GEOHYDROLOGY AND GROUND-WATER GEOCHEMISTRY AT A SUB-ARCTIC LANDFILL, FAIRBANKS, ALASKA

By Joe S. Downey and Peter O. Sinton

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CONVERSION FACTORS AND ABBREVIATIONS

For readers who may prefer to use metric (International System) units rather than inch-pound units, the conversion factors for the terms used in this report are listed below:

Multiply inch-pound unit	by	To obtain metric unit
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
acre	0.4047	hectare
foot per mile (ft/mi)	0.1894	meter per kilometer (m/km)
foot per day (ft/d)	0.3048	meter per day (m/d)
cubic foot per second per mile [(ft^3 /s)/mi]	0.0176	cubic meter per second per kilometer [(m^3 /s)/km]
square foot per day (ft^2 /d)	0.09290	square meter per day (m^2 /d)
degree Fahrenheit (°F)	°C = 5/9 x (°F-32)	degree Celsius (°C)

Other abbreviations in this report are:

mg/L, milligrams per liter
µS/cm, microsiemens per centimeter at 25 degrees Celsius
mS/m, millisiemens per meter

ALTITUDE DATUM

Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)--a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called "Sea Level Datum of 1929."

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GEOHYDROLOGY AND GROUND-WATER GEOCHEMISTRY

AT A SUB-ARCTIC LANDFILL, FAIRBANKS, ALASKA

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ABSTRACT

The Fairbanks-North Star Borough landfill is located on silt, sand, and gravel deposits of the Tanana River flood plain, about 3 miles south of the city of Fairbanks water-supply wells. The landfill has been in operation for about 25 years in this sub-arctic region of discontinuous permafrost. The cold climate limits biological activity within the landfill with corresponding low gas and leachate production. Chloride concentrations, specific conductance, water temperatures, and earth conductivity measurements indicate a small plume of leachate flowing to the northwest from the landfill. The leachate remains near the water table as it flows northwestward toward a drainage ditch. Results of computer modeling of this local hydrologic system indicate that some of the leachate may be discharging to the ditch. Chemical data show that higher-than-background concentrations of several ions are present in the plume. However, the concentrations appear to be reduced to background levels within a short distance along the path of ground-water flow from the landfill, and thus the leachate is not expected to affect the water-supply wells.

INTRODUCTION

Geochemical and biological processes occurring in arctic and sub-arctic landfills are poorly understood. Near Fairbanks, Alaska, where mean annual temperature is 25 °F, an opportunity to define these processes was present in an area that has been operated as a landfill for about 25 years. Available data have shown high chloride concentrations in wells in or near the landfill, indicating the possible production and movement of a leachate.

In 1982, the U.S. Geological Survey, in cooperation with the Fairbanks-North Star Borough, undertook a study of the geohydrology and geochemistry of the ground-water system in and near the Fairbanks-North Star Borough landfill. The objectives of this study were (1) to determine the extent of any degradation of ground-water quality by leachate from the landfill, and (2) to assess the potential for the leachate to affect the Fairbanks municipal water supply. This report presents the results of the study.

Previous Studies

Landfills in cold regions have been the subject of several studies. Weaver and Keagy (1952) studied the operation of a landfill at Mandan, North Dakota, and described nearly all the methods currently used in the operation of sanitary landfills in arctic regions. Straughn (1972) studied a landfill at Eielson Air Force Base, about 25 mi southeast of Fairbanks, for about 2 years starting in 1967. Both studies produced data indicating major differences in the decomposition rate of refuse between landfills in arctic and sub-arctic regions and those located in warmer climates. Because of low ground temperature for almost the entire year, chemical and biological reactions in landfills in arctic regions occur at very slow rates. The small quantities of methane gas present in arctic region landfills indicate this low level of biological activity and waste decomposition.

R&M Consultants and Arctic Environmental Engineers (1975) conducted a brief survey of the quality of ground water in the vicinity of the Fairbanks-North Star Borough landfill. Their report stated that "while a certain amount of leachate is indicated under the landfill, concentrations are not high and they reduce to background levels within a short distance of the landfill." Baseline concentrations of chemical constituents used for comparison with the ground water beneath the landfill were obtained from wells in the uplands north of Fairbanks as well as on the Tanana River flood plain. However, other studies (Krumhardt, 1982; Nelson, 1978) have shown that ground-water quality in these two areas is dissimilar; concentrations of many dissolved chemical constituents in the water are lower on the flood plain than in the uplands. Additionally, the 1975 study included only two wells downgradient from the landfill. Most of the well, water-level, and water-quality data used in this report were reported by Flynn (1985).

Description of Landfill

The city of Fairbanks and the Fairbanks-North Star Borough are located in central Alaska (fig. 1). Fairbanks, the second largest city in Alaska, is the primary trade and transportation center for interior and arctic Alaska. The Fairbanks-North Star Borough landfill is on the Tanana River flood plain, approximately 0.5 mi north of the Tanana River and about 3 mi south of the south bank of the Chena River where the city's water-supply wells are located (fig. 1). The Tanana levee (fig. 2), a flood-control embankment directly south of the landfill area, extends 16 mi to the east and about 4 mi to the west, where it terminates just southwest of Fairbanks.

For the past 25 years, the landfill has received refuse from the Fairbanks area. The landfill, which covers about 75 acres, contains mainly municipal refuse, and solid and liquid industrial waste. Until the early 1970's, disposal practices were similar to those followed in many cold-climate areas. Refuse was simply dumped in abandoned gravel pits or other depressions and left uncovered because excavation of cover material is difficult in areas of frozen ground. For most of the year, the dump area was unattended, and no restrictions were made on the type of material allowed in the refuse. In 1974, the landfill was closed because of deteriorating conditions, but was reopened later in the year and "semi-sanitary" landfill practices (fig. 3) have been employed since that time. In 1979, the Borough installed a high-pressure baler at the landfill. The baler compacts refuse into 4-foot-square bales that are transported to the landfill area, stacked in tiers, and covered with a 6-inch-thick layer of earth without further compaction.

Study Methods

During the first phase of this study, a network of observation wells was established in and near the landfill. The network included a well designated "Baler" located in the baler building, and wells LF-1 through LF-16, P-178, P-179, P-53, Flood-34 (fig. 2) and Fort Wainwright (fig. 1). The wells are all screened in sandy gravel (figs. 4 and 5). In the second phase of the study -- which consisted of data collection and modeling the transport of conservative solutes -- water-level data and water samples for chemical analysis were collected from all wells and from the Tanana and Chena Rivers. Data-collection procedures and well, water-level, and water-quality data are presented by Flynn (1985). A digital model was developed and used to simulate the flow and quality of ground water in the landfill area. In addition, an electromagnetic survey of the area was conducted to determine if a leachate plume was detectable using this geophysical method.

