Water Movement and Water Chemistry in the Unsaturated Zone at a Low-Level Radioactive-Waste Disposal Site Near Sheffield, Illinois, 1986–87

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Water Movement and Water Chemistry in the Unsaturated Zone at a Low-Level Radioactive-Waste Disposal Site Near Sheffield, Illinois, 1986–87

By PATRICK C. MILLS

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
square millimeter (mm^2)	0.001550	square inch (in^2)
cubic centimeter (cm^3)	0.06102	cubic inch (in^3)
cubic meter (m^3)	35.31	cubic foot (ft^3)
hectare (ha)	2.471	acre
gram per cubic centimeter (g/cm^3)	0.5780	ounce per cubic inch (oz/in^3)
milliliter (mL)	0.0002642	gallon (gal)
millimeter per millimeter (mm/mm)	0.03937	inch per inch (in/in)
millimeter per day (mm/d)	0.03937	inch per day (in/d)
meter per second (m/s)	3.281	foot per second (ft/s)
meter per day (m/d)	3.281	foot per day (ft/d)
millimeter per year (mm/yr)	0.03937	inch per year (in/yr)
centimeter per year (cm/yr)	0.3937	inch per year (in/yr)
cubic millimeter per day (mm^3/d)	0.00006102	cubic inch per day (in^3/d)
degree Celsius (°C)	°F = 1.8 × °C + 32	degree Fahrenheit (°F)
curie (Ci)	3.701×10^{10}	Becquerel (Bq)
picocurie per liter (pCi/L)	0.03701	Becquerel per liter (Bq/L)
nanocurie per liter (nCi/L)	37.01	Becquerel per liter (Bq/L)
nanocurie per year per square centimeter [$(nCi/yr)/cm^2$]	37.010	Becquerel per year per square centimeter [$(Bq/yr)/cm^2$]
microgram per liter ($\mu g/L$)	1.0	part per billion (ppb)
milligram per liter (mg/L)	1.0	part per million (ppm)
milligram per liter calcium carbonate (mg/L $CaCO^3$)	1.219	milligram per liter bicarbonate (mg/L HCO^3)

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.

Water Movement and Water Chemistry in the Unsaturated Zone at a Low-Level Radioactive-Waste Disposal Site Near Sheffield, Illinois, 1986–87

By Patrick C. Mills

Abstract

Hydrologic research was conducted at the low-level radioactive-waste disposal site near Sheffield, Ill., during 1986–87. Radioactive wastes were buried at the site during 1967–78 in 21 trenches constructed in unconsolidated glacial and postglacial deposits that overlie Pennsylvanian bedrock. The purpose of the research was to address questions generated by earlier studies at the disposal site from 1981 to 1985. The specific goals of the research were (1) to characterize temporal trends in water movement and water chemistry over several (5–11) years, (2) to evaluate preferential movement of water and leachate (soluble trench-waste constituents) in an unsaturated glacial sand deposit underlying several disposal trenches, and (3) to determine the extent to which a tunnel, used in the study to access geologic deposits below four trenches, affected the natural movement of water in the unsaturated deposits.

Annual (July through June) precipitation at the site decreased from 928 mm (millimeters) (1982–83) and 968 mm (1983–84) to 774 mm (1984–85), 864 mm (1985–86), and 695 mm (1986–87). A corresponding decrease occurred in estimates of annual seepage to the trenches and (or) ground-water recharge from 107 mm (1982–83 and 1983–84) to 49 mm (1984–85), 74 mm (1985–86), and 48 mm (1986–87).

The seasonal pattern of early spring recharge to the unsaturated zone below the trenches, as observed in a 1981–85 study of the site, was obscured in 1986–87 by the large reduction in pressure-head fluctuation and an overall decline in pressure heads during the period; an additional recharge period also was observed in fall 1986. Peak soil-water fluxes at two gravity lysimeter locations decreased from about 15 and 11 mm/d (millimeters per day), respectively, in 1985, to about 0 and 6 mm/d, respectively, in 1986–87. Water-table altitudes decreased from historical highs in March 1985 to near-historical lows in 1986–87.

Average tritium concentrations in soil water increased from 70,100 pCi/L (picocuries per liter) from July 1982 through June 1984 to 153,000 pCi/L from April 1986 through July 1987 at below-trench vacuum lysimeter locations. Tritium concentrations as high as 15,000,000 pCi/L were detected below one trench in soil water from the Hulick Till Member of the Glasford Formation. Volatile organic compounds were detected in a synoptic sample from the Toulon Member of the Glasford Formation. Concentrations of inorganic ions in soil water and ground water changed little from 1982 to 1987

Flow is unevenly distributed through the Toulon Member. Slow, continuous water movement appears to occur through most areas of the sand deposit; localized, preferential flow along near-saturated to saturated flow paths occurs as well. Data from the 7 (of 16) gravity lysimeters in which free drainage of soil water occurred indicate that the flow paths may be less than 1 square millimeter in cross-sectional area. Because of their localized occurrence and small size, the flow paths were not readily identified by soil-moisture tensiometers. Average annual tritium flux through the Toulon Member was estimated to be 0.59 nanocurie per year per square centimeter.

The location of preferential flow paths in the Toulon Member appears to be related to the location of flow paths in the overlying trenches. The timing and rates of water movement through the sand deposit are related to precipitation patterns, seasonal climatic cycles, and factors such as trench-interior characteristics.

Tritium concentrations in the water moving preferentially through the Toulon Member fluctuate seasonally. Concentrations increase as tritiated water is flushed from the trenches during spring recharge; in some cases concentrations decrease, apparently as a result of dilution by recent recharge water. Changes in tritium concentrations also appear to occur as waste containers deteriorate and as flow paths in the trenches change location.

Pressure-head data from tensiometers, soil-moisture-content data, and tritium concentration data from sediment cores and numerical simulations indicate that the tunnel has neither a consistent nor pronounced effect on the natural movement of water. The tunnel appears to perturb natural water movement most directly above and below the tunnel.

INTRODUCTION

The Low-Level Radioactive-Waste Policy Act (Public Law 96–573—December 22, 1980) and the Low-Level Radioactive-Waste Policy Act Amendment of 1985 (Public Law 99—January 15, 1986) mandated the responsibility for disposal of locally generated low-level radioactive wastes to each State. The U.S. Geological Survey (USGS) was directed by Congress to conduct research to aid other Federal and State agencies in developing earth science criteria that could be used in the selection, construction, and monitoring of future radioactive-waste disposal sites. One such research project was the study of an existing disposal site near Sheffield, Bureau County, Ill., from 1981 to 1985. The comprehensive research project included studies of the hydrogeology (Foster and Erickson, 1980; Foster, Erickson, and Healy, 1984; Foster, Garklavs, and Mackey, 1984a,b; Garklavs and Toler 1985; Garklavs and Healy, 1986), runoff, and landform modification (Gray, 1984, 1986; Gray and McGovern, 1986) at the site. Subjects of studies of the unsaturated zone, also undertaken as part of that project, include evapotranspiration and microclimate of a trench cover (Healy, deVries, and Sturrock, 1989), water movement through a trench cover (Healy, 1989), gaseous transport of radionuclides (Striegl, 1988), waste-induced effects on water chemistry (Peters and others, 1992), and water movement through the full thickness of the unsaturated zone (Mills and Healy, 1991).

Peters and others (1992) concluded that, with the exception of increased concentrations of tritium and dissolved organic carbon, water chemistry near the disposal trenches was not substantially different from natural, offsite water chemistry. Mills and Healy (1991) concluded that (1) water movement through the unsaturated zone to the saturated zone occurs primarily as a single, seasonal event, usually confined to late winter through early summer, and (2) water and tritium movement are spatially variable; liquid pressure heads varied over a wider range, both spatially and temporally, in unsaturated clayey silt deposits, and tritium concentrations generally were greatest in unsaturated sand deposits.

Three important questions generated by the 1982–85 studies of Peters and others (1992) and Mills and Healy (1991) are as follow:

1. What are the longer term (5–11 years) trends in water movement and water chemistry, and how are these trends affected by climate and waste-burial conditions?
2. How do water and certain leachates (soluble trench-waste constituents) in the water move through an unsaturated sand deposit (Toulon Member of the Glasford Formation) that underlies several disposal trenches? Limited water movement (but increased tritium concentrations) was detected within this deposit, which, elsewhere at the Sheffield site, is the principal conduit for ground-water flow and tritium migration (Foster, Erickson, and Healy, 1984, p. 23).
3. What is the extent of the influence of the research tunnel that was constructed to allow access to the subsurface for study of the natural movement of water draining from the trenches and the intertrench geologic deposits?

The study from January 1986 through October 1987, described herein, focused on these questions. The study was an outgrowth of, and was intended to supplement, the work conducted by Peters and others (1992) and Mills and Healy (1991), as well as the earlier (1976–84) ground-water studies by Foster, Erickson, and Healy (1984) and Foster, Garklavs, and Mackey (1984a).

Purpose and Scope

This report describes the water-budget, water-movement, and water-chemistry data collected as part of a study of the unsaturated zone at the low-level radioactive-waste disposal site near Sheffield, Ill., to address questions generated by earlier studies. Precipitation, soil-water-content, liquid pressure-head (hereafter referred to as pressure head), soil-water-flux, water-table-altitude, computer-simulated-flow, radiochemistry, and inorganic-chemistry data are discussed in this report. Three virtually independent substudies are described: (1) longer term temporal trends in the water budget and in water movement and water chemistry in the unsaturated and saturated zones (this substudy includes a comparative analysis of data collected in 1986–87 with data collected in 1976–85); (2) water movement and water chemistry in the unsaturated Toulon Member sand deposit where it directly underlies the disposal trenches (this substudy, based on 1986–87 data, addresses the movement and chemistry of water in preferential flow paths through the Toulon Member sand deposit); and (3) the effect of the research tunnel on water movement in the adjacent unsaturated geologic deposits.

The Sheffield site, the research tunnel, and most instruments used in the substudies are described only briefly. The reader is referred to Peters and others (1992) and Mills and Healy (1991), as well as other previously mentioned studies of the site, for detailed descriptions of the history and techniques of radioactive-waste burial, climate, and hydrogeology of the tunnel area and site. The tunnel and instrumentation used in the study are discussed in detail in Mills and Healy (1991) and Healy and others (1986), respectively.

Description of Study Area

The low-level radioactive-waste disposal site is located on 8.1 hectares about 5 kilometers southwest of Sheffield, Ill. (fig. 1). During 1967–78, about 90,000 cubic meters of radioactive waste that contained about 60,000

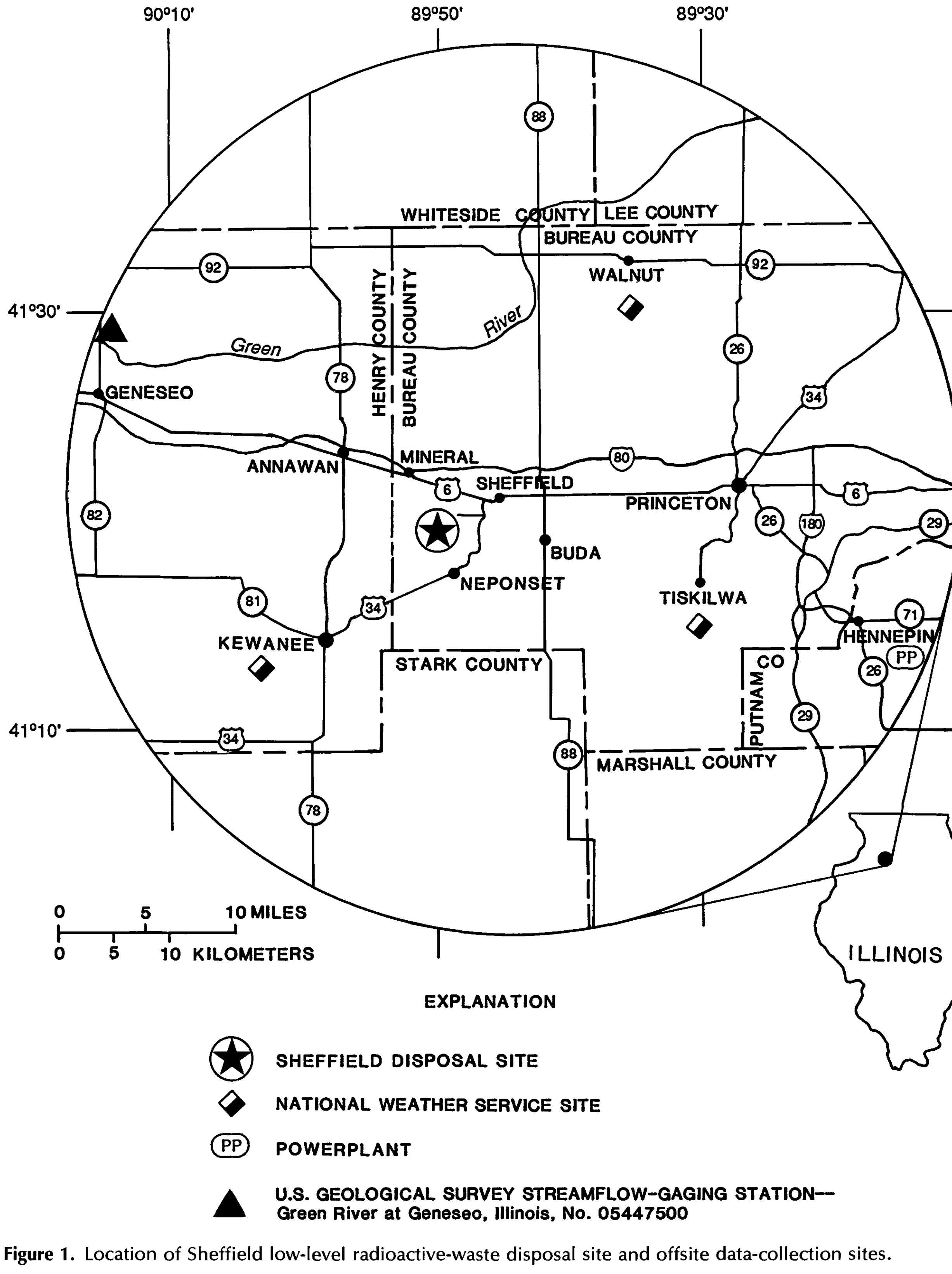


Figure 1. Location of Sheffield low-level radioactive-waste disposal site and offsite data-collection sites.

curies of activity (Illinois Department of Nuclear Safety, written commun., 1979) were buried in 21 disposal trenches (fig. 2). Buried wastes include resins, carcasses of animals, solidified liquid wastes, glassware, paper clothing, containerized gases, building and construction materials, and cleanup materials (Foster, Erickson, and Healy, 1984, p. 8). Waste containers include steel drums, wood crates, plastic containers, concrete casks, and cardboard cartons. The disposal trenches were constructed in the unconsolidated Quaternary deposits that overlie the bedrock.

During 1978–79, a 120-m (meter)-long by 2-m-diameter horizontal tunnel (fig. 3) was constructed in the unconsolidated glacial deposits that underlie four disposal trenches (Foster and Erickson, 1980). The tunnel was constructed to aid hydrogeologic investigations at the disposal site (Foster, Erickson, and Healy, 1984; Mills and Healy, 1991). By using air spades, a 90-m tunnel (section A'–A'' in fig. 3) was dug beneath the trenches and lined with bolted steel plates; the tunnel was extended by attaching a 30-m section (tunnel section south of A' in fig. 3) of corrugated steel culvert to the exposed opening of the 90-m section and backfilling over the extension with excavated fill material. The annulus beyond the bolted liner plates was grouted to prevent seasonal water seepage into the tunnel from the surrounding generally unsaturated deposits. Some slight seepage did occur through the tunnel liner in years when ground-water-recharge rates were very high.

Bedrock at the disposal site consists of about 140 m of shale, mudstone, and coal assigned to the Pennsylvanian Carbondale Formation (fig. 4). Eight Quaternary stratigraphic units, ranging in thickness from 3 to 27.4 m, have been identified at the site; the oldest are Illinoian glacial deposits of the Glasford Formation (Willman and Frye, 1970, p. 12, 52). Wisconsinan deposition is represented predominantly by eolian silt assigned to the Roxana Silt and the Peoria Loess. Holocene deposition is represented by isolated deposits of Cahokia Alluvium. Soil cover at the site is assigned to Modern Soil (Willman and Frye, 1970, p. 89). Most of the site is overlain by reworked earth fill. The stratigraphic nomenclature used in this report is that of the Illinois State Geological Survey and does not necessarily follow the usage of the USGS.

The disposal site covers parts of three small basins drained by intermittent streams that contribute flow to a tributary of Lawson Creek (fig. 2). North of the site, the contact between undisturbed Quaternary deposits and strip-mine spoils defines a ground-water divide. West of the site, a bedrock high forms a ground-water divide. South of the site, the Lawson Creek tributary forms a ground-water sink (Garklavs and Healy, 1986, p. 7). Precipitation that falls within the basins is the source of ground-water recharge.

A pebbly sand unit, the Toulon Member of the Glasford Formation, which underlies about 67 percent of the site, is the principal conduit of ground-water flow (Foster, Erickson, and Healy, 1984, p. 1). This unit conveys ground water from the northern three-fourths of the site southward and eastward toward a strip-mine lake (fig. 2). Ground water from the southern one-fourth of the site flows eastward along a pathway generally coincident with the Lawson Creek tributary. Surface discharge of ground water is to the strip-mine lake and to the Lawson Creek tributary (Foster, Erickson, and Healy, 1984, p. 20). Coal seams within the bedrock and buried channels on the bedrock surface are suspected of conveying some ground water under and around the strip-mine lake (Jeanine Morse, Illinois Environmental Protection Agency, oral commun., 1988). The thick sequence of shale- and mudstone-dominated bedrock underlying the Quaternary deposits is assumed to hydraulically isolate the shallow ground-water system from the deeper, regional aquifers.

The study area for this project was the southeastern quadrant of the disposal site (figs. 2 and 3). The predominant geologic units of the study area are shown in figure 5 (lines of section are shown in fig. 3). Isolated deposits of the Roxana Silt and the Duncan Mills Member of the Glasford Formation are also present in the study area. The geologic units of primary hydrologic interest are the Peoria Loess (wind-blown silt) and three units of the Glasford Formation—the Radnor Till Member (clayey silt), the Toulon Member (silt; well-sorted, medium-grained sand; and pebbly sand), and the Hulick Till Member (clayey silt). The unconsolidated deposits in the study area range in thickness from about 5 to 20 m and directly overlie weathered shale. The unconsolidated deposits, for the most part, are unsaturated (fig. 5), but the Hulick Till Member is partly saturated throughout most of the study area, and the water table periodically rises to the base of the Toulon Member in the northeastern and southern parts of the study area.

Acknowledgments

The author thanks the Illinois Department of Nuclear Safety for sharing hydrochemical information from the Sheffield site and for assisting in providing health-physics services during several phases of the study. The disposal-site operator, US Ecology, Inc., and their onsite manager, Mr. Bowen, are acknowledged for the assistance and cooperation they provided throughout the course of study.

METHODS OF STUDY

The purpose, scope, and approach to research for the three substudies are presented in the following sections. Data for the substudies were collected from three principal locations within the study area (fig. 3)—the cover of trench 2; the tunnel underlying trenches 1, 2, 3, and 11; and four ground-water observation wells flanking the tunnel. All

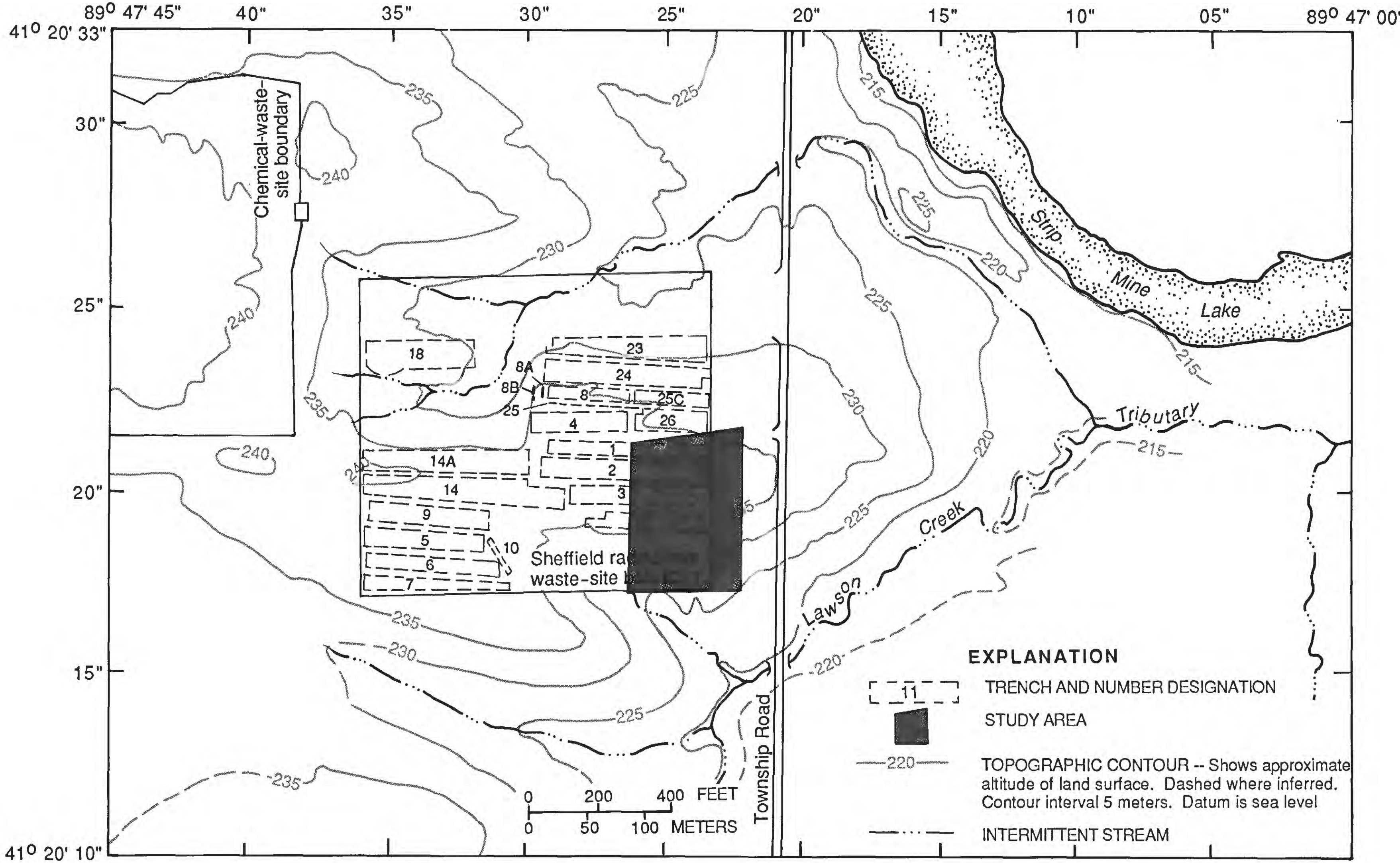


Figure 2. Location of disposal trenches and study area at the Sheffield site. (Modified from Garklavs and Healy, 1986, fig. 3.)

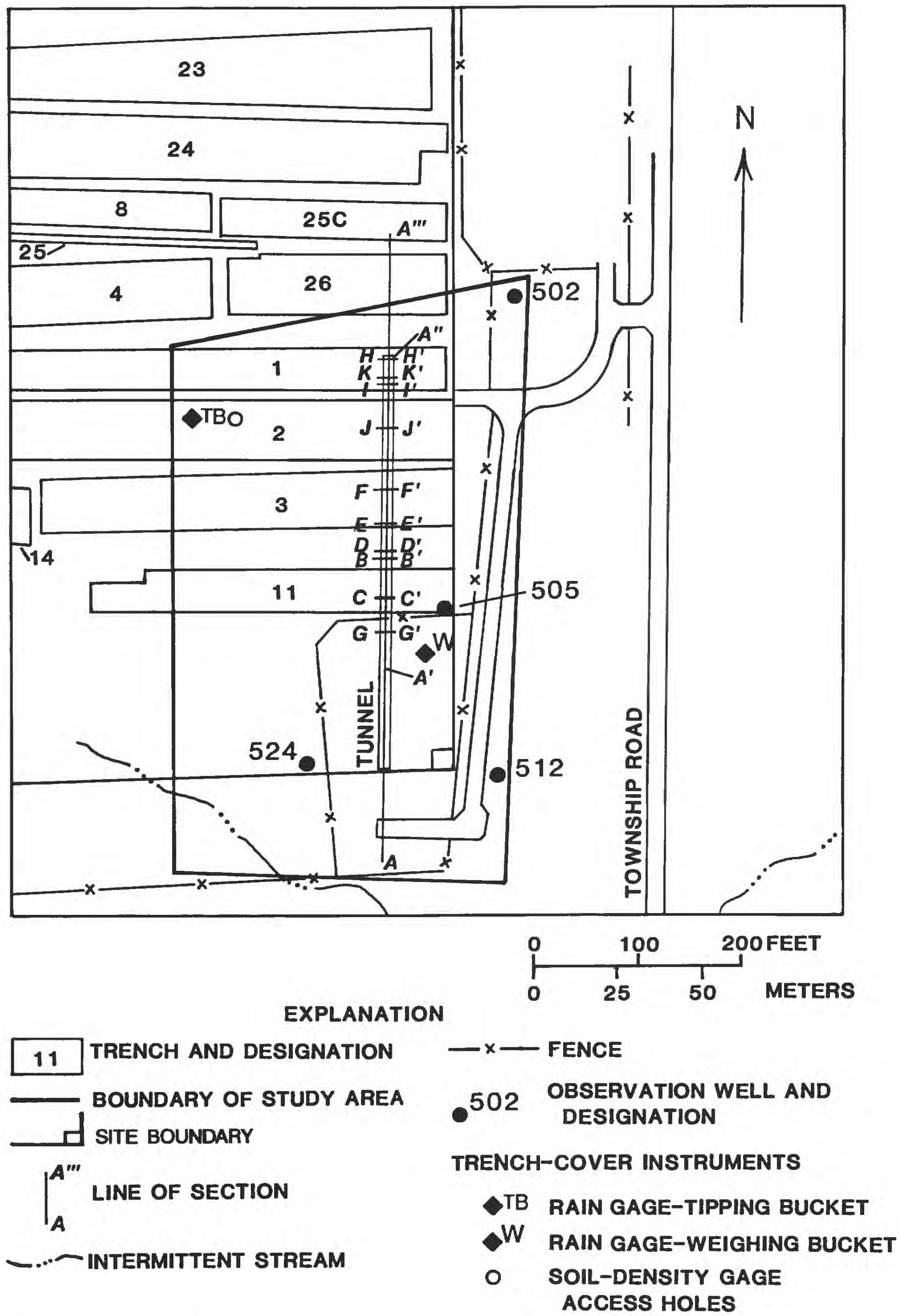
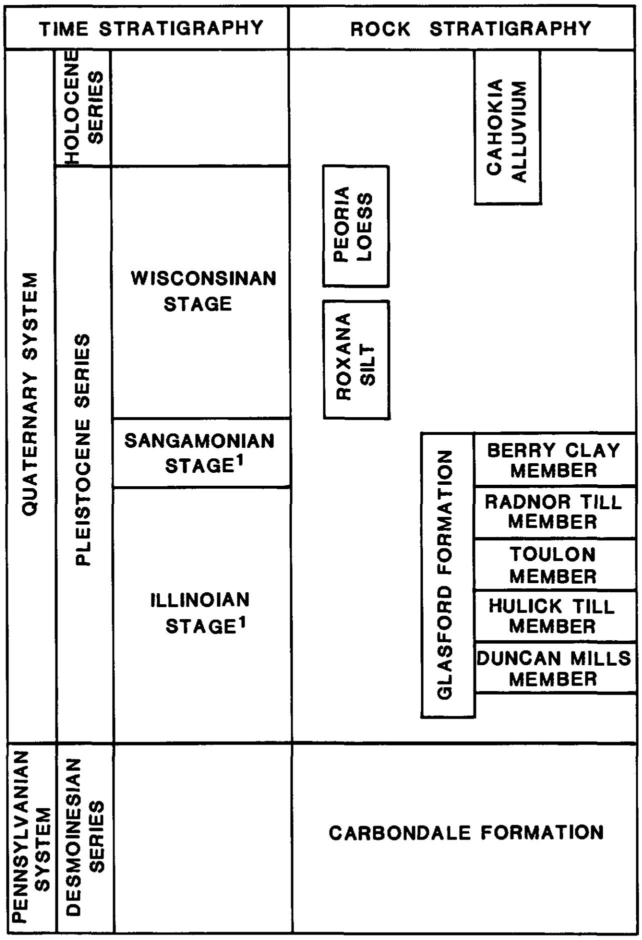


Figure 3. Detail of the study area with location of the trench-cover monitoring instruments, tunnel, ground-water observation wells, and lines of section.

instruments in the tunnel were installed in the original 90-m section of the tunnel. In the text and figures of this report, the horizontal distances of the instruments in the tunnel are relative to the south end of the 90-m section (*A′* in fig. 3).

Determination of Temporal Trends

The purpose of this substudy was to provide a general understanding of longer term temporal trends in the water



[1]Designated informal time terms by the U.S. Geological Survey.

Figure 4. Time-stratigraphic and rock-stratigraphic classification of the geologic units in the study area. Nomenclature is that of the Illinois State Geological Survey. (Modified from Willman and Frye, 1970, fig. 1.)

budget, water movement, and water chemistry and not an in-depth analysis of spatial variability of hydraulic properties and flow within individual hydrogeologic units. With this purpose in mind, only precipitation, evapotranspiration, runoff, pressure-head, ground-water-level, and water-chemistry data from monitoring instruments (or a subset of the instruments) installed during both the 1976–85 and 1986–87 study periods were included in the analysis.

Because of the interrelation of the various Sheffield site studies, many of the data in this substudy are presented in table and figure formats that are similar to the formats used in earlier reports; this approach is intended to allow ease of comparison. In some cases, data from the earlier reports are included in this report to show changes in previously described trends or reinterpretation of the trends. To avoid substantial replication of data, however, the reader generally is referred to the earlier reports (Foster, Garklavs, and Mackey, 1984a; Healy, deVries, and Sturrock, 1989; Mills and Healy, 1991; and Peters and others, 1992) for discussions of pre-1986 data.

The water budget at the Sheffield site was analyzed by using runoff, precipitation, and soil-moisture content data. Onsite runoff data (J.R. Gray, U.S. Geological Survey, written commun., 1986) were supplemented by offsite data from the nearest USGS streamflow-gaging station (fig. 1). Onsite precipitation was collected with a tipping-bucket rain gage and a weighing-bucket rain gage (fig. 3) and supplemented with data from three nearby National Weather Service (NWS) stations (fig. 1). Soil-moisture content was calculated from measurements of soil density in the top 2 m of the cover of trench 2 (fig. 3) during each site visit (weekly to monthly); soil density was determined by using a gamma-attenuation soil-density gage. Water movement and water chemistry were evaluated in the unsaturated geologic units below trenches 1, 2, 3, and 11 (primarily the Toulon Member and the Hulick Till Member of the Glasford Formation, which are intersected by the tunnel) and in the saturated zone below and adjacent to the tunnel. Changes in pressure head and the timing of water movement were analyzed by using as many as 50 soil-moisture tensiometers (fig. 6; only instruments referred to in the text are labeled in the figure). Tensiometers were equipped with pressure transducers, and pressure heads were recorded by automatic data loggers. Pressure head was recorded at intervals ranging from 2 hours to monthly. Data from gravity (free-drainage) lysimeters (GL1–GL3 (fig. 6)) were used to estimate soil-water fluxes at three locations; drainage volumes were recorded at each site visit. The operation of gravity lysimeters and the approach used in estimating flux are described in detail in the section "Determination of Preferential Water Movement and Water Chemistry."

Ground-water movement was evaluated by measuring depth to the water table in the observation wells that flank the tunnel (fig. 3) and in five piezometers that penetrate the tunnel floor (fig. 6). Ground-water levels in wells were recorded automatically at 15-minute intervals; water levels in piezometers were measured manually during each site visit.

Subtrench (below-trench) unsaturated-zone water chemistry was analyzed by using water samples collected from 12 vacuum lysimeters (fig. 6), 3 gravity lysimeters, sediment cores, and seeps that developed during instrument installation; details concerning the technique used to collect sediment cores are described in Mills and Healy (1991, p. 37, 40). Saturated-zone water chemistry was determined from water samples collected from wells and piezometers.

Vacuum lysimeters, wells, and piezometers were sampled quarterly; analyses included gross-alpha and gross-beta activity, tritium concentration, specific conductance, pH, and alkalinity (as $CaCO_3$). Gross-alpha and gross-beta activity were measured with an NMC Model PC-5 gas proportional counter (Nuclear Measurements Corporation,

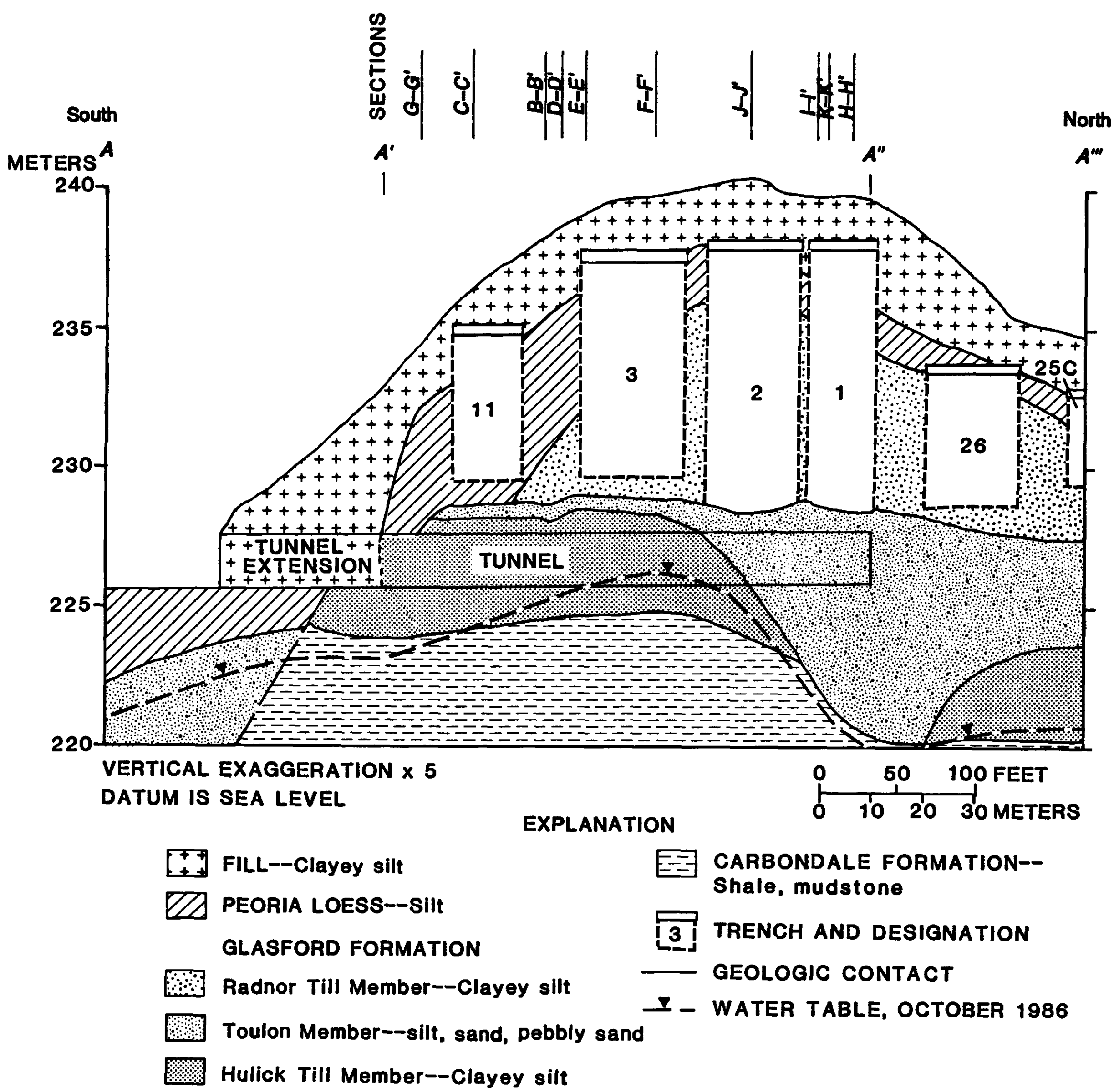


Figure 5. Hydrogeologic section *A–A'''* of the study area. (Modified from Foster, Erickson, and Healy, 1984; see fig. 3 for location of lines of section.)

