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WATER AND TRITIUM MOVEMENT THROUGH THE UNSATURATED ZONE AT A LOW-LEVEL RADIOACTIVE-WASTE DISPOSAL SITE NEAR SHEFFIELD, ILLINOIS, 1981-85

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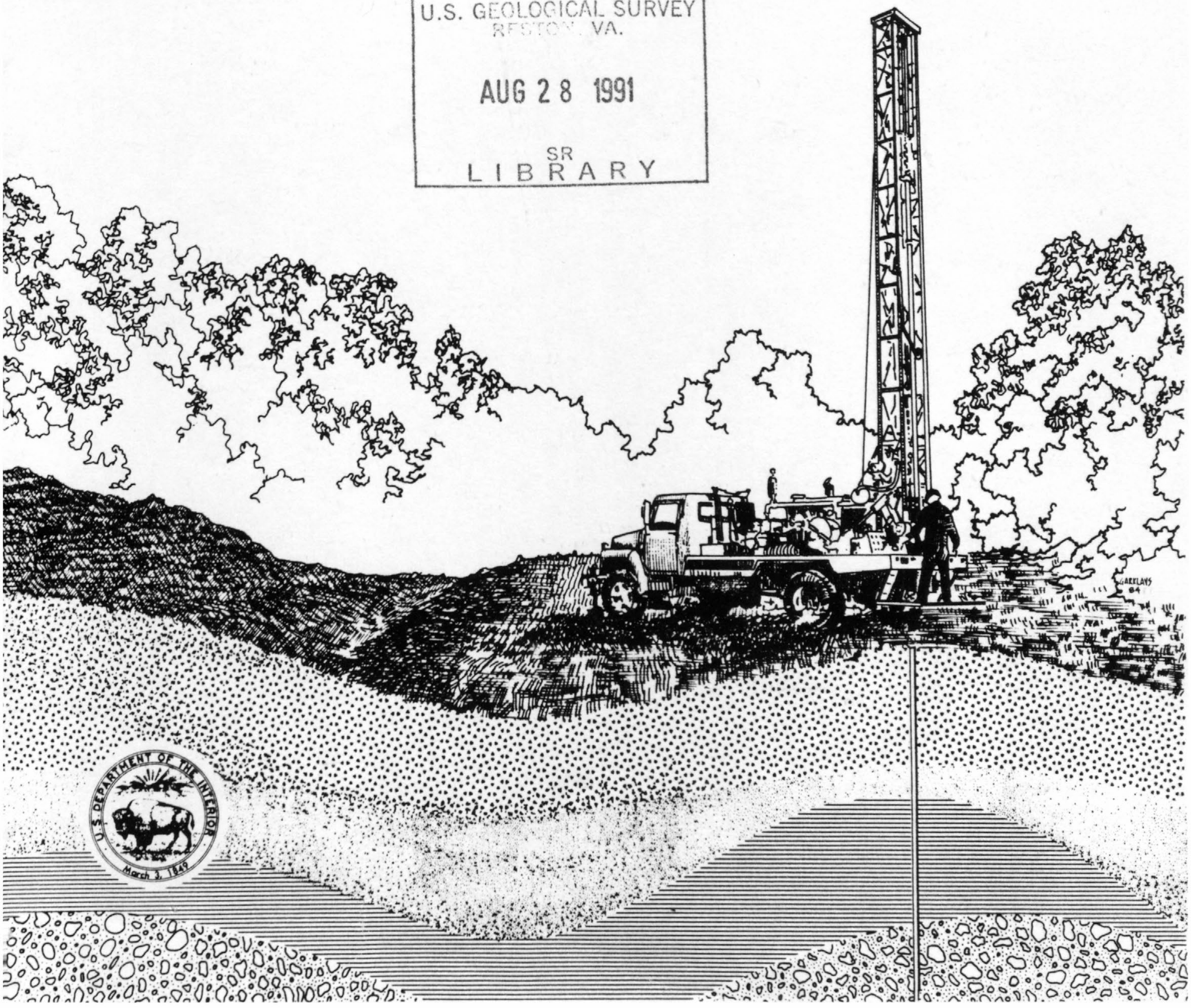

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by Patrick C. Mills and Richard W. Healy

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CONVERSION FACTORS

Metric (International System) units used in this report may be converted to inch-pound units by use of the following conversion factors:

Multiply Metric Unit	By	To Obtain Inch-Pound Unit
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
square meter (m^2)	10.76	square foot (ft^2)
kilometer (km)	0.6214	mile (mi)
gram (g)	0.03527	ounce, avoirdupois (oz)
gram per cubic centimeter (g/cm^3)	0.5780	ounce per cubic inch (oz/in^3)
kilogram (kg)	2.205	pound, avoirdupois (lb)
cubic meter (m^3)	35.31	cubic foot (ft^3)
hectare (ha)	2.471	acre
liter (L)	0.2642	gallon (gal)
liter per minute (L/min)	0.2642	gallon per minute (gal/min)
millimeter per millimeter (mm/mm)	0.03937	inch per inch (in/in)
millimeter per day (mm/d)	0.03937	inch per day (in/d)
millimeter per year (mm/yr)	0.03937	inch per year (in/yr)
degree Celsius (°C)	F = 1.8 x °C + 32	degree Fahrenheit (°F)

Radiometric

curie (Ci)	3.701×10^{10}	becquerel (Bq)
curie per cubic meter (Ci/m^3)	3.701×10^{10}	becquerel per cubic meter (Bq/m^3)
picocurie per liter (pCi/L)	0.03701	becquerel per liter (Bq/L)
nanocurie per liter (nCi/L)	37.01	becquerel per liter (Bq/L)
millicurie per year (mCi/yr)	3.701×10^{7}	becquerel per year (Bq/yr)

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 AND TRITIUM MOVEMENT THROUGH THE UNSATURATED ZONE AT A LOW-LEVEL RADIOACTIVE-WASTE DISPOSAL SITE NEAR SHEFFIELD, ILLINOIS, 1981-85

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ABSTRACT

The movement of water and tritium through the unsaturated zone was studied at a low-level radioactive-waste disposal site near Sheffield, Bureau County, Illinois, from 1981 to 1985. Water and tritium movement occurred in an annual, seasonally timed cycle; recharge to the saturated zone generally occurred in the spring and early summer. Mean annual precipitation (1982-85) was 871 millimeters; mean annual recharge to the disposal trenches (July 1982 through June 1984) was estimated to be 107 millimeters. Average annual tritium flux below the study trenches was estimated to be 3.4 millicuries per year. Site geology, climate, and waste-disposal practices influenced the spatial and temporal variability of water and tritium movement. Of the components of the water budget, evapotranspiration contributed most to the temporal variability of water and tritium movement.

Disposal trenches are constructed in complexly layered glacial and post-glacial deposits that average 17 meters in thickness and overlie a thick sequence of Pennsylvanian shale. The horizontal saturated hydraulic conductivity of the clayey-silt to sand-sized glacial and postglacial deposits ranges from 4.8×10^{-1} to 3.4×10^{4} millimeters per day.

A 120-meter-long horizontal tunnel provided access for hydrologic measurements and collection of sediment and water samples from the unsaturated and saturated geologic deposits below four disposal trenches. Trench-cover and subtrench deposits were monitored with soil-moisture tensiometers, vacuum and gravity lysimeters, piezometers, and a nuclear soil-moisture gage. A cross-sectional, numerical ground-water-flow model was used to simulate water movement in the variably saturated geologic deposits in the tunnel area. Concurrent studies at the site provided water-budget data for estimating recharge to the disposal trenches.

Vertical water movement directly above the trenches was impeded by a zone of compaction within the clayey-silt trench covers. Water entered the trenches primarily at the trench edges where the compacted zone was absent and the cover was relatively thin. Collapse holes in the trench covers that resulted from inadequate compaction of wastes within the trenches provided additional preferential pathways for surface-water drainage into the trenches; drainage into one collapse hole during a rainstorm was estimated to be 1,700 liters. Till deposits near trench bases induced lateral water and tritium movement. Limited temporal variation in water movement and small flow gradients (relative to the

till deposits) were detected in the unsaturated subtrench sand deposit; maximum gradients during the spring recharge period averaged 1.62 millimeters per millimeter. Time-of-travel of water moving from the trench covers to below the trenches was estimated to be as rapid as 41 days (assuming individual water molecules move this distance in one recharge cycle).

Tritium concentrations in water from the unsaturated zone ranged from 200 (background) to 10,000,000 pCi/L (picocuries per liter). Tritium concentrations generally were higher below trench bases (averaging 91,000 pCi/L) than below intertrench sediments (averaging 3,300 pCi/L), and in the subtrench Toulon Member of the Glasford Formation (sand) (averaging 110,000 pCi/L) than in the Hulick Till Member of the Glasford Formation (clayey silt) (averaging 59,000 pCi/L). Average subtrench tritium concentration increased from 28,000 to 100,000 pCi/L during the study period. Within the trench covers, there was a strong seasonal trend in tritium concentrations; the highest concentrations occurred in late summer when soil-moisture contents were at a minimum. Subtrench tritium movement occurred in association with the annual cycle of water movement, as well as independently of the cycle, in apparent response to continuous water movement through the subtrench sand deposits and to the deterioration of trench-waste containers.

The increase in concentrations of tritium with increasing distance from the trench bases in the sand unit indicates that water movement through the unit may be more pronounced than indicated by the pressure-head data. Localized, preferential flow paths may have gone undetected by the monitoring instruments used in the study.

INTRODUCTION

The Low-Level Radioactive-Waste Policy Act (Public Law 96-573--December 22, 1980) and the Low-Level Radioactive-Waste Policy Amendment Act of 1985 (Public Law 99--January 15, 1986) require that each State, by 1990, accept responsibility for disposal of low-level radioactive wastes produced within its borders. Most States have chosen to form compacts with neighboring States to develop regional disposal sites. New disposal sites must be designed to minimize the contact between water and buried wastes according to U.S. Nuclear Regulatory Commission guidelines in 10 CFR (Code of Federal Regulations) 61. The U.S. Geological Survey has been directed by Congress to conduct research useful to other governmental agencies that are responsible for establishing earth-science criteria for selection and development of the future disposal sites. The traditional method of solid, low-level radioactive-waste disposal has been shallow land burial above the water table. Most previous studies of radioactive-waste sites have addressed the role of the saturated zone (Fischer, 1983, p. 52); the focus of this study was the role of the unsaturated zone.

The movement of water and contaminants through the unsaturated zone only recently has received considerable attention. Segol (1982) simulated water movement through the unsaturated zone at two field sites but with few field data, a problem he notes and cites as being typical for such studies. Freeze and Banner (1970), Schneider and others (1987), and Dreiss and Anderson (1985) conducted field-scale studies of the role of the unsaturated zone in aquifer recharge. Trautwein and others (1983) studied seepage of liquid wastes from an evaporation pond. Schulin and others (1987) conducted tracer tests to evaluate solute transport through the unsaturated zone. Jury and others (1986) studied herbicide movement through unsaturated soil. Guirtzman and Magaritz (1986) used naturally occurring tritium to study unsaturated-zone water movement in an irrigated area.

Existing sites of low-level radioactive-waste disposal have provided the opportunity for specifically characterizing the geologic and hydrologic factors that control water and radionuclide movement through the unsaturated zone. Isaacson and others (1974) presented a thorough study of unsaturated-zone water movement at a site near Hanford, Washington. Johnson and others (1983) examined water movement through experimental disposal-trench covers at a location adjacent to the Sheffield site. Schulz (1984) studied unsaturated water movement through disposal-trench covers at a site near Maxey Flats, Kentucky. Deeper percolation through coarse-grained deposits at a site near Beatty, Nevada, was the subject of a study by Morgan and Fischer (1984). Gruber (1983) and Dennehy and McMahon (1989) looked at water movement and leachate migration between disposal trenches and the water table at two sites in South Carolina. Levin and Verhagen (1985) examined soil-moisture movement at a semiarid site in South Africa.

The above-mentioned studies of water and contaminant migration through the unsaturated zone differ from this study, undertaken between 1981 and 1985 at a low-level radioactive-waste disposal site near Sheffield, Bureau County, Illinois. They either did not look specifically at radionuclide migration, were limited to the soil zone, or were conducted at climatically and(or) geologically dissimilar sites. This study paid particular attention to water and tritiated-water movement (hereafter called tritium movement) through that portion of the unsaturated zone beneath the soil zone that contains the waste-disposal trenches.

This study was one part of a comprehensive study by the U.S. Geological Survey of water and radionuclide movement through the unsaturated zone at the Sheffield site. The other parts of this comprehensive study included analysis of runoff and landform modification (Gray, 1984, 1986; Gray and McGovern, 1986), water movement through disposal-trench covers (Healy, 1983, 1989; Healy and others, 1983), evapotranspiration and the microclimate of disposal-trench covers (Healy and others, 1989), hydrogeochemistry (Peters, 1985), and gaseous transport (Striegl and Ruhl, 1986; Striegl, 1988a, 1988b).

The U.S. Geological Survey began investigations at the site in 1976. Early studies characterized the ground-water hydrogeology within and adjacent to the site (Foster and Erickson, 1980; Foster and others, 1984; 1984a; 1984b). During the course of these studies, tritium concentrations above background levels were detected in ground water from several on- and off-site wells. In the study by Foster and Erickson (1980, p. 23), tritium-migration rates up to eight times greater than calculated ground-water-flow velocities were noted along a flow path south of one trench. These relatively high transport rates indicated that the unsaturated zone exerts an important influence in radionuclide movement at the Sheffield disposal site. Interest was focused on understanding the nature of water movement through the unsaturated zone because of its role in radionuclide movement (Siefken and Starmer, 1983, p. 7). Understanding the nature of water movement is essential to understanding the nature of tritium movement because tritiated water is funtionally equivalent to normal water in the hydrologic cycle (Thatcher, 1969, p. 155).

Purpose and Scope

This report characterizes water and tritium movement through the unsaturated zone in an area within the Sheffield disposal site. The report describes (1) the physical setting of the study area; (2) the physical and hydraulic properties of the unconsolidated geologic materials; (3) the timing, paths, quantity, and rate of water movement through the unsaturated zone; (4) the factors that influence unsaturated-zone water movement; (5) the spatial and temporal patterns of tritium concentrations within the unsaturated zone; and (6) the application of study-area results to the site as a whole.

Acknowledgments

The authors would like to thank the Illinois Department of Nuclear Safety for providing the opportunity to conduct research at the Sheffield site, supplying health-physics support during tunnel construction, and assisting in soil and water radiochemistry analyses. Additionally recognized are the University of Illinois Environmental Research Lab, the Illinois State Geological Survey, and the University of Illinois Department of Geology for providing soil-radiochemistry, soil-moisture retention, and soil-petrographic analyses. The U.S. Nuclear Regulatory Commission is acknowledged for providing funding support for tunnel construction, as is the site operator, US Ecology, Inc., for their cooperation throughout the duration of the research activities.

STUDY AREA

The physical setting of the study area is described in the following section of the report; brief comparative information regarding the radioactive-waste disposal site ("the site") as a whole also is presented. The reader is referred to Foster and Erickson (1980), Foster and others (1984; 1984a; 1984b), and Healy and others (1989) for more detailed descriptions of the physical setting of the site. The physical setting, including waste-disposal history and techniques and the climatic, geologic, and hydrologic settings, is described because a sound understanding of these features allows improved insight into the factors influencing subsurface water and tritium movement. The physical setting is described for the study area and the site to provide a basis for judging the application of the study-area results to the site as a whole and because there was a reliance, in part, on data collected outside the limits of the study area.

The site is located about 5 km (kilometers) southwest of Sheffield, Illinois (fig. 1), and is contained within 8.1 ha (hectares) of rolling terrain (fig. 2). The study was restricted to the southeast quadrant of the

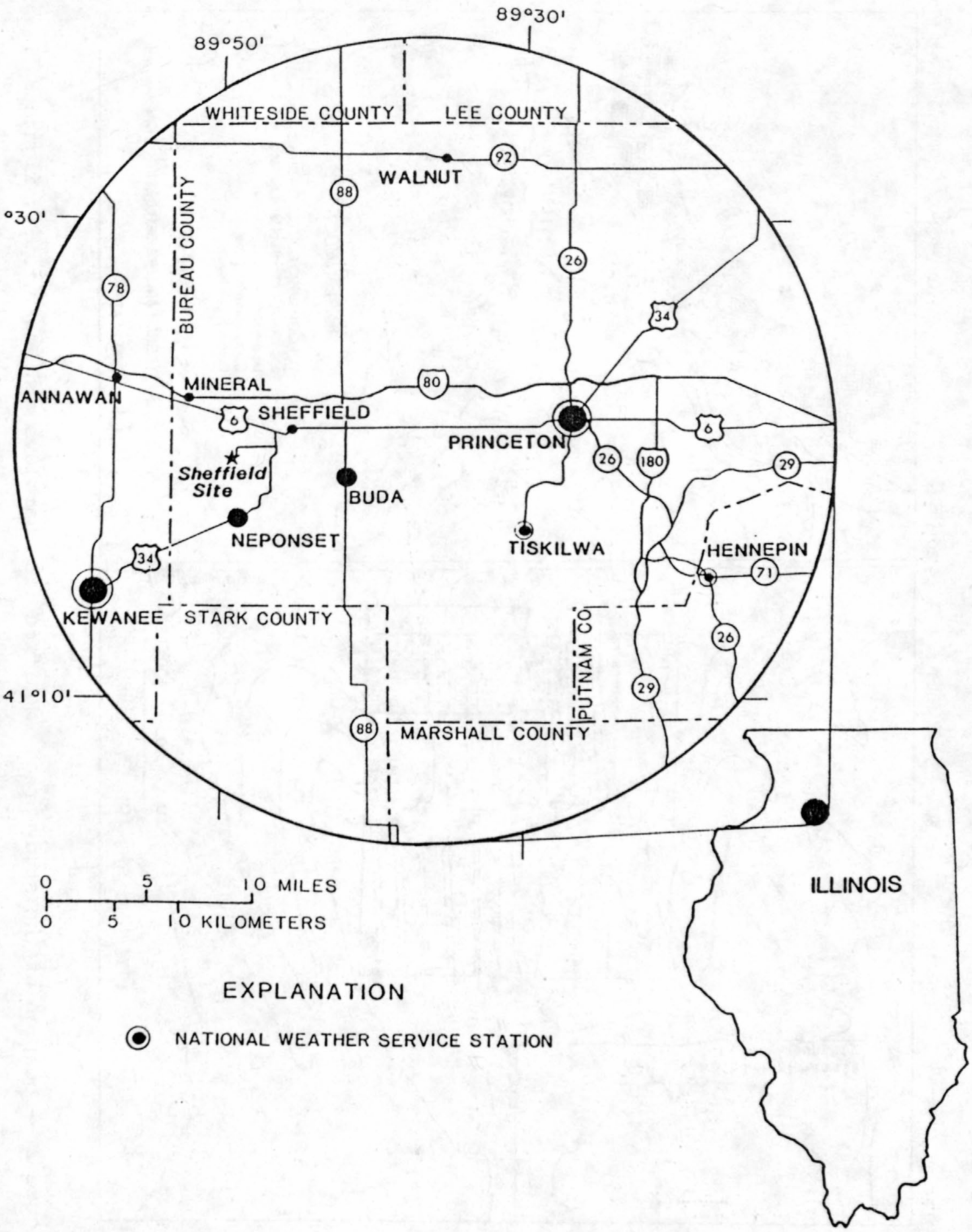


Figure 1.--Location of Sheffield low-level radioactive-waste disposal site and National Weather Service stations.

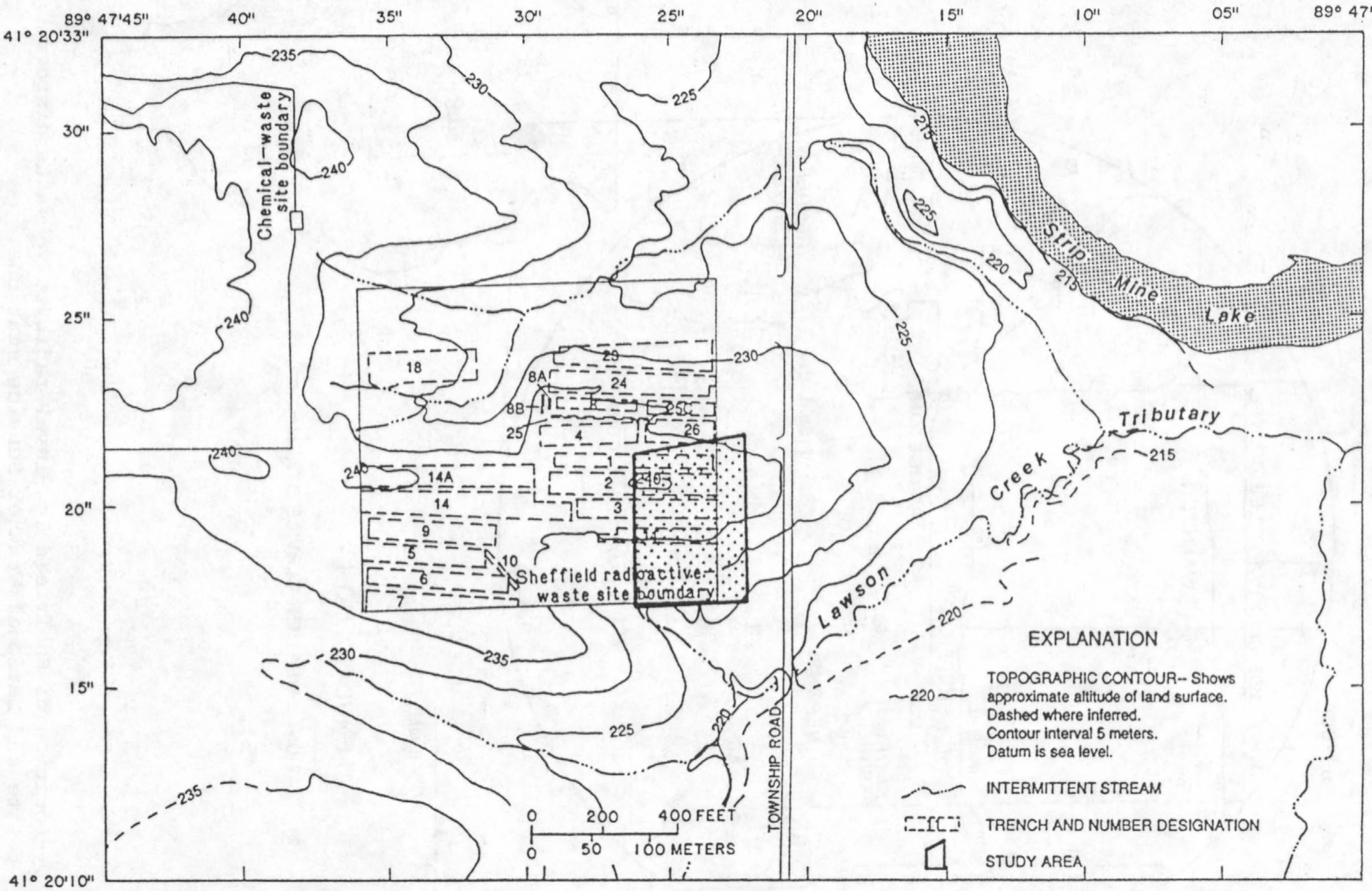


Figure 2.--Location of the study area. Modified from Garklavs and Healy, 1986, figure 3.

site (fig. 2). The study area is approximately bounded by well 502 to the northeast, well 512 to the southeast, well 524 to the southwest, and a weather station on trench 2 to the northwest (fig. 3). Section A-A''', through the eastern ends of disposal trenches 1, 2, 3, and 11 (fig. 3), was the focus of much of the study. Access to the region below the trenches was provided by a north-south trending horizontal tunnel (figs. 3 and 4).

Waste Disposal

The site was established in 1963 by authority of the Illinois Radioactive Waste Act; waste burial operations were conducted from 1967 to 1978. During this period, approximately 85,000 m^3 (cubic meters) of radioactive wastes, including 60,000 curies of byproduct material, 14 kg (kilograms) of plutonium-239, 1.7 g (grams) of uranium-233, 41 kg of uranium-235, and 271,000 kg of source material were disposed of in 21 burial trenches (Foster and others, 1984, p. 8). The site is managed by a private company and is under the regulatory responsibility of the Illinois Department of Nuclear Safety (IDNS). A chemical-waste disposal facility is located northwest of the site and is separated by a 60-m (meter)-wide buffer zone (fig. 2).

Trenches in the study area range from 107 to 137 m in length, 12 to 18 m in width, and 5 to 8 m in depth. Trench dimensions elsewhere range from 11 to 177 m in length, 2 to 21 m in width, and 2 to 8 m in depth. Trench construction was by a cut-and-fill process. After filling 19 trenches, burial locations that conformed to the IDNS regulations, limiting trench depth to maintain a minimum of 3.1 m between the trench base and the saturated zone, were exhausted. Two additional trenches (14 and 14a, outside the study area) were constructed using earth fill to build up the existing land surface and construct trench walls.

The standard trench has sloped walls and a lengthwise sloping floor (fig. 5). A 0.6-m by 0.6-m rock-filled French drain extending the length of the floor is designed to direct leachate to a sump at the low end of the trench. The sump is accessed for monitoring and removal of leachate by a sump pipe. Trenches are overlain by a mounded clayey-silt to silt fill cover, which may include a compacted layer consisting of silty clay to clayey silt. Loosely compacted fill material, primarily composed of silt, underlies the compacted layer and is intermixed with waste containers. Composite earth-fill materials were used in construction of trench covers and to raise land surface in low areas. Trench surfaces support a vegetative cover of brome grass, red clover, and alfalfa.

At trench 2, the compacted layer is composed of clayey silt and is approximately 0.3 m thick; the mounded clayey-silt cover is about 1.5 m thick at the crest and 0.5 m thick at the edge. The boundary between the compacted clayey-silt layer and the underlying trench-fill material is quite sharp, whereas the boundary between the compacted layer and the overlying mounded material is gradational.

Illinois statutes limited waste disposal to solids, immobilized or solidified liquids, and containerized gases at less than one atmosphere of pressure. Activities could not exceed 35 Ci/m^3 (curies per cubic meter).

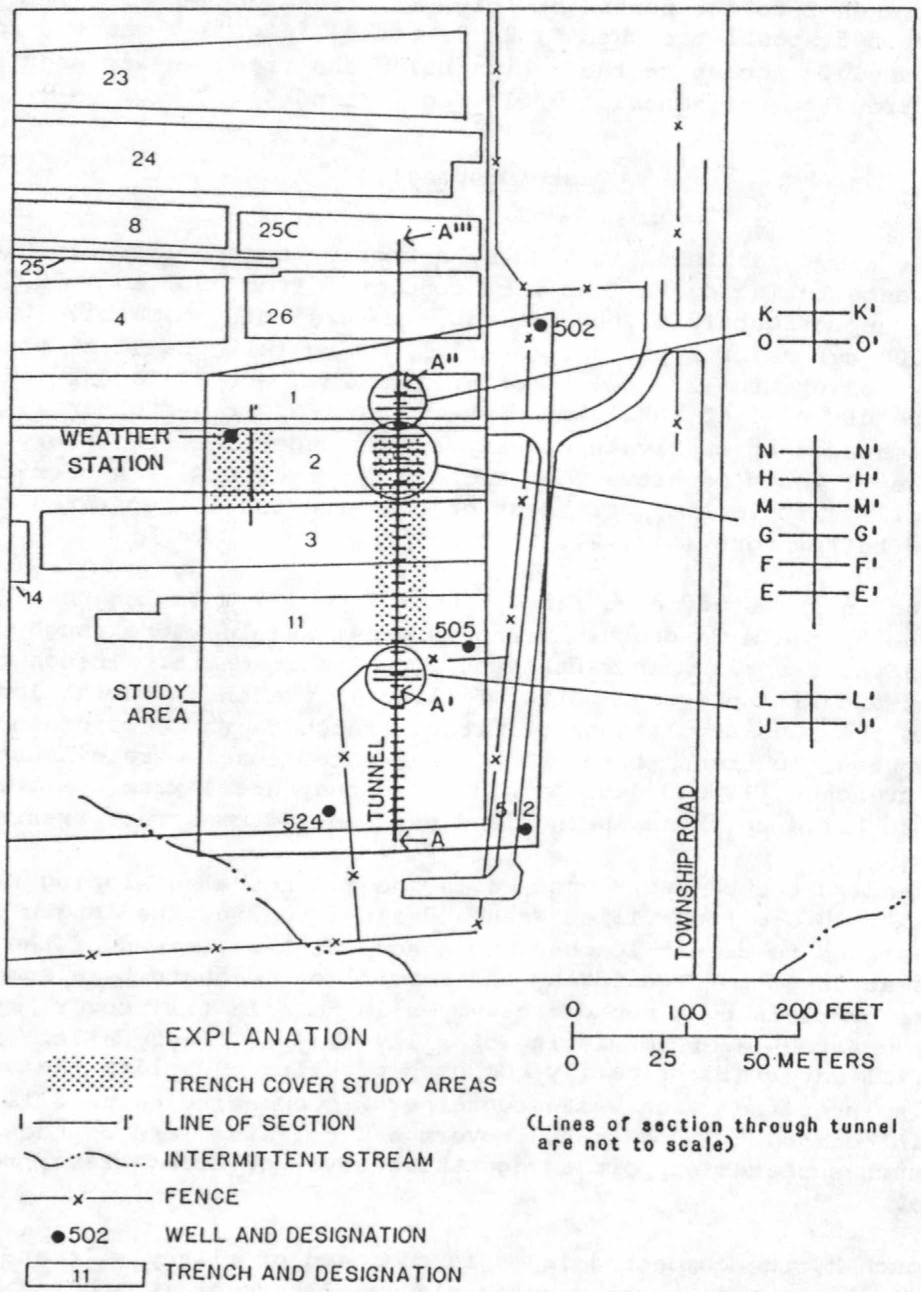


Figure 3.--Detail of the study area and location of geologic sections in the tunnel area and in the cover of trench 2.

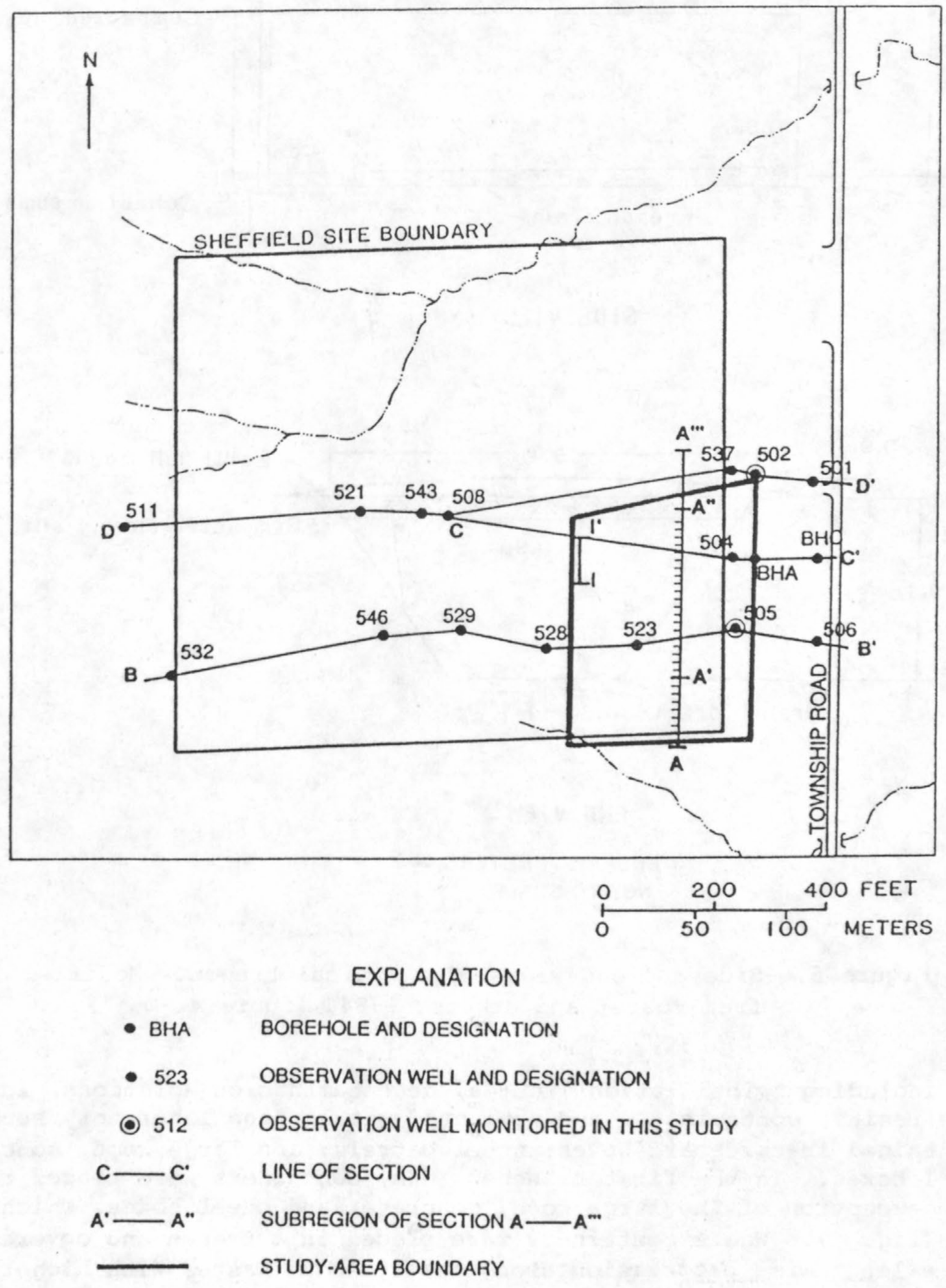


Figure 4.--Location of ground-water observation wells and geologic sections in the vicinity of the study area.