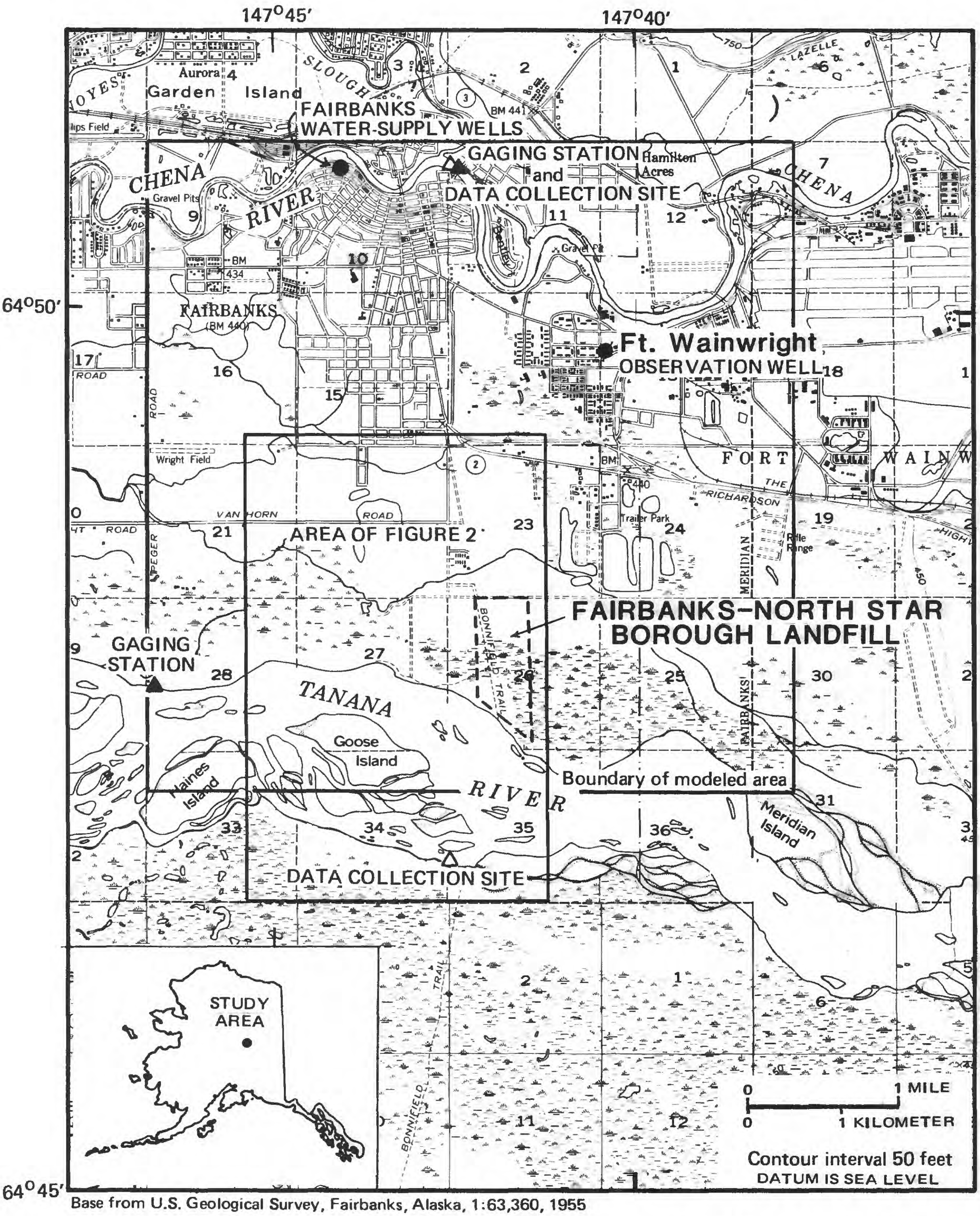
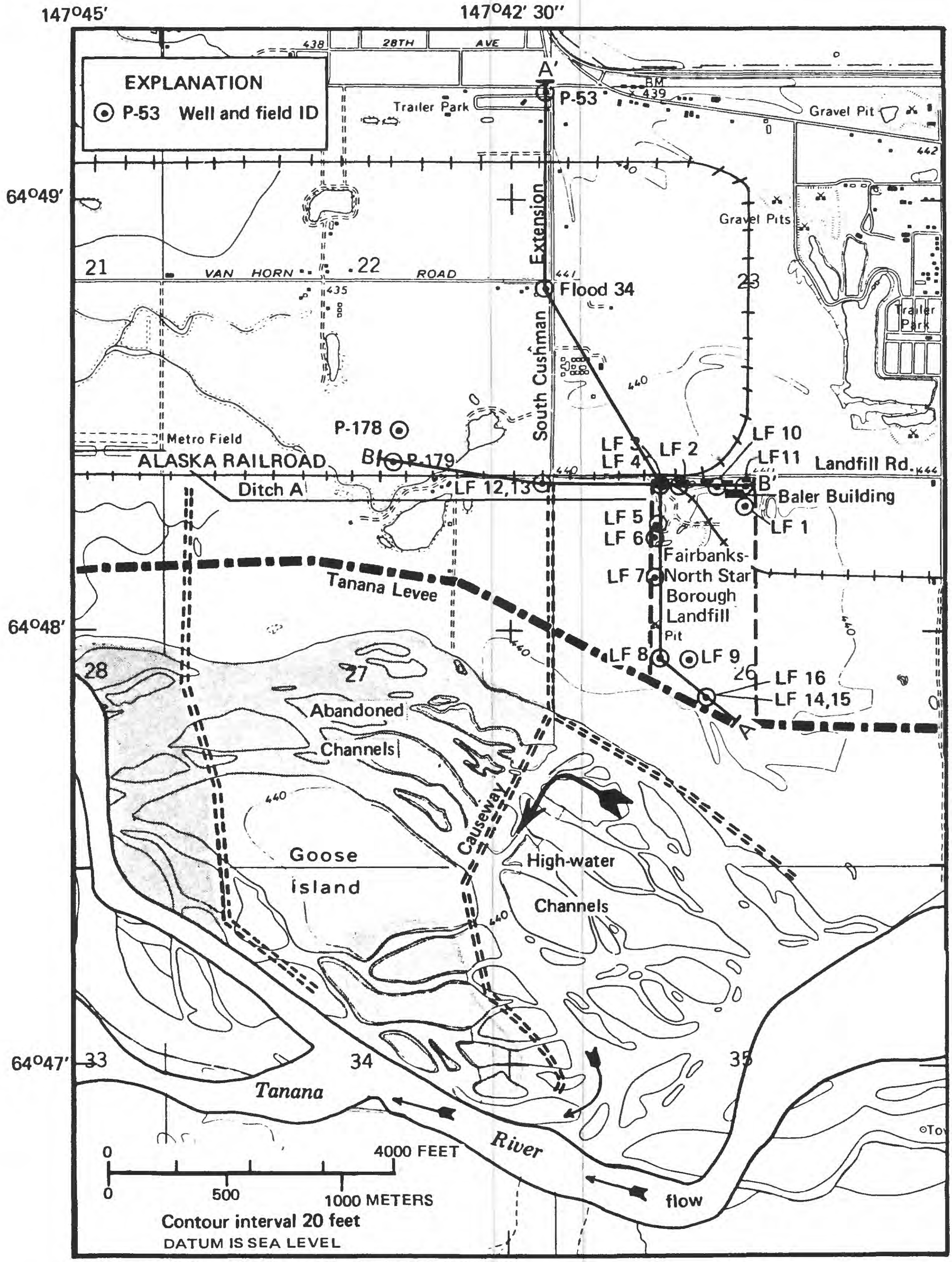


Figure 1.--Location of the Fairbanks-North Star Borough landfill, U.S. Geological Survey river-gaging stations, Fairbanks water-supply wells, and the Fort Wainwright observation well.



Base from U.S. Geological Survey Fairbanks, D-2, 1:24,000

Figure 2.--Fairbanks-North Star Borough landfill area, and locations of observation wells and geologic sections A-A' and B-B'.

Figure 3. -- Fairbanks-North Star Borough landfill showing semi-sanitary landfill practice of covering refuse with fine sand and silt, summer 1982.

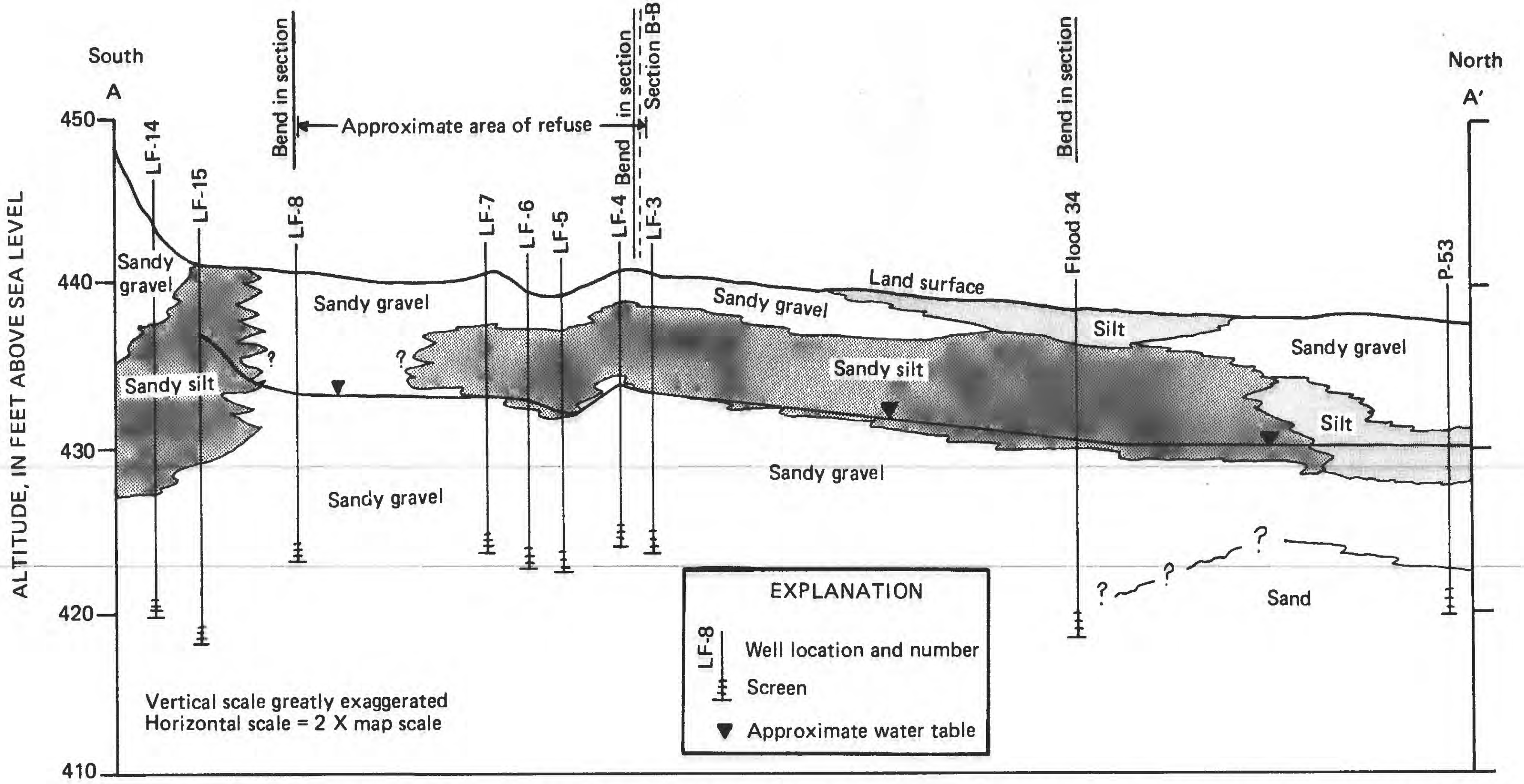


Figure 4.--North-south geologic section through the Fairbanks-North Star Borough landfill. (Line of section shown on figure 2.)