1975), and tritium concentrations were measured by liquid scintillation (Thatcher and others, 1977, p. 63–71). One sample from each vacuum lysimeter and well was analyzed for the major inorganic ions; the analyses were conducted by the USGS National Water Quality Lab by using methods described by Skougstad and others (1979). Tritium analysis was planned for water collected from gravity lysimeters GL1–GL3; however, interfering constituents in the water induced excessive quenching that prevented accurate tritium analysis by the liquid scintillation method (Thatcher and others, 1977, p. 63).

Determination of Preferential Water Movement and Water Chemistry

To evaluate the movement and chemistry of water within preferential flow paths, the Toulon Member, an unsaturated sand deposit, was instrumented in an area where the deposit is overlain by trench 2 to the south and by the clayey silt Radnor Till Member of the Glasford Formation between trenches 1 and 2 to the north (fig. 6). The sand deposit in the 18-m-long study section (60.7 to 78.7 m from the south end of the original tunnel (designated *A'* in figs. 3

and 6)) ranged from about 1.5 to 6 m thick (from south to north). Gravity lysimeters and tensiometers were installed in the sand deposit (fig. 6) at distances of about 0.05 to 2.5 m below the trench bases and about 13 m below land surface.

Four hundred and forty core samples collected from 26 coreholes in a 1.75-m by 18-m horizontal plane for a related study by Healy and Mills (1991) were used to describe the physical and hydraulic properties of the sand and tritium concentrations of the soil water in the sand. The coreholes for the Mills and Healy (1991) study were located within 1.2 to 11 m of the instruments installed for the study of preferential water movement. The cores were collected over a 9-day period in June 1987 by thin-walled metal tubes; collection of the cores is described in detail in Healy and Mills (1991). Sixteen gravity lysimeters (GL1, GL4–GL17, GLB) (fig. 6) collected leachate samples for estimating flux and analyzing water chemistry. Two tensiometers (T15, T73B), located within about 1 m of several gravity lysimeters (fig. 6), were used to measure pressure head. Data were collected for a 13-month period from September 1986 through October 1987.

For the gravity lysimeters to measure soil-water movement, the host sediments must be at saturation (Hornby and others, 1986) to allow soil water to drain freely to the lysimeters. Using gravity lysimeters for water-chemistry sampling in the unsaturated zone is documented in Tadros and McGarity (1976), Tyler and Thomas (1977), Haines and others (1982), Oaksford (1983), and Schneider and others (1987). At the Sheffield site, gravity lysimeters also were used to evaluate the spatial and temporal distribution of water movement through the Toulon Member sand deposit. Soil-moisture tensiometers, which are typically used for flow-monitoring studies, measure pressure head only in the immediate vicinity of a porous cup (Stannard, 1986). The small monitoring area of tensiometers probably is responsible for their inability to detect localized, preferential flow paths suspected of being present in the Toulon Member sand deposit. The gravity lysimeters used in this study could monitor water movement over a larger area than tensiometers.

Two gravity lysimeter designs were used in the study—tube-type (fig. 7) and box-type (figs. 8 and 9). The tube-type lysimeters, constructed of thin-walled galvanized-steel conduit, were driven into the sand, thus allowing sand to fill the lysimeter tube. One 0.05-m-diameter by 0.5-m-long tube-type lysimeter (GL1) was installed vertically through the ceiling of the tunnel, and 14 0.1-m-diameter tube-type lysimeters (GL4–GL17), ranging in length from 0.8 to 1.8 m, were installed through the sidewalls of the tunnel (fig. 10). The sidewall lysimeters were installed at upward angles of 10 to 50 degrees; the orifice of these lysimeters was cut so that it was oriented horizontally, thus maximizing the flow-capture area. The capture area of the vertical lysimeter was about 2,000 mm^2 (square millimeters); the capture areas of the nonvertical lysimeters ranged from about 42,000 to 120,000 mm^2. The single box-type lysimeter (GLB), constructed of 12 75-mm (millimeter) -diameter sand-packed glass funnels, was installed below the intertrench till deposit to evaluate small-scale spatial variations in water movement. Using an access chamber with a retractable top allowed the box-type lysimeter to be installed 1 m beyond the tunnel liner and in hydraulic contact with the sand deposit. The capture area of this lysimeter was about 53,000 mm^2. Water that discharged through the gravity lysimeters to sample bottles was collected during each site visit. Collection intervals ranged from 18 hours to 4 weeks; typical intervals were about 2 weeks. During most of the study, water from one lysimeter (GL9) was collected by an automatic sampler at 3-day intervals.

Determination of Effects of the Tunnel on Water Movement

Three approaches were used to analyze the effects of the tunnel on water movement. First, soil-moisture tensiometers were installed in a cluster in a vertical cross section perpendicular to the length of the tunnel and in pairs at several additional locations around the circumference of the tunnel to collect pressure-head data. Second, sediment cores were collected from radially projecting coreholes along the length of the tunnel; the cores were analyzed for volumetric soil-moisture content and tritium concentration. Third, a two-dimensional, finite-difference ground-water-flow model (Lappala and others, 1987) was used to simulate water movement in two vertical cross sections perpendicular to the length of the tunnel.

Field Measurements

The study section with the tensiometer cluster was located in the Hulick Till Member (section *B–B′*), near the south end of the tunnel (fig. 6). On the basis of pressure-head response to seasonal wetting, as identified by Mills and Healy (1991, p. 60–67), this region of the tunnel held the greatest potential for affecting water movement and for identifying the effects of the tunnel. The lack of an identifiable wetting phase (requiring analysis of water movement under steady-state flow) and the smaller absolute range of pressure heads (as compared to the Hulick Till Member) inhibited identification of the effects of the tunnel in the Toulon Member.

The tensiometer cluster in geologic section *B–B′* was located 31 m north of the tunnel origin; it consisted of nine tensiometers (TX1–TX9) configured as shown in figure 11. Data from section *B–B′* were used to evaluate unsaturated flow above the tunnel and beyond the sidewalls of the tunnel. Pressure heads were monitored in section *B–B′* from May 1986 through September 1987. Pressure heads were

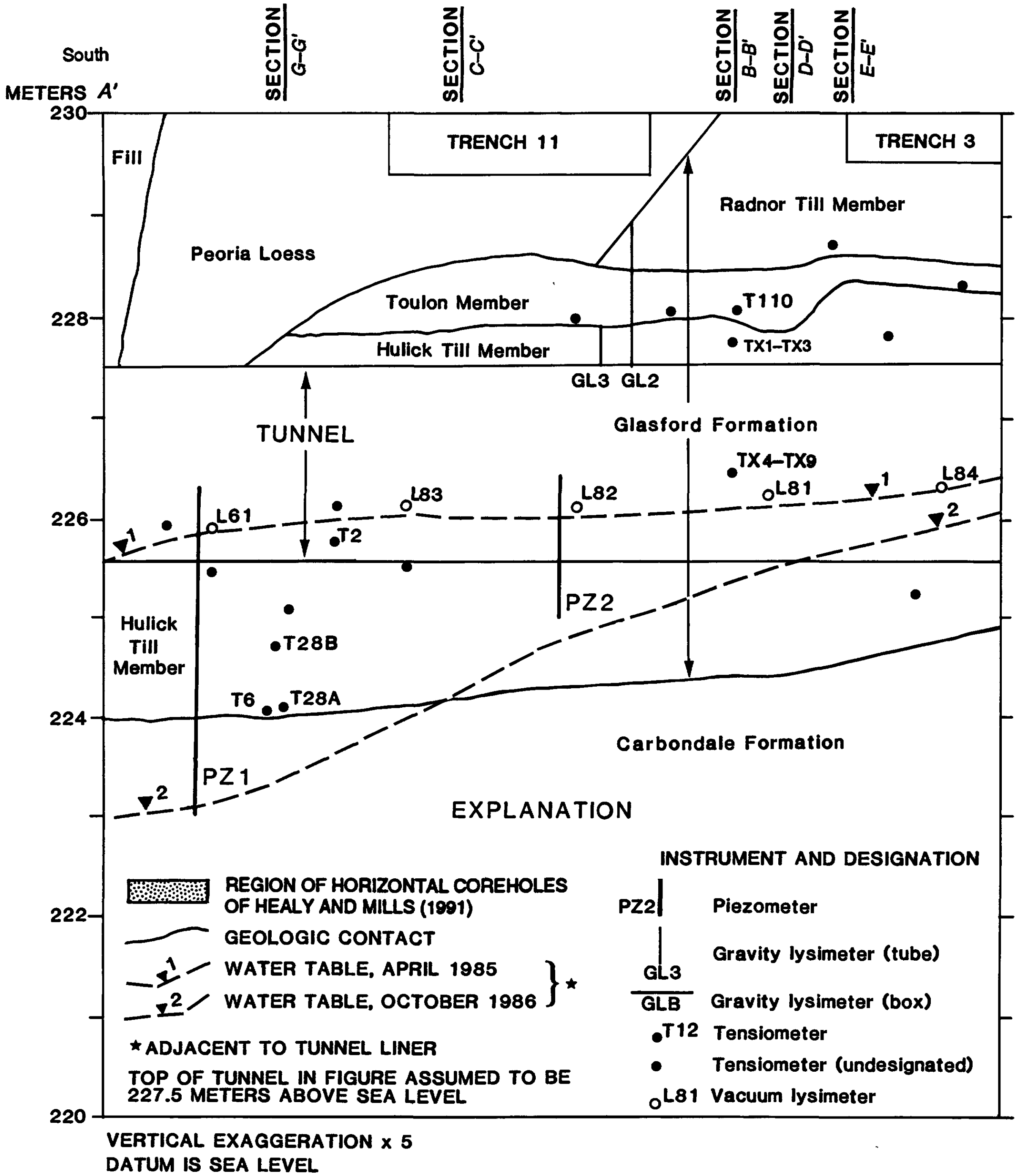


Figure 6. Locations of soil- and ground-water instrumentation in the tunnel area. (Modified from Mills and Healy, 1991, fig. 26; see fig. 3 for location of lines of section.)

monitored at the paired-tensiometer locations in the Toulon Member and in the Hulick Till Member from January 1982 through September 1987.

In all, approximately 750 sediment cores were collected from 71 coreholes in the Radnor Till, the Toulon, and the Hulick Till Members of the Glasford Formation, and in the Carbondale Formation. The cores included approximately 300 cores collected during the 1981–85 (Peters and others, 1992; Mills and Healy, 1991) and 1986–87 unsaturated-zone studies of the Sheffield site and 440 cores collected in the related study by Healy and Mills (1991). The reader is referred to Healy and others (1986), Mills and Healy (1991), and Healy and Mills (1991) for descriptions of the collection and handling of the cores.

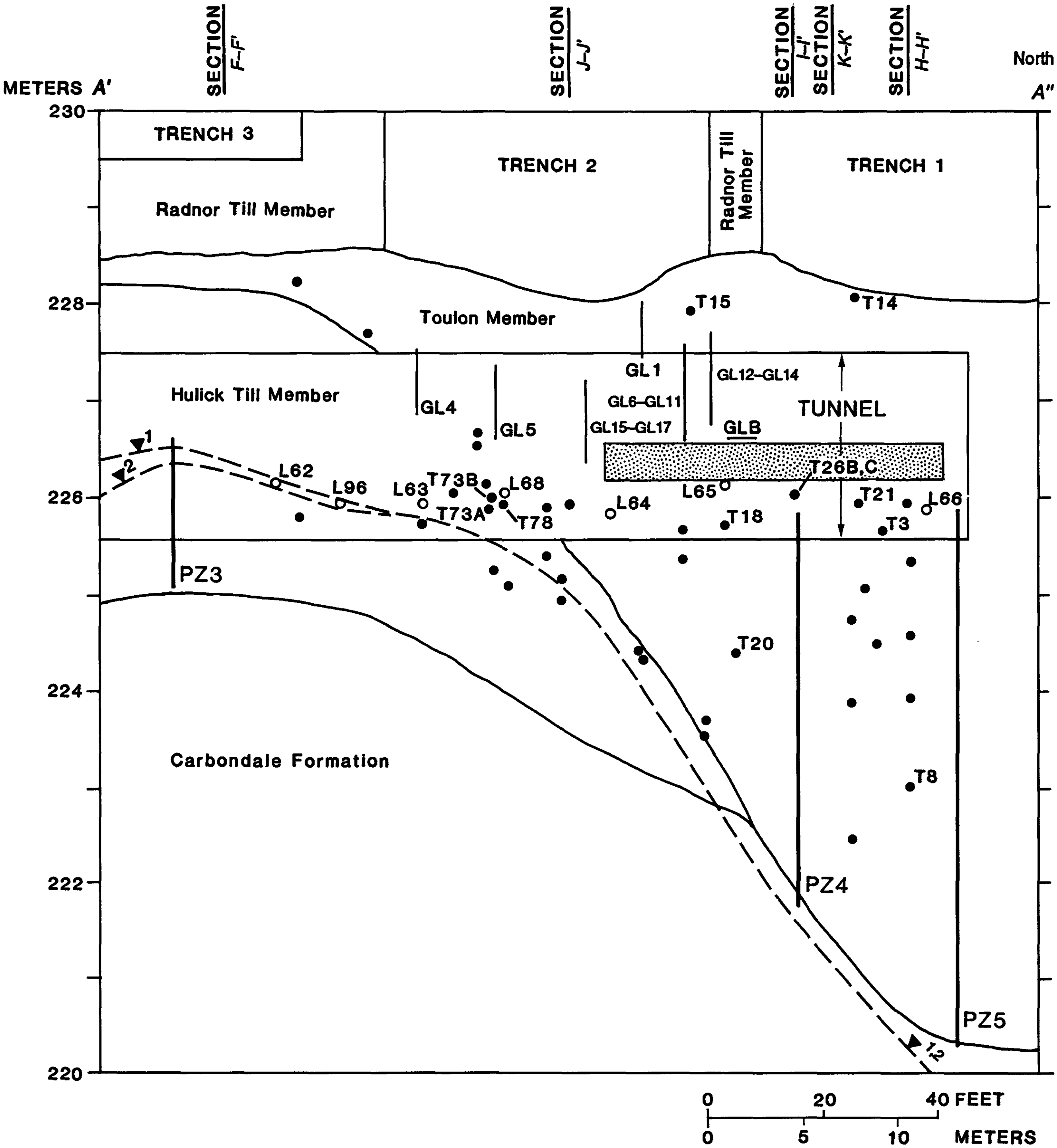


Figure 6.—Continued.

Numerical Simulations

Computer simulation of steady-state water movement within vertical sections through the unsaturated geologic deposits surrounding the tunnel allowed analysis of the tunnel's effect on natural flow patterns under a wide range of sediment-hydraulic properties and flux rates. The numerical model used in the study (Lappala and others, 1987) is based on the modified Richards equation; the model incorporates the Brooks and Corey formula (Brooks and Corey, 1964) to represent the moisture-retention and hydraulic-conductivity curves of the individual lithologic units. For a detailed discussion of the model and its previous application

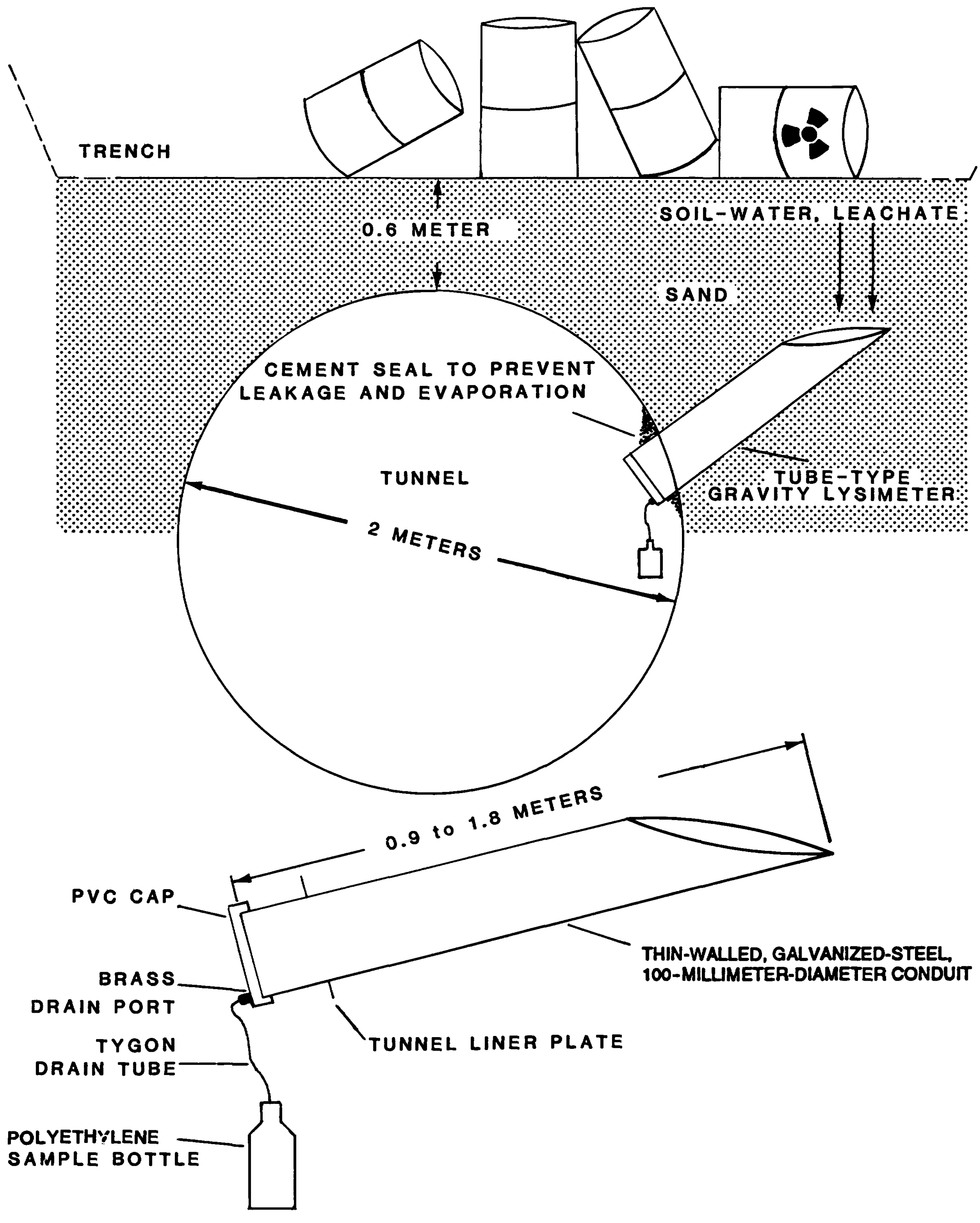


Figure 7. Typical construction and installation of tube-type gravity lysimeters.

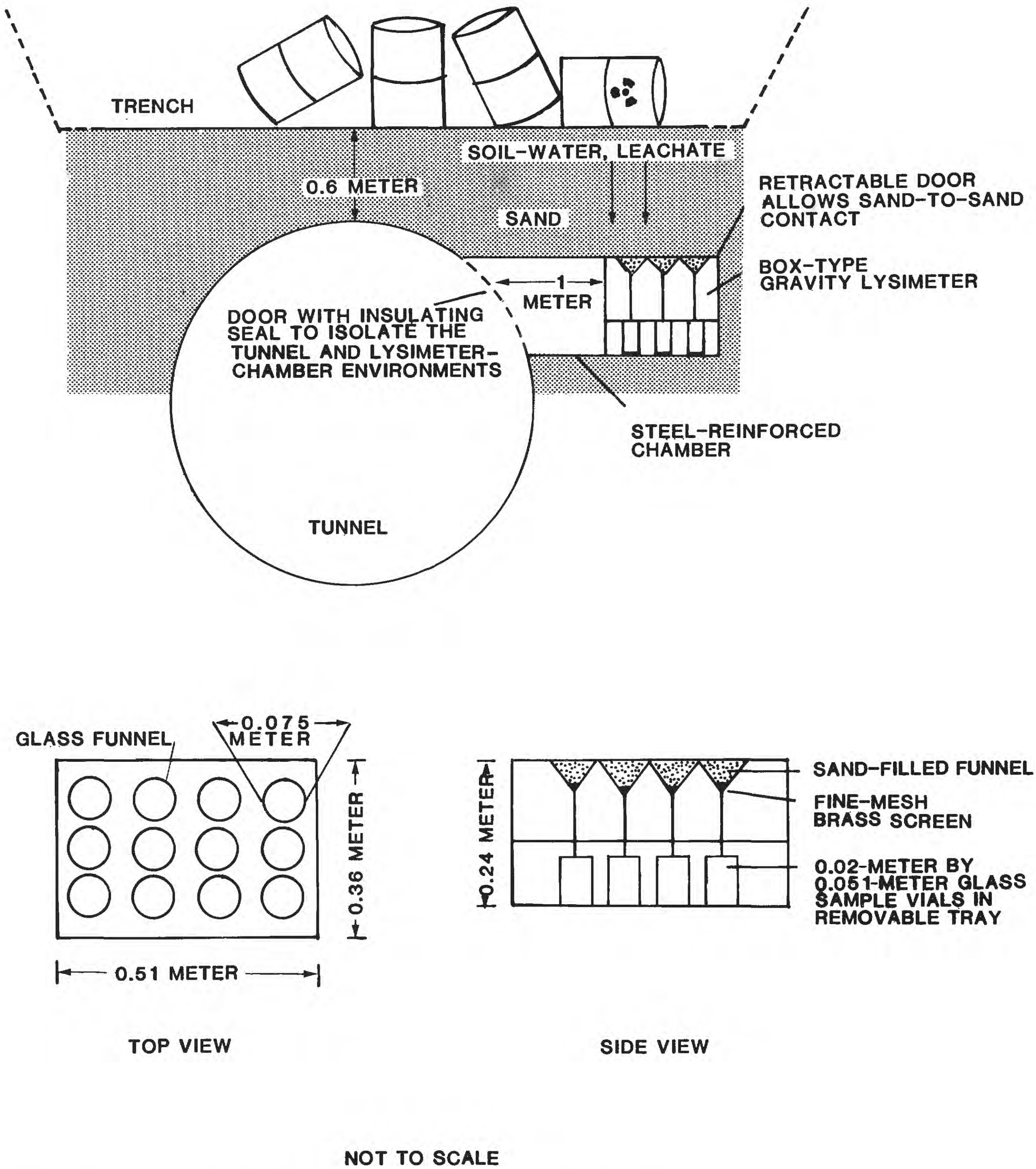
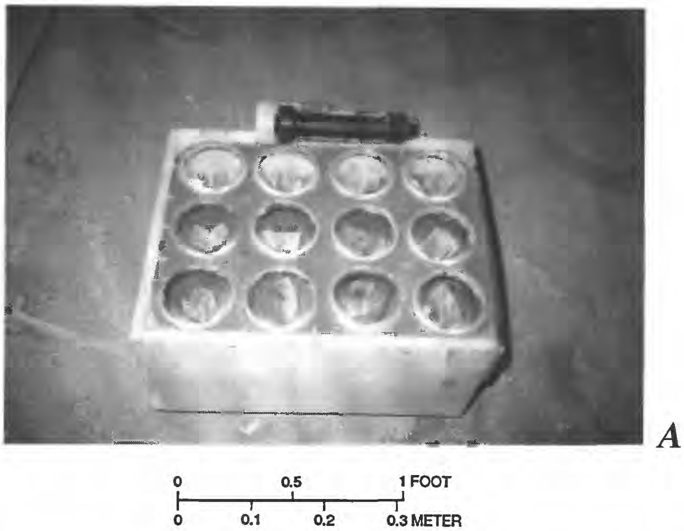


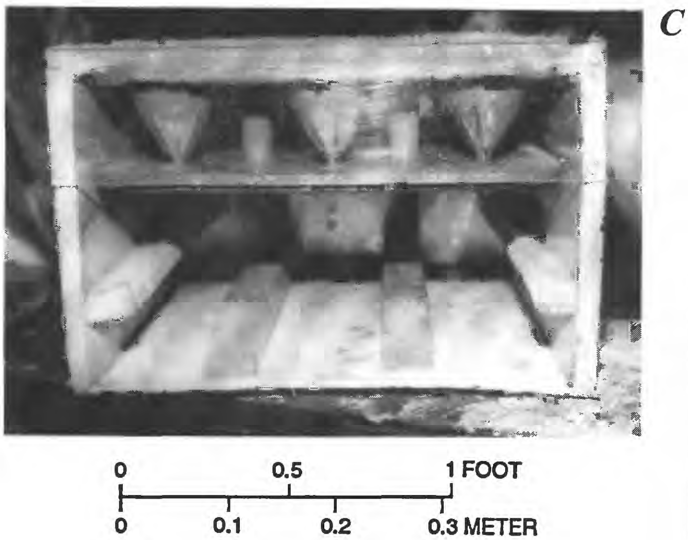
Figure 8. Construction and installation of the box-type gravity lysimeter.

to soil-water movement at the Sheffield site, refer to Lappala and others (1987) and Mills and Healy (1991, p. 74–80), respectively.

One model section (referred to as the till section) represented the southern end of the tunnel (near the TX1–TX9 tensiometer cluster in section *B–B′*; figs. 6 and 11), where the 0.6-m-thick lens of the Toulon Member (sand) overlies the 3.6-m-thick Hulick Till Member. The other model section (referred to as the sand section) represented the northern end of the tunnel (near the GL6–GL11 gravity lysimeter cluster; fig. 6), where the 4.8-m-thick Toulon Member is overlain by trench 2 and underlain by the Hulick Till Member.

Because of the symmetry of the tunnel cross sections, water movement was simulated through only half of the sections (from the vertical midpoint of the tunnel laterally to a point well beyond the tunnel sidewall). Figure 12 shows the discretized geologic sections, the positions of the litho-





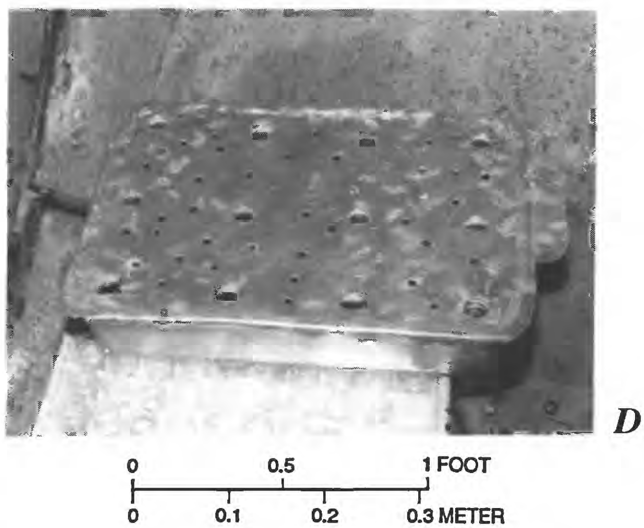


Figure 9. Box-type gravity lysimeter. *A*, Glass funnels and brass-screen filters; *B*, Sand-filled funnels; *C*, Funnels and collection-vial chamber; *D*, Collection vials in removable tray.

logic units, and the boundary conditions specified in the simulations. The till section was represented by an 18- by 21-node grid consisting of 378 cells; the section was 3.6 m in length and 4.2 m in height. The upper boundary, represented by constant-flux nodes, coincided with the approximate top of the Toulon Member. The lower boundary, represented by a constant-head boundary, corresponded to the average water-table altitude in the Hulick Till Member. The east (right) boundary corresponded to a no-flow divide designated along the midsection of the tunnel. The western (left) boundary was an assumed no-flow boundary, remote from the tunnel's effect on vertical water movement. The tunnel liner was treated as a no-flow boundary. The sand section was represented by a 16- by 26-node grid consisting of 416 cells; the section was 3.2 m in length and 5.2 m in height. The upper boundary, represented by constant-flux nodes, coincided with the approximate top of the Toulon Member. The lower boundary, represented by a constant-head boundary, corresponded to the average water-table altitude near the top of the Hulick Till Member. The east, west, and tunnel boundaries were similar to those in the till section. Values for the physical and hydraulic properties of the lithologic units used in the simulations are presented in table 1.

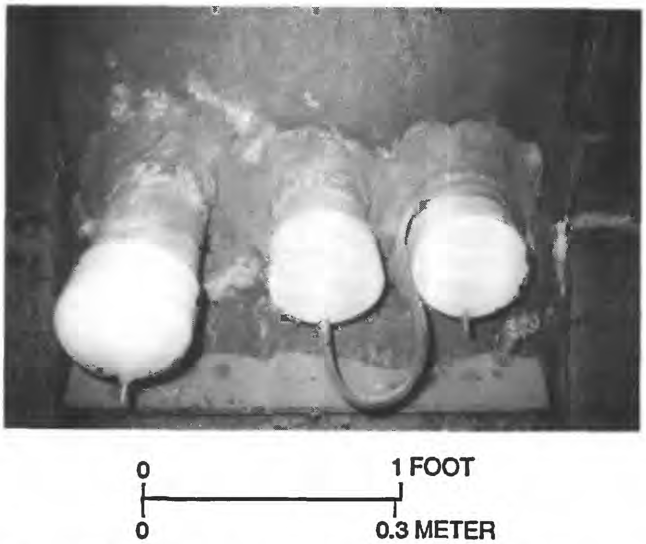


Figure 10. Tube-type gravity lysimeters installed through sidewall of tunnel.

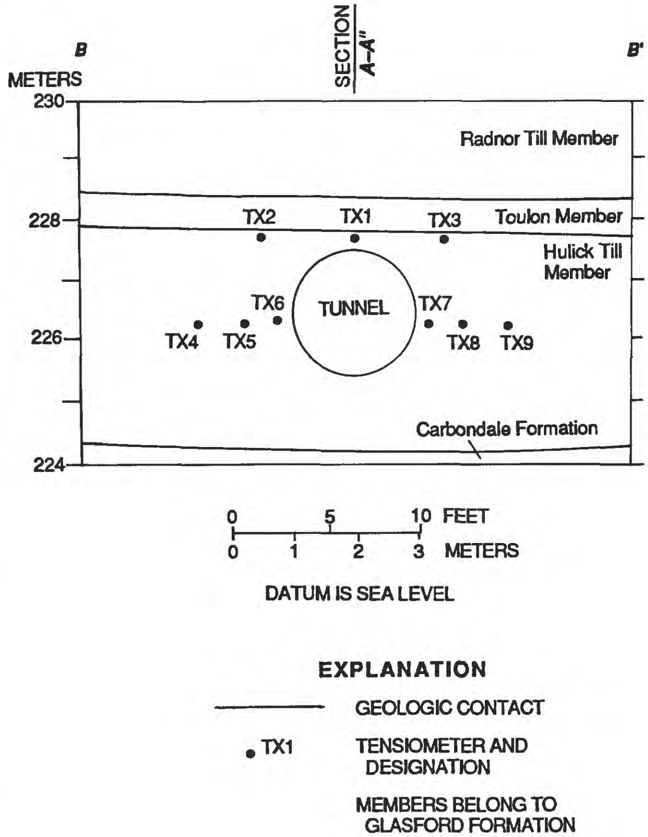


Figure 11. Clustered soil-moisture tensiometers along geologic section *B–B'* through the tunnel. (See figs. 3 and 6 for location of lines of section.)

Table 1. Physical and hydraulic properties of lithologic deposits in the tunnel area

[Values derived from analysis of lithologic samples that were collected from the Sheffield site but not necessarily from the tunnel area. mm/d, millimeters per day; —, dimensionless; mm, millimeters]

Material (lithologic unit)	Saturated hydraulic conductivity[1] (mm/d)	Porosity (—)	Residual moisture content[2] (—)	Bubbling pressure[2] (mm)	Pore-size distribution[2] (—)
Sand (Toulon Member of the Glasford Formation).	3.4×10^4	0.36	0.03	−150	1.75
Pebbly clayey silt (Hulick Till Member of the Glasford Formation).	4.1	.34	.30	−1,000	.50

[1] Values of vertical and horizontal saturated hydraulic conductivity were determined in the laboratory by the constant-head method. No distinction is made here or elsewhere in the report between vertical and horizontal hydraulic conductivity because, at the Sheffield site, the sand of the Toulon Member and the pebbly clayey silt of the Hulick Till Member are considered to be isotropic.

[2] Brooks and Corey (1964) values used to determine the relation between liquid pressure head and relative hydraulic conductivity in the Lappala and others (1987) variably saturated flow model. Residual moisture content represents the amount of water in a porous medium not drained by gravitational forces. Bubbling pressure represents the liquid pressure head required to desaturate the largest pores in a porous medium. Pore-size distribution is an index that is a function of soil texture; soil texture affects the moisture-retention characteristics of a porous medium.

The natural distribution of pressure heads (assuming vertical downward water movement) in the tunnel-area sediments is represented by results of one-dimensional flow simulations. The one-dimensional model cross sections were similar to the above-described two-dimensional sections, except that no tunnel nodes were included.

Several measures were taken to simplify the simulations. The system was simulated at steady state (soil-water flux and the position of the water-table boundary were held constant with respect to time). In actuality, soil-water flux and the position of the water table (most notably near the southern end of the tunnel) do fluctuate with time. Steady-state simulation is justified because (1) soil-water flux extremes were used to evaluate a worst-case scenerio of tunnel influence (intermediate pressure-head distributions during transient phases were not the focus of the simulations) and (2) the region where the water table noticeably fluctuates is remote from the base of the tunnel section in the numerical simulations. Lithologic unit contacts were assumed to be horizontal, an assumption that allowed the influence of the tunnel to be evaluated and not the influence of sloping contacts (for a discussion of the influence of sloping contacts on simulation of tunnel-area water

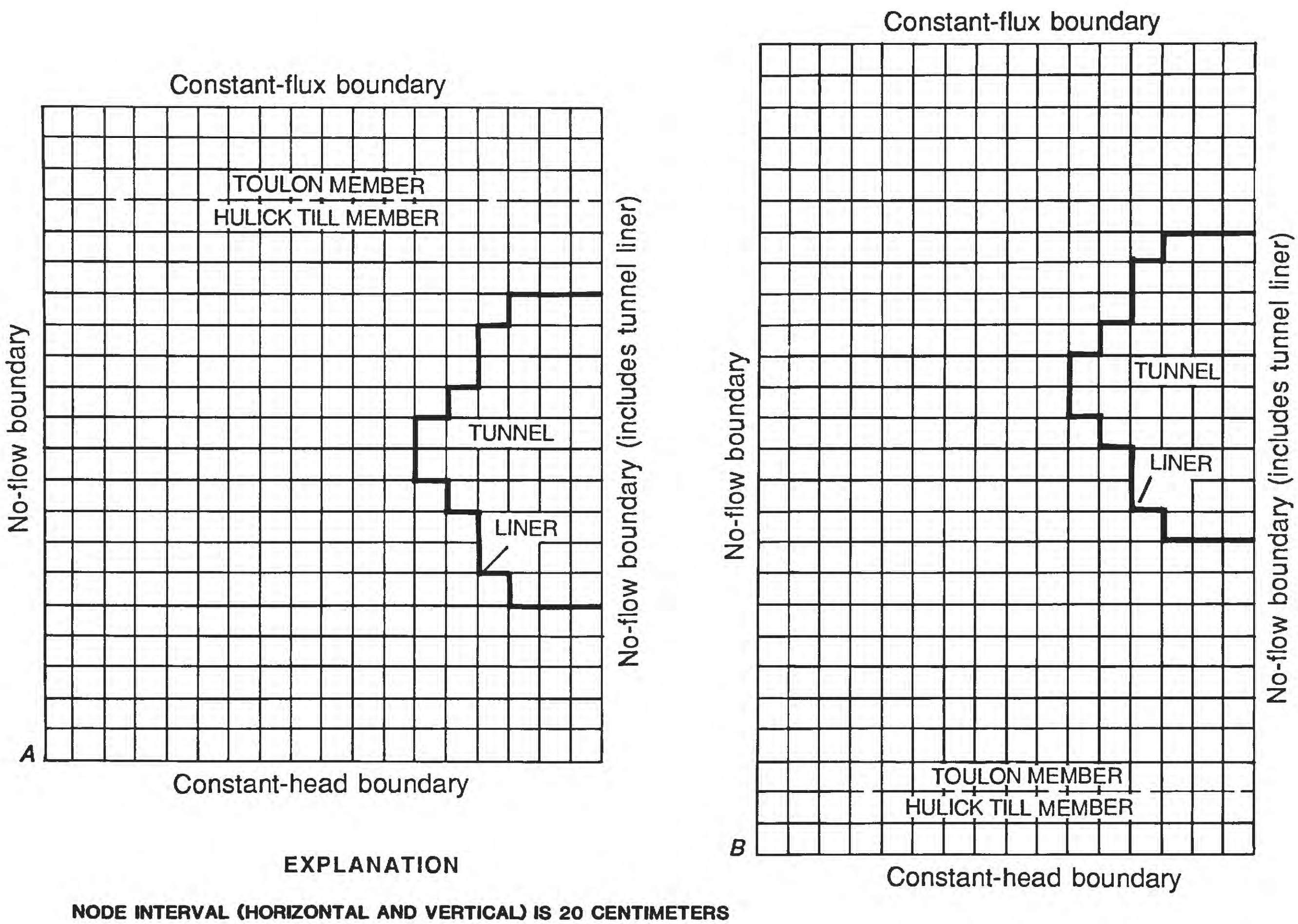


Figure 12. Model grids for cross sections through one-half of the tunnel and the (*A*) till section and the (*B*) sand section.

movement, see Mills and Healy (1991, p. 78–80)). The geologic deposits were assumed to be homogeneous (supported by soil-core analysis), isotropic (constant-head measurements of vertical and horizontal hydraulic conductivity are similar), and in complete contact with the tunnel liner (the tunnel annulus has been grouted throughout much of the tunnel length). Finally, the cross sections were assumed to lie along a stream line; that is, water movement is co-planar to the sections. This assumption is inherent in two-dimensional, vertical, cross-sectional models.

