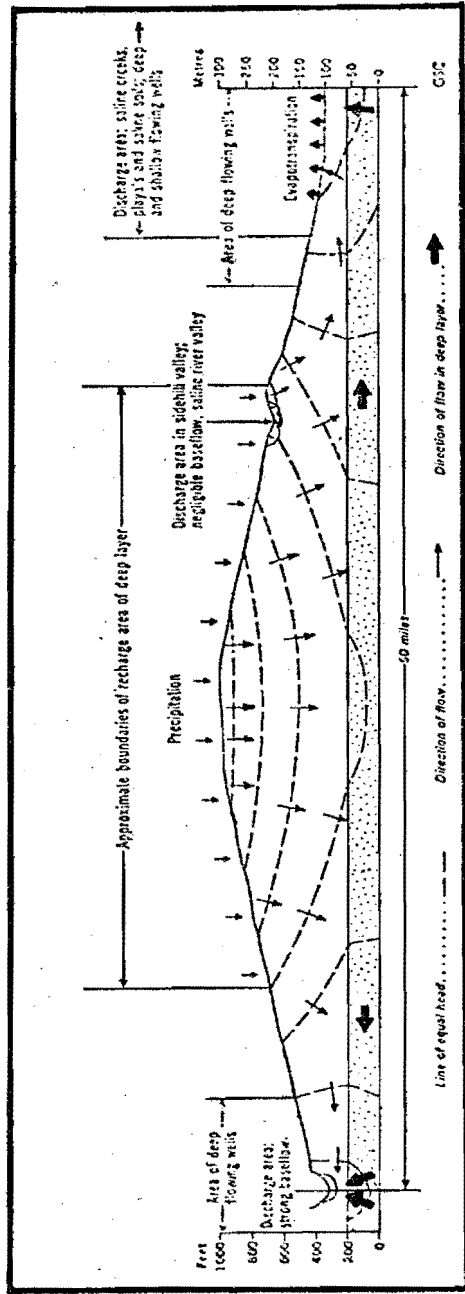
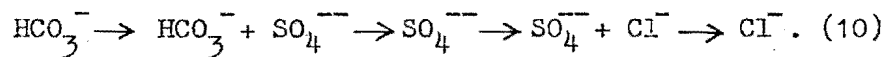


Fig. 9.—The Prairie Profile (from Meyboom, 1963, p. 27).

Back (1960) have used groundwater chemistry to indicate groundwater flow directions.

Chebotarev's (1955) hydrochemical model was developed using the analyses of several thousand groundwater samples. The sequence (Figure 10) that develops is



The solubilities of common salts and the length of contact time between water and sediment results in a hydrochemical sequence that proceeds toward a saline composition. Theoretically the longest flow path should be the most saline.

The time of contact between groundwater and sediment should result in a characteristic type of water. Water along a short flow path (or in a local flow system) should be rich in carbonate. Bicarbonate and sulfate water should develop in an intermediate flow system. Regional flow systems should be rich in bicarbonate, sulfate, and chloride. Deviations from these hydrochemical patterns may be due too short a flow path for the particular type of water to develop. The presence of very soluble minerals may cause anomalous water types.

THE CHEBOTAREV SEQUENCE

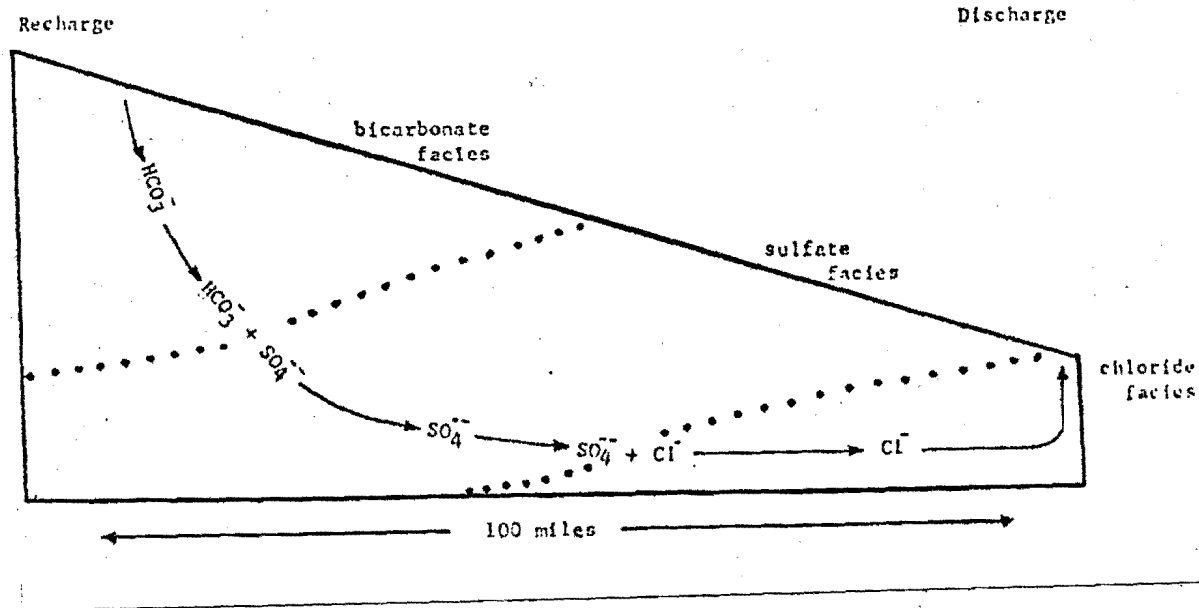


Fig. 10.—Hydrochemical model for regional groundwater flow systems (from Hagmaier, 1971, p. 34).

CHAPTER V

GROUNDWATER OF THE MANDAN LANDFILL AREA

Introduction

The purpose of this chapter is to describe the groundwater flow systems in the study area and to evaluate the contamination of groundwater in the landfill area.

The groundwater flow system was determined using (1) selected values of hydraulic potential, (2) the location of recharge and discharge areas, (3) composition, physical properties, and stratigraphy of the sediment, (4) topography, (5) chemical and physical properties of the groundwater. A cross-section was made through part of the landfill area to show the groundwater flow patterns.

Several assumptions were made for this study. Flow is assumed to be in a steady state. Water levels are assumed to have changed very little over a season and over a 30 year period. The sediment is assumed to be homogenous on a large scale. An impermeable boundary is assumed to exist at depth. The Pierre Formation forms the base of the regional flow system in the study area and separates it from deeper flow systems.

Hydraulic potential data obtained by piezometers and water chemistry were used to evaluate the groundwater flow systems. A piezometer is a cased well, screened at the bottom, and sealed in the borehole with cement for a short distance above the screen. It is

used to measure the hydraulic potential at a point in the groundwater flow system. A discussion of the type of piezometer used in this study and installation procedures are given in Appendix A. The theory and characteristics of various piezometers used in a North Dakota groundwater study are summarized by Schulte (1972).

Piezometers were installed in critical locations in the study area. The purpose was to be able to construct a detailed cross-section of the flow system and to monitor the water quality through time. Piezometers were installed within the landfill, on the perimeter of the landfill, and on the uplands next to the landfill.

The effects of potential generation of leachate in the landfill were evaluated by analyzing groundwater samples from piezometers and nonpiezometers (several existing wells). The groundwater samples were analyzed for the major cations and anions. The chemistry of groundwater upgradient from the landfill, beneath the landfill, and leaving the landfill area was monitored.

Field Studies

A total of twenty-one piezometers were installed in the study area (Figure 11). Of the thirteen wells drilled, eight contained multiple-piezometer installations (two in a borehole) and five wells contained single piezometers. Figure 12 shows a typical multiple-piezometer installation with a galvanized-steel pipe used as a protective cover. Four existing wells (nonpiezometers) in the area were also used to collect water samples.

Field procedures included measuring the hydraulic potential,

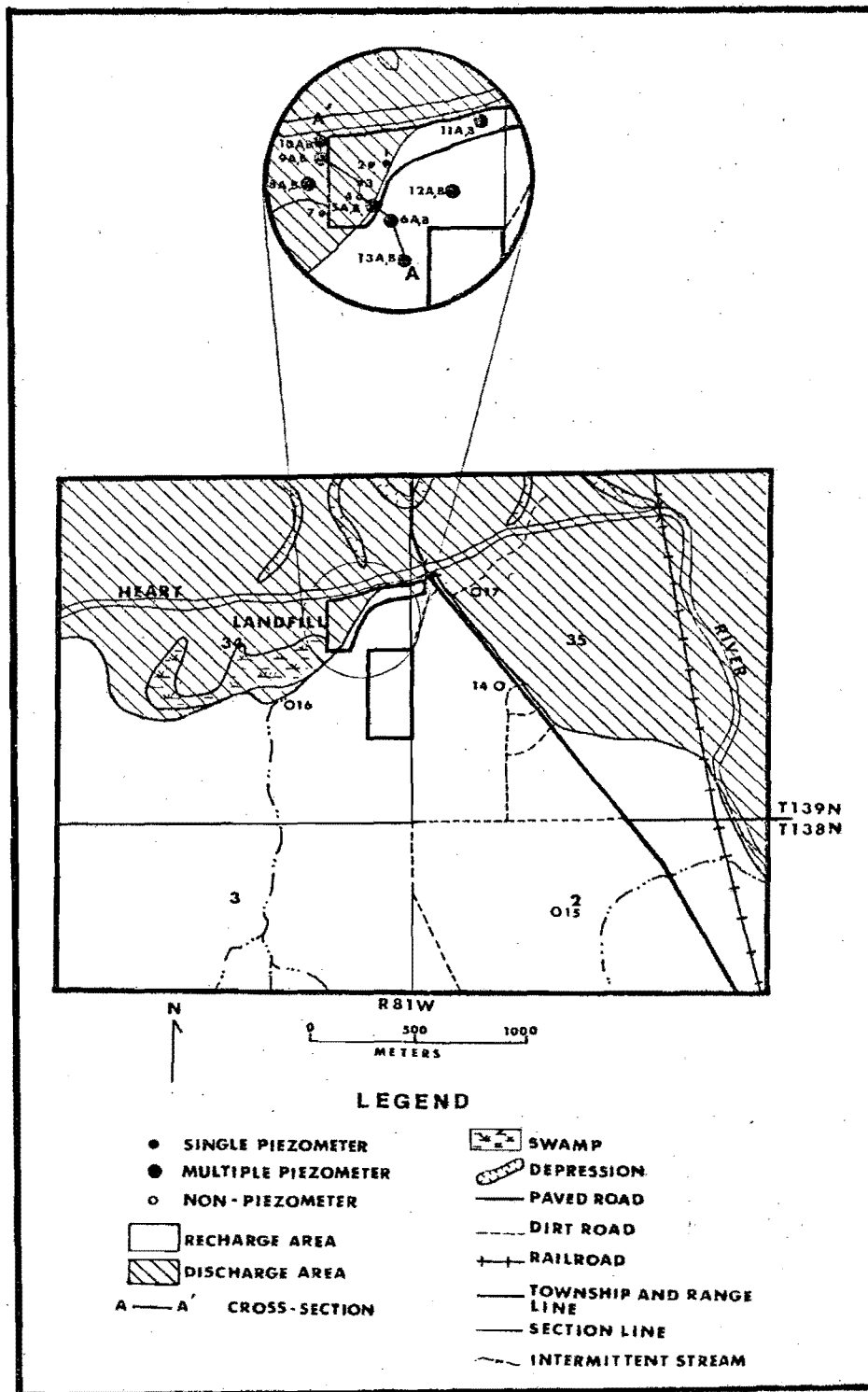


Fig. 11.—Map showing the location of recharge and discharge areas and wells in the study area.

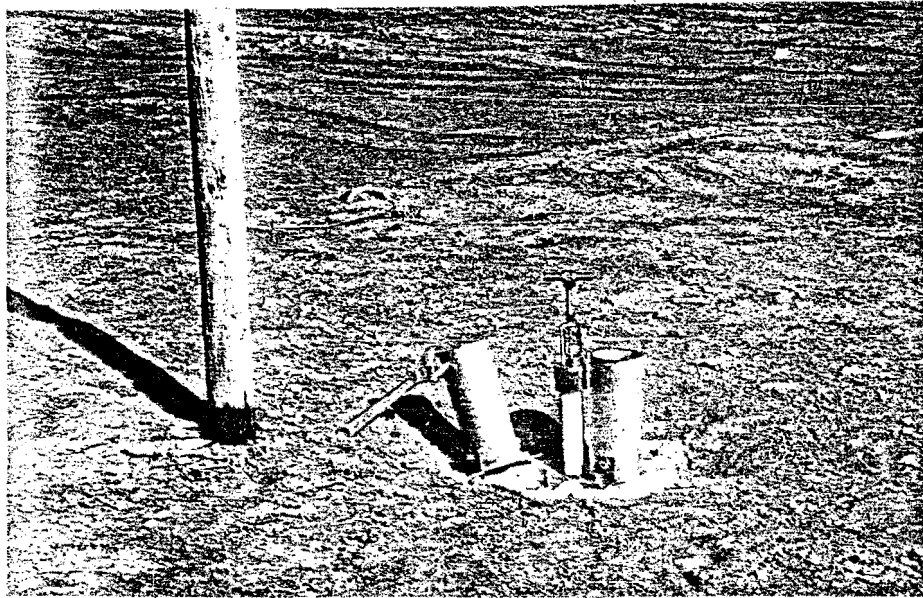


Fig. 12.—Photograph of a multiple piezometer installation.

temperature of groundwater, pH, and specific conductance. Water samples were collected for later analyses. The physical properties of groundwater samples such as color, odor, and turbidity were noted. Procedures used in this part of the study are described in Appendix A.

Laboratory Methods

Groundwater samples were collected monthly and stored for later analyses. The samples were analyzed for calcium, magnesium, total hardness, carbonate, bicarbonate, total alkalinity, sulfate, chloride, nitrate, total iron, sodium, and potassium. Analytical methods and results of chemical analyses are given in Appendix A and D, respectively.

Groundwater Flow

Three types of groundwater flow systems affect the landfill area: local, intermediate, and regional. A local flow system recharges in the upland area next to the landfill and discharges in the Heart River valley (Figure 11). The length of the flow path is about 100 m. The groundwater flow pattern for this system is shown in Figure 13.

An intermediate flow system recharges in the upland to the south and west of the study area and discharges, in part, in the Heart River valley. The length of the flow path is several thousand meters. The groundwater flow pattern for this system is shown in Figure 14.