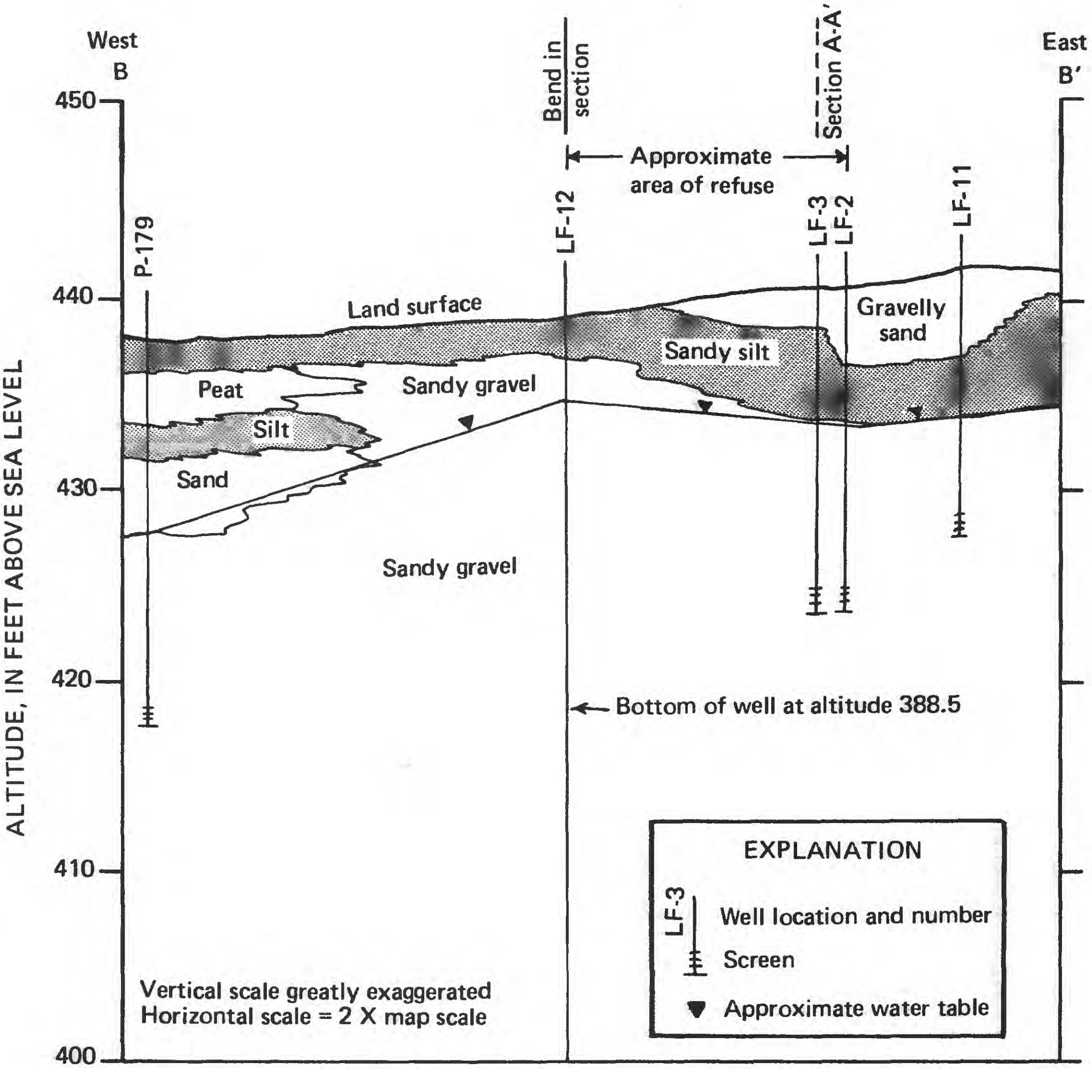


Figure 5.--East-west geologic section through the Fairbanks-North Star Borough landfill. (Line of section shown on figure 2.)

GEOHYDROLOGY OF THE LANDFILL SITE

The Fairbanks-North Star Borough landfill is located on silt, sand, and gravel deposits of the Tanana River flood plain; these deposits are probably several hundreds of feet thick. The Fairbanks area is underlain by discontinuous permafrost (perenially frozen ground), but no frozen ground was reported in drillers' logs of a 90-foot-deep well at the landfill baler building or in 20 shallower wells (most about 20 ft deep) within or adjacent to the landfill. However, several frozen zones were reported between depths of 40 and 80 ft in a well at Fort Wainwright, 2 mi north of the landfill (fig. 1).

Ground water flows northwestward beneath the landfill and toward the city of Fairbanks. The flow direction (perpendicular to water-table contours) and elevation of the water table change seasonally due to the effects of changing stage in the Tanana River (figs. 6-9). Most of the flow of the Tanana is derived from melting snow and ice; highest flows usually occur in July and August. During summer, ground-water levels at the landfill may also be affected by pumping in gravel-mining areas nearby.

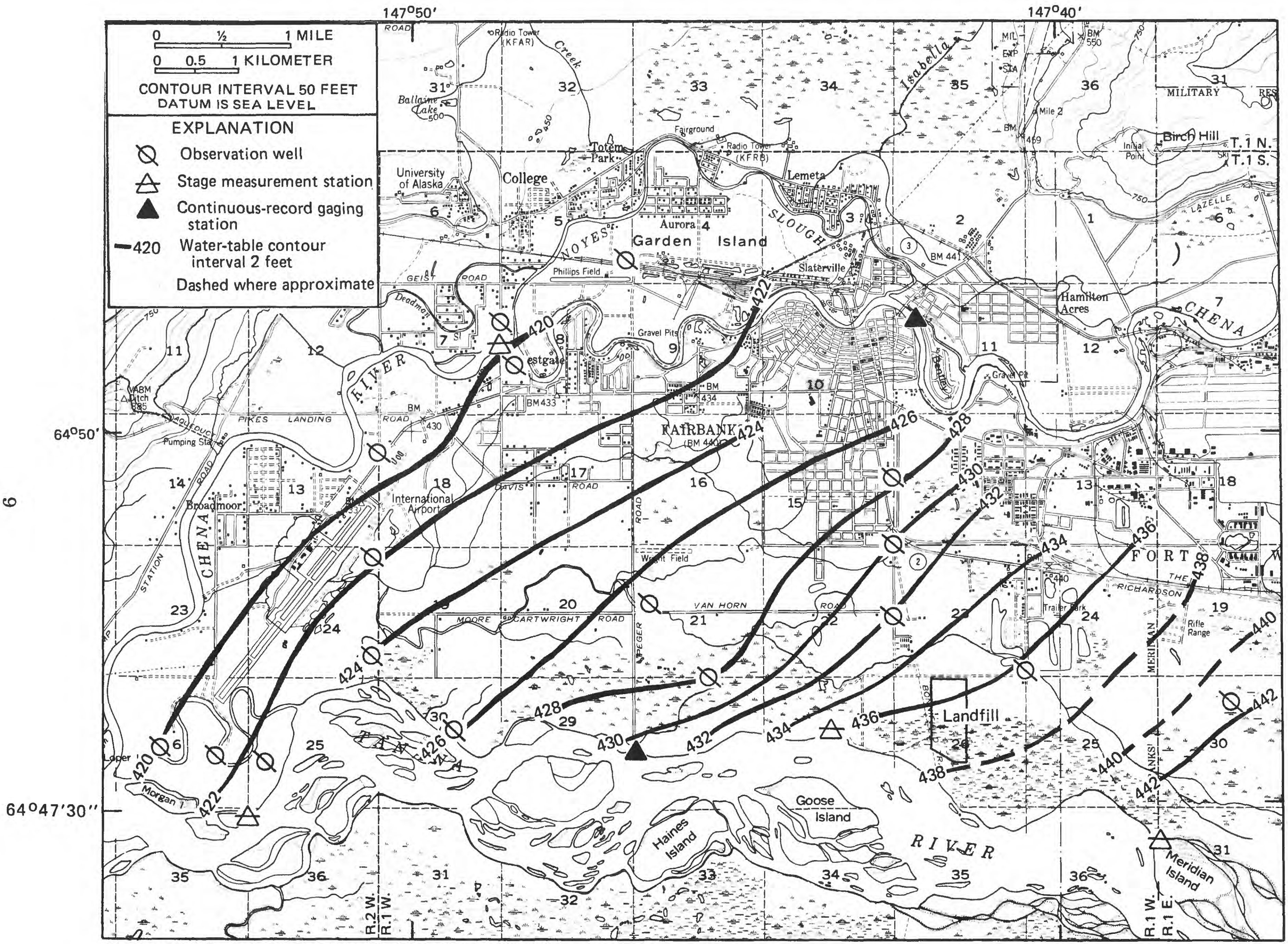
The Goose Island causeway also modifies flow near the landfill. The abandoned channels downstream from the causeway (fig. 8-9) are as much as 6 ft below the level of the river upstream from the causeway. Ground water discharges into these channels, creating a localized southward flow within a ground-water system in which most flow is toward the northwest.

The regional ground-water system has a vertically upward component of flow along the Tanana River (fig. 10). But water levels in closely spaced wells completed at different depths, such as LF-12 (screened from 48.4 to 50.4 ft below land surface) and LF-13 (screened from 14.5 to 16.5 ft), are similar, indicating that shallow ground-water flow beneath the landfill is primarily horizontal.

The aquifer beneath the landfill consists primarily of glaciofluvial deposits of sand and gravel that contain some silt and organic matter. The U.S. Army Corps of Engineers (1974) reports that the hydraulic conductivity of similar materials near Moose Creek Dam, about 16 mi east of the landfill, is approximately 1,000 ft/d. Assuming a porosity of 30 percent and a hydraulic slope of 2 to 4 ft/mi, the velocity of water through the material's pores would be about 1 to 2.5 ft/d. This range of velocities indicates that it would take from 6 to 15 years for water to travel 1 mi in the aquifer beneath the landfill.