The simulations represented the wetting phase or period of spring recharge to the saturated zone, when flux rates are at a maximum. This representation allowed evaluation of a worst-case scenario of the tunnel influence on water movement. Annual recharge rates were modified to represent the observed case that actual recharge to the saturated zone occurs over several months between late winter and early summer. For example, the estimated average annual recharge rate of 107 mm (Mills and Healy, 1991, p. 59) was assumed to occur over a 90-day period, thus resulting in an approximate flux rate of 1 mm/d (millimeter per day). This rate was varied to examine the effects of the tunnel during periods of increased and decreased recharge. Simulated flux rates ranged from 0.01 to 10 mm/d in both the till and sand sections. Simulated pressure-head distributions were compared to observed distributions to assure that the applied flux rates were realistic. Flux rates resulting in model cross sections dominated by positive pressure heads or pressure heads less than about −2,500 mm in the till deposit and −700 mm in the sand deposit were considered unrealistic (not consistent with field observations). Values of saturated hydraulic conductivity were varied from field values (table 1) by up to one order of magnitude to evaluate sensitivity to variations in sediment-hydraulic properties.

TEMPORAL TRENDS IN THE WATER BUDGET, WATER MOVEMENT, AND WATER CHEMISTRY

Water Budget

Water-budget information is useful in waste-disposal-site applications because it defines the components of the

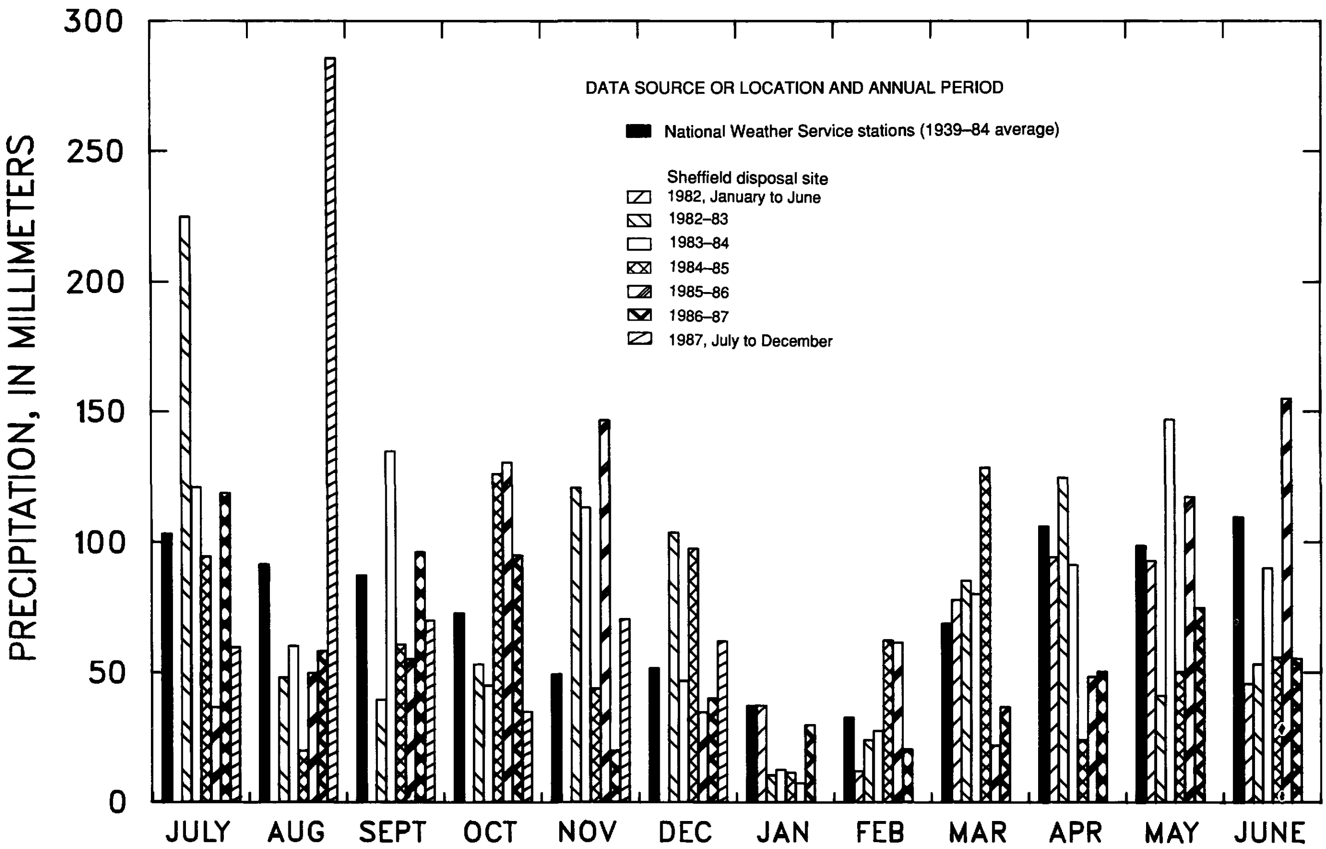


Figure 13. Total monthly precipitation at the Sheffield site (1982–87) and long-term (1939–84) average monthly precipitation averaged from three nearby National Weather Service stations (locations shown in fig. 1). (Modified from Mills and Healy, 1991, fig. 7.)

hydrologic cycle. Knowledge of the components of the hydrologic cycle, in turn, allows one to assess (1) the potential vulnerability of a disposal site to such conditions as surface erosion (due to substantial overland runoff) or ground-water migration of contaminants (due to substantial ground-water recharge) and (2) the relation of the water budget to trends in soil- and ground-water movement and water chemistry. Because the value of the water-budget components and site-surface and waste-burial conditions can vary from year to year, water budgets, soil- and ground-water movement, and water chemistry should be analyzed over several years to better define average values and longer term trends. This need is particularly true at the relatively young Sheffield site, where annual precipitation can be quite variable (Healy, Gray, and others, 1989, p. 381) and site conditions are still stabilizing (Gray and McGovern, 1986).

Annual precipitation was 839 mm in 1986 and 849 mm in 1987 (the record for September through December 1987 was estimated from an average of the three NWS stations). Annual precipitation was 949 mm in 1982 (the record for January through June was estimated from an average of the three NWS stations), 859 mm in 1983, 890 mm in 1984, and 785 mm in 1985. Long-term (1939–84) annual precipitation at the NWS stations averaged 890 mm, with a minimum of 646 mm and a maximum of 1,330 mm. Annual precipitation in 1986–87 was in the range of both the 1982–85 period of record for the site and the long-term period of record for the three nearby NWS stations (U.S. Department of Commerce, 1939–84). Annual precipitation for the period 1982–87 was greatest in 1982 and least in 1985. Monthly precipitation in 1986 and 1987 generally was equivalent to totals during previous years (fig. 13). Precipitation in August 1987 totaled 286 mm—an amount that clearly exceeded all previous monthly totals.

A water budget, as defined in equation 1, was prepared for the Sheffield site for the 3-year period July 1984 through June 1987:

$$P = ET + R + \Delta S + D, \qquad (1)$$

where

P = precipitation, in milliliters,
ET = evapotranspiration, in milliliters,
R = runoff, in milliliters,
ΔS = change in soil-zone storage, in milliliters, and
D = seepage to trenches and (or) ground-water recharge, in milliliters.

Data used in the analysis included the above-described precipitation data, runoff data collected at the site through 1985 (J.R. Gray, U.S. Geological Survey, written commun., 1986), and soil-moisture data collected from the cover of trench 2. Annual runoff data for July 1985 through June 1987 were estimated by comparing rainfall-runoff relations at the Sheffield site for the period July 1982 through December 1985 and rainfall-discharge relations at the USGS streamflow-gaging station (Green River at Geneseo, Ill., station no. 05447500, 27.6 river miles from the site) for the period July 1982 through June 1987; the estimate was not statistically based because of the limited annual runoff data for the Sheffield site. Change in soil moisture in trench covers (soil-zone storage) and seepage to trenches and (or) movement into the saturated zone (ground-water recharge) were determined by the zero-flux-plane method using trench-cover soil-moisture-content-profile data (Richards and others, 1956; Healy, 1989, p. 213). In this study, the estimated rate of seepage into the trenches is not equated with the rate of ground-water recharge; evidence of tritium in the vegetative cover at the site indicates that some of the water in the trenches is returning to the atmosphere by transpiration (Mills and Healy, 1991, p. 59, 91). Evapotranspiration was estimated as the residual in the reformulated water-budget equation:

$$ET = P - R - \Delta S - D. \qquad (2)$$

Values for the components of the water budget, as estimated for July 1984 through June 1987, are presented in table 2. Annual water budgets for July through June 1982–83, 1983–84, 1984–85, 1985–86, and 1986–87 are presented in table 3; budgets for the period 1982–84 were prepared by Mills and Healy (1991). Annual water budgets were compiled for the period July through June to allow comparison with previously reported water-budget data for the site (Healy, deVries, and Sturrock, 1989; Healy, Gray, and others, 1989; Mills and Healy, 1991).

The water-budget values should be viewed with some caution for several reasons: (1) The runoff data are estimated for two of the annual budgets (1985–86 and 1986–87); (2) there is inherent (but unquantifiable) uncertainty in determining seepage and recharge from soil-moisture-content-profile data; (3) there is some degree of instrument-induced error, especially during cold-weather measurements; and (4) evapotranspiration is derived from the estimated and (or) uncertain values. Because of the limitations, these water-budget data are most useful when evaluated on an annual basis and discussed in terms of annual trends.

Table 2. Estimates of water-budget components at the Sheffield site, July 1984 through June 1987

[All values in millimeters; —, no data]

Date	Precipitation	Evapotranspiration[1]	Runoff[2]	Change in soil-zone[3] storage	Seepage to trenches and (or) ground-water recharge
06–20–84	—	—	—	—	—
07–05–84	36.58	37.4	0.94	−1.8	0
07–19–84	43.18	61.0	.14	−35.5	17.5
08–08–84	48.77	81.0	1.44	−38.2	4.5
10–26–84	162.31	149.2	3.26	2.4	7.4
11–27–84	88.14	27.1	12.64	48.4	0
01–14–85	101.10	40.0	8.65	102.9	0
02–19–85	16.25	42.0	0	−25.8	0
02–22–85	40.39	0	42.99	−1.3	3.2
03–14–85	100.83	0	45.44	111.6	0
04–04–85	41.37	43.5	20.94	−23.1	0
05–17–85	67.56	176.6	.13	−120.6	11.4
06–10–85	7.87	69.5	0	−61.8	.2
06–24–85	37.34	61.5	0	−26.7	2.5
07–11–85	21.59	56.2	0	−49.4	14.8
07–23–85	5.58	26.4	0	−23.0	2.2
08–15–85	56.89	47.2	0	8.9	.8
10–16–85	127.24	80.4	0	40.2	6.6
12–11–85	253.98	0	50.65	218.2	0
01–07–86	10.17	—	—	−28.6	0
01–22–86	1.27	—	—	17.2	0
03–03–86	63.26	—	—	−70.1	40.5
04–01–86	22.60	—	—	20.0	0
05–07–86	49.00	—	—	−48.6	14.2
06–17–86	170.94	—	—	24.4	0
07–30–86	217.41	—	—	−14.0	0
09–02–86	59.43	—	—	−61.1	14.0
09–22–86	52.06	—	—	−38.5	2.6
10–21–86	96.50	—	—	52.6	3.0
11–25–86	62.21	—	—	43.4	0
12–16–86	40.12	—	—	39.4	0
01–08–87	4.83	—	—	11.2	0
02–26–87	30.98	—	—	−8.6	10.0
03–19–87	18.54	—	—	22.3	0
04–29–87	82.54	—	—	−13.5	5.2
06–03–87	74.67	—	—	−105.8	11.8
06–24–87	46.98	—	—	−33.6	1.2

[1] Evapotranspiration (ET) was assigned the value 0 when the ET residual in the water-budget calculation was negative; where runoff data are unavailable, evapotranspiration cannot be estimated.

[2] Runoff values for July 1984 through December 1985 from J.R. Gray, U.S. Geological Survey (written commun., 1986); no site data available beyond December 1985.

[3] Soil zone is considered to be the top 2 m of a trench cover.

The least precipitation for the 5-year period (July 1982 through June 1987) occurred in 1986–87, and the greatest in 1983–84. Evapotranspiration was least in 1985–86 and varied by less than 10 percent in the other years. Runoff was greatest in 1982–83. The increased amount of precipitation in 1982–83 may have contributed to the increased runoff during that period; however, the amount of annual precipitation does not fully account for the increased runoff. Despite a greater amount of precipitation in 1983–84 than in 1982–83, the amount of runoff in

Table 3. Annual estimates of water-budget components at the Sheffield site, July 1982 through June 1987

[All values in millimeters per year]

Water-budget components	Annual periods (July to June)				
	1982–83[1]	1983–84[1]	1984–85	1985–86	1986–87
Precipitation	928	968	774	864	695
Evapotranspiration.[2]	625	689	683	543	640
Runoff[3]	208	112	130	125	125
Change in soil-zone storage.[4]	−12	60	−88	122	−118
Seepage to trenches and (or) ground-water recharge.	107	107	49	74	48

[1] Water budget values for 1982–83 and 1983–84 from Mills and Healy (1991).

[2] Evapotranspiration values for July 1982 through June 1984 from Healy, deVries, and Sturrock (1989).

[3] Runoff values for July 1982 through June 1985 from J.R. Gray, U.S. Geological Survey (written commun., 1986); values for July 1985 through June 1987 are estimated.

[4] Soil zone is considered to be the top 2 m of a trench cover.

1983–84 was less. The pattern (timing, intensity, antecedent soil-moisture content) of individual precipitation events appears to best explain the increased runoff. The increased amount of runoff produced from several large rainstorms in July and December 1982 and April 1983 probably accounts for the greater amount of runoff in 1982–83 than in 1983–84. The fact that site-surface conditions (vegetative cover and surface drainageways) were still undergoing stabilization from site construction in 1982–83 also may have contributed to the greater amount of runoff during that period.

Runoff was estimated to be 125 mm/yr (millimeters per year) during 1985–86 and 1986–87. This estimate, which is close to the measured runoff of 130 mm in 1984–85, was used because (1) site-surface conditions generally had stabilized by late summer 1983; (2) precipitation and drainage varied little during the three annual periods; and (3) discharge patterns at the offsite gaging station (346 mm in 1982–83, 233 mm in 1983–84, 239 mm in 1984–85, 230 mm in 1985–86, and 237 mm in 1986–87), which paralleled discharge patterns at the site, indicated little change in discharge totals in the four annual periods between July 1983 and June 1987.

Change in soil-water storage in the trench covers was variable from year to year, in an apparent relation to precipitation and evapotranspiration; during wet years (high precipitation and low evapotranspiration) storage increased, and during dry years (low precipitation and high evapotranspiration) storage decreased. This relation was not true in 1982–83 for precipitation or in 1983–84 for evapotranspiration (possibly because of the pattern of precipitation events and changes in site-surface conditions). Annual seepage into the trenches and (or) ground-water recharge in 1984–87 was almost half that recorded in 1982–84, in direct relation to precipitation totals. Finally, it should be noted that, despite precipitation that regularly exceeded 700 mm/yr, runoff rarely exceeded 200 mm/yr (assuming that estimations for 1985–87 are reasonable), and seepage (recharge) was never much more than 100 mm/yr. Values of both runoff and seepage generally were stable from year to year; runoff changed less than 100 mm, and seepage (recharge) changed by no more than 50 mm.

With the exception of the 1985–86 rate (543 mm), evapotranspiration estimates for the 3-year period from July 1984 through June 1987 were similar to the more rigorously derived estimates for July 1982 through June 1984 given by Healy, deVries, and Sturrock (1989) and within the range of rates estimated for northern Illinois (635 to 760 mm) given by Jones (1966, p. 12). For the study by Healy, deVries, and Sturrock (1989), the ratio of evapotranspiration to pan evaporation at Hennepin, Ill. (fig. 1), ranged from 0.81 (1982–83) to 0.85 (1983–84); in the present study, the ratio was 0.81 in 1984–85, 0.61 in 1985–86, and 0.76 in 1986–87. The similarity of the ratios indicates that the evapotranspiration estimates for 1984–87 are reasonable.

For the annual periods 1982–83 and 1983–84, the ratio of evapotranspiration to precipitation was between 0.69 and 0.71 (Healy, deVries, and Sturrock, 1989). In the present study, the ratio was 0.88 in 1984–85, 0.63 in 1985–86, and 0.92 in 1986–87. The ratios in 1984–85 and 1986–87 appear high relative to the ratios in 1982–84. They may be reasonable, however, if most of the precipitation in the latter 2 years occurred during the high evapotranspiration months of April through October. In 1986–87, this was the case; 79 percent of the precipitation occurred during the high evapotranspiration months, as opposed to 63 to 71 percent during the 2-year study of Healy, deVries, and Sturrock (1989). In 1984–85, only 56 percent of the precipitation occurred during the high evapotranspiration period. It must be pointed out that this ratio does not represent a true functional relation; the amount of evapotranspiration that occurs annually is dependent on the interrelation of many factors, only one of which is precipitation.

Although air temperature is not a component of the water budget, it has an important relation to the water budget (Mills and Healy, 1991, p. 50, 60); temperature affects evapotranspiration rates and infiltration of precipitation into the soil (no infiltration occurs when temperatures are below freezing). Average annual temperature at the Sheffield site was 10.9 °C (degrees Celsius) in 1986 and 11.2 °C in 1987. From 1982 through 1985, average annual temperature ranged from 9.2 to 10.9 °C; the long-term (1939–84) average annual temperature, as determined by averaging the records from the three nearby NWS stations, is 10.3 °C. Increased temperatures were most notable for the period January through July 1987.

Water Movement

Temporal trends in water movement, through the unsaturated subtrench geologic deposits and to the saturated zone, were noticeably different in the study periods 1981–85 and 1986–87. Figure 14 shows pressure-head trends at six tensiometer locations in the typically unsaturated Hulick Till and Toulon Members of the Glasford Formation for the period of record (1982–87); the three locations in each unit generally are representative of ranges and temporal trends in pressure head throughout the respective units.

In the initial study period (1981–85), an annual cycle of water movement was identified in which a pronounced wetting phase (corresponding to an increase in pressure head) was followed by a drying phase (corresponding to a decrease in pressure head). Typically, the wetting phase occurred in late winter to early summer; the drying phase followed and extended to the beginning of the wetting phase in the next annual cycle. In the second study (1986–87), an annual cycle was identified as well, but pressure-head fluctuation was much less; the diminished fluctuation tended to obscure the timing pattern of seasonal wetting and drying. Additionally, in early fall 1986, a second wetting phase was identified. Pressure-head fluctuations in this fall wetting phase were nearly equal in magnitude to the fluctuations in the spring wetting phase. A fall wetting phase was tentatively identified during the earlier study period, but its significance was discounted; the magnitude of pressure-head fluctuations was very small in comparison to the fluctuations that occurred during the spring wetting phase. Also, the pressure-head fluctuations that were associated with the fall wetting phase were observed in only one annual cycle and at only a few isolated locations. The most obvious difference between the two study periods, however, was the consistent decrease in pressure head (indicating a decrease in soil-moisture content) during the 1986–87 period.

The trend in decreasing pressure head was most obvious in the till and sand deposits near the southern end of the tunnel, clearly represented in the pressure-head trends of tensiometers T2, T28A, and T110 (figs. 6 and 14). The decrease in pressure head was apparent, but less obvious, in the sand deposit near the northern end of the tunnel; Mills and Healy (1991, p. 67) noted that the sand deposit in this region typically displays minimal fluctuation in pressure head.

The general drying trend (and the obscured wetting phases) during 1986–87 also is indicated by the reduced soil-water flux through gravity lysimeters GL2 and GL3 (fig. 15; see also table 12, which follows the "References Cited" section). No drainage occurred from GL2 during that period; during 1985, drainage occurred for about 4 months, with a peak flux of about 15 mm/d. At GL3, drainage occurred for about 2 months during 1986, with a peak flux of about 4 mm/d, and drainage did not occur during 1987; drainage occurred for about 5 months during 1985, with a peak flux of about 11 mm/d. Drainage did not occur at gravity lysimeter GL1 during 1985–87.

Decreasing water-table altitudes in the observation wells and piezometers also were indicative of the general drying trend in 1986 and 1987. Water levels in the wells (fig. 16*A*) during 1986–87 were near the historical (1976–87) lows of 1977–78 (Foster and others, 1984a); this decrease (1986–87) in water levels followed the occurrence of historical highs in March 1985. A similar decrease in water levels from 1985 through 1987 was seen in the piezometers (fig. 16*B*); water levels in PZ1, PZ4, and PZ5 were below the piezometer bases (water levels in PZ4 and PZ5 are not shown in figure 16 because of the limited number of measurements made before water levels decreased to below the piezometer bases). The water level did not decrease appreciably in PZ3, possibly because of the piezometer's proximity to a ground-water divide through the site (shown, in part, in figure 6 as a water-table high) or pathways of preferential water movement through the overlying unsaturated sediments.

The decrease of water movement through the unsaturated zone during 1986–87 coincides with the water-budget estimates for seepage to the trenches and (or) ground-water recharge. Those estimates indicated an average reduction in seepage (recharge) of 47 percent from the 2-year period of July 1982 through June 1984 to the 3-year period of July 1984 through June 1987 (table 3).

One anomaly that must be explained is the pronounced wetting phase in 1985, a year in which the water-budget estimate indicated a 54 percent reduction in seepage (recharge) from the previous year. One explanation for the anomaly may be related to the timing of climatic events associated with spring recharge. Rapid snowmelt in late February 1985, coupled with heavy rainfall in late February and early March 1985, probably explains the sharp rise in subtrench pressure heads and ground-water levels. Snowmelt and rainfall appear to have been more evenly distributed through time in the previous years, thus producing a greater amount of annual seepage to the trenches and (or) ground-water recharge with less obvious impact on pressure heads and ground-water levels. In light of observations by Mills and Healy (1991, p. 60) that initial saturation and meteorologic patterns play an important part in the timing and intensity of water movement through the unsaturated zone, this explanation for the sharp rise in pressure head and ground-water levels in 1985 appears reasonable.

Error in the derivation of seepage (recharge) estimates from soil-moisture-content-profile data is another explanation for the anomaly in 1984–85. Such an error does not seem likely, considering that measured precipitation in 1984–85 was much reduced from the previous 2 years, the evapotranspiration-precipitation ratio was high (as would be

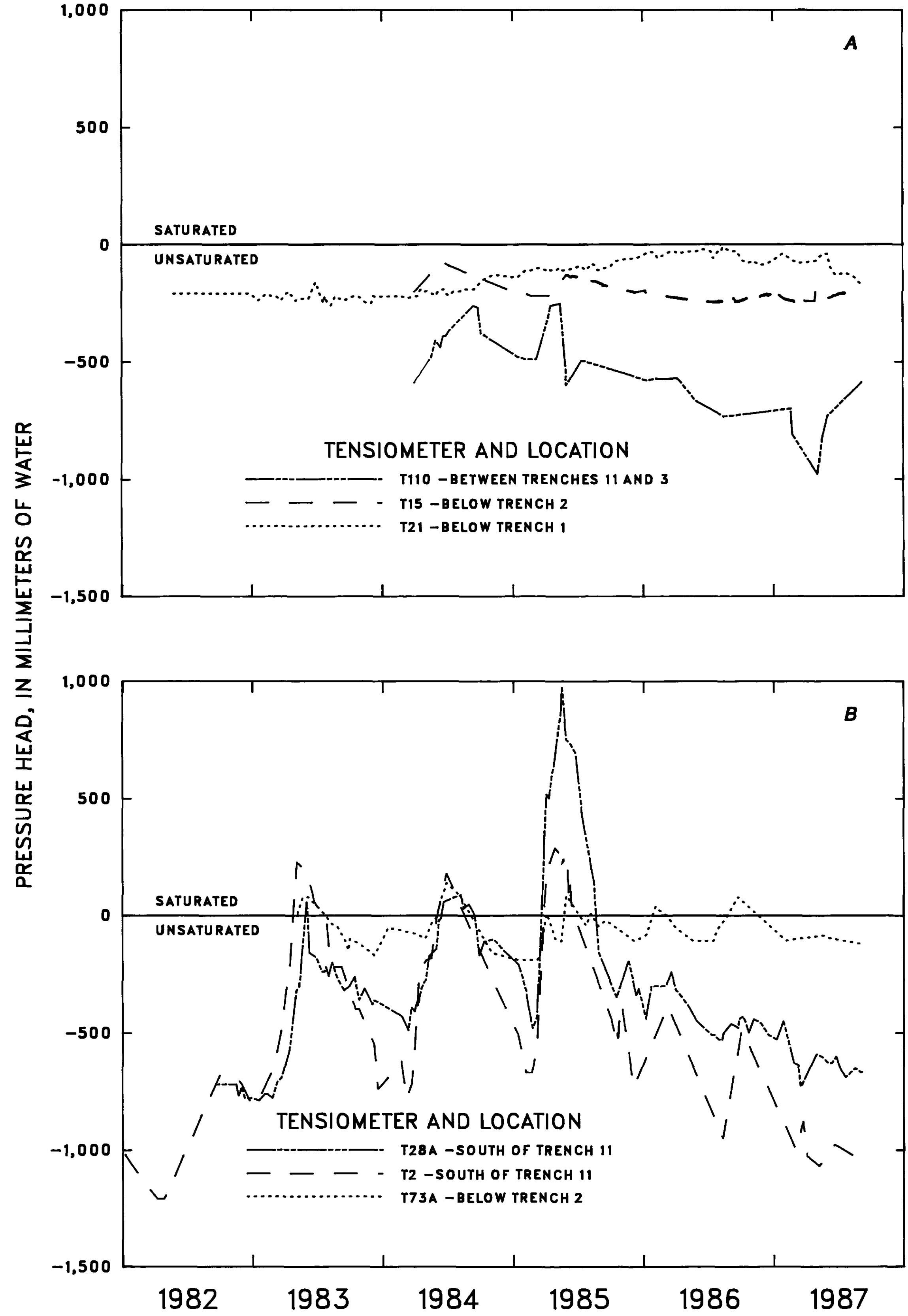


Figure 14. Typical temporal trends in liquid pressure head at below-trench locations in the (*A*) Toulon and (*B*) Hulick Till Members of the Glasford Formation, 1982–87. (Modified from Mills and Healy, 1991, fig. 37.)

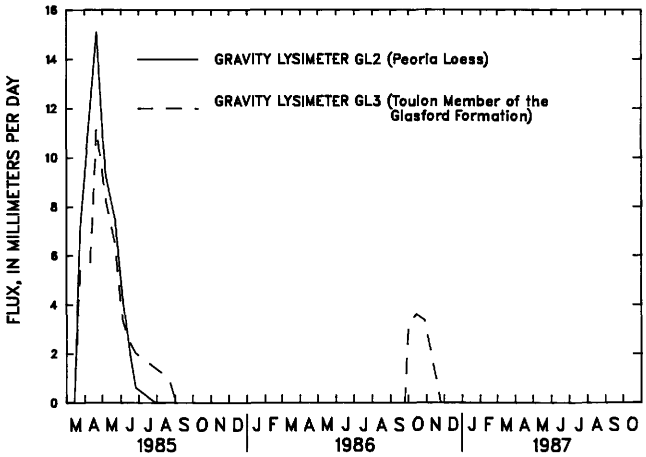


Figure 15. Temporal trends in soil-water flux at below-trench locations in the Peoria Loess and the Toulon Member of the Glasford Formation, March 1985 through October 1987. (Modified from Mills and Healy, 1991, fig. 42.)

expected during periods of reduced precipitation), and runoff totals were average. Under these conditions, limited water would be available for seepage (recharge) to the subsurface, as the data indicate.

Water Chemistry

Tritium was detected in concentrations higher than its background concentration (that is, 200 pCi/L (picocuries per liter)) in soil-water and ground-water samples. Gross-alpha and gross-beta activities of soil water were at background levels. Tritium and other soil-water-chemistry data from the subtrench vacuum lysimeters for the period April 1986 through July 1987 are presented in table 4; a statistical summary of the data is presented in table 5. Comparative data for the same lysimeter locations for the period November 1982 through June 1984 can be found in Peters and others (1992). Tritium concentrations in samples from

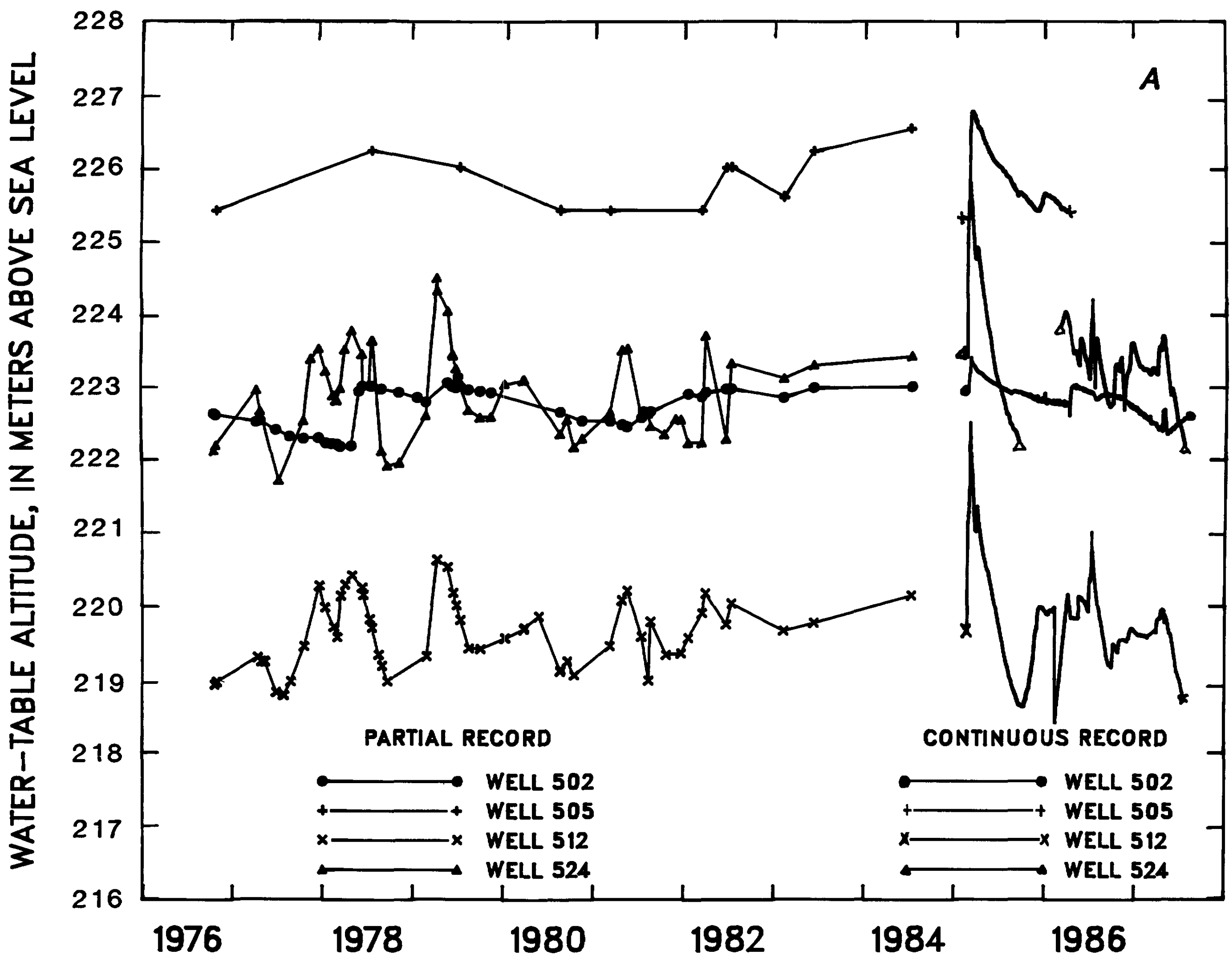


Figure 16. Temporal trends in water-table altitudes in the study area, 1976–87. *A*, Wells; *B*, Piezometers. (Modified from Mills and Healy, 1991, fig. 38.)

vacuum lysimeters from both periods are shown in figure 17. For ease of viewing, tritium concentrations in all tables and geologic cross sections (unless otherwise noted) are presented in nanocuries per liter (1 nanocurie per liter equals 1,000 picocuries per liter). Text discussions and graphs, however, are presented in picocuries per liter.

Tritium concentrations in water samples from the vacuum lysimeters ranged from 1,000 to 640,000 pCi/L and averaged 152,000 pCi/L. Increases in concentrations were noted at most lysimeter locations (8 of 12) between the periods 1982–84 and 1986–87. The minimum, maximum, and average concentrations for 1982–84 were 200, 453,000, and 70,100 pCi/L, respectively (Peters and others, 1992). Large increases in tritium concentrations were detected at vacuum lysimeters L61, L62, L65, L68, and L83. A large decrease in concentration occurred at L82. The reported tritium concentrations are not decay corrected; adjusting for radioactive decay will result in greater increases or lesser decreases in concentrations over time.

The maximum tritium concentration detected in subtrench soil water during the 1986–87 study was 15,000,000 pCi/L. This concentration was found in water draining from sediment exposed during instrument installation in the Hulick Till Member below trench 11 (23 m from the south end of the tunnel, on the western side); concentrations of five water samples collected over 6 weeks averaged about 11,000,000 pCi/L at this location. Tritium concentrations in sediment-core samples, collected at the same location on the east side of the tunnel, averaged about 9,000,000 pCi/L. Similar concentrations (11,000,000 pCi/L) were detected in water from sediment cores at a location 18 m from the south end of the tunnel (eastern side). During tunnel construction in 1978, the maximum tritium concentration detected in sediment cores was 2,600,000 pCi/L (Foster, Erickson, and Healy, 1984, p. 33); this concentration was detected 18.1 m from the tunnel origin (centerline of tunnel). In 1985, a single sample of water having a tritium concentration of 10,000,000 pCi/L was collected (Mills and Healy, 1991, p. 90); the water sample, collected 24 m from the south end of the tunnel (directly above the tunnel), had been trapped in a cavity in the grout that fills the annulus between the tunnel wall and adjacent geologic units.