A regional flow system recharges in the upland of the Missouri Slope and discharges in the Missouri River valley. A limited amount of available data suggests the flow path is several tens to several hundred kilometers in length. This flow system is assumed to have a somewhat impermeable base in the Pierre Formation. The regional

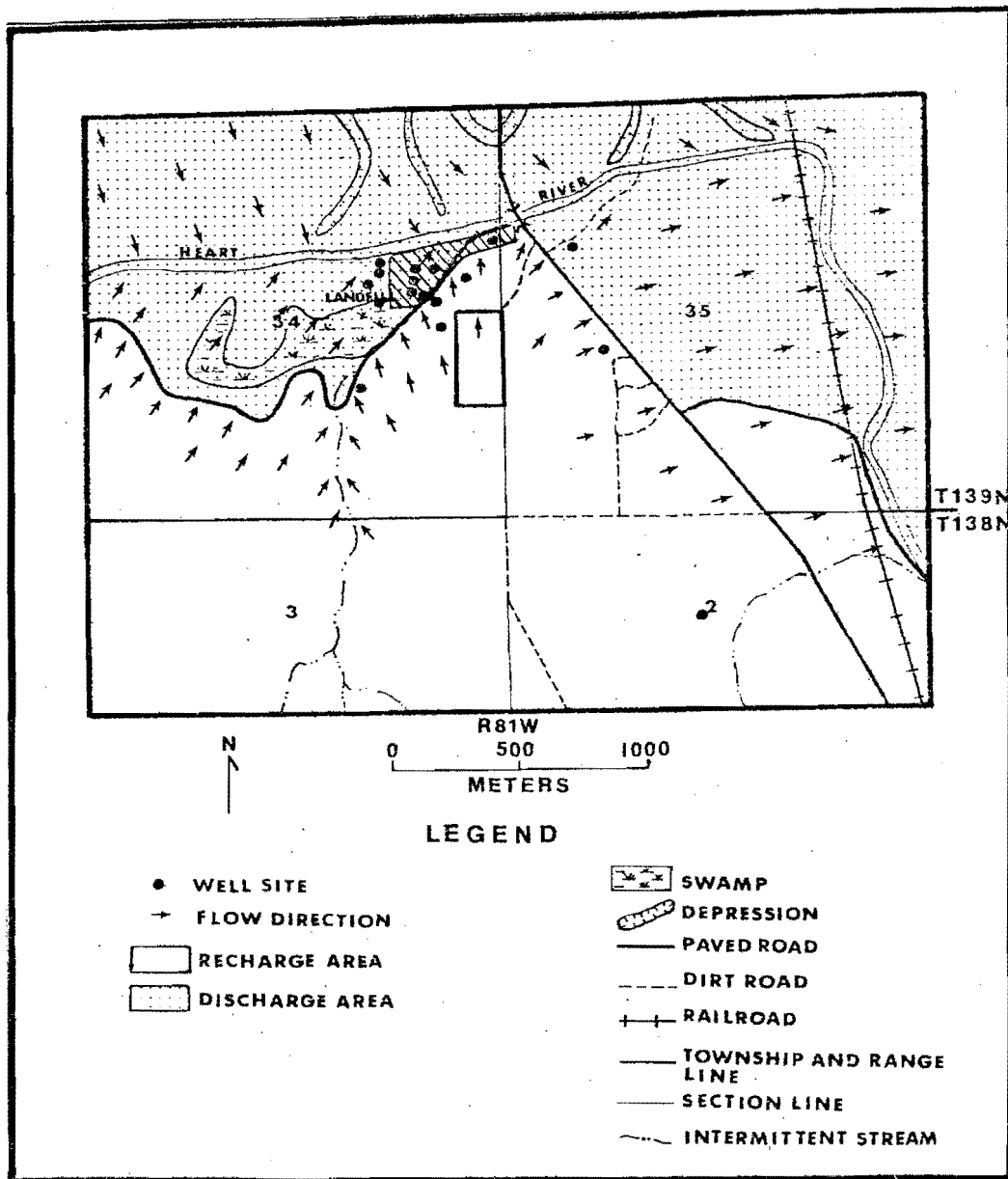


Fig. 13.—Map showing the pattern of local groundwater-flow systems in the Mandan landfill area. (General recharge and discharge areas for the study area are also given.)

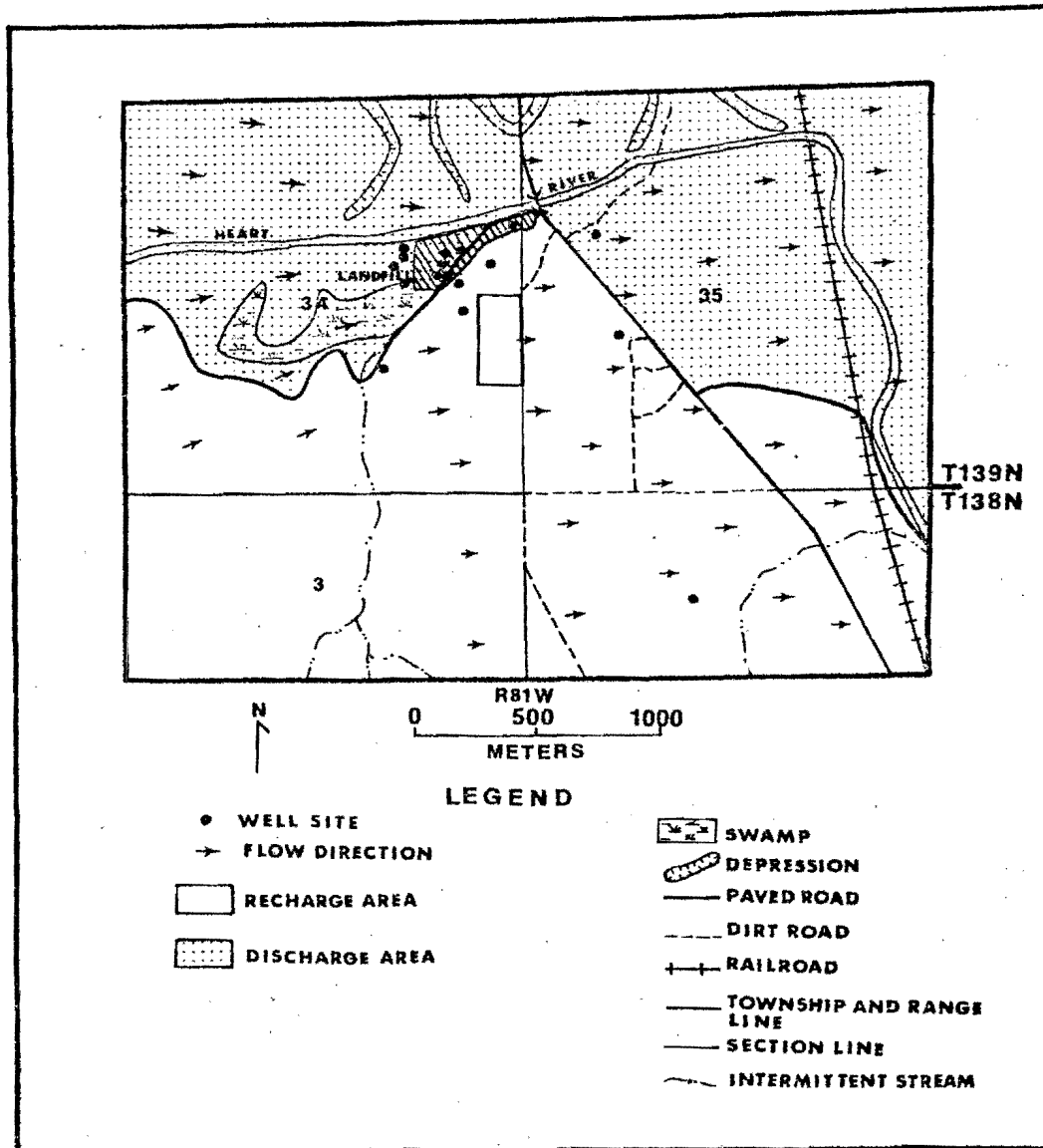


Fig. 14.—Map showing the pattern of intermediate groundwater-flow system in the Mandan landfill area. (General recharge and discharge areas in the study area are also given.)

flow system affects the potential distribution of the intermediate flow system in the area.

A deeper groundwater flow system occurs below the Pierre Formation at a depth of 670 m. The Dakota Group is a part of this flow system. Recharge occurs over a wide area in the northern Great Plains. Discharge occurs partly in eastern North Dakota. This flow system is believed to have little effect on the important flow systems in the study area.

Local and Intermediate Flow Systems

Recharge to the local flow system is greatest part way up the valley wall (Figure 15). Recharge is through a thick deposit of fluvial terrace sand and silt of the Four Bears Formation and through a silty, clayey sand of the Cannonball Formation.

Recharge to the intermediate flow system occurs in the upland south and west of the landfill area. The recharge is downward through loam soils on Quaternary deposits and on the Cannonball Formation. Low soil permeability and high rainfall intensity cause much overland flow. Runoff from chestnut soils found on the upland is high. Runoff from sandy soils is low. Only a small amount of precipitation infiltrates into the ground over most of the study area.

The hydraulic conductivity of the Cannonball Formation is calculated from the results of field slug tests (Appendix A). The vertical hydraulic conductivity ranges from 1.1×10^{-5} m/s to 1×10^{-7} m/s. The horizontal hydraulic conductivity is estimated to be one to two orders of magnitude greater than the vertical hydraulic conductivity. Randich (1965) reported a yield of generally less than

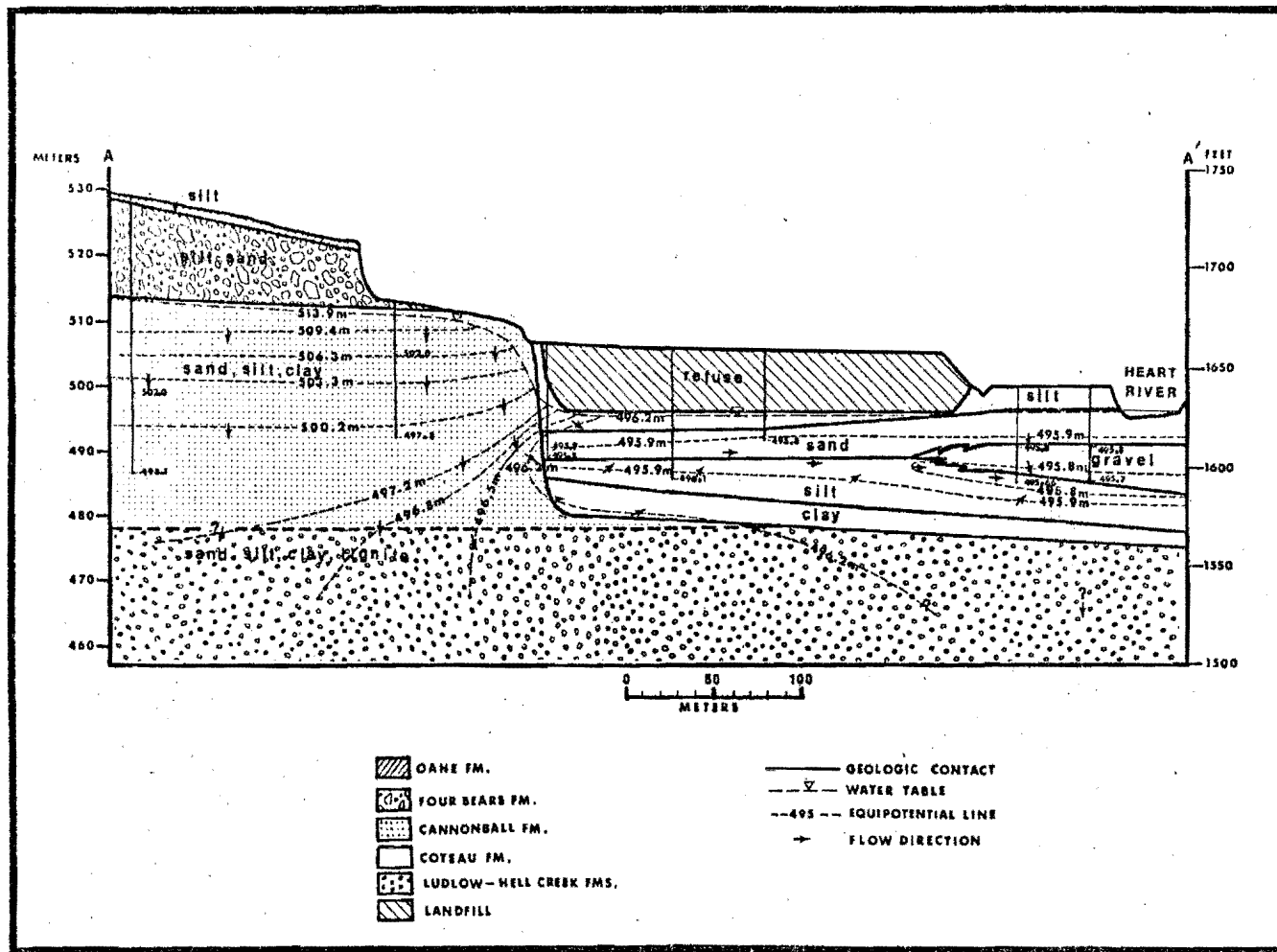


Fig. 15.—Geology and pattern of groundwater flow in the Mandan landfill area along cross-section A-A' (Fig. 11).

$3.1 \times 10^{-3} \text{ m}^3/\text{s}$ (50 gpm) from the Cannonball Formation in Burleigh County. Tyschen (1949) reported yields of $4.3 \times 10^{-4} \text{ m}^3/\text{s}$ (7 gpm) to $6.3 \times 10^{-4} \text{ m}^3/\text{s}$ (10 gpm) from sandier parts of the Cannonball.

The downward hydraulic gradient is greatest part way up the valley wall (Figure 15). It is calculated to be 0.02 m/m.

The hydraulic conductivity of the Coteau Formation is calculated from the results of field slug tests. It ranges from $3.2 \times 10^{-4} \text{ m/s}$ to $6.4 \times 10^{-7} \text{ m/s}$. The lower conductivity occurs in fine sand and silt layers. The higher conductivity occurs in gravel layers. Wells in the Coteau Formation can be pumped dry but quickly refill.

The upward hydraulic gradient at the base of the valley wall near the landfill is $1.2 \times 10^{-3} \text{ m/m}$. It decreases away from the valley wall and is $6 \times 10^{-4} \text{ m/m}$ near the river. The upward gradient is small because this reach of the Heart River is not the center of discharge. The lateral and longitudinal flow components are much greater than the vertical flow component.

Discharge of the local flow system is concentrated at the base of the valley wall and is commonly accompanied by a moderate to strong upward gradient. Often groundwater marshes form similar to the one located west of the landfill.

Discharge of the intermediate flow system occurs, in part, in the Heart River valley. Discharge occurs mainly from the Cannonball Formation to the Coteau Formation. Vertical hydraulic gradients are small. The lateral and longitudinal flow components are affected by the regional flow system.

The Hell Creek Formation may be a lateral drain for groundwater because parts of the formation are generally more permeable than parts of the Coteau or Cannonball Formations in the study area. (Randich, 1973). Limited piezometric data suggests that at a depth of about 30 m below the floodplain there may be seepage through the Hell Creek Formation (Figure 15).