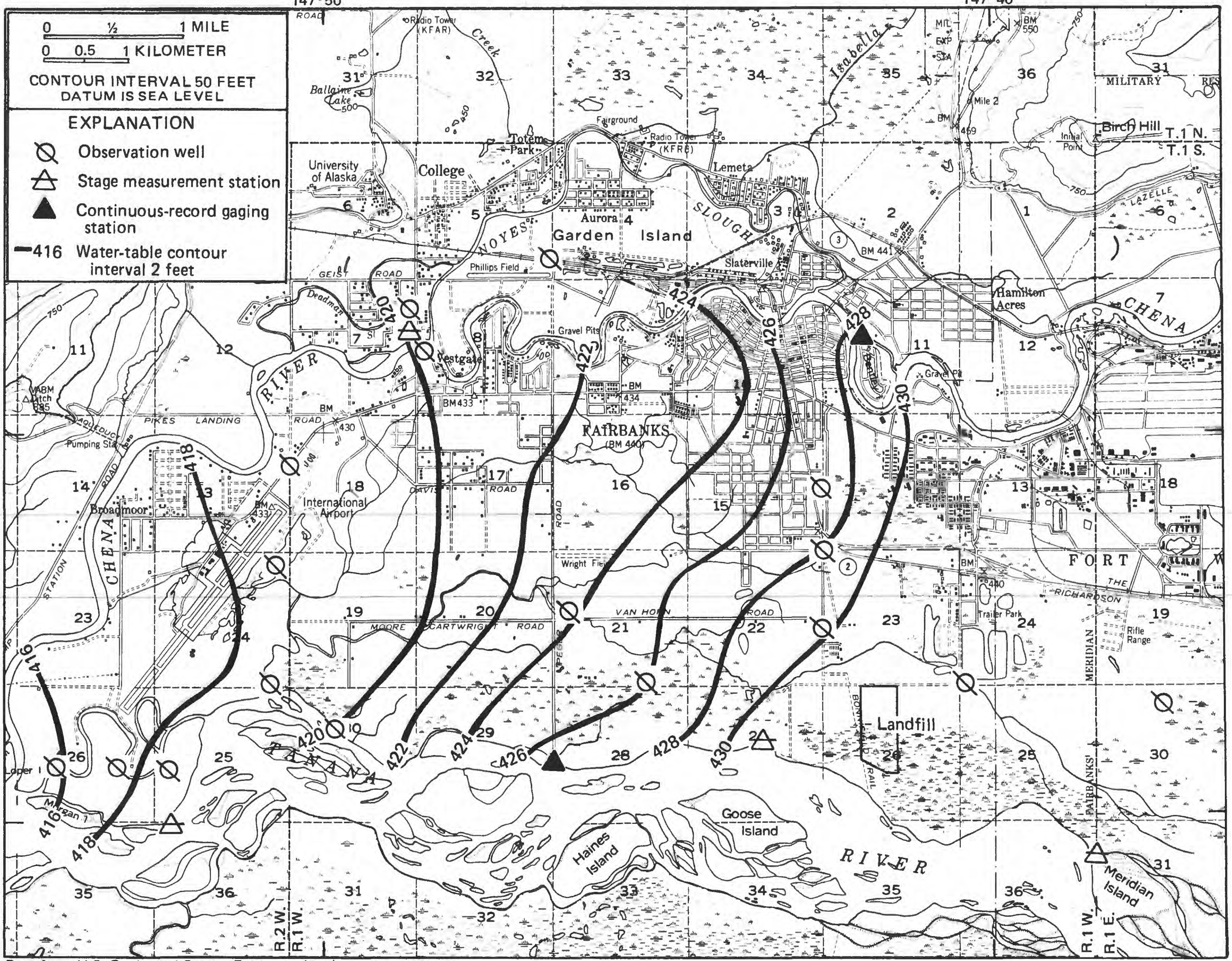
In 1982, the Corps of Engineers began construction of a drainage channel, locally referred to as "Ditch A" (fig. 2), that extends westward 4 mi from the west boundary of the landfill to a point southwest of Fairbanks where it discharges near the mouth of the Chena River. The drainage channel is designed to provide the city of Fairbanks protection from seepage under the Tanana levee and from local surface runoff. Seasonally, Ditch A may intersect the water table at several points near the landfill; a number of seeps occur along the banks of the ditch (fig. 11). A sketch of the shallow ground-water system for the Tanana River to Ditch A (fig. 12) illustrates that local ground-water flow originating from the Tanana River may keep leachate generated from the landfill near the water-table surface and move it toward the ditch.

Water-level data from wells at the landfill indicate an elevated water table, or ground-water mound, in the underlying aquifer. This mound is probably created by a slow but continuous leakage of water stored in the landfill. Presumably, precipitation on the landfill surface infiltrates the refuse and the water is temporarily stored. Slow release of the water recharges the aquifer, causing a mound to form on the water table. As with the regional water table, the mound configuration



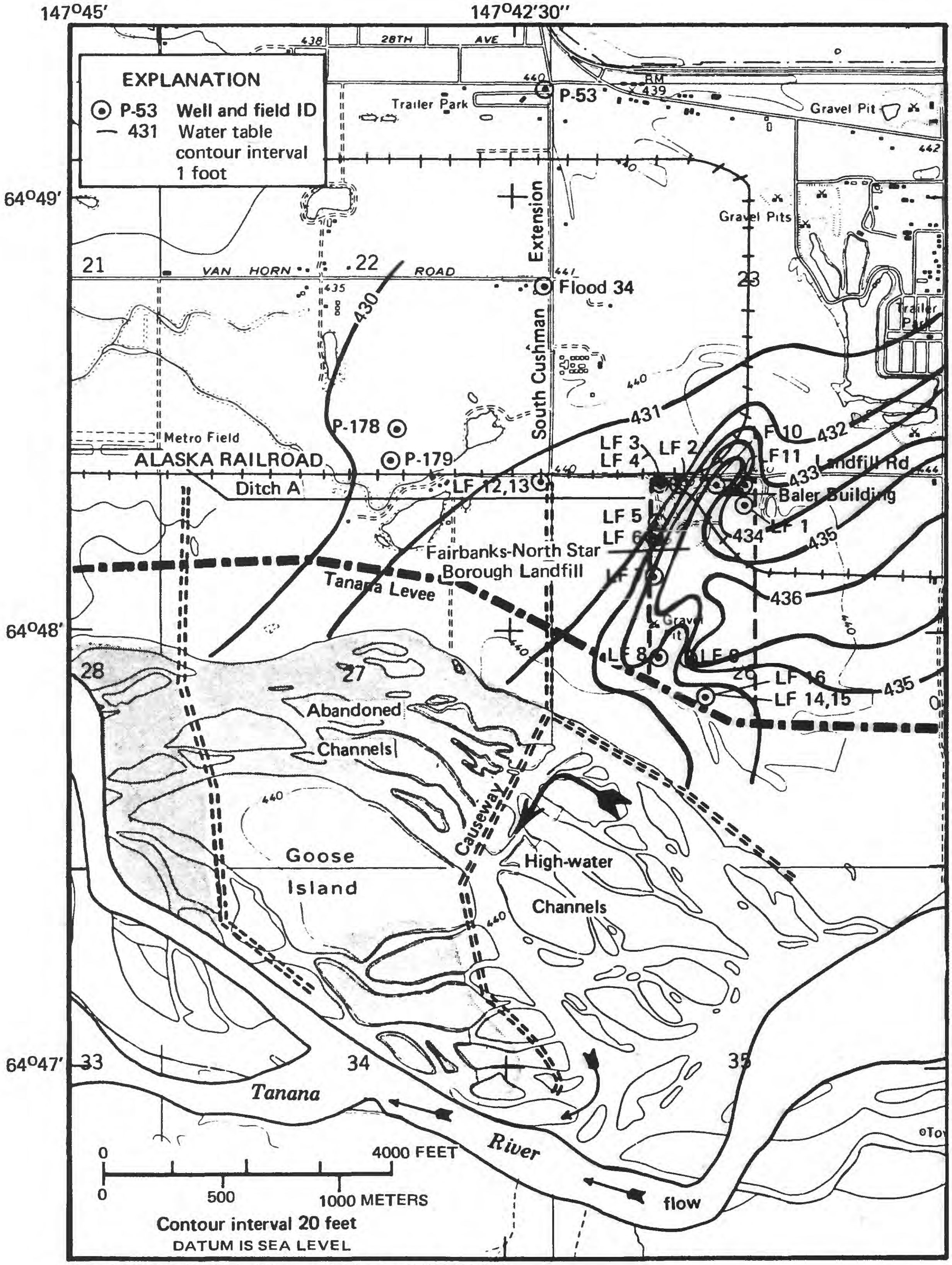
Base from U.S. Geological Survey, Fairbanks (D-2), Alaska, 1:63, 360

Figure 6.--Potentiometric surface in the aquifer with high stage in the Tanana River and low stage in the Chena River (modified from Nelson, 1978).