The large difference in tritium concentrations below trench 11 between 1979 and 1987 suggests that either tritium migration in this area of the tunnel has increased significantly since 1979 or that tritium migration occurs

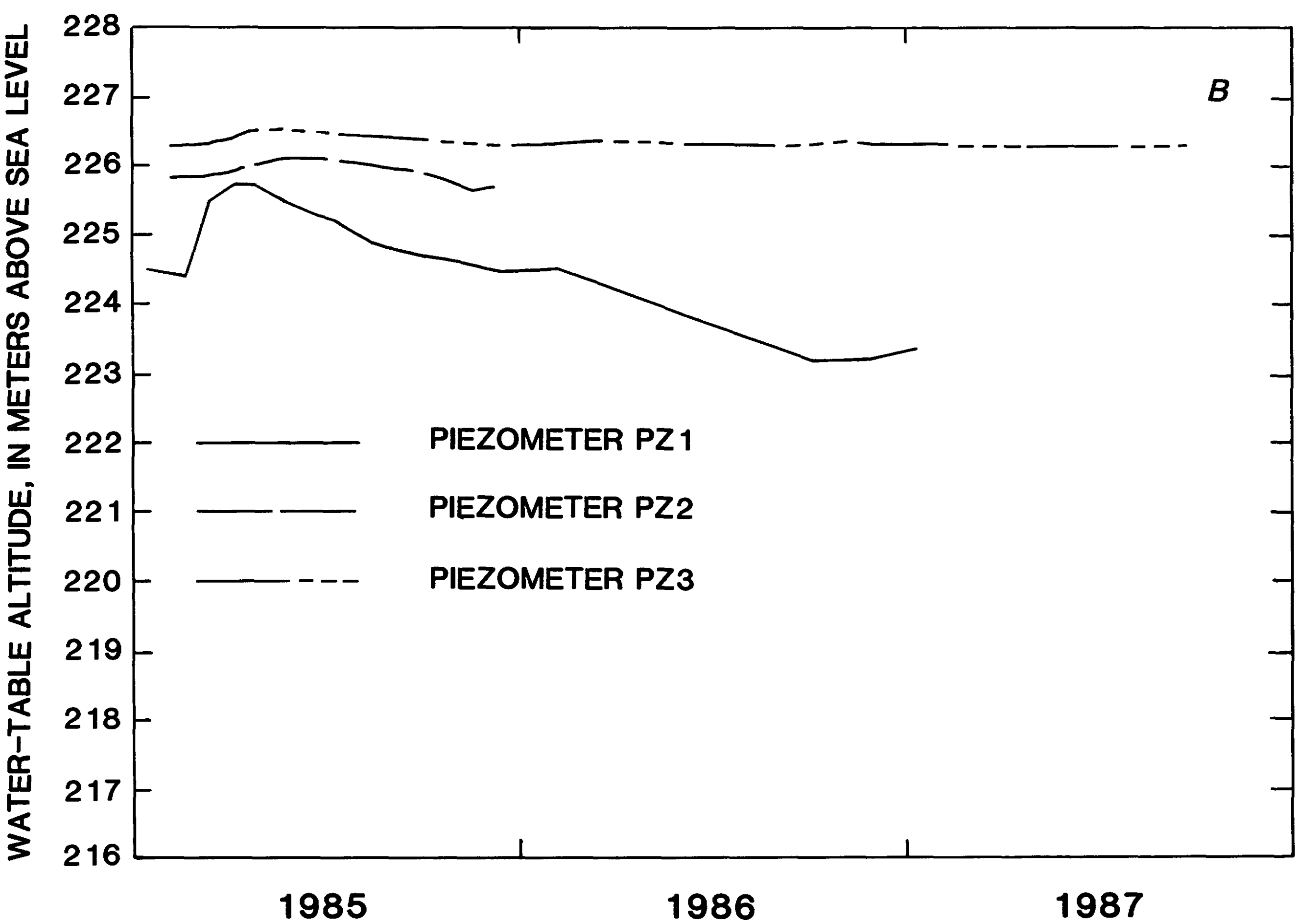


Figure 16.—Continued.

Table 4. Chemistry of soil water from below-trench vacuum lysimeters in the unsaturated glacial deposits, April 1986 through July 1987

[μS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; μg/L, micrograms per liter; nCi/L, nanocuries per liter[1]; —, no data]

Date of sample	Specific conductance (μS/cm)	pH (standard units)	Calcium (mg/L as Ca)	Magnesium (mg/L as Mg)	Sodium (mg/L as Na)	Alkalinity (mg/L as $CaCO_3$)	Sulfate (mg/L as SO_4)	Chloride (mg/L as Cl)	Silica (mg/L as SiO_2)	Iron (μg/L as Fe)	Zinc (μg/L as Zn)	Tritium (nCi/L)	Dissolved organic carbon (mg/L)
					L61								
11–04–86	—	—	—	—	—	—	—	—	—	—	—	32	—
01–27–87	—	—	—	—	—	—	—	—	—	—	—	62	—
04–30–87	1,120	8.0	—	—	—	—	—	—	—	—	—	85	—
07–22–87	1,130	7.4	—	—	—	—	—	—	—	—	—	78	—
					L62								
11–04–86	—	—	—	—	—	—	—	—	—	—	—	460	—
01–27–87	—	—	—	—	—	—	—	—	—	—	—	610	—
04–30–87	1,000	6.8	—	—	—	—	—	—	—	—	—	620	—
07–22–87	1,100	6.8	—	—	—	—	—	—	—	—	—	640	—
					L63								
04–09–86	970	7.4	—	—	—	380	—	—	—	—	—	15	5.4
07–10–86	1,150	—	—	—	—	430	—	—	—	—	—	19	—
11–04–86	991	7.3	—	—	—	430	—	—	—	—	—	18	—
01–27–87	1,040	7.5	—	—	—	440	—	—	—	—	—	22	—
04–30–87	1,030	7.0	—	—	—	430	—	—	—	—	—	23	—
07–22–87	1,080	6.5	—	—	—	440	—	—	—	—	—	24	—
					L64								
07–11–86	14,400	8.5	—	—	—	—	—	—	—	—	—	—	—
11–04–86	25,000	8.8	—	—	—	—	—	—	—	—	—	—	—
01–27–87	27,500	9.0	—	—	—	—	—	—	—	—	—	—	—
04–30–87	25,000	9.0	—	—	—	—	—	—	—	—	—	—	—
07–22–87	20,000	9.0	—	—	—	—	—	—	—	—	—	—	—
					L65								
04–09–86	2,000	8.1	120	65	14	230	130	13	57	8	24	530	110
07–10–86	1,920	—	—	—	—	240	—	—	—	—	—	540	—
11–04–86	1,780	7.9	—	—	—	280	—	—	—	—	—	450	—
01–27–87	1,870	8.0	—	—	—	250	—	—	—	—	—	490	—
04–30–87	1,860	7.7	—	—	—	250	—	—	—	—	—	520	—
07–22–87	1,980	6.4	—	—	—	280	—	—	—	—	—	510	—
					L66								
11–04–86	—	—	—	—	—	—	—	—	—	—	—	20	—
01–27–87	—	—	—	—	—	—	—	—	—	—	—	30	—
04–30–87	1,390	6.8	—	—	—	—	—	—	—	—	—	39	—
07–22–87	1,550	7.3	—	—	—	—	—	—	—	—	—	18	—

Table 4. Chemistry of soil water from below-trench vacuum lysimeters in the unsaturated glacial deposits, April 1986 through July 1987—Continued

Date of sample	Specific conductance (µS/cm)	pH (standard units)	Calcium (mg/L as Ca)	Magnesium (mg/L as Mg)	Sodium (mg/L as Na)	Alkalinity (mg/L as $CaCO_3$)	Sulfate (mg/L as SO_4)	Chloride (mg/L as Cl)	Silica (mg/L as SiO_2)	Iron (µg/L as Fe)	Zinc (µg/L as Zn)	Tritium (nCi/L)	Dissolved organic carbon (mg/L)
					L68								
04-09-86	1,150	7.5	120	63	49	320	260	18	46	70	46	—	8.0
07-10-86	1,380	—	—	—	—	380	—	—	—	—	—	84	—
11-04-86	1,180	7.7	—	—	—	380	—	—	—	—	—	76	—
01-27-87	1,200	7.9	—	—	—	340	—	—	—	—	—	84	—
04-30-87	1,180	6.9	—	—	—	330	—	—	—	—	—	89	—
07-22-87	1,260	6.5	—	—	—	390	—	—	—	—	—	87	—
					L81								
04-09-86	990	7.6	120	61	10	450	120	7.0	42	790	1,800	1.7	6.2
07-10-86	1,040	—	—	—	—	440	—	—	—	—	—	1.4	—
11-04-86	—	—	—	—	—	—	—	—	—	—	—	1.2	—
01-27-87	970	7.6	—	—	—	440	—	—	—	—	—	1.6	—
04-30-87	950	7.0	—	—	—	450	—	—	—	—	—	1.6	—
07-22-87	1,010	6.4	—	—	—	450	—	—	—	—	—	2.1	—
					L82								
04-09-86	1,120	7.2	130	77	10	560	68	13	58	310	—	260	34
07-10-86	1,210	—	—	—	—	540	—	—	—	—	—	210	—
11-04-86	1,030	7.2	—	—	—	560	—	—	—	—	—	180	—
01-27-87	1,100	7.3	—	—	—	540	—	—	—	—	—	170	—
04-30-87	1,090	6.8	—	—	—	550	—	—	—	—	—	160	—
07-22-87	—	6.5	—	—	—	560	—	—	—	—	—	150	—
					L83								
11-04-86	1,040	7.5	—	—	—	—	—	—	—	—	—	69	—
01-27-87	—	—	—	—	—	—	—	—	—	—	—	170	—
04-30-87	1,120	7.0	—	—	—	—	—	—	—	—	—	240	—
07-22-87	1,550	7.3	—	—	—	—	—	—	—	—	—	280	—
					L84								
11-04-86	—	—	—	—	—	—	—	—	—	—	—	1.0	—
04-30-87	855	7.5	—	—	—	—	—	—	—	—	—	10	—
07-22-87	854	8.1	—	—	—	—	—	—	—	—	—	2.4	—
					L96								
04-09-86	750	7.2	83	46	10	360	57	9.2	49	20	150	4.0	28
07-10-86	660	—	—	—	—	340	—	—	—	—	—	4.4	—
11-04-86	741	7.4	—	—	—	390	—	—	—	—	—	3.3	—
01-27-87	508	7.5	—	—	—	220	—	—	—	—	—	6.8	—
04-30-87	508	7.1	—	—	—	240	—	—	—	—	—	7.3	—
07-22-87	565	6.4	—	—	—	240	—	—	—	—	—	6.5	—

[1] Nanocuries per liter × 1,000 = picocuries per liter (1 nanocurie = 1,000 picocuries).

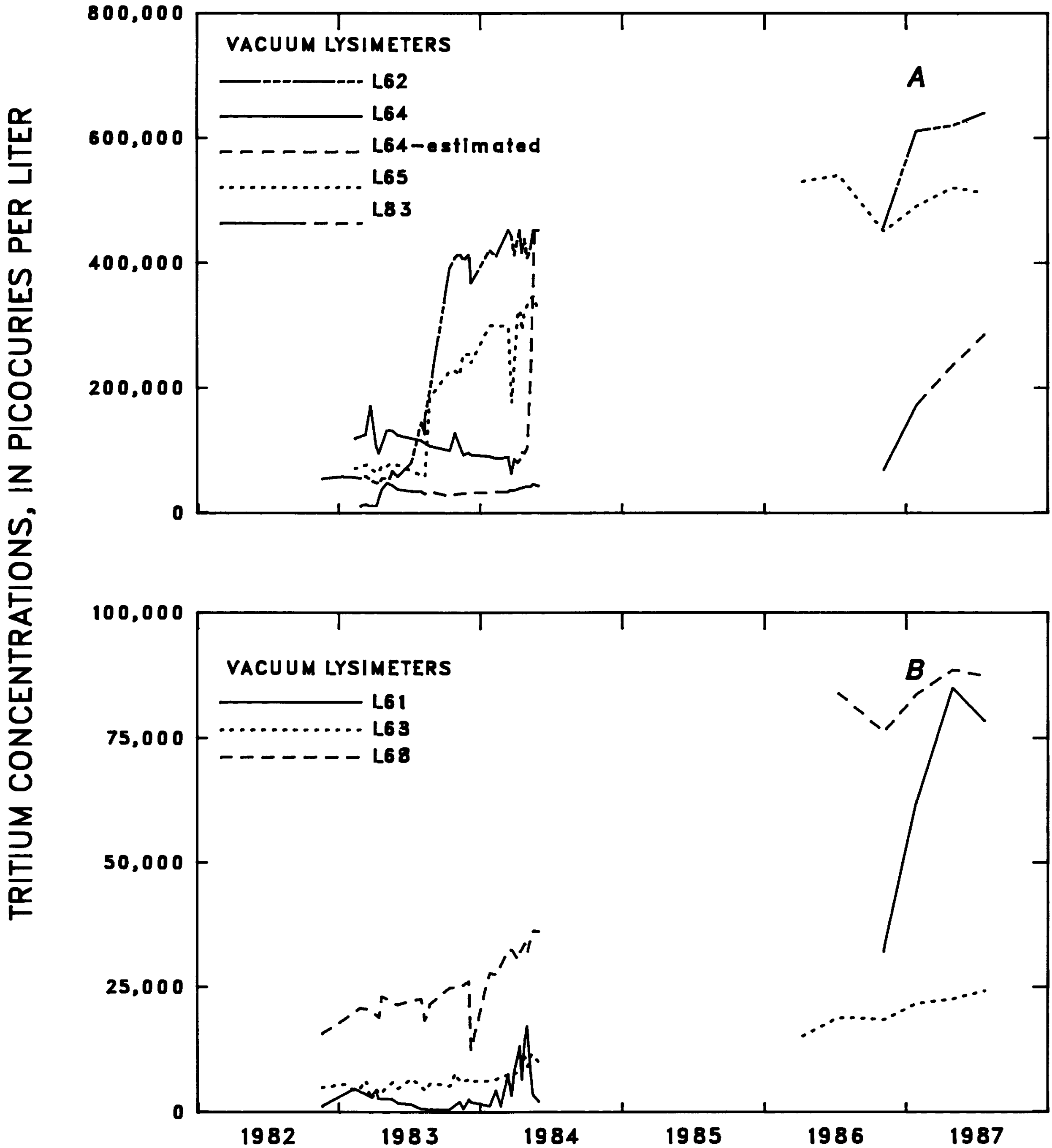


Figure 17. Temporal trends in tritium concentrations at below-trench locations in the Toulon and Hulick Till Members of the Glasford Formation, November 1982 through June 1984 and April 1986 through July 1987. (Modified from Mills and Healy, 1991, fig. 53.)

along isolated flow paths that can easily go undetected during sampling and monitoring operations, especially when using routine methods such as those that employ vacuum lysimeter samplers, which have a small sample-capture area. Although no firm evidence exists, Mills and Healy (1991, p. 80) suggest that fractures may provide an avenue for preferential water movement through the clayey silt till deposits; such fractures contribute to tritium migration through the till deposits at the radioactive-waste disposal site at West Valley, N.Y. (Prudic, 1986).

Seasonal fluctuations in tritium concentrations that were seen during 1982–84 in samples from several vacuum lysimeters were absent during 1986–87. Water-sampling intervals during 1986–87 may have been too large

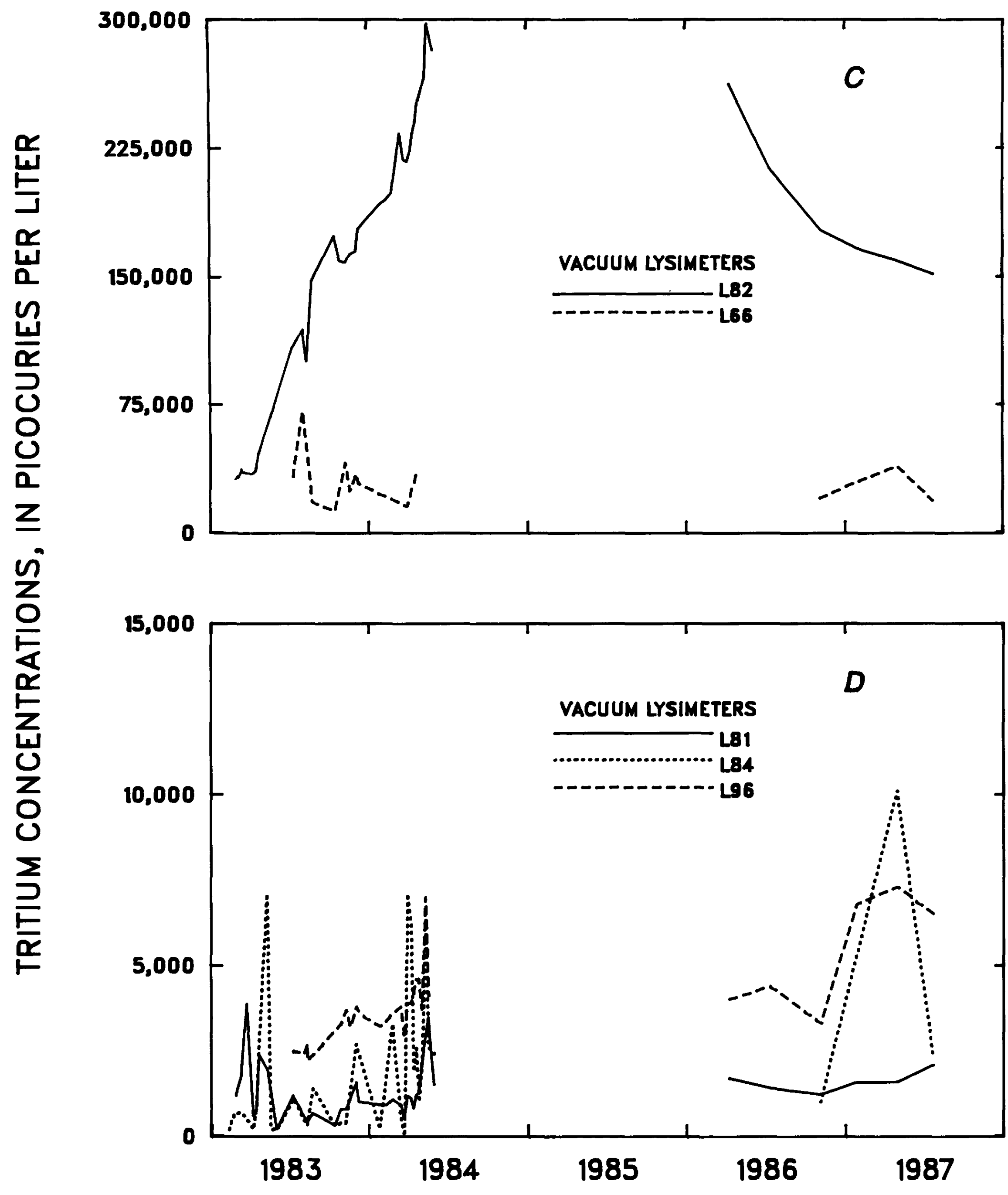


Figure 17.—Continued

(quarterly, as opposed to biweekly) to allow delineation of seasonal changes in concentration, or the overall reduction in water movement during that period may have limited seasonal tritium migration. If the latter explanation is true, then the general increases in tritium concentrations throughout the tunnel area need to be explained. The increases may represent the slow, continuous movement of water and tritium from the trenches in the absence of large influxes of freshwater during annual recharge periods. Water samples from several vacuum lysimeters in the 1982–84 study (Mills and Healy, 1991, p. 98) revealed large increases in tritium concentrations that may have been related to water movement through collapse holes in the trench covers and to the natural deterioration of trench-waste containers. The pattern of increasing tritium concentrations in the absence of significant ground-water recharge during the 1986–87 study also can be attributed to the deterioration of containers. However, the large number and wide spatial distribution of

Table 5. Statistical summary of soil-water-chemistry data, April 1986 through July 1987

[μS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; nCi/L, nanocuries per liter[1]; —, no data]

Vacuum lysimeter	Statistic	Specific conductance (μS/cm)	pH (standard units)	Alkalinity (mg/L as $CaCO_3$)	Tritium (nCi/L)
L61	Mean	1,120	7.6	—	64
	Standard deviation	7	—	—	24
	Number of samples	2	2	—	4
L62	Mean	1,050	6.8	—	580
	Standard deviation	70	—	—	80
	Number of samples	2	2	—	4
L63	Mean	1,040	7.0	420	20
	Standard deviation	60	—	20	3
	Number of samples	6	5	6	6
L64	Mean	22,400	8.8	—	—
	Standard deviation	5,200	—	—	—
	Number of samples	5	5	—	—
L65	Mean	1,900	7.0	260	510
	Standard deviation	80	—	20	30
	Number of samples	6	5	6	6
L66	Mean	1,470	7.0	—	27
	Standard deviation	110	—	—	10
	Number of samples	2	2	—	4
L68	Mean	1,220	7.0	—	84
	Standard deviation	80	—	—	5
	Number of samples	6	5	—	5
L81	Mean	990	6.9	450	1.6
	Standard deviation	30	—	5	.3
	Number of samples	5	4	5	6
L82	Mean	1,110	6.9	550	190
	Standard deviation	60	—	10	40
	Number of samples	5	5	6	6
L83	Mean	1,240	7.2	—	190
	Standard deviation	270	—	—	90
	Number of samples	3	3	—	4
L84	Mean	840	7.7	—	4.5
	Standard deviation	20	—	—	4.8
	Number of samples	2	2	—	3
L96	Mean	620	6.9	300	5.4
	Standard deviation	110	—	70	1.9
	Number of samples	6	5	6	6

[1] Nanocuries per liter × 1,000 = picocuries per liter (1 nanocurie = 1,000 picocuries).

locations having increasing concentrations, and the reduced occurrence of collapse holes during the period, indicate that water movement through collapse holes was not a contributing factor in the increase in subtrench tritium concentrations.

Volatile organic compounds (VOC's) in the soil water prevented accurate liquid-scintillation analysis of tritium concentrations at vacuum lysimeter L64 (figs. 6 and 17). Synoptic analysis of organic compounds in the water from lysimeter L64 revealed the presence of a variety of halogenated aliphatic hydrocarbons, halogenated aromatic hydrocarbons, nonhalogenated aromatic hydrocarbons, and methyl esters. Detailed results of that analysis can be found in Mills and deVries (1988, p. 60–61). From 1982 to 1984, tritium concentrations at that location increased greatly. Ever-increasing quenching during the 1986–87 tritium analyses suggested a continuing increase in tritium concentrations and VOC's.

Lysimeter L64 was not the only location where trench leachate other than tritium was detected. Dissolved organic carbon, at concentrations ranging from 5.4 to 70 mg/L (milligrams per liter), was detected at 10 vacuum lysimeter locations during the 1982–84 study period of Peters and others (1992, p. 44). Concentrations at three lysimeters showed marked changes by 1986 (from 41 to 110 mg/L at L65, 8.8 to 34 mg/L at L82, and 70 to 28 mg/L at L96). Coloration and odor of soil-water samples suggested the presence of organic leachate at several gravity lysimeters in the Toulon Member; further discussion of the presence of organic leachate in the gravity lysimeter samples is presented in the section "Chemistry of Water in the Preferential Flow Path."

Specific conductance of the vacuum lysimeter water samples during 1986–87 ranged from 508 to 27,500 μS/cm (microsiemens per centimeter at 25 degrees Celsius) and averaged 3,280 μS/cm. Excluding the extremely high specific conductances at lysimeter L64, the maximum specific conductance of the vacuum lysimeters was 2,000 μS/cm, and the average was 1,150 μS/cm. During the 1982–84 study period, the maximum specific conductance at L64 was only 3,500 μS/cm (Peters and others, 1992). The average specific conductance at lysimeter L96 increased slightly from 442 to 622 μS/cm between the two study periods; the increase was associated with slight increases in tritium concentrations and alkalinity. Values at all other locations remained relatively stable over time.

The pH values generally were stable through the 1982–84 and 1986–87 study periods; a slight decrease in pH was observed at several locations in the final sampling in July 1987. These data, however, should be viewed with caution. Errors in pH measurement in the unsaturated zone can occur readily (Peters and others, 1992, p. 53), and the sudden decrease in such a large and widely distributed number of water samples suggests such an error. A slight increase in pH was observed at lysimeter L64; this increase appears to be related to the concomitant increases in specific conductance, tritium, and VOC's. During 1986–87, pH ranged from 6.4 to 9.0 and averaged 7.0 (average hydrogen-ion concentration expressed as pH); excluding data from the last sampling date and from lysimeter L64, the range was from 6.8 to 8.1, and the average was 7.2.

In the 1986–87 period, alkalinity ranged from 220 to 560 mg/L and averaged 390 mg/L. These values were similar to the 1982–84 values; there was a slight decrease in alkalinity at lysimeter L65, from an average of 390 (1982–84) to 260 (1986–87) mg/L, and a slight increase at lysimeter L96, from an average of 160 (1982–84) to 300 (1986–87) mg/L. The alkalinity of soil water from lysimeter L64 could not be determined during 1986–87 because of chemical interference from trench-waste products.

In their 1982–84 study, Peters and others (1992) analyzed water from 13 vacuum lysimeters quarterly for the major ions shown in table 4; no apparent relation was found between waste burial and inorganic water chemistry, and concentrations generally remained stable over time. Ionic concentrations were remeasured at five of the lysimeters once during the 1986–87 study; the concentrations were similar to those recorded by Peters and others (1992, p. 101–106, 108, 109).

Ground-water chemistry data for August 1985 through July 1987 from the wells (fig. 3) and piezometers (fig. 6) are presented in table 6; a statistical summary of the data is presented in table 7. Tritium concentrations in ground water from the wells ranged from 300 to 3,500 pCi/L and averaged 1,400 pCi/L. With the exception of a small increase in concentrations at well 512 and a small decrease in concentrations at well 502 during 1986–87, there were no discernible tritium-concentration trends in the ground water in the study area during either the 1982–84 (Peters and others, 1992, p. 113–115) or 1986–87 study periods. It should be noted that, during 1982–84, tritium concentrations averaged 102,000 pCi/L at well 505 (located several meters east of trench 11); during the 1986–87 study, the ground-water surface was below the base of the well screen, and so water-chemistry analysis, including tritium analysis, was prevented. Tritium concentrations in ground water from piezometers directly below the four study trenches ranged from 1,700 to 920,000 pCi/L and averaged 180,000 pCi/L. The concentrations generally were stable during 1985–87 (data were not available prior to 1985); a relatively small increase was detected at piezometer PZ3, and a pronounced decrease was detected at piezometer PZ5 (possibly associated with the steady decrease in the ground-water surface below the base of the piezometer screen).

There were no pronounced temporal trends in specific conductance, pH, alkalinity, or major ions in ground water during the period of record (1982–87). Specific conductances in the ground water ranged from 440 to 2,840 μS/cm and averaged 1,090 μS/cm. The highest specific-conductance values were from piezometers open to the Hulick Till Member near the southern end of the tunnel (below trench 11). The high values may be related to the increased tritium concentrations in this area. The absence of casings or screens on the piezometers below the floor of the tunnel, resulting in suspended sediment in the water samples, may also explain the high specific-conductance values. Ground-water pH ranged from 5.3 to 9.4; excluding the minimum and maximum values, which were found in ground water directly below trenches, pH ranged from 6.5 to 8.5. Alkalinity ranged from 50 to 640 mg/L and averaged 330 mg/L. Alkalinity values were lowest in water from piezometer PZ3 (located close to the ground-water divide that runs from southwest to northeast through the disposal site).

PREFERENTIAL WATER MOVEMENT THROUGH AN UNSATURATED SAND DEPOSIT

The study by Mills and Healy (1991) indicated that the characteristics of water movement through the subtrench till deposit (Hulick Till Member of the Glasford Formation) differed from those through the subtrench sand deposit (Toulon Member of the Glasford Formation); the difference clearly is represented in the pressure-head records of tensiometers installed in the two deposits (fig. 14). A seasonal cycle of wetting and drying was readily detected in the till deposits near the south end of the tunnel. During a typical year (1984, for example), the average pressure head of the unit varied over a range of 350 mm. Water movement through the sand deposits near the northern end of the tunnel displayed limited seasonal variability; average pressure head varied over a range of only 40 mm. Small head gradients, which generally were constant over time, indicated that water movement through the sand deposit is typically slow and continuous. Pressure heads at one location, tensiometer T15 (figs. 6 and 14), indicated that localized, preferential pathways of water movement may exist within the sand deposit. At this location, pressure heads fluctuated seasonally and generally were greater than elsewhere in the sand deposit.

A detailed study of the Toulon Member deposit was undertaken to improve an understanding of water movement through this sand deposit. Special emphasis was placed on evaluating the potential for preferential movement of water and soluble trench-waste constituents along localized, preferential flow paths where flow rates are more rapid and more temporally variable than generally detected in the deposit. The goals of the study were to (1) identify the spatial and temporal distribution of water and tritium (the primary leachate constituent) movement, (2) describe the general water chemistry, (3) estimate the flux of soil water and tritium, and (4) determine the factors influencing soil-water and tritium movement.

Spatial and Temporal Variations in Water and Tritium Movement

Free drainage of water to the Toulon Member gravity lysimeters indicated that water and tritium movement varies in both space and time in the sand deposit and that preferential movement occurs along localized pathways where sediments are saturated. Nearby tensiometers gave

Table 6. Chemistry of ground water from the glacial deposits, August 1985 through July 1987

[μS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; μg/L, micrograms per liter; nCi/L, nanocuries per liter[1]; <, less than; —, no data]

Date of sample	Specific conductance (μS/cm)	pH (standard units)	Calcium (mg/L as Ca)	Magnesium (mg/L as Mg)	Sodium (mg/L as Na)	Alkalinity (mg/L as $CaCO_3$)	Sulfate (mg/L as SO_4)	Chloride (mg/L as Cl)	Silica (mg/L as SiO_2)	Iron (μg/L as Fe)	Zinc (μg/L as Zn)	Tritium (nCi/L)	Dissolved organic carbon (mg/L)
						Well 502							
04–09–86	820	7.2	87	42	19	420	30	4.9	13	3,400	72	1.4	3.8
07–11–86	760	—	—	—	—	390	—	—	—	—	—	1.5	—
11–05–86	840	7.1	—	—	—	410	—	—	—	—	—	1.1	—
04–30–87	660	6.7	—	—	—	370	—	—	—	—	—	.7	—
07–22–87	660	6.7	—	—	—	340	—	—	—	—	—	.3	—
						Well 512							
04–09–86	590	8.0	—	42	13	240	72	2.5	55	280	14	1.2	—
07–11–86	780	—	—	—	—	300	—	—	—	—	—	1.6	—
11–05–86	740	7.5	—	—	—	370	—	—	—	—	—	1.7	—
04–30–87	—	6.7	—	—	—	320	—	—	—	—	—	2.3	—
07–22–87	660	6.7	—	—	—	290	—	—	—	—	—	3.5	—
						Well 524							
04–09–86	880	7.9	49	88	14	430	63	3.1	12	980	<50	1.3	3.5
07–11–86	910	—	—	—	—	640	—	—	—	—	—	1.3	—
11–05–86	850	—	—	—	—	480	—	—	—	—	—	1.0	—
04–30–87	800	—	—	—	—	430	—	—	—	—	—	1.0	—
07–22–87	820	—	—	—	—	430	—	—	—	—	—	1.1	—
						Piezometer PZ1							
08–27–85	—	—	—	—	—	—	—	—	—	—	—	250	—
11–04–86	2,100	7.5	—	—	—	600	—	—	—	—	—	—	—
						Piezometer PZ2							
08–27–85	—	—	—	—	—	—	—	—	—	—	—	160	—
07–10–86	2,840	—	—	—	—	130	—	—	—	—	—	200	—
11–05–86	1,580	7.4	—	—	—	360	—	—	—	—	—	60	—
01–27–87	2,160	7.2	—	—	—	320	—	—	—	—	—	110	—
04–29–87	2,230	6.9	—	—	—	380	—	—	—	—	—	—	—
07–22–87	2,300	6.5	—	—	—	350	—	—	—	—	—	120	—
						Piezometer PZ3							
08–27–85	—	—	—	—	—	—	—	—	—	—	—	1.7	—
07–10–86	830	—	—	—	—	50	—	—	—	—	—	7.6	—
11–04–86	750	8.2	—	—	—	50	—	—	—	—	—	6.2	—
01–27–87	720	8.5	—	—	—	50	—	—	—	—	—	6.8	—
04–29–87	810	9.4	—	—	—	92	—	—	—	—	—	6.6	—
07–21–87	830	7.2	—	—	—	70	—	—	—	—	—	9.8	—

Table 6. Chemistry of ground water from the glacial deposits, August 1985 through July 1987—Continued

Date of sample	Specific conductance (µS/cm)	pH (standard units)	Calcium (mg/L as Ca)	Magnesium (mg/L as Mg)	Sodium (mg/L as Na)	Alkalinity (mg/L as $CaCO_3$)	Sulfate (mg/L as SO_4)	Chloride (mg/L as Cl)	Silica (mg/L as SiO_2)	Iron (µg/L as Fe)	Zinc (µg/L as Zn)	Tritium[1] (nCi/L)	Dissolved organic carbon (mg/L)
Piezometer PZ4													
08–27–85	—	—	—	—	—	—	—	—	—	—	—	42	—
Piezometer PZ5													
04–02–86	—	—	—	—	—	—	—	—	—	—	—	920	—
07–27–86	—	—	—	—	—	—	—	—	—	—	—	680	—
07–10–86	440	5.3	—	—	—	520	—	—	—	—	—	300	—
11–05–86	—	7.0	—	—	—	510	—	—	—	—	—	—	—

[1] Nanocuries per liter × 1,000 = picocuries per liter (1 nanocurie = 1,000 picocuries).

no indication of the existence of the preferential pathways; the tensiometers indicated only slow and continuous matrix flow at pressure heads less than atmospheric (0 mm). The inability of the tensiometer to detect water movement along preferential pathways is shown, in part, by the soil-water-flux and tritium-concentration records of the gravity lysimeters and the pressure-head records of nearby tensiometers (fig. 18). Free drainage of water occurred at 7 of 16 gravity lysimeters (fig. 19, see also table 12). These seven lysimeters were all located below trench 2. Six of the seven lysimeters (GL6–GL11) were located in a cluster below the northern edge of the trench (fig. 6); the seventh (GL4) was located 14 m to the south of the clustered lysimeters (fig. 6). No drainage was detected from lysimeters GLB and GL12–GL14, located below the intertrench till deposit. From the time of lysimeter installation, drainage was continuous at three lysimeters (GL9–GL11) and periodic at four (GL4, GL6–GL8). Where periodic drainage occurred, it was either delayed (it did not begin until December at lysimeters GL6–GL8, after which it was continuous) or intermittent (GL4).

There is no evidence that indicates whether the saturated flow along the preferential pathways is sustained below the gravity lysimeter locations. The gravity lysimeters were located very close to the trench bases, the apparent origin of the saturated flow. Below this point, the flow may continue downward along the saturated pathways or be dispersed as the water moves by capillary dispersion into the drier sediments adjacent to the flow paths. In studies of wetting-front instability and the development of fingerlike saturated flow paths in unsaturated coarse-grained sediments (not unlike the preferential flow paths detected in this study), Glass and others (1987, p. 72) observed that the saturated cores of fingers persist even though lateral spreading of fingers occurs over time and depth because of capillary gradients. Because the soil-moisture content is higher in the flow paths than in the adjacent sediments, a higher vertical hydraulic conductivity is maintained in the flow paths. Thus, gravitationally induced flow is sustained along the flow paths.