The longitudinal flow component is calculated to be 3×10^{-4} m/m and the lateral flow component is 1×10^{-4} m/m. Longitudinal flow is greater than lateral flow for two reasons. First, a buried gravel layer about 3 m thick and 15 m below the floodplain, is highly permeable. This layer thickens to the north and east of the landfill (Figure 15). Seepage of groundwater to this layer increases the longitudinal flow. The second reason for large longitudinal flow is the presence of the north-south trending valley of the Missouri River. Lateral flow toward the Heart River decreases and longitudinal flow toward the Missouri River valley increases.

In the landfill area the horizontal flow resultant is calculated to be 4.3×10^{-4} m/m. It is at an angle of about 0.77 rad (45°) to the Heart River. The total flow vector nearly parallels the Heart River and is angled slightly downward.

The velocity of flow in the Coteau Formation is calculated to be 3×10^{-5} m/s in the highly permeable parts and 5×10^{-6} m/s in less permeable parts. (This is about 10 feet a year.)

In summary, groundwater movement beneath the landfill is angled toward the river. It is slightly upward over part of the area next to the valley wall and mostly lateral and longitudinal over the landfill area.

Infiltration through the layers of refuse is downward. Recharge rarely occurs because, even during a heavy thunderstorm, the wetting front seldom moves below 1 to 2 m. The greatest infiltration occurs at the start of rainfall and decreases with time.

Infiltration through the upper layers of refuse is reduced for several reasons. Compaction by landfill equipment and traffic reduces the permeability of the fill. Montmorillonite clays in the cover material tend to absorb moisture and swell, thus reducing the infiltration. Ponds of water may form on the upper surface of the landfill after a storm.

Infiltration may be increased in areas containing demolition rubble and large trees. Cavities within this refuse were detected by drilling. Other cavities exist where large objects such as large appliances and car bodies are buried.

In general, drilling indicates that most of the landfill is well compacted. Areas of garbage are generally more compacted than areas of rubbish.

To have recharge in the refuse layers, it is necessary for the field capacity of the material to be exceeded. Reduced infiltration through the surface, low water content of refuse before burial, and a generally shallow wetting front inhibit recharge. Local pockets of saturated refuse may occur where water is channeled from above, where the refuse has been exposed by erosion, or where the water table has risen and saturated part of the lower layer of refuse (the first refuse layer was placed near the water table). Drilling indicated the material at the bottom of the fill was partly wet and decomposed.

The shape of the water table in the study area roughly follows the topography. The water table is 10 to 20 m below the upland surface and 6 to 7 m below the floodplain. Tyschen (1949) reported 6.3 m (about 19 feet) as the average depth to the water table below the floodplain and 10 m (about 30 feet) as the average depth below the upland.

Landfill operations have intersected the water table on the slope near well 6 (T.139N., R.81W., sec. 34, SE $\frac{1}{4}$, NW $\frac{1}{4}$, SE $\frac{1}{4}$) and exposed a yellow-brown oxidized zone of the Cannonball Formation above a gray, reduced zone. The mottled contact of the two zones is above a carbonate-cemented sandstone layer at an elevation of 557 m. Where operations have removed parts of this layer, high water levels during the spring create quick conditions in sandy sediment. A perched water table occurs after summer thunderstorms.

The water table is near the surface in large gullies along the valley wall. Several of the gullies have small springs and seep areas at their heads which have accelerated erosion and created deep, narrow valleys.

Fluctuations of the water table follow periods of precipitation and evaporation. A large storm August 18, 1972, produced 20 mm of precipitation. An immediate rise in upland wells occurred. This was due to rapid infiltration through very permeable terrace sediment. Slight rises in water levels occurred 1 to 2 days later in wells on the floodplain. The water table beneath the floodplain is flat and shows very little change in response to storms.

Water levels in wells in the landfill area had a normal seasonal decline. During the monitored period, August to November, 1972, the decline was 0.3 m.

In general recharge areas showed the greatest changes in water levels. Discharge areas had only slight changes. The seasonal decline decreased after the third week in September when frost stopped most evapotranspiration.

Regional Flow System

The regional groundwater flow system recharges, on its western flank, on the upland of the Missouri Slope and discharges in the Missouri River valley. Lateral flow toward the Missouri River near Mandan is rapid. The Pierre Formation is assumed to form an impermeable base to this system.

The regional flow pattern has smaller flow systems superimposed on it. The small amount of data on hydraulic potential makes it difficult to define the groundwater flow system. Stratigraphy, groundwater chemistry, topography, and the location of recharge and discharge areas were used to define the regional groundwater flow system.

The effect of the regional flow system is to increase longitudinal flow in the intermediate flow system. It is believed that the Hell Creek Formation may be lowering the potential in the landfill area and increasing the underflow. Seepage from smaller flow systems may be considerable below a depth of 30 m in the study area.

Deeper Regional Flow System

A deeper flow system, of which the Dakota Group is a part, occurs below the Pierre Formation at a depth of about 670 m. Recharge to this flow system is believed to take place over the northern Great Plains. Seepage from superimposed flow systems may add considerable recharge. Discharge of the deep flow system occurs in the Red River valley of the eastern Dakotas.

This deep regional flow system has very little effect on the local and intermediate flow systems in the study area, but may receive recharge from the regional flow system of the Missouri River. It is not known how much recharge takes place.

Groundwater Chemistry

The purpose of this section is to describe the physical and chemical properties of groundwater in the landfill area, and to describe leachate generation in the Mandan landfill.

The quality of shallow groundwater upgradient from the landfill, groundwater beneath the landfill, and groundwater downgradient from the landfill is compared to determine the degree of contamination of groundwater by leachate. Changes in water quality over a period of time were determined by collecting samples at monthly intervals from August to October 1972.

Chemical analyses were made on fifty-four groundwater samples collected from shallow and deep wells ranging in depth from 10 m to 100 m. The major cations and anions determined were calcium, magnesium, sodium, potassium, iron, carbonate, bicarbonate, sulfate, nitrate, and chloride. Also determined were the pH, temperature, specific conductance, total alkalinity, total hardness, and total dissolved solids. Appendices C and D give the results of chemical analyses and summarize the important properties of groundwater samples.

Water Chemistry of Uncontaminated Groundwater

Groundwater chemistry of the Hell Creek, Cannonball, and Coteau Formations in the study area is discussed in detail. Chemical analyses were made on groundwater samples collected from a relatively small area and small number of wells in these formations. The results of these analyses are characteristic of groundwater in parts of the formations in the study area.

Water samples were collected from three wells in the Hell Creek Formation in the study area. The Hell Creek has predominately sodium bicarbonate-chloride to sodium-calcium bicarbonate-chloride type water. The water is generally soft and the total dissolved solid range from 1501 to 1935 ppm. The pH is about 8.0.

Water samples were collected from eight wells in the Cannonball Formation in the study area. The water type in the Cannonball ranges from predominately calcium-sodium sulfate-bicarbonate to sodium-calcium bicarbonate-sulfate and calcium bicarbonate-sulfate. The water is moderately soft and has a range of total dissolved solids from about 830 to 1180 ppm. The pH ranges from 7.25 to 8.15. Chloride is generally low and iron is absent. High amounts of calcium and magnesium reflect a short flow (local flow system). Deep wells in the Cannonball Formation contain sodium and sulfate.

Water samples were collected from nine uncontaminated wells in the Coteau Formation in the study area. The water type in the Coteau ranges from calcium-sodium sulfate-bicarbonate to calcium-sodium bicarbonate-sulfate and calcium-magnesium bicarbonate. The water is moderately hard and the total dissolved solids range from 669 to 1667 ppm. The pH ranges from 7.22 to 7.66. Water from the Coteau is free of iron and carbonate and low in nitrate and chloride. Generally shallow wells yield calcium, magnesium, and bicarbonate water. They reflect short flow paths. Deep wells yield water with sodium and sulfate, possibly from water of the Cannonball Formation discharging into the Coteau in the

Heart River valley. The chemical analyses for groundwater from the Coteau are given in Table 4.

Water Chemistry of Contaminated Groundwater

Water samples from wells in the Coteau Formation beneath the Mandan landfill showed varying amounts of contamination. In general, total hardness, total alkalinity, total dissolved solids, iron, and chloride have increased. Decreases occurred in sulfate and pH. The greatest changes in water chemistry occurred in wells near the center of the landfill. The groundwater is contaminated to a depth of about 2 m. The contaminated water follows the lateral flow direction for about 150 m toward the Heart River. Most contamination occurs near wells 2 and 3 (Figure 16). Table 4 gives the results of chemical analyses of shallow groundwater from wells beneath the landfill.

The total hardness ranges from 240 to 760 ppm and the total alkalinity from 250 to 600 ppm, which is as much as a 100 percent increase. The total dissolved solids range from 625 to 1774, which is as much as a 100 percent increase. Iron has increased from zero to about 0.39 ppm and chloride has increased from an average of 18 ppm to 333 ppm maximum. Sulfate has decreased to as little as zero ppm. The pH has decreased to a about 6.9 to 7.4.

In general the greatest changes in water chemistry of shallow wells in the landfill area were the increased hardness, total dissolved solids, total alkalinity, chloride, and decrease in sulfate and pH.

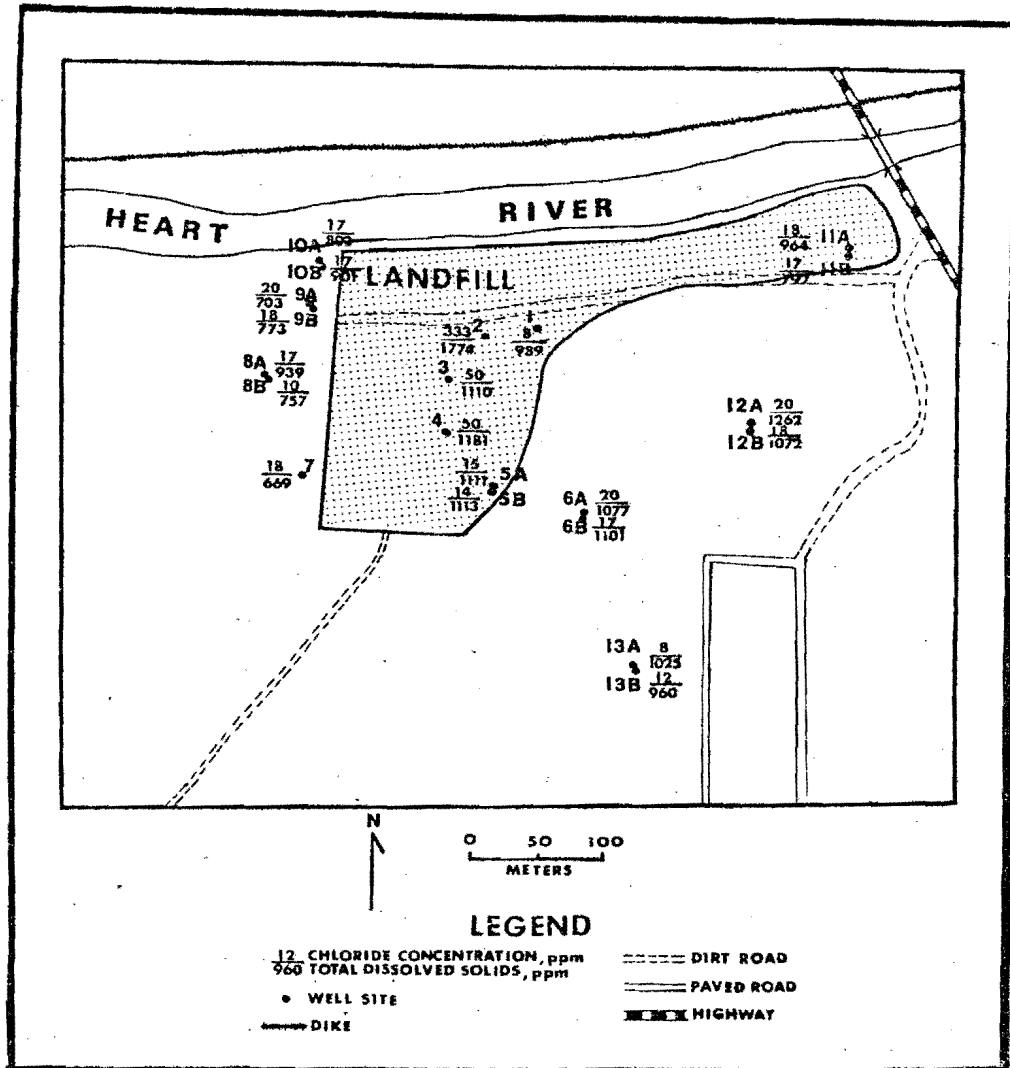


Fig. 16.—Map showing values of chloride and total dissolved solids for shallow wells in the Mandan landfill area.

TABLE 4

CHEMICAL ANALYSES OF SHALLOW GROUNDWATER FROM THE COTEAU FORMATION
IN THE MANDAN LANDFILL AREA (in ppm)

WELL NUMBER	SAMPLE NUMBER	SPECIFIC CONDUCTANCE	PH	HCO ₃	CO ₃	TOTAL ALKALINITY	CA	MG	TOTAL HARDNESS
1	1	1190.0	7.30	420.0	0.0	420.0	290.0	175.0	465.0
1	2	1000.0	7.09	430.0	0.0	430.0	255.0	205.0	460.0
1	3	1190.0	7.25	400.0	0.0	400.0	250.0	180.0	430.0
2	1	1950.0	7.20	325.0	0.0	325.0	260.0	240.0	500.0
2	2	1830.0	7.40	350.0	0.0	350.0	190.0	250.0	440.0
2	3	1920.0	6.94	600.0	0.0	600.0	395.0	365.0	760.0
3	1	1000.0	7.20	250.0	0.0	250.0	125.0	125.0	250.0
3	2	1020.0	7.08	280.0	0.0	280.0	140.0	140.0	280.0
3	3	960.0	7.50	480.0	0.0	480.0	345.0	135.0	480.0
4	1	1450.0	7.30	340.0	0.0	340.0	150.0	90.0	240.0
4	2	1470.0	7.70	400.0	0.0	400.0	145.0	105.0	250.0
4	3	1275.0	7.07	335.0	0.0	335.0	150.0	100.0	250.0
5A	3	990.0	7.48	410.0	0.0	410.0	300.0	230.0	530.0
5B	3	1000.0	7.43	380.0	0.0	380.0	275.0	235.0	510.0
7	2	710.0	7.66	280.0	0.0	280.0	190.0	130.0	320.0
8A	3	970.0	7.56	305.0	0.0	305.0	230.0	135.0	365.0
8B	3	705.0	7.48	305.0	0.0	305.0	200.0	115.0	315.0
9A	3	920.0	7.46	205.0	0.0	205.0	70.0	40.0	110.0
9B	3	1005.0	7.62	220.0	0.0	220.0	65.0	55.0	120.0
10A	3	880.0	7.41	210.0	0.0	210.0	150.0	100.0	250.0
10B	3	980.0	7.56	220.0	0.0	220.0	160.0	100.0	260.0