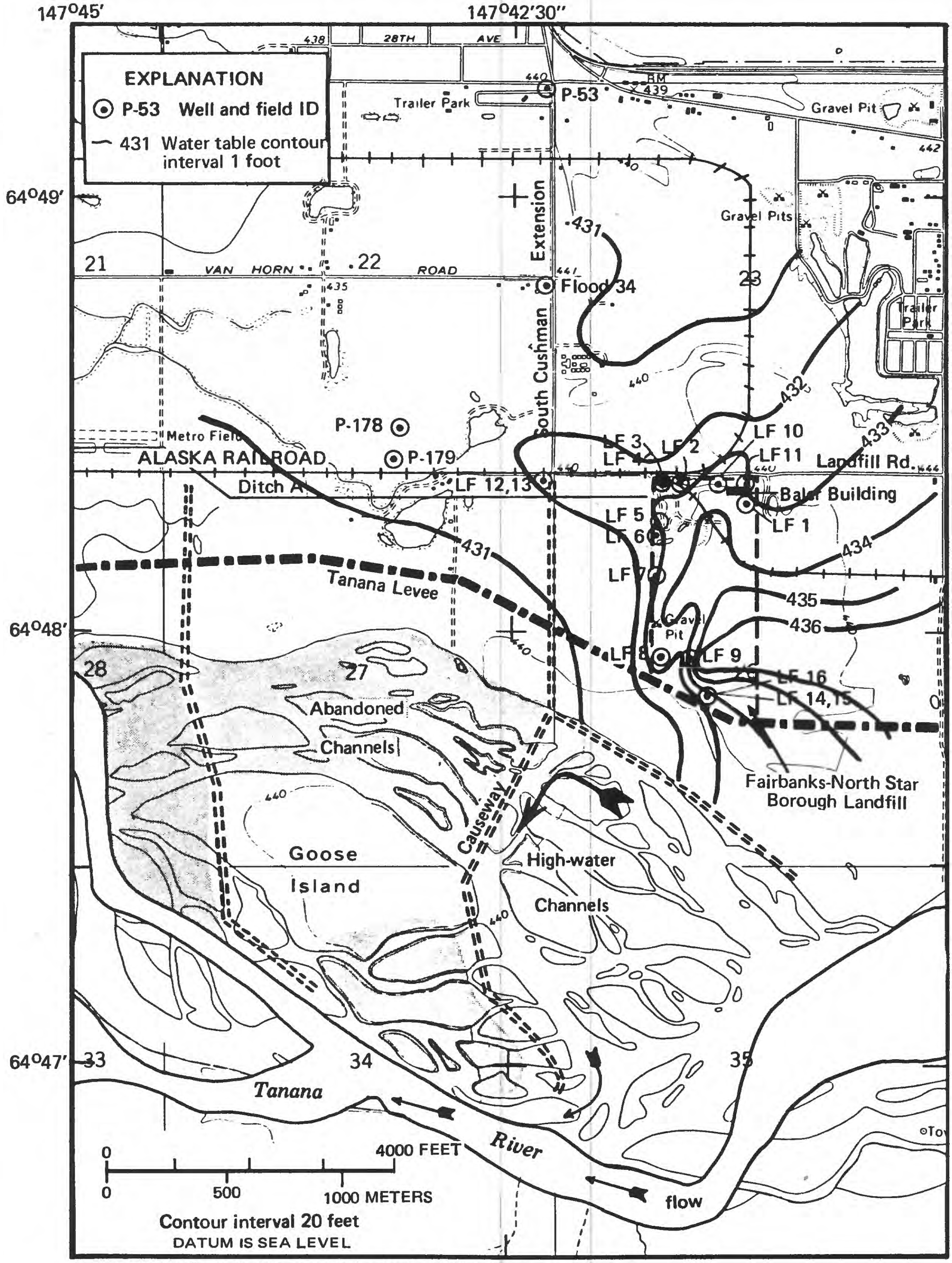
Base from U.S. Geological Survey, Fairbanks (D 2), Alaska, 1:63,360

Figure 7.-- Potentiometric surface in the aquifer when both the Tanana and the Chena Rivers are at high stage (modified from Nelson, 1978).



Base from U.S. Geological Survey Fairbanks, D-2, 1:24,000

Figure 8.--Potentiometric surface in the aquifer, January 1983.



Base from U.S. Geological Survey Fairbanks, D-2, 1:24,000

Figure 9.--Potentiometric surface in the aquifer, September 1983.

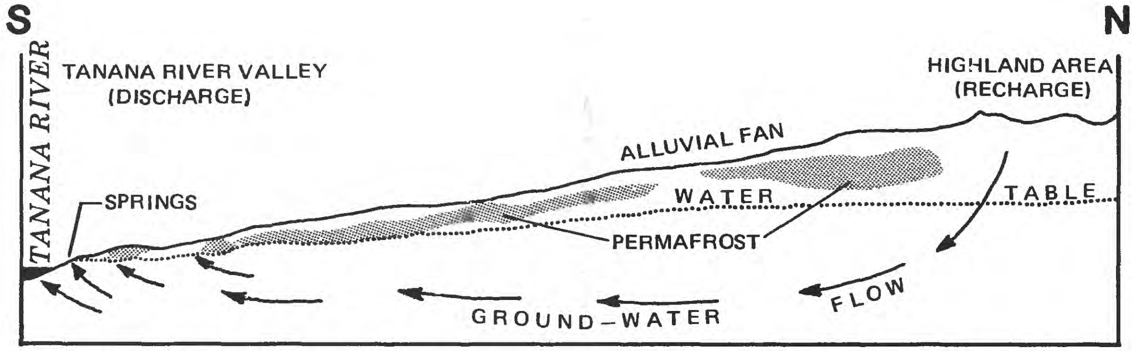


Figure 10. -- Sketch showing ground-water flow from highland recharge areas to discharge areas in the Tanana River valley

Figure 11. -- Ditch A west of the Fairbanks-North Star Borough landfill in the summer of 1982. Landfill area is to the right with the Baler Building in the background. X marks seeps along the bank of Ditch A where ground water is discharging.

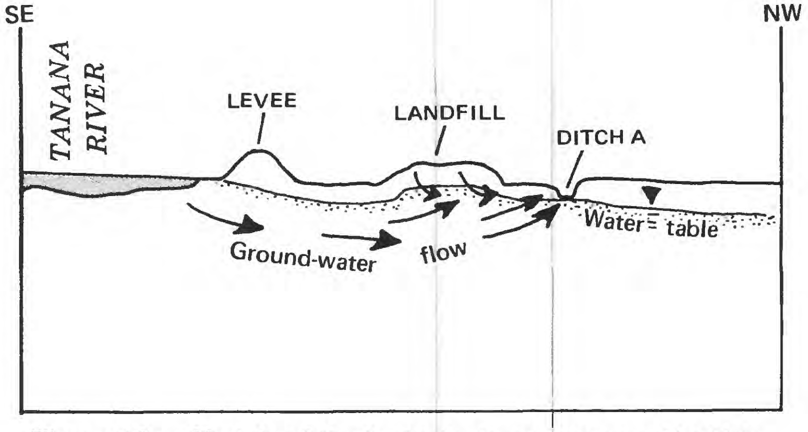


Figure 12. -- Sketch of the hydrologic system near the Fairbanks-North Star Borough landfill showing ground-water flow into Ditch A.

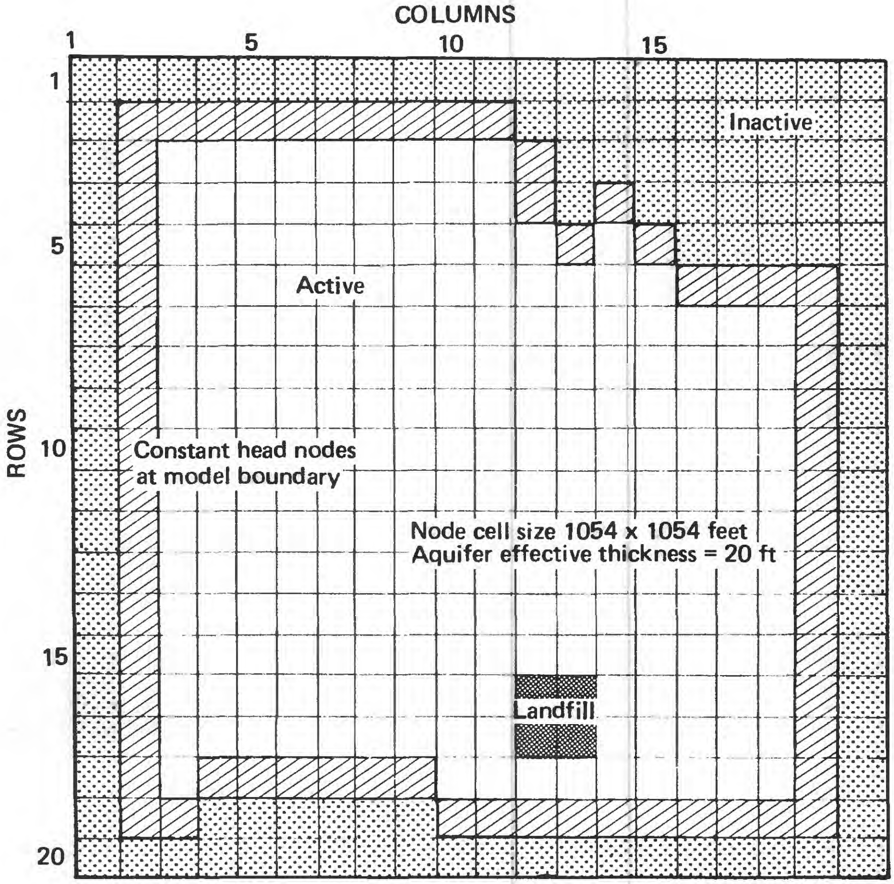


Figure 13. -- Finite difference grid used for digital model of the ground-water system underlying the Fairbanks landfill See figure 1 for location of model boundary.

changes seasonally. The mound is more pronounced in winter when the regional water table is near its annual low. During the summer, a higher regional water table tends to mask the recharge contribution from the landfill.

A digital ground-water flow and mass transport model was developed and used to simulate water-level, flow, and water-quality conditions beneath and near the landfill. The model was based on a method-of-characteristics, finite difference procedure developed by Konikow and Bredehoeft (1978). The boundary of the modeled area is shown in figure 1 and boundary conditions assumed for the model are shown in figure 13. Because the stages of the Tanana and Chena Rivers are the dominant factors influencing ground-water levels in the aquifer, and because the hydraulic gradient is small and relatively constant throughout the year, constant head nodes were used to approximate the boundaries of the flow model.

Near the landfill, ground water flows through sand and gravel deposits in the upper part of the aquifer. Water infiltrating the landfill surface may move only a few feet into the saturated deposits and may not immediately enter a deeper ground-water flow system. The model was tested both with and without Ditch A. Comparison of the results (figs. 14 and 15) shows that contours on the simulated water levels are displaced when Ditch A is represented, as would be expected if some ground water is captured by the ditch. Because of continuing construction along Ditch A during this study, no attempt was made to monitor its surface flow.

The model was also used to simulate ground-water flow into Ditch A at different rates. Model results indicate that for very low values of flux [less than 2 (ft^3/s)/mi of ditch length], landfill leachate tends to move under the ditch in a relatively unaffected manner. At fluxes greater than 2 (ft^3/s)/mi, however, almost all of the leachate plume flows into the ditch. Because an inflow of 2 (ft^3/s)/mi into Ditch A is a reasonable value, it is probable that most of the leachate emanating from the landfill enters Ditch A and moves out of the area as surface flow if ground-water levels are above the bottom of the drainage channel. Because of the high transmissivity of the underlying sands and gravels (Nelson, 1978), vertical flow beneath the landfill was estimated to be negligible. However, some vertical dispersion probably occurs, causing dilution of the plume as it migrates downgradient (north-northwestward) from the landfill.