The conclusion that preferential water movement occurs along saturated flow paths is based on the assumption that drainage from the gravity lysimeters represents natural, undisturbed flow and not drainage induced by the presence of the instruments. The strongest case for artificially induced drainage may be the delayed periodic drainage response at gravity lysimeters GL6–GL8. If one assumes, however, that the sand deposit is at a uniform level of saturation throughout the study area (as generally indicated by tensiometer data) and is homogeneous in texture (as indicated by sediment-core data), then artificially induced drainage should be expected at all gravity lysimeter locations. This, however, was not the case. Drainage occurred immediately following instrument installation at three lysimeter locations, was intermittent at one

Table 7. Statistical summary of ground-water-chemistry data, August 1985 through July 1987

[μS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; nCi/L, nanocuries per liter[1]; —, no data]

Well or piezometer	Statistic	Specific conductance (μS/cm)	pH (standard units)	Alkalinity (mg/L as $CaCO_3$)	Tritium (nCi/L)
502	Mean	750	6.9	390	1.0
	Standard deviation	83	—	30	.5
	Number of samples	5	4	5	5
512	Mean	690	7.0	300	2.1
	Standard deviation	80	—	50	.9
	Number of samples	4	4	5	5
524	Mean	850	7.9	480	1.1
	Standard deviation	50	—	90	.2
	Number of samples	5	1	5	5
PZ1	Mean	2,100	7.5	600	250
	Standard deviation	—	—	—	—
	Number of samples	1	1	1	1
PZ2	Mean	2,,220	6.9	310	130
	Standard deviation	450	—	100	50
	Number of samples	5	4	5	5
PZ3	Mean	790	7.7	62	6.4
	Standard deviation	50	—	19	2.7
	Number of samples	5	4	5	6
PZ4	Mean	—	—	—	42
	Standard deviation	—	—	—	—
	Number of samples	—	—	—	1
PZ5	Mean	440	5.6	520	630
	Standard deviation	—	—	10	310
	Number of samples	1	2	2	3

[1] Nanocuries per liter × 1,000 = picocuries per liter (1 nanocurie = 1,000 picocuries).

location, and did not occur at all at nine other locations. The variable manner in which drainage of water from the sand deposit occurred strongly indicates that, even if the gravity lysimeters were responsible for the observed drainage, there had to be preexisting locations in the sand deposit where soil-moisture contents were naturally elevated and preferential water movement occurred (whether or not there was truly saturated flow).

Chemistry of Water in the Preferential Flow Paths

Water collected from the gravity lysimeters where drainage occurred (GL4, GL6–GL11) was analyzed for tritium following each site visit; water samples were analyzed quarterly for gross-alpha and gross-beta activity. For most of the gravity lysimeters, water samples were analyzed twice during the study for specific conductance and pH. Lysimeter GL1 was analyzed once, and GL9 was analyzed eight times for specific conductance and pH.

Table 8. Soil-water and tritium-concentration data used to estimate tritium flux in the unsaturated sand of the Toulon Member of the Glasford Formation

[cm^3, cubic centimeters; cm/yr, centimeters per year; nCi/L, nanocuries per liter[1]; $(nCi/yr)/cm^2$, nanocuries per year per square centimeter]

Gravity lysimeter	Annual volume of water collected (cm^3)	Annual soil-water flux (cm/yr)	Average annual tritium concentration (nCi/L)	Annual tritium flux ($(nCi/yr)/cm^2$)
GL4	1,080	0.91	380	0.35
GL6	360	.77	490	.38
GL7	530	1.21	500	.60
GL8	570	1.23	530	.65
GL9	2,430	5.80	630	3.65
GL10	1,450	3.35	640	2.14
GL11	2,600	5.63	670	3.77

[1] Nanocuries per liter × 1,000 = picocuries per liter (1 nanocurie = 1,000 picocuries).

Tritium concentrations ranged from 288,000 pCi/L (at GL4) to 963,000 pCi/L (at GL11) and averaged 590,000 pCi/L (see table 12). Average tritium concentrations were least at lysimeter GL4 and greatest at lysimeter GL11 (table 8). Average tritium concentrations increased from GL6 to GL11 (from south to north). Tritium concentrations of water from lysimeters GL9 to GL11 exceeded the concentrations at all other sample locations in the sand deposit; concentrations at lysimeters GL4 and GL6–GL8 were among the highest detected elsewhere in the sand deposit. Gross-alpha and gross-beta activities were at background levels.

Specific conductance and pH values from representative gravity lysimeter water samples are shown in table 9; with the exception of vacuum lysimeter L64, the values were similar to the values from all vacuum lysimeter samples in the Toulon Member (table 4). With the exception of gravity lysimeter GL9, specific conductance and pH of the water generally were similar for two sampling dates that represent typical months of subtrench sediment drying (March) and wetting (July). Coloration of the gravity lysimeter samples (see table 12) and quenching during tritium analysis suggested that VOC's may be present; VOC's inducing similar coloration of the water and similar quenching characteristics were detected in soil water from vacuum lysimeter L64, located within 5 m of gravity lysimeter GL6.

Flux of Water and Tritium

Determination of soil-water and tritium fluxes through subtrench soils is important because waste-site managers and environmental-safety regulators can use the information to (1) assess the competence of waste-disposal systems by determining the rate at which waste constituents

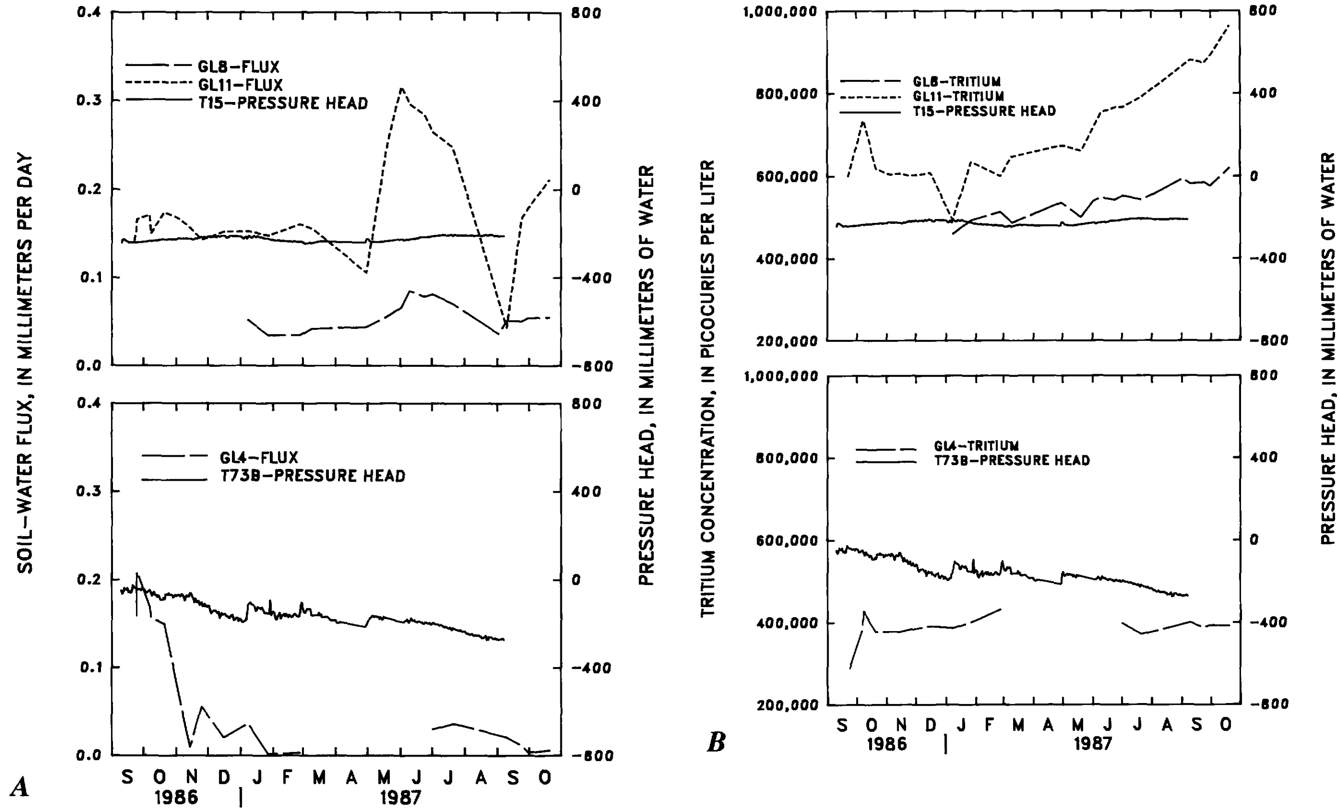


Figure 18. Relation of (*A*) soil-water flux and (*B*) tritium concentration in the unsaturated sand of the Toulon Member of the Glasford Formation at select gravity lysimeter locations to liquid pressure head at nearby soil-moisture tensiometer locations, September 1986 through October 1987.

are leached from disposal trenches and (2) provide data necessary for estimating the ultimate effect of leachates on water quality in ground-water systems. Soil-water-flux estimates are important because water movement through the unsaturated zone generally is considered to be the primary mechanism for the transport of leachate from disposal trenches; estimating the flux of leachates (including tritium), therefore, requires knowledge of the soil-water-flux rate.

In the areas of nonpreferential water movement, steady-state, one-dimensional, vertical specific flux (Darcian flux) was estimated by using tensiometer-based pressure-head data. A single flux was estimated by this method from one pair of vertically aligned tensiometers (T18 and T20; fig. 6). The single value is temporally representative because fluxes at this and most other locations in the sand deposit typically are invariant over time (Mills and Healy, 1991, p. 67). The single value also appears to be spatially representative, based on tensiometer-based flux estimates by Mills and Healy (1991). On the basis of sediment-core data, however, Healy and Mills (1991) estimated that flux through the sand deposit can vary by more than an order of magnitude. It is likely, however, that their distribution of sediment cores included regions of nonpreferential and preferential water movement.

Darcian flux was determined from the tensiometer data by using the following form of Darcy's equation (Healy, Gray, and others, 1989, p. 385):

$$q = K(\psi)[\partial\psi/\partial z + 1], \tag{3}$$

where

q = vertical Darcian flux, in millimeters per day,
$K(\psi)$ = unsaturated hydraulic conductivity, in millimeters per day,
ψ = pressure head, in millimeters,
z = depth, in millimeters, and
$[\partial\psi/\partial z + 1]$ = total hydraulic gradient, which is dimensionless.

In equation 3, $\partial\psi/\partial z$ represents the capillary gradient; the gravitational gradient for vertically downward water movement is 1. The $K(\psi)$ relation was determined by methods described by van Genuchten (1978; 1980).

In the areas of more rapid preferential water movement, where the sand deposits were saturated, specific flux was estimated by using gravity lysimeter data. To distinguish the difference in estimating techniques, specific

Table 9. Specific conductance and pH of soil water from the unsaturated sand of the Toulon Member of the Glasford Formation, 1987

[Measured at gravity lysimeter locations GL4, GL6–11. μS/cm, microsiemens per centimeter at 25 degrees Celsius]

Sample period		Specific conductance	pH
Starting	Ending	(μS/cm)	(standard units)
		GL4	
07–02–87	07–21–87	1,410	6.9
		GL6	
03–10–87	04–30–87	2,020	8.1
07–02–87	07–21–87	2,000	7.8
		GL7	
03–10–87	04–30–87	1,190	7.5
07–02–87	07–21–87	1,440	7.7
		GL8	
03–10–87	04–30–87	1,320	6.1
07–02–87	07–21–87	1,200	7.4
		GL9	
03–18–87	03–21–87	1,560	8.3
03–21–87	03–24–87	1,600	8.2
03–24–87	03–27–87	1,540	8.5
03–27–87	03–30–87	1,540	8.4
03–30–87	04–02–87	1,570	8.5
04–02–87	04–30–87	1,750	8.1
04–24–87	06–25–87	2,730	7.0
07–18–87	07–21–87	2,790	7.1
		GL10	
03–10–87	04–30–87	2,120	7.6
07–02–87	07–21–87	2,600	7.4
		GL11	
03–10–87	04–30–87	2,320	7.5
07–02–87	07–21–87	2,720	7.7

flux determined by using gravity lysimeter data will hereafter be referred to as soil-water flux (Q). This approach was used because previous experience (Mills and Healy, 1991, p. 73) indicated that the tensiometer-based flux rates for the Sheffield site were inappropriate for areas of preferential water movement (either the small-diameter cups of the tensiometers failed to intercept the localized preferential flow paths or the tensiometer cups were too large to adequately monitor pressure head in the proportionally smaller flow paths). Soil-water flux (Q) was determined by using the following equation:

$$Q = D/A, \tag{4}$$

where

Q = soil-water flux, in millimeters per square millimeters per day, expressed as millimeters per day,
D = volume-rate discharge from the gravity lysimeter, in cubic millimeters per day, and
A = area of the gravity lysimeter orifice perpendicular to the flow path, in square millimeters.

All values of specific flux should be considered estimates and viewed with caution because of the assumptions inherent in their calculation. The assumptions included are that (1) flow paths through the sediments are vertical, (2) steady-state flow occurs during the sampling interval, (3) flow is evenly distributed through the sediments across the full orifice area, and (4) the instruments do not artificially induce saturation of the sediments.

The tensiometer-based Darcian flux (q), representative of regions of nonpreferential water movement in the sand deposit, was 0.20 mm/d. Mills and Healy (1991, p. 69) estimated that q in the sand deposit averaged 0.17 mm/d. Gravity-lysimeter-based fluxes (Q), representing areas of preferential water movement, ranged from 0 to 0.69 mm/d (see table 12 and fig. 19). The lack of a substantial difference between (1) estimated flux rates in the areas of preferential flow and (2) estimated flux rates in the areas of nonpreferential flow indicates that water movement is unequally distributed across the gravity lysimeter orifices; that is, saturated flow occurs through only a small part of the orifice area. If the entire orifice area is saturated, then the flux should approximate the saturated hydraulic conductivity of the sand deposit (assuming that water movement is vertical and under a unit hydraulic gradient), which averages 3.4×10^4 mm/d (Mills and Healy, 1991). The small flux estimates in the areas of preferential flow also can be explained by fast-pulsed, transient-flow events that were not detected and, therefore, were time-averaged over inappropriately long sampling intervals. However, data collection at intervals as short as 18 hours and at regulated intervals of 3 days at one lysimeter (GL9) revealed no evidence of fast-pulsed flow events that would produce flux estimates that are substantially different from values reported here.

Rearrangement of equation 4 in the following manner,

$$A = D/Q, \tag{5}$$

allows estimation of the cross-sectional area of the preferential flow path (or cumulative cross-sectional area of multiple flow paths) intersected by an individual gravity lysimeter, assuming that the flow path is fully saturated. By further assuming that the flux at full saturation is equivalent to the average saturated hydraulic conductivity of the sand deposit (3.4×10^4 mm/d), and with knowledge of the maximum measured discharge from the gravity lysimeters (2.93×10^4 cubic millimeters per day at GL9), one can calculate that the cross-sectional area of a flow path is no greater than 8.6×10^{-1} mm^2. It appears that the regions of preferential flow are similar to the narrow fingers of rapid, saturated water movement described by Palmquist and Johnson (1962), Glass and others (1987), and Oosting and others (1987) in their studies of water movement in unstable-flow systems where fine-grained deposits overlie

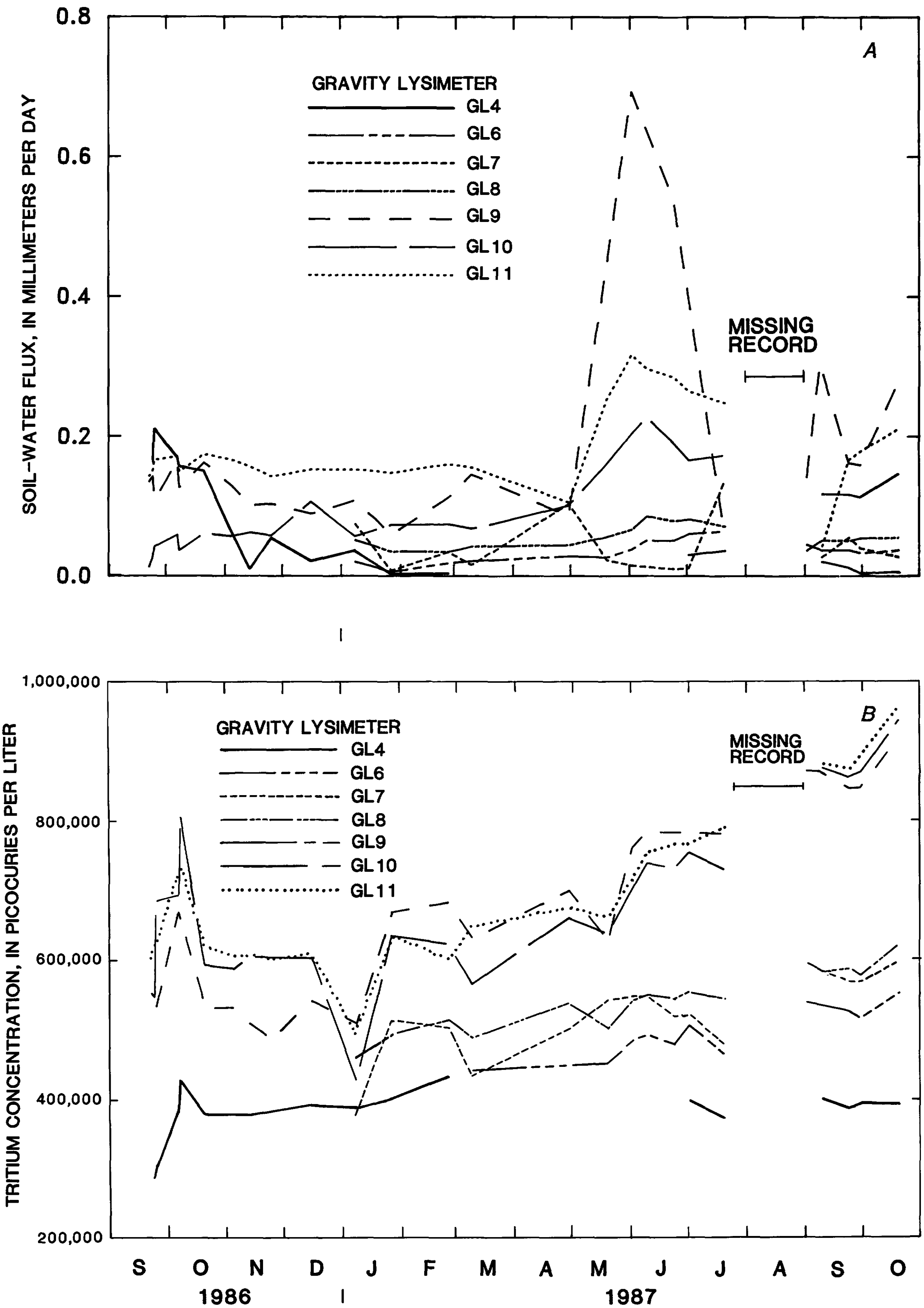


Figure 19. (*A*) Soil-water flux and (*B*) tritium concentration in the unsaturated sand of the Toulon Member of the Glasford Formation, September 1986 through October 1987.

coarse-grained deposits. The estimated cross-sectional area of the preferential flow path appears reasonable in light of observations by Oosting and others (1987, p. 5); they reported cross-sectional areas of fingers as small as about 20 mm^2. Their value represented the saturated core and the unsaturated fringe of the fingers; the value estimated by using gravity lysimeter data represents only the saturated core.

Tritium flux through the sand deposit at gravity lysimeter locations was estimated from the product of the tritium concentration and soil-water flux. Annual tritium flux was calculated at gravity lysimeter locations GL4 and GL6–GL11 (table 8) on the basis of the annual volume of water collected (to determine the annual soil-water flux) and the average annual tritium concentration. Annual tritium flux at the seven lysimeters ranged from 0.35 to 3.77 $(nCi/yr)/cm^2$ (nanocuries per year per square centimeter).

To estimate average annual tritium flux from the overlying trenches, data were included from the seven lysimeters located in the regions of preferential flow and the nine lysimeters located in the regions of nonpreferential flow (where soil-water flux was 0 cm/yr (centimeter per year)). On the basis of an average annual specific flux of 1.03 cm/yr and an average annual tritium concentration of 570,000 pCi/L, the average annual tritium flux was estimated to be 0.59 $(nCi/yr)/cm^2$.

The flux estimates should be viewed with caution because (1) average annual tritium concentrations were used in their derivation, (2) periods of missing data were not accounted for, and (3) in the case of estimating average flux from the trenches, drainage distribution within the lysimeter network was assumed to represent the normal distribution of preferential and nonpreferential flow through the sand deposit.

Factors Affecting Water and Tritium Movement

The location of soil-water movement along preferential flow paths through the sand deposit appears to be related to the hydrogeologic characteristics of the till and loess deposits and the location of trenches that overlie the sand deposit. The apparent absence of preferential flow below the intertrench Radnor Till Member supports other field evidence for limited water movement into and out of the till deposit. Mills and Healy (1991) noted that water moving downward through the Peoria Loess, above the southern end of the tunnel (fig. 6), was diverted laterally when the water reached the less permeable Radnor Till Member. Tensiometers located near the base of the till deposit indicated that pressure heads in that area remained negative and varied little over time; gravity lysimeters and tensiometers located at and near the Peoria Loess-Radnor Till Member interface indicated that sediments in that region were occasionally saturated. A similar phenomenon should occur in the area between trenches 1 and 2, where flow from the Peoria Loess is diverted into trenches 1 and 2 at the interface with the underlying till deposit.

Preferential flow paths below the intertrench till deposit (and through the sand deposit) may exist but have gone undetected. Studies of water movement through layered deposits where fine-grained sediments overlie coarse-grained sediments have shown that fingers of saturated flow can occur in the coarse-grained sediments (Palmquist and Johnson, 1962; Glass and others, 1987). Under certain unsaturated conditions, fine-grained sediments can be more permeable than underlying coarse-grained sediments. Thus, the fine-grained sediments can be a better medium for water movement than the coarse-grained sediments and, if sloped, can enhance lateral flow and inhibit vertical flow into the underlying sediments (Hillel, 1980, p. 24–25; Miller and Gardner, 1962; Clothier and others, 1977; and Johnson and others, 1983, p. 34). This phenomenon is shown graphically in figure 20 by the hydraulic-characteristic curves for the Hulick Till Member (hydraulically similar to the intertrench Radnor Till Member) and the Toulon Member (see Mills and Healy, 1991, p. 41, 42, 48, and 50 for an explanation of the characteristic curves, which represent average values for sediment samples collected throughout the Sheffield site). At pressure heads less than about 350 mm, the till deposit has a greater hydraulic conductivity than the sand. As soil-moisture content increases at the sediment interface, the area becomes increasingly unstable; breakthrough ultimately occurs, and water moves rapidly through the sand along locally restricted flow paths. However, because most of the intertrench Radnor Till Member has been removed by trench construction and the sloping topography of the intertrench deposits that remain tends to direct flow into adjacent trenches, preferential water movement into the sand deposit that can occur under the condition of unstable flow is probably limited (Mills and Healy, 1991, p. 25).

Textural variations within coarse-grained deposits have been suggested as a determining factor in the location of preferential flow paths (Palmquist and Johnson, 1962, p. 143). This relation does not appear to be the case at the Sheffield site. Particle-size distribution within the sand deposit is 84 percent sand, 10 percent silt, and 6 percent clay (Mills and Healy, 1991, p. 47). Table 10, a statistical summary of various physical and hydraulic properties of the sediment cores from the Toulon Member (Healy and Mills, 1991), shows that the coefficients of variation (standard deviation ÷ mean) for bulk density, porosity, and median particle size are all less than 8 percent. Visual examination of cores and excavation faces indicates that the sand tends to be well sorted and that the silt and clay are evenly distributed throughout the deposit. Although not indicated by visual inspection, flow-influencing textural variations may be present at a scale too small to be visually or

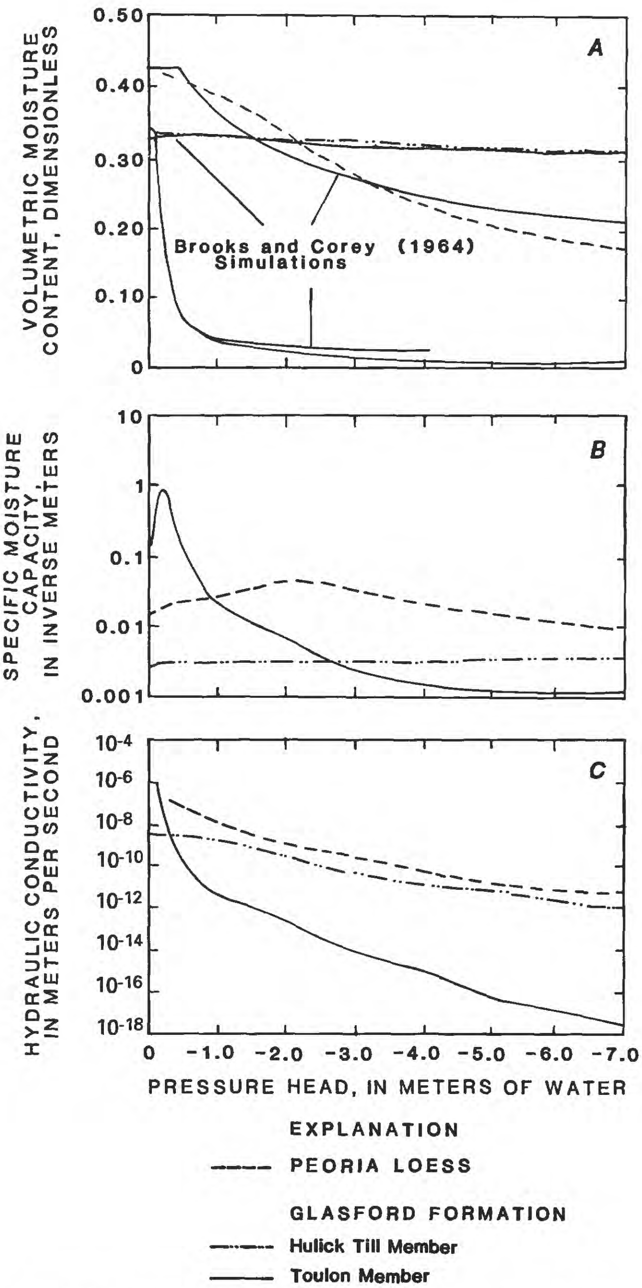


Figure 20. Typical hydraulic-characteristic curves for the silt of the Peoria Loess, the sand of the Toulon Member of the Glasford Formation, and the clayey silt of the Hulick Till Member of the Glasford Formation. *A*, Volumetric moisture content with respect to liquid pressure head; *B*, Specific moisture capacity with respect to liquid pressure head; *C*, Hydraulic conductivity with respect to liquid pressure head. (Modified from Healy and others, 1986, fig. 5.)

statistically identified in the 50-cubic-centimeter and larger cores.

The locations of preferential flow paths in the sand deposit appear to be most directly attributable to trench-cover and trench-interior conditions that influence the location of water movement into and through the overlying trenches. The trenches contain numerous voids, as indicated by photographs of waste burial (fig. 21) and a history of trench-cover collapses (Gray and McGovern, 1986) (fig. 22). The voids within the trenches can provide conduits for saturated flow through the trenches (Mills and Healy, 1991, p. 81), and the location and configuration of the voids can influence the manner in which water moves into and through the underlying trenches.

Table 10. Statistical summary of selected physical and hydraulic properties of the unsaturated sand of the Toulon Member of the Glasford Formation

[Modified from Healy and Mills (1991, table 1); m/d, meters per day; mm, millimeter; g/cm^3, grams per cubic centimeter; nCi/L, nanocuries per liter[1]]

Property	Mean value	Coefficient of variation, in percent	Number of samples
Porosity	38.4 percent	4.0	196
Particles less than 0.297 mm in diameter.	15.7 percent	37.2	231
Particles less than 0.595 mm in diameter.	88.1 percent	12.7	231
Geometric mean particle size.	.287 mm	48.1	231
Median particle size	.330 mm	7.5	231
Bulk density	1.64 g/cm^3	2.7	210
Field moisture content, by volume.	6.0 percent	16.1	210
Saturated hydraulic conductivity.	34.0 m/d	44.8	114
Tritium concentration	73.3 nCi/L	173.3	104

[1] Nanocuries per liter × 1,000 = picocuries per liter (1 nanocurie = 1,000 picocuries).

The locations of interconnected voids, and thus flow paths, within the trenches are impossible to predict, even in areas where wastes are buried in an orderly manner, because of the types and sizes of waste containers (fig. 21*B*). Prediction of flow-path locations is further complicated by the lack of standard records that detail the burial characteristics of each trench. However, analysis of the locations of water entry into the trenches can help predict the locations of flow paths within the trenches. Healy and others (1984, p. 827) found that the primary location of water entry into a trench is along its edge. Because the surface drainageways between trenches are slightly inclined, water often ponds in the intertrench swales during rainstorms. Also, a compacted clayey silt layer, which inhibits water movement through the trench cover, can be absent or disrupted by freeze-thaw, plant roots, and (or) animal borings near the trench edge. Gray and McGovern (1986, p. 737) also showed that collapse holes, which can be direct conduits for water movement into the trenches, form primarily along trench edges (but may form at random locations). Water entering trenches along a trench edge

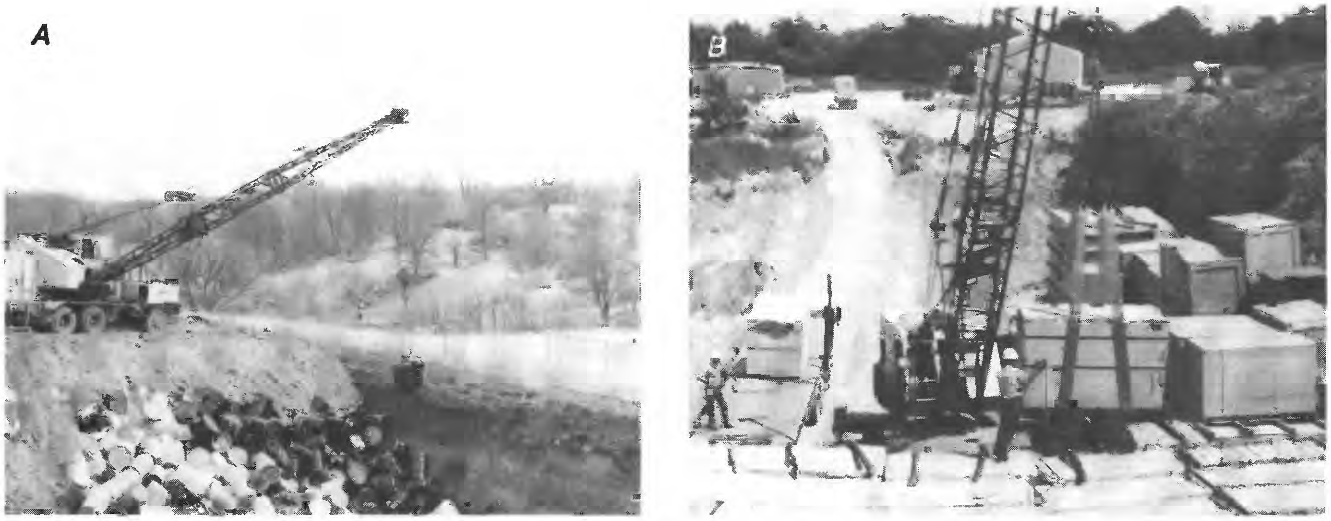


Figure 21. Waste-burial practices at the Sheffield site. *A*, Random arrangement of barrels in trench 11 (looking southeast); *B*, Ordered arrangement of large wood, concrete, and steel containers in trench 24 (looking east). (Photographs by US Ecology, Inc.)

Figure 22. Surface-water runoff into a trench-cover collapse hole, November 1985 (looking southwest).

should continue flowing downward along the sides of the trenches. Six of the seven gravity lysimeters at which preferential flow paths were identified were located below the northern edge of trench 2. Also, soil-water flux and tritium concentrations generally increased with proximity to the trench edge.

The factors that induced the varied drainage-timing and drainage-rate patterns at the gravity lysimeter locations are not fully understood. The 3-month delay in the start of drainage at lysimeters GL6–GL8 (following instrument installation) may be related to climatic trends. A steady supply of precipitation during fall and early winter months (September through December 1986) (fig. 23), coupled with the typical seasonal decrease in evapotranspiration rates (table 2), may have increased the supply of soil water available for percolation to the subtrench sand deposit. Contradictory evidence indicates, however, that this explanation is not fully satisfactory. First, Mills and Healy (1991, p. 60–65) have shown that the fall is typically a period of reduced water movement through the subtrench deposits, as shown by pressure-head data collected during the 1986–87 study period (fig. 19). Second, climate should not selectively influence percolation patterns. However, drainage at lysimeters GL9–GL11 was continuous; at lysimeters GL6–GL8 (located less than 0.3 m away), drainage was delayed periodic; and at GL4, drainage was intermittent. Additional factors, such as geology and trench-interior conditions, likely contribute to the varied drainage patterns seen at the lysimeters.

The occurrence of continuous drainage through the sand deposit suggests that water enters the trench interiors either continuously, or at closely spaced intervals, throughout the year. Rapid infiltration into the trench interiors following all storms, however, is not supported by data from Healy (1989, p. 225); during July 1982 through June 1984, water movement into trench 2 at the trench edge was recorded after only 28 of 87 rainstorms (defined as at least 5 mm of precipitation).

Continuous drainage through the sand deposit also can be explained by the presence of perched water within the trench interiors (above an area of compacted clay-rich intertrench fill material, for example). Drainage to the underlying sand deposit from the area of perched water can be nearly continuous to continuous, fluctuating in response to the volume of water available in the perched zone. Perched-water zones in the trenches have not been verified. If, in fact, they do exist, they are most likely limited in occurrence and size, as indicated by the limited occurrence and size of preferential flow paths within the underlying sand deposit and by the absence of water in drains that run the length of the trench floors (Foster and others, 1984, p. 17).

The temporal variability in soil-water flux at individual lysimeters appears to be a function of the timing and intensity of precipitation and seasonal climatic trends. Soil-water flux varied in response to precipitation, but the response was neither instantaneous nor consistent (fig. 23). The delay in response to precipitation events is related, in part, to the thickness of the transmission zone (distance between land surface and lysimeters). Soil-water flux was somewhat elevated in early fall, when precipitation rates were relatively high (especially August 1987) and evapotranspiration rates were relatively low. Flux was at a minimum in the winter when precipitation often occurs as snow, and at a maximum in early summer, following the early spring period of snowmelt, low evapotranspiration rates (table 2), and increased precipitation rates. It is assumed that the increase in soil-water flux in fall 1987 would have been more pronounced if the record precipitation in August had not been preceded for several months by a period of relatively limited precipitation and seasonally high rates of evapotranspiration. As with soil-water flux, tritium concentrations of the preferentially flowing water responded somewhat to individual precipitation events, but, in general, responses were much more obvious when related to total precipitation during a recording period or to seasonal climatic trends (fig. 23).

Three patterns were identified in the relation between fluctuations in tritium concentration and soil-water flux; these patterns indicate that tritium and soil-water movement from the trenches is complex. In the first pattern, tritium concentrations followed a seasonal trend similar to that of soil-water flux (fig. 24*E–G*). This pattern suggests that tritiated soil water is flushed from the trenches as water percolates through the trenches during periods of seasonal wetting. The flushing process is complex, as indicated by the wide range and low degree of correlation between tritium-concentration and soil-water-flux values; correlation coefficients for individual lysimeters ranged from -0.56 to 0.53.

In the second pattern, decreases in tritium concentrations were associated with increases in soil-water flux (fig. 24*C*); this association suggests that, in some instances, water draining to trenches during seasonal wetting dilutes preexisting tritium concentrations. This pattern was less prevalent than the first pattern.

In the third pattern, increases in tritium concentrations appeared to be independent of increases in soil-water flux. Tritium concentrations at several gravity lysimeters (fig. 24*E–G*) increased through late summer and fall 1987, a period when soil-water flux typically decreases seasonally. The increase may be related to a large, late summer influx of water from the record precipitation during August. However, because one would expect the tritium concentrations to decrease somewhat in response to the midsummer decrease in soil-water flux, the pattern most likely represents changes in waste-burial conditions within the trenches. Waste containers within the overlying trench may have deteriorated or flow paths through the trench may have altered course, thus increasing the supply of leachable tritium. Under those conditions, tritium concentrations could increase despite a decrease in soil-water flux.

EFFECTS OF THE TUNNEL ON WATER MOVEMENT

In-situ study of hydrogeologic conditions in the subtrench environment was made possible by the unique use of the tunnel. To assure that the hydrologic data obtained from the tunnel instruments and data-collection activities accurately represented natural conditions, the potential effects of the tunnel on the subtrench environment were assessed. A brief assessment of the tunnel's effects is described in Mills and Healy (1991, p. 44); a more detailed assessment is presented here.