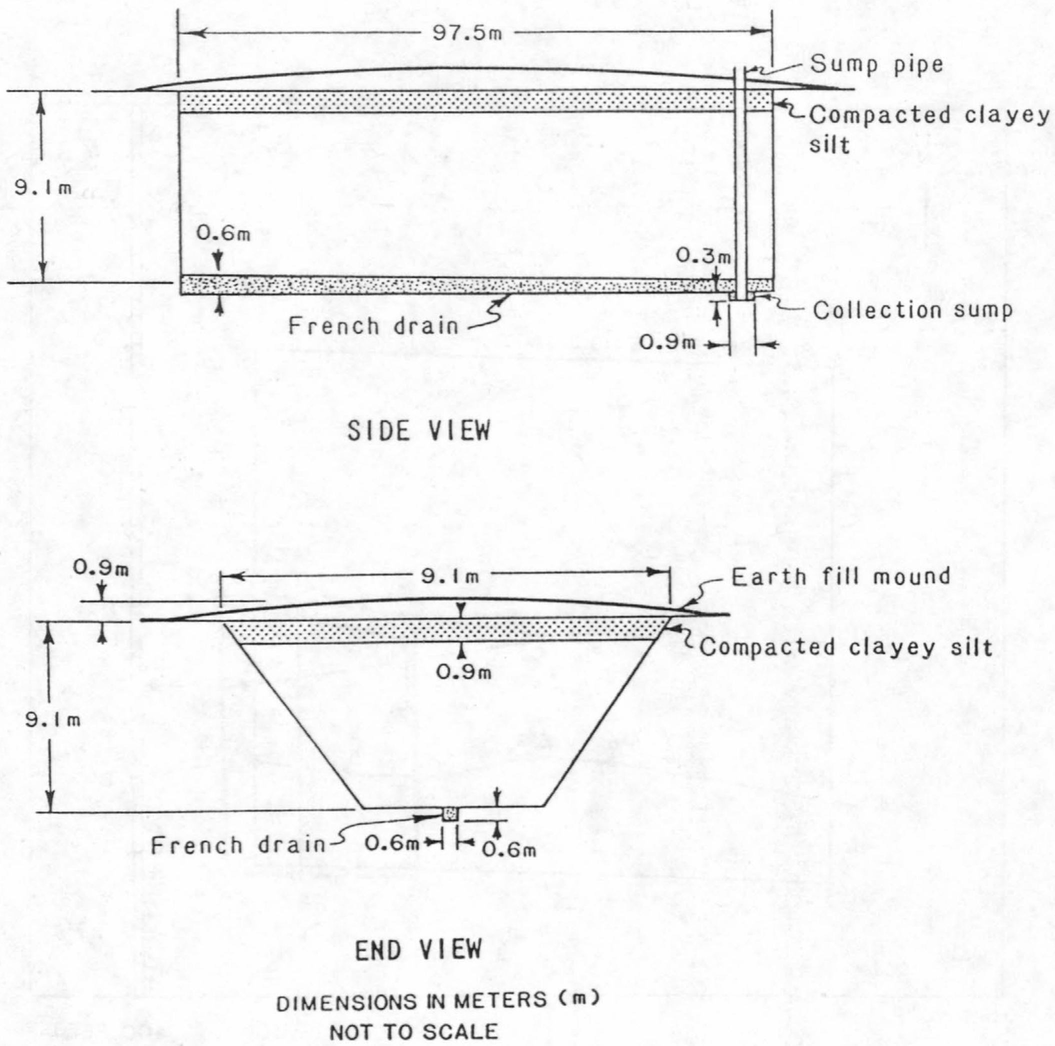
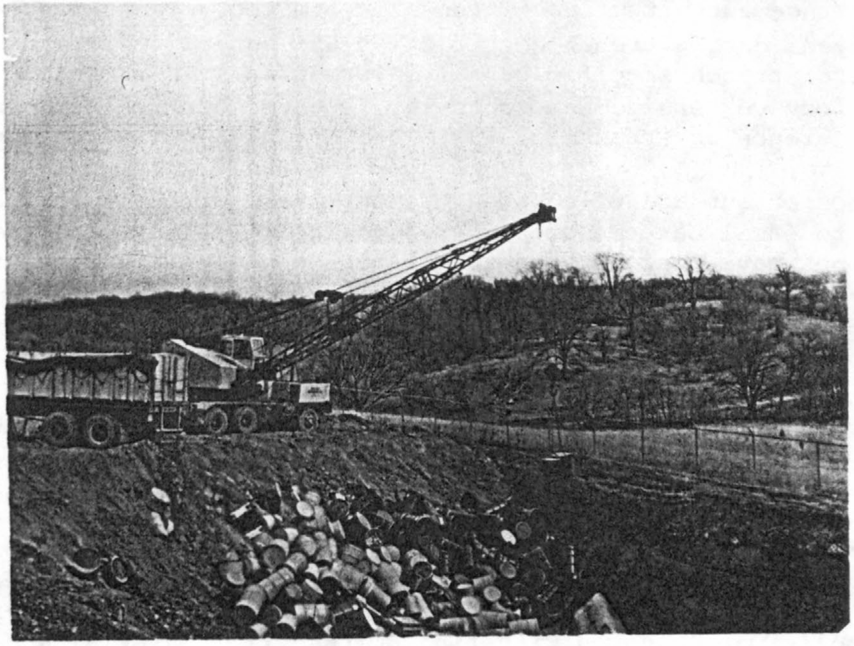


Figure 5.--Side and end views of a typical trench. Modified from Foster and others, 1984, figure 4.

Wastes, including scintillation liquids, decontamination solutions, ion-exchange resins, contaminated and activated metals, and laboratory supplies, were contained in cardboard boxes; steel barrels; and large wood, concrete, and steel boxes. In the first trenches, many containers were placed randomly, with the exception of the large wood, concrete, and steel boxes, which were stacked (fig. 6). Waste containers were placed in a trench and covered with soil in a lengthwise progression along the trench. Wastes with higher concentrations of radioactivity were located adjacent to the trench wall and covered immediately (Foster and others, 1984, p. 9).

Waste-burial records provided trench dimensions and a general inventory of radioactive wastes (Kahle and Rowlands, 1981). These records, however, were not detailed documents defining the exact trench contents. Information on types of radioactive wastes, activity levels, types of waste containers,



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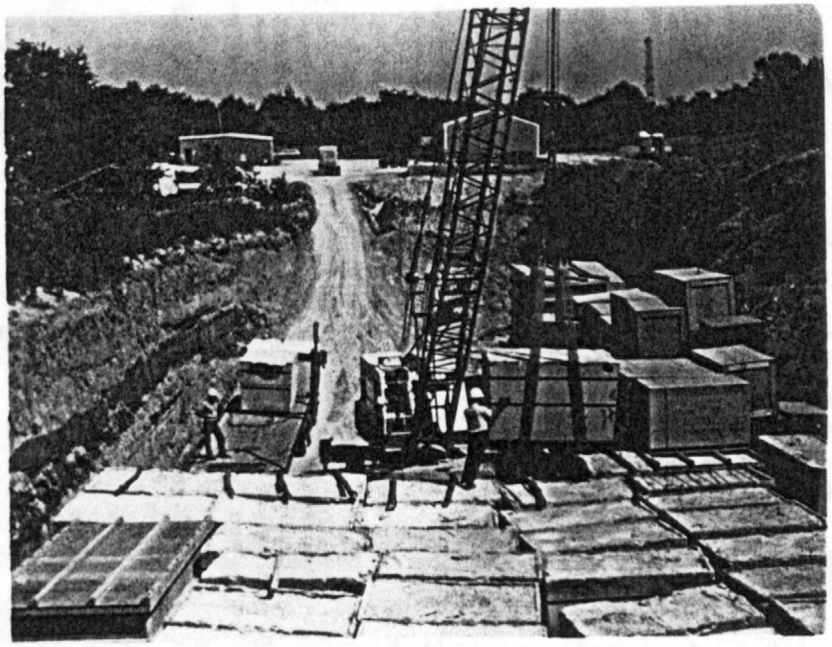


B

Figure 6.--Waste burial: 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 reproduced with permission of US Ecology, Inc.

and burial arrangement within each trench is limited. Photographs taken by company employees during trench construction and burial operations were a source of useful trench-specific burial information. Information that is available reflects extensive heterogeneity, both within and between trenches, as related to trench construction, waste content, and burial arrangement.

The contoured surface of mounded trench covers with intertrench swales was designed to facilitate runoff and reduce infiltration. In some cases, steepened slopes have concentrated runoff in the swales and accelerated trench-cover erosion (Heim and Machalinski, 1980, p. 7). Efforts to combat erosion have included application of supplemental earth fill and erosion mats, land-surface recontouring, and development of planned drainageways.

Collapse holes have developed in trench covers and in trench walls that were weakened by rain during construction. The site is inspected regularly for collapse holes (Kahle and Rowlands, 1981; A. Armbrust, US Ecology, Inc., written commun., 1984), and repair is within days of their occurrence. They are filled with silty-clay soil that is compacted by heavy earth-moving equipment. On isolated occasions, when the fine-grained fill material has been frozen, collapse holes have been filled with sand. Upon thawing, the sand-filled holes were covered with fine-grained fill material and compacted.

Climatic Setting

Details on climatic conditions are extremely important to the study of water movement through the unsaturated zone. Water enters the unsaturated zone from precipitation. Much of the infiltrating precipitation may eventually return to the atmosphere by the process of evapotranspiration. Knowledge of rates and timing of precipitation and evapotranspiration can provide insight into the rates and timing of water movement through the unsaturated zone. Healy and others (1989) conducted a detailed study of the microclimate and evapotranspiration rates at the study site for a 2-year period (July 1982 through June 1984), and Gray (1984, 1986) measured precipitation rates at the site for a 30-month period (July 1982 through December 1985). The reader is referred to those works for a full explanation of results and techniques; only a brief summary is presented here. In addition to the data presented in the above-mentioned studies, long-term (45 years) daily records of precipitation and temperature are available from the National Oceanic and Atmospheric Administration for the following National Weather Service (NWS) stations: Kewanee, 16 km southwest; Walnut, 31 km northeast; and Tiskilwa, 23 km south-east of the site (fig. 1) (U.S. Department of Commerce, 1939-84). Pan evaporation data are available from the Hennepin powerplant NWS station, located on the Illinois River near Hennepin, 39 km southeast of the site.

Long-term (1939-84) annual precipitation at the NWS stations averaged 890 mm (millimeters) having a minimum of 646 mm and a maximum of 1,330 mm. During the study period (1982-85), annual precipitation at the site averaged 871 mm; annual precipitation was 949 mm in 1982 (January through June record estimated from average of three above-listed NWS stations), 859 mm in 1983, 890 mm in 1984, and 785 mm in 1985. With the exception of 1985, annual precipitation at the site was close to the long-term mean at the NWS stations.

During 1982 through 1985, July was the wettest month, averaging 119 mm of precipitation, and January was the driest, averaging 18 mm. Most precipitation occurs during April through September, a period dominated by convective thunderstorms (Huff, 1979). Figure 7 shows long-term mean monthly precipitation at the NWS stations, as well as monthly precipitation measured at the site for the years 1982 through 1985. Although there is substantial variation over the period of study, two trends are exhibited: (1) There were no extended dry periods (although the spring and summer of 1985 were unusually dry), and (2) the majority of precipitation fell in the spring and summer. Average annual snowfall at the NWS stations was 850 mm, with snow on the ground for an average of 53 days a year. A snow gage was not maintained at the site.

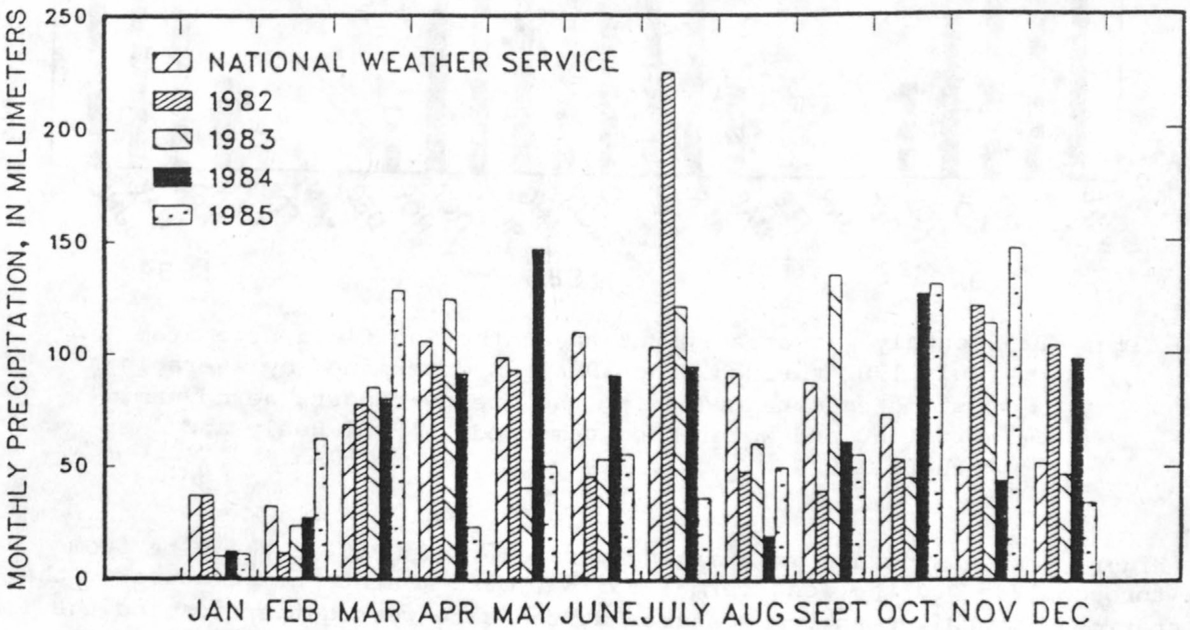


Figure 7.--Monthly precipitation at the Sheffield site (1982-85) and mean monthly precipitation at nearby National Weather Service stations (1929-84).

Next to precipitation, evapotranspiration is the largest component of the water budget in northwestern Illinois; Jones (1966, p. 12) estimated that evapotranspiration in northern Illinois was 635 to 760 mm/yr (millimeters per year). Healy and others (1989) determined mean annual evapotranspiration at the site by averaging estimates from the energy-budget, aerodynamic-profile, and water-budget methods. Their estimated evapotranspiration rate was 657 mm/yr for the apparently typical 2-year study period. This rate was equivalent to 70 percent of precipitation and 75 percent of potential evapotranspiration. Monthly evapotranspiration estimates for the study period are shown in figure 8. Evapotranspiration rates were highest in June and July and virtually zero during the winter months. In general, evapotranspiration exceeds precipitation only during May through August.

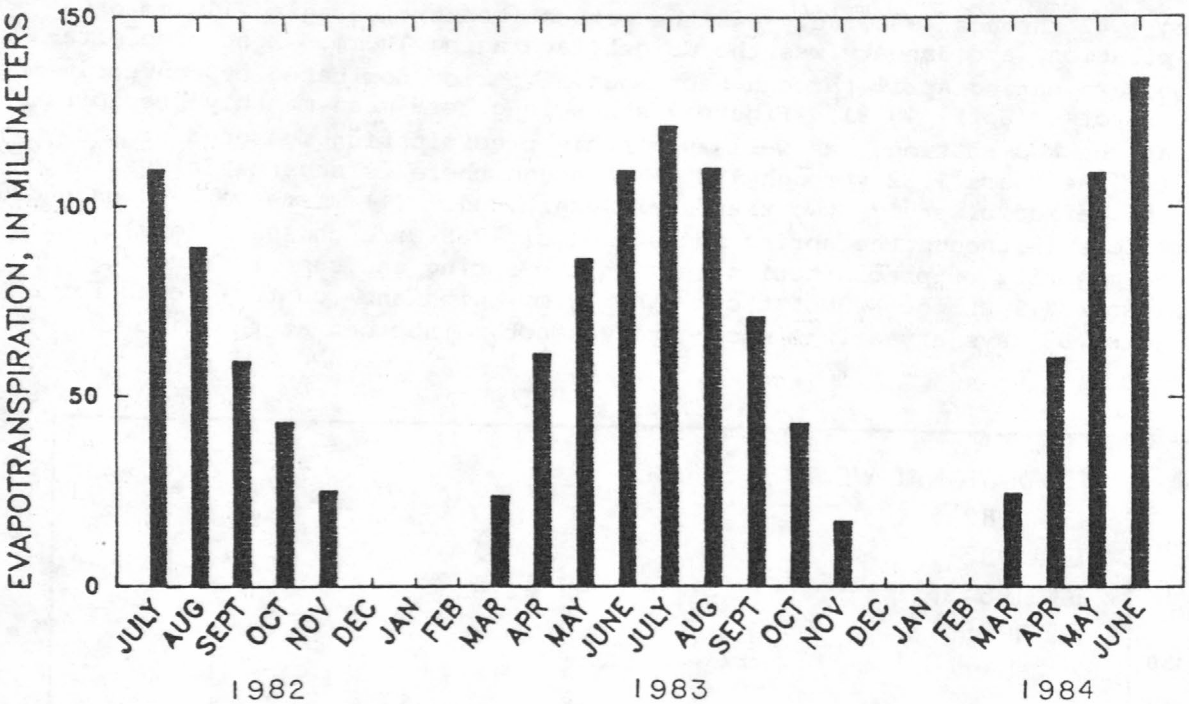


Figure 8.--Monthly evapotranspiration at the Sheffield site from July 1982 through June 1984, as determined by averaging estimates obtained using the energy-budget, aerodynamic-profile, and water-budget methods. From Healy and others, 1987.

Figure 9 shows monthly mean air temperature measured at the site from 1982 through 1985 and the long-term (1939-84) mean monthly temperature at the NWS stations; monthly mean temperatures at the site were quite close to the long-term means. The annual mean temperature at the site was 9.5 °C (degrees Celsius) in 1982, 10.9 °C in 1983, 9.2 °C in 1984, and 10.5 °C in 1985. The mean annual temperature at the NWS stations was 10.3 °C.

Soil temperature is important in analyzing infiltration because little or no infiltration is expected to occur when the ground is frozen. Daily mean soil temperature at a depth of 20 mm from August 1982 through June 1984 is shown in figure 10.

Geologic Setting

The site is located in the Galesburg Plain division of the Till Plains physiographic region. Unconsolidated Pleistocene glacial and eolian sediments, ranging in thickness from 3.0 to 27.4 m, and averaging 16.8 m in thickness, overlie approximately 140 m of Pennsylvanian shale, mudstone, and coal. The stratigraphic nomenclature used in this report is that of the Illinois State Geological Survey (ISGS) (Willman and Frye, 1970, p. 12) and does not necessarily follow the usage of the U.S. Geological Survey. Figure 11 shows the ISGS time-stratigraphic and rock-stratigraphic classifications.

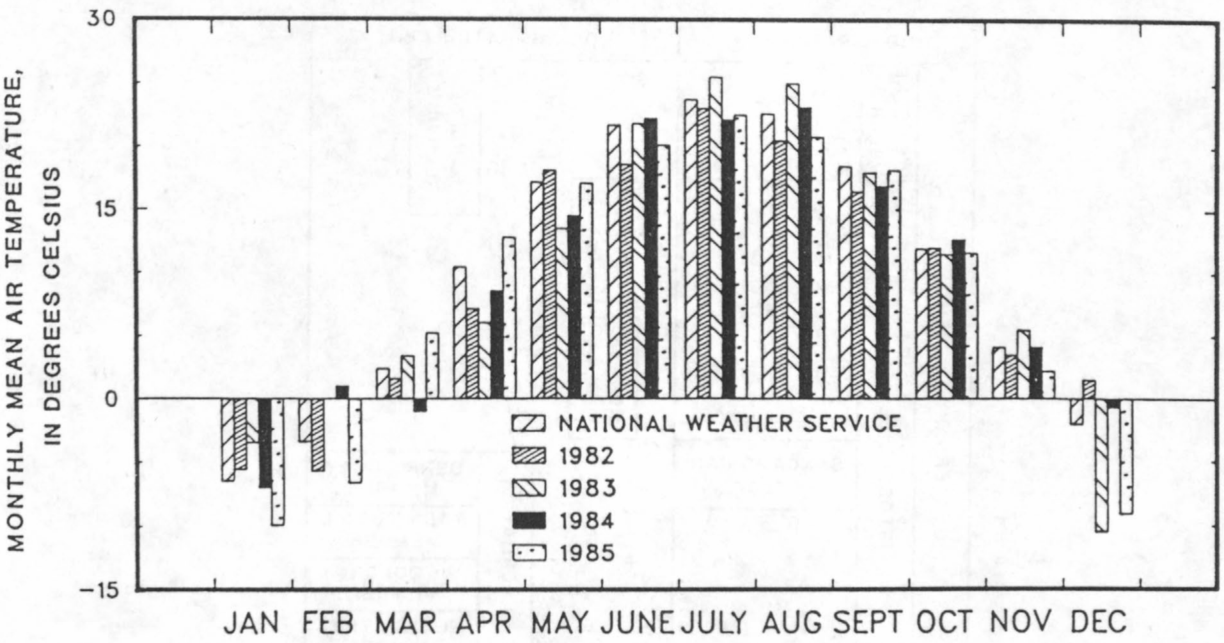


Figure 9.--Monthly mean air temperature at the Sheffield site (1982-85) and mean monthly temperature at nearby National Weather Service stations (1939-84).

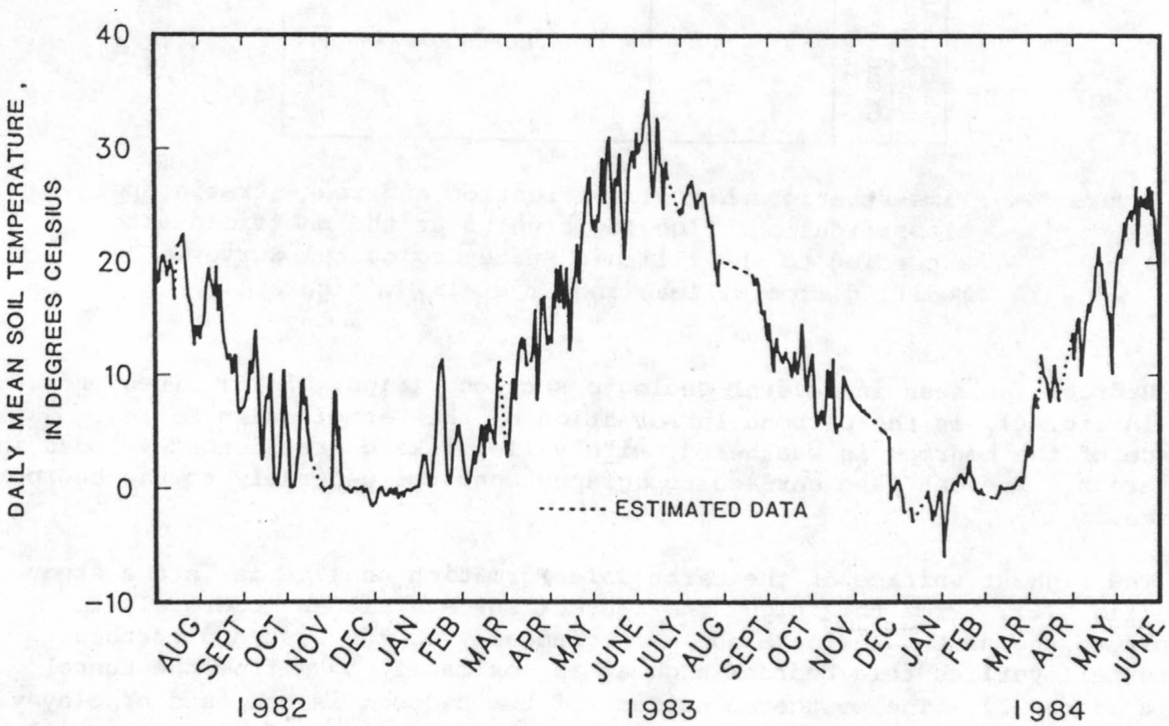


Figure 10.--Daily mean soil temperature at a depth of 20 millimeters from August 1982 through June 1984.

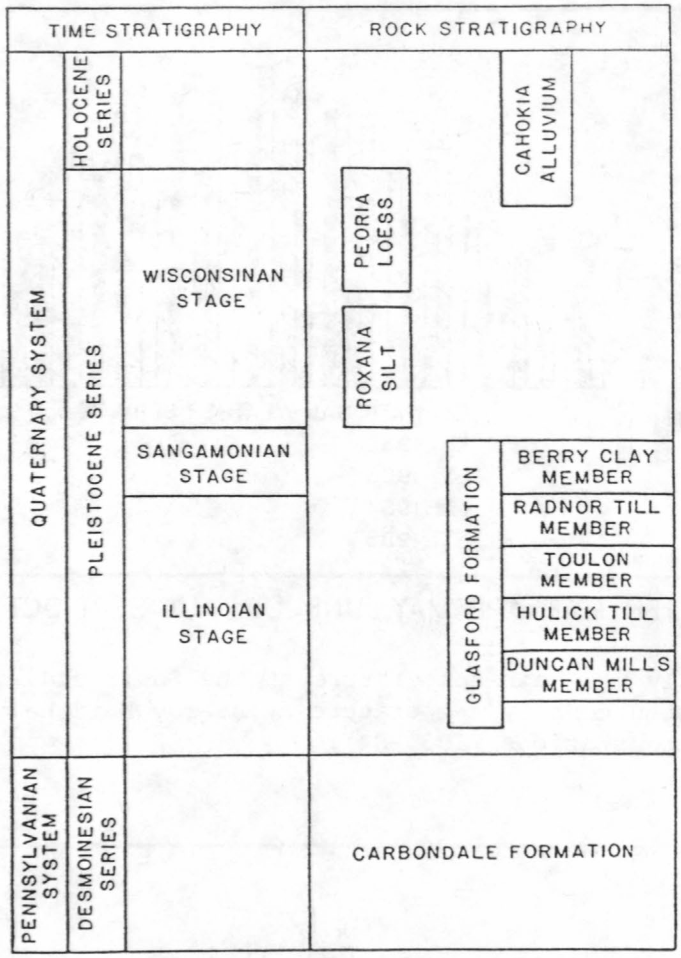


Figure 11.--Time-stratigraphic classification and rock-stratigraphic classification of geologic units at the Sheffield site according to the Illinois State Geological Survey. Modified from Willman and Frye, 1970, figure 1.

Bedrock, as seen in several geologic sections (figs. 12-15; lines of section in fig. 4), is the Carbondale Formation of the Desmoinesian Series. The surface of the bedrock is weathered, with valley-like depressions developed in some areas. Present land-surface topography conforms generally to the bedrock surface.

The highest surface of the Carbondale Formation on-site is in the study area (fig. 16). From this high, the bedrock surface slopes moderately to steeply to the north and south and more gradually to the east and northeast. The tunnel overlies this bedrock high at approximately 55 m from the tunnel origin (fig. 12). The weathered surface of the bedrock is composed of clayey silt from intermixed deposits of the Carbondale Formation and overlying till units. The weathered surface is intersected along the first 10.5 m of the tunnel floor. Core samples suggest that the weathered deposits in the tunnel section range in thickness from about 0.8 to 1.6 m.

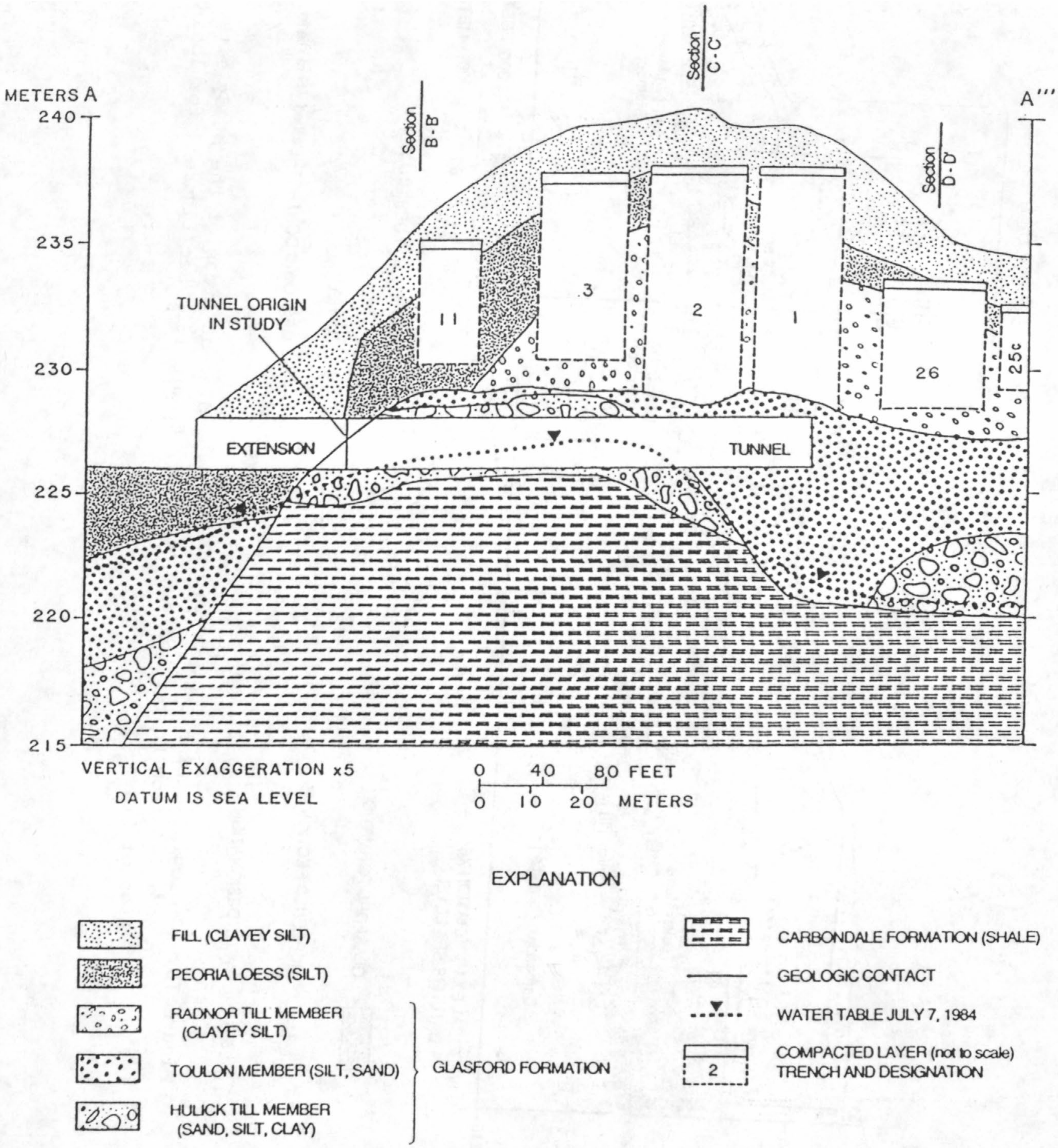


Figure 12.--Geologic section A-A''' of the tunnel and adjacent areas of the study site. Modified from Foster and others, 1984, figure 18. See figures 3 and 4 for location of lines of section.