GEOCHEMISTRY

Water Quality

Ground water in Fairbanks that is intended for potable supply usually must be treated to remove excessive amounts or iron and manganese, which are weathering products of the mafic (containing iron and magnesium) and sulfide minerals in the area. Iron commonly exceeds by thirtyfold the 0.3 mg/L limit suggested by the U.S. Environmental Protection Agency (1977), and the concentration of manganese is commonly two to three times greater than the suggested limit of 0.05 mg/L. Concentrations of several chemical constituents in water samples from wells in the landfill are higher than background levels in other ground water from the general Fairbanks area (table 1; Flynn, 1985).

Although chemical and biological reaction rates are retarded by the cold ground temperatures, there apparently is sufficient activity within the Fairbanks landfill to generate small amounts of heat that affect the shallow ground water. Values of temperature and specific conductance of ground water in the landfill area suggest that a plume of warmer, as well as more mineralized, water is

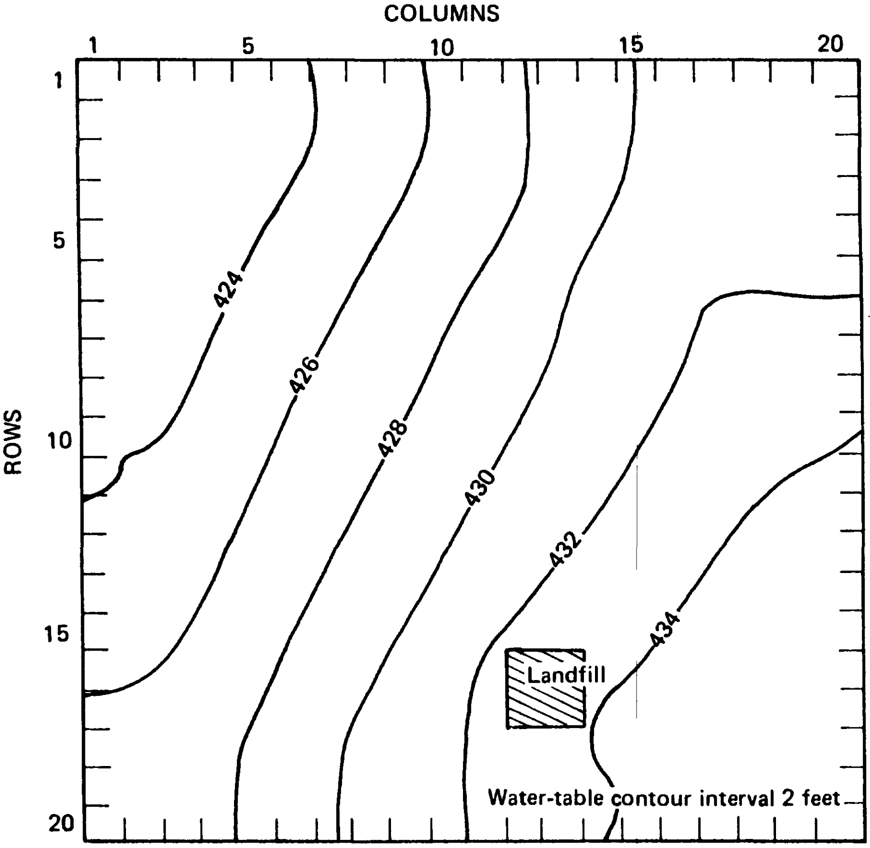


Figure 14. -- Simulated water-table surface in the aquifer underlying the Fairbanks-North Star Borough landfill without Ditch A. See figure 1 for location of model boundary.

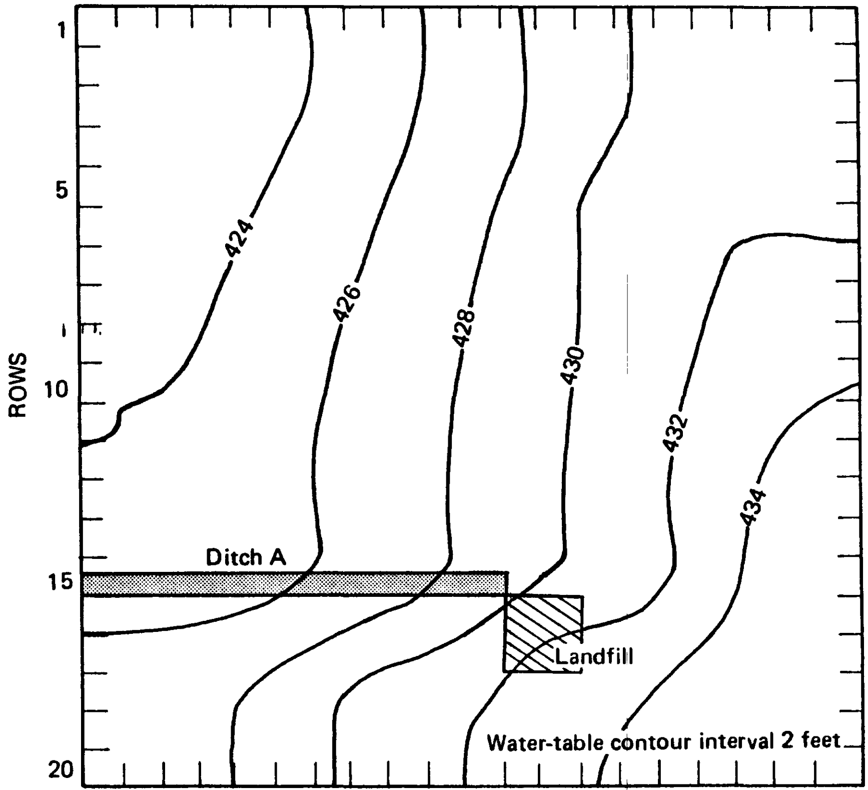


Figure 15. -- Simulated water-table surface in the aquifer under-the Fairbanks-North Star Borough landfill with 3.75 $(ft^3/s)/mi$ inflow into Ditch A. See figure 1 for location of model boundary.

Table 1.--*Background and March 1983 values of selected constituents in ground water from the Fairbanks North Star Borough landfill*

[Values in milligrams per liter, except as noted; µS/cm, microsiemens per centimeter at 25 °C]

Constituent	Background value	Well LF-1	Well LF-4	Well LF-7
Specific conductance (µS/cm)	400	1,500	1,250	1,400
Temperature (°C)	1.5	2.5	1.5	1.0
pH (units)	7.0	6.65	7.1	6.75
Dissolved oxygen	.0	.0	--	.0
Dissolved solids (sum of constituents)	250	860	630	810
Silica (dissolved, as SiO_2)	16-27	37	34	23
Alkalinity (as $CaCO_3$)	200	341	290	670
Chloride (dissolved, as Cl)	2-3	280	130	53
Nitrogen (total, as N)	1.0	--	.8	--
Carbon (total, as C)	5.0	--	8.8	--
Aluminum (dissolved, as Al)	.02	.01	--	.02
Arsenic (dissolved, as As)	.013	.008	.013	.003
Barium (dissolved, as Ba)	.4	.82	--	1.3
Iron (dissolved, as Fe)	0.01-10	11	10	42
Lithium (dissolved, as Li)	.01	.011	--	.009
Manganese (dissolved, as Mn)	1.5	2.7	4.9	3.5

present between wells LF-7, the baler well, and well LF-3 (fig. 16). The data also indicate that the elevated values observed in water samples from near the landfill reduce to background level within about 1,500 ft along the flow path from the landfill. The higher temperatures of the ground water are probably due to warmer water emanating from the landfill.

An absence of dissolved oxygen in samples from water in the aquifer near the Fairbanks landfill (table 1) may be due to a high organic content of the silt deposits interbedded with fluvial sands and gravels. As water moves from the Tanana River into the aquifer it loses oxygen to decaying organic matter in these deposits. Oxidation of sulfides and mafic minerals in these deposits may also cause a loss of oxygen and lead to higher concentrations of iron, manganese, and possibly arsenic in the ground water.

Isotope Data

Stable isotopes of hydrogen (deuterium, designated by D) and of oxygen (oxygen-18, designated by ^{18}O) occur naturally. Comparison of their ratios in a water sample to their ratios in average sea water (SMOW, Standard Mean Ocean Water) or the Meteoric Water Level (MWL) has been used as an index to the history of the sample's source (Gat, 1980). The relative enrichment or impoverishment of the isotopes in water samples is expressed as a δD or $\delta\ ^{18}O$ departure above or below SMOW = 0, in parts per thousand (Hem, 1985, p. 162). Tritium also may be used to date certain waters because of its relatively short half-life of 12.3 years.

Three water samples collected near the landfill were analyzed for tritium, deuterium, and oxygen-18 (table 2). Oxygen-18 and deuterium values for samples from the Tanana River and from wells P-179 and Flood-34 plot just below the MWL (fig. 17). The position of these data points so close to the MWL suggests that the ground water near the landfill is relatively young, and that the water was only recently recharged to the ground-water system. Concentrations of tritium in water samples from the Tanana River and from wells P-179 and Flood-34 (table 2) indicate that the ground water is less than 20 to 30 years old.

Chloride Concentrations

High concentrations of the chloride ion are commonly present in landfill leachate. Because chloride moves through most soils with less retardation or loss than other ions tested (Hem, 1985, p. 118), it has been used as a tracer for or indicator of the presence of leachate. Chloride concentrations ranging from 11 to 280 mg/L were present in samples from six of the wells in and adjacent to the Fairbanks-North Star Borough landfill (Flynn, 1985, table 3). Concentrations in the Fort Wainwright well (4.5 mg/L) and Flood 34 (3.3 mg/L) are assumed to indicate the background concentrations of chloride in ground water in the Fairbanks area.