The tunnel can have three primary effects on water movement through the unsaturated subtrench geologic deposits:

(1) The essentially impermeable tunnel liner can inhibit the natural vertical movement of water in the adjacent sediments and induce lateral flow around the tunnel. In this case, soil-moisture content will be artificially increased directly above and adjacent to the sidewalls of the tunnel and decreased directly below the tunnel (creating a rainshadow effect). Soil-moisture content should increase with proximity to the tunnel above and adjacent to the sidewalls of the tunnel and decrease with proximity to tunnel below the tunnel.

(2) Excavating the sediments to a diameter greater than that of the tunnel liner (overdigging) during tunnel construction may have created annular cavities that can channel lateral movement of water along the tunnel exterior. Similarly, stress redistribution associated with sediment excavation during tunnel construction may have induced caving, slumping, or cracking in the overlying sediments, thus creating conditions conducive to preferential water movement beyond the immediate vicinity of the tunnel liner.

(3) The low-humidity air provided to the tunnel interior by the ventilation system (Mills and Healy, 1991, p. 32, 92) can dry sediments close to the tunnel and, thereby, induce water movement toward the tunnel.

Results of the analysis of the effects of the tunnel are presented in two sections, one describing field-data meas-

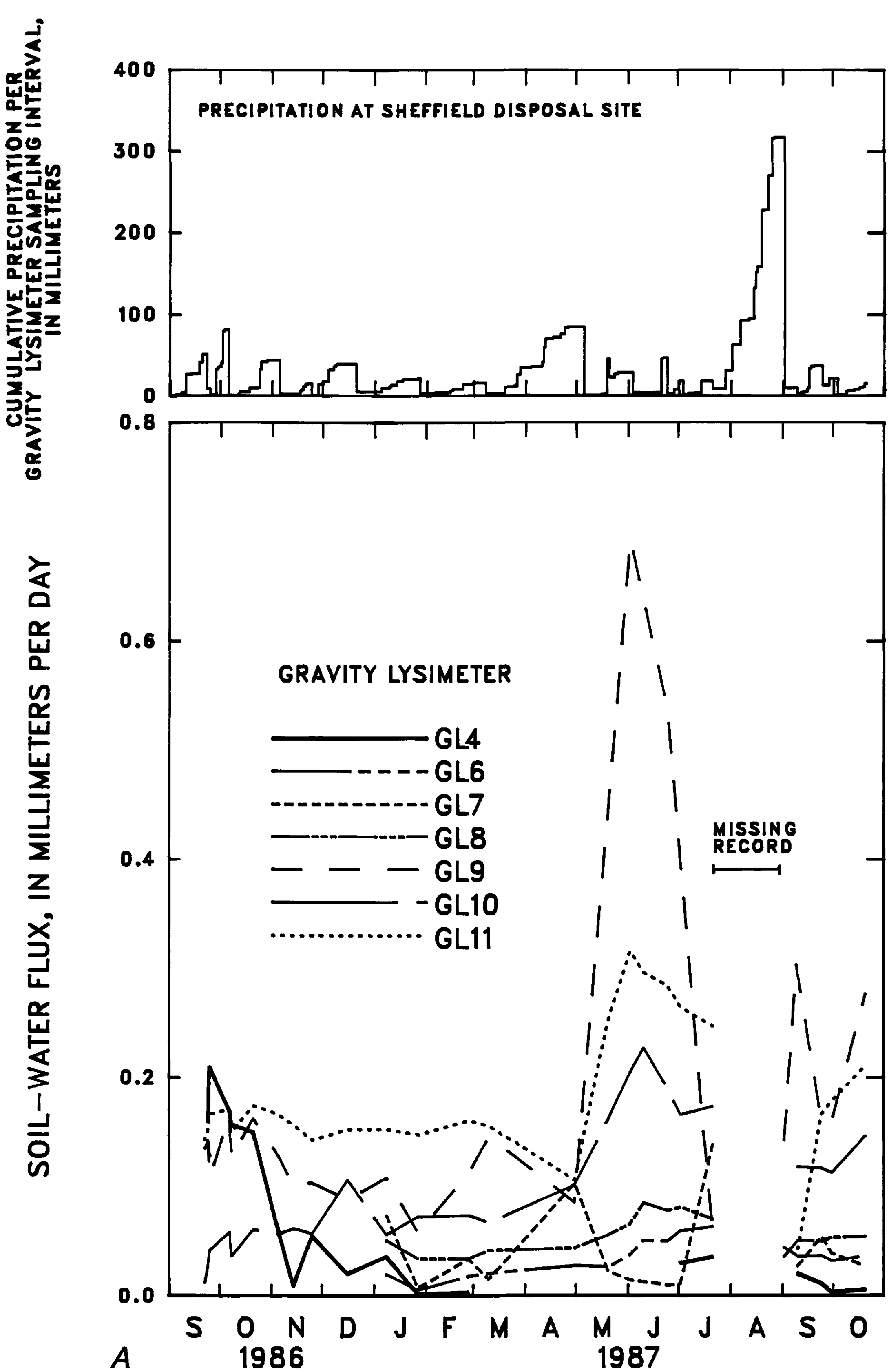


Figure 23. (*A*) Soil-water flux and (*B*) tritium concentration in the unsaturated sand of the Toulon Member of the Glasford Formation with respect to precipitation, September 1986 through October 1987.

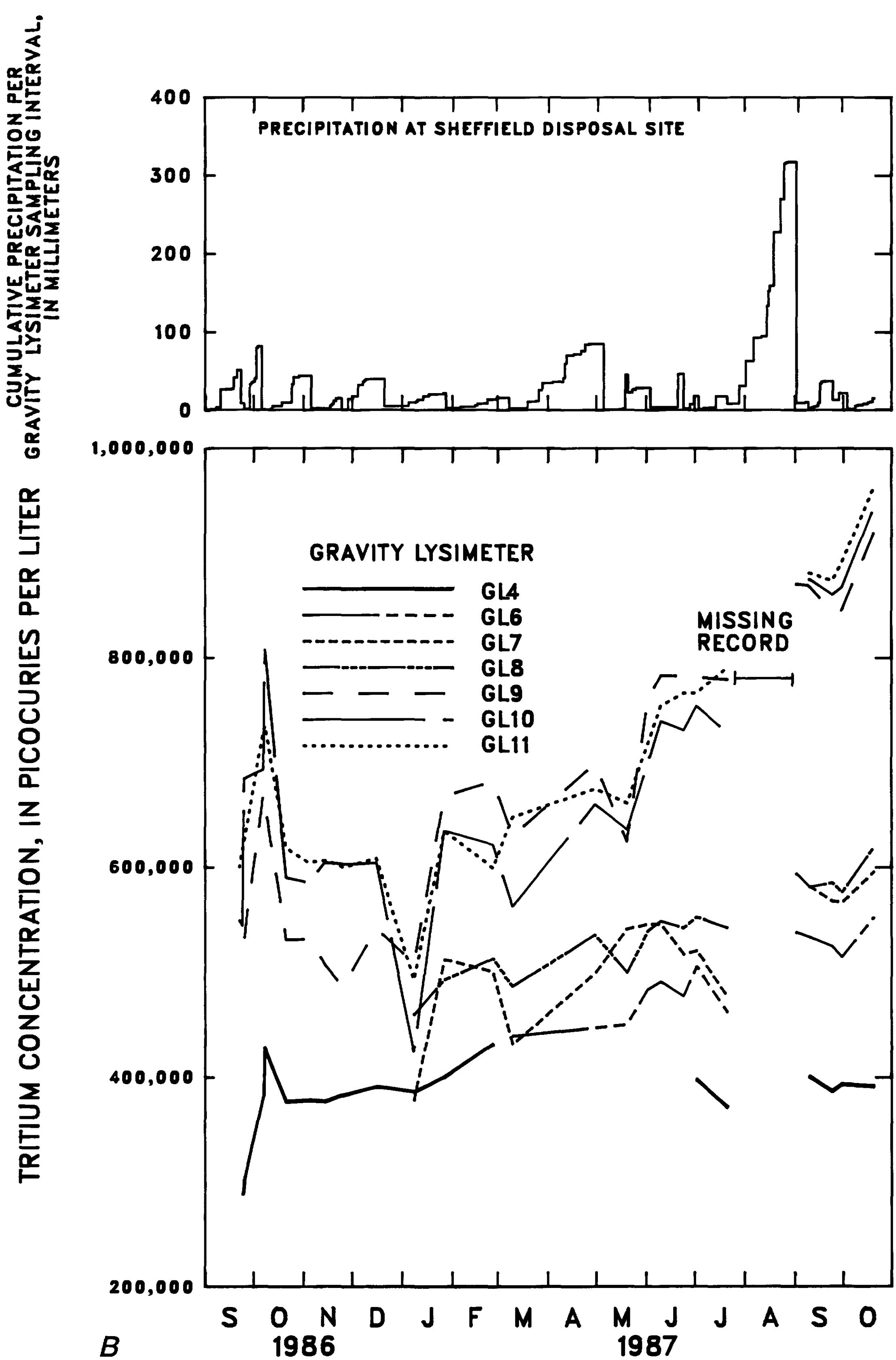


Figure 23.—Continued.

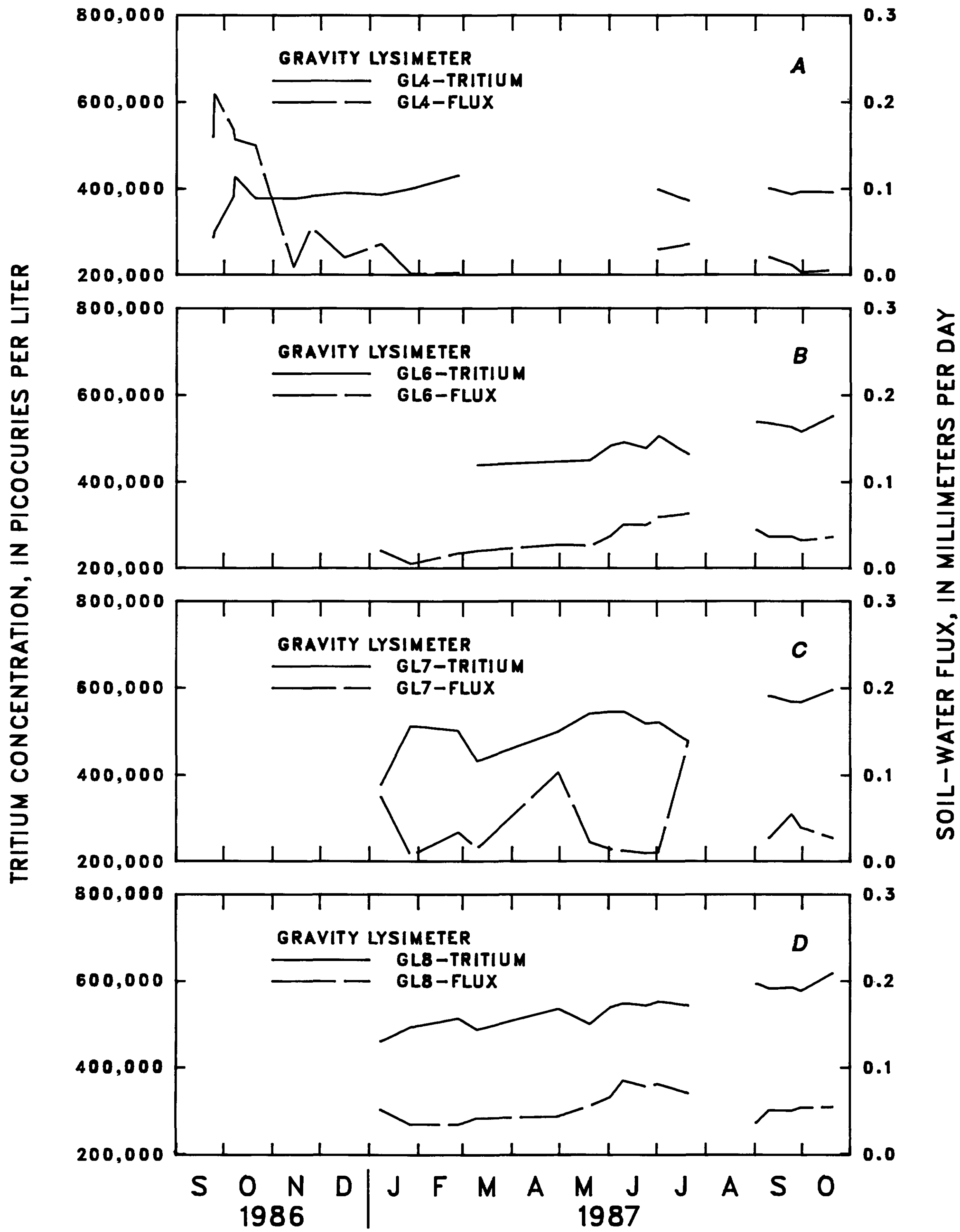


Figure 24. Tritium concentration with respect to soil-water flux in the unsaturated sand of the Toulon Member of the Glasford Formation, September 1986 through October 1987.

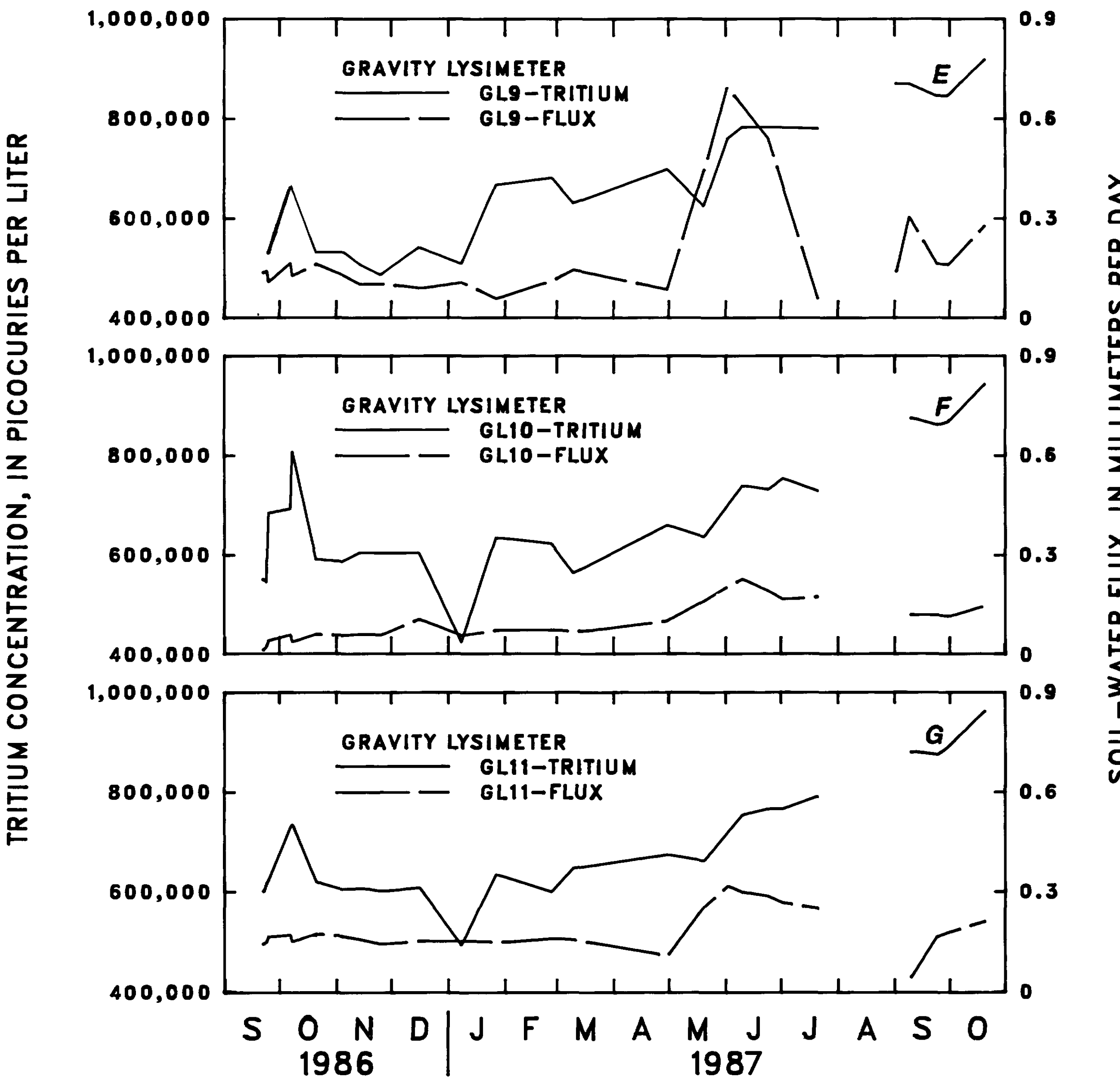


Figure 24.—Continued.

urements and one describing computer-generated numerical simulations. The effects of the tunnel are discussed first in terms of flow through the layered glacial deposits, which consist primarily of the Hulick Till Member of the Glasford Formation, and then in terms of flow through the Toulon Member sand deposit, also of the Glasford Formation.

Measured Effects

The clustered tensiometers (TX1–TX9) in section *B–B′* (figs. 6 and 11) were designed to evaluate the effects of the impermeable tunnel on flow within a vertical plane. Hydrologic conditions and technical problems, however, limited their usefulness in the study. During the 17-month operation of the tensiometer cluster, flow conditions were near steady state; during a 3-month period from July through September 1986, soil-water flux increased slightly. Under these conditions, the tunnel's effects on flow were subtle and difficult to discern. Analysis of the tunnel's effects was further complicated by the periodic malfunction of several tensiometers in the cluster, including TX3–TX6. Pressure-head records of tensiometers TX1, TX2, and TX7–TX9 are presented in figure 25.

Flow directly above the tunnel can be influenced by the impermeable tunnel, as indicated by pressure-head data from tensiometers TX1 and TX2. Pressure heads generally were about 350 mm greater at TX1, located above the

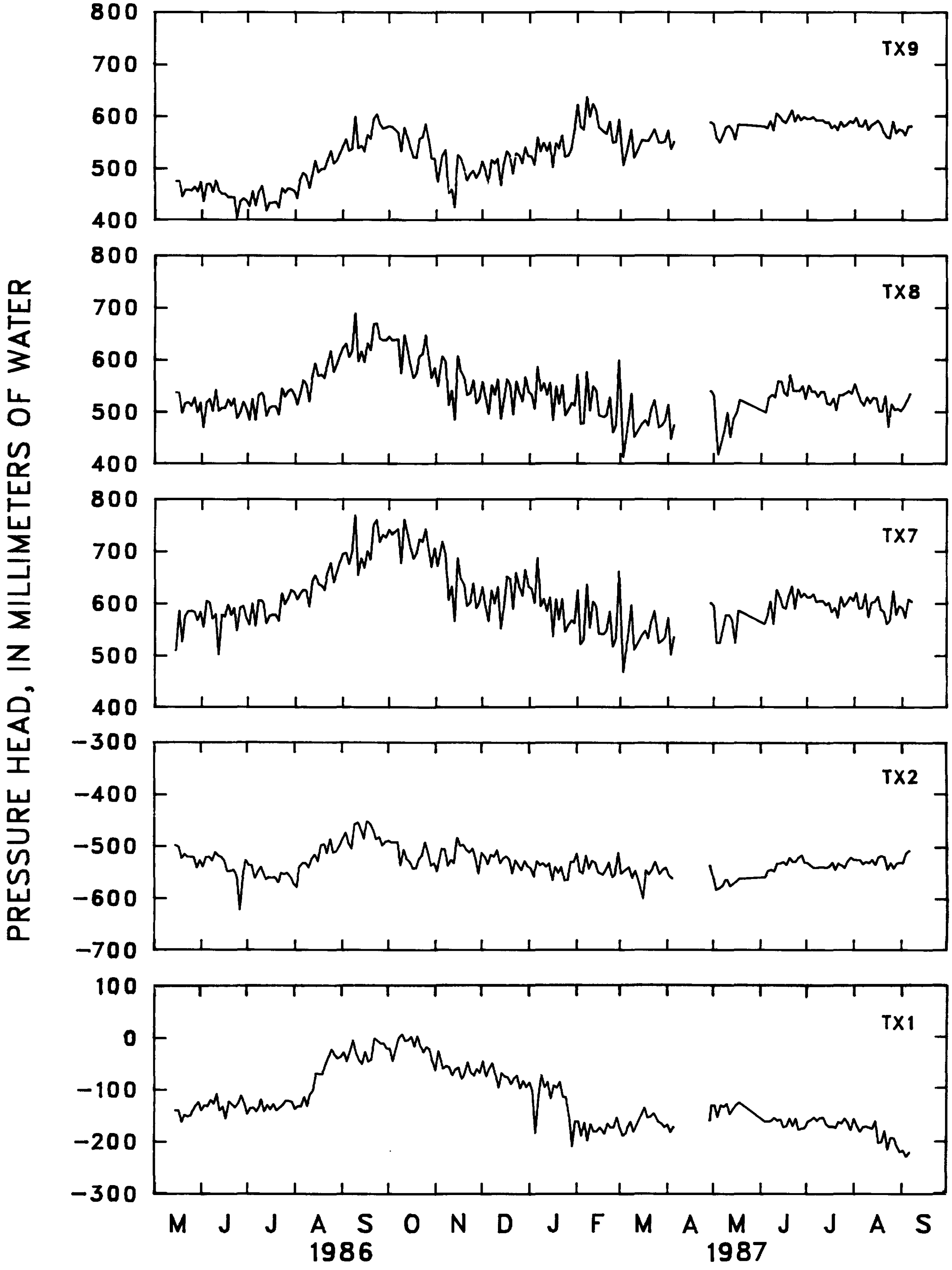


Figure 25. Liquid pressure head along geologic section *B–B′*, May 1986 through September 1987. (See fig. 11 for location of tensiometers in section *B–B′*; see figs. 3 and 6 for location of line of section.)

tunnel, than at TX2, located beyond the lateral limits of the tunnel (figs. 11 and 25), at the same elevation as TX1. However, during the late summer wetting phase in 1986, when the tunnel's effects on water movement should have been most evident, the head difference between TX1 and TX2 increased only marginally. The pressure-head difference between the two locations can be explained instead by natural, spatial variability of water movement. Mills and Healy (1991) have documented larger variabilities in pressure head than that noted between TX1 and TX2 over similar distances throughout the Hulick Till Member. Even if the difference in pressure heads at TX1 and TX2 is tunnel related, the overall influence of the tunnel on water movement through the Hulick Till Member should be minimal. In the observed range of pressure heads, the moisture content in the till unit will vary by less than 1 percent.

Sediment-core analysis revealed no obvious effects of the tunnel on vertical profiles of soil-moisture content or tritium concentration in the layered clayey silt and sand deposits above the southern end of the tunnel (fig. 26, sections *D–D′*, *F–F′*). Soil-moisture content generally was consistent in the profile in section *F–F′*; the data shown for section *D–D′* may be inconclusive with respect to a possible tunnel influence. The increase in moisture content and tritium concentrations immediately above the tunnel in section *D–D′* may indicate that the tunnel inhibits vertical water movement through the till unit. If this is the case, then the tunnel does not appear to influence flow consistently at all locations along its length. Furthermore, any effect that the tunnel may have on flow does not appear to extend more than several tenths of a meter above the tunnel.

The moisture-content and tritium-concentration profiles in sections *D–D′* and *F–F′* suggest that flow probably is controlled more by the layering of geologic deposits of variable textures than by the presence of the tunnel. The increased moisture content near the contact between the Toulon Member and the Hulick Till Member (section *D–D′*) and the increased tritium concentrations above that contact (section *F–F′*) indicate that the Hulick Till Member, which is less permeable than the Toulon Member, inhibits vertical flow and enhances lateral flow in the sand. This increase in moisture content and tritium concentration at the sand-till contact has been identified throughout the tunnel area by Mills and Healy (1991, p. 92). The increase in tritium concentration with depth may simply represent the vertical movement of a slug of tritiated water from an overlying trench source.

The influence, if any, that the tunnel has on flow directly above the tunnel does not appear to consistently translate downward to the area near the sidewalls of the tunnel. Although evidence is conflicting, one location where the tunnel may influence water movement adjacent to the tunnel sidewall is the area of tensiometers TX4–TX9 (figs. 6, 11, and 25), where saturated sediments were unexpectedly encountered.

The pressure-head data from tensiometers TX7–TX9 (figs. 11 and 25) indicated saturated conditions with a total-head gradient of about 0.1 mm/mm (millimeter per millimeter) toward the tunnel. No change in the gradient was observed during the period of wetting that occurred from July through September 1986. From November 1986 through January 1987, the pressure head at TX9 (0.25 m from the tunnel) increased to a level approximating that at TX7 (1.5 m from the tunnel). No consistent increase in pressure head was recorded at TX7 or TX8 (0.75 m from the tunnel) during this period. The increase in pressure head near the tunnel can be attributed to diverted flow around the tunnel liner, but malfunction of tensiometer TX9 also may be a possibility. No obvious malfunction of TX9 was detected, although malfunctions that can cause such slight shifts in pressure head can be very difficult to detect.

The saturation of sediments in the area of tensiometers TX4–TX9 can be attributed to preferential water movement within ungrouted overdig cavities or fractures; however, neither cavities nor fractures were revealed during instrument installation. The saturated sediments also can be explained by natural spatial variation in water movement. Mills and Healy (1991, p. 71, 86) indicate that numerous flow paths converge along sloped lithologic contacts that overlie this location, thus inducing locally increased drainage through the underlying Hulick Till Member deposit.

Mills and Healy (1991, p. 92–95) indicated that tritium concentrations in many sediment cores from the Hulick Till Member in the area of tensiometers TX4–TX9 increased with proximity to the tunnel. Because (1) this trend was not present in all cores, (2) soil-moisture content did not increase with tunnel proximity, and (3) most coreholes were nonvertical or nonhorizontal, it was unclear if the trends represented a tunnel influence on flow or, more simply, changes in concentration with respect to tritium-source location in and vertical distance from the overlying trenches. To resolve this question, coreholes were bored horizontally from the tunnel sidewalls. Tritium-concentration trends were variable, and soil-moisture contents were consistent along the horizontal profiles (fig. 26, sections *C–C′* and *E–E′*). These data appear to support the assumption that the tunnel does not strongly influence natural flow patterns.

Tensiometer data from the Hulick Till Member showed that pressure heads below the tunnel, at tensiometers T6 and T28A (figs. 6 and 27), were not differentially affected by the tunnel's presence. Mills and Healy (1991, p. 44) showed that the timing of seasonal water movement and the soil-moisture content were essentially equivalent both directly below the tunnel and beyond its lateral limits (at the same 1.4-m distance below the tunnel floor).

In the Toulon Member, analysis of sediment cores shows that soil-moisture-content profiles (corehole for tensiometer T14) above the tunnel generally were equivalent to profiles below the tunnel (corehole for tensiometer T8 (figs.

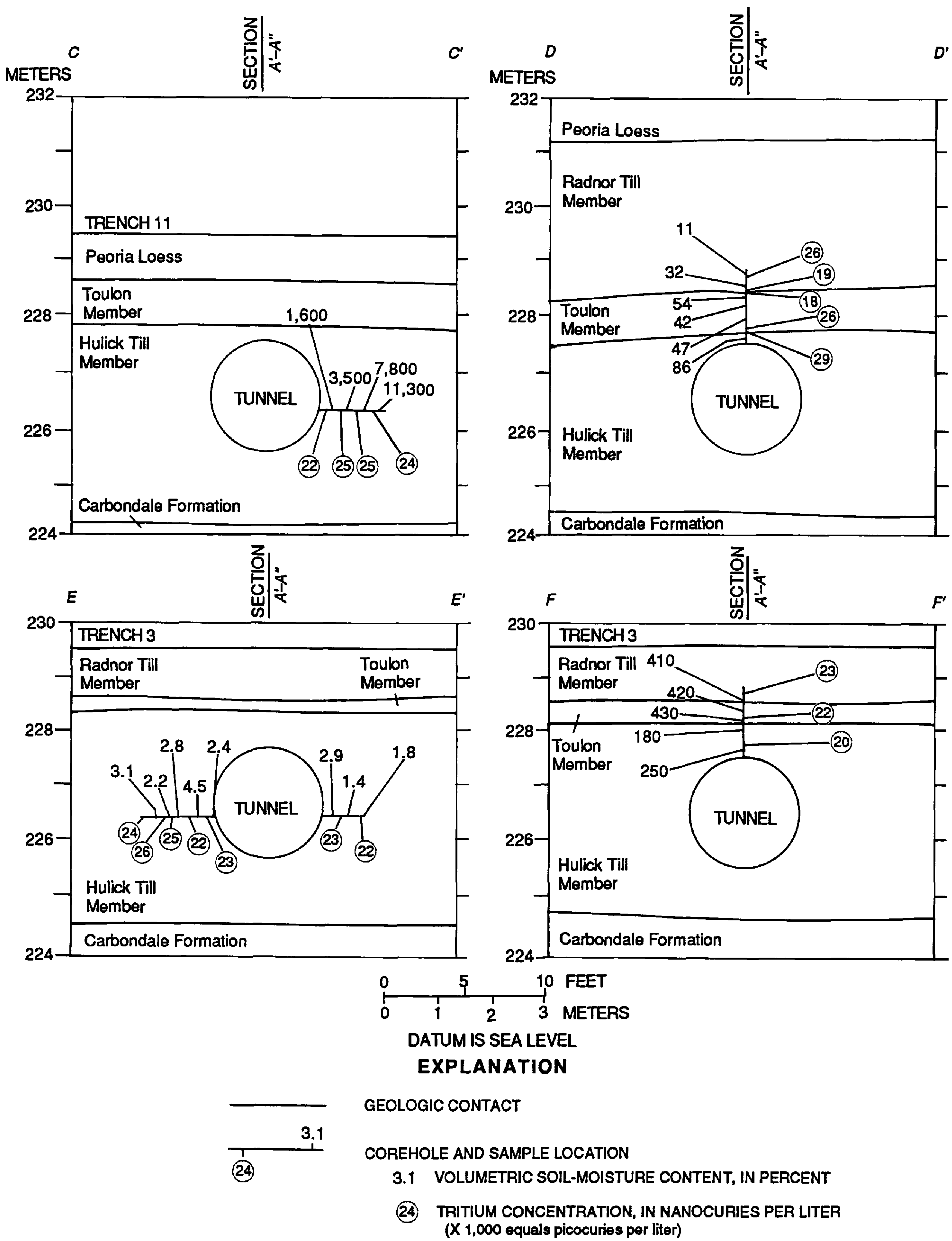


Figure 26. Soil-moisture content and tritium concentration of sediment cores along geologic sections *C–C'*, *D–D'*, *E–E'*, and *F–F'*. (See figs. 3 and 6 for location of lines of section.) Members belong to Glasford Formation.

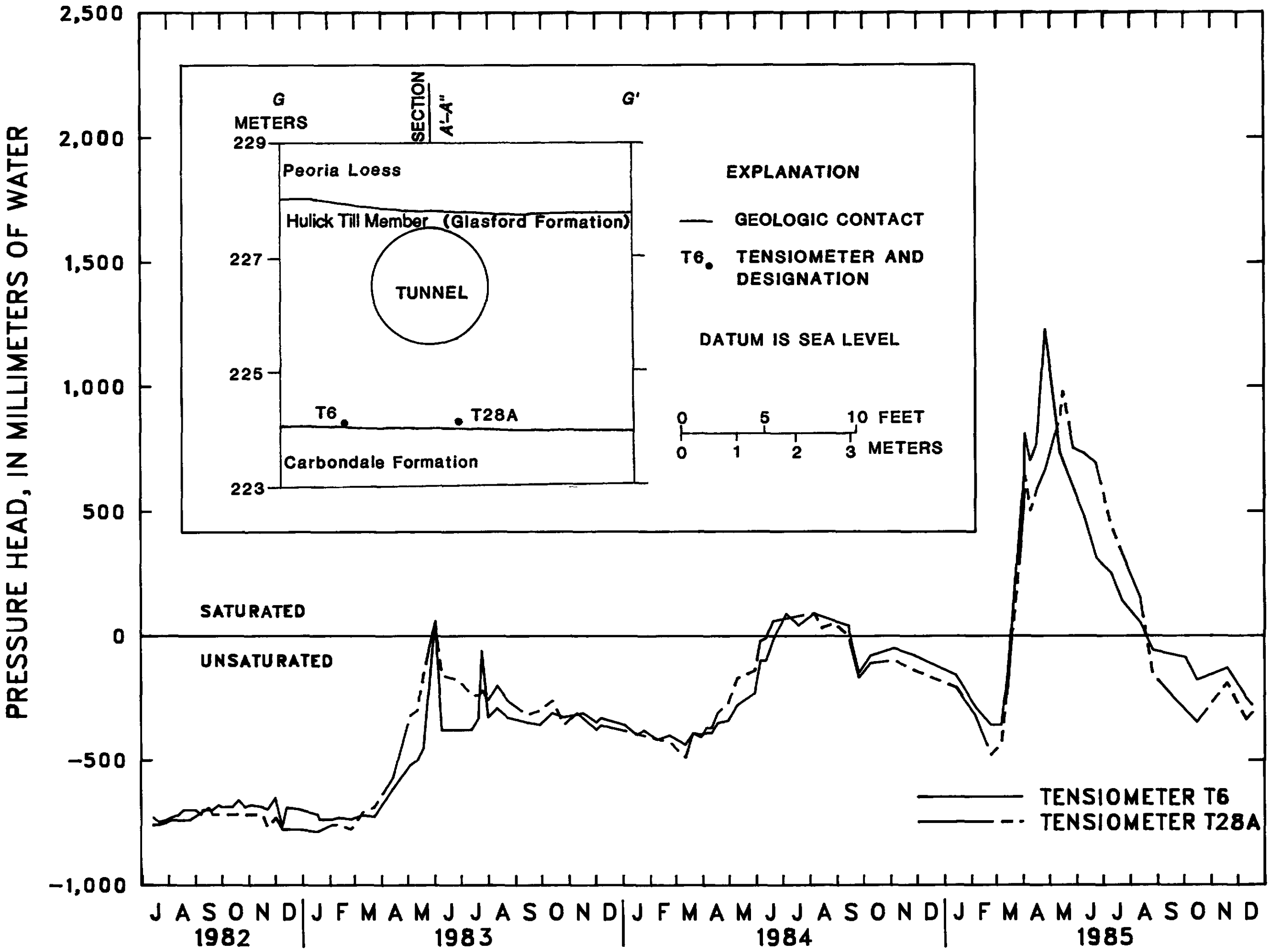


Figure 27. Liquid pressure head in the Hulick Till Member of the Glasford Formation at two locations below the tunnel floor along geologic section G–G′, July 1982 through December 1985. (See figs. 3 and 6 for location of lines of section.) Inset shows location of instruments.

6 and 28)). Analysis of cores also showed that, with the exception of a minor increase in soil-moisture content in the first 0.3 m above the tunnel, soil-moisture contents generally were consistent throughout the vertical profiles.

Pressure heads were monitored at two distances (0.8 and 1.3 m) beyond the sidewall of the tunnel in the Toulon Member by tensiometers T26B and T26C, respectively. As figure 29 shows, pressure heads at the two locations did not differ appreciably; this similarity suggests that at least beyond 0.8 m there was no tunnel influence on water movement.

In Mills and Healy's (1991) evaluation of sediment cores from the Toulon Member, soil-moisture content was typically nonvariant with respect to tunnel proximity; tritium concentrations either decreased with proximity to the tunnel or showed no discernible trend. As with the Hulick Till Member cores, most of the Toulon Member cores also were obtained from nonhorizontal coreholes. Horizontal-corehole data obtained during the present study (fig. 30) and during the study by Healy and Mills (1991) (fig. 31) also revealed no correlation between distance from the tunnel and soil-moisture content or tritium concentration.

The potential for preferential water movement induced by (1) sediment disturbance during tunnel construction or (2) the use of the tunnel ventilation system was not extensively examined. Although qualitative examination of obvious construction-induced features, such as caving and overdig, is possible, quantification of the effects of construction-disturbed sediments on flow is very difficult. The task requires the separation of those effects from natural preexisting effects, such as lithologic heterogeneity and fractures created by isostasy during glacial-ice melting.