TABLE 4--Continued

WELL NUMBER	SAMPLE NUMBER	SO4	NO3	CL	FE	NA	K	TOTAL DISSOLVED SOLIDS
1	1	187.5	0.003	5.0	0.00	56.00	9.15	1143.0
1	2	75.0	0.120	14.0	0.00	58.00	9.18	1046.0
1	3	87.5	0.020	8.0	0.00	55.20	8.35	989.0
2	1	175.5	0.240	50.0	0.00	56.40	14.00	1118.0
2	2	50.0	0.030	67.0	0.00	70.00	10.00	987.0
2	3	0.0	0.020	333.0	0.15	69.00	12.00	1774.0
3	1	50.0	0.060	25.0	0.00	41.40	9.00	625.0
3	2	50.0	0.060	33.0	0.00	40.20	8.75	692.0
3	3	50.0	0.020	50.0	0.15	41.40	8.30	1110.0
4	1	435.0	0.060	40.0	0.00	193.00	31.00	1279.0
4	2	250.0	0.016	50.0	0.00	208.00	23.00	1181.0
4	3	300.0	0.020	40.0	0.39	170.00	21.00	1116.0
5A	3	100.0	0.020	15.0	0.00	46.40	9.10	1110.0
5B	3	150.0	0.032	17.0	0.00	41.80	14.00	1113.0
7	2	50.0	0.016	20.0	0.00	36.40	7.90	714.0
8A	3	150.0	0.032	17.0	0.00	92.00	7.20	936.0
8B	3	62.5	0.032	10.0	0.00	59.00	5.55	757.0
9A	3	225.0	0.032	20.0	0.00	134.00	9.20	703.0
9B	3	225.0	0.032	18.0	0.00	178.00	12.00	773.0
10A	3	200.0	0.032	17.0	0.00	109.00	16.00	802.0
10B	3	275.0	0.032	17.0	0.00	113.00	16.00	901.0

Among the inorganic materials leached from refuse are chloride, calcium, magnesium, and iron. Chloride is readily leached from refuse once the field capacity is reached (Apgar, 1971). Chloride is a good indicator of leachate generation because it is relatively inert to reactions with surrounding materials and it is easily traced. The pattern of chloride concentration in the Mandan landfill shows an increase with distance along the groundwater flow direction from well 4 to well 2 and a maximum concentration near well 2 (Figure 16). It is believed that chloride concentrations decrease downgradient from wells 1 and 2. There were no wells drilled downgradient from these wells because of drilling difficulties in that area. Dilution and dispersion of contaminated groundwater decreases the chloride concentration. In addition, little or no leachate is added beyond well 2 because the refuse is mostly demolition concrete, auto bodies, some trees, and large appliances (Figure 7).

The total dissolved solids roughly follow the same trend as the chloride concentration. Increases in calcium, magnesium, and bicarbonate add most to total dissolved solids. An example of the amounts of these ions leached from a landfill at Riverside, California is reported by Merz (1962), who states that

. . . it may be expected that continuous leaching of an acre-foot of a sanitary landfill will result in a minimum extraction of approximately 1.5 tons of sodium plus potassium, 1.0 tons of calcium plus magnesium, 0.91 tons of chloride, 0.23 tons of sulfate, and 3.9 tons of bicarbonate. Leaching of these quantities takes place in less than one year. Removals would continue with subsequent years, but at a very slow rate.

The Heart River near the Mandan landfill is contaminated very little by groundwater from beneath the landfill. The amount of contamination depends on the amount of contamination of groundwater beneath the landfill by leachate and on the amount of flow in the river. For river flows ranging from $0.3 \text{ m}^3/\text{s}$ (10 cfs) to $3 \text{ m}^3/\text{s}$ (100 cfs), the dilution of contaminated groundwater discharging into the river ranges from 1000 to 10,000 times, respectively. For example, if the chloride concentration is 100 ppm, the concentration would decrease to 0.001 ppm for a flow of $3 \text{ m}^3/\text{s}$ and 0.1 ppm for a flow of $0.3 \text{ m}^3/\text{s}$. These small values indicate almost undetectable changes, for a wide range of flows, in water quality of the Heart River due to contaminated groundwater discharging from the landfill area.

For the monitored period (August to October, 1972), groundwater quality beneath the landfill decreased with time. However, the monitored period was short and evidence for changes in water quality with time may be inconclusive.

Factors of Leachate Generation

The generation and movement of refuse leachate controls the amounts of contamination of shallow groundwater in the Mandan landfill area. Some of the factors controlling the generation and composition of leachate are (1) spatial and time distribution of moisture, (2) composition of refuse, (3) temperature of refuse cell, (4) available oxygen, (5) depth of burial and degree of compaction, and (6) length of time since burial. The effects of each generally overlap one another.

Effects of Moisture, Oxygen, Depth of Burial, and Compaction

Refuse may receive moisture from (1) storm infiltration, (2) channeled runoff, (3) bank storage of floodwater, (4) groundwater, (5) by-products of decomposition, and (6) water content of refuse before burial.

Topography, geology, and climate control the amount and rate of infiltration. The surface of the Mandan landfill slopes gently toward the Heart River. Rainfall ponds on this upper surface and at the base of ramping operations. When precipitation occurs infiltration is through the surface of the landfill. The soil is normally below field capacity causing the wetted front to move as deep as 1 to 2 m. Moisture is stored in the topcover until it either drains to underlying layers or evaporates. Evaporation usually removes this moisture. Therefore, recharge to groundwater does not occur often. Also, with each additional layer of refuse added, the distance moisture has to travel to recharge the groundwater increases.

The landfill is covered with a sandy loam. The field capacity for fine sandy loam is about 15.3 percent moisture (Grunes, 1963). This amounts to 430 mm (17 inches) of water stored in the upper 2 m of soil (Haas, 1962). Matthews (1960) reported 16 to 20 percent, or less than 80 mm (3 inches) of precipitation in the area is stored in the soil. This amount of moisture is far below the field capacity.

Remson (1968) calculated that in Pennsylvania about 80 mm (3 inches) of rain is needed to bring 0.3 (1 foot) of refuse to field capacity. This amount of moisture is usually not available

in the study area because the field capacity of refuse is rarely exceeded. The intensity of rainfall is normally greater than the rate of infiltration causing mostly runoff.

The moisture content of refuse ready for burial in 1952 in the Mandan landfill was about 23 percent (Weaver, 1964). A similar value of 18 percent was reported for landfills in northeastern Illinois (Fungaroli, 1971). Comparing these values to the amount of moisture at field capacity of soils in the area, it appears that as much moisture is needed to bring a layer of refuse to field capacity as is needed for a layer of soil. After the upper meter of topcover of the landfill reaches field capacity, excess moisture generally saturates only a thin layer of underlying refuse. Evaporation removes much of the stored moisture in the soil within a few days.

The amount of water available from decomposing refuse is generally too small to aid in further decomposition. Decomposition in the Mandan landfill is very slow and aerobic decomposition produces very little water.

Several gullies occur on the flanks of the landfill. The gullies cut into bulky wastes such as trees, tires, large metal objects, and demolition waste. Runoff from the gullies to the refuse is generally insignificant.

Some water from Heart River flooding may seep into the flanks of the landfill. This water generally seeps into refuse composed of trees, auto bodies, large appliances, and demolition waste. It is believed that the addition of water from seepage has little effect on promoting decomposition in this part of the landfill.

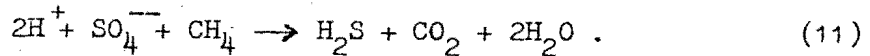
Much of the moisture available for leachate generation in the landfill comes from groundwater. During the spring a high water table intersects the lower meter or two of refuse and saturates the material. This is a seasonal event at best, but enough water may recharge the refuse to accelerate decomposition and produce leachate. Contaminants that have migrated to the lower layer of refuse, or contaminants generated in this layer, enter the groundwater by direct contact in the layer or by downward movement to the water table at some later time.

Data obtained by drilling indicated a low moisture content of refuse and soil to a depth of 11 to 12 m. Below this the material was partly saturated or saturated by moisture from groundwater.

In general the upper 10 m of refuse is an aerobic environment. With depth, particularly near the lower few meters of refuse, oxygen decreases and moisture increases. Water chemistry of wells in the landfill area reflect these conditions. Anaerobic decomposition is greater than aerobic decomposition. Localized pockets of aerobic or anaerobic environments may exist but were not investigated.

Anaerobic conditions beneath the landfill are indicated by a decrease in sulfate in shallow groundwater. Drilling indicated blue-gray (reduced) sediment near the lower layer of refuse and below the water table. An odor of hydrogen sulfide was detected in the piezometers and in water samples collected over a period of several months.

The decrease in sulfate is because it is reduced by bacteria. Krauskopf (1967, p. 276) gives a symbolic reaction for sulfate reduction using the simplest organic compound, methane (CH_4)



The reduction is slow when only organic matter is present. Anaerobic bacteria may act as a catalyst and accelerate the reaction. Anaerobic bacteria are generally present in landfills in semiarid areas (Stone, 1970).

The products of sulfate reduction are hydrogen sulfide, carbon dioxide, and water. These products are present in the Mandan landfill. Dissolved hydrogen sulfide gas, (H_2S), was detected by its odor in wells 2, 3, and 4. The pH of the water is decreased according to the reaction

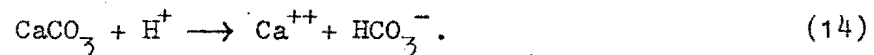


Carbon dioxide (equation 11) combines with water to form carbonic acid (H_2CO_3). Carbonic acid may dissociate to form hydrogen ions (H^+) and bicarbonate



Bicarbonate has increased two to three times in wells beneath the landfill. From a normal range of pH of 7.3 to 7.8 in uncontaminated groundwater, the pH of contaminated groundwater decreased to about 6.9 to 7.4.

The increase in hydrogen ions (H^+) may cause calcium carbonate (CaCO_3) to go into solution and release calcium or magnesium ions (Ca^{++} , Mg^{++})



The calcium and magnesium in contaminated groundwater has increased as much as two times.

Carbon dioxide is an important product of aerobic and anaerobic

decomposition. Its density is greater than air, causing it to diffuse downward. The total alkalinity and total hardness are increased.

Total iron increases slightly in contaminated groundwater. Anaerobically-produced iron is mostly ferrous iron, Fe^{++} (Langmuir, 1969). It combines with water to form ferric hydroxides such as $Fe(OH)_3$. Ferric iron, Fe^{+++} , is stable under low Eh and low pH conditions. It may oxidize to ferrous iron. In this report iron is reported as total iron and the relative proportions of each are not known.

Ammonia (NH_3) may be produced by anaerobic decomposition of refuse. Ammonia is stable under low Eh and low pH conditions. Nitrate (NO_2-NO_3) is an oxidized form of nitrogen and exists in high Eh-pH environments. Nitrogen compounds have not contaminated the groundwater in the Mandan landfill area. Nitrogen compounds are not produced in sufficient amounts to contaminate the groundwater (Table 4).

Effects of Composition

Refuse in the Mandan landfill contains a large amount of paper and paper products (cellulose base). Typically, the refuse consists of 65 percent paper (by volume), 25 percent grass and garden trimmings, 5 percent organic garbage, and 5 percent inorganic matter (North Dakota Health Service, 1970). At Mandan the refuse is about half from homes and half from business (van Derwerker, 1952).

Cellulose compounds are biochemically oxidized by bacteria in aerobic or anaerobic environments. Water-soluble compounds such as carbon dioxide are produced. Stone (1970) reported that aerobic

thermophilic organisms biochemically oxidize carbonaceous compounds and slowly consume more complex nutrients like cellulose. This is assumed to be a slow process in the Mandan landfill.

Bacteria consume oxygen in respiration. The biological oxygen demand is a measure of the amount of oxygen bacteria need and, therefore, a measure of the rate of decomposition. Consumption of the readily decomposed organic matter produces a high biological oxygen demand and a high oxygen (O_2) demand. After about 6 weeks of burial in the Mandan landfill, a maximum O_2 has been used and decomposition slows (van Derwerker, 1952). Weaver (1964) reported a 5-day biological demand of 77,050 ppm for refuse ready for burial in Mandan landfills. After 1 year of burial the biological oxygen demand was reduced by over 50 percent to 30,000 ppm, and after two years it was reduced to 23,500 ppm. For the same periods, the oxygen consumed was 271,000, 208,000, and 230,000 ppm, respectively. These figures indicate maximum decomposition within 1 year of burial in the Mandan landfill.

Effects of Temperature

Temperature is an important factor affecting decomposition of refuse in the Mandan landfill. Almost no decomposition occurs in Mandan landfills until the summer months (van Derwerker, 1952). Temperatures in three refuse cells were recorded during 1950 to 1951. Figure 17 shows the temperature profiles for air and refuse cells for a Mandan landfill. Cell 1 was completed in November, cell 2 in November, and cell 3 in the summer. Cell temperatures are stable for cells 1 and 2, indicating very little biological activity. Cell 3 had a

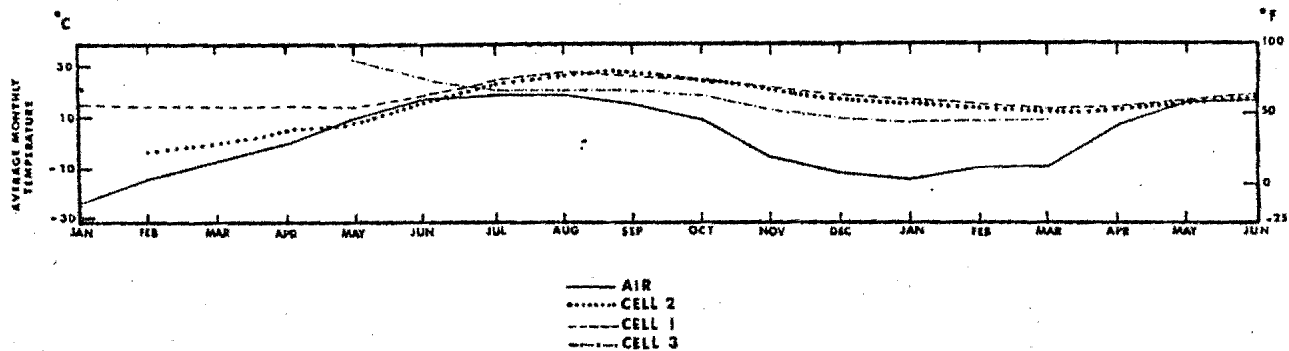


Fig. 17.—Temperature profiles for air and refuse cells in the Mandan landfill (modified from van Derwerker, 1952).

maximum temperature of 34°C (93°F) which declined to 28°C (83°F) within 2 weeks, indicating maximum bacterial action and digestion of organic material soon after burial. In general the highest number of microorganisms occur at 15°C to 20°C (Camp, 1963). With a 5°C drop the microorganisms decrease 10 to 20 percent. The temperature of the cells in the Mandan landfills are low compared to temperatures of 60°C (140°F) to 80°C (180°F) reported in other landfills (van Derwerker, 1952). Decomposition of refuse in the Mandan landfill is slowed considerably by the low mean annual air temperature of 5°C (41°F).