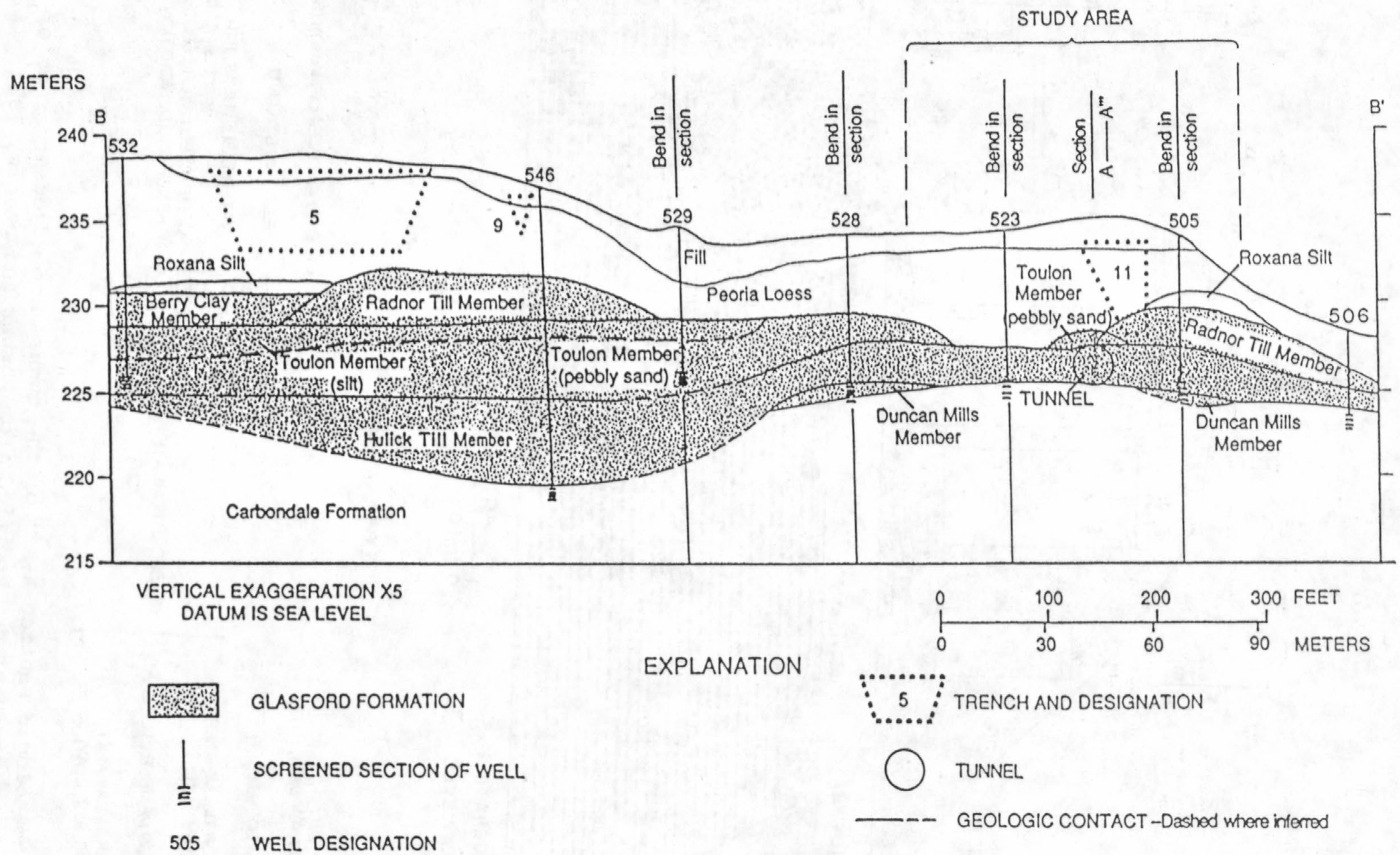


Figure 13.--Geologic section B-B' of the tunnel and adjacent areas of the study site. Modified from Foster and others, 1984, figure 16. See figure 4 for location of lines of section.

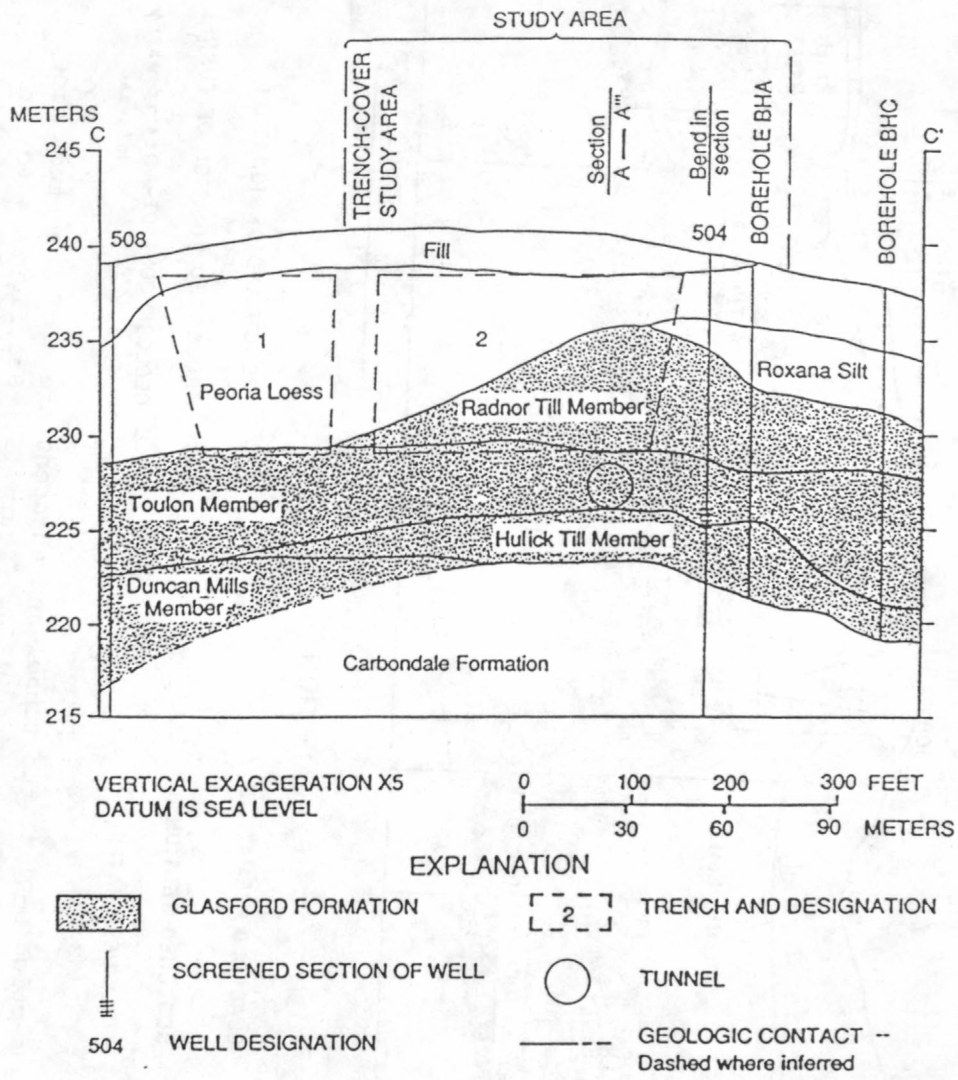


Figure 14.--Geologic section C-C' of the tunnel and adjacent areas of the study site. See figure 4 for location of lines of section.

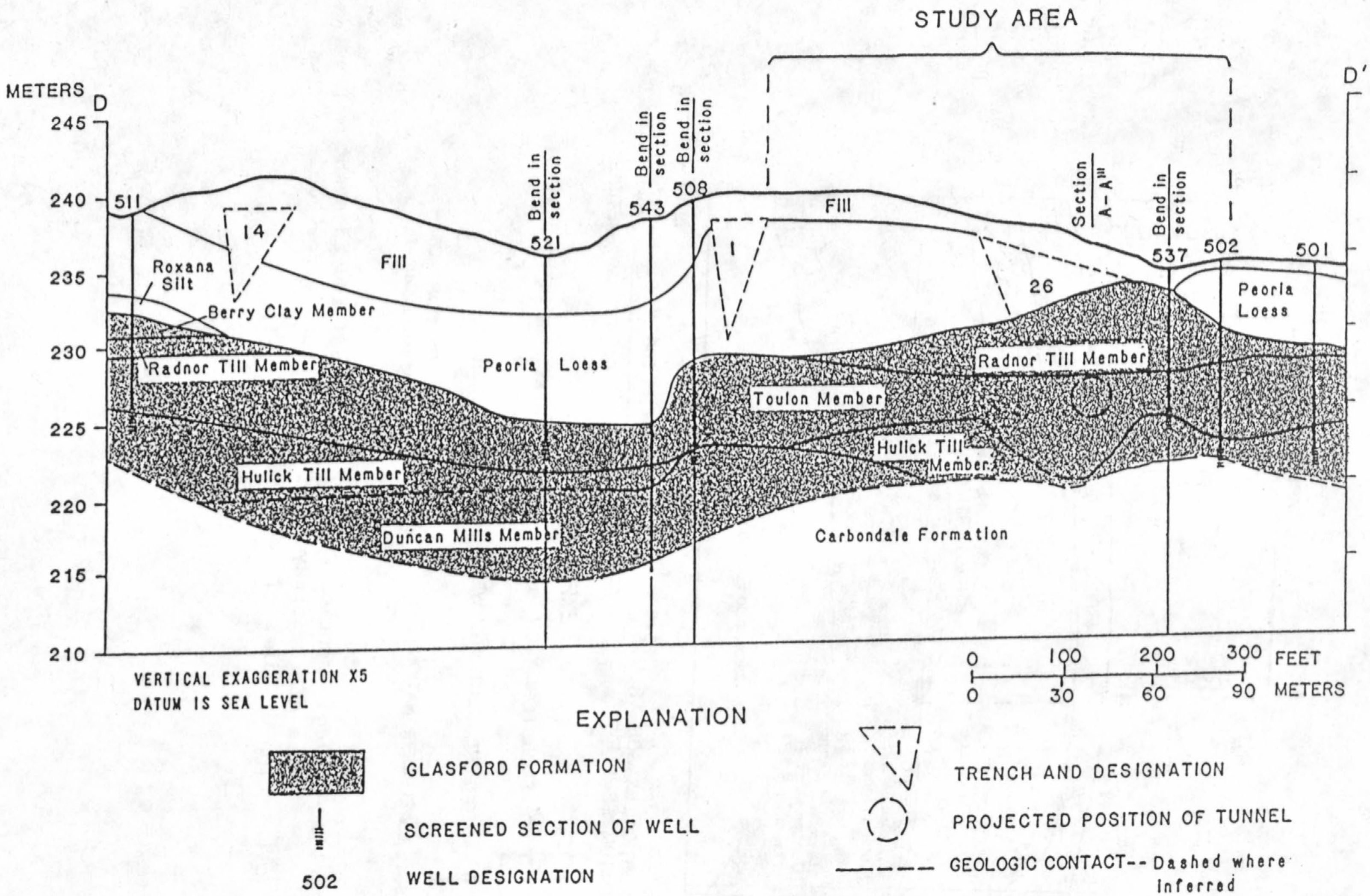


Figure 15.--Geologic section D-D' of the tunnel and adjacent areas of the study site. Modified from Foster and others, 1984, figure 15. See figure 4 for location of lines of section.

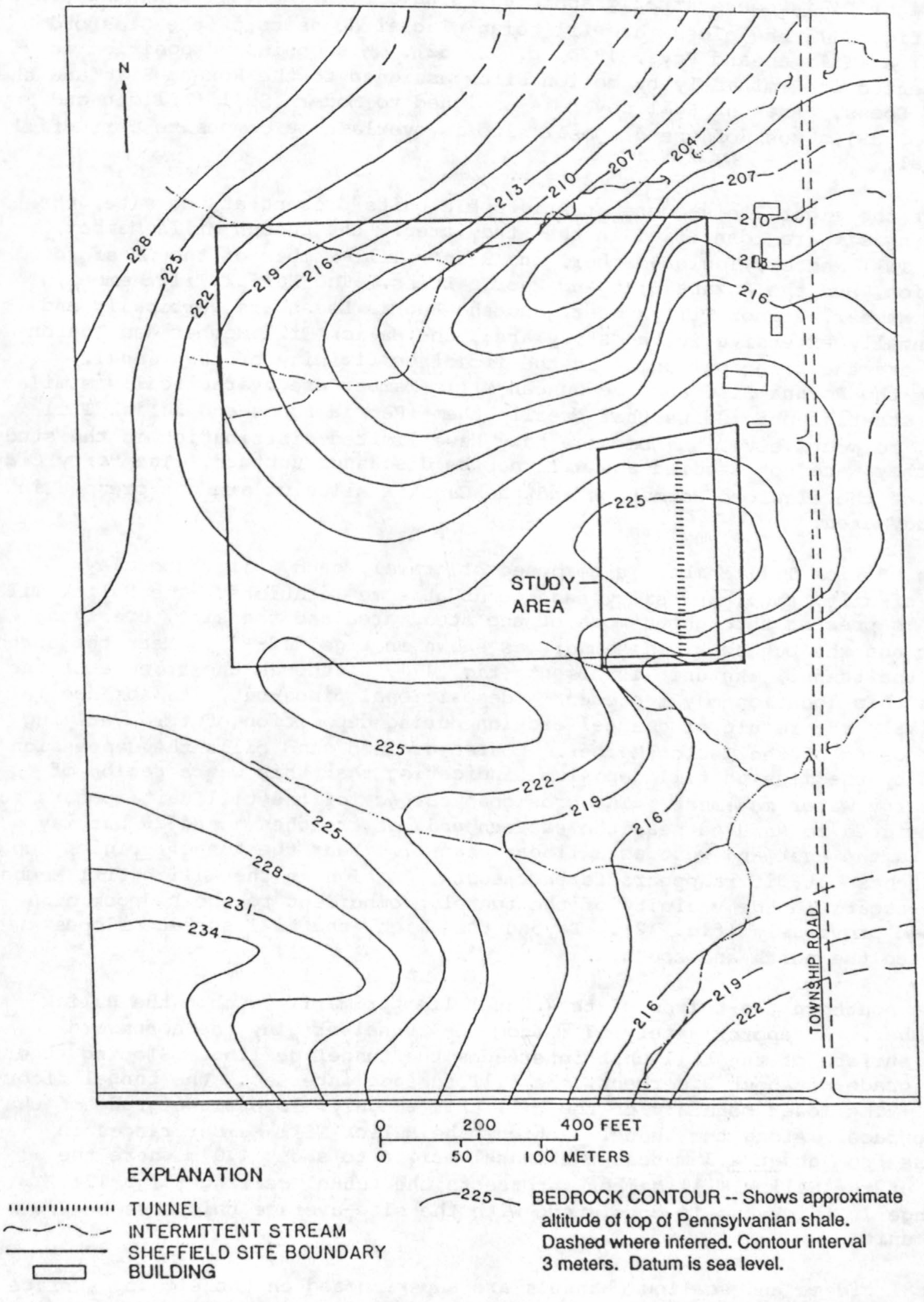


Figure 16.--Bedrock (Carbondale Formation) topography of the Sheffield site. Modified from Foster and others, 1984, figure 10.

Eight Pleistocene stratigraphic units have been identified at the disposal site (fig. 11); the oldest are Illinoian glacial deposits of the Glasford Formation (Willman and Frye, 1970, p. 12, 52). Wisconsinan deposition is represented predominantly by eolian silts assigned to the Roxana Silt and the Peoria Loess. Present soil cover is assigned to Modern Soil (Willman and Frye, 1970, p. 89). Most of the disposal site is overlain by composite earth-fill material.

Of the eight Pleistocene stratigraphic units present at the site, the following six are identified in the study area: the Duncan Mills Member, Hulick Till Member, Toulon Member, and Radnor Till Member of the Glasford Formation, and the Roxana Silt and Peoria Loess. The Hulick Till Member, Toulon Member, Radnor Till Member, and the Peoria Loess are vertically and horizontally extensive in the study area; the Hulick Till Member and Toulon Member are the principal units in the immediate vicinity of the tunnel. Because the Roxana Silt and the Duncan Mills Member are hydraulically similar to the stratigraphic units that overlie them (Peoria Loess and Hulick Till Member, respectively), and because they have limited distribution in the study area, they were not studied and will not be discussed further. The Berry Clay Member of the Glasford Formation and the Cahokia Alluvium are not present in the study area.

The Hulick Till Member is composed of gravel, sand, silt, and clay. Lenses of silt, sand, and silty sand occur at some locations. The Hulick Till Member is present throughout most of the study area and the site, overlying bedrock and the Duncan Mills Member (as shown in figs. 12-15). Near the north end of the tunnel, the unit is absent (fig. 17). Although the absence of the unit at this location may represent a depositional pinch-out, its absence is more likely the result of channel erosion during deposition of the overlying sand deposits of the Toulon Member. Coarse-grained sand fills the depression created by the missing till deposits, indicating that this was a region of high-energy water movement. The erosional surface of the till unit appears to be restricted to an area near the eastern ends of trenches 1 and 26 but may extend to the east and west as a linear channel. Near the tunnel origin, the unit pinches out; it reappears farther south. A high in the Hulick Till Member surface occurs in the vicinity of the tunnel, coincident to the bedrock high mentioned previously (fig. 12). Beyond this high, the till surface slopes steeply to the north and south.

The southern two-thirds of the tunnel lies primarily within the Hulick Till Member. At approximately 57 m from the tunnel origin, the northward sloping surface of the till unit intersects the tunnel ceiling. Sloping at a steeper grade of about 9 percent, the till surface intersects the tunnel floor at 67 m. The lower boundary of the till unit roughly mirrors the grade of the upper surface. Along the tunnel section, the Hulick Till Member ranges in thickness from about 2.3 m near the tunnel origin to about 4.0 m where the surface of the Hulick Till Member intersects the tunnel ceiling (fig. 12). This range in thickness is consistent with the site-average thickness of 2.0 m for the unit.

Local ridges and shallow channels are superimposed on the sloping surface of the Hulick Till Member in the tunnel area (fig. 18), suggesting a gently undulating surface. Local highs in the till surface flank the tunnel. At the

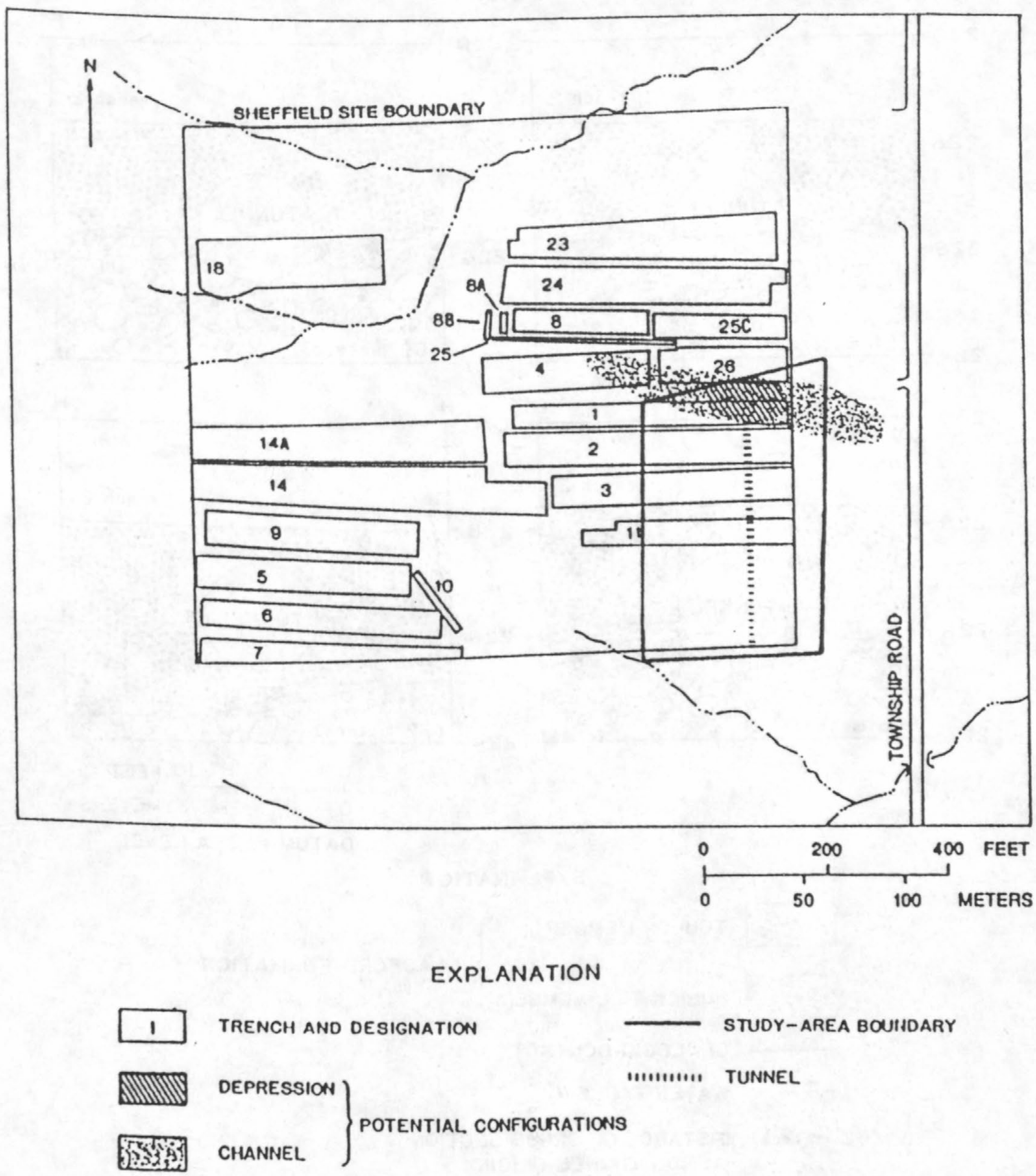


Figure 17.--Potential configurations of the region where the Toulon Member of the Glasford Formation directly overlies the Carbondale Formation.

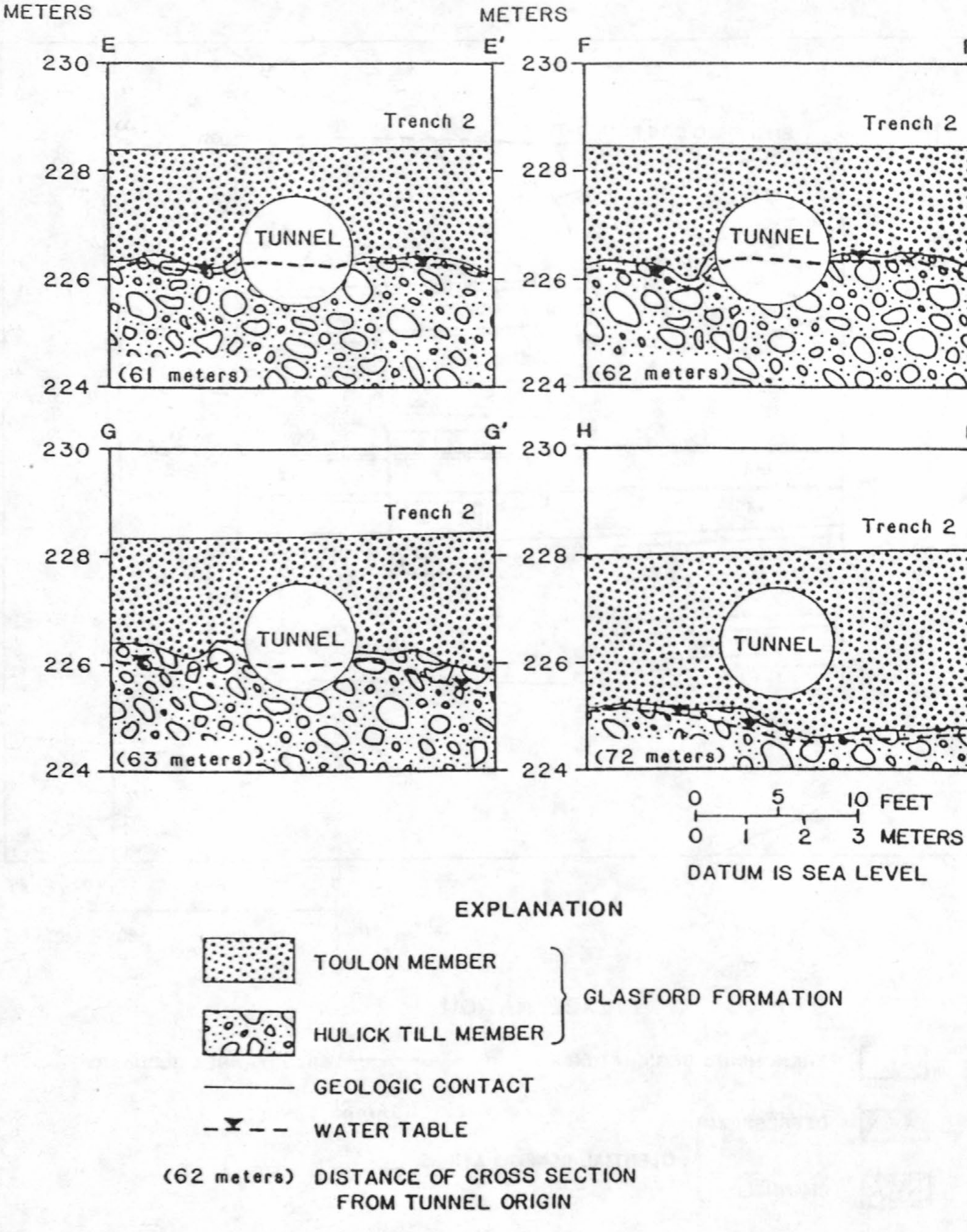


Figure 18.--Geologic sections E-E', F-F', G-G', and H-H' of the tunnel area. See figure 3 for location of lines of section.

topographic high in the till surface near mid-tunnel (fig. 12), the surface of the unit is about 0.5 m higher than surrounding till surfaces. About 23 m to the south, a secondary inflection of several centimeters creates a shallow depression. Beyond the depression, the till surface slopes gently southward toward the tunnel origin.

The Toulon Member occurs as two lithologic subunits: a channel-like outwash deposit composed of silty to pebbly sand and a lacustrine-like deposit composed of silt-clay. The Toulon Member is primarily restricted to the northern third of the study area (fig. 19), but it is represented in the south by a thin lens that is bisected by the tunnel trace. The tunnel-area deposits are primarily well-sorted, medium-grained sand; pebbly sand is present at the base of the unit near the north end of the tunnel. The silt content of the sand unit increases where the unit thins near the south end of the tunnel; the lacustrine-like unit replaces the sand unit south of the tunnel.

The Toulon Member, which overlies the Hulick Till Member throughout most of the site, overlies the Carbondale Formation near the north end of the tunnel. It is overlain by the Peoria Loess where the Radnor Till Member is absent (figs. 12-15). Within the northern 30 m of the tunnel, the Toulon Member sand reaches a maximum thickness of about 8 m, of which 1.5 to 2.4 m is the basal, coarse-grained facies; elsewhere on-site, the maximum thickness of the sand unit is about 6 m. Toward the south end of the tunnel, the unit thins to about 0.5 m thick, pinching out about 10 m north of the tunnel origin.

The Radnor Till Member is comprised of clayey silt and sand-silt-clay with a few sand and silt lenses and a basal gravel lens. The unit is distinguished in the study area by the basal gravel lens and a lower percentage of illite clay [42 percent compared to 75 percent elsewhere on-site (C. A. Peters, U.S. Geological Survey, written commun., 1985)]. The unit is present in the northeastern half of the study area (fig. 20); it occurs in the southern half of the site at two locations. The Radnor Till Member overlies the Toulon Member throughout its areal extent (figs. 12-15), except to the east of trench 11, where it overlies the Hulick Till Member. All but one trench in the study area (trench 11) penetrates the Radnor Till Member.

Where identified, the Radnor Till Member ranges in thickness from about 0.5 to 6.5 m. The northwest-southeast trending, dome-shaped deposit (figs. 12 and 20) reaches its maximum thickness near the eastern end of trench 3, approximately 25 m east of the trace of the underlying tunnel. The unit pinches out to the south, beneath trench 11, and extends eastward, westward, and northward from the tunnel area. The maximum slope of the till surface is to the southwest.

The Peoria Loess, a well-sorted silt, covers the entire site. All disposal trenches are constructed, at least partially, in this unit. In the tunnel area, the Peoria Loess deposit roughly parallels the contours of the underlying Radnor Till Member, thickening from about 1 m near trench 26c to about 4.5 m near trench 11 (fig. 12). Elsewhere on-site, the unit ranges in thickness from 0.3 to 9.1 m.

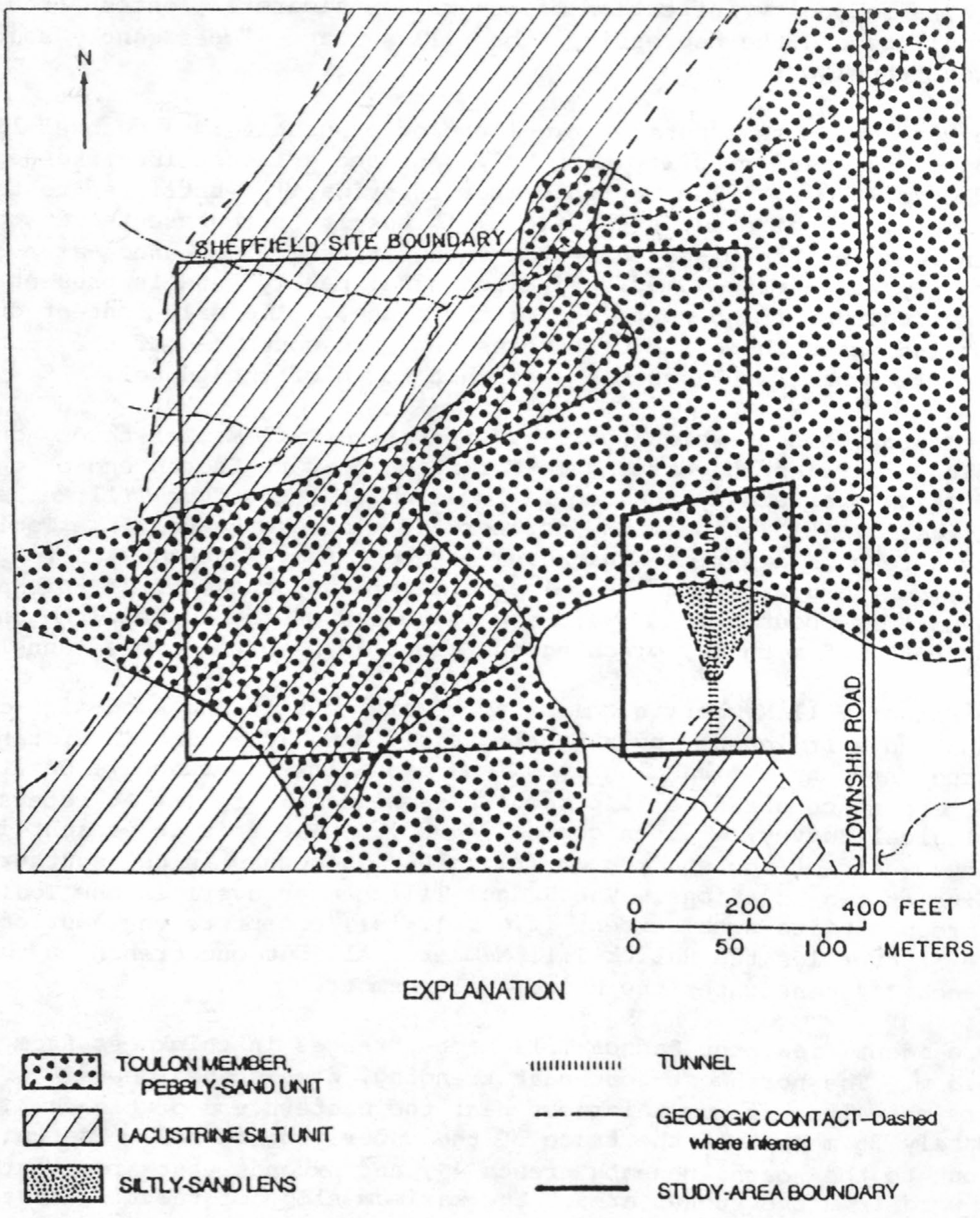


Figure 19.--Areal distribution of the Toulon Member of the Glasford Formation in the vicinity of the study area. Modified from Foster and others, 1984, figure 19.