There was no evidence of slumping or caving in the overlying till deposits during tunnel construction. Annular overdig cavities are present along the length of the tunnel within the Hulick Till Member; their presence is evident in

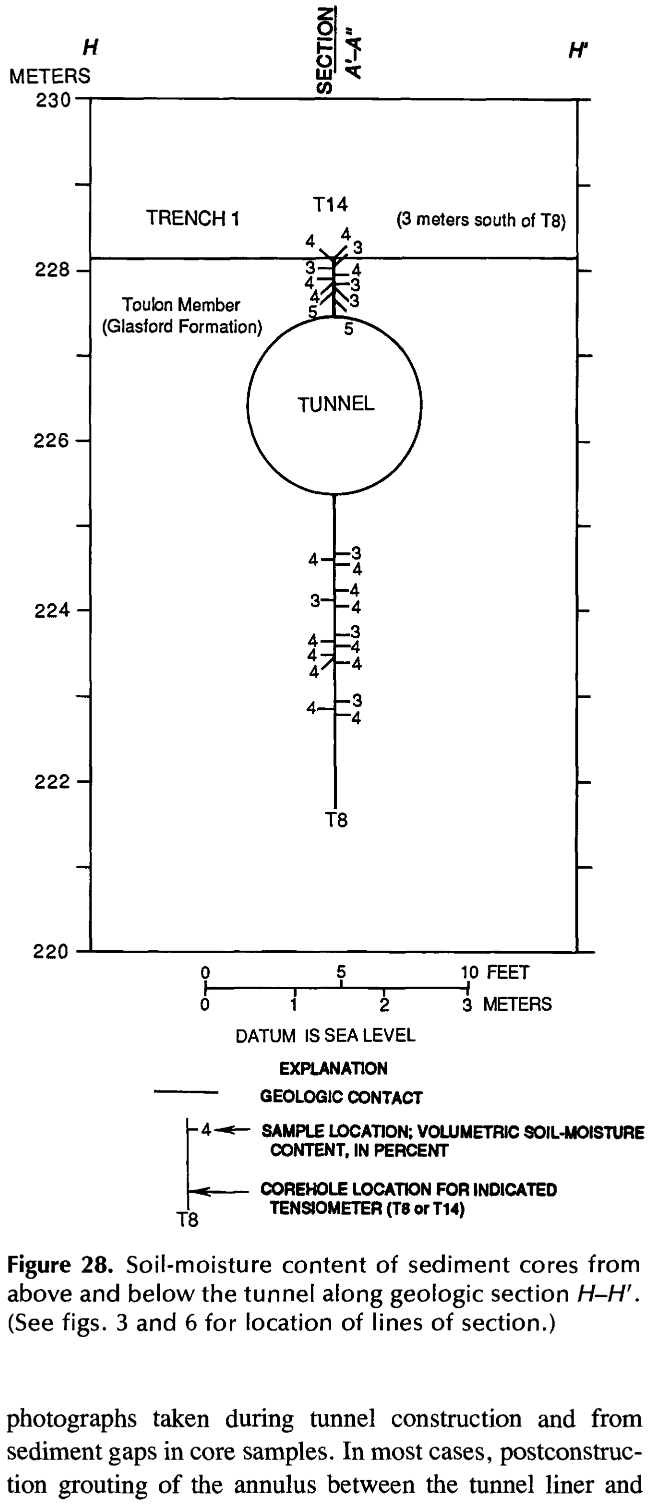


Figure 28. Soil-moisture content of sediment cores from above and below the tunnel along geologic section *H–H'*. (See figs. 3 and 6 for location of lines of section.)

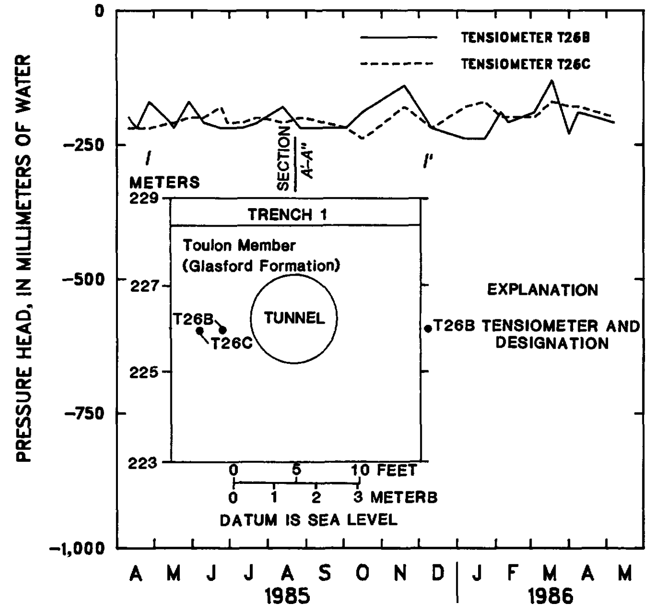


Figure 29. Liquid pressure head in the Toulon Member of the Glasford Formation at two locations adjacent to the sidewall of the tunnel along geologic section *I–I'*, April 1985 through May 1986. (See figs. 3 and 6 for location of lines of section.) Inset shows location of instruments.

photographs taken during tunnel construction and from sediment gaps in core samples. In most cases, postconstruction grouting of the annulus between the tunnel liner and adjacent sediments (Mills and Healy, 1991, p. 32) has filled the resultant cavities. The unfilled cavities can allow preferential flow, if those cavities are interconnected.

Annular cavities were not detected in the Toulon Member except at two locations where wood planking was used to stabilize overlying sand during tunnel construction. Collapse of sand around the tunnel liner may have eliminated cavities that were created during tunnel construction, but there is only one report of collapse—below trench 11 where support plankings were not used (the void was filled by pressure-grouted portland cement). Values of bulk density indicate that, at most locations, the Toulon Member sand deposits have not been disturbed (table 11).

Circulation of low-humidity air through the tunnel can dry the sediments within the immediate vicinity of the tunnel liner and, thus, induce preferential flow toward the tunnel. The ventilation system was designed to maintain a relative humidity of 55 percent in the tunnel, a level much less than the near-100-percent humidity of the pore-space atmosphere. Periodic malfunction of the system often resulted in the circulation of ventilated air having humidity approaching 100 percent. There is some evidence that the pore-space atmosphere and the tunnel atmosphere were not always in equilibrium. Exchange between the two atmospheres is indicated by observations that carbon dioxide concentrations in the ventilated tunnel air were higher than should be expected (R.G. Striegl, U.S. Geological Survey, oral commun., 1986). This exchange can occur if the pore-water in the sand is drying and degassing. The extent of the exchange has not been quantified. Although soil-moisture content was depressed near the tunnel liner at some locations in the Toulon Member (fig. 31), thus suggesting a drying effect, the random occurrence of the depressed moisture content is not indicative of the non-

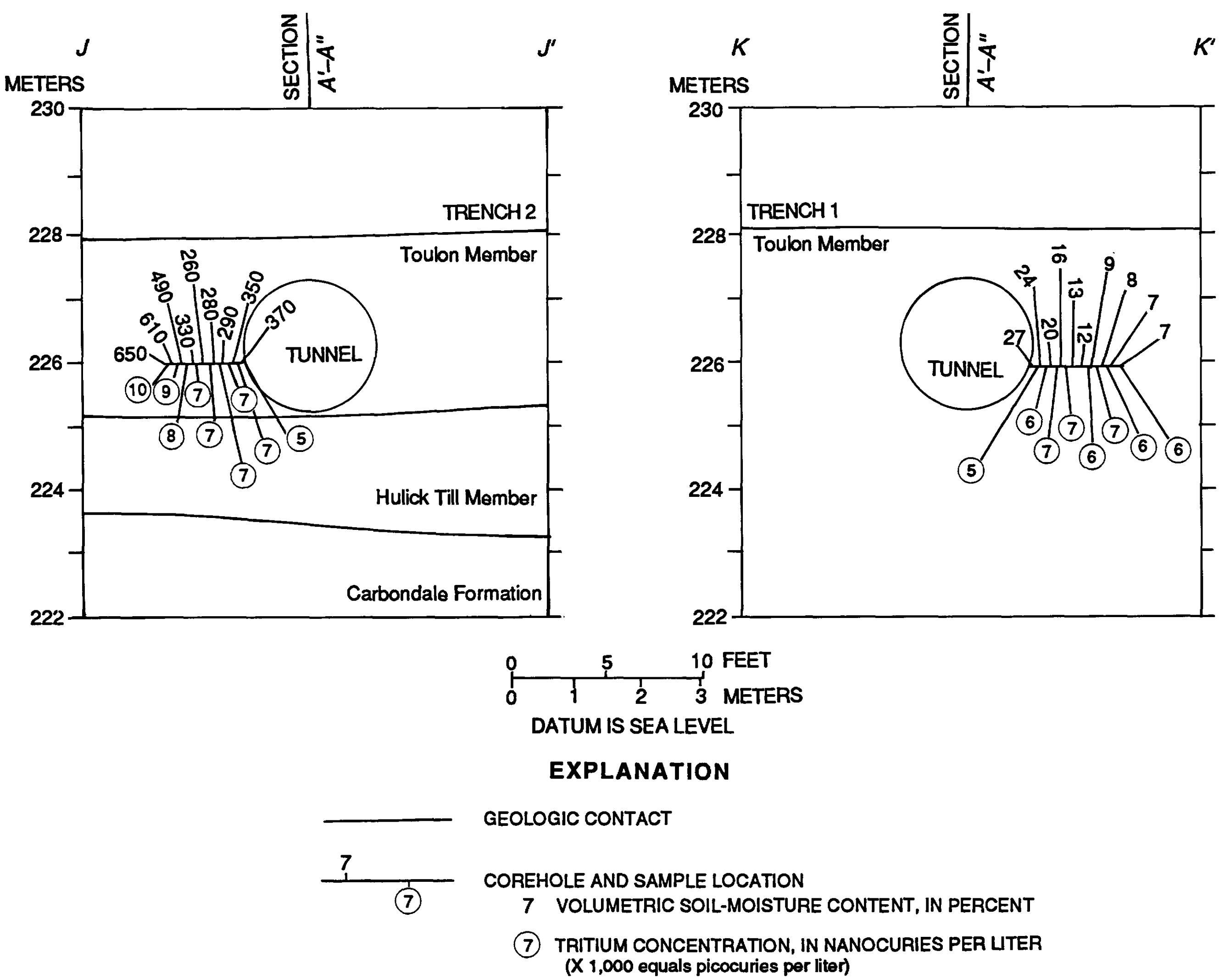


Figure 30. Soil-moisture content and tritium concentration of sediment cores of the unsaturated sand of the Toulon Member of the Glasford Formation along geologic sections *J–J'* and *K–K'*. (See figs. 3 and 6 for location of lines of section.)

selective effects one would expect from the ventilation system.

In conclusion, evaluation of available pressure-head, soil-moisture, tritium-concentration, soil-bulk-density, and tunnel-construction information indicates that preferential flow may be occurring in sediments that were disturbed during construction; however, such preferential flow is most likely a limited and localized phenomenon (table 12). Use of the tunnel ventilator does not appear to have affected natural flow in the tunnel-area sediments.

Simulated Effects

Results of simulations of water movement through the till section, made on the basis of measured values of hydraulic conductivity and flux, are presented in figure 32. The simulated pressure heads compare favorably with the range of field-observed pressure heads in the vicinity of the tunnel (fig. 14). As expected, water movement, as shown indirectly by pressure head (water movement is in the direction of lower pressure heads) in figure 32, is vertically downward. As water nears the tunnel, water movement is increasingly perturbed. Pressure heads are greater than natural (unperturbed by the presence of the tunnel) values above the tunnel and less than natural values below the tunnel (indicating a rainshadow effect).

Divergence of perturbed pressure heads from natural pressure heads is shown in figure 32*B*. The values in this figure are the difference between the pressure head in a given grid cell (fig. 32*A*) and the unperturbed pressure head at the same elevation as indicated by one-dimensional simulation. A positive value indicates that the perturbed pressure head is greater than the natural pressure head; a

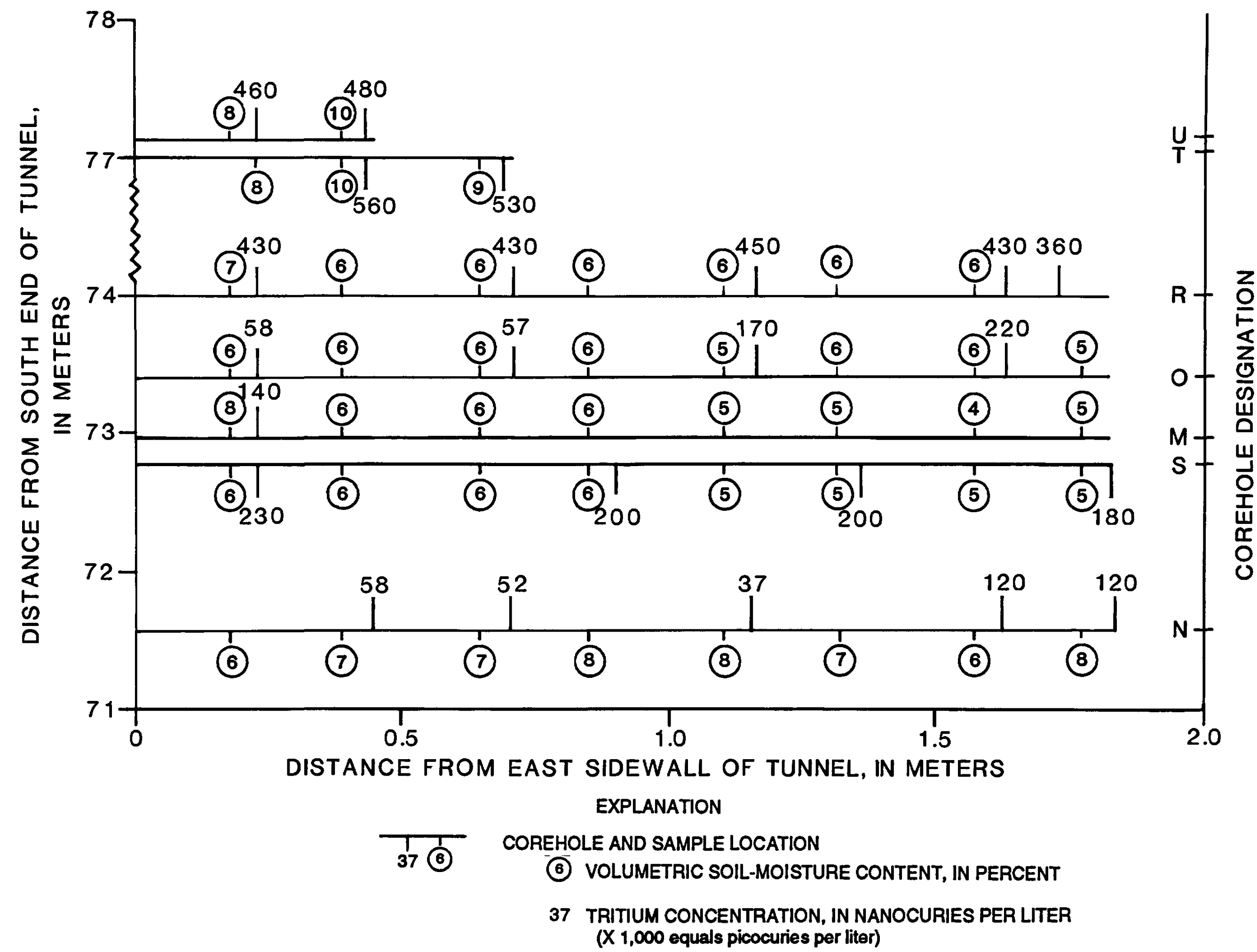
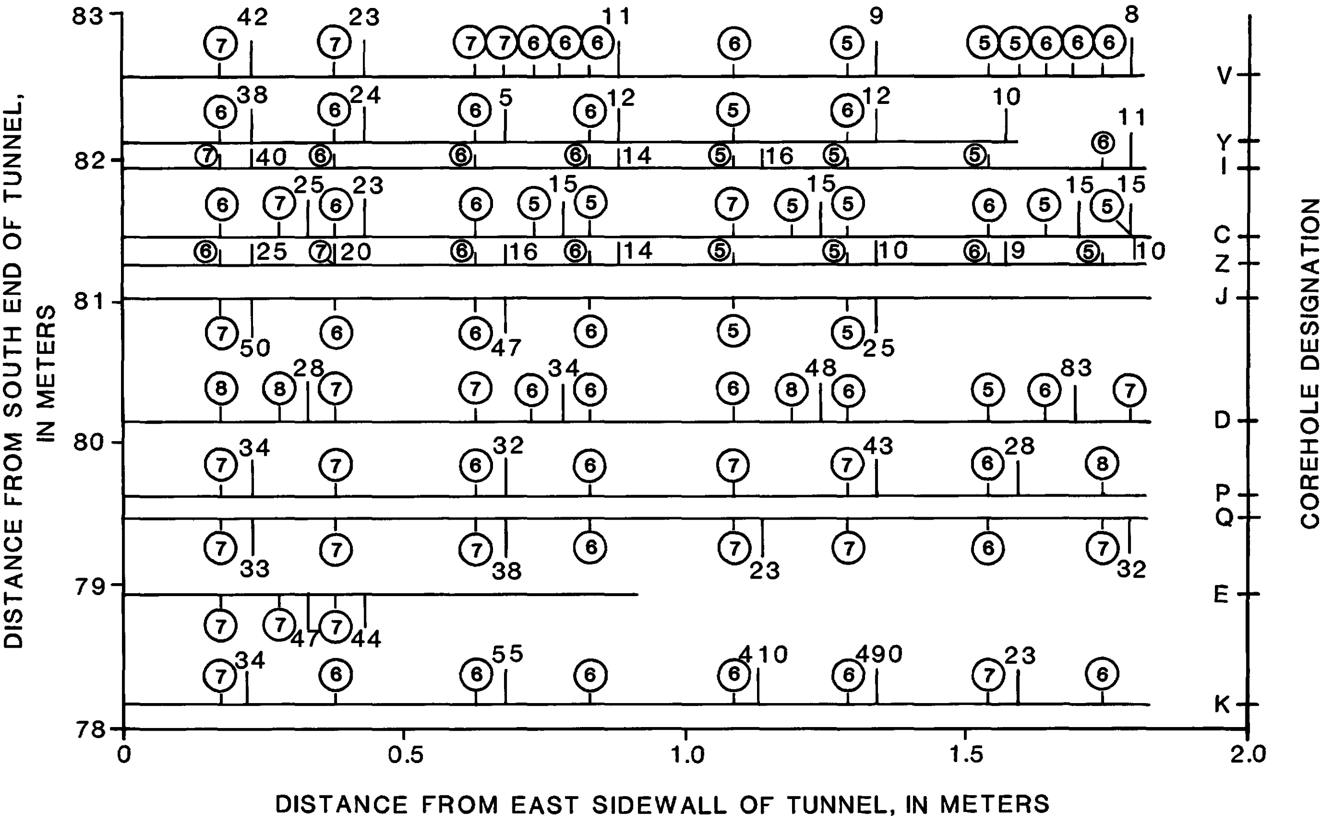


Figure 31. Soil-moisture content and tritium concentration of sediment cores from horizontal coreholes A to Z through the tunnel sidewall and into the unsaturated sand of the Toulon Member of the Glasford Formation. Data from Healy and Mills (1991). (See fig. 6 for region of horizontal coreholes in tunnel. South end of tunnel refers to point *A'* in figs. 3 and 5.)

negative value indicates that the perturbed pressure head is less than the natural pressure head. The maximum divergence from natural pressure heads (+460 mm) occurred above the midpoint of the tunnel ceiling; pressure-head divergence was greater in the sediments above the tunnel than in the sediments below the tunnel. Lateral water movement was induced in the vicinity of the tunnel as vertical water movement was inhibited by the tunnel.

The tunnel's influence appears to be limited to a distance of about 0.6 m from the tunnel in the below-tunnel sediments and 0.8 m in the above-tunnel sediments. Beyond those distances, pressure heads diverged from natural values typically by less than +100 mm. This difference is probably within the measurement error for tensiometers installed in clayey silt and represents a range of less than 1 percent in soil-moisture content. Minimal perturbation occurred in the region that is below the lateral limits of the tunnel; most pressure heads diverged from natural values by less than about ±50 mm.

The 1-mm/d flux rate used in the simulation was derived from annual recharge rates for the period July 1982 through June 1984, a period of maximum estimated recharge. Estimated recharge rates at the Sheffield site were less than 0.5 mm/d in subsequent years. Flux rates greater than the maximum estimated rates were used in the simulations to account for estimation error. Doubling the flux rate to 2 mm/d increased pressure heads above the tunnel and decreased pressure heads below the tunnel, a relation similar to that obtained by using 1 mm/d. Doubling the flux rate also increased pressure heads over the entire model area, produced about the same degree of lateral flow above the tunnel as the 1-mm/d rate, and produced a larger decrease in pressure heads from natural values below the



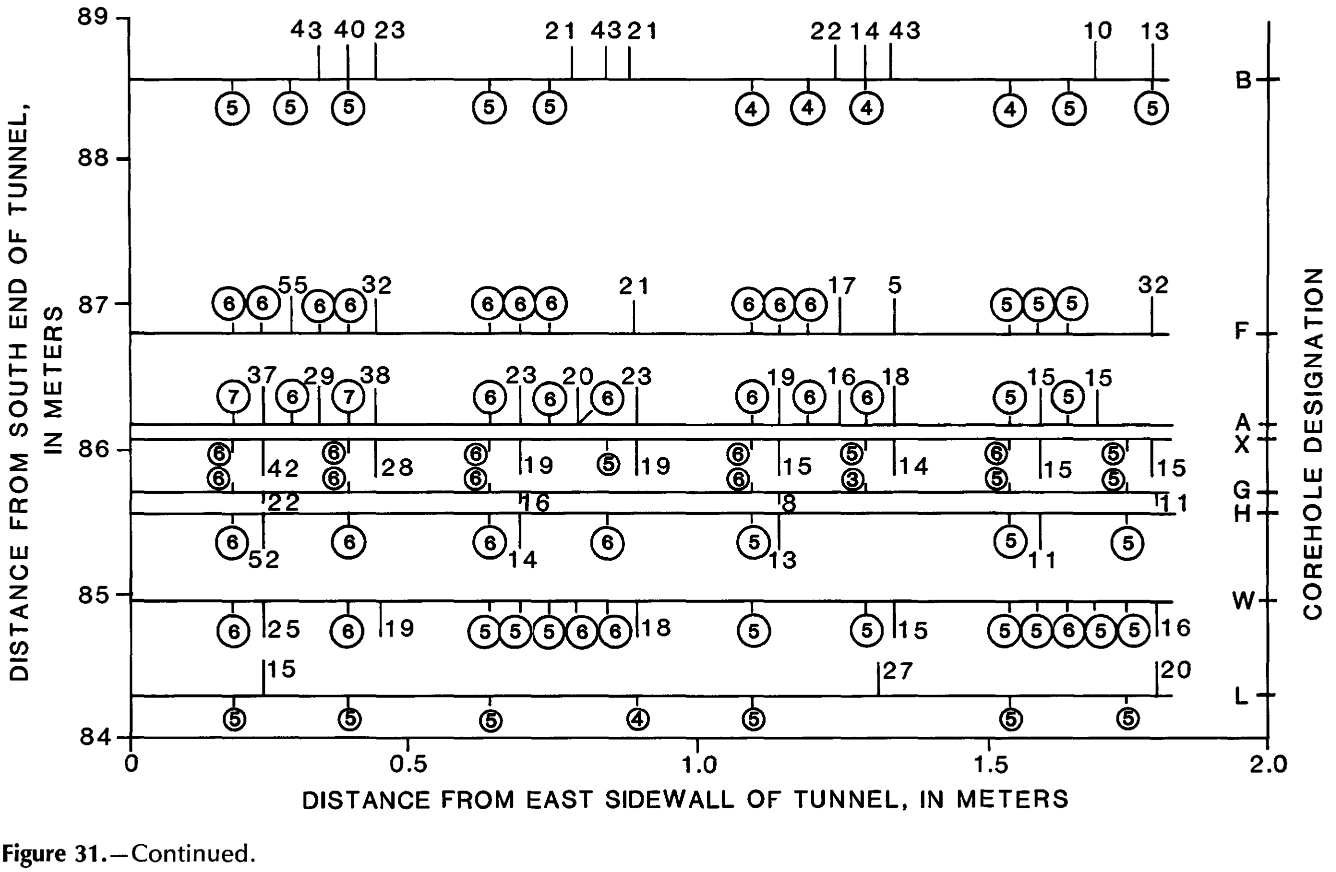


Figure 31.—Continued.

Table 11. Mass bulk density of representative sediment cores from the unsaturated sand of the Toulon Member of the Glasford Formation

[m, meters; g/cm³, grams per cubic centimeter; nCi/L, nanocuries per liter[1]]

Corehole[2] (letter) and sample (numeral) designation	Distance from south end (origin) of tunnel (m)	Distance from east sidewall of tunnel (m)	Mass bulk density (g/cm³)
N1	71.6	0.15–0.20	1.62
N2	71.6	.36– .41	1.67
N3	71.6	.61– .66	1.67
N4	71.6	.81– .86	1.64
N5	71.6	1.07–1.12	1.64
N6	71.6	1.27–1.32	1.60
N7	71.6	1.52–1.58	1.60
N8	71.6	1.73–1.78	1.56
R1	74.1	.15– .20	1.64
R2	74.1	.36– .41	1.65
R3	74.1	.61– .66	1.71
R4	74.1	.81– .86	1.67
R5	74.1	1.07–1.12	1.65
R6	74.1	1.27–1.32	1.64
R7	74.1	1.52–1.58	1.59
T1	77.1	.15– .20	1.68
T2	77.1	.36– .41	1.70
T3	77.1	.61– .66	1.55
T21–1	83.8	.05– .10	1.62
T21–2	83.8	.15– .20	1.65
T21–3	83.8	.25– .30	1.69
T21–4	83.8	.36– .41	1.72
T21–5	83.8	.46– .51	1.69
X1	86.3	.15– .20	1.70
X2	86.3	.36– .41	1.66
X3	86.3	.61– .66	1.69
X4	86.3	.81– .86	1.62
X5	86.3	1.07–1.12	1.64
X6	86.3	1.27–1.32	1.64
X7	86.3	1.52–1.58	1.70
X8	86.3	1.73–1.78	1.62

[1] Nanocuries per liter × 1,000 = picocuries per liter (1 nanocurie = 1,000 picocuries).

[2] General characteristics of coreholes: N, Tritium concentrations decrease with proximity to tunnel; R, Tritium concentrations are elevated (exceed 300 nCi/L); T, Tritium concentrations are elevated (exceed 500 nCi/L) and soil-moisture contents are elevated (exceed 8 percent); T21, Tritium concentrations do not change with proximity to tunnel; X, Tritium concentrations increase with proximity to tunnel.

tunnel (more pronounced rainshadow (fig. 33*A*)) than did the 1-mm/d rate. The spatial limits of the tunnel influence varied with the increase in flux (fig. 33*B*) and extended beyond 2 m from the tunnel; the tunnel influence was not substantially different in the sediments below the lateral limits of the tunnel with increased flux. Tripling the flux rate to 3 mm/d produced unrealistic pressure heads (saturated sediments at most locations). As flux rates were decreased from 1 mm/d, simulated pressure heads throughout the section decreased, and so did the effect of the tunnel on natural water movement

Hydraulic-conductivity values also were varied from those indicated by field and laboratory measurements to account for potential variations in the values due to spatial variability or measurement error. Reducing the hydraulic conductivity of the till deposit by one-half, to 2.05 mm/d, produced results essentially identical to those produced by doubling the flux rate. Reducing hydraulic conductivity of the till deposits by much more than one-half resulted in an unrealistic distribution of saturated sediments. As hydraulic conductivity was increased, pressure-head divergence from natural values decreased. Response to changes in hydraulic conductivity of the overlying sand deposit was minimal.

There was a boundary effect on simulated till-section pressure heads described in this report. The western boundary was not sufficiently removed from tunnel-affected flow patterns to allow natural flow patterns to develop. As a result, pressure heads were slightly too high at all model nodes; the effect was more pronounced with increased flux rates. The presence of the boundary effect, however, did not interfere with the purpose of the flow simulations. Increasing the distance of the western boundary from the tunnel produced pressure-head-distribution patterns that differed minimally from those presented in this report. With the boundary effect eliminated, pressure-head divergence from natural values is actually less than that shown here.

Results of water movement through the sand section simulated with measured values of hydraulic conductivity and flux are shown in figure 34. The simulated pressure heads compare favorably with the range of field-observed pressure heads (fig. 14). In general, pressure-head patterns in the sand section are similar to those in the till section—pressure heads increase over the tunnel and decrease below the tunnel. The tunnel's effect on water movement was considerably less in the sand section (fig. 34*B*) than in the till section, probably because of the higher hydraulic conductivity of the sediments in the sand section. Maximum divergence of pressure heads from natural values was only −370 mm. Also, in the sand section, maximum divergence of pressure heads from natural values occurred directly below the vertical midpoint of the tunnel floor (in contrast to the till section, where maximum divergence of pressure heads occurred above the tunnel). In all locations beyond a distance of about 0.2 m from the tunnel, except below the vertical midpoint of the tunnel floor, pressure heads diverged from natural values by less than +100 mm; beyond a distance of 1 m, pressure heads essentially were unperturbed by the tunnel.

Increasing flux, even by as much as one order of magnitude (to 10 mm/d), induced little change in the simulated results (fig. 35*A*). Pressure heads increased by about 200 mm throughout the simulated region, but the degree and pattern of divergence from natural values (fig.

-55	-55	-55	-55	-55	-55	-55	-55	-55	-55	-55	-55	-55	-55	-55	-55	
-37	-37	-37	-37	-37	-37	-37	-37	-37	-37	-37	-37	-37	-37	-37	-37	SAND
-148	-148	-148	-148	-147	-147	-146	-145	-144	-143	-141	-138	-135	-132	-129	-128	
-147	-147	-147	-146	-146	-145	-144	-143	-142	-139	-137	-133	-129	-124	-119	-117	
-146	-146	-145	-145	-144	-143	-142	-141	-138	-136	-132	-127	-121	-114	-104	-101	
-144	-144	-143	-143	-142	-141	-139	-137	-135	-131	-127	-121	--114	-104	****	****	
-141	-141	-140	-140	-139	-138	-136	-133	-130	-126	-121	-115	-110	****			
-137	-137	-136	-136	-135	-133	-132	-129	-125	-121	-114	-106	-98				
-131	-131	-131	-130	-129	-128	-126	-124	-120	-116	-109	-97	****				
-123	-123	-123	-122	-121	-120	-119	-117	-114	-111	-109	****			TUNNEL		TILL
-113	-113	-112	-112	-111	-110	-109	-108	-106	-105	-105	****					
-100	-99	-99	-99	-98	-97	-97	-96	-96	-96	-98	-104	****				
-85	-85	-85	-84	-84	-84	-83	-83	-83	-84	-86	-90	-93				
-71	-71	-71	-70	-70	-70	-70	-70	-70	-71	-73	-75	-77	****			
-56	-56	-56	-56	-56	-56	-56	-56	-57	-58	-59	-61	-63	-67	****	****	
-42	-42	-42	-42	-42	-42	-42	-42	-43	-43	-44	-46	-48	-50	-53	-54	
-28	-28	-28	-28	-28	-28	-28	-28	-28	-29	-30	-31	-32	-33	-35	-35	
-14	-14	-14	-14	-14	-14	-14	-14	-14	-14	-15	-15	-16	-16	-17	-17	
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	

A

EXPLANATION
PRESSURE HEAD, IN CENTIMETERS OF WATER
(x 10 equals millimeters of water)
NODE INTERVAL (HORIZONTAL AND VERTICAL) IS 20 CENTIMETERS
SATURATED HYDRAULIC CONDUCTIVITY OF TILL IS 4.1 MILLIMETERS PER DAY
SATURATED HYDRAULIC CONDUCTIVITY OF SAND IS $3.4X10^4$ MILLIMETERS PER DAY
SOIL-WATER FLUX RATE IS 1 MILLIMETER PER DAY
**** TUNNEL LINER

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	SAND
0	0	0	0	1	1	2	3	4	5	7	10	13	16	19	20	
1	1	1	2	2	3	4	5	6	9	11	15	19	24	29	31	
1	1	2	2	3	4	5	6	9	11	15	20	26	33	43	46	
1	1	2	2	3	4	6	8	10	14	18	24	31	41	****	****	
2	2	3	3	4	5	7	10	13	17	22	28	33	****			
3	3	4	4	5	7	8	11	15	19	26	34	42				
4	4	4	5	6	7	9	11	15	19	26	38	****				
5	5	5	6	7	8	9	11	14	17	19	****			TUNNEL		TILL
5	5	6	6	7	8	9	10	12	13	13	****					
5	6	6	6	7	8	8	9	9	9	7	1	****				
5	5	5	6	6	6	7	7	7	6	4	0	-3				
4	4	4	5	5	5	5	5	5	4	2	0	-2	****			
4	4	4	4	4	4	4	4	3	2	1	-1	-3	-7	****	****	
3	3	3	3	3	3	3	3	2	2	1	-1	-3	-5	-8	-9	
2	2	2	2	2	2	2	2	2	1	0	-1	-2	-3	-5	-5	
1	1	1	1	1	1	1	1	1	1	0	0	-1	-1	-2	-2	
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	

B

EXPLANATION
DIVERGENCE OF PERTURBED PRESSURE HEADS FROM UNPERTURBED PRESSURE HEADS, IN CENTIMETERS OF WATER
(x 10 equals millimeters of water)
NODE INTERVAL (HORIZONTAL AND VERTICAL) IS 20 CENTIMETERS
SATURATED HYDRAULIC CONDUCTIVITY OF TILL IS 4.1 MILLIMETERS PER DAY
SATURATED HYDRAULIC CONDUCTIVITY OF SAND IS $3.4X10^4$ MILLIMETERS PER DAY
SOIL-WATER FLUX RATE IS 1 MILLIMETER PER DAY
**** TUNNEL LINER

Figure 32. Numerical simulation of the tunnel effect on water movement in the till section obtained by using known values of saturated hydraulic conductivity and soil-water flux.

35*B*) essentially were equivalent to those obtained with a flux rate of 1 mm/d. As would be expected, an even smaller tunnel effect on natural water movement was indicated as flux was reduced further from the 1-mm/d rate. Although there was an overall shift in pressure heads throughout the simulated section, neither a decrease or increase in the hydraulic conductivity of the sand deposit by one order of magnitude resulted in substantial changes in the degree and distribution of pressure-head divergence in the simulated section.