Effects of Time

Stabilization of the Mandan landfill is proceeding slowly. Drilling indicates fresh refuse to about 5 m (upper layer), fairly fresh refuse from 5 m to 7 m, partly decomposed refuse from 7 m to 10 m, and badly decomposed refuse and crude fiber from 10 m to 12 or 13 m below the upper surface. For example, newspaper print buried for about 8 years was readable. Rags, paper products, and paper buried for 8 years or less were decomposed very little or not at all.

CHAPTER VI

CONCLUSIONS

The following is a summary of conclusions reached in this study.

- (1) The Heart River valley near the Mandan landfill is the discharge area for a local flow system and part of an intermediate flow system.
- (2) The potential distribution is affected to a depth of 30 m by the valley.
- (3) Recharge to the local flow system is concentrated in an area along the valley wall. Discharge of the local flow system is greatest at the base of the valley wall.
- (4) The recharge area of the intermediate flow system occurs in the upland area to the south and west of the landfill. The discharge area occurs mostly in the Missouri River valley. There is some seepage of the intermediate flow system to the Heart River valley.
- (5) Groundwater flow near the landfill is mostly lateral and longitudinal. Beneath the landfill, flow is about at an angle of 0.7 rad to the Heart River.
- (6) Much of the groundwater leaves this part of the valley as underflow.
- (7) The velocity of groundwater flow near the landfill is about 3 m a year.

(8) Shallow groundwater of the Heart River valley near the landfill is generally a calcium-magnesium bicarbonate or calcium-sodium bicarbonate-sulfate type. The groundwater chemistry reflects the short flow path of a local flow system.

(9) Deep groundwater of the study area is a sodium-calcium sulfate-bicarbonate to a calcium-sodium bicarbonate-sulfate type. This reflects the long flow path of an intermediate flow system.

(10) Very deep groundwater in this study is a sodium-calcium bicarbonate-chloride to sodium bicarbonate-chloride type. This reflects a long flow path of a regional flow system.

(11) Shallow groundwater beneath the landfill has been contaminated by refuse leachate. Total hardness, total dissolved solids, alkalinity, and chloride have increased as much as several times. Sulfate and pH have decreased.

(12) Beneath the landfill the groundwater shows an increase of contamination along the direction of groundwater flow. The amount of contamination is greatest near the center of the landfill and is believed to decrease toward the north and east.

(13) The Heart River near the Mandan landfill is contaminated very little by groundwater from beneath the landfill. The amount of dilution of contaminated groundwater by the Heart River ranges from 1000 to 10,000 times, depending on the amount of flow in the river and the amount of contamination of groundwater by leachate.

(14) Refuse contaminants have entered the flow system by contact with a high water table, by infiltration through a relatively thin layer of refuse (during the early years of the landfill), and

possibly by infrequent recharge through parts of the landfill. Recharge rarely occurs because small amounts of precipitation and high evaporation leave the material below field capacity much of the time.

(15) The low temperatures occurring much of the year slow bacterial action and cause a very slow rate of decomposition of refuse.

(16) The large amount of cellulose-based refuse takes much time to decompose.

(17) The main processes operating in the Mandan landfill are reduction of sulfate, production of carbon dioxide (and related reactions), and leaching of chloride, calcium, magnesium, and possibly other minor metals.

(18) The data on leachate generation and movement in the Mandan landfill can be used to evaluate potential contamination of groundwater by leachate from landfills in much of southwestern North Dakota.

APPENDIX A

METHODS OF DATA COLLECTION AND WATER ANALYSIS

METHODS OF DATA COLLECTION AND WATER ANALYSIS

Location Format

The location format used in this study for the location of test wells follows the scheme shown in Figure 18. The first numeral of this system is the township north of its base, the second is the range west of the principal meridian, and the third is the section in which the well is located. The lower case letters following the section number are the position of the well within the section. The first letter is the quarter section (160 acre tract), the second letter is the quarter-quarter section (40 acre tract), and the third letter is the 10 acre subdivision within the quarter-quarter section. The subdivisions of the sections, quarter sections, and quarter-quarter sections are lettered a, b, c, and d in a counterclockwise direction beginning in the northeast quarter. A well located in NE $\frac{1}{4}$ of the SW $\frac{1}{4}$ of the NE $\frac{1}{4}$ of sec. 35, T.139N., R.81W. is designated 139-81-35aca.

Drilling and Piezometer Installation

The purpose of the test-drilling was to collect stratigraphic information and to install piezometers. The piezometers were used to determine the groundwater flow pattern and to collect water samples.

The test wells in the Mandan landfill area were made with two different drilling rigs. A truck-mounted hydraulic rotary rig was contracted from a private well driller who drilled about 75 percent of the test holes for the study. Several shallow holes in the landfill were made with the North Dakota Geological Survey truck-mounted auger (0.15 m diameter).

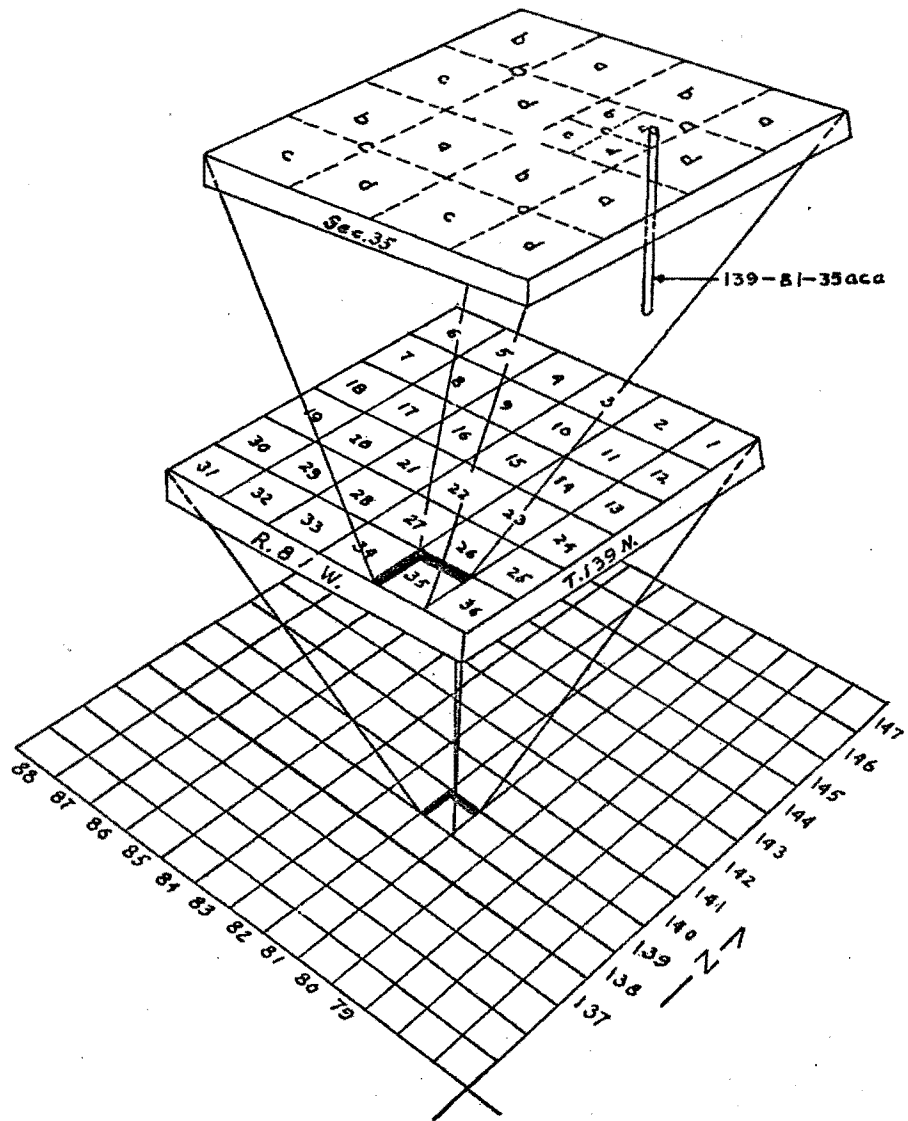


Fig. 18.—Diagram showing the location format.

The sediment was inspected at about 0.3 m intervals and lithologic logs of the stratigraphic units were compiled. The field descriptions of the stratigraphic units are given in Appendix B.

The advantages and disadvantages of drilling with the truck-mounted auger and truck-mounted hydraulic rotary rig in most types of sediment are discussed by Schulte (1972) in a study of the ground-water geology of the Spiritwood Lake area in central North Dakota. Drilling in refuse with each of the two types of drilling rigs caused advantages and disadvantages for each.

The truck-mounted auger is less expensive than the hydraulic rotary rig. Good stratigraphic samples with original moisture content are obtained. The auger cannot be used to drill in refuse that offers resistance to drilling (concrete, metal, trees, and rags), or in unconsolidated sediment such as that found below the water table. Test holes cannot be flushed prior to installing piezometers.

The hydraulic rotary rig is about five times as expensive as the auger (Schulte, 1972). However, the hydraulic rotary rig can be used to drill through most types of refuse in landfills (rocks, light metal, small trees, rags, and some demolition concrete). The stratigraphic samples are often very disturbed and are lacking original moisture contents. Loss of circulation water to large cavities in the refuse and clogging of the circulation system with refuse also occurs. The resulting odor of refuse and its unsanitary nature make drilling very unpleasant. An advantage is that test holes can be flushed before piezometers are installed.

Open standpipe piezometers were installed in the Mandan landfill area (Casagrande, 1949). The piezometers were installed in 0.1 m (4 inch) diameter holes and 0.15 m (6 inch) diameter holes. All standpipes were 0.025 m (1 inch) diameter. Single and multiple piezometers (two in a borehole) were installed.

The procedures followed for installing the piezometers were generally the same. A length of plastic pipe about 0.6 m to 1 m longer than the test hole was prepared. The lower end of the pipe was plugged with a 0.025 m (1 inch) plastic cap. The lower 0.75 m of pipe was slotted with a hacksaw. The slots were about 0.025 m apart and cut a third of the way into the pipe in a spiralling-up manner.

The plastic pipe was then inserted into the test hole. Fine to medium gravel (buckshot) was packed around the screened interval and packed for a short distance above that. A 1 m thickness of neat cement was used to seal the screened interval from the open hole. A single installation was completed by backfilling the hole to the top with silty, clayey material. After the backfill settled, cement was used to seal the open hole at ground level. The plastic pipe was cut about 0.18 m (7 inches) above ground level. Protective pipe of galvanized 0.08 m (3 inches) diameter steel was installed around the plastic pipe and cemented in the ground. The standpipe was closed with a vented 0.025 m plastic cap. Wood fence posts were installed to mark locations of the wells.

Multiple piezometer installations were made in a similar manner. Two sections of pipe, complete with screens and end caps, were

installed in the borehole. One pipe was staggered 3 to 5 m above the lower end of the other pipe. The lower pipe was gravel packed, cemented, and backfilled to the lower end of the upper pipe. The upper pipe was then completed in a similar manner. The two pipes were cut 0.18 m above ground, cemented, enclosed with steel pipe, and capped.

Boreholes made with hydraulic rotary equipment were flushed before piezometers were installed. Once installed, the piezometers were cleaned by adding water (from the Heart River) and then bailing water out of the pipe. Auger holes were not cleaned before piezometers were installed. Water was later poured into the standpipe and bailed out. Much of the sediment was removed in this manner because samples collected later from the bottom of the piezometer were free of sediment.

The piezometers were not used for 1 to 2 weeks after installation. Water levels were allowed to come to equilibrium and groundwater was allowed to clear.

Methods used for piezometer installation follow general techniques used by Schulte (1972). Slotted pipes were very efficient in the sediment found in the study area. Sediment permeabilities were great enough to allow water to enter the standpipe faster than it could be removed. The piezometers responded to changes in water levels with very little lag time (as much as 2 days).

The method of sealing the bottom of the piezometers from the open borehole was effective. With the exception of possibly two installations, most piezometers were properly sealed with cement above the screened interval. Some difficulty occurs in sealing each piezometer properly

in a multiple installation. Care must be taken to pack a sealing material, such as clay, in the part of the borehole between the cemented section of the lower piezometer and the bottom of the upper piezometer. If this is done correctly, a good seal should result for both piezometers.

Collection of Water Samples

Water samples that are representative of the source at the time of sampling were collected. Procedures used by the United States Geological Survey (Rainwater and Thatcher, 1960) were generally followed in this study. Alternate procedures are also described.

Water samples were obtained from standpipe piezometers and from pumped wells in the study area. The water samples were collected in high-density polyethylene bottles with polyethylene-lined bakelite screw caps. The sample bottles were rinsed with distilled water and labeled with masking tape and permanent ink before collection. After the samples were collected, the caps were tightly screwed down and sealed with tape to create a seal for transportation and storage.

Groundwater samples were collected from two kinds of wells, standpipe piezometers and pumped domestic and stock wells. The pumped wells ranged in depth from 30 m to 100 m and were operated by either surface pumps (electric) or submersible pumps. Stagnant water was cleared from the casing of the pumped wells by pumping for several minutes. The standpipe piezometers were flushed at the time of installation and were bailed periodically during the field season. Most of the water samples are representative of the water at the point of collection because (1) the piezometer standpipes are plastic and

do not react with water or ions in the water, and (2) most of the samples were collected near the slots at the bottom of the standpipe.

Water samples from standpipe piezometers were collected using a sampler consisting of a 0.45 m (18-inch) piece of 0.018 m (3/4-inch) diameter plastic pipe. One end of the pipe is open and has a nylon line attached through two holes drilled below the upper rim. The nylon line is used to raise or lower the sampler through the standpipe. The lower end of the sampler is closed with a plastic-coated metal cap. Plastic-coated lead weights are used to increase the weight of the sampler. The sampler is lowered to the water level in the standpipe and then allowed to free fall to the bottom. Water will begin to fill the sampler once it stops free falling. The water sampler is retrieved using the attached nylon line.

Water Level Measurements

The elevation of the static water level in a piezometer is considered to be hydraulic potential at the bottom of the well. It is assumed that the piezometer standpipe does not leak and that the water in the standpipe is sealed off from all pressure except the pore pressure at the bottom of the well. The static water level is assumed to have recovered from any addition or subtraction of water.

The first two assumptions are valid for most of the piezometers in the study area because care was taken to properly complete and seal the piezometers. The piezometers stabilized within a few days after adding or subtracting water. The piezometers were monitored almost daily for a month after installation and at longer periods thereafter.

The water level in standpipe piezometers was measured with a battery operated electric water-level indicator (Soiltest, model DR-760A). The total head at the bottom of the piezometer was determined by subtracting the measured depth to water from the elevation of ground level.

Elevation Determinations

The study area is covered in the Mandan Quadrangle and Bismarck Quadrangle of the United States Geological Survey 7.5 minute (scale 1:24,000) series of topographic maps. The topographic coverage was considered inadequate for determining well elevations. A base station was set up on the floodplain west of the landfill. The elevation of this station (496.9 m or 1640 feet) was determined with an American Paulin Altimeter (Model M-1) using a nearby benchmark for vertical control. Elevations of all the piezometers (at ground level) and selected points in the study area were then determined to hundredths of a meter by the transit-stadia method. Several traverses were established to provide topographic coverage of most of the study area. Topographic maps were used to determine elevations of selected points in the southern part of the study area.