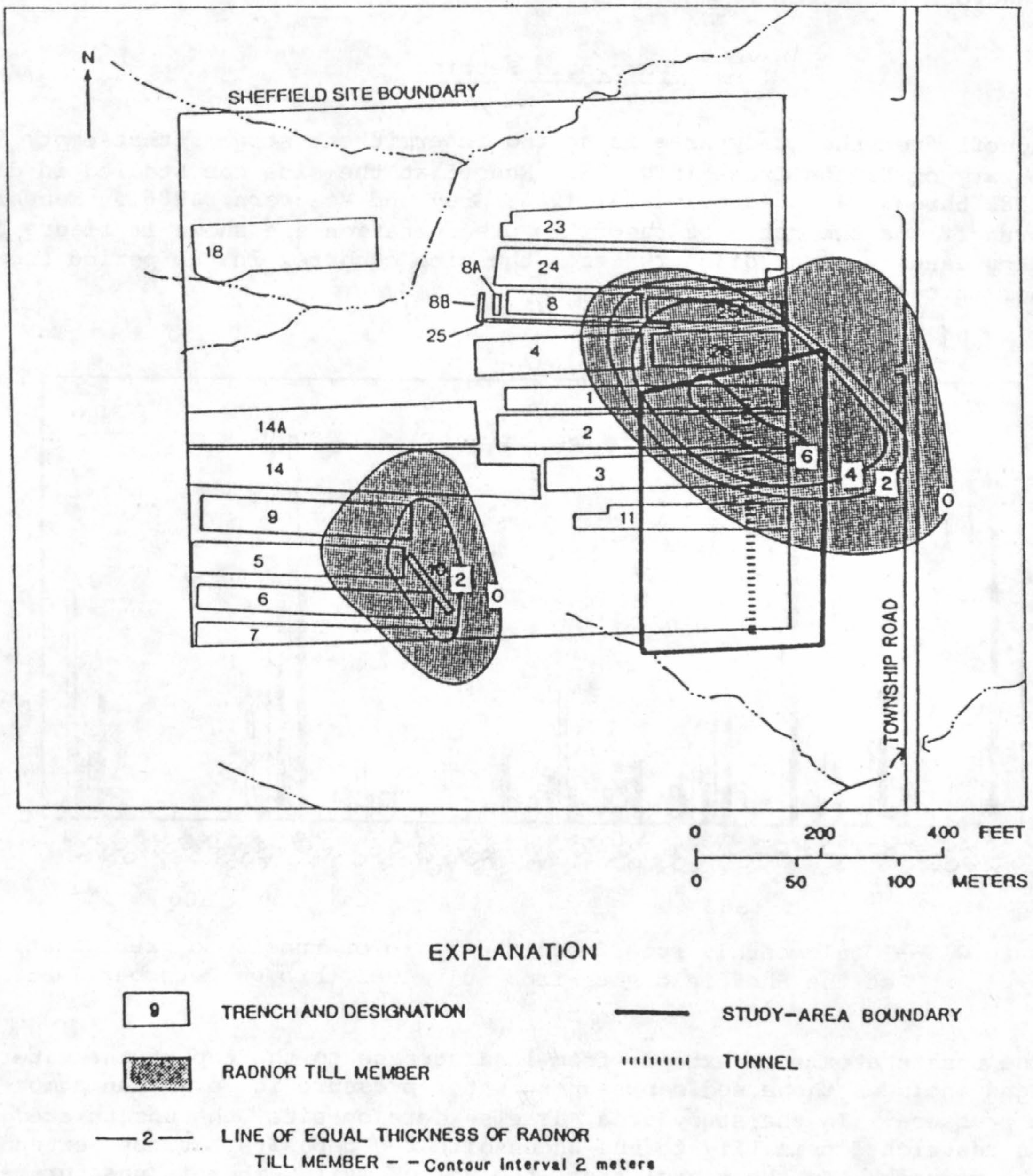


Figure 20.--Areal distribution and thickness of the Radnor Till Member of the Glasford Formation in the vicinity of the study area.

Earth-fill material, comprised of reworked loess, till, and shale deposits at the site, is clayey silt to silt. The fill material ranges in thickness from about 0.5 to 4 m in the study area and up to 7 m (Foster and others, 1984, p. 15) across the site.

Hydrologic Setting

Runoff from the study area is to two intermittent streams that empty into a tributary of Lawson Creek (fig. 2). Runoff at the site was studied in detail from 1982 through 1985 (Gray, 1984, 1986; Gray and McGovern, 1986). Monthly total runoff and the ratio of runoff to precipitation are shown in figure 21. Excluding January, most discharge from the site occurred in the period from November through April.

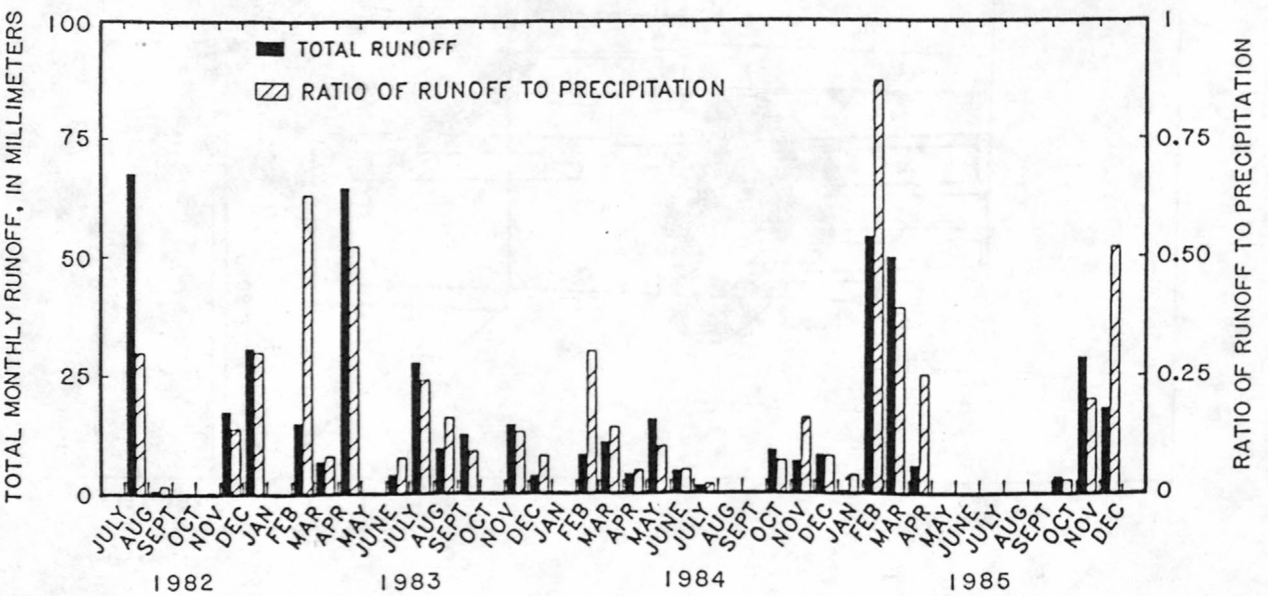


Figure 21.--Total monthly runoff and the ratio of runoff to precipitation at the Sheffield site from July 1982 through December 1985.

The unsaturated zone extends from land surface to the top of the water table and includes those sediments where water pressure is less than atmospheric pressure. In the study area, as elsewhere on-site, the unsaturated zone is restricted primarily to the unconsolidated deposits but does extend into the bedrock. In the tunnel area, the Hulick Till Member is unsaturated through about half of its thickness (fig. 12). The Toulon Member is unsaturated through most of its thickness; the water table does extend into the base of the unit at the north end of the tunnel. The unsaturated zone ranged in thickness from about 7 m near the south end of the tunnel to about 18.4 m at the north end of the tunnel. Across the site, the unsaturated zone ranges in thickness from about 1.5 m in the valleys to about 18.4 m on the hilltops (Foster and others, 1984, p. 15).

The saturated zone lies below the water table and includes the geologic deposits where water pressure is greater than atmospheric pressure. The saturated zone includes most of the bedrock, much of the Hulick Till Member, and the Toulon Member in isolated locations. To the north of the study area, the saturated zone extends into the Toulon Member and the Peoria Loess in many locations. The shallow, unconfined ground-water system in the unconsolidated deposits is isolated from confined, regional aquifer systems by the thick, low permeability bedrock (Foster and others, 1984, p. 15). Saturated-zone thickness in the unconsolidated deposits in the tunnel area ranged up to about 1.5 m (fig. 12); elsewhere on-site, thickness ranges from about 1.5 m (beneath the valleys) to 11 m (beneath the hilltops) and averages 6.2 m.

The highly permeable Toulon Member, typically unsaturated in the study area, is partially to completely saturated across about 80 percent of its areal extent (Garklavs and Healy, 1986, p. 16) and is the primary unit in which ground water flows at the site. The underlying Hulick Till Member functions as a semipermeable layer that restricts ground-water flow. A ground-water divide generally coincides with the elevated disposal-trench area that extends through the study area (figs. 2 and 22). Ground water flows northward and southward from the divide. Ultimately, about 70 percent of the ground-water flow beneath the site is to the northeast through the sand unit of the Toulon Member (Garklavs and Healy, 1986, p. 33); the remainder is to the southeast, through fine-grained deposits. Elevated tritium concentrations in several wells [well 602, for example (fig. 4)] beyond the southeastern boundary of the site indicate an additional path of ground-water movement (Garklavs and Healy, 1986, p. 18-19). In this region, wells are screened in the Hulick Till Member; the overlying sand unit of the Toulon Member is unsaturated. The mechanism for the apparently rapid movement of ground water through the low permeability till unit is not presently understood.

Ground-water-flow boundaries at the site, representing an area of approximately 35 ha, are a strip-mine lake to the east, Lawson Creek tributary to the south, strip-mine spoils to the north, and a bedrock high west of the site (features shown, in part, in fig. 22). The northern and western boundaries act as ground-water divides. Because of these boundaries, virtually all water in the saturated zone is derived from local precipitation. Ground-water discharge is primarily to the strip-mine lake. A slight amount of ground-water discharge occurs through transpiration by isolated trees and bushes.

Water-table altitudes in observation wells ranged from 222.4 m (well 502, near the hilltop north of trench 2) to 225.8 m (well 524, in the southern valley) (figs. 2 and 3). Water-table fluctuations ranged from 1.0 m (well 502) to 3.9 m (well 512). Excessive precipitation in July 1985 accounted for more pronounced water-level fluctuations in 1985 than in 1981-84, even though annual precipitation in 1985 was less than annual precipitation in each of the 4 previous years. Excluding 1985, the maximum water-table altitude at well 524 was 223.7 m and water-level fluctuations ranged from 0.6 m at well 502 to 1.4 m at well 524. In comparison, water-level measurements at site wells from 1976 to 1979 indicated that water-table altitudes ranged from 215.7 m (east of trench 18) to 228.8 m (west of trench 14a) (fig. 2); average fluctuations were 0.8 m in hilltop wells, 1.1 m in side-hill wells, and 1.8 m in valley wells (Foster and others, 1984, p. 21). The water-table altitudes, which conform in part to

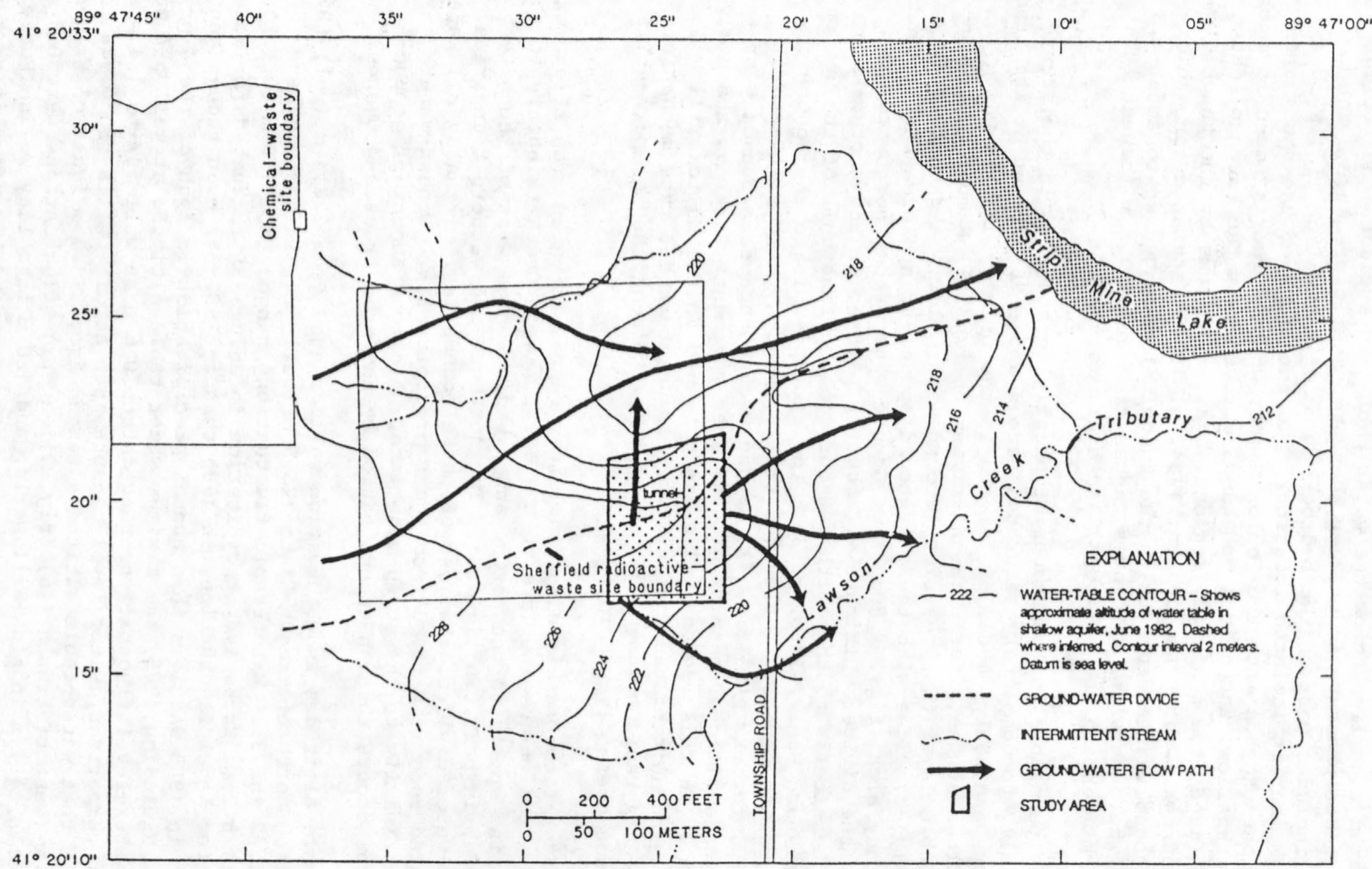


Figure 22.--Configuration of water table and principal flow paths at the Sheffield site. Modified from Garklavs and Healy, 1986, figure 10.

the surficial topography (Foster and others, 1984, p. 19), are influenced by the composition and stratigraphy of the unconsolidated geologic deposits. Water-level fluctuations occur in response to recharge to the saturated zone. The range of water-level fluctuations is dependent on surface topography and the lithology of the screened section of the well; water-level fluctuations are dampened most in wells penetrating hills and screened in the sand deposits of the Toulon Member (Foster and others, 1984, p. 21).

Mobilization of radionuclides depends, in part, on the amount of water available for infiltration. Foster and others (1984, p. 20) estimated ground-water recharge at the site to be between 25 and 50 mm a year. On the basis of ground-water-flow modeling, Garklavs and Healy (1986, p. 26) estimated annual recharge to be between 10 and 150 mm.

Ground water in the vicinity of the study area is a calcium magnesium bicarbonate type. With the exception of elevated concentrations of sulfate, iron, and sodium, the concentrations of inorganic constituents in ground water are very similar to those of surface water (Foster and others, 1984, p. 30). The inorganic chemistry of soil water in the unsaturated zone is similar to that of ground water, and, except for tritium and dissolved organic carbon, there is little change in water chemistry with respect to depth and distance from trenches (C. A. Peters, U.S. Geological Survey, oral commun., 1985).

METHODS OF STUDY

Approach

Analysis of unsaturated flow requires characterization of at least three hydrologic components: (1) surface infiltration (movement of precipitation of water into the subsurface); (2) unsaturated-zone percolation (movement of water through the unsaturated subsurface); and (3) unsaturated-zone/saturated-zone interaction (movement of water from one zone to the other). Physical and hydraulic properties of the unconsolidated geologic materials were determined. Stratigraphic units were identified on the basis of the physical properties of the geologic materials. Instruments were installed in and between several trench covers for analysis of surface infiltration and percolation during and following precipitation events. The unique use of the tunnel provided access to unsaturated-zone deposits immediately below the trenches (an area often overlooked in hydrologic investigations because of the difficulty of installing instruments in the region) for analysis of percolation through deeper unsaturated-zone deposits and unsaturated-zone/saturated-zone interaction. Full evaluation of each of the components of unsaturated flow was complicated at the Sheffield site by inadequate records of trench construction and waste burial, the extensive variability of the site geology, and restrictions that prevented instrumentation of disposal-trench interiors.

Pressure head and soil-moisture content were measured to determine hydraulic gradients and rates and directions of water movement. Water samples from the unsaturated and saturated zones were obtained at various distances from the disposal trenches to detect chemical changes and rates of constituent movement. Water-table altitudes were monitored to analyze recharge and ground-water-flow patterns.

Other studies at the site provided water-budget data for estimation of recharge to the trenches. A computer model was used to simulate water movement in the vicinity of the tunnel. Data were collected from July 1981 through December 1985. The data-collection network was fully operational from July 1982 through June 1984.

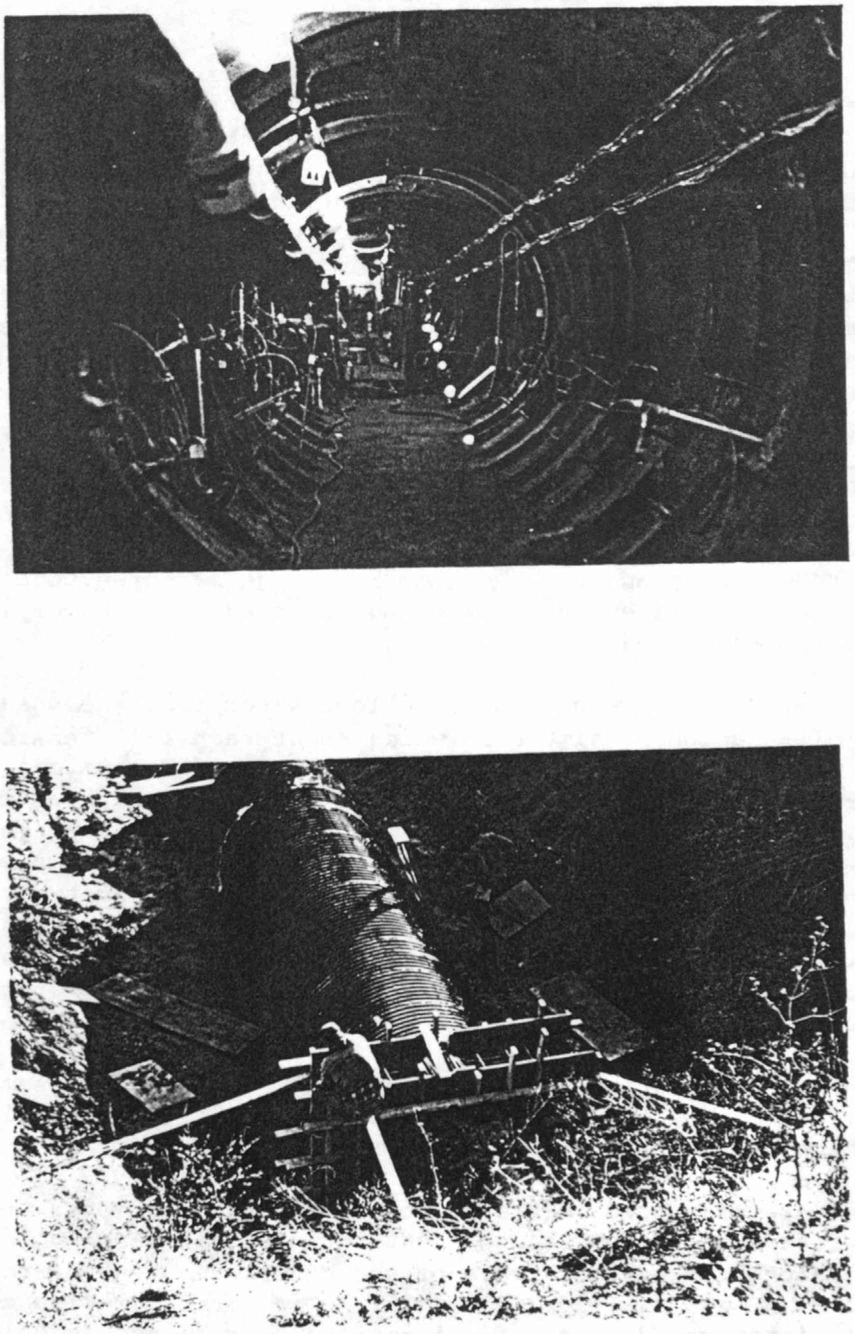
Tunnel

Construction of the 120-m-long by 2-m-diameter tunnel (figs. 3 and 12) began in November 1978 and was completed in March 1979; construction was undertaken in two phases. In the initial phase, sediment cover in a hillside south of trench 11 was removed to accomodate construction. A 90-m-long tunnel section was dug northward into the exposed hillface (fig. 12) and was lined with bolted rings of steel plates (fig. 23). In the second phase, a 30-m-long tunnel extension of ribbed steel culvert pipe was installed in the excavated tract south of the 90-m-long section and was covered with earth material (figs. 12 and 23) so that the original topography of the hillside was retained as much as possible.

The floor of the tunnel is at an altitude of approximately 226 m above sea level. Although generally horizontal, the tunnel has minor undulations along its length; maximum vertical undulation is about 0.5 m. The south end of the steel-plate-lined section (about 15 m south of trench 11) is approximately 4.8 m below land surface. The tunnel is about 12.0 m below land surface near its northern end. Prior to tunnel construction, a minimum clearance of 1.7 m between the tunnel ceiling and the floor of trench 11 was anticipated; an even thicker sediment buffer was anticipated below trenches 1, 2, and 3. Lithologic sampling and instrument implacement during the course of the study indicate that anticipated clearances beneath trenches 11 and 3 were valid; however, clearances beneath trenches 1 and 2 were as little as 0.6 m.

A concerted effort was made to isolate the tunnel completely from the local hydrogeologic environment. The annulus between the tunnel lining and the surrounding sediments was grouted to eliminate soil-water (in this report, soil water and soil moisture refer to pore water distributed throughout the unsaturated zone) seepage into the tunnel and to prevent artificially induced water movement along and within the tunnel. Grout also was used during and following tunnel construction to stabilize loose sand deposits below trench 11 and near the north end of the tunnel. An air-conditioning unit was installed to provide fresh air to workers; it also served as a dehumidifier.

The tunnel intersects natural geologic deposits and backfill material (fig. 12). Because primary interest was in the natural and man-made geologic units directly associated with waste burial, the backfill deposits overlying the tunnel extension south of trench 11 were not studied. The longitudinal position of cross sections, geologic and hydrologic features, trenches, and instruments are referenced to the southern origin of the plate-lined section of the tunnel that extends northward below trenches 11, 3, 2, and 1.



A

B

Figure 23.--Sheffield tunnel: A, Interior of original section lined with steel plates, looking north; B, Steel-culvert extension during installation, looking south.

Instrumentation

As many as 87 soil-moisture tensiometers, similar in design to those described by Stannard (1986), were used to measure liquid pressure head (hereafter, referred to as pressure head). All but 20 of the tensiometers were outfitted with differential pressure transducers. The pressure transducers used in the study relate the difference between liquid pressure and atmospheric pressure as output voltage. Pressures sensed by transducers were recorded automatically by an analog data recorder. The remaining tensiometers were outfitted with manometers. The manometers measured pressure head in millimeters of mercury; this measurement was converted to millimeters of water (hereafter, pressure heads are presented in millimeters of water). Manometer-sensed pressures were recorded manually.

A gamma-ray attenuation density gage (soil-moisture probe) was used to determine soil-moisture content within and adjacent to the trench covers. Gamma-ray attenuation measurements were made in the soil zone at 50-mm intervals. A separate nuclear source and detector were lowered down paired aluminum access tubes 0.3 m apart. The gamma-ray gage measures total density. Moisture content was determined by subtracting the predetermined dry density of the soil from the measurements.

Two types of lysimeters were used to collect water from the unsaturated zone. Vacuum (soil-suction) lysimeters, which counteract soil tensions within the unsaturated zone, were used to obtain water samples for chemical analysis. Gravity (free-drainage) lysimeters, which capture water percolating through the unsaturated zone when the sediments are at or near full saturation (100 percent of the soil-pore space is filled with water) (Hornby and others, 1986), were used to monitor soil-water flux and water chemistry. Gravity lysimeters were installed in locations difficult to instrument with tensiometers or vacuum lysimeters. Healy and others (1989) further describe the construction, installation technique, and operation of the unsaturated-zone monitoring instruments used in this study.

Piezometers and observation wells were used for ground-water sampling and water-level monitoring. Water levels were measured manually by steel tape or recorded automatically by analog-digital paper-punch recorders.

Instruments were clustered in trench covers at two locations: (1) near the midsection of trench 2, from trench crest to intertrench swale (figs. 3 and 24); and (2) along the surface trace of the underlying tunnel, in and adjacent to trenches 2, 3, and 11 (figs. 3 and 25). The first location contained as many as 32 tensiometers, 3 pairs of soil-moisture probe access holes, and 5 vacuum lysimeters. The instruments, which penetrated to a maximum depth of 2.1 m, were installed in all near-surface natural and engineered stratigraphic units. The second location consisted of seven lysimeters installed at depths of 0.7 to 2.3 m. Lysimeters were isolated from other monitoring instruments to prevent recording lysimeter-induced influences on the natural movement of water.

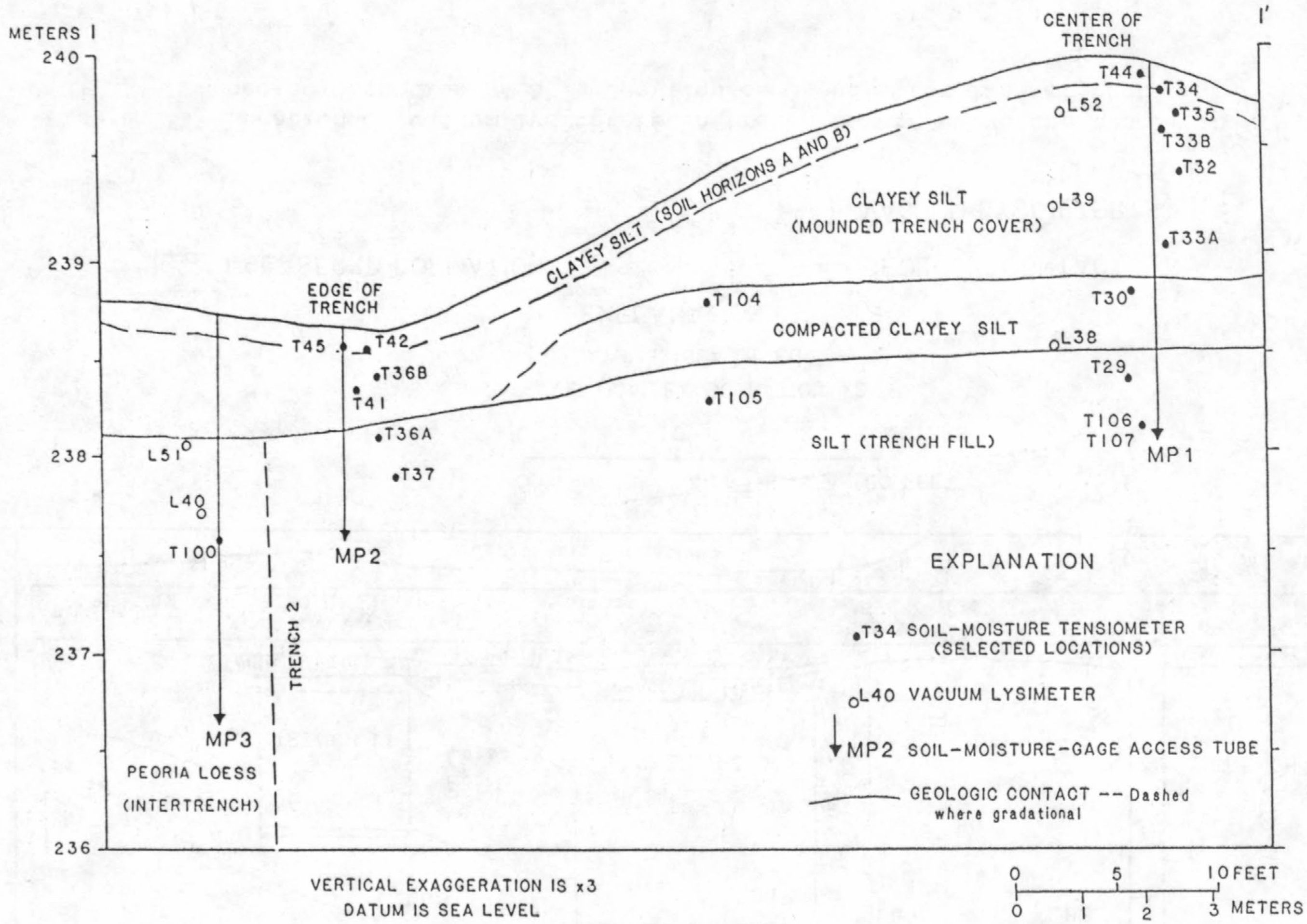


Figure 24.--Lithologic units and location of instruments for monitoring soil-water movement within a trench cover in geologic section I-I'. See figure 3 for location of line of section.

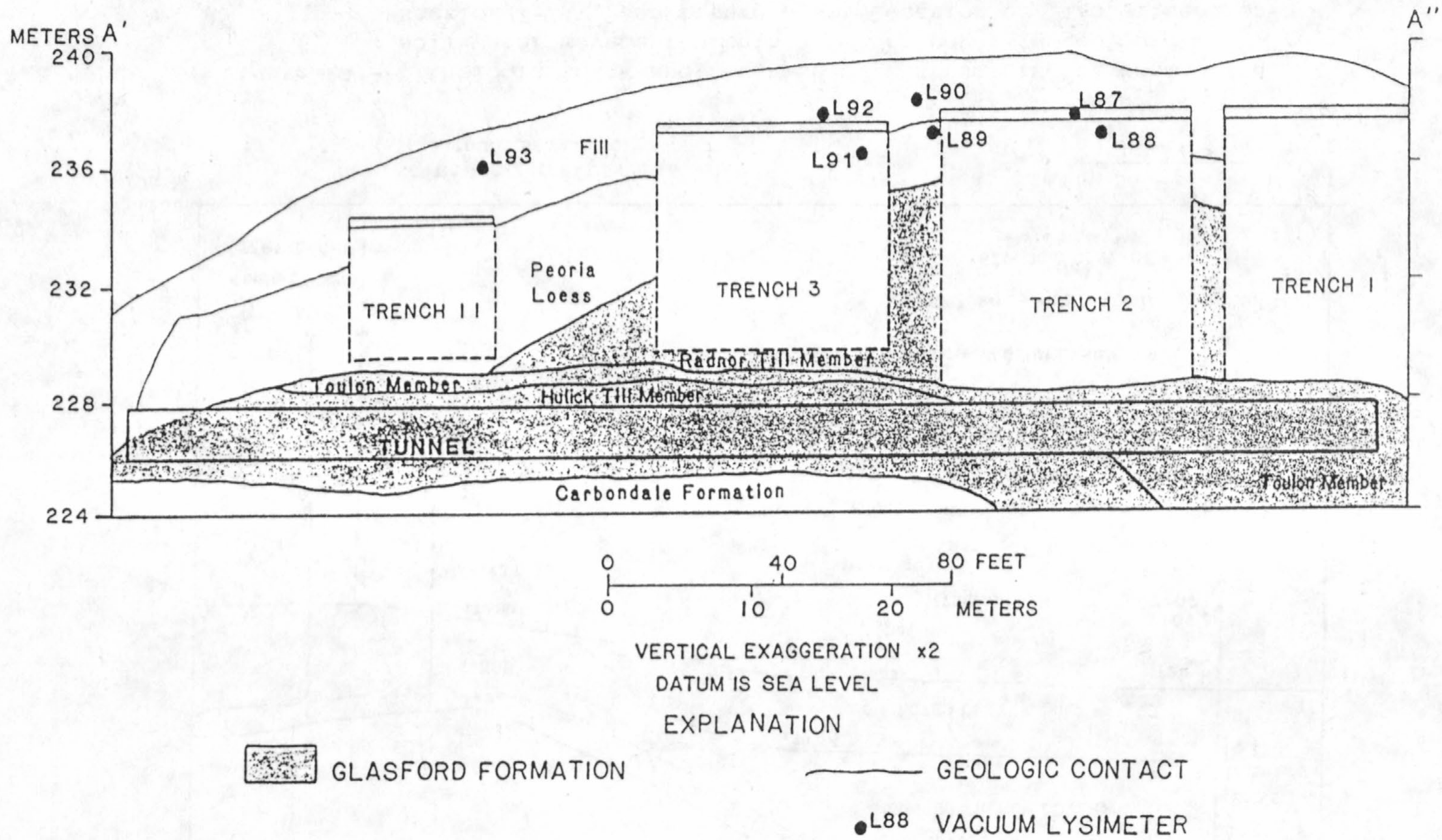


Figure 25.--Location of vacuum lysimeters in trench covers above the tunnel in geologic section A'-A". See figures 3 and 4 for line of section.

Tunnel instruments were installed radially around the tunnel into all accessible stratigraphic units from trench bases to the saturated zone (fig. 26). Fifty-five tensiometers were installed at distances of 0.1 to 4.9 m from the tunnel. Clusters of tensiometers were located at hydrologically significant localities such as the Peoria Loess/Radnor Till Member interface, the Toulon Member lens above the tunnel, and the sloping Toulon Member/Hulick Till Member interface. Trench boundaries were mapped using trench construction records; the mapped positions of the trench edges and the bases of trenches 3 and 11 may be approximate. The mapped positions of instruments in relation to trenches may, therefore, be approximate.