-50	-50	-50	-50	-50	-50	-50	-50	-50	-50	-50	-50	-50	-50	-50	-50	
-32	-32	-32	-32	-32	-32	-32	-32	-32	-32	-32	-32	-32	-32	-32	-32	SAND
-119	-118	-118	-118	-117	-116	-114	-112	-109	-106	-102	-97	-93	-88	-84	-82	
-116	-116	-115	-114	-113	-111	-109	-106	-102	-98	-93	-88	-82	-77	-72	-69	
-112	-111	-110	-109	-108	-105	-102	-99	-95	-90	-95	-79	-73	-65	-56	-53	
-105	-105	-104	-102	-100	-98	-95	-91	-87	-82	-77	-71	-64	-54	****	****	
-97	-96	-95	-94	-92	-90	-87	-84	-80	-75	-70	-63	-58	****			
-88	-87	-86	-85	-84	-82	-80	-77	-73	-69	-63	-55	-46				
-79	-79	-78	-77	-76	-75	-73	-71	-68	-64	-59	-47	****				
-71	-70	-70	-69	-68	-68	-66	-65	-64	-62	-60	****			TUNNEL		TILL
-63	-62	-62	-62	-61	-61	-60	-60	-60	-60	-61	****					
-55	-54	-54	-54	-54	-54	-54	-54	-55	-57	-61	-72	****				
-47	-47	-47	-47	-47	-47	-47	-48	-49	-52	-56	-63	-70				
-39	-39	-39	-39	-39	-39	-40	-41	-43	-45	-48	-53	-57	****			
-31	-31	-31	-31	-31	-32	-32	-33	-35	-37	-40	-44	-48	-55	****	****	
-23	-23	-23	-23	-24	-24	-25	-25	-27	-28	-30	-33	-37	-42	-47	-49	
-15	-15	-15	-15	-16	-16	-16	-17	-18	-19	-20	-22	-25	-27	-30	-32	
-7	-7	-7	-8	-8	-8	-8	-8	-9	-9	-10	-11	-12	-13	-15	-15	
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	

A

EXPLANATION
PRESSURE HEAD, IN CENTIMETERS OF WATER
(x 10 equals millimeters of water)
NODE INTERVAL (HORIZONTAL AND VERTICAL) IS 20 CENTIMETERS
SATURATED HYDRAULIC CONDUCTIVITY OF TILL IS 4.1 MILLIMETERS PER DAY
SATURATED HYDRAULIC CONDUCTIVITY OF SAND IS 3.4×10^4 MILLIMETERS PER DAY
SOIL-WATER FLUX RATE IS 2 MILLIMETERS PER DAY
**** TUNNEL LINER

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	SAND
3	4	4	4	5	6	8	10	13	16	20	25	29	34	38	40	
5	5	6	7	8	10	12	15	19	23	28	33	39	44	49	52	
8	9	10	11	12	15	18	21	25	30	25	41	47	55	64	67	
13	13	14	16	18	20	23	27	31	36	41	47	54	64	****	****	
18	19	20	21	23	25	28	31	35	40	45	52	57	****			
22	23	24	25	26	28	30	33	37	41	47	55	64				
23	23	24	25	26	27	29	31	34	38	43	55	****				
21	22	22	23	24	24	26	27	28	30	32	****			TUNNEL		TILL
18	19	19	19	20	20	21	21	21	21	20	****					
16	17	17	17	17	17	17	17	16	14	10	-1	****				
14	14	14	14	14	14	14	13	12	9	5	-2	-9				
12	12	12	12	12	12	11	10	8	6	3	-2	-6	****			
9	9	9	9	9	8	8	7	5	3	0	-4	-8	-15	****	****	
7	7	7	7	6	6	5	5	3	2	0	-3	-7	-12	-17	-19	
5	5	5	5	4	4	4	3	2	1	0	-2	-5	-7	-10	-12	
3	3	3	2	2	2	2	2	1	1	0	-1	-2	-3	-5	-5	
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	

B

EXPLANATION
DIVERGENCE OF PERTURBED PRESSURE HEADS FROM UNPERTURBED PRESSURE HEADS, IN CENTIMETERS OF WATER
(x 10 equals millimeters of water)
NODE INTERVAL (HORIZONTAL AND VERTICAL) IS 20 CENTIMETERS
SATURATED HYDRAULIC CONDUCTIVITY OF TILL IS 4.1 MILLIMETERS PER DAY
SATURATED HYDRAULIC CONDUCTIVITY OF SAND IS 3.4×10^4 MILLIMETERS PER DAY
SOIL-WATER FLUX RATE IS 2 MILLIMETERS PER DAY
**** TUNNEL LINER

Figure 33. Numerical simulation of the tunnel effect on water movement in the till section obtained by using known values of saturated hydraulic conductivity and by using known values of soil-water flux increased twofold.

-63	-63	-63	-63	-63	-63	-63	-63	-63	-63	-63	-63	-63	-63	
-63													-63	
-63													-63	
-63		-63									-62	-61	-60	
-63									-62	-60	-55	-47	-45	
-63							-62	-62	-59	-53	-45	****	****	
-63						-62	-62	-61	-58	-54	****			
-63						-62	-61	-58	-52	-44				
-63					-62	-61	-57	-50	-42	****				
-63				-62	-61	-59	-56	-52	****		TUNNEL			SAND
-63			-62	-62	-61	-59	-55	-52	****					
-63			-62	-62	-60	-58	-56	-55	-65	****				
-63		-62	-62	-61	-60	-58	-56	-56	-63	-74				
-63		-62	-62	-61	-60	-58	-57	-57	-62	-69	****			
-63	-62	-62	-62	-61	-60	-58	-57	-58	-62	-68	-79	****	****	
-63	-62	-62	-61	-61	-59	-58	-58	-59	-62	-67	-76	-89	-100	
-62	-62	-62	-61	-61	-60	-59	-58	-59	-62	-67	-74	-83	-91	
-62	-62	-62	-61	-60	-60	-59	-59	-60	-62	-66	-72	-79	-85	
-62	-62	-62	-61	-60	-60	-59	-59	-60	-62	-66	-71	-76	-80	
-62	-62	-62	-61	-61	-60	-60	-60	-61	-62	-65	-68	-70	-72	
-54	-54	-54	-54	-54	-54	-54	-54	-54	-54	-55	-55	-56	-56	
-36	-36	-36	-36	-36	-36	-36	-36	-36	-36	-36	-36	-36	-36	
-16	-16	-16	-16	-16	-16	-16	-16	-16	-16	-16	-16	-16	-16	
0	0	0	0	0	0	0	0	0	0	0	0	0	0	TILL

A

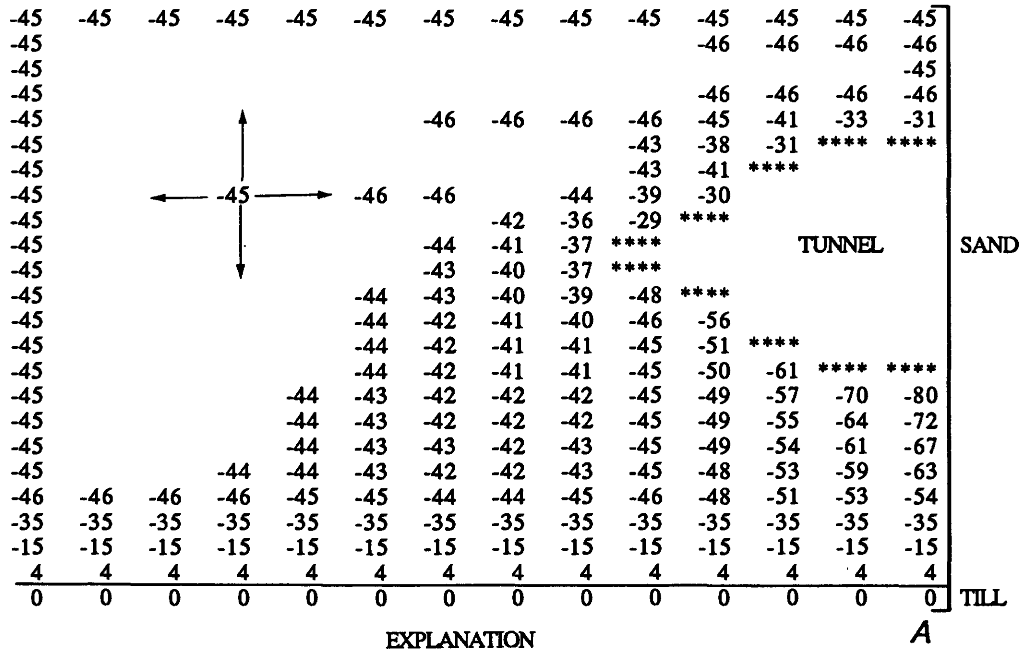
EXPLANATION
PRESSURE HEAD, IN CENTIMETERS OF WATER
(x 10 equals millimeters of water)
NODE INTERVAL (HORIZONTAL AND VERTICAL) IS 20 CENTIMETERS
SATURATED HYDRAULIC CONDUCTIVITY OF TILL IS 4.1 MILLIMETERS PER DAY
SATURATED HYDRAULIC CONDUCTIVITY OF SAND IS 3.4×10^4 MILLIMETERS PER DAY
SOIL-WATER FLUX RATE IS 1 MILLIMETER PER DAY
**** TUNNEL LINER

0	0	0	0	0	0	0	0	0	0	0	0	0	0	
0													0	
0													0	
0		0									1	2	3	
0									1	3	8	16	18	
0							1	1	4	10	18	****	****	
0						1	1	2	5	9	****			
0						1	2	5	11	19				SAND
0					1	2	6	13	21	****				
0				1	2	4	7	11	****		TUNNEL			
0			1	1	2	4	8	11	****					
0			1	1	3	5	7	8	-2	****				
0		1	1	2	3	5	7	7	0	-11				
0		1	1	2	3	5	6	6	1	-6	****			
0	1	1	1	2	3	5	6	5	1	-5	-16	****	****	
0	1	1	2	2	4	5	5	4	1	-4	-13	-26	-37	
0			1	1	2	3	4	3		-5	-12	-21	-29	
0			1	2	2	3	3	2		-4	-10	-17	-23	
0			1	2	2	3	3	2		-4	-9	-14	-18	
0	0		1	1	2	2	2	1		-3	-6	-8	-10	
0										-1	-1	-2	-2	
0													0	
0													0	
0	0	0	0	0	0	0	0	0	0	0	0	0	0	TILL

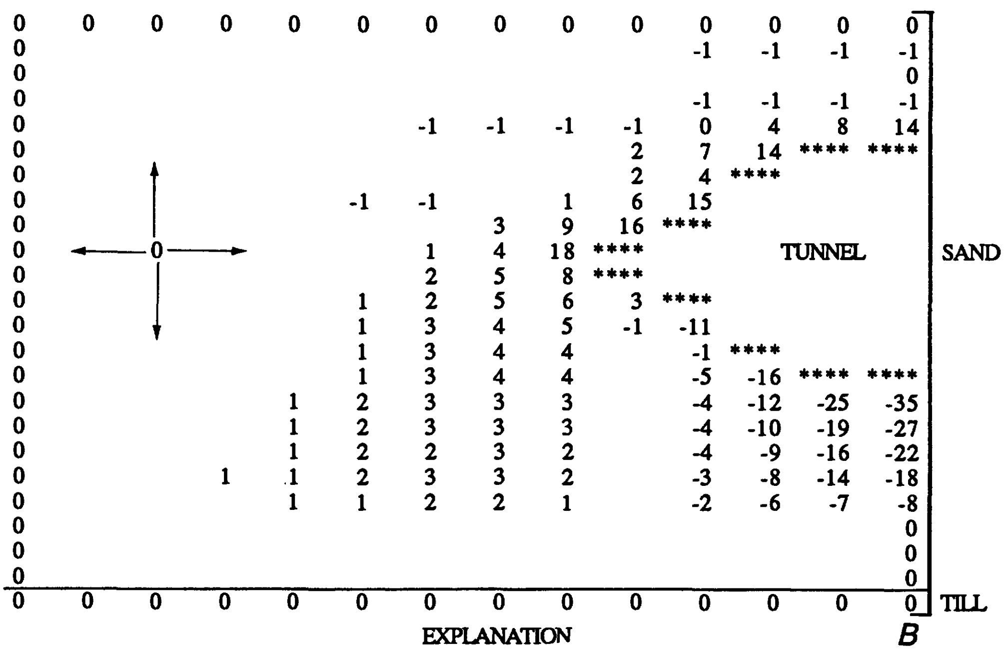
B

EXPLANATION
DIVERGENCE OF PERTURBED PRESSURE HEADS FROM UNPERTURBED PRESSURE HEADS, IN CENTIMETERS OF WATER
(x 10 equals millimeters of water)
NODE INTERVAL (HORIZONTAL AND VERTICAL) IS 20 CENTIMETERS
SATURATED HYDRAULIC CONDUCTIVITY OF TILL IS 4.1 MILLIMETERS PER DAY
SATURATED HYDRAULIC CONDUCTIVITY OF SAND IS 3.4×10^4 MILLIMETERS PER DAY
SOIL-WATER FLUX RATE IS 1 MILLIMETER PER DAY
**** TUNNEL LINER

Figure 34. Numerical simulation of the tunnel effect on water movement in the sand section obtained by using known values of saturated hydraulic conductivity and soil-water flux.



EXPLANATION
PRESSURE HEAD, IN CENTIMETERS OF WATER
(x 10 equals millimeters of water)
NODE INTERVAL (HORIZONTAL AND VERTICAL) IS 20 CENTIMETERS
SATURATED HYDRAULIC CONDUCTIVITY OF TILL IS 4.1 MILLIMETERS PER DAY
SATURATED HYDRAULIC CONDUCTIVITY OF SAND IS $3.4X10^4$ MILLIMETERS PER DAY
SOIL-WATER FLUX RATE IS 10 MILLIMETERS PER DAY
**** TUNNEL LINER



EXPLANATION
DIVERGENCE OF PERTURBED PRESSURE HEADS FROM UNPERTURBED PRESSURE HEADS, IN CENTIMETERS OF WATER
(x 10 equals millimeters of water)
NODE INTERVAL (HORIZONTAL AND VERTICAL) IS 20 CENTIMETERS
SATURATED HYDRAULIC CONDUCTIVITY OF TILL IS 4.1 MILLIMETERS PER DAY
SATURATED HYDRAULIC CONDUCTIVITY OF SAND IS $3.4X10^4$ MILLIMETERS PER DAY
SOIL-WATER FLUX RATE IS 10 MILLIMETERS PER DAY
**** TUNNEL LINER

Figure 35. Numerical simulation of the tunnel effect on water movement in the sand section obtained by using known values of saturated hydraulic conductivity and by using known values of soil-water flux increased tenfold.

Simulations of water movement through the till and sand sections indicate that hydrologic data collected represent natural conditions in the vicinity of the tunnel. The hydrologic data collected from the fine-grained sediments of the till section may be less representative of natural conditions if the estimated flux rate of 1 mm/d during the recharge period was substantially less than the actual flux rate. The tunnel apparently induces minimal disturbance to the natural patterns of water movement beyond about 0.6 to 0.8 m in the till section, where fine-grained sediments dominate, and beyond about 0.2 m in the sand section. Most tensiometers and lysimeters were located 1 m beyond the tunnel sidewalls. These results may have been affected by the limiting assumptions that were used for the simulations.

SUMMARY

Soil-water movement and water chemistry in the unsaturated zone were studied during 1986–87 at a low-level radioactive-waste disposal site near Sheffield, Ill.; the study was undertaken to address several questions generated by earlier studies. Radioactive wastes were buried at the 8.1-hectare site during 1976–78 in 21 trenches constructed in clayey silt to pebbly sand glacial and postglacial deposits that overlie a thick sequence of Pennsylvanian bedrock.

The focus of the study was to (1) characterize temporal trends in water movement and water chemistry over several (5–11) years, (2) evaluate preferential movement of water and trench leachate in an unsaturated glacial sand deposit, and (3) determine the extent to which the research tunnel used in the study affected the natural movement of water in the surrounding glacial deposits.

A gamma-attenuation soil-density gage installed in a trench cover was used to evaluate soil-water movement into trenches. Data for a water-budget analysis were collected onsite and supplemented with data from three offsite National Weather Service stations and a U.S. Geological Survey streamflow-gaging station. A 2-m-diameter by 120-m-long horizontal tunnel provided access to the variably saturated till and sand deposits underlying four waste-disposal trenches. Sediment cores were used to analyze sediment properties, soil-moisture contents, and tritium concentrations. Soil-moisture tensiometers and gravity lysimeters were used to monitor soil-water movement beneath the trenches. Vacuum and gravity lysimeters were used to collect soil water beneath the trenches for chemical analysis. Wells and piezometers were used to measure depth to the water table and to collect ground-water samples for chemical analysis. Data collected during 1986–87 were compared to data collected during 1976–85 to evaluate temporal variability. A cross-sectional, numerical, ground-water-flow model aided interpretation of the affect of the tunnel on water movement.

Annual precipitation decreased from 928 and 968 mm during the 2 years from July 1982 through June 1984, respectively, to 774, 864, and 695 mm during the 3 years from July 1984 through June 1987, respectively. Estimated seepage to the trenches and (or) ground-water recharge decreased accordingly, from 107 and 107 mm (July 1982 through June 1984) to 49, 74, and 48 mm (July 1984 through June 1987).

The seasonal pattern of early spring recharge to the unsaturated zone below the trenches and the saturated zone, as observed during 1981–85, was obscured during 1986–87 by the large reduction in pressure-head fluctuation and an overall decline in pressure heads during the period; an additional recharge period during fall also was observed in 1986. Peak soil-water fluxes at two gravity lysimeter locations decreased from about 15 and 11 mm/d, respectively, in 1985, to about 0 and 6 mm/d, respectively, during 1986–87. Water-table altitudes at nine measuring locations decreased from historical (1976–87) highs in March 1985 to near-historical lows during 1986–87.

Average tritium concentrations in soil water from 12 below-trench vacuum lysimeters increased from 70,100 to 153,000 pCi/L from 1982–84 to 1986–87. Maximum concentrations of tritium in the range of 9,000,000 to 15,000,000 pCi/L were detected in soil-water seeps and sediment cores at several locations below trench 11. Gross-alpha and gross-beta activities were at background levels. Volatile organic compounds, including halogenated aliphatic hydrocarbons, halogenated aromatic hydrocarbons, nonhalogenated aromatic hydrocarbons, and methyl esters, were detected in a synoptic sample from the Toulon Member of the Glasford Formation (sand deposit). Concentrations of inorganic ions in soil water changed little from 1982 to 1987.

Flow is unevenly distributed through the Toulon Member. Slow, continuous water movement appears to occur through most areas of the sand deposit; localized, preferential flow along near-saturated to saturated flow paths occurs as well. Data from the 7 (of 16) gravity lysimeters in which free-drainage of soil water occurred indicate that the flow paths may be less than 1 mm^2 in cross-sectional area. Because of their localized occurrence and small size, the flow paths were not readily identified by soil-moisture tensiometers. Drainage was intermittent at four lysimeter locations and continuous at three. Tritium concentrations in the drainage water ranged from 288,000 to 963,000 pCi/L. Average annual tritium flux through the Toulon Member was estimated to be 0.59 $(nCi/yr)/cm^2$.

The location of preferential flow paths in the Toulon Member appears to be related to the location of preferential flow paths in the overlying trenches. Flow paths into and through the trenches apparently are related to trench-cover-construction characteristics, the structural integrity of the trench covers, and the distribution of waste containers and soil backfill within the trenches. The timing and rates of water movement through the sand deposit are influenced by precipitation patterns, seasonal climate cycles, and factors such as trench-interior characteristics.

Tritium concentrations of the preferentially moving water in the Toulon Member fluctuate seasonally. Concentrations increase as water is flushed from the trenches during spring recharge; in some instances, concentrations decrease, apparently by dilution from recent recharge water. Changes in tritium concentrations also appear to occur as waste containers deteriorate and flow paths in the trenches change location.

Pressure-head data from tensiometers, soil-moisture content data, and tritium-concentration data from sediment cores and numerical simulations indicate that the tunnel has neither a consistent nor pronounced effect on the natural movement of water. The tunnel appears to perturb natural water movement most directly above and below the tunnel. Most instrument measurements and water samples were obtained beyond the tunnel sidewalls at a minimum distance of 1 m from the tunnel. Perturbation of water movement occurs primarily within about 0.7 m of the tunnel in the Hulick Till Member and within about 0.2 m of the tunnel in the Toulon Member.

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TABLE 12

Table 12. Soil-water flux and tritium concentration of drainage water from below-trench gravity lysimeters in the unsaturated glacial deposits, March 1985 through October 1987

[h, hour; mL, milliliter; mL/d, milliliters per day; mm/d, millimeters per day; nCi/L, nanocuries per liter[1]; —, no data]

Starting Date	Starting Time (h)	Ending Date	Ending Time (h)	Volume (mL)	Drainage rate (mL/d)	Soil-water flux (mm/d)	Tritium concentration (nCi/L)	Remarks
					GL2			
03–04–85	—	03–14–85	—	0.0	—	—	—	
03–14–85	—	04–04–85	—	200.0	9.52	7.118	102	
04–04–85	—	04–17–85	—	208.0	16.00	11.958	78.3	
04–17–85	—	04–26–85	—	182.0	20.22	15.114	46.4	
04–26–85	—	05–15–85	—	249.0	13.11	9.795	65.9	
05–15–85	—	05–29–85	—	140.0	10.00	7.474	64.2	
05–29–85	—	06–10–85	—	70.0	5.83	4.360	58.0	
06–10–85	—	06–24–85	—	37.0	2.64	1.975	67.8	
06–24–85	—	07–11–85	—	13.0	.76	.572	73.5	
07–11–85	—	10–20–85	—	.0	—	—	—	
Minimum						0.572	46.4	
Maximum						15.114	102	
Mean						7.296	69.5	
Standard deviation						4.947	16.3	
Number of samples						8	8	
					GL3[2]			
03–04–85	—	03–14–85	—	0.0	—	—	—	
03–14–85	—	04–04–85	—	208.0	9.90	5.418	149	
04–04–85	—	04–17–85	—	133.0	10.23	5.597	86.0	
04–17–85	—	04–26–85	—	184.0	20.44	11.184	42.1	
04–26–85	—	05–15–85	—	304.0	16.00	8.753	46.6	
05–15–85	—	05–29–85	—	166.0	11.86	6.486	56.2	
05–29–85	—	06–10–85	—	73.0	6.08	3.328	54.0	
06–10–85	—	06–24–85	—	62.0	4.43	2.423	65.5	
06–24–85	—	07–11–85	—	63.0	3.71	2.027	61.9	
07–11–85	—	08–15–85	—	91.0	2.60	1.422	67.6	
08–15–85	—	08–27–85	—	21.0	1.75	.957	52.9	
08–27–85	—	09–25–85	1310	.0	—	—	—	
Minimum						0.957	42.1	
Maximum						11.184	149	
Mean						4.760	68.1	
Standard deviation						3.365	30.9	
Number of samples						10	10	
09–25–86	1200	10–07–86	1751	72.0	5.88	3.217	—	
10–07–86	1751	10–21–86	1649	92.0	6.59	3.606	178	
10–21–86	1649	11–04–86	1700	86.0	6.14	3.359	89.7	
11–04–86	1700	11–25–86	1000	35.7	1.72	.943	365	
11–25–86	1700	10–20–87	1310	.0	—	—	—	
Minimum						0.943	89.7	
Maximum						3.606	365	
Mean						2.781	211	
Standard deviation						1.236	140	
Number of samples						4	3	

Table 12. Soil-water flux and tritium concentration of drainage water from below-trench gravity lysimeters in the unsaturated glacial deposits, March 1985 through October 1987—Continued

Starting Date	Starting Time (h)	Ending Date	Ending Time (h)	Volume (mL)	Drainage rate (mL/d)	Soil-water flux (mm/d)	Tritium concentration (nCi/L)	Remarks
					GL4			
09–22–86	1400	09–24–86	1417	38.0	18.89	0.159	288	
09–24–86	1417	09–25–86	1236	23.0	24.75	.209	301	
09–25–86	1236	10–07–86	1801	244.0	19.96	.168	383	
10–07–86	1801	10–08–86	1212	14.0	18.48	.156	428	
10–08–86	1212	10–21–86	1650	233.0	17.66	.149	376	
10–21–86	1650	11–04–86	1715	108.0	7.70	.065	378	
11–04–86	1715	11–14–86	1449	10.8	1.09	.009	376	
11–14–86	1449	11–25–86	1026	71.0	6.56	.055	383	
11–25–86	1026	12–16–86	1902	49.5	2.32	.020	391	
12–16–86	1902	01–08–87	1112	97.0	4.28	.036	385	
01–08–87	1112	01–27–87	1805	39.8	.10	.001	400	
01–27–87	1805	02–26–87	1635	10.1	.34	.003	431	
02–26–87	1635	06–24–87	1525	.0	—	—	—	
06–24–87	1525	07–02–87	1115	27.6	3.53	.030	397	
07–02–87	1115	07–21–87	1400	81.7	4.27	.036	371	
07–21–87	1400	09–02–87	0815	—	—	—	—	Missing record.
09–02–87	0815	09–10–87	0902	19.5	2.43	.020	401	
09–10–87	0902	09–24–87	0905	18.2	1.30	.011	386	
09–24–87	0905	09–30–87	1702	2.4	.38	.003	393	
09–02–87	1702	10–20–87	1310	14.2	.72	.006	391	
Minimum						0.001	288	
Maximum						.209	431	
Mean						.063	381	
Standard deviation						.070	35	
Number of samples						18	18	
					GL6			
09–11–86	1000	12–16–87	1902	0.0	—	—	—	
12–16–86	1902	01–08–87	1112	21.4	0.94	0.020	—	Light amber color.
01–08–87	1112	01–27–87	1809	4.6	.24	.005	—	Do.
01–27–87	1809	02–26–87	1635	26.0	.87	.018	—	Do.
02–26–87	1635	03–10–87	1529	12.2	1.02	.021	440	Do.
03–10–87	1529	04–30–87	1455	67.6	1.33	.028	—	Light amber color.
04–30–87	1455	05–30–87	1015	24.5	1.24	.026	450	
05–20–87	1015	06–02–87	1245	23.7	1.81	.038	484	
06–02–87	1245	06–10–87	1709	20.0	2.44	.051	491	
06–10–87	1709	06–24–87	1525	33.5	2.41	.050	477	
06–24–87	1525	07–02–87	1038	22.4	2.87	.060	506	
07–02–87	1038	07–21–87	1400	58.3	3.05	.064	462	
07–21–87	1400	08–17–87	1725	—	—	—	—	Missing record.
08–17–87	1725	09–02–87	0815	32.8	2.10	.044	538	
09–02–87	0815	09–10–87	0902	14.0	1.74	.036	533	
09–10–87	0902	09–24–87	0905	25.0	1.79	.037	524	
09–24–87	0905	09–30–87	1701	9.8	1.55	.032	514	
09–30–87	1702	10–20–87	1310	35.0	1.76	.037	552	
Minimum						0.005	440	
Maximum						.064	552	
Mean						.035	498	
Standard deviation						.016	36	
Number of samples						16	12	

Table 12. Soil-water flux and tritium concentration of drainage water from below-trench gravity lysimeters in the unsaturated glacial deposits, March 1985 through October 1987—Continued

Starting Date	Starting Time (h)	Ending Date	Ending Time (h)	Volume (mL)	Drainage rate (mL/d)	Soil-water flux (mm/d)	Tritium concentration (nCi/L)	Remarks
					GL7			
09–11–86	1000	12–16–86	1902	0.0	—	—	—	
12–16–86	1902	01–08–87	1112	73.7	3.25	0.074	377	
01–08–87	1112	01–27–87	1809	5.7	.30	.007	512	
01–27–87	1809	02–26–87	1635	45.2	1.51	.034	500	
02–26–87	1635	03–10–87	1529	7.8	.65	.015	431	
03–10–87	1529	04–30–87	1455	231.1	4.53	.103	499	
04–30–87	1455	05–20–87	1015	19.1	.96	.022	541	
05–20–87	1015	06–02–87	1245	8.2	.63	.014	546	
06–02–87	1245	06–10–87	1709	4.3	.53	.012	546	
06–10–87	1709	06–24–87	1525	5.5	.39	.009	517	
06–24–87	1525	07–02–87	1038	3.8	.49	.011	521	
07–02–87	1038	07–21–87	1400	116.2	6.07	.138	476	
07–21–87	1400	09–02–87	0815	—	—	—	—	Missing record.
09–02–87	0815	09–10–87	0902	9.5	1.18	.027	582	
09–10–87	0902	09–24–87	0905	33.8	2.41	.055	567	
09–24–87	0905	09–30–87	1702	10.8	1.71	.039	566	
09–30–87	1702	10–20–87	1310	24.0	1.21	.027	596	
Minimum						0.007	377	
Maximum						.138	596	
Mean						.039	518	
Standard deviation						.038	58	
Number of samples						15	15	
					GL8			
09–11–86	1000	12–16–86	1902	0.0	—	—	—	
12–16–86	1902	01–08–87	1112	53.5	2.36	0.051	459	
01–08–87	1112	01–27–87	1809	30.6	1.59	.034	493	
01–27–87	1809	02–26–87	1635	46.5	1.55	.034	513	
02–26–87	1635	03–10–87	1529	23.1	1.93	.042	486	
03–10–87	1529	04–30–87	1455	104.8	2.06	.044	536	
04–30–87	1455	05–30–87	1015	51.3	2.59	.056	499	
05–20–87	1015	06–02–87	1245	40.0	3.05	.066	540	
06–02–87	1245	06–10–87	1709	32.2	3.93	.085	549	
06–10–87	1709	06–24–87	1525	50.5	3.63	.078	542	
06–24–87	1525	07–02–87	1038	29.1	3.73	.081	552	
07–02–87	1038	07–21–87	1400	62.2	3.25	.070	542	
07–21–87	1400	08–17–87	1725	—	—	—	—	Missing record.
08–17–87	1725	09–02–87	0815	25.8	1.65	.036	594	
09–02–87	0815	09–10–87	0902	19.0	2.37	.051	581	
09–10–87	0902	09–24–87	0905	32.2	2.30	.050	585	
09–24–87	0905	09–30–87	1702	15.8	2.50	.054	576	
09–30–87	1702	10–20–87	1310	50.2	2.53	.055	619	
Minimum						0.034	459	
Maximum						.085	619	
Mean						.055	542	
Standard deviation						.016	44	
Number of samples						16	16	

Table 12. Soil-water flux and tritium concentration of drainage water from below-trench gravity lysimeters in the unsaturated glacial deposits, March 1985 through October 1987—Continued

Starting Date	Starting Time (h)	Ending Date	Ending Time (h)	Volume (mL)	Drainage rate (mL/d)	Soil-water flux (mm/d)	Tritium concentration (nCi/L)	Remarks
					GL9			
09–11–86	1000	09–22–86	1316	63.0	5.66	0.135	683	Slight golden brown color.
09–22–86	1400	09–24–86	1423	12.0	5.95	.142	567	
09–24–86	1424	09–25–86	1232	4.2	4.55	.108	533	
09–25–86	1232	10–07–86	1808	85.0	6.95	.165	670	
10–07–86	1808	10–08–86	1214	4.0	5.30	.126	—	
10–08–86	1214	10–21–86	1659	90.0	6.82	.162	530	
10–21–86	1659	11–05–86	1246	79.3	5.35	.127	532	
11–05–86	1246	11–14–86	1449	38.0	4.18	.100	506	
11–14–86	1450	11–25–86	1035	46.8	4.32	.103	486	
11–25–86	1035	12–16–86	1902	79.1	3.70	.088	542	Very light amber color.
12–16–86	1902	01–08–87	1112	103.3	4.55	.108	508	
01–08–87	1112	01–27–87	1209	46.5	2.44	.058	668	
01–27–87	1202	02–26–87	1705	142.0	4.70	.112	682	
02–26–87	1705	03–10–87	1705	73.3	6.11	.145	629	
03–10–87	1705	04–30–87	1431	181.0	3.56	.085	699	
04–30–87	1455	05–20–87	1015	370.0	18.68	.445	624	
05–20–87	1015	06–02–87	1245	381.7	29.12	.693	760	
06–02–87	2400	06–10–87	2400	73.8	9.23	.220	789	
06–10–87	1730	06–24–87	1620	316.0	22.65	.539	782	
06–24–87	1620	07–21–87	2400	66.8	2.45	.058	779	
07–21–87	2400	08–17–87	1740	—	—	—	—	Missing record.
08–17–87	1740	09–02–87	0815	122.6	7.86	.187	870	
09–02–87	0815	09–09–87	1517	51.6	7.08	.168	868	
09–09–87	1517	09–24–87	0905	99.6	6.76	.161	844	
09–24–87	0950	09–30–87	1702	42.0	6.63	.158	845	
09–30–87	1702	10–20–87	1310	231.0	11.64	.277	919	
Minimum						0.058	486	
Maximum						.693	919	
Mean						.187	680	
Standard deviation						.153	136	
Number of samples						25	24	
					GL10			
09–11–86	1000	09–22–86	1316	5.8	0.52	0.012	548	
09–22–86	1400	09–24–86	1426	2.3	1.14	.026	544	
09–24–86	1426	09–25–86	1234	1.7	1.84	.042	585	
09–25–86	1234	10–07–86	1809	32.0	2.62	.059	693	
10–07–86	1809	10–08–86	1214	1.2	1.59	.036	808	
10–08–86	1214	10–21–86	1652	35.6	2.70	.061	589	
10–21–86	1652	11–04–86	1718	34.5	2.46	.056	585	
11–04–86	1718	11–14–86	1449	27.1	2.74	.062	604	
11–14–86	1450	11–25–86	1030	27.0	2.50	.057	602	
11–25–86	1030	12–16–86	1902	100.0	4.68	.106	604	
12–16–86	1902	01–08–87	1112	56.0	2.47	.056	424	
01–08–87	1112	01–27–87	1814	62.5	3.24	.073	635	
01–27–87	1814	02–26–87	1635	97.7	3.26	.074	621	
02–26–87	1625	03–10–87	1529	35.5	2.97	.067	562	
03–10–87	1529	04–30–87	1455	226.6	4.45	.101	660	
04–30–87	1455	05–20–87	1015	141.0	7.12	.161	635	
05–20–87	1015	06–02–87	1245	118.0	9.00	.204	—	
06–02–87	1245	06–10–87	1709	82.0	10.02	.227	739	
06–10–87	1709	06–24–87	1525	117.0	8.40	.190	730	
06–24–87	1525	07–02–87	1038	56.9	7.29	.165	754	

Table 12. Soil-water flux and tritium concentration of drainage water from below-trench gravity lysimeters in the unsaturated glacial deposits, March 1985 through October 1987—Continued

Starting Date	Starting Time (h)	Ending Date	Ending Time (h)	Volume (mL)	Drainage rate (mL/d)	Soil-water flux (mm/d)	Tritium concentration (nCi/L)	Remarks
					GL10—Continued			
07–02–87	1038	07–21–87	1400	146.4	7.65	.173	728	
07–21–87	1400	09–02–87	0815	—	—	—	—	Missing record.
09–02–87	0815	09–10–87	0902	41.5	5.17	.117	875	
09–10–87	0902	09–24–87	0905	71.8	5.13	.116	860	
09–24–87	0905	09–30–87	1702	31.2	4.93	.112	867	
09–30–87	1702	10–20–87	1310	128.0	6.45	.146	943	
Minimum						0.012	424	
Maximum						.227	943	
Mean						.100	674	
Standard deviation						.059	127	
Number of samples						25	24	
					GL11			
09–11–86	1000	09–22–86	1316	73.0	6.56	0.142	600	Very light golden color.
09–22–86	1400	09–24–86	1428	14.0	6.93	.150	617	
09–24–86	1428	09–25–86	1235	7.1	7.70	.166	624	
09–25–86	1234	10–07–86	1810	97.0	7.93	.171	730	
10–07–86	1810	10–08–86	1215	5.2	6.90	.149	734	
10–08–86	1215	10–21–86	1651	106.0	8.04	.174	618	
10–21–86	1651	11–04–86	1717	108.0	7.70	.166	604	
11–04–86	1717	11–14–86	1449	71.5	7.22	.156	606	
11–14–86	1450	11–25–86	1029	71.0	6.56	.142	600	
11–25–86	1902	12–16–86	1902	148.0	7.05	.152	608	
12–16–86	1902	01–08–87	1112	160.0	7.06	.152	492	
01–08–87	1112	01–27–87	1814	131.0	6.79	.147	635	
01–27–87	1814	02–26–87	1635	221.1	7.39	.160	599	
02–26–87	1635	03–10–87	1529	85.9	7.19	.155	648	
03–10–87	1529	04–30–87	1455	248.2	4.87	.105	675	
04–30–87	1455	05–20–87	1015	232.4	11.73	.253	661	
05–20–87	1015	06–02–87	1245	192.0	14.65	.316	—	
06–02–87	1245	06–10–87	1709	112.0	13.69	.296	754	
06–10–87	1709	06–24–87	1525	183.0	13.14	.284	766	
06–24–87	1525	07–02–87	1038	95.2	12.20	.264	766	
07–02–87	1038	07–21–87	1400	219.1	11.45	.247	791	
07–21–87	1400	09–02–87	0815	—	—	—	—	Missing record.
09–02–87	0815	09–10–87	0902	16.0	1.99	.043	881	
09–10–87	0902	09–24–87	0905	107.8	7.70	.166	873	
09–24–87	0905	09–30–87	1702	52.2	8.24	.178	891	
09–30–87	1702	10–20–87	1310	194.0	9.78	.211	963	
Minimum						0.043	492	
Maximum						.316	963	
Mean						.182	697	
Standard deviation						.063	118	
Number of samples						25	24	

[1] Nanocuries per liter × 1,000 = picocuries per liter (1 nanocurie = 1,000 picocuries).

[2] Because there was a significant hiatus in drainage from GL3, the data for the two periods of drainage are summarized separately.

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