Analysis of Water Samples

The temperature, specific conductance, pH, and concentration of major cations and anions were determined for 54 groundwater samples collected in the study area. Other chemical analyses published by the United States Geological Survey and Tyschen (1949) were used in

evaluating the water chemistry of the area but are not included in the discussion of analytical methods.

The temperature, specific conductance, and pH of water samples were determined in the field. The water samples were refrigerated after collection until they were transported to the laboratory. The changes in water chemistry occurring during transport are assumed to be insignificant. Before analysis in the laboratory, the samples were prepared for storage following procedures of Rainwater and Thatcher (1960).

Three sets of groundwater samples were collected over a period of several months. All the samples of a particular set were collected within a few hours on the same day and physical measurements were made at that time.

The following procedures are described in the order in which the samples were analyzed. The reproducibility of some of the methods (temperature, specific conductance, and pH) was determined by repeating the sample analysis. Accuracy of methods used is based on manual specifications of the instrument.

Water Temperature

Groundwater temperatures were determined in the field at the bottom of standpipe piezometers. Measurements were made with a Whitney portable thermister (Model TC-5A) equipped with about 61 m (200 feet) of insulated cable and 0.019 m (3/4-inch) diameter temperature probe. For each reading, the probe was lowered to the bottom of the standpipe and allowed to come to an equilibrium temperature. The temperature was recorded when it remained constant for a few minutes.

The accuracy of the thermister is about 0.1°C for the range 0°C to 40°C . Temperatures measured in the field were reproducible to 0.02°C .

pH

The pH of water samples was measured in the field and later in the laboratory. The Coleman Precision Portable pH Meter (Model 37A) was used with a Coleman 3-472 Tri-Purpose Shielded Glass Electrode and a 3-711 reference electrode. A 7.0 pH buffered solution was used to standarize the instrument before each use. The instrument was checked against buffered solutions of pH 6.0 to pH 8.0. All solutions were temperature corrected with the manual temperature compensator. The Precision Portable pH Meter is accurate to ± 0.005 pH units and, ideally, readings are reproducible to ± 0.001 pH units.

The pH values were remeasured in the laboratory with the same instrument. The pH of samples with an original pH of 6.9 to 7.2 showed the most change. The changes were as large as ± 0.6 pH units, but more commonly were about ± 0.3 units. The pH values measured in the field are used in this report.

Specific Conductance

The specific conductance was measured in the field with a Solu Bridge Conductivity Meter (Soiltest Model A-105). The meter measures conductance in the range of 50 to 8000 micromhos and has a manual temperature compensator. Measurements are made by immersing the electrode in the groundwater sample. The results are generally reproducible to within ± 10 percent.

Alkalinity ($\text{HCO}_3^- + \text{CO}_3^{--}$)

In groundwater chemistry, alkalinity is the capacity of a water to neutralize a strong acid and mostly depends on the carbonate and bicarbonate in solution (Rainwater and Thatcher, 1960, p.93).

Alkalinity of water samples in this study was determined by the potentiometric method. This method consists of titrating a 50 ml sample of water with a 0.02 normal solution of sulfuric acid against a pH meter to the end points of pH 8.0 for carbonate and pH 4.0 for bicarbonate. The total alkalinity, carbonate, and bicarbonate were calculated following the procedures given by APHA (1965, p.52).

The normality of the sulfuric acid was checked periodically against a sodium carbonate standard to check its stability. The values determined for alkalinity were reproducible to within ± 2 percent.

Calcium and Magnesium (Hardness)

Hardness in natural water is caused by calcium and magnesium ions. The concentrations of calcium and magnesium were determined by titration with a 0.01 normal solution of CDTA (disodium dihydrogen 1, 2-cyclhexanediaminetetraacetate). Calcium was determined by adding 1 ml of 9 normal sodium hydroxide to a 10 ml sample diluted to 100 ml and titrating with CDTA in the presence of Cal-red indicator to an end point (color change from red to pure blue). The total hardness was determined by diluting a 10 ml sample to 100 ml, adding 1 ml non-ammonia buffer, and titrating with CDTA in the presence EBT indicator to an end point (color change red to pure blue). The concentration of magnesium was calculated as the difference between total hardness and

calcium concentration. The reagent was checked for stability by titrating a standard solution of calcium chloride.

Calcium determinations were reproducible to within ± 1 ppm and magnesium to within ± 2 ppm.

Sulfate

The turbidimetric method was used to determine the sulfate concentration (APHA, 1965). The value of light absorbance through a suspension of barium sulfate in the water sample was determined using a Hellige Turbidimeter. The absorbance values were determined by passing light through a blue filter. A 10 ml water sample was diluted to 50 ml, 10 ml of Sulfaver salt-acid solution added, and barium chloride crystals added to form a suspension of barium sulfate. Absorbance values were compared with a calibration curve that was constructed using absorbance values from several standard solutions. The concentration of sulfate in the water sample was read directly from the curve.

There is about ± 5 percent error in the determination. The accuracy of the instrument was about ± 0.5 percent.

Chloride

The chloride concentration was determined with a Coleman Chloride Ion-Selective Electrode (3-802). The selective-ion electrodes are similar to glass electrodes used to measure pH. The selective-ion electrode, the Calomel reference-electrode, and Coleman Precision Portable pH Meter (Model 37A) were used in combination to measure the activity of the chloride ion.

The procedure was to prepare a standard 1 molar solution of

of chloride and make several solutions ranging in concentration from 1 molar to 1×10^{-6} molar by dilution of the 1 molar solution with distilled water. The solutions are maintained at 25°C and each is measured with the chloride probe to obtain a reading in millivolts on the pH meter. A calibration curve of chloride concentration and millivolts is constructed and used as a reference for determining the chloride concentration in a water sample.

Ideally, the reproducibility of chloride concentration was within ± 1 ppm of the initial value.

Nitrate

Nitrate concentration was determined by the cadmium-reduction wet chemical method (Hach Chemical Company Catalog number 10, 1968, p.42). An 80 ml water sample is treated with 2 ml concentrated ammonium chloride. The sample is passed through the cadmium-reduction column. Then a 25 ml aliquot is treated with 1/2 ml sulfanilic acid and 1/2 ml alpha-naphthylamine and allowed to stand 20 minutes. A Hellige Colorimeter was used to read the nitrate concentration.

The reproducibility of nitrate determinations is about ± 10 percent.

Iron, Potassium, Sodium

The concentrations of iron, sodium, and potassium in water samples were determined with a Perkin-Elmer model 403 Atomic Absorption/Flame Emission Spectro-Photometer using an air-acetylene mixture. Specified currents and flow rates for each element were used. Wave lengths were set using the rating specifications. The instrument

was calibrated for each use with prepared standards whose concentrations were in the optimum operating range for the particular element being determined. The instrument has single readouts, averages of ten readouts, and averages of one hundred readouts. The averages of one hundred readouts were used in most cases. The instrument was recalibrated periodically or when readouts were unstable. Samples having concentrations greater than the optimum operating range were diluted 100 to 400 times with double-distilled water (1 part sample, 99 parts distilled water for dilution of 100 times).

The concentrations of the elements determined with the atomic absorption unit were reproducible to within ± 1 percent under ideal conditions.

Total Dissolved Solids

The total dissolved solids were determined by calculation following Rainwater and Thatcher (1960, p.271). The constituents were converted to forms in the anhydrous state and summed. The method assumes that all constituents were analyzed. In this study manganese, silica, and trace elements were not determined. Several samples were analyzed for manganese but the amount present was generally much less than 1 ppm. It is assumed no large error was made by ignoring minor constituents.

Hydraulic Conductivity and Rate of Flow Determinations

Slug tests (falling-head) were used to determine in situ permeabilities of sediment in the Cannonball and Coteau Formations in the Mandan landfill area. The sediment surrounding the screened interval of several piezometers was slug-tested. The sediment ranged from silty, sandy clay to medium gravel.

In the slug test, water is added to a stabilized piezometer and the hydraulic head is measured at different times. From the equation for the basic time lag ratio (Hvorslev, 1951)

$$\frac{t}{T} = \ln \frac{H_0}{H_0 - y} = \ln \frac{H_0}{H} \quad (15)$$

the equation

$$t_2 - t_1 = T \left(\ln \frac{H_0}{H_2} - \ln \frac{H_0}{H_1} \right) = \frac{A}{FK} \ln \frac{H_1}{H_2} \quad (16)$$

can be derived. Equation 16 relates time (t_1, t_2, \dots) to head measurements (H_0, H_1, H_2, \dots), cross-sectional area of piezometer (A), shape factor of piezometer (F), and hydraulic conductivity (K).

Rearranging equation 16 for the hydraulic conductivity, K (in cm/s),

$$K = \frac{A}{F(t_2 - t_1)} \ln \frac{H_1}{H_2} \quad (17)$$

gives the equation used to calculate the hydraulic conductivity based

on field data where t_1, t_2, \dots = measured time, s,

H_1, H_2, \dots = measured head, m,

A = cross-sectional area of piezometer, cm^2 , and

F = shape factor of piezometer, cm,
(about 134 cm for 0.025 m diameter water intake, 0.031 m diameter stand-pipe, and about 1m screened interval).

2.50 m
3.10 m
100

Water from the Heart River near the landfill was used in the slug tests. The specific conductivity of this water ranged from 1300 to 1500 micromhos per centimeter.

The hydraulic conductivity of sandy, silty, clay and fine sand of the Cannonball Formation ranged from 1×10^{-5} m/s to 1×10^{-7} m/s. The hydraulic conductivity of fine sand and medium gravel in the Coteau Formation in the landfill area was 6.4×10^{-7} m/s and 3.2×10^{-4} m/s, respectively.

The rate (velocity) of flow of shallow groundwater in the landfill was calculated from the equation for the rate of flow,

$$v = K i n , \quad (18)$$

where v = rate (velocity) of flow, m/s,

K = hydraulic conductivity, m/s,

i = hydraulic gradient, m/m, and

n = porosity, % X 100.

The rate of flow of groundwater in the Coteau Formation in the landfill area ranged from 3×10^{-5} m/s in permeable sediment (gravel) to 5×10^{-6} m/s in less permeable sediment (fine sand and silt).

APPENDIX B

LITHOLOGIC LOGS OF TEST HOLES

IN THE MANDAN LANDFILL AREA

139-81-34adc1

Well Number 1

Elevation: 503.43 m (1661.50 feet)

Material	Thickness, m	Depth, m
Landfill		
Topcover; fine sands, silts of Cannonball Formation	0.6	0-0.6
Refuse; fresh, undecomposed paper, food, rags	3.3	0.6-3.9
Refuse; mixed with clay	1.5	3.9-5.4
Refuse; fairly fresh	0.9	5.4-6.3
Refuse; fairly fresh, mixed with rock	0.3	6.3-6.6
Coteau Formation		
Clay; dark gray, dense, reduced	2.1	6.6-8.7
Clay; silty, dark gray	2.4	8.7-11.1
Clay; sandy	1.2	11.1-12.3
Sand; fine to medium, blue	2.4	12.3-14.7
Sand; silty, clayey, blue	0.9	14.7-15.6
Clay; dark blue, dense	0.6	15.6-16.2

One piezometer was installed at a depth of 15.5 m in the sand.

139-81-34adc2

Well Number 2

Elevation: 506.37 m (1660.24 feet)

Material	Thickness, m	Depth, m
Landfill		
Topcover; fine sands, silts of Cannonball Formation	0.6	0-0.6
Refuse; very fresh	3.6	0.6-4.2
Cover material; dark-gray clay	0.6	4.2-4.8
Refuse; partially decomposed	0.9	4.8-5.7
Refuse; decomposed	1.5	5.7-7.2
Refuse; badly decomposed	1.5	7.2-8.7
Refuse; fibrous, mixed with silt and clay	1.5	8.7-10.2
Coteau Formation		
Sand; fine, blue, reduced	3.3	10.2-13.5

One piezometer was installed at a depth of 11.7 m in the sand.

139-81-34adc3

Well Number 3

Elevation: 506.34 m (1660.13 feet)

Material	Thickness, m	Depth, m
Landfill		
Topcover; fine sand, silt of Cannonball Formation	0.6	0-0.6
Refuse; fresh	3.3	0.6-3.9
Cover material; gray, silty clay	0.3	3.9-4.2
Refuse; fairly fresh	1.5	4.2-5.7
Refuse; fibrous, mixed with gray, silty clay	3.0	5.7-8.7
Refuse; fibrous, mixed with silty, sandy clay	2.9	8.7-11.6
Coteau Formation		
Clay; blue-gray, dense, reduced	0.3	11.6-11.9
Sand; fine, blue, reduced	1.3	11.9-14.2

One piezometer was installed at a depth of 14.2 m in the sand.

139-81-34 adc4

Well Number 4

Elevation: 506.57 m (1660.88 feet)

Material	Thickness, m	Depth, m
Landfill		
Topcover; fine sands, silts of Cannonball Formation	0.6	0-0.6
Refuse; fairly fresh	3.9	0.6-4.5
Refuse; gas pockets (H ₂ S)	1.8	4.5-6.3
Refuse; partly decomposed	4.5	6.3-10.8
Refuse; decomposed, stony	2.1	10.8-12.9
Coteau Formation		
Clay; sandy	9.0	12.9-21.9
Clay; gray	3.7	21.9-25.5

One piezometer was installed at a depth of 20.4 m in the sandy clay.

139-81-34adc5

Well Number 5A

Elevation: 507.65 m (1664.42 feet)

139-81-34adc6

Well Number 5B

Elevation: 507.65 m (1664.42 feet)

Material	Thickness, m	Depth, m
Landfill		
Topcover; fine sands, silts of Cannonball Formation	0.6	0-0.6
Refuse; fresh, plastic, paper	4.6	0.6-5.2
Coteau Formation		
Clay; gray	0.9	5.2-6.1
Silt; sandy	0.6	6.1-6.7
Clay	0.6	6.7-7.3
Clay; silty	1.9	7.3-9.2
Sand; fine, yellow	2.8	9.2-12.0
Clay; silty	2.3	12.0-14.3
Sand; fine to medium, blue	4.0	14.3-18.3

Two piezometers were installed: one at a depth of 16.0 m in the blue sand and another at a depth of 18.3 m in the blue sand.

Well number 5A is the shallow well.