Three gravity lysimeters were installed in geologic deposits above the tunnel ceiling (fig 26). One lysimeter (GL1) was located in the Toulon Member directly below trench 2. Two lysimeters (GL2 and GL3) were installed near trench 11 to monitor flow along the Peoria Loess/Radnor Till Member and Toulon Member/Hulick Till Member interfaces, respectively. Lysimeters GL1 and GL3 were installed by driving them into the geologic deposits. Because of the remote position of the Peoria Loess/Radnor Till Member interface, lysimeter GL2 required an augered hole for installation. The interior of lysimeter GL2, unlike that of lysimeters GL1 and GL3, was free of sediment. Thirteen vacuum lysimeters were located in the Hulick Till Member and Toulon Member along the length of the tunnel.

For use in this study, 9 piezometers and observation wells within and adjacent to the tunnel (figs. 26 and 3) were selected from more than 100 wells across the site (Foster and Erickson, 1980; Foster and others, 1984a). Three wells (502, 512, and 524) that flank the tunnel were fully cased and screened primarily in the Toulon Member; a fourth well (505) was screened in the Hulick Till Member. The piezometers in the tunnel were installed through the tunnel floor. Three piezometers (PZ1, PZ2, and PZ3) were open boreholes in the weathered shale below the tunnel that were cased above the tunnel floor. Two piezometers (PZ4 and PZ5) were fully cased and screened in the Toulon Member.

Frequency of data recordings and sample collections were determined from hydraulic-response times and seasonal hydrologic patterns. Automatic data collection provided a near-continuous record of selected hydrologic events. Monitoring near-surface infiltration during and immediately following precipitation events required data collection at a relatively rapid rate as wetting fronts can move quickly through the shallow soil zone. Tensiometers in and adjacent to trench covers were monitored automatically at 5-minute intervals. Slower responses in the deeper unsaturated zone and the saturated zone allowed for less frequent recording intervals. Tensiometers and most wells were automatically monitored at 1- to 2-hour intervals. Data from other instruments were collected during scheduled site visits every 2 to 3 weeks. Water-sampling schedules were dependent on existing hydraulic conditions. Water samples for tritium analysis generally were collected bimonthly; samples were collected more frequently during periods of seasonal recharge.

Analyses

Geologic samples were obtained from well borings and from borings for instrument installation. Samples were collected by use of either metal core tubes, split-spoon samplers, or soil augers. All samples were sealed in the

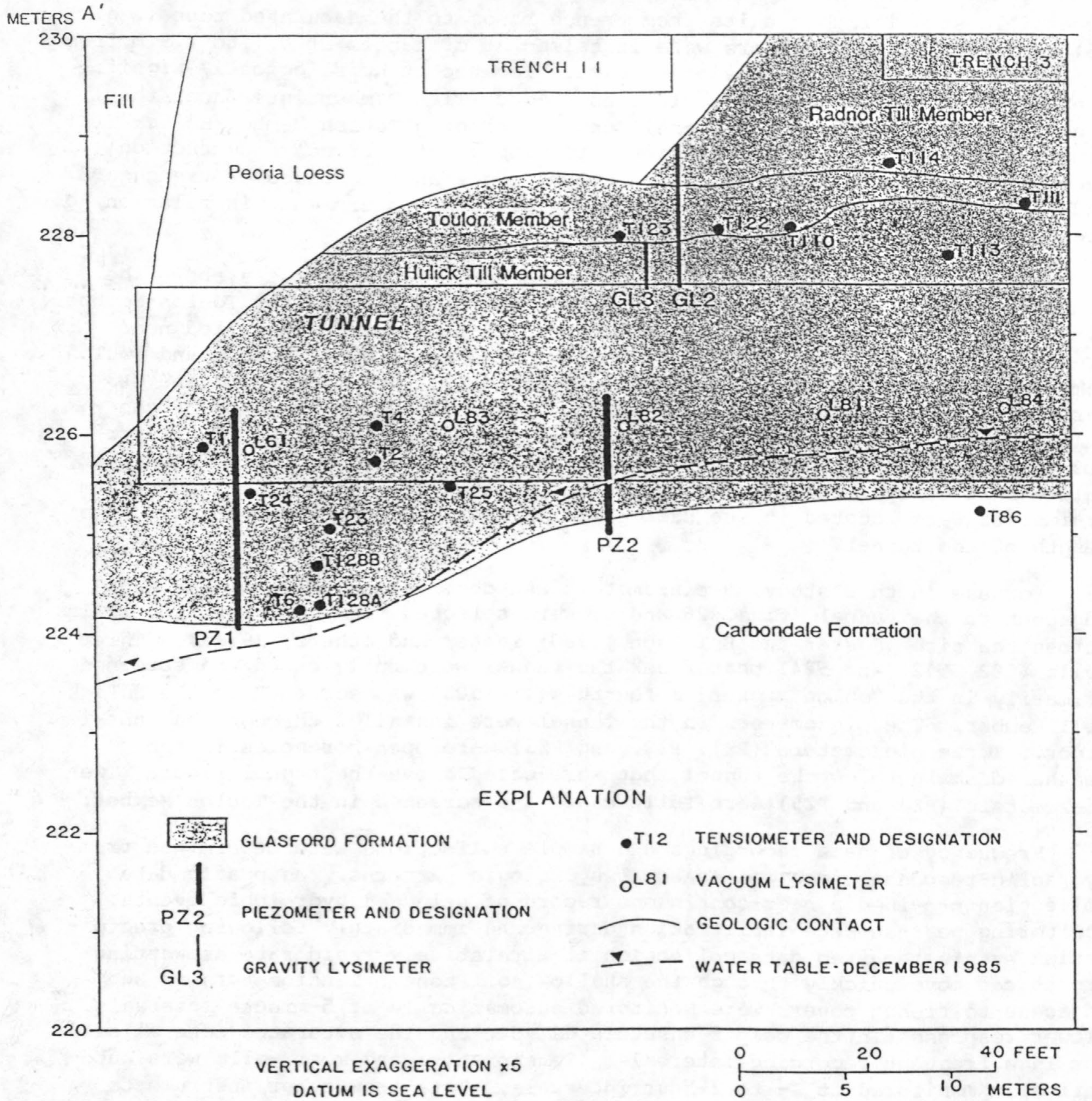


Figure 26.--Location of instruments in the subtrench tunnel area in geologic section A'-A". See figures 3 and 4 for location of line of section.

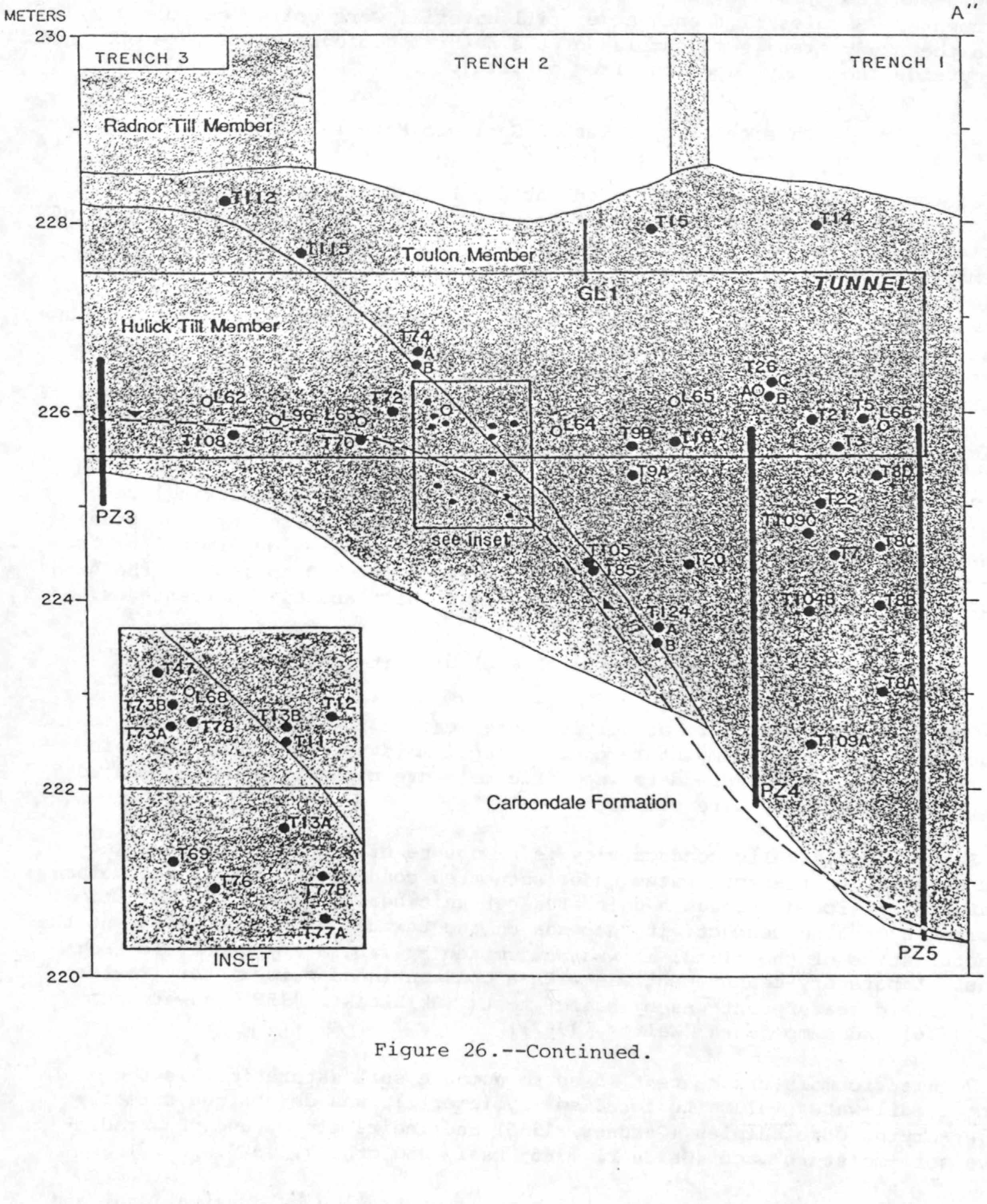


Figure 26.--Continued.

field to prevent moisture loss. Water samples were either obtained from geologic samples by heat extraction or collected directly from water-sampling instruments. Samples of trench-cover fill material were collected solely within the study area; some samples of the natural geologic units were obtained from outside the study area (but from on-site).

Physical Properties of Geologic Materials

Geologic materials were analyzed for dry bulk density, porosity, and particle-size distribution. Dry bulk density is an indicator of the degree of material compaction and provides a means for calculating porosity. It was determined by dividing the mass of an oven-dried sample by its field volume.

Porosity, the ratio of volume of voids in the material to the total volume of the material, indicates the water-bearing capacity of a geologic material. It was determined by mercury porsimeter (Vomocil, 1965). For the purpose of comparison, porosity also was determined by a method described by Freeze and Cherry (1979, p. 337) in which dry bulk density is divided by a standard particle mass density 2.65 grams per cubic centimeter.

Sediment texture (particle-size distribution, shape, and packing) contributes to a geologic material's ability to hold water (porosity) and transmit water (permeability). Particle-size distributions were determined by the sieve-pipette method (Day, 1965), in which a sieve is used to isolate the sand fraction and settling rates are used to estimate silt and clay percentages.

Hydraulic Properties of Geologic Materials

The following hydraulic properties were measured: saturated hydraulic conductivity, volumetric moisture content (soil-moisture content), and moisture retention. From these data, specific moisture capacity and unsaturated hydraulic conductivity were computed.

Saturated hydraulic conductivity is a measure of the capacity of a geologic material to transmit water under saturated conditions. It is the volume of water transmitted through a unit area per unit head gradient per unit time. Saturated hydraulic conductivity depends on the texture of the sediment and the characteristics of the fluid; it was determined by laboratory and field techniques. Laboratory measurement was with a constant-head permeameter (Taylor, 1948). Field measurement was by bailer tests (Skibitzki, 1958; Bouwer and Rice, 1976) and pump tests (Walton, 1962).

Volumetric moisture content, used to compute soil saturation, is the ratio of soil-water volume to total soil volume. It was determined directly by oven-drying core samples (Gardner, 1965) and indirectly by use of a radioactive soil-moisture gage (Gardner, 1965; Healy and others, 1986, p. 27).

Water movement in the unsaturated zone is controlled by gravitational and capillary forces (Hillel, 1980b, p. 20). Water movement through porous media is generally downward under the influence of gravity. Upward movement can occur by capillarity near the water table and in the root zone when pressure head responds to changes in evapotranspiration. The direction of water movement is influenced by variations in hydraulic conductivity; however, water moves in response to gradients of total head. The equation for total head [assuming there are no osmotic pressures (Freeze and Cherry, 1979, p. 105)] is

$$ht = z + hp, \tag{1}$$

where ht = total head (L),
z = elevation head (L), and
hp = liquid pressure head (L).

Average linear velocities in the vertical direction are calculated by

$$v = [K/\theta]i, \tag{2}$$

where v = average linear velocity (LT^{-1}),
K = unsaturated hydraulic conductivity (LT^{-1}),
θ = moisture content (dimensionless), and
i = vertical hydraulic gradient (dimensionless).

In homogeneous, isotropic sediments, gravitational flow is vertically downward. Lithologic variations within and(or) between geologic units can impede vertical water movement, with flow being concentrated above lithologic interfaces of contrasting permeability (Hillel, 1980b, p. 9; Miller and Gardner, 1962, p. 117-118). Where interfaces are sloped, lateral flow can occur.

The amount of water retained in a volume of soil (soil-moisture content) is a function of several factors including liquid pressure head. As pressure head becomes increasingly negative, soil moisture decreases. The hydraulic properties of unsaturated sediments are typically depicted by a series of characteristic curves because of the nonlinear relations that exist between these properties. The "moisture retention curve" depicts the relation between pressure head and soil-moisture content. The moisture retention curves developed in this study are actually simplifications of the true relation between pressure head and soil-moisture content. They are the main drying curves. The actual relation between pressure head and soil-moisture content is hysteretic; soil-moisture content depends on whether pressure head is increasing or decreasing--that is, whether the sediment is wetting or drying. Because of the complexity of the hysteretic phenomenon, main drying curves are typically used to determine soil-moisture content from pressure head and the relation between pressure head and soil-moisture content are assumed to be nonhysteretic. The shape of the moisture-retention curve depends on pore size because water drains more readily from large pores than from small pores. Moisture-retention curves for drying sediments were determined in the laboratory with use of Tempe cells or a pressure membrane extractor (Bouma and others, 1974). The curves may be described by theoretical equations, such as that developed by Brooks and Corey (1964):

$$\theta(hp) = \theta r + (\phi - \theta r)\,(hb/hp)^{\lambda}, \tag{3}$$

where hp = liquid pressure head (L),

θr = residual moisture content (dimensionless),

ϕ = porosity (dimensionless),

hb = bubbling pressure (L), and

λ = a pore-size distribution index (dimensionless).

Values of θr, hb, and λ were determined by fitting a curve to the laboratory-derived pressure head versus moisture-content data. The reader is referred to Brooks and Corey (1964) for further discussion of the definition and derivation of θr, hb, and λ.

Additional characteristic curves define the specific moisture capacity/pressure head relation and the hydraulic conductivity/pressure head relation. Specific moisture capacity is the amount of change in moisture content per unit change in pressure head (the slope of the moisture-retention curve). The relation between hydraulic conductivity and pressure head describes the hydraulic conductivity of unsaturated geologic materials. This relation was determined analytically by the following series of Brooks and Corey (1964) equations:

$$K = Ks[Kr(hp)], \tag{4}$$

where Ks = saturated hydraulic conductivity (LT^{-1}), and

Kr = relative hydraulic conductivity (dimensionless), where

$$Kr(hp) = (hb/hp)^{2+3\lambda}. \tag{5}$$

Healy and others (1986, p. 12-15) provide additional discussion of the development and hydrologic implications of characteristic curves. Johnson and others (1983) discuss characteristic curves as they relate to trench-cover materials at the Sheffield site.

Radiologic Properties of Water and Geologic Materials

Tritium activity and concentration in water samples were determined by liquid scintillation techniques (Thatcher and others, 1977). Immediately after collection, soil samples were scanned with a geiger counter for abnormally high beta and gamma activity. In the laboratory, soil and water samples were analyzed for gross alpha and beta activity using techniques described in Thatcher and others (1977). For the purpose of this report, a background tritium concentration of 200 pCi/L (picocuries per liter) was assumed. This concentration was based on the minimum detection level of the liquid scintillation method used for tritium analyses. The maximum permissable concentration for controlled release to unrestricted areas established by the U.S. Nuclear Regulatory Commission (10 CFR 20, B, II) is 3,000,000 pCi/L. Standards of 30 pCi/L for gross alpha and 60 pCi/L for gross beta were used to evaluate migration of radionuclides other than tritium. These standards represent site criteria established by IDNS (Dave Ed, Illinois Department of Nuclear Safety, oral commun., 1988).

QUALITY ASSURANCE

Measures were used to ensure that the data collected in this study were valid and reliable. Analyses of the physical and hydraulic properties of the geologic materials were typically performed by multiple methods or by multiple agencies.

All pressure transducers were calibrated in the laboratory and field before use. As a field check, tensiometers were outfitted as mercury manometers prior to use with pressure transducers. Readings were then cross-checked to determine instrument performance. During site visits, each tensiometer was visually inspected for air; water lines were flushed with gas-free water if air bubbles were present.

The performance of the tensiometers was further evaluated by comparing tensiometer pressure-head responses with the responses of other instruments (gravity lysimeters, piezometers, and observation wells) monitoring soil- and ground-water movement. Figure 27 shows that tensiometer responses compared favorably with the responses of other monitoring instruments.

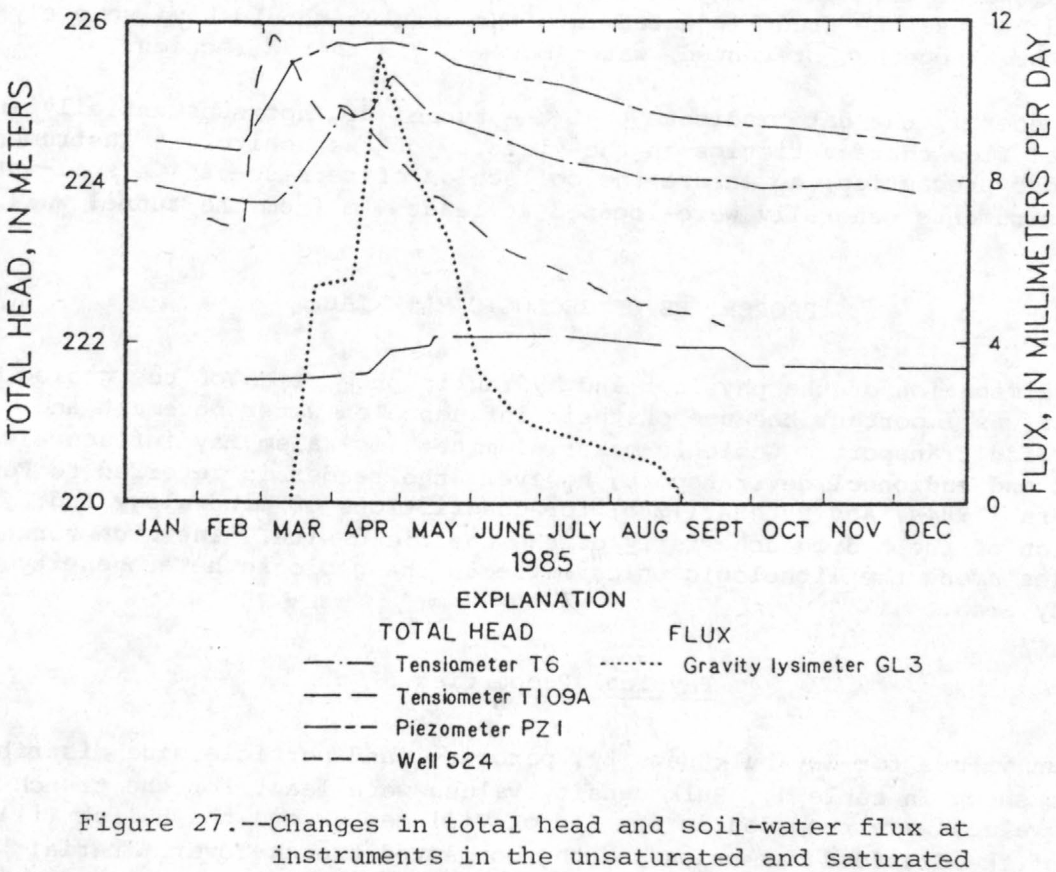


Figure 27.--Changes in total head and soil-water flux at instruments in the unsaturated and saturated zones, 1985.

Because one goal of instrumentation and data collection is accurate representation of natural conditions, it was important to assess the potential effect of the tunnel on the environment being monitored. In addition to the previously mentioned locations at which tensiometers were concentrated, tensiometers also were located immediately above, below, and adjacent to the tunnel to provide an indication of the influence of the tunnel on water movement through the unsaturated subtrench deposits.

Vertical water movement through the tunnel section may be inhibited by the impermeable tunnel, resulting in variable flow rates in the adjacent sediments with increases in soil-moisture content directly above the tunnel and decreases in soil-moisture content directly below the tunnel. Comparison of pressure heads at similar vertical positions below (tensiometer T28A) and beyond the lateral limits (tensiometer T6) of the tunnel (figs. 26 and 28) revealed no pronounced differences in the timing of seasonal water movement or in soil-moisture content. Additionally, no significant trends or differences in soil-moisture content were indicated by the comparison of soil-moisture profiles above and below the tunnel (fig. 29). The tunnel air-conditioning system may tend to dry soils closely surrounding the tunnel. Soil-moisture contents in soil cores immediately flanking the tunnel in the Hulick Till Member and the Toulon Member did not suggest a consistent pattern of drying. Horizontal water movement along the annulus outside the tunnel lining was not evaluated because the grout injected into the annulus should have severely limited, or altogether prevented, water movement in that direction.

In general, the data indicate that the tunnel did not substantially influence local flow characteristics in the vicinity of the monitoring instruments. As an added precaution, to ensure the collection of representative soil-water data, instruments generally were located at least 1 m from the tunnel wall.

PROPERTIES OF GEOLOGIC MATERIAL

Determination of the physical and hydraulic properties of the geologic materials was important because of their influence on water movement and radionuclide transport. Geologic-material mineralogy also may influence water movement and radionuclide transport; however, the reader is referred to Foster and others (1984a) and Peters (1985) for descriptions of mineralogy and discussion of the hydrogeochemistry of the Sheffield site. The wide range of properties among the lithologic units reflects the geologic heterogeneity of the study area.

Physical Properties

Mean values for dry bulk density, porosity, and particle-size distribution are shown in table 1. Bulk density values were least for the trench fill; largest values were recorded in the Radnor Till Member and the Hulick Till Member of the Glasford Formation and the compacted trench-cover material.

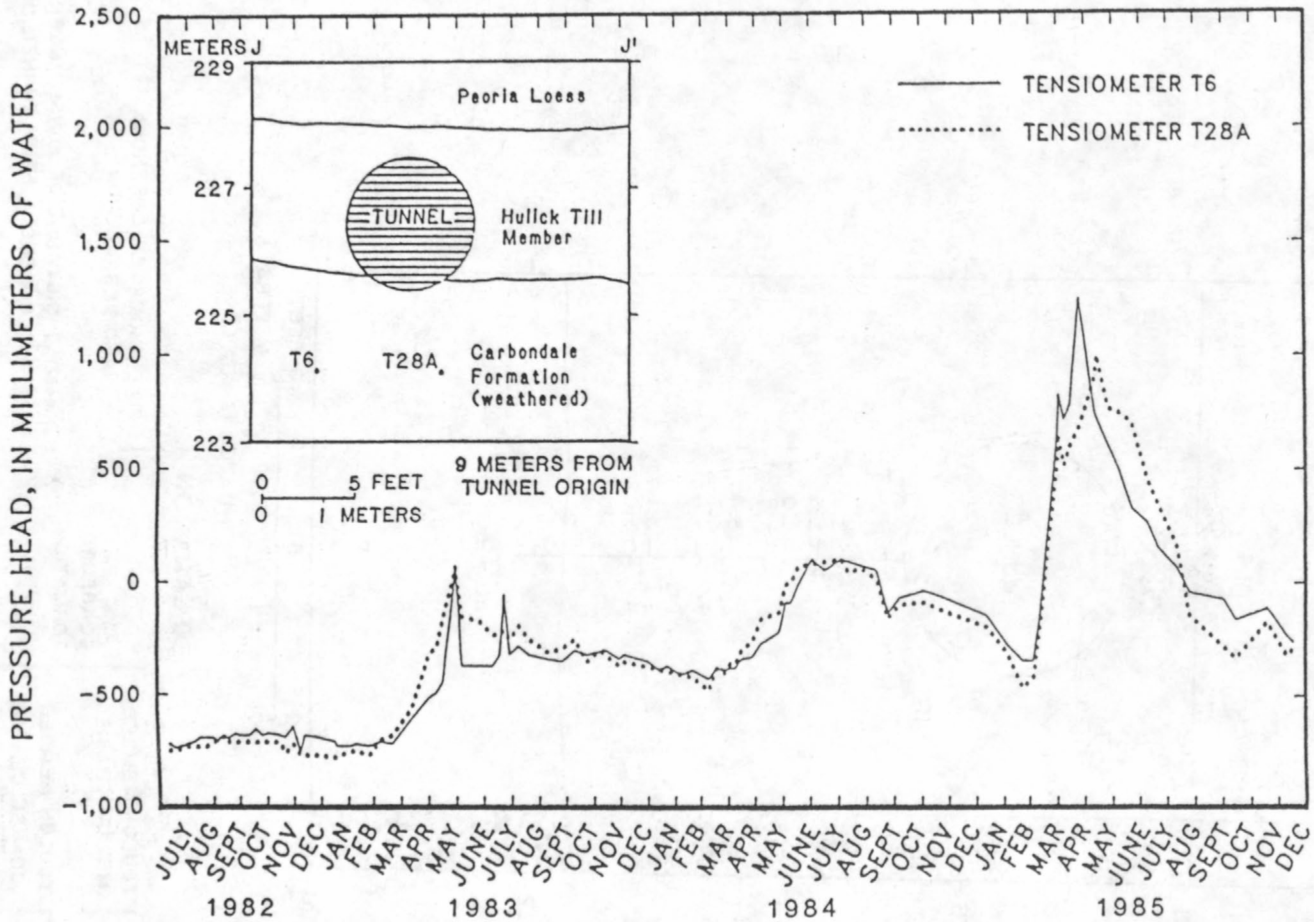


Figure 28.--Fluctuations in liquid pressure head in the Hulick Till Member of the Glasford Formation at two locations below the tunnel floor in geologic section J-J', July 1982 through December 1985. See figure 3 for location of line of section.

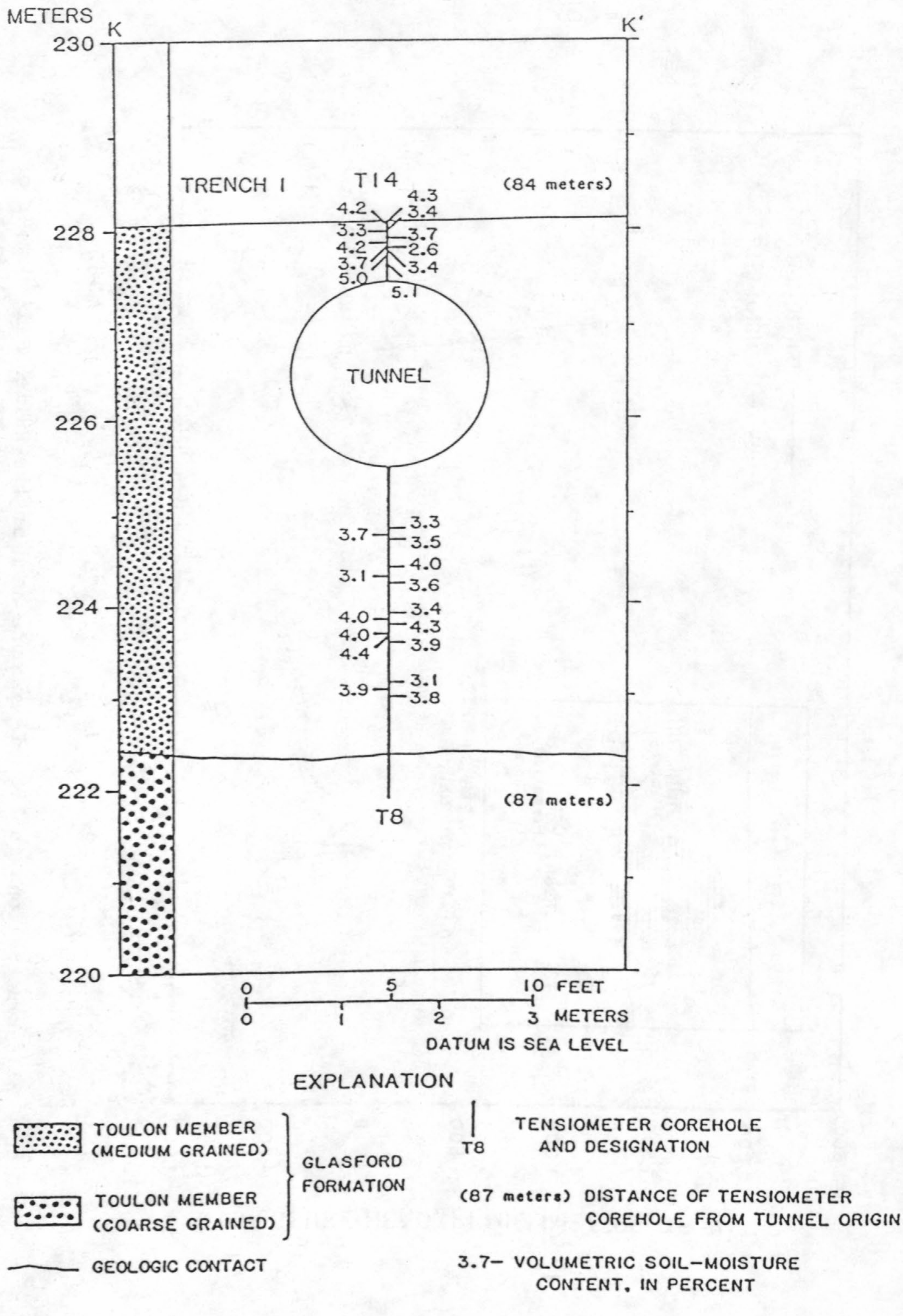


Figure 29.--Soil-moisture content of soil cores above and below the tunnel in geologic section K-K'. See figure 3 for location of line of section.

Table 1.--Mean values for selected physical properties of the unconsolidated geologic materials

[g/cm^3, grams per cubic centimeter; d, dimensionless; dashes indicate no data]

Material (lithologic unit)	Dry bulk density[1] (g/cm^3)	Porosity[2] (d)	Particle-size distribution[3] (percent)		
			Clay	Silt	Sand
Clayey silt (Soil horizons A and B)	1.65	--	--	--	--
Clayey silt (Mounded trench-cover fill)	1.65	0.411	23	66	11
Clayey silt (Compacted layer)	1.85	.398	27	68	5
Silt (Trench fill)	1.25	.426	17	79	4
Silt (Peoria Loess)	1.45	.426	15	81	4
Pebbly clayey silt (Radnor Till Member of the Glasford Formation)	1.90	[4].316	29	53	18
Sand (Toulon Member of the Glasford Formation)	1.60	.349	6	10	84
Pebbly clayey silt (Hulick Till Member of the Glasford Formation)	1.85	.338	30	43	27

[1]Determined by mass of oven-dried sample/field volume.
[2]Determined by mercury porsimeter (Vomocil, 1965).
[3]Determined by sieve-pipette method (Day, 1965).
[4]Estimated by comparison with the Hulick Till Member (similar physical appearance and particle-size distributions).

Porosity was least for the Hulick Till Member and the Radnor Till Member and greatest for the Peoria Loess and the trench fill. Porosity values, as determined by the two analytical procedures, generally were in good agreement; the correlation coefficient (r) was 0.71. The bulk-density method appeared to overestimate the porosity of the Toulon Member and underestimate the porosity of the compacted layer.

Particle-size distribution (sand-silt-clay percentages) were similar for the Hulick Till Member and the Radnor Till Member; trench-fill material was generally equivalent to that of the Peoria Loess. Material textures in the compacted layer and the overlying mounded layer of the trench cover were generally equivalent in type and distribution.

Hydraulic Properties

Mean values for saturated hydraulic conductivity are shown in table 2. The most conductive geologic material in the study area is the sand of the Toulon Member of the Glasford Formation. The least conductive material is the weathered shale of the Carbondale Formation. The compacted layer of the trench cover and the pebbly clayey silts of the Radnor Till Member and Hulick Till Member are only slightly less conductive than the weathered shale. Similarity between laboratory measurements of vertical and horizontal hydraulic conductivity indicates that the natural fine-grained geologic materials are generally isotropic (Foster and others, 1984, p. 18). The homogeneous texture of the sand deposits indicates that the Toulon Member also is isotropic. Although no quantitative data are available, near-surface (root zone) trench-cover deposits may be anisotropic because of the effects of roots, animal borings, and freeze-thaw.