Assuming that most of the chloride transport occurs in the upper 30 ft of the aquifer, and that flow is horizontal, then the upper 30 ft of the aquifer can be modeled independently of the rest of the aquifer. The transmissivity of this 30-foot "aquifer" is 30,000 ft^2 /d. Using the mass transport simulation capability of the digital model, steady-state flow beneath the landfill was simulated. Chloride concentration in the leachate was set at 25 mg/L for the simulation. Longitudinal dispersivity was assumed to be 30 ft and the ratio of longitudinal to transverse dispersivity was assumed to be 0.1. The background chloride concentration used in the model was assumed to be 0.0 mg/L.

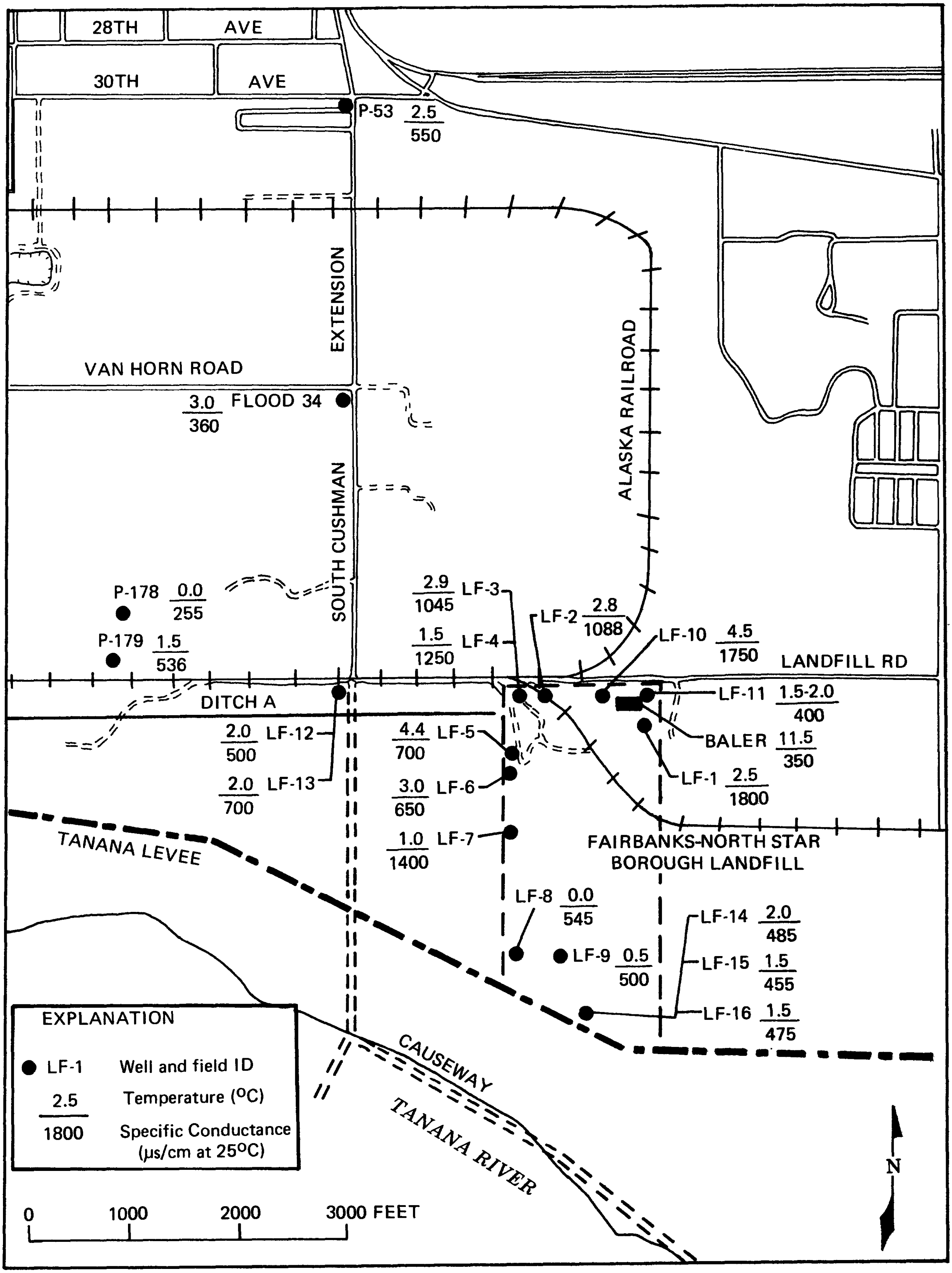


Figure 16.--Specific conductance and temperature of ground water from the Fairbanks-North Star Borough landfill area, March 1983. See figure 1 for location. (Data from Flynn, 1985.)

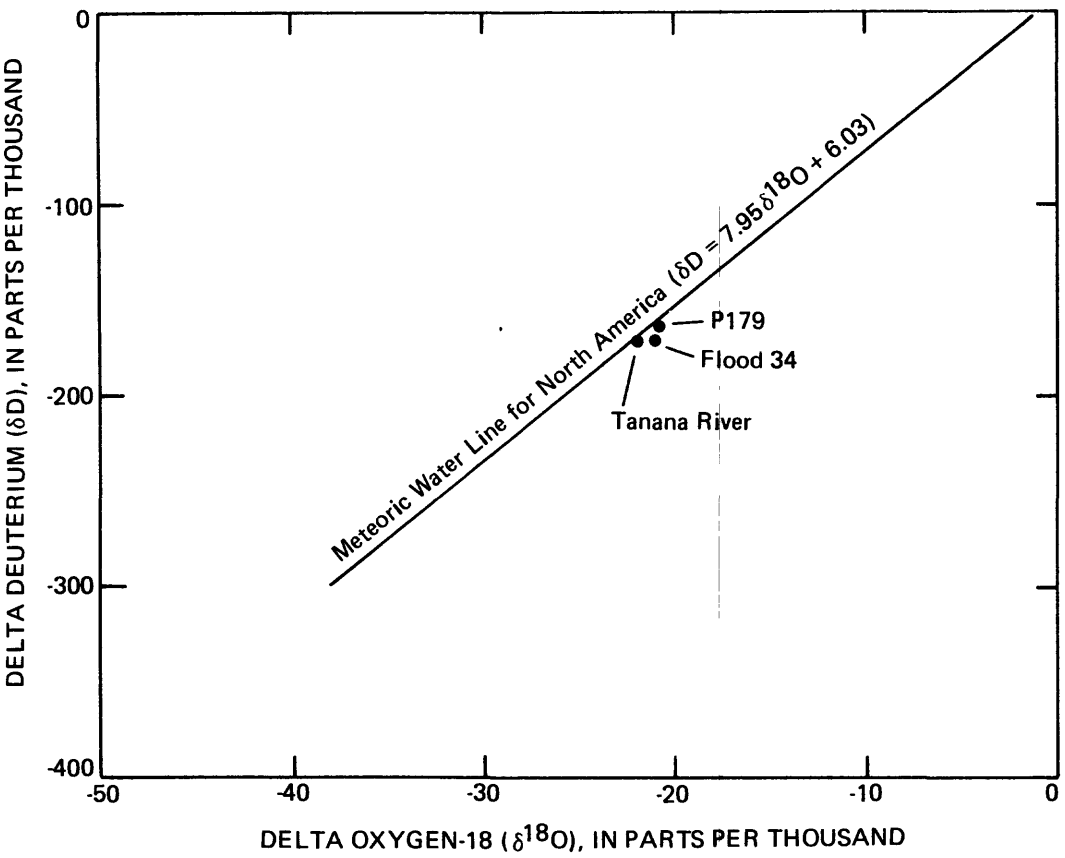


Figure 17.--Ratio of oxygen-18 to deuterium.

Table 2.-- *Tritium, deuterium, and oxygen-18 values in water samples from the Tanana River and two wells*

Location	Tritium (units)	Deuterium (δD in parts per thousand)	Oxygen ($\delta^{18}O$ in parts per thousand)
Tanana River	200	-170	-22.0
Well P-179	400	-165	-20.8
Well Flood-34	330	-169	-20.9

The model-simulated concentrations of chloride in the leachate plume after a period of 9.9 years without and with Ditch A are shown in figures 18 and 19. Elevated chloride concentrations were shown to occur within 10,500 ft of the landfill without Ditch A and within 9,500 ft of the landfill with Ditch A present. Lower concentrations of leachate in the ground water northwest of the landfill with Ditch A in place are due to ground-water discharge into the ditch. However, the rate of ground-water discharge into Ditch A is dependent on ground-water levels; when ground-water levels are below the bottom of the ditch, no discharge will occur.

It is emphasized that this model is not calibrated to accurately depict actual conditions. The model is intended to represent what might occur under idealized conditions.

Ground-Conductivity Survey

A ground conductivity survey was conducted in the landfill area using Geonics[1] EM-34 equipment (fig. 20) to locate and define the areal extent of contamination. The elevated values of conductivity represent the approximate areal extent of the leachate plume and indicate the direction in which the leachate plume has moved (fig. 21). The extension of the plume in a north-northwestward direction agrees with the ground-water flow direction indicated by contour lines in figures 6-9.

SUMMARY AND DISCUSSION

The Fairbanks-North Star Borough landfill has been in operation for about 25 years. By several methods, this study demonstrates the existence of a small plume of slightly chemically enriched water emanating from the landfill. The plume contains elevated (higher-than-background) concentrations of chloride. However, concentrations of most dissolved constituents in the plume, including chloride, are generally within the recommended limits for drinking water, with iron, manganese, barium, and arsenic being the exceptions.

The Fairbanks landfill is similar to other landfills in cold regions in the production of decomposition products and their release to the underlying ground-water system. Long, cold winters and low ground temperatures inhibit chemical and biological reactions, so that decomposition of refuse is limited to only the top few inches of material. This lack of biological activity and associated decomposition results in very little heat being generated within the landfill. However, the plume of mineralized water directly below the landfill does show a minor elevation of temperature, about 1 °C, above background ground-water temperatures.