139-81-34add1
 Well Number 6A
 Elevation: 513.93 m (1685.00 feet)

139-81-34add2
 Well Number 6B
 Elevation: 513.93 m (1685.00 feet)

Material	Thickness, m	Depth, m
Cannonball Formation		
Sand; fine, yellow	2.1	0-2.1
Clay; silty	0.9	2.1-3.0
Clay; sandy	0.6	3.0-3.6
Clay	0.3	3.6-3.9
Clay; silty	0.4	3.9-4.3
Shale; calcareous	0.3	4.3-4.6
Clay	2.4	4.6-7.0
Clay; sandy, blue	0.6	7.0-7.6
Clay; gray	4.6	7.6-12.2
Clay; silty, sandy	2.9	12.2-15.1
Shale; dense, light blue-gray	0.5	15.1-15.6
Sand; silt; clay; alternating	2.8	15.6-18.4
Sand; fine	3.5	18.4-22.9
Sand; silt; clay; alternating	3.0	22.9-25.9
Sand; fine to medium	1.6	25.9-27.5

Two piezometers were installed: one at a depth of 27.5 m in a sand and another at a depth of 13.8 m in a silty, sandy clay. Well number 6B is the shallow well.

139-81-34acd1

Well Number 7

Elevation: 500.74 m (1641.76 feet)

Material	Thickness, m	Depth, m
Coteau Formation		
Topsoil; silty, light brown	0.6	0-0.6
Clay; yellow	2.2	0.6-2.8
Clay; sandy	0.9	2.8-3.7
Gravel; fine, clayey, gastropod fragments	0.3	3.7-4.0
Sand; fine, gravelly	0.6	4.0-4.6
Sand; fine, yellow	1.5	4.6-6.1
Gravel; fine, sandy	0.9	6.1-7.0
Gravel; fine, sandy, blue	0.6	7.0-7.6
Gravel; fine	0.6	7.6-8.2
Gravel; sand; lignite fragments	0.9	8.2-9.1
Sand; medium, lignite fragments	1.9	9.1-11.0
Sand; medium	2.1	11.0-13.1
Clay	0.6	13.1-13.7
Gravel; fine, sandy, lignite fragments	1.5	13.7-15.2
Clay; blue	1.0	15.2-16.2

One piezometer was installed at a depth of 8.9 m in gravel.

139-81-34acd2

Well Number 8A

Elevation: 500.20 m (1640.00 feet)

139-81-34acd3

Well Number 8B

Elevation: 500.20 m (1640.00 feet)

Material	Thickness, m	Depth, m
Coteau Formation		
Topsoil; sandy, light brown	0.6	0-0.6
Clay; yellow	2.5	0.6-3.1
Clay; silty, yellow	0.9	3.1-4.0
Clay; blue	0.6	4.0-4.6
Clay; blue, gastropod and lignite fragments	2.1	4.6-6.7
Gravel; fine, sandy	0.9	6.7-7.6
Gravel; coarse, sandy	1.6	7.6-9.2
Clay; blue, lignite fragments	0.9	9.2-10.1
Gravel; fine to medium	0.6	10.1-10.7
Gravel; medium to coarse, lignite fragments	3.0	10.7-13.7

Two piezometers were installed: one was installed at a depth of 7.2 m in a fine gravel and another was installed at a depth of 10.9 m in a coarse gravel. Well number 8A is the shallow well.

139-81-34acd3
Well Number 9A
Elevation: 500.57 m (1641.20 feet)

139-81-34acd4
Well Number 9B
Elevation: 500.57 m (1641.20 feet)

Material	Thickness, m	Depth, m
Coteau Formation		
Topsoil; silty, light brown	0.9	0-0.9
Clay; silty	1.9	0.9-2.8
Sand; fine, lignite and gastropod fragments	0.3	2.8-3.1
Sand; fine to medium, yellow	0.6	3.1-3.7
Clay; yellow, lignite fragments	0.9	3.7-4.6
Lignite; sand; gastropod fragments	0.3	4.6-4.9
Sand; medium, lignite and gastropod fragments	0.6	4.9-5.5
Sand; fine to medium	1.5	5.5-7.0
Sand; medium, lignite fragments	1.9	7.0-8.9
Gravel; fine, clayey	0.3	8.9-9.2
Gravel; medium, lignite fragments	0.9	9.2-10.1
Gravel; coarse	1.8	10.1-11.9
Clay; gray	1.8	11.9-13.7
Clay; silty, sandy	0.9	13.7-14.6
Clay	1.9	14.6-16.5
Clay; silty, sandy	2.7	16.5-19.2
Clay	0.6	19.2-19.8
Clay; lignite fragments	0.3	19.8-20.1
Clay; sandy	2.8	20.1-22.9

Two piezometers were installed: one at a depth of 10.0 m in medium gravel and another at a depth of 14.9 m in clay. Well number 9A is the shallow well.

139-81-34acd6
Well Number 10A
Elevation: 500.82 m (1642.02 feet)

139-81-34acd7
Well Number 10B
Elevation: 500.82 m (1642.02 feet)

Material	Thickness, m	Depth, m
Coteau Formation		
Topsoil; silty, light brown	0.6	0-0.6
Clay; silty, yellow, lignite fragments	1.5	0.6-2.1
Clay; yellow	2.3	2.1-4.4
Clay; blue	0.2	4.4-4.6
Silt; lignite and gastropod fragments	1.2	4.6-5.8
Sand; fine to medium, blue	0.9	5.8-6.7
Gravel; medium	2.2	6.7-8.9
Clay; blue, silty	0.6	8.9-9.5
Sand; fine to medium, gravelly	2.1	9.5-11.6
Gravel; medium, lignite fragments	0.6	11.6-12.2
Gravel; coarse	2.4	12.2-14.6
Gravel; medium to fine, sandy	0.7	14.6-15.3
Gravel; medium to coarse	0.9	15.3-16.2
Clay; silty, lignite fragments	1.2	16.2-17.4

Two piezometers were installed: one was installed at a depth of 9.9 m in medium sand and another at a depth of 14.4 m in coarse gravel. Well number 10A is the shallow well.

139-81-34ada1

Well Number 11A

Elevation: 504.05 m (1652.63 feet)

139-81-34ada2

Well Number 11B

Elevation: 504.05 m (1652.63 feet)

Material	Thickness, m	Depth, m
Landfill		
Topcover; sand, silt, rubble	0.6	0-0.6
Cannonball Formation		
Sandstone; fine, calcareous, dense	0.6	0.6-1.2
Clay; silty, sandy, yellow	5.8	1.2-7.0
Sand; fine, yellow	1.2	7.0-8.2
Clay; yellow, silty	1.0	8.2-9.2
Clay; blue, sandy	3.6	9.2-12.8
Clay; silty, dense, blue-gray	9.6	12.8-22.4
Sandstone; fine, calcareous, dense	0.3	22.4-22.7
Clay; blue-gray	2.0	22.7-24.7
Ludlow-Hell Creek Formations (?)		
Clay; lignitic	0.3	24.7-25.0
Clay; gray, sandy	0.6	25.0-25.6
Sand; fine	1.2	25.6-26.8
Clay; gray, dense	0.7	26.8-27.5

Two piezometers were installed: one at a depth of 15.4 m in silty clay and another at a depth of 26.6 m in fine sand. Well number 11A is the shallow well.

139-81-34add1
Well Number 12A
Elevation: 522.49 m (1713.07 feet)

139-81-34add2
Well Number 12B
Elevation: 522.49 m (1713.07 feet)

Material	Thickness, m	Depth, m
Oahe Formation		
Topsoil; silty, sandy, light brown	0.6	0-0.6
Cannonball Formation		
Clay; yellow	2.8	0.6-3.4
Clay; dark gray, yellow, mottled	1.2	3.4-4.6
Clay; sandy	0.6	4.6-5.2
Clay; sandy, silty, yellow	0.9	5.2-6.1
Clay; dark gray, yellow, mottled	1.5	6.1-7.6
Sandstone; fine, calcareous, light blue-gray	0.5	7.6-8.1
Clay; silty, dark gray, yellow	1.1	8.1-9.2
Clay; light gray, bentonitic	0.6	9.2-9.8
Clay; silt; sand; dark green, interbedded	0.6	9.8-10.4
Clay; greenish-brown, sandy	12.5	10.4-22.9
Sandstone; fine, calcareous, dense	0.9	22.9-23.8
Sand; fine, clayey	2.5	23.8-26.3
Sand; blue-green		26.3-27.5

Two piezometers were installed: one at a depth of 22.3 m in sandy clay and another at a depth of 27.3 m in sand. Well number 12A is the shallow well.

139-81-34dab1
Well Number 13A
Elevation: 529.90 m (1737.38 feet)

139-81-34dab2
Well Number 13B
Elevation: 529.90 m (1737.38 feet)

Material	Thickness, m	Depth, m
Oahe Formation		
Topsoil; silt, sand, light brown	0.6	0-0.6
Sand; fine, yellow	0.9	0.6-1.5
Four Bears Formation		
Clay; yellow	0.9	1.5-2.4
Sand; fine, lignite fragments	1.3	2.4-3.7
Sand; fine, silty	0.9	3.7-4.6
Sand; fine to medium	2.7	4.6-7.3
Sand; fine to medium, lignite fragments	4.9	7.3-12.2
Clay; yellow	1.5	12.2-13.7
Sand; medium	0.9	13.7-14.6
Sand; medium, some lignite fragments	1.6	14.6-16.2
Cannonball Formation		
Clay; gray, silty	2.1	16.2-18.3
Clay; gray	11.6	18.3-29.9
Clay; silty, sandy	2.1	29.9-32.0
Sand; fine, silty, clayey	4.6	32.0-36.6
Sand; fine, clayey, silty	9.2	36.6-45.8

Two piezometers were installed: one at a depth of 29.8 m in clay and another at a depth of 41.9 m in silty, clayey sand. Well number 13 a is the shallow well.

APPENDIX C

PHYSICAL WELL DATA

PHYSICAL WELL DATA

Explanations of the headings used on pages 109 to 111 are given below.

NUMBER	= number given to the source of water where: letter A usually indicates the shallow well in a multiple piezometer installation, letter B usually indicates the deep well in a multiple piezometer installation.
LOCATION	= location of well (see Figure 18).
SAMPLE	= number assigned to the water sample where: number 1 indicates a sample collected 8-16-72, number 2 indicates a sample collected 9-8-72, number 3 indicates a sample collected 10-14-72.
FORMATION	= formation in which well is completed where: Qc is the Coteau Formation, Tc is the Cannonball Formation, Tl is the Ludlow Formation, Khc is the Hell Creek Formation.
EL (FT)	= elevation of well (measured from land surface datum) in feet above mean sea level.
EL (M)	= elevation of well (measured from land surface datum) in meters above mean sea level.

DEPTH	= depth of well in meters from the ground surface to bottom of the well.
SCREENED	= elevation in meters of the top and bottom of screened interval in the well.
SOURCE	= geological material or source of water.
S.W.L.	= elevation in meters of the static water level in well.
TEMP.C	= temperature of water in degrees Centigrade at time sample was collected.
PH	= negative logarithm of the hydrogen-ion concentration.
SP.COND	= specific conductance of water measured in micromhos.
DATE	= month-day-year sample was collected.

NUMBER	LOCATION	FORMATION	EL (FT)	EL (M)	DEPTH	SCREENED	SOURCE	S.W.L.	DATE
1	139-81-34adc1	Qc	1661.50	506.76	15.7	490.3-491.1	sand	495.70	9- 8-72
2	139-81-34adc2	Qc	1660.24	506.37	11.6	494.1-494.8	sand	495.64	9- 8-72
3	139-81-34adc3	Qc	1660.13	506.34	14.0	491.6-492.4	sand	495.80	9- 8-72
4	139-81-34adc4	Qc	1660.88	506.57	20.4	485.5-486.2	clay	496.10	9- 8-72
5A	139-81-34adc5	Qc	1664.42	507.65	16.0	490.9-491.7	sand	495.90	9- 8-72
5B	139-81-34adc6	Qc	1664.42	507.65	18.3	488.6-489.3	sand	495.80	9- 8-72
6A	139-81-34add1	Tc	1685.00	513.93	27.6	485.5-486.3	sand	497.80	9- 8-72
6B	139-81-34add2	Tc	1685.00	513.93	13.8	499.4-500.1	clay	502.00	9- 8-72
7	139-81-34acd1	Qc	1641.76	500.74	8.9	492.1-492.8	gravel	497.11	9- 8-72
8A	139-81-34acd2	Qc	1640.00	500.20	7.2	492.3-493.0	gravel	497.46	9- 8-72
8B	139-81-34acd3	Qc	1640.00	500.20	10.9	488.5-489.3	gravel	497.48	9- 8-72
9A	139-81-34acd4	Qc	1641.20	500.57	10.0	489.9-490.6	gravel	495.80	9- 8-72
9B	139-81-34acd5	Qc	1641.20	500.57	14.9	484.9-485.7	clay	495.66	9- 8-72
10A	139-81-34acd6	Qc	1642.02	500.82	9.9	490.1-490.9	sand	495.80	9- 8-72
10B	139-81-34acd7	Qc	1642.02	500.82	14.4	485.7-486.4	gravel	495.70	9- 8-72
11A	139-81-34ada1	Tc	1652.63	504.05	15.4	487.9-488.6	clay	496.11	9- 8-72
11B	139-81-34ada2	Tl-Khc	1652.63	504.05	26.6	476.7-477.5	sand	496.07	9- 8-72
12A	139-81-34add1	Tc	1713.07	522.49	22.3	499.5-500.2	clay	501.62	9- 8-72
12B	139-81-34add2	Tc	1713.07	522.49	27.3	494.4-495.2	sand	501.50	9- 8-72
13A	139-81-34dab1	Tc	1737.38	529.90	29.8	499.3-500.1	clay	502.00	9- 8-72
13B	139-81-34dab2	Tc	1737.38	529.90	41.9	487.2-488.0	sand	498.10	9- 8-72
14	139-81-35cba	Khc	1670.0	509.4	53.4	456.0-457.8	sand	486.5	8-17-72
15	138-81-02bda	Khc	1790.0	546.0	94.5	447.8-451.5	sand	437.4	8-17-72
16	139-81-34dbd	Tc	1646.0	502.0	22.9	?	sand	.	8-17-72
17	139-81-35bca	Khc	1640.0	500.2	30.5	?	sand	490.0	8-17-72