The characteristic curves for three representative geologic units in the study area are shown in figure 30. Figure 30A shows the relation between pressure head and soil-moisture content. Moisture content decreases least over the range of decreasing pressure heads in the Hulick Till Member; moisture content decreases most in the Toulon Member.

Figure 30B shows the relation between pressure head and specific moisture capacity. The greatest change in moisture content per unit change in pressure head is in the Toulon Member; the change is greatest at a pressure head of approximately -30 mm.

Figure 30C shows the relation between pressure head and hydraulic conductivity. Hydraulic conductivity decreases least over the range of decreasing pressure heads in the Hulick Till Member and the Peoria Loess; hydraulic conductivity decreases most in the Toulon Member.

Values of θr, hb, and λ are presented in table 2. These values were the basis of the Brooks and Corey (1964) simulations of the moisture-retention curves shown in figure 30. As can be seen, the simulated curves match the laboratory-derived curves well.

WATER MOVEMENT THROUGH THE UNSATURATED ZONE

Results of the study are presented in three sections: (1) "Water movement above the disposal trenches;" (2) "Water movement below the disposal trenches;" and (3) "Conceptualization of water movement through the disposal trenches." Physical data presented in the first two sections serve as the basis for the more conceptual analysis presented in the third section. Data in the first section pertain only to the period July 1982 through June 1984, because trench-cover infiltration data were collected in conjunction with the evapotranspiration data of Healy and others (1989). The third section describes water movement through the disposal trenches, as well as through the intertrench geologic deposits.

Table 2.--Mean saturated hydraulic conductivity and representative Brooks and Corey (1964) values for the unconsolidated geologic materials

[mm/d, millimeters per day; d, dimensionless; mm, millimeters; dashes indicate no data]

Material (lithologic unit)	Saturated hydraulic conductivity, Ks[1] (mm/d)	Residual moisture content, θr (d)	Bubbling pressure, hb (mm)	Pore size distribution index, λ (d)
Clayey silt (Soil horizons A and B)	[2]1.3×10^{2}	--	--	--
Clayey silt (Mounded trench-cover fill)	[2]3.4×10^{1}	0.15	-800	0.60
Clayey silt (Compacted layer)	[2]3.5×10^{-1}	.25	-900	.70
Clayey silt (Trench fill)	[2]1.9×10^{2}	.01	-600	.30
Silt (Peoria Loess)	[2,3]6.6×10^{1}	.01	-600	.30
Pebbly clayey silt (Radnor Till Member of the Glasford Formation)	[4,5]5.8×10^{-1}	.25	-1,200	.50
Sand (Toulon Member of the Glasford Formation)	[4]3.4×10^{4}	.03	-150	1.75
Pebbly clayey silt (Hulick Till Member of the Glasford Formation)	[3,4]4.8×10^{-1}	.30	-1,000	.50
Weathered shale (Hulick Till Member/ Carbondale Formation interface)	[3,4]3.2×10^{-2}	--	--	--

[1]Determined by constant-head permeameter (Taylor, 1948), bailer (Skibitzki, 1958; Bouwer and Rice, 1976), and pump (Walton, 1962) tests.
[2]Vertical hydraulic conductivity.
[3]Value from Foster and others (1984).
[4]Horizontal hydraulic conductivity.
[5]Estimated value based on comparison with Hulick Till Member.

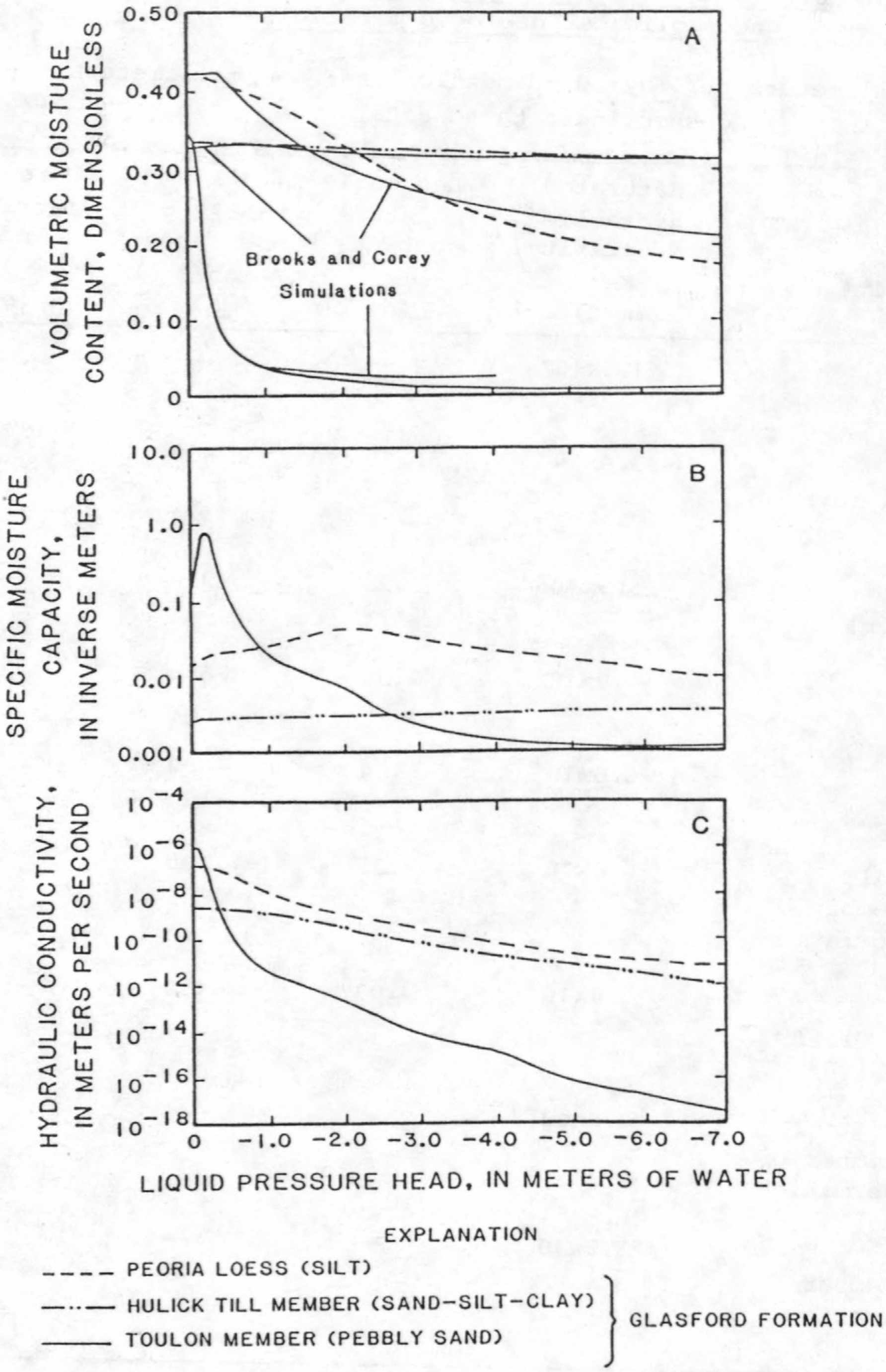


Figure 30.--Hydraulic properties of three geologic units in the study area: A, Volumetric moisture content as a function of liquid pressure head; B, Specific moisture capacity as a function of liquid pressure head; C, Hydraulic conductivity as a function of liquid pressure head. Modified from Healy and others, 1986, figure 5.

Water Movement Above the Disposal Trenches

Trench covers, constructed primarily with clayey silt, can store significant quantities of water. Figure 24 shows the lithologic composition and geomorphology of the cover of trench 2. Physical descriptions and hydraulic properties of the sediments that comprise a typical trench cover and adjacent lithologic units are given in tables 1 and 2. The compacted layer is a particularly interesting feature. Although the compacted layer of trench 2 is compositionally similar to the overlying material, it has a higher bulk density and a much lower saturated hydraulic conductivity. The actual amount of water stored in the trench-cover materials varied greatly on a seasonal basis. Figure 31 shows the change in stored water within the top 1.75 m of land surface (determined by integrating the change of moisture content over time over the thickness of the cover) of trench 2 for the period November 1982 through June 1984. The trench cover held the most water in early spring (March and April); the water content decreased steadily throughout late spring and summer, reaching a minimum in late summer. A steady increase is noted from early fall to the following spring. For the period November 1982 through June 1983, the trench covers were at maximum saturation (highest percentage of pore space filled with water) during the first week in April. For the following annual period ending in June 1984, the trench covers were at maximum saturation during several periods including late March, April, and May.

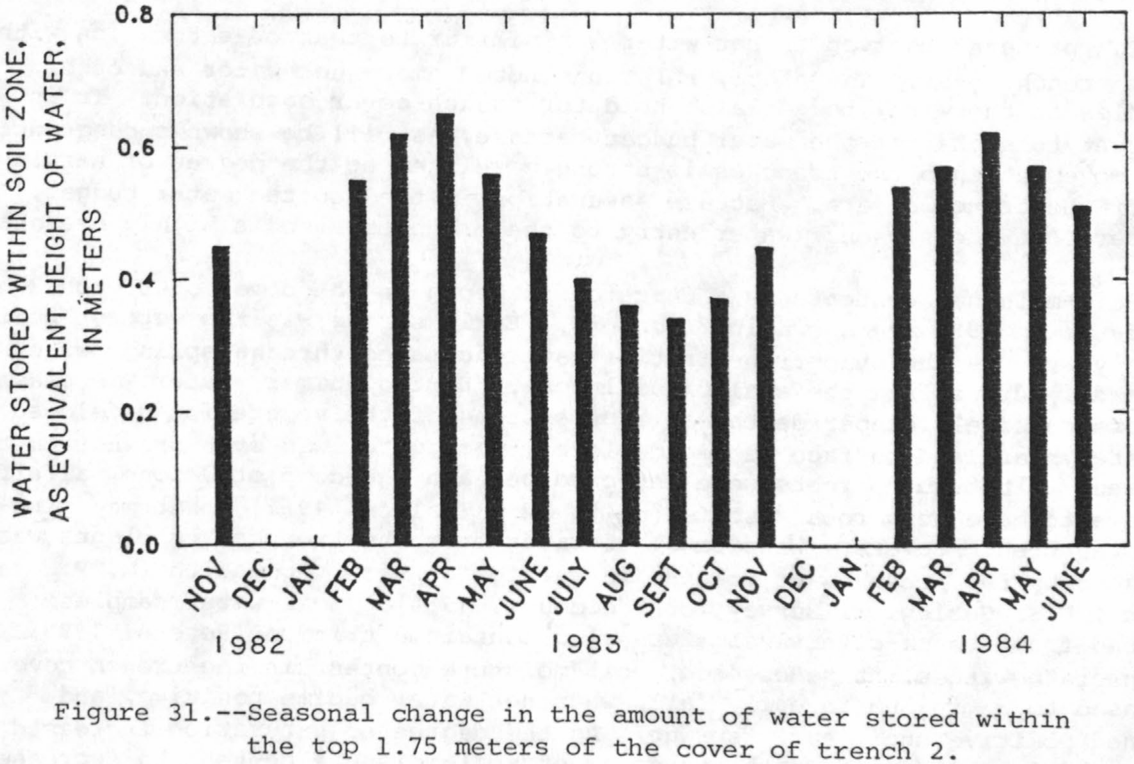


Figure 31.--Seasonal change in the amount of water stored within the top 1.75 meters of the cover of trench 2.

The seasonal cycle of saturation within the trench covers is related to trends in the water budget. Figure 32 shows the monthly values for each of the components of the water budget and an additional value identified as "net water." Net water is defined as precipitation minus evapotranspiration minus runoff. When net water is positive (water surplus), the trench cover gains water; the water may be stored in the trench cover or percolate downward as recharge to the saturated zone. When net water is negative (water deficit), water is withdrawn from the trench cover (released to the atmosphere by evapotranspiration). Net water generally was positive during fall and winter and negative during late spring and summer. Correlation coefficients between each component of the water budget and net water were calculated on a monthly basis for the 2-year period from July 1982 through June 1984. Although the correlations were generally weak, several trends were indicated. Net water was inversely correlated with evapotranspiration ($r = -0.62$), displaying the seasonal nature of evapotranspiration. Precipitation had a moderate positive correlation ($r = 0.39$) with net water, in that net water was typically positive during spring when precipitation rates were high. However, because precipitation was more uniformly distributed throughout the year than evapotranspiration, the correlation between precipitation and water surplus was less strong. Runoff had a low correlation ($r = 0.26$) with net water, apparently caused by an anomalous relation between the two. Runoff rates may be high during periods of both water surplus (in summer, when the infiltration capacity of the upper trench-cover sediments is exceeded during short, intense rainstorms) and water deficit (in winter and early spring, when the trench-cover sediments are frozen or approach full saturation).

The pattern observed in net water was similar to that of saturation within the trench cover. Therefore, relations noted among net water and other variables of the water budget also hold for trench-cover saturation. It is important to emphasize the water budget because, as will be shown subsequently, water movement into the trenches is strongly related to the degree of saturation of the trench covers. Because saturation is tied to the water budget, and therefore the seasons, water entry to the trenches also is highly seasonal.

Soil-moisture contents as a function of depth in the cover of trench 2 at four dates in 1983 are shown in figure 33. Early spring was the wettest period of the year. As the evapotranspiration rate increased through spring, water was readily drawn from the shallow soil zone. During summer, water was drawn from progressively deeper depths as root systems of the vegetation developed and water near land surface became depleted; some water was even drawn from the trenches. Although no roots were detected beneath the compacted zone, alfalfa is known to have long root systems [up to 12 m (Bolton, 1962)] that may penetrate the trench covers. Withdrawal of water from the trenches by plants was suggested by the presence of tritium in samples of site vegetation (M. P. deVries, U.S. Geological Survey, oral commun., 1984). Soil-water samples obtained from trench-cover lysimeters also contained tritium (Peters, 1985). Commensurate with plant senescence, soil-moisture content in the trench covers decreased to a minimum in early fall, when net water became positive, and remained positive until early spring. As the degree of saturation increased during the fall and winter, the tendency of soil-moisture content to decrease with depth reversed. Soil-moisture content in the soil near land surface increased first and slowly propagated downward (fig. 33).

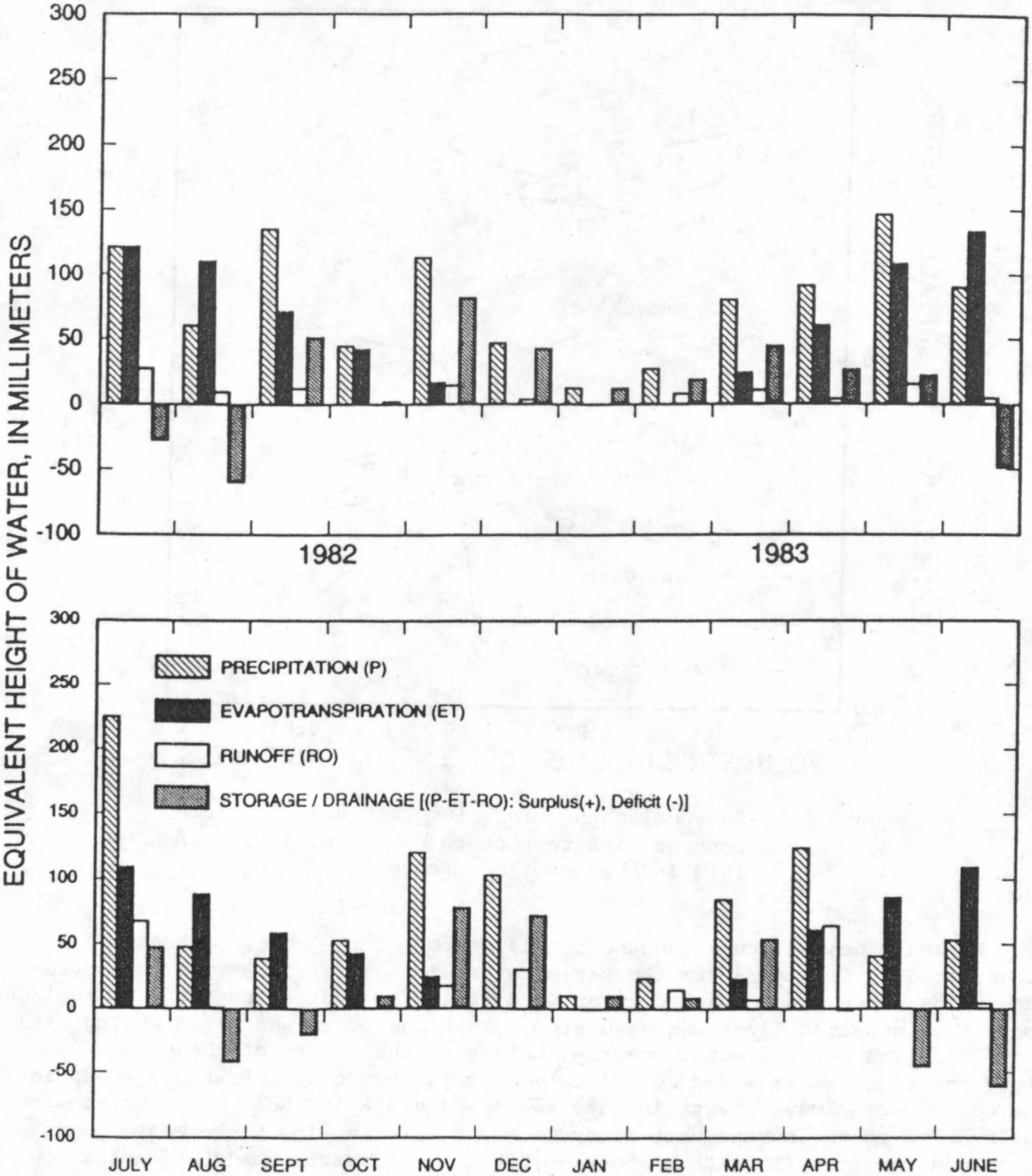


Figure 32.--Monthly values of water-budget components, July 1982 through June 1984.

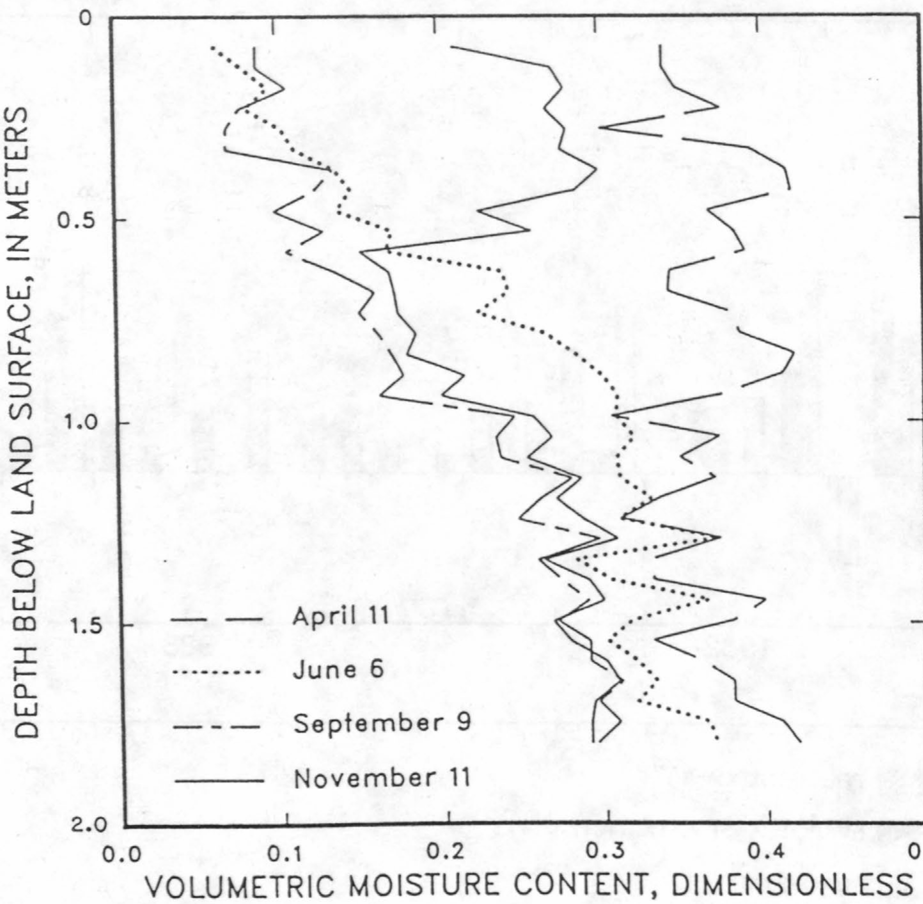


Figure 33.--Seasonal change in volumetric soil-moisture content with respect to depth for 4 days in 1983 in the cover of trench 2.

Pressure head at three depths at the center of the cover of trench 2 is illustrated in figure 34 for the period of study. In early spring, the pressure heads above the compacted layer were positive, indicating that the horizon above the compacted layer was saturated. This phenomena was noted during 1983 and 1984. The perched water occurred only near the center of the cover. Along the edge, water moved more freely through the cover. Pressure heads in the cover were always lowest in late summer to midfall. Near land surface, soils dried to the extent that pressure heads were too low to be measured using tensiometers (less than about -8,500 mm). Pressure heads at depths of 0.5 m or greater were always within the measurement range of tensiometers. As with soil-moisture content, the variation in pressure head with time was largest at land surface and decreased with depth. In the trench-fill material below the compacted layer, there was little variation in pressure head.

The movement of water through a trench cover depends on several factors. Figure 35 shows the maximum depths of wetting fronts for individual storms at the center and at the edge of the cover as functions of initial saturation of

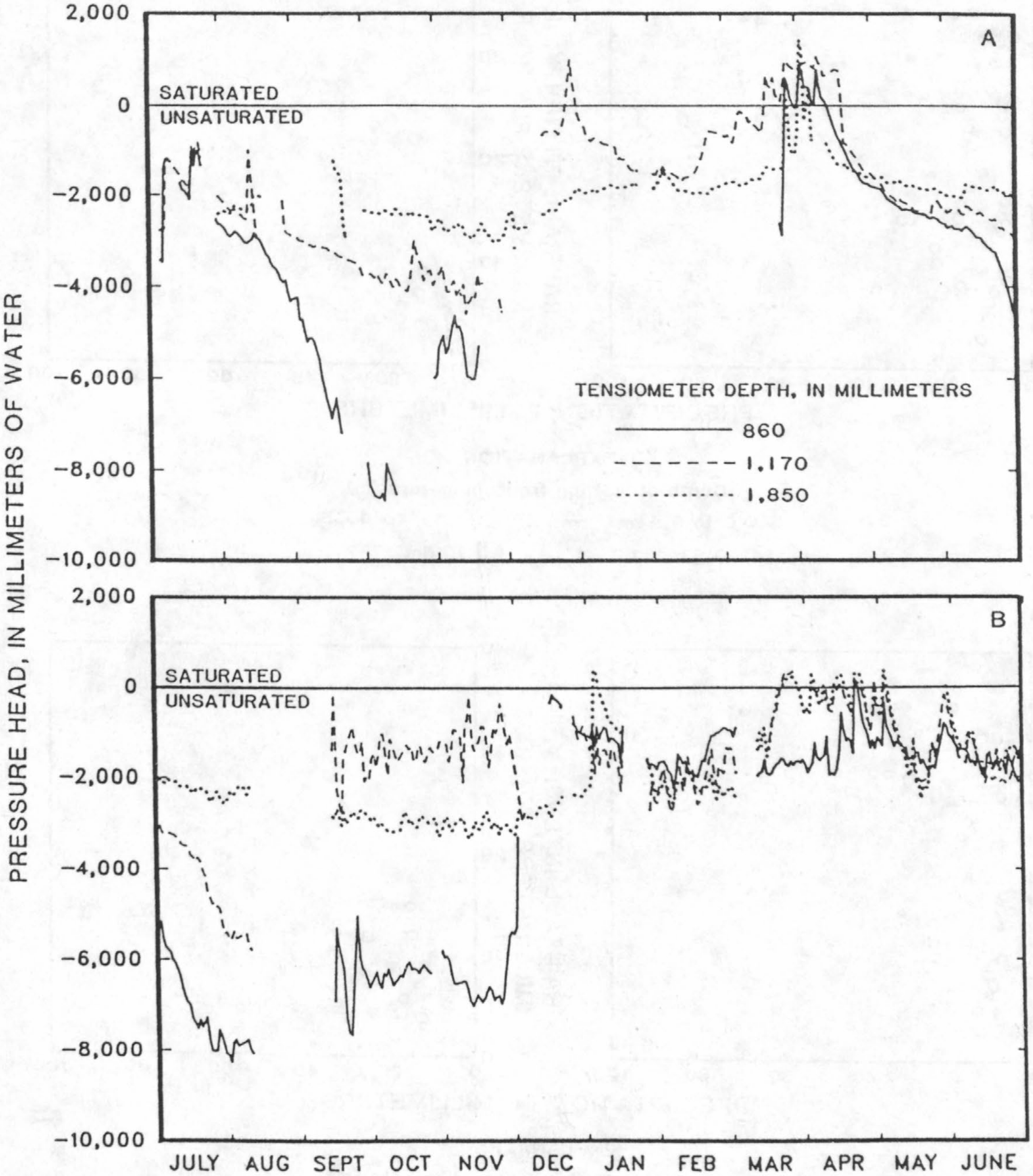


Figure 34.--Pressure head at three depths below land surface at the center of the cover of trench 2: A, July 1982 through June 1983; B, July 1983 through June 1984.

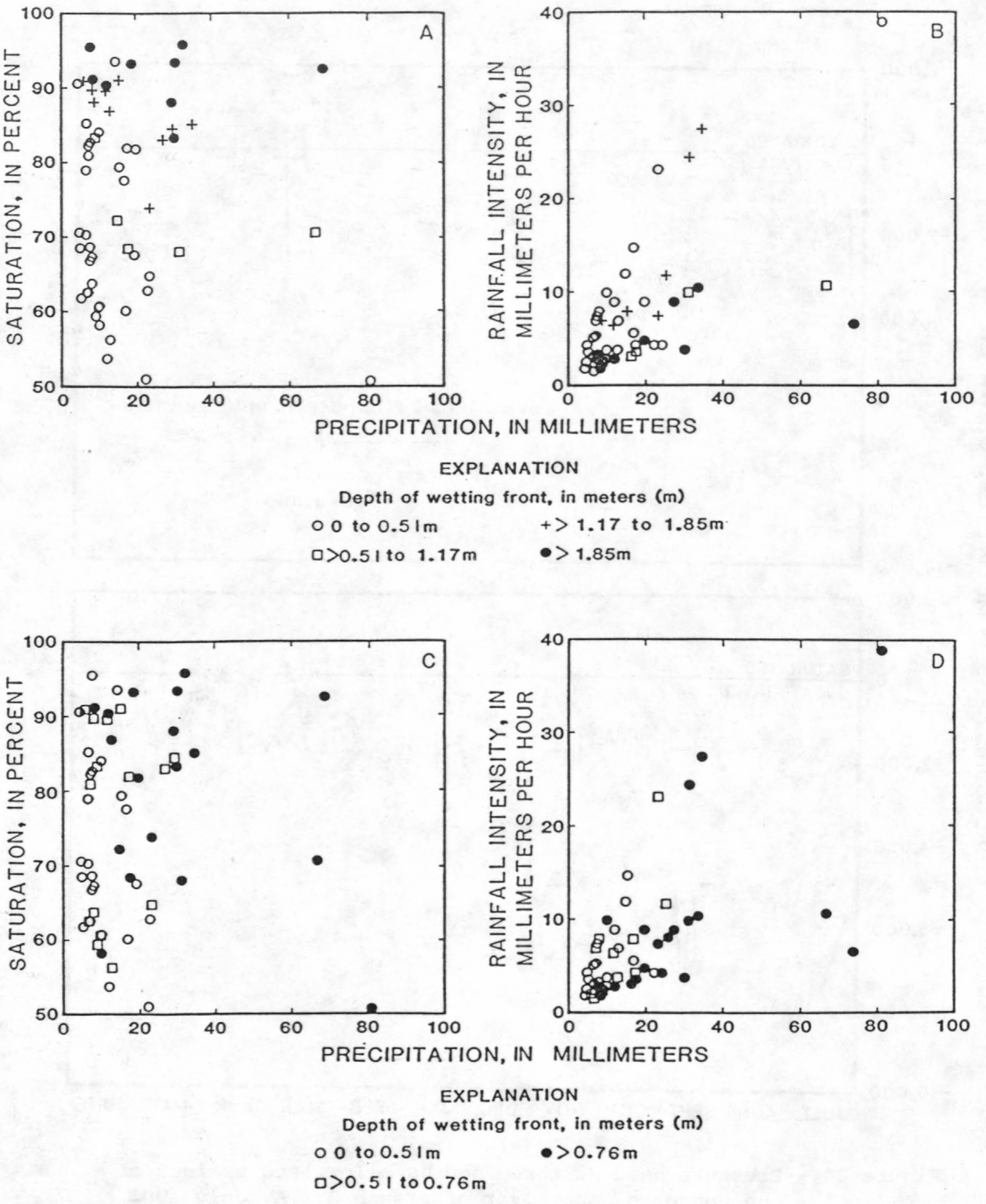


Figure 35.--Maximum depth of wetting-front movement in the cover of trench 2 as a function of A, Initial saturation and precipitation at the center of the cover; B, Maximum 60-minute rainfall intensity and precipitation at the center of the cover; C, Initial saturation and precipitation at the edge of the cover; D, Maximum 60-minute rainfall intensity and precipitation at the edge of the cover.

the cover, total storm precipitation, and maximum 60-minute rainfall intensity. The maximum depth of a wetting front is defined in this report as the maximum depth of measurable change in pressure head. Initial saturation was more important than total precipitation in controlling the depth of wetting-front movement at the center of the cover. However, at the edge, correlation of wetting-front depth with total precipitation was slightly better than it was with initial saturation. For storms of the same total precipitation, there was an inverse relation between wetting-front depths and rainfall intensity at the center of the cover. This trend was not apparent at the edge of the cover. Of the 87 storms that produced at least 5 mm of precipitation between July 1982 and June 1984, Healy (1989) estimated that wetting fronts moved deep enough to enter the trench on 28 occasions at the trench edge but on only 10 occasions at the trench center.

Figure 35 shows that wetting fronts from the same storm move deeper along the edge than at the center of the trench cover. For most storms, the wetting front also moved downward at a faster rate along the edge. This is illustrated in figure 36, which shows changes in pressure head with respect to depth and time for the storm of November 1, 1982. There are two apparent reasons for the quicker and deeper wetting-front movements along the edge of the cover: (1) Surface runoff was much slower along the edge where water would often pond in swales between adjacent trench covers over much of the site for short periods immediately following precipitation; and (2) the presence of the compacted layer and the greater thickness of the cover at the trench center offers a much greater resistance to water flow there than at the trench edge. Although not supported by data from the three tensiometer clusters in the cover of trench 2 (fig. 24), a third explanation may be that water is supplied to the trench edge by downslope flow above the compacted layer.

The difference in water movement across the width of the trench cover is further illustrated by examining seepage into the trench. Healy (1989) used the Darcy method with tensiometer data to estimate fluxes at the center and at the edge of the trench cover for the period July 1982 through June 1984. At the center, seepage into the trench averaged 78 mm/yr, whereas at the edge, seepage was 600 mm/yr. Because of the dependence of wetting-front movement on initial saturation and the seasonality of saturation of the cover, most of the water movement occurred in early spring, the time of highest saturation of the cover.

A water-budget analysis can be used to obtain an estimate of the amount of water that enters disposal trenches. The water budget can be rewritten as

$$QD = PR - ET - R - \Delta S, \tag{6}$$

where QD = rate of water entry to the trench (LT^{-1}),
PR = preciptation rate (LT^{-1}),
ET = evapotranspiration rate (LT^{-1}),
R = runoff (LT^{-1}), and
ΔS = change in the amount of water stored within the trench cover (LT^{-1}).