The leachate generated in the landfill refuse moves downward to the top of the water table. Before the construction of Ditch A, this leachate most likely moved toward the northwest, away from the landfill. Diffusion and dispersion of the plume probably cause dilution of the leachate to background concentrations in a very short distance. Detectable levels of leachate were not found in samples of water from well Flood-34, about 3,000 ft northwest of the landfill.

Construction of Ditch A appears to have modified the local ground-water flow system so that some of the leachate may be captured by the ditch and may flow westward. Some of this water may

1. Use of the trade name "Geonics" in this report is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.

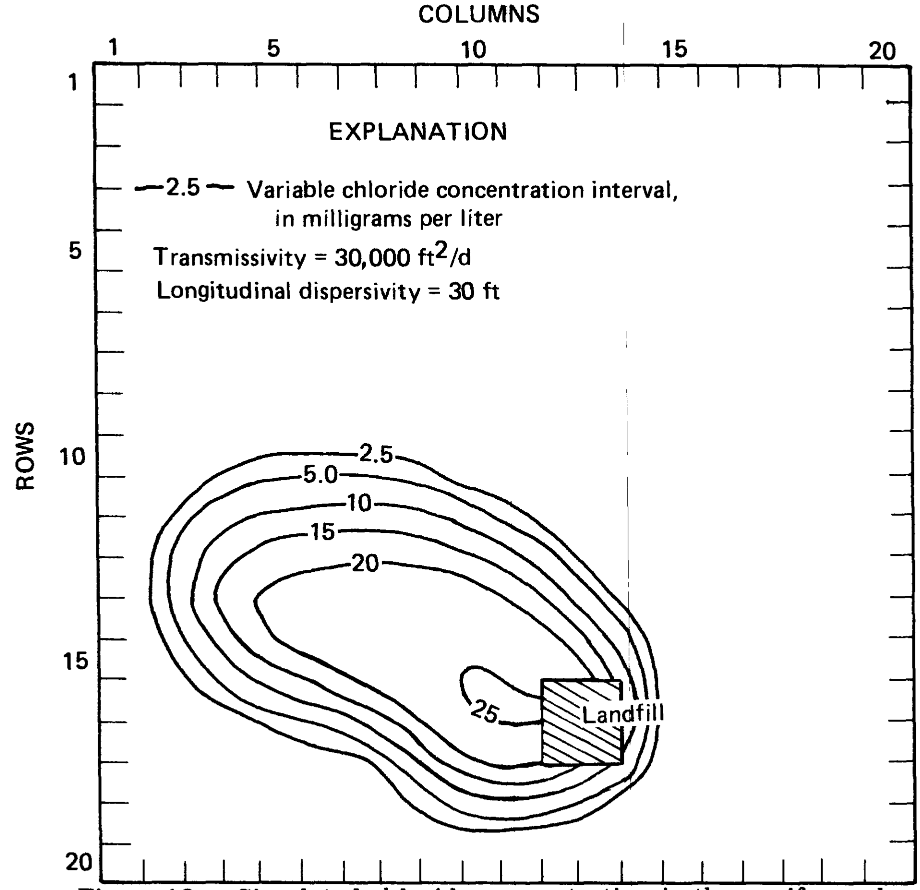


Figure 18. -- Simulated chloride concentration in the aquifer underlying the Fairbanks-North Star Borough landfill after 9.9 years without Ditch A. See figure 1 for location of model boundary.

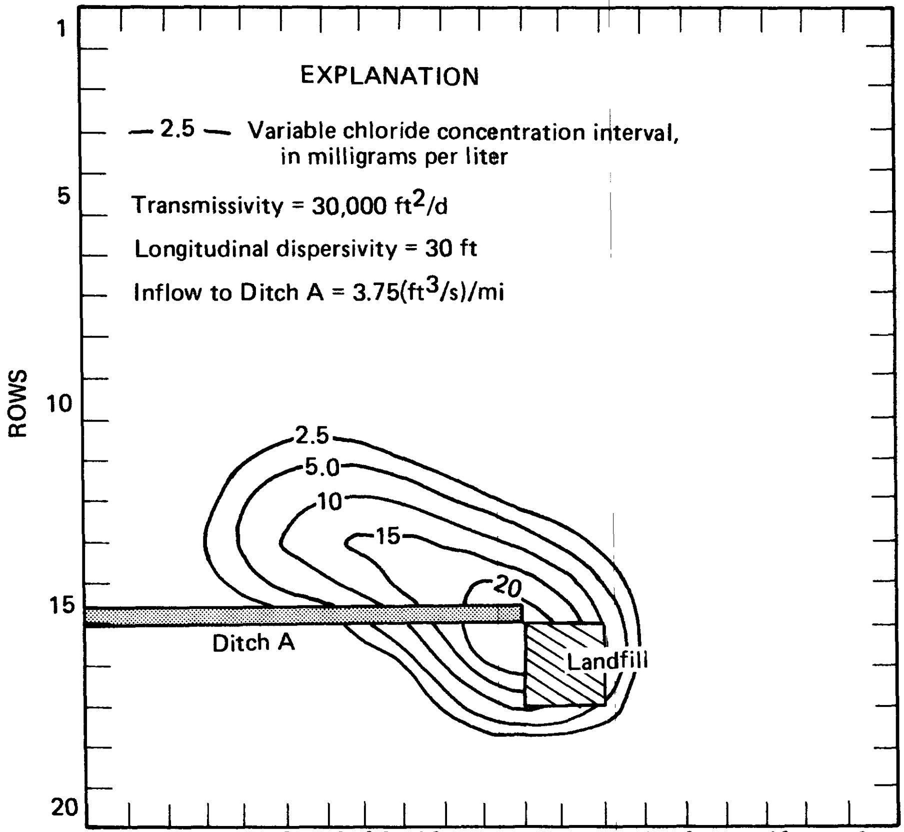


Figure 19. -- Simulated chloride concentration in the aquifer underlying the Fairbanks-North Star Borough landfill after 9.9 years with Ditch A. See figure 1 for location of model boundary.

Figure 20. -- Geonics EM-34 in use at the Fairbanks-North Star Borough landfill in the summer of 1983. A, transmitter and readout device. B, transmitting coil shown in horizontal mode.

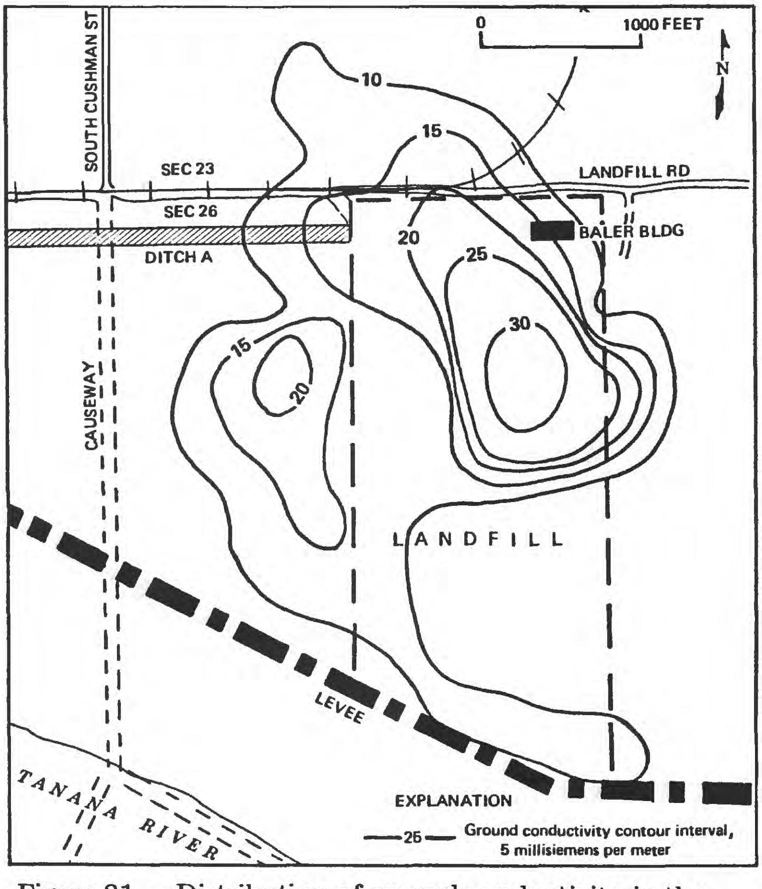


Figure 21. -- Distribution of ground conductivity in the vicinity of the Fairbanks-North Star Borough landfill from EM-34 survey in the horizontal dipole mode. See figure 1 for location of landfill.

then reinfiltrate the ground or may flow as surface water into the Chena River. Mixing with other surface water in Ditch A, however, may result in dilution of the leachate before it reaches the river.

Analyses of isotopes of hydrogen and oxygen in samples of ground water beneath the landfill suggest the water is relatively young -- about 20 to 30 years old. Thus the shallow ground-water system is probably recharged primarily by direct infiltration of precipitation and by shallow subsurface flow of water from the nearby Tanana River.

Data collected during this study indicate that the plume of mineralized water from the Fairbanks landfill is partially intercepted by a drainage ditch north of the landfill. Concentrations of minerals from the landfill approach background values within about 1,500 ft downgradient. Thus, it appears that the city's water-supply wells will not be affected by the leachate.

SUGGESTED FUTURE STUDIES

The following items are suggested as possible future work in order to monitor leachate production from the landfill:

* Monitor temperature of water in wells near and within the landfill. With time, the mean annual internal temperature of the landfill may increase, leading to an increase of leachate production. The above-suggested monitoring system would provide warning if this event occurs.

* Install and monitor several shallow wells to the northwest of the landfill in the path of the leachate plume, both north and south of Ditch A. Periodically, collect water samples for chemical analysis from these wells on a long-term basis.

* Determine the seasonal surface-water flow in Ditch A. Collect samples for chemical analysis from water in Ditch A to determine if leachate is present in its water.

* Monitor dissolved organics.

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