NUMBER	LOCATION	SAMPLE	TEMP.C	PH	SP.COND	DATE
1	139-81-34adc1	1	9.26	7.30	1190	8-16-72
1	139-81-34adc1	2	..	7.09	1000	9- 8-72
1	139-81-34adc1	3	..	7.25	900	10-14-72
2	139-81-34adc2	1	11.65	7.20	1950	8-16-72
2	139-81-34adc2	2	..	7.40	1830	9- 8-72
2	139-81-34adc2	3	..	6.94	1920	10-14-72
3	139-81-34adc3	1	10.18	7.20	1000	8-16-72
3	139-81-34adc3	2	..	7.08	1020	9- 8-72
3	139-81-34adc3	3	..	7.35	960	10-14-72
4	139-81-34adc4	1	10.31	7.30	1450	8-16-72
4	139-81-34adc4	2	..	7.70	1470	9- 8-72
4	139-81-34adc4	3	..	7.07	1275	10-14-72
5A	139-81-34adc5	1	9.40	7.45	1400	8-16-72
5A	139-81-34adc5	2	..	7.27	1060	9- 8-72
5A	139-81-34adc5	3	..	7.48	990	10-14-72
5B	139-81-34adc6	1	8.68	7.75	1490	8-16-72
5B	139-81-34adc6	2	..	7.22	1260	9- 8-72
5B	139-81-34adc6	3	..	7.43	1000	10-14-72
6A	139-81-34add1	1	9.28	7.58	1040	8-16-72
6A	139-81-34add1	2	..	7.76	1080	9- 8-72
6A	139-81-34add1	3	..	7.33	1010	10-14-72
6B	139-81-34add2	1	9.48	7.98	1090	8-16-72
6B	139-81-34add2	2	..	7.95	1070	9- 8-72
6B	139-81-34add2	3	..	7.40	1160	10-14-72
7	139-81-34acd1	2	7.68	7.66	710	9- 8-72
7	139-81-34acd1	3	..	7.50	665	10-14-72
8A	139-81-34acd2	2	7.45	7.41	750	9- 8-72
8A	139-81-34acd2	3	..	7.56	970	10-14-72
8B	139-81-34acd3	2	7.00	7.39	970	9- 8-72
8B	139-81-34acd3	3	..	7.48	705	10-14-72
9A	139-81-34acd4	1	8.10	7.43	1190	8-16-72
9A	139-81-34acd4	3	..	7.46	920	10-14-72
9B	139-81-34acd5	2	8.75	7.60	1140	9- 8-72
9B	139-81-34acd5	3	..	7.62	1005	10-14-72

NUMBER	LOCATION	SAMPLE	TEMP.C	PH	SP.COND	DATE
10A	139-81-34acd6	2	8.91	7.76	1050	9- 8-72
10A	139-81-34acd6	3	. .	7.41	880	10-14-72
10B	139-81-34acd7	2	8.10	7.72	1080	9- 8-72
10B	139-81-34acd7	3	. .	7.56	980	10-14-72
11A	139-81-34ada1	2	9.50	7.79	1100	9- 8-72
11A	139-81-34ada1	3	. .	7.58	1000	10-14-72
11B	139-81-34ada2	2	9.00	7.50	1005	9- 8-72
11B	130-81-34ada2	3	. .	7.39	955	10-14-72
12A	139-81-34add1	2	9.26	7.55	1200	9- 8-72
12A	139-81-34add1	3	. .	7.34	1440	10-14-72
12B	139-81-34add2	1	8.95	7.88	1100	8-16-72
12B	139-81-34add2	3	. .	7.50	1100	10-14-72
13A	139-81-34dab1	2	6.39	7.80	930	9- 8-72
13A	139-81-34dab1	3	. .	7.58	925	10-14-72
13B	139-81-34dab2	2	6.30	8.15	1050	9- 8-72
13B	139-81-34dab2	3	. .	7.78	900	10-14-72
14	139-81-35cba	1	8.90	7.95	1990	8-16-72
15	138-81-02bda	1	9.40	8.23	2230	8-16-72
16	139-81-34dbd	2	6.30	7.25	1410	9- 8-72
17	139-81-35bca	2	6.30	8.01	2800	9- 8-72

APPENDIX D

CHEMICAL DATA

CHEMICAL DATA

Explanations of the headings used on pages 115 to 118 are given below.

NUMBER	= number given to the source of water where:
	letter A usually indicates the shallow well in a multiple piezometer installation,
	letter B usually indicates the deep well in a multiple piezometer installation.
LOCATION	= location of well (see Figure 18).
SAMPLE	= number assigned to the water sample where:
	number 1 indicates a sample collected 8-16-72,
	number 2 indicates a sample collected 9-8-72,
	number 3 indicates a sample collected 10-14-72.
HCO ₃	= bicarbonate concentration in parts per million.
CO ₃	= carbonate concentration in parts per million.
ALK	= total alkalinity measured in parts per million CaCO ₃ .
CA	= calcium concentration in parts per million.
MG	= magnesium concentration in parts per million.
T.HRD	= total hardness measured in parts per million CaCO ₃ .

S04	= total sulfate concentration in parts per million.
NO3	= nitrate concentration in parts per million.
CL	= chloride concentration in parts per million.
FE	= iron concentration in parts per million.
NA	= sodium concentration in parts per million.
K	= potassium concentration in parts per million.
TDS	= total dissolved solids measured in parts per million.

NUMBER	LOCATION	SAMPLE	HCO3	CO3	ALK	CA	MG	T.HRD
1	139-81-34adc1	1	420.0	0.0	420.0	290.0	175.0	465.0
1	139-81-34adc1	2	430.0	0.0	430.0	255.0	205.0	460.0
1	139-81-34adc1	3	400.0	0.0	400.0	250.0	180.0	430.0
2	139-81-34adc2	1	375.0	0.0	325.0	260.0	240.0	500.0
2	139-81-34adc2	2	350.0	0.0	350.0	190.0	250.0	440.0
2	139-81-34adc2	3	600.0	0.0	600.0	395.0	365.0	760.0
3	139-81-34adc3	1	250.0	0.0	250.0	125.0	125.0	250.0
3	139-81-34adc3	2	280.0	0.0	280.0	140.0	140.0	280.0
3	139-81-34adc3	3	480.0	0.0	480.0	345.0	135.0	480.0
4	139-81-34adc4	1	340.0	0.0	340.0	150.0	90.0	240.0
4	139-81-34adc4	2	400.0	0.0	400.0	145.0	105.0	250.0
4	139-81-34adc4	3	335.0	0.0	335.0	150.0	100.0	250.0
5A	139-81-34adc5	1	450.0	0.0	450.0	250.0	235.0	485.0
5A	139-81-34adc5	2	250.0	0.0	250.0	165.0	220.0	385.0
5A	139-81-34adc5	3	410.0	0.0	410.0	300.0	230.0	530.0
5B	139-81-34adc6	1	430.0	0.0	430.0	280.0	220.0	500.0
5B	139-81-34adc6	2	420.0	0.0	420.0	320.0	200.0	520.0
5B	139-81-34adc6	3	380.0	0.0	380.0	275.0	235.0	510.0
6A	139-81-34add1	1	240.0	0.0	240.0	190.0	90.0	280.0
6A	139-81-34add1	2	250.0	0.0	250.0	140.0	140.0	280.0
6A	139-81-34add1	3	240.0	0.0	240.0	145.0	140.0	285.0
6B	139-81-34add2	1	210.0	0.0	210.0	115.0	85.0	200.0
6B	139-81-34add2	2	210.0	0.0	210.0	115.0	95.0	210.0
6B	139-81-34add2	3	270.0	0.0	270.0	125.0	125.0	250.0
7	139-81-34acd1	2	280.0	0.0	280.0	190.0	130.0	320.0
7	139-81-34acd1	3	290.0	0.0	290.0	210.0	105.0	315.0
8A	139-81-34acd2	2	300.0	0.0	300.0	200.0	90.0	290.0
8A	139-81-34acd2	3	305.0	0.0	305.0	230.0	135.0	365.0
8B	139-81-34acd3	2	250.0	0.0	250.0	170.0	100.0	270.0
8B	139-81-34acd3	3	305.0	0.0	305.0	200.0	115.0	315.0
9A	139-81-34acd4	1	250.0	0.0	250.0	130.0	60.0	190.0
9A	139-81-34acd4	3	205.0	0.0	205.0	70.0	40.0	110.0
9B	139-81-34acd5	2	240.0	0.0	240.0	70.0	30.0	100.0
9B	139-81-34acd5	3	220.0	0.0	220.0	65.0	55.0	120.0

NUMBER	LOCATION	SAMPLE	HC03	CO3	ALK	CA	MG	T.HRD
10A	139-81-34acd6	2	250.0	0.0	250.0	160.0	90.0	250.0
10A	139-81-34acd6	3	210.0	0.0	210.0	150.0	100.0	250.0
10B	139-81-34acd7	2	250.0	0.0	250.0	165.0	85.0	250.0
10B	139-81-34acd7	3	220.0	0.0	220.0	160.0	100.0	260.0
11A	139-81-34ada1	2	240.0	0.0	240.0	145.0	110.0	255.0
11A	139-81-34ada1	3	225.0	0.0	225.0	140.0	140.0	280.0
11B	139-81-34ada2	2	200.0	0.0	200.0	110.0	110.0	220.0
11B	139-81-34ada2	3	190.0	0.0	190.0	100.0	100.0	200.0
12A	139-81-34add1	2	225.0	0.0	225.0	90.0	60.0	150.0
12A	139-81-34add1	3	275.0	0.0	275.0	145.0	105.0	250.0
12B	139-81-34add2	1	220.0	0.0	220.0	95.0	155.0	250.0
12B	139-81-34add2	3	245.0	0.0	245.0	110.0	100.0	210.0
13A	139-81-34dab1	2	340.0	0.0	340.0	260.0	155.0	415.0
13A	139-81-34dab1	3	360.0	0.0	360.0	285.0	160.0	445.0
13B	139-81-34dab2	2	320.0	0.0	320.0	240.0	140.0	380.0
13B	139-81-34dab2	3	300.0	10.0	310.0	235.0	140.0	375.0
14	139-81-35cba	1	925.0	0.0	925.0	10.0	5.0	15.0
15	138-81-02bda	1	730.0	20.0	750.0	15.0	25.0	40.0
16	139-81-34dbd	2	300.0	0.0	300.0	200.0	170.0	370.0
17	139-81-35bca	2	940.0	0.0	940.0	15.0	25.0	40.0

NUMBER	LOCATION	SAMPLE	SO4	NO3	CL	FE	NA	K	TDS
1	139-81-34adc1	1	187.5	0.003	5.0	0.00	56.0	9.15	1143.0
1	139-81-34adc1	2	75.0	0.120	14.0	0.00	58.0	9.18	1046.0
1	139-81-34adc1	3	87.5	0.020	8.0	0.00	55.2	8.35	989.0
2	139-81-34adc2	1	172.5	0.240	50.0	0.00	56.4	14.00	1118.0
2	139-81-34adc2	2	50.0	0.030	67.0	0.00	70.0	10.00	987.0
2	139-81-34adc2	3	0.0	0.020	333.0	0.15	69.0	12.00	1774.0
3	139-81-34adc3	1	50.0	0.060	25.0	0.00	41.4	9.00	625.0
3	139-81-34adc3	2	50.0	0.020	33.0	0.00	40.2	8.75	692.0
3	139-81-34adc3	3	50.0	0.060	50.0	0.15	41.4	8.30	1110.0
4	139-81-34adc4	1	435.0	0.016	40.0	0.00	193.0	31.00	1279.0
4	139-81-34adc4	2	250.0	0.020	50.0	0.00	208.0	23.00	1181.0
4	139-81-34adc4	3	300.0	0.032	40.0	0.39	170.0	21.00	1116.0
5A	139-81-34adc5	1	390.0	0.720	67.0	1.63	131.0	41.00	1566.0
5A	139-81-34adc5	2	75.0	0.020	17.0	0.00	43.6	12.00	783.0
5A	139-81-34adc5	3	100.0	0.032	15.0	0.00	46.4	9.10	1111.0
5B	139-81-34adc6	1	525.0	2.100	50.0	0.15	127.0	35.00	1667.0
5B	139-81-34adc6	2	175.0	0.032	22.0	0.00	61.0	29.00	1229.0
5B	139-81-34adc6	3	150.0	0.032	17.0	0.00	41.8	14.00	1113.0
6A	139-81-34add1	1	360.0	0.154	18.0	0.00	120.0	14.00	1032.0
6A	139-81-34add1	2	400.0	0.040	22.0	0.00	131.0	16.00	1099.0
6A	139-81-34add1	3	387.5	0.370	20.0	0.00	130.0	14.00	1077.0
6B	139-81-34add2	1	465.0	0.448	14.0	0.00	135.0	20.00	1044.0
6B	139-81-34add2	2	250.0	0.020	13.0	0.00	132.0	16.00	831.0
6B	139-81-34add2	3	362.5	0.016	17.0	0.00	185.0	16.00	1101.0
7	139-81-34acd1	2	50.0	0.032	20.0	0.00	36.4	7.90	714.0
7	139-81-34acd1	3	0.0	0.040	18.0	0.00	39.2	6.70	669.0
8A	139-81-34acd2	2	125.0	0.032	12.0	0.00	55.0	6.00	788.0
8A	139-81-34acd2	3	150.0	0.560	17.0	0.00	92.0	7.20	936.0
8B	139-81-34acd3	2	125.0	0.032	15.0	0.00	89.0	7.40	757.0
8B	139-81-34acd3	3	62.5	0.168	10.0	0.00	59.0	5.55	757.0
9A	139-81-34acd4	1	525.0	0.032	18.0	0.00	54.0	6.00	1043.0
9A	139-81-34acd4	3	225.0	0.040	20.0	0.00	134.0	9.20	703.0
9B	139-81-34acd5	2	300.0	0.040	22.0	0.00	188.0	10.00	860.0
9B	139-81-34acd5	3	225.0	0.032	18.0	0.00	178.0	12.00	773.0

NUMBER	LOCATION	SAMPLE	SO4	NO3	CL	FE	NA	K	TDS
10A	139-81-34acd6	2	250.0	0.112	17.0	0.00	123.0	16.00	906.0
10A	139-81-34acd6	3	200.0	0.032	17.0	0.00	109.0	16.00	802.0
10B	139-81-34acd7	2	275.0	0.020	18.0	0.00	125.0	12.00	930.0
10B	139-81-34acd7	3	275.0	0.032	17.0	0.00	113.0	16.00	901.0
11A	139-81-34ada1	2	300.0	0.060	15.0	0.00	135.0	12.00	957.0
11A	139-81-34ada1	3	300.0	0.032	18.0	0.00	121.0	20.00	964.0
11B	139-81-34ada2	2	300.0	0.240	22.0	0.00	143.0	24.00	909.0
11B	139-81-34ada2	3	250.0	0.032	17.0	0.00	117.0	23.00	797.0
12A	139-81-34add1	2	300.0	0.024	18.0	0.00	191.0	16.00	900.0
12A	139-81-34add1	3	487.5	0.032	20.0	0.00	214.0	16.00	1263.0
12B	139-81-34add2	1	525.0	0.470	14.0	0.00	176.0	21.00	1206.0
12B	139-81-34add2	3	387.5	0.020	18.0	0.00	195.0	16.00	1072.0
13A	139-81-34dab1	2	125.0	0.112	12.0	0.00	51.2	8.55	952.0
13A	139-81-34dab1	3	150.0	0.015	8.0	0.00	54.0	8.10	1025.0
13B	139-81-34dab2	2	150.0	0.060	11.0	0.00	82.0	8.90	952.0
13B	139-81-34dab2	3	150.0	0.032	12.0	0.00	104.0	8.75	950.0
14	139-81-35cba	1	7.5	0.450	67.0	0.00	472.0	14.00	1501.0
15	138-81-02bda	1	330.0	0.112	100.0	0.13	468.0	10.00	1698.0
16	139-81-34dbd	2	325.0	0.240	25.0	0.00	151.0	8.25	1179.0
17	139-81-35bca	2	0.0	0.024	400.0	0.32	548.0	6.20	1935.0

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