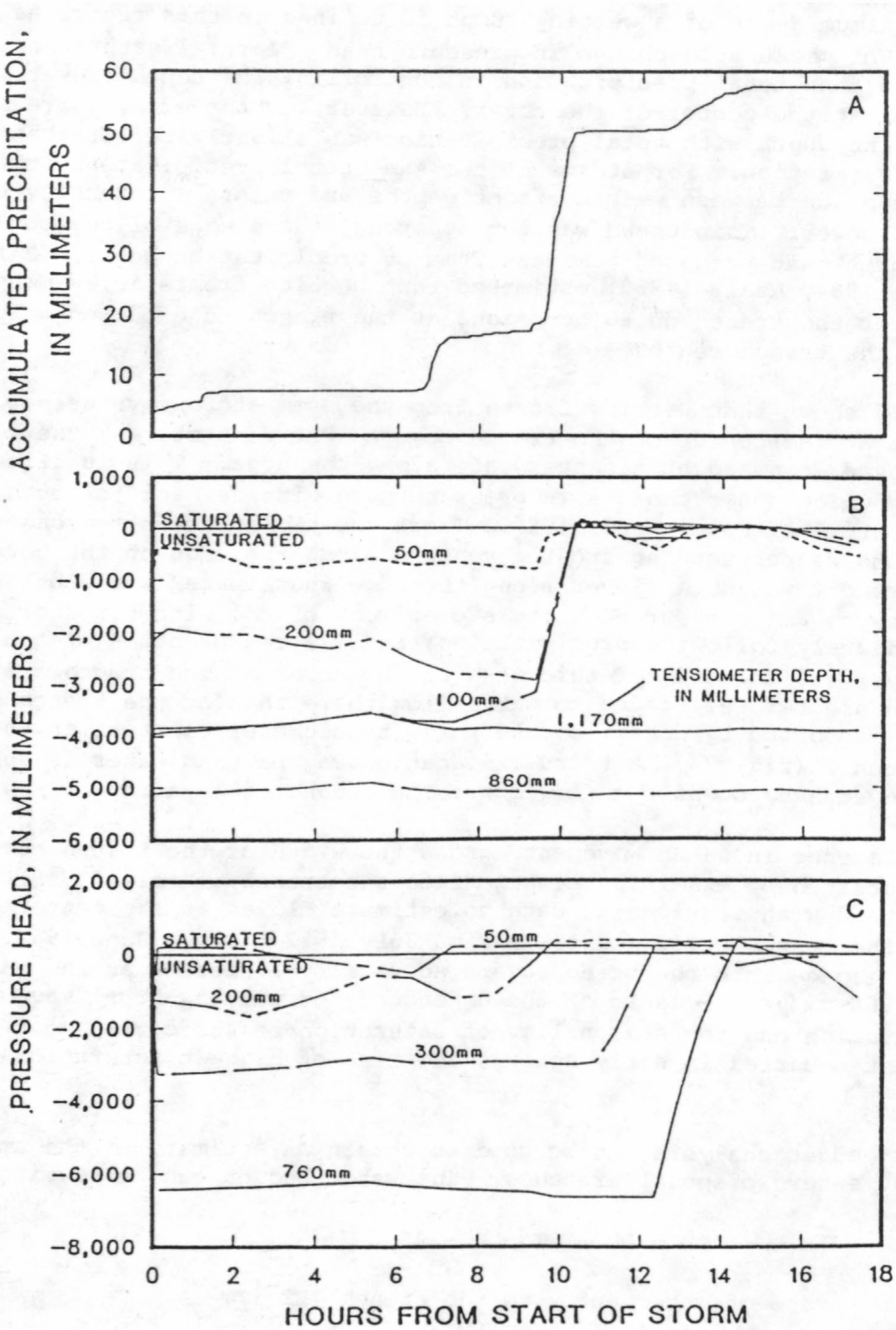


Figure 36.--Change in soil-moisture content in the cover of trench 2 during the rainstorm of November 1, 1982: A, Accumulated precipitation; B, Pressure head at the center of the cover; C, Pressure head at the edge of the cover.

Derivation of equation 6 assumes that all terms are averaged over the length of the sampling period and that all water flow is vertical. Table 3 shows the annual values of precipitation, evapotranspiration, runoff, change in soil-moisture content, and seepage into trench 2 for July 1982 through June 1984. For July 1983 through June 1984, the change in water stored in the trench cover was 60 mm. Data were not available from July through September 1982 to estimate the change in storage in the trench cover from July 1982 through June 1983. It was assumed that the change in water stored in the cover for those months was identical to that for July through September 1983. Comparisons of soil-water tensions between the first and second years implies that this assumption is reasonable. It must be realized that the values presented in table 3 are estimates that may contain errors that cannot be quantified (see Healy and others, 1989). Nevertheless, the mean annual rate of water movement into the trenches of 107 mm calculated from these estimates approximates the estimate of 209 mm calculated by the Darcy method (Healy, 1989) and the ground-water recharge estimate of 48 mm/yr given by Garklavs and Healy (1986). It should be noted that the calculated rate of water movement into the trenches cannot be directly equated to 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.

Table 3.--Annual estimates of components of the water budget

[All values in millimeters]

Water budget components	July 1982 through June 1983	July 1983 through June 1984
Precipitation[1]	928	968
Evapotranspiration[2]	625	689
Runoff[1]	208	112
Change in soil moisture in the trench cover	-12	60
Seepage into trench	107	107

[1]J.R. Gray (U.S. Geological Survey, written commun., 1986).
[2]Healy and others (1989).

A generalized water budget (recharge = precipitation - evapotranspiration - runoff) at the disposal site was compared to an approximated water budget from an undisturbed control site 0.5 km south of the disposal site to provide a general measure of the effect of trench cover and trench construction on recharge (to the unsaturated/saturated zone). This control site was monitored by Gray (1984) to collect comparative precipitation and runoff data. That study found no significant difference in measured precipitation between the two sites. For the 2-year period, July 1982 through June 1984, mean annual runoff at the control site (11 mm) was about one-fourteenth that of runoff at the disposal site (160 mm) (J. R. Gray, U.S. Geological Survey, written commun., 1986). Somewhat similar vegetative covers and soils at the two sites allows the assumption of generally equivalent evapotranspiration rates. Comparison of the estimated water budgets from the control site and from the disposal site indicates that there was about twice as much annual recharge at the undisturbed control site than at the disposal site (280 mm versus 132 mm). Compaction and mounding of trench covers appeared to have reduced recharge to the trenches and the saturated zone. In an earlier study, Foster and Erickson (1980, p. 21) also concluded that trench-cover construction reduced infiltration, as indicated by the comparatively small fluctuations of water levels in hilltop wells.

Water Movement Below the Disposal Trenches

Measured

Pressure heads, moisture content, and saturation data indicated that water movement through the unsaturated geologic deposits below the trenches typically occurred in an annual cycle without response to individual precipitation events and that the timing and rate of water movement was highly variable along the length of the tunnel.

The annual cycle of water movement at depth consisted of two primary phases, roughly seasonal in timing: (1) a wetting (recharge) phase and (2) a drying phase. During some annual cycles, and at some locations, an additional low-flow phase was evident. The annual cycle of water movement can be inferred from figure 37, which shows typical temporal trends in pressure head at five tensiometer locations. The seasonally timed wetting phase was typically marked by a gradual increase in soil-moisture content beginning in late winter or early spring. This initial increase was sometimes followed later in the spring by a more rapid increase. Maximum saturation occurred during late spring to midsummer. There was no apparent response to individual precipitation events at depth similar to that as observed in the soil zone near land surface. Following maximum saturation, the drying phase began as soil-moisture content decreased through the summer and into the fall and winter. During late fall through late winter, soil saturation and soil-water movement were at a minimum. During the low-flow phase, pressure heads remained nearly stable or slowly decreased from late fall until late winter or early spring. In like manner, ground-water levels characteristically rose in the spring and subsided through the summer (fig. 38). At some locations, a small rise in ground-water levels was detected in late fall.

Annual meteorological patterns influenced the timing and intensity of wetting and drying phases, and as a result, the characteristics of water movement may vary somewhat from year to year. The effect of meteorology on cycle characteristics can be shown by looking at pressure-head trends, air and soil temperatures, evapotranspiration, and trench-cover saturation from mid-1982 through mid-1984 (fig. 39). In the winter of 1982-83, the site was blanketed

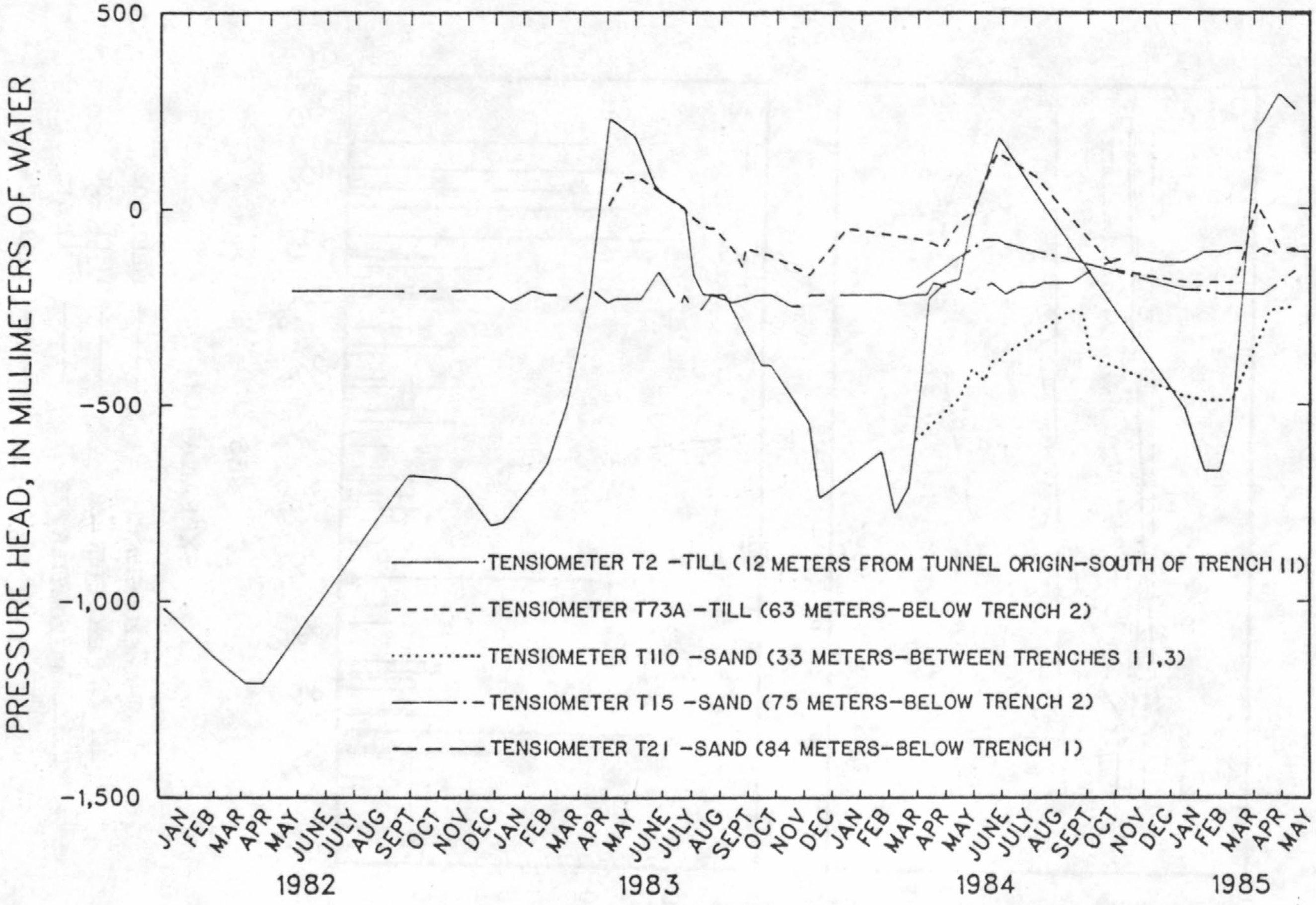


Figure 37.--Typical subtrench pressure-head trends, January 1982 through May 1985.

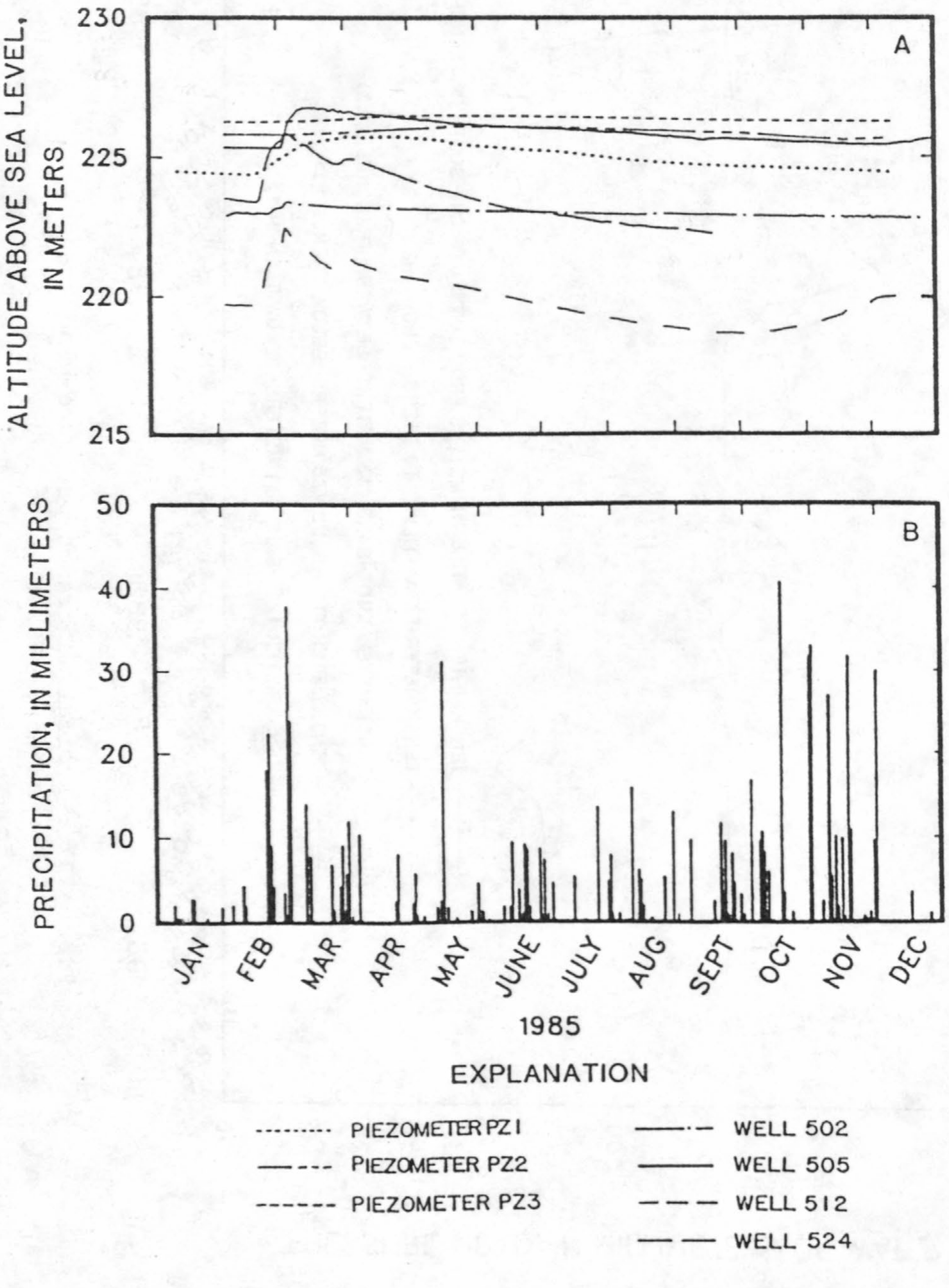


Figure 38.--Water-table altitudes in piezometers and wells in and adjacent to the tunnel (A) and daily precipitation (B), 1985.

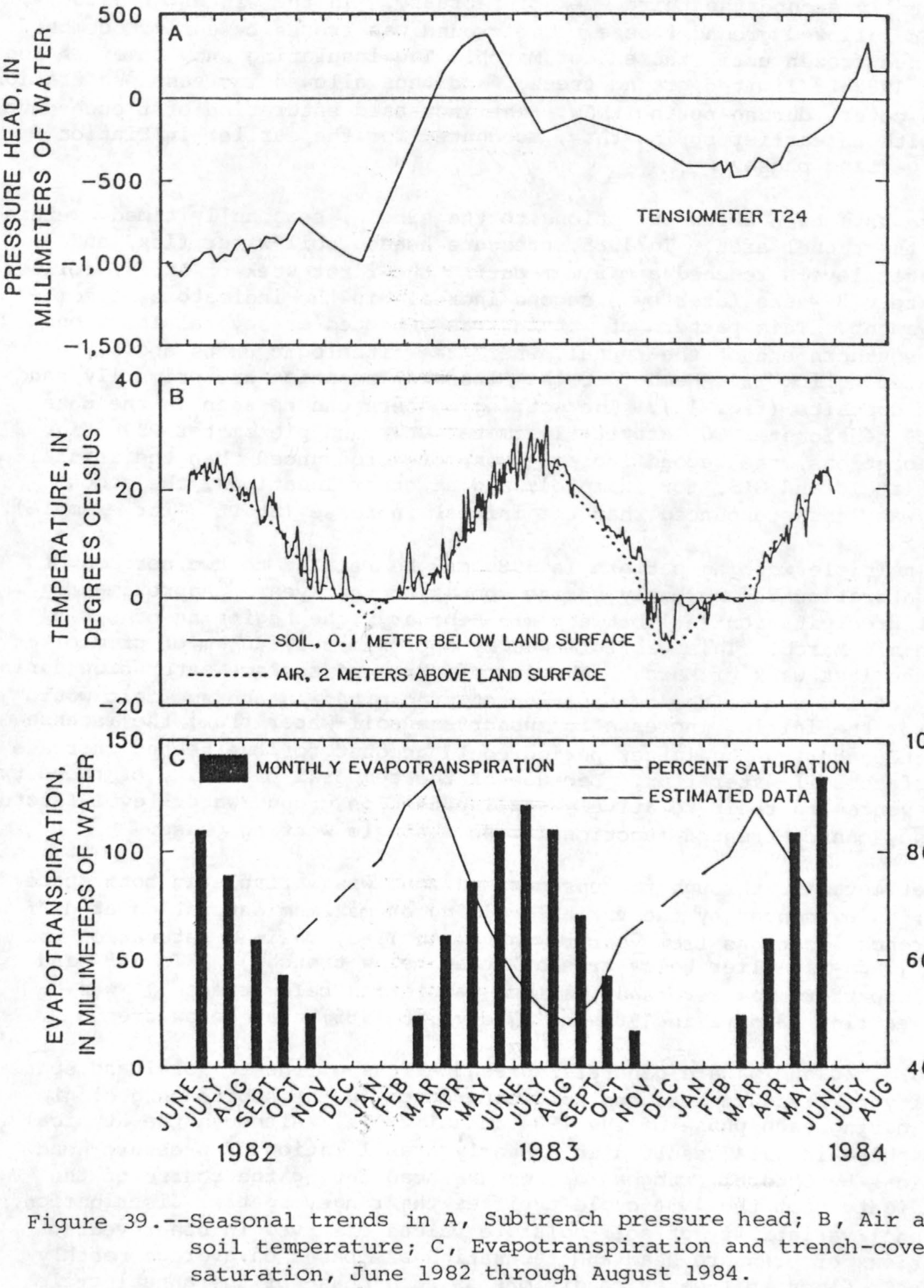


Figure 39.--Seasonal trends in A, Subtrench pressure head; B, Air and soil temperature; C, Evapotranspiration and trench-cover saturation, June 1982 through August 1984.

with snow by December. The soil (at 0.1 m below land surface) did not become continuously frozen until early January. Snowmelt and ground thaw began almost coincidentally around the third week of February. In the winter of 1983-84, snow cover followed ground freeze. The ground was frozen by early December and remained frozen until the end of March. The insulating snow cover in the winter of 1982-83 limited ground freeze, and thus allowed increased saturation of trench covers during spring thaw. The increased saturation of trench covers, coupled with an earlier spring thaw, accounted for the earlier initiation of the 1983 wetting phase.

There have been a few exceptions to the single, seasonally timed, wetting event in the tunnel area. In 1985, pressure heads, soil-water flux, and ground-water levels reached a maximum during the first week of April, followed approximately 3 weeks later by a second increase in the indicators of soil-water movement. This pattern of wetting was detected at several locations near the southern end of the tunnel, where the lithologic units above the instrumented Hulick Till Member of the Glasford Formation are primarily sand and loess deposits (fig. 12). The wetting pattern can be seen in the data records of tensiometer T6, gravity lysimeter GL3, and piezometer PZ1 (fig. 27). At some locations, the second increase was more pronounced than the initial increase (at T6 and GL3, for example), and at other locations, the second increase was less pronounced than the initial increase (at PZ1, for example).

The multiple wetting pattern in 1985 may be related to two periods of surface saturation in the early spring months of that year. Approximately 140 mm of precipitation fell between mid-February (the beginning of spring thaw) and mid-March. This was followed by approximately 40 mm of precipitation in the last week of March. The large degree of surface saturation during the early period due to the combination of precipitation and snowmelt would account for the initial increase in subsurface soil-water flux; the intense precipitation during the latter period could account for the second increase in subsurface soil-water flux. Because of the temporal proximity of these two wetting events and their relatively small effect on ground-water-level fluctuation, they can be treated functionally as a single wetting phase.

Water movement through the unsaturated zone was variable in both space and time, as evidenced by the variable timing of maximum saturation at different subtrench locations from year to year. In 1983, maximum saturation was detected 13 days earlier below trench 2 than below trench 11. In 1984 and 1985, this pattern was reversed; maximum saturation below trench 11 was detected earlier (8 days in 1984 and 17 days in 1985) than below trench 2.

Figures 40 and 41 are general representations of the temporal and spatial variability of pressure head and soil saturation in the subtrench geologic deposits during each phase of the 1984 annual cycle. Although the atypical low-flow phase in 1984 resulted in an early stabilization of pressure-head fluctuations by October, ranges in pressure head during the course of the study indicate that the 1984 cycle typifies the range, spatial distribution, and seasonal variability of soil-moisture values observed in other years. Distributions of pressure head and saturation are based on average monthly values and reflect soil-water conditions as each phase of the annual cycle began.

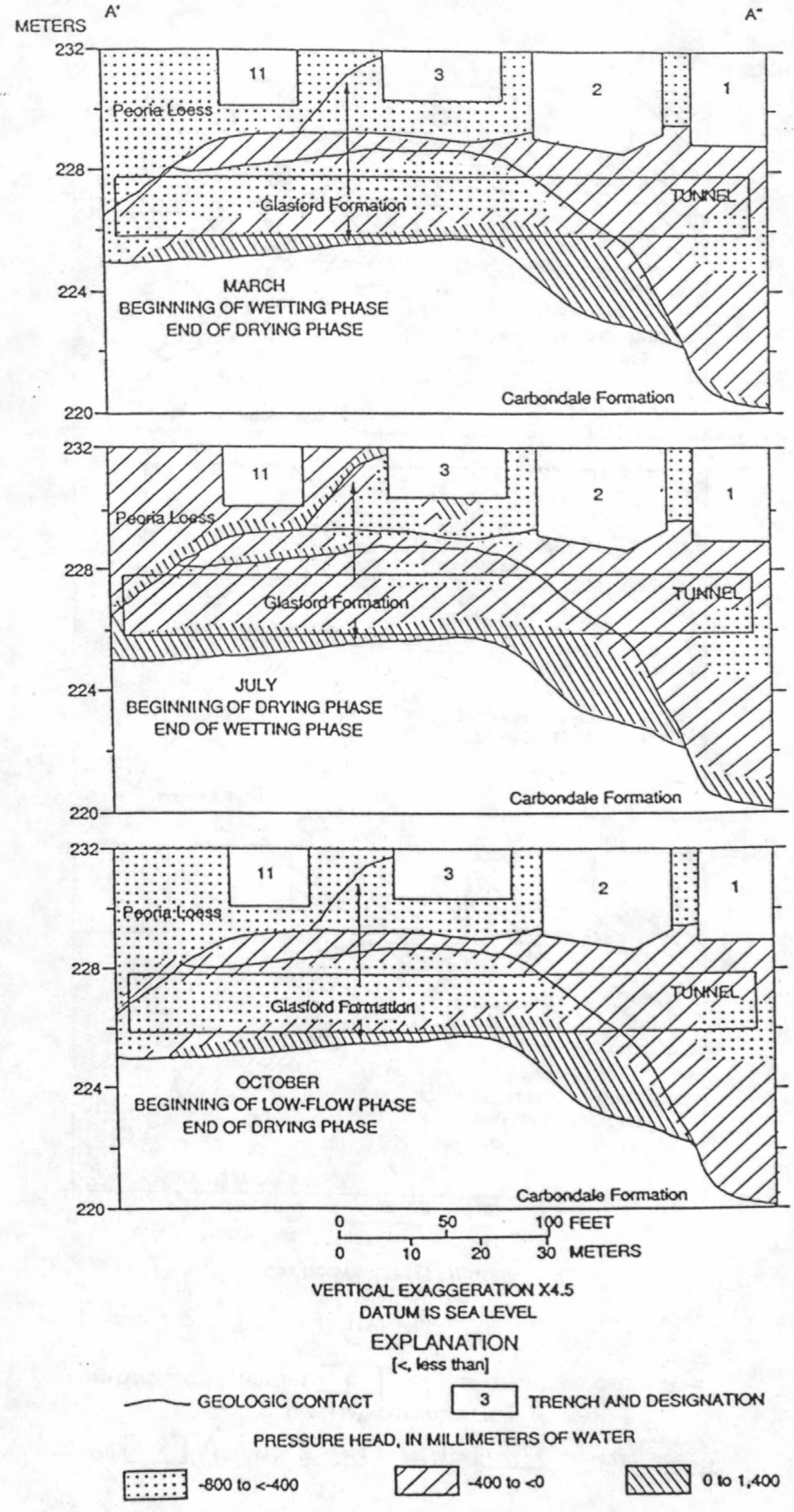


Figure 40.--Seasonal cycles of pressure head in subtrench glacial deposits in geologic section A'-A", 1984. See figures 3 and 4 for location of line of section and figure 12 for designation of geologic units.

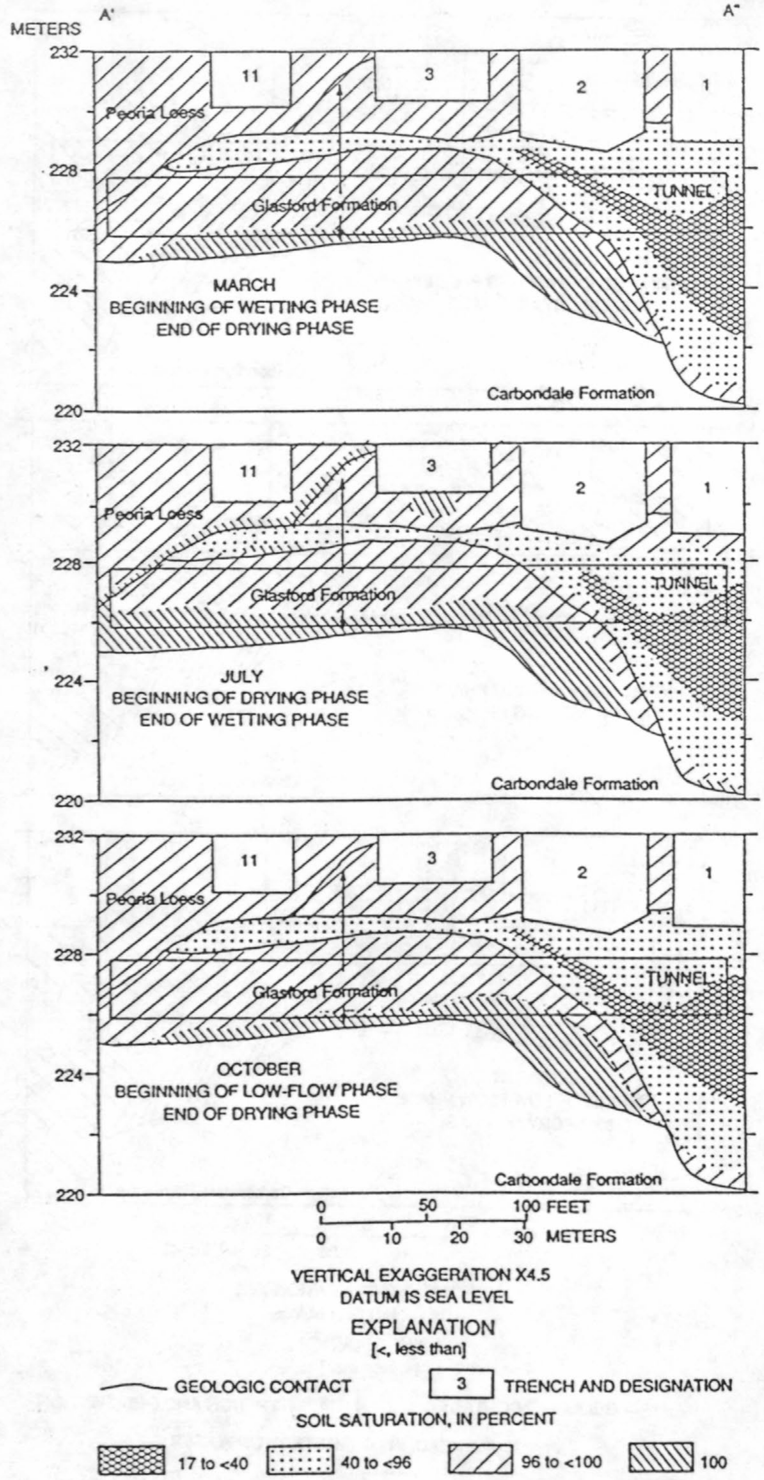


Figure 41.--Seasonal cycles of soil saturation in subtrench glacial deposits in geologic section A'-A", 1984. See figures 3 and 4 for location of line of section and figure 12 for designation of geologic units.

Pressure heads in the unsaturated portions of the subtrench geologic units during 1981-85 ranged from about -800 to -300 mm in the Radnor Till Member, -1,600 to +1,200 mm (seasonally saturated) in the Hulick Till Member, and -800 to -80 mm in the Toulon Member of the Glasford Formation. During 1984, pressure heads ranged from about -800 to -400 mm in the Radnor Till Member, -680 to +210 mm in the Hulick Till Member, and -600 to -110 mm in the Toulon Member (fig. 40). In the Hulick Till Member, average low-flow pressure heads during March, the month that preceded the initiation of the wetting cycle, were about -340 mm; average pressure heads during July, the month of maximum wetting, were about +10 mm. In the Toulon Member, average low-flow pressure heads were about -370 mm, and average pressure heads at maximum wetting were about -330 mm.

During 1984, the Radnor Till Member of the Glasford Formation was consistently about 99 percent saturated (fig. 41). The Hulick Till Member was typically 99 percent saturated, except during wetting phases, when portions of it were 100 percent saturated. Saturation in the Toulon Member ranged from 16 to 95 percent. Average saturation of the Toulon Member during the low-flow phase was about 25 percent, and average saturation during maximum wetting was about 29 percent. Saturation of the subtrench geologic units was not computed for years other than 1984; the range of pressure heads in those units indicated that volumetric moisture content, and thus saturation, varied little during the study period.

The range of pressure heads in the deeper unsaturated-zone deposits was generally less extreme than the range of pressure heads in deposits near land surface (approximately -8,500 to +1,000 mm in the trench cover) because of the absence of the influence of evapotranspiration at depth. The wide range of pressure heads in the Hulick Till Member (relative to the Toulon Member) is indicative of the temporal and spatial variability of soil-water movement within this unit, as well as the distribution of the monitoring instruments. Several tensiometers in the Hulick Till Member were installed near the saturated zone and responded to the seasonal rise of the water table. Additionally, these pressure-head/saturation data indicate the following: (1) Pressure heads in the the Hulick Till Member were more variable in both space and time than in the Toulon Member; (2) the Hulick Till Member and Radnor Till Member were continuously near or at full saturation, having minimal variability in moisture content; (3) pressure heads, moisture content, and saturation in the Toulon Member varied minimally over time; spatial variability in the unit was more pronounced; and (4) temporal variability of pressure head was limited in the Radnor Till Member.

Minimum and maximum vertical hydraulic gradients in the Hulick Till Member and the Toulon Member from 1981-85 (table 4) were computed using pressure-head data from nearby, vertically paired tensiometers. Gradients in the Hulick Till Member, at 6 to 12 m in from the south end of the tunnel, ranged from -0.28 to 2.57 mm/mm (millimeter per millimeter) (positive being downward) with an average minimum of 0.47 mm/mm and an average maximum of 1.67 mm/mm. Near the sloping interface in the midsection of the tunnel (at 62 to 67 m), gradients ranged from -0.03 to 2.71 mm/mm. The average minimum in this vicinity was 0.22 mm/mm, and the average maximum was 1.52 mm/mm. Gradients in the Toulon Member (at 67 to 86 m) ranged from 0.50 to 2.41 mm/mm with an average minimum of 1.09 mm/mm and an average maximum of 1.62 mm/mm.

Table 4.--Maximum and minimum vertical hydraulic gradients at selected subtrench locations in the Glasford Formation

[Gradients in millimeters per millimeter]

Hulick Till Member (near south end of tunnel)			Hulick Till Member (near sloping sand-till interface)			Toulon Member (near north end of tunnel)		
Tensiometer pairs	Date	Gradient	Tensiometer pairs	Date	Gradient	Tensiometer pairs	Date	Gradient
24 - 6	08-24-84	1.63	47 - 73B	12-07-83	1.10	109C - 7	04-18-84	2.37
	05-05-83	.53		07-05-84	-.03		03-14-85	1.46
23 - 28B	06-02-83	2.16	4 - 73A	05-14-85	.93	21 - 109C	06-21-85	1.35
	12-18-83	.69		05-26-84	.08		04-18-84	1.11
23 - 28A	01-12-83	1.12	13A - 77B	06-30-83	1.04	21 - 109B	06-21-85	1.07
	12-18-83	.71		10-26-83	.03		03-20-84	1.05
24 - 28A	12-18-83	1.42	77B - 77A	08-01-83	1.54	7 - 109B	01-14-85	.67
	05.14-85	.61		08-23-83	.70		05-14-85	.50
24 - 28B	04-15-83	2.29	1 - 13A	05-16-84	1.40	12 - 13B	05-29-84	2.05
	08-03-82	.94		03-23-82	.19		04-27-82	.65
28B - 28A	02-22-85	.77	77B - 73A	10-27-83	2.71	9B - 9A	04-08-82	2.41
	05-17-85	-.28		02-05-85	.09		06-09-83	.94
24 - 23	03-14-85	2.57	2 - 73A	05-14-85	2.40	5 - 3	05-29-84	1.95
	01-12-83	.30		06-26-84	.58		09-29-83	1.22
2 - 23	05-05-83	1.65	7 - 11	07-23-84	1.00	21 - 3	05-24-85	2.39
	06-24-82	.62		07-26-83	.15		04-18-84	1.63
23 - 6	05-19-83	1.43				21 - 22	06-02-83	1.10
	04-27-85	.11					10-15-83	.88
						22 - 7	10-13-83	2.37
							04-11-84	1.70
						18 - 20	06-26-84	1.14
							01-25-84	1.06
						21 - 7	06-24-85	1.41
							06-09-82	1.24
						109C - 109B	05-29-84	.84
							04-27-85	.72

Gradients in both units were typically larger during wetting or drying phases because of the unequal distribution of soil water across the unsaturated zone at these times. Gradients in the 6- to 12-m and 62- to 67-m till localities were generally similar. Negative gradients (indicating capillary rise) did not occur in the sand. Hydraulic gradients fluctuated less between the wetting and drying phases in the sand unit than in the till unit.

Estimates of linear vertical velocities of water movement through the unsaturated subtrench deposits were computed using equation 2 and hydraulic gradients presented in table 4. Maximum linear velocities were estimated to be 3.9 mm/d (millimeters per day) [between tensiometers T23 and T28B, June 1983 (fig. 27a)] in the Hulick Till Member and 660 mm/d [between T21 and T22, June 1983 (fig. 27b)] in the Toulon Member. Maximum linear velocities averaged 2.3 mm/d in the till unit and 1.7 mm/d in the sand unit.

Water movement through the subtrench geologic deposits near trench 11 was evaluated during 1985 by monitoring drainage discharge to gravity lysimeters GL2 and GL3 (fig. 42). Water movement through both the Peoria Loess (GL2) and the Hulick Till Member (GL3) was first detected in late March. Drainage from lysimeter GL3, installed to the stratigraphically lower interface between the Toulon and Hulick Till Members, continued for about a month longer than drainage from lysimeter GL2. No water movement was detected at lysimeter GL1 (below trench 2) in 1985.

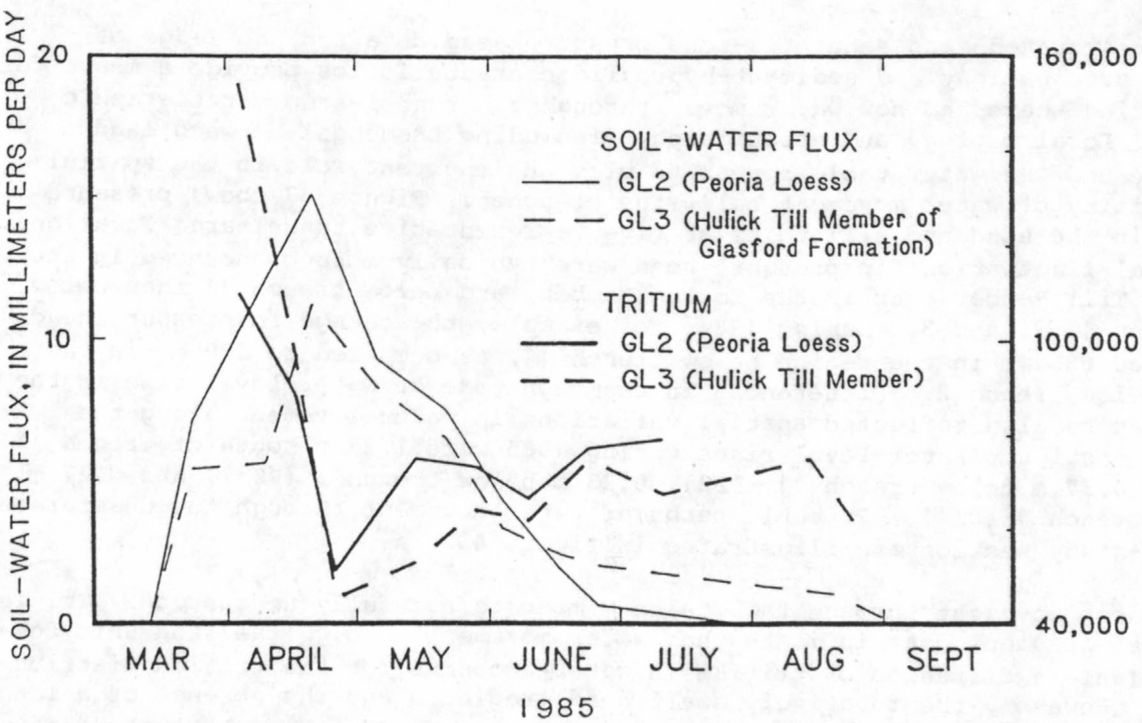


Figure 42.--Soil-water flux and tritium concentrations in soil water at gravity lysimeters GL2 and GL3, March through September 1985.

Soil-water fluxes through the Peoria Loess and Hulick Till Member were indirectly estimated by computing volume discharge per orifice area of the gravity lysimeter. Computation of flux by this method is only possible when the sediments are near, or at, full saturation; otherwise, drainage will not occur. Maximum flux through the two units averaged 13.0 mm/d. Prior to mid-June, soil-water flux was greater in the Peoria Loess than the Hulick Till Member. The temporal pattern of water movement seems to represent the natural downward movement of a wetting front from the upper horizon of the Peoria Loess to the lower horizon of the Toulon Member. Greater volumes of water generally drained from the lower horizon, suggesting that the Toulon Member sand deposits became more saturated relative to the Peoria Loess as vertical flow in the sand unit was impeded by the underlying, poorly permeable Hulick Till Member.

Estimates of flux generally should be less than estimates of flow velocity (Hillel, 1980a, p. 177). The fact that flux estimates (as determined from gravity lysimeters) exceeded flow velocity estimates (as determined from soil-moisture tensiometers) appears to be an additional indication of the variability of pressure-head and soil-water movement in the subtrench geologic deposits. Other explanations may include (1) vertical flow is assumed in the calculation of linear velocity and flux, but there may have been some contribution from lateral flow along sloping geologic interfaces; (2) errors in the estimation of hydraulic conductivity; and (3) instrument accuracy (soil-moisture tensiometer and(or) gravity lysimeter).

Unsaturated- and saturated-zone pressure-head data and knowledge of tunnel-area geology and sediment-hydraulic characteristics provide a means for evaluating where and how water moves through the tunnel-area stratigraphic units. Local geology and stratigraphy (including trenches) between land surface and the water table appear to play an important role in the spatial variability of water movement below the trenches. Figure 37 shows pressure heads in the sand and till units at five representative tunnel-area locations. Temporal fluctuations in pressure head were typically more pronounced in the Hulick Till Member than in the Toulon Member, and below trench 11 than below trenches 1, 2, and 3. During 1984, for example, the change in pressure head averaged 820 mm in the region below trench 11, as compared to 200 mm in the area below trench 2. Differences in the magnitude of water-level rise in the piezometers also reflected spatial variations in water movement along the tunnel section. Water-level rises during 1985 were 1.27 m south of trench 11 (PZ1), 0.37 m below trench 11 (PZ2), 0.23 m below trench 3 (PZ3), and 0.27 m below trench 1 (PZ4). Probable paths of water movement through the unsaturated tunnel-study section are illustrated in figure 43.

Water movement through the Toulon Member is not fully understood. Tritium and head-gradient data indicate that water movement through the sand unit does occur (unless diffusion of tritium in water accounts for the tritium distribution). However, the relatively small head gradients and the absence of a large seasonal influx of soil water do not seem to account for the relatively fast rates and large distances of tritium migration from the trenches. With the exception of two tensiometer locations, T110 [in the sand lens below trenches 3 and 11 (fig. 26A)] and T15 [directly below trench 2 (fig. 26B)], little to

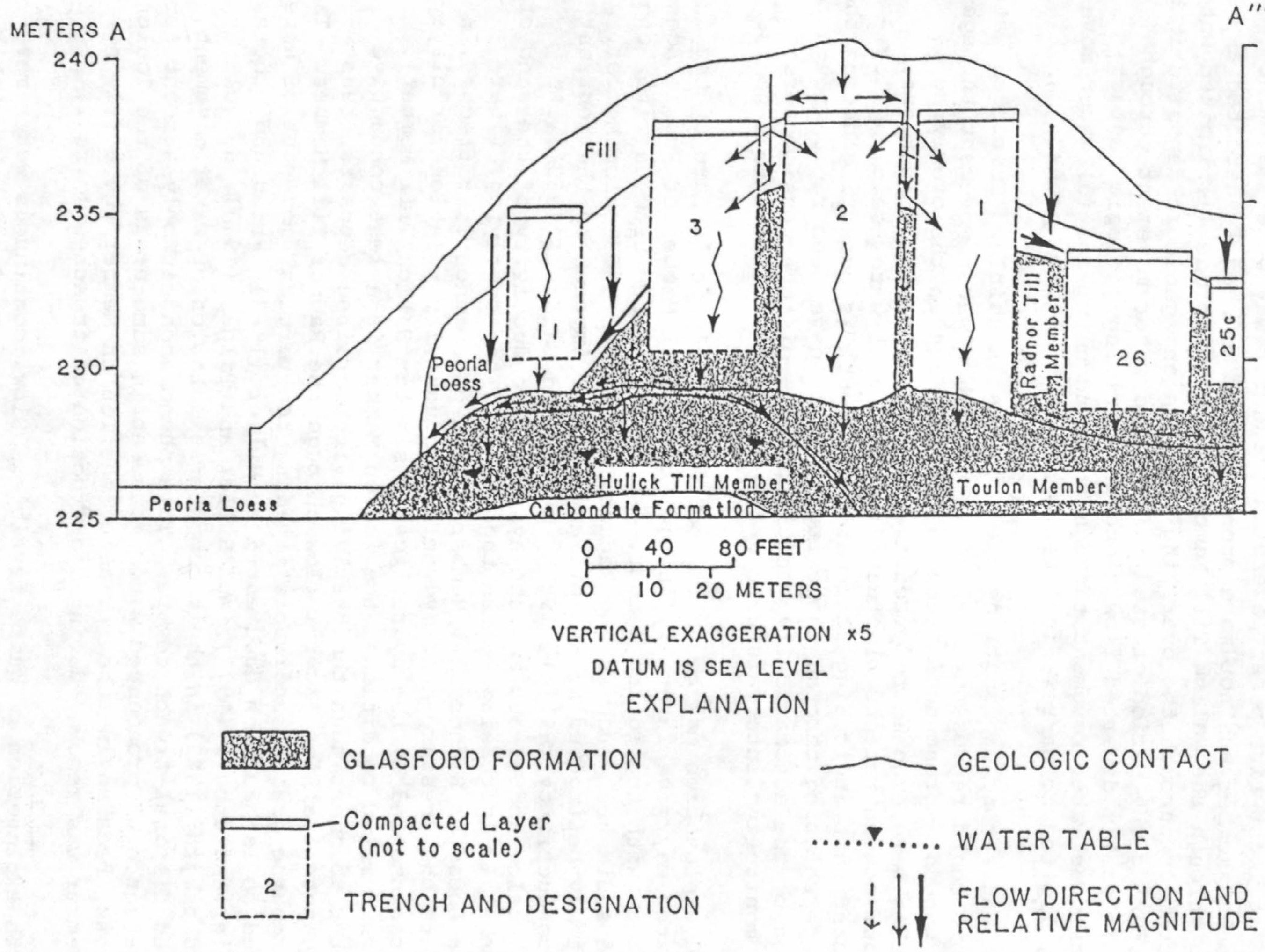


Figure 43.--Probable flow paths through the unsaturated geologic deposits and trenches in geologic section A-A'''. See figures 3 and 4 for location of line of section.

no seasonal fluctuation in pressure head or soil saturation (figs. 37, 40, and 41) was detected in the sand unit. The pressure-head record of tensiometer T21 (fig. 37) is typical of most tensiometers in the sand unit. Seasonal water-level fluctuations in piezometers PZ4 and PZ5, screened in the sand unit, also were limited.

There are at least five possible explanations for why water movement through the Toulon Member was not more pronounced or as readily detected as water movement through the Hulick Till Member. These include (1) limited water and tritium movement through the overlying trenches and geologic deposits into the sand unit during the period of study; (2) rapid water movement through the sand; (3) laterally diverted flow along an overlying geologic contact; (4) slow, continuous water movement through the sand unit; and (5) water movement primarily limited to narrow, isolated, preferential flow paths.

The first and second explanations are the least feasible. Tritiated water in the sand unit could represent a period in time when water movement through the sand unit was more pronounced, such as while wastes in the overlying disposal trenches were exposed to precipitation during burial operations. However, tritium concentrations fluctuated at most soil-water-sampling locations in the sand unit indicating that water movement was occurring during the study. Water percolating through the unit could not have been rapid enough to avoid detection by the automatically monitored soil-moisture tensiometers; pressure-head monitoring intervals were as frequent as 5 minutes to 2 hours.

The third explanation may be valid, but if so, only for a part of the sand unit. Water may move laterally in the Radnor Till Member or Peoria Loess above the contact with the Toulon Member. At the interface between fine- and coarse-grained sediments, such as the Radnor Till Member and Toulon Member, water movement may be impeded by a capillary barrier imposed by the contrast in hydraulic conductivity (Hillel, 1980b; Miller and Gardner, 1962). At pressure heads below about -350 mm, the hydraulic conductivity of the sand of the Toulon Member is increasingly less than that of the overlying, finer-grained Peoria Loess or Radnor Till Member. This phenomenon is reflected in figure 30 (where the pressure-head/hydraulic-conductivity relation for clayey-silt till is represented by the hydraulically similar Hulick Till Member). Except under very moist conditions, the Toulon Member is a less conductive medium for water movement than the overlying finer-grained deposits, thus increasing the potential for lateral flow through the Radnor Till Member. The phenomenon of coarse-grained sediments impeding the vertical movement of water through layered soils has been documented by Miller (1963), Frind and others (1976), Clothier and others (1977), and Hillel and Talpaz (1977), as well as by Johnson and others (1983) in their computer simulation of water movement through layered disposal-trench covers. This phenomenon can only account for the apparent absence of pronounced water movement in some areas of the Toulon Member sand lens, because in other areas of the Toulon Member the overlying Radnor Till Member was removed during construction of trenches 1 and 2.

The fourth explanation is quite feasible. Slow, continuous water movement could account for the general absence of pressure-head and water-table fluctuations, as well as the typically consistent vertical hydraulic gradients.

Fluctuations in tritium concentrations, however, indicate that at some locations water movement through the sand is periodic. A variable tritium source coupled with slow, continuous water movement could produce fluctuations in tritium concentrations; however, the cyclical nature of the tritium-concentration fluctuations appears more indicative of periodic water movement.

The fifth explanation also is quite feasible. Unsaturated flow through layered fine- and coarse-grained sediments, similar to the sand of the Toulon Member, may be restricted to very narrow flow paths (Palmquist and Johnson, 1962, p. 143). The identification of several areas in the Toulon Member where soil-water velocities were somewhat elevated appears to support the existence of localized, preferential flow paths. Locations of elevated tritium concentrations also may be indicative of preferential flow paths in the sand unit but also could represent the locations of deteriorating waste containers in the overlying trenches. The fact that localized flow paths were not readily detected by the conventional soil-water monitoring instruments (tensiometers and small-diameter gravity lysimeters) used in this study, indicates that such instruments may be inappropriate for fully characterizing water movement through coarse-grained sediments, such as sand. In all likelihood, water movement through the sand of the Toulon Member can be accounted for, in varying degrees, by a combination of the five above-listed mechanisms.

Water that moves downward through the Toulon Member may follow several paths before it reaches the underlying Hulick Till Member. Soil water that percolates downward north of the surface high in the Hulick Till Member may be diverted northerly along the sloping face of the sand-till interface (fig. 43). Soil water draining south of the surface high either flows southward along the sand-till interface into the Peoria Loess, where the sand unit pinches out, or continues percolating downward into the underlying Hulick Till Member. During periods of recharge, perched-water conditions develop above local depressions in the till surface (figs. 26A, 40, and 41) creating sufficent head pressure to allow infiltration into the till by a mechanism analogous to depression-focused recharge as described by Lissey (1971). Water movement through the till was quite pronounced just south of the surface high in the till unit, between trenches 3 and 11. Local highs in the till surface that flank the tunnel in some areas (fig. 13) indicate that, in addition to the dominant north-south direction of flow in the tunnel area, flow along the till surface also may have an east-west component.

Soil water that percolates through the Toulon Member or Hulick Till Member ultimately reaches the water table. The water table was in the Hulick Till Member along most of the length of the tunnel; it was in the basal deposits of the Toulon Member near the north end of the tunnel, where the Hulick Till Member is absent (fig. 12). Ground-water flow in the immediate vicinity of the tunnel is northward and southward from the ground-water divide below trench 3 (fig. 43).

The absence of the Hulick Till Member near the north end of the tunnel may provide an explanation for the apparently rapid movement of tritium beyond the eastern boundary of the site toward well 602 (fig. 4). Garklavs and Healy (1986) were unable to explain this phenomenon. The hydraulic connection between the saturated Toulon Member and bedrock near the north end of the tunnel may allow leakage into shallow underlying coal seams or fracture zones (fig. 44) that dip to the southeast. Coal seams and fracture zones are reported as sources of moderate water yields from the bedrock in the area (Bergstrom, 1956, p. 15). Additionally, erosion of the till unit may represent an isolated outwash channel (fig. 17) where eastward ground-water movement occurs.

Simulated

Water movement in the sediments underlying the four disposal trenches was simulated by means of a two-dimensional finite-difference model (Lappala and others, 1987). The goals of modeling were to (1) characterize the unsaturated-flow system, (2) aid in the design of the instrumentation and data-collection network, and (3) assess the validity of the hydrogeologic data. The numerical model is based on the modified Richards equation

$$S dh/dt = \nabla . (K(hp) \nabla h) + Q, \qquad (7)$$

where S = storage term (L^{-1}),
= specific moisture capacity, for unsaturated conditions,
= specific storage, for saturated conditions,
h = total hydraulic head (L),
t = time (T),
∇ = gradient with respect to X, Z (L^{-1}), and
Q = a general source/sink flux in terms of volume per unit volume (T^{-1}).

A 47-node by 36-node rectangular grid consisting of 1,692 cells represented the modeled area. At each node of the grid, equation 7 was approximated by a finite-difference equation. This set of equations was then solved simultaneously for each time step. More detail on the finite-difference approximations, as well as information on use of the computer model, can be obtained in Lappala and others (1987).

The modeled area of geologic section A-A'" is shown in figure 45. It corresponds to a north-south section parallel to and 1.5 m east of the section in which the tunnel lies; the tunnel itself is not present in the section. The section is 102.3 m in length and 10.9 m in height. The upper boundary represents an altitude of 229.6 m, which generally coincides with the bases of trenches 3 and 11. The bases of trenches 1 and 2 are approximately 1 m lower. The lower boundary, at an altitude of 218.7 m, corresponds to what was originally assumed to be the lowest altitude of the bedrock surface (at the northern end of the section). Subsequent investigation indicated that the actual altitude of the bedrock surface is approximately 1.5 m lower. The northern boundary corresponds to a ground-water divide in the saturated zone. The southern boundary corresponds to a water-table location where the amplitude of water-level fluctuations are small, thus approximating a ground-water divide. Ideally, this boundary should extend to a true ground-water divide 80 m to the south. Figure 45 also shows the divisions between lithologic units that were used for simulation; values for the hydraulic properties of the units are given in table 2.

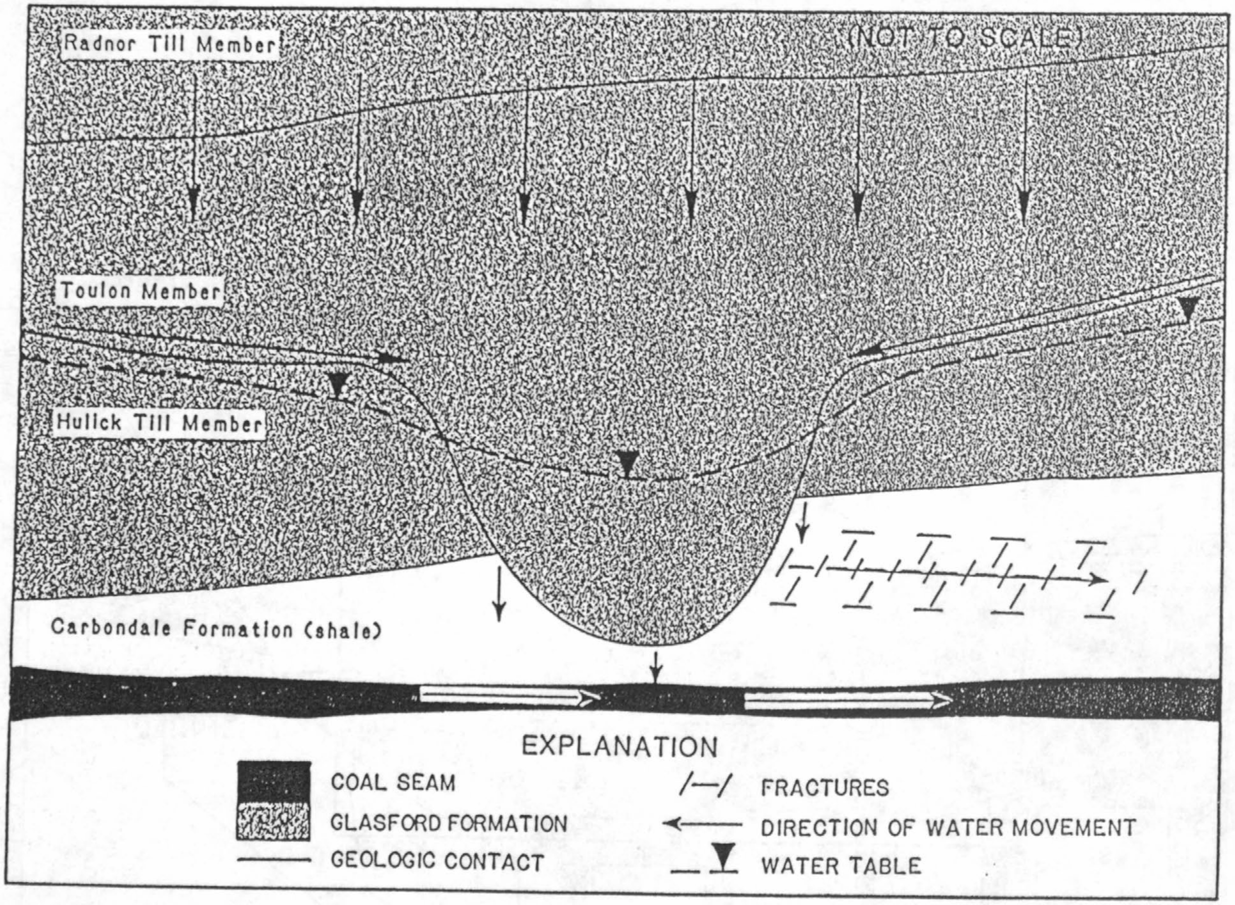


Figure 44.--Generalized diagram showing potential flow paths of water and tritium into and through glacial deposits and bedrock.

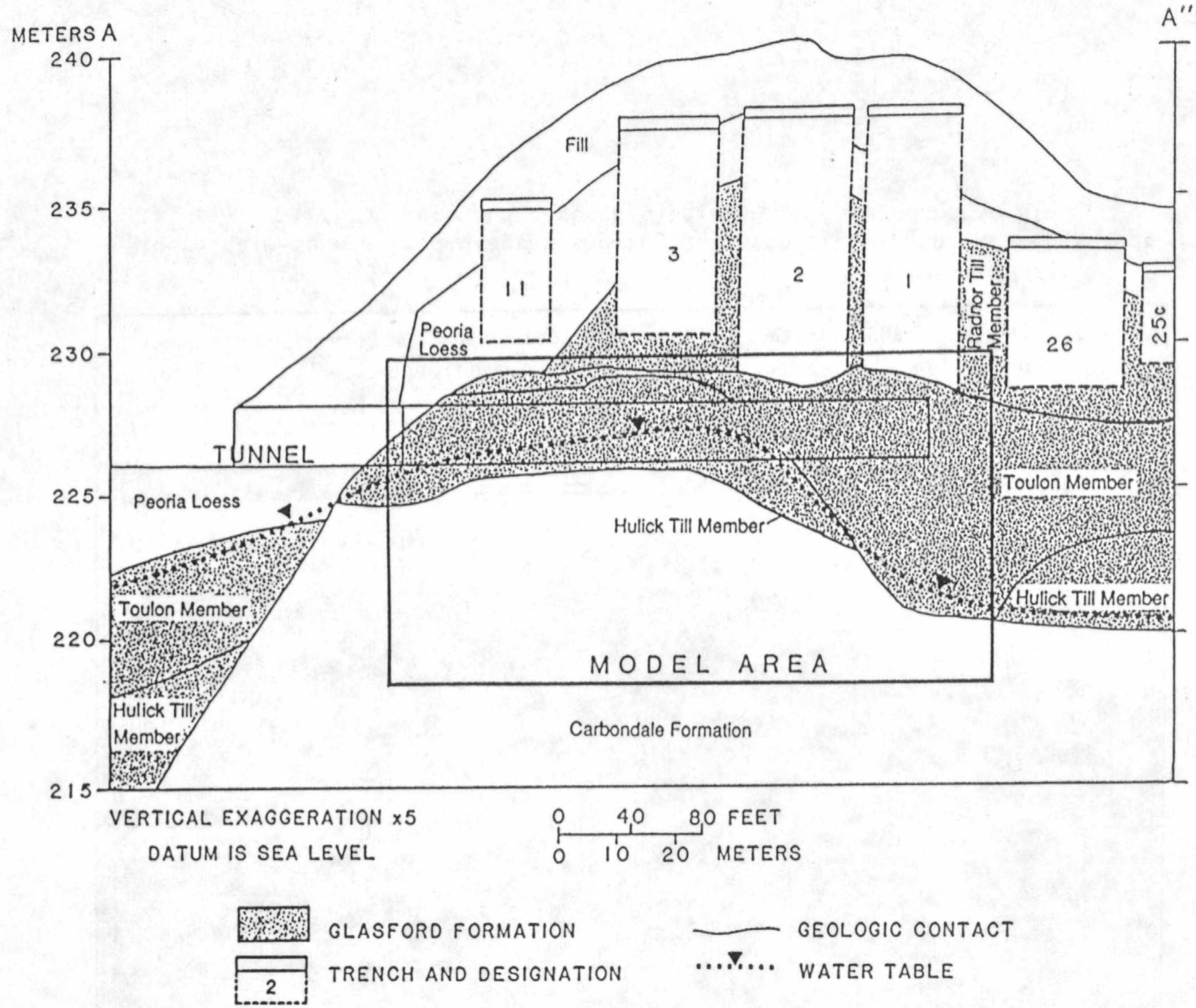


Figure 45.--Discretized model area in geologic section A-A''' with flow boundaries and soil-texture classes. See figures 3 and 4 for line of section.

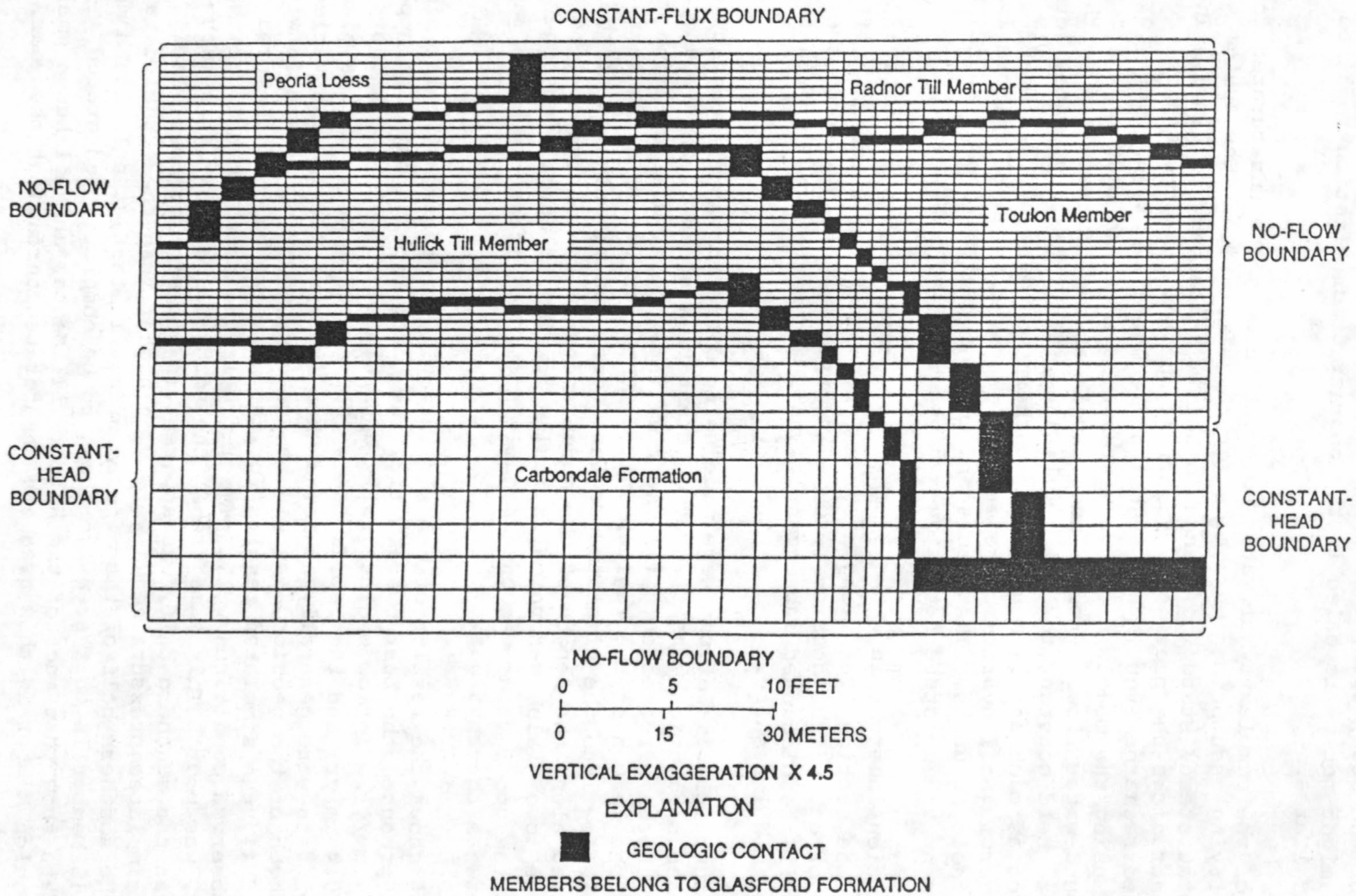


Figure 45.--Continued.

The simulated area was only a small part of the study area. By examining a subsection of the study area, it was hoped that many details might be revealed that might not be revealed in the coarser discretization required for the larger model area.

Because of the complexity of water movement through the unsaturated zone, several simplifying assumptions were made for the simulation. The system was assumed to be at steady state (no change in head with respect to time). This assumption contradicts the previously described observation of a single, seasonally restricted recharge event; this transient recharge event was, therefore, not evaluated using the model. It also was assumed that the bedrock was impermeable to ground-water flow. Ground-water levels at the northern and southern boundaries were held constant for all simulations. In actuality, water levels have fluctuated as much as 1.4 m near the southern boundary and 0.2 m near the northern boundary. Soil hydraulic properties were assumed to be uniform in individual lithologic units. The Brooks and Corey formulas (eqs. 1 and 2) were used to represent the moisture-retention and conductivity curves.

An assumption inherent in a two-dimensional, cross-sectional vertical model is that the section lies along a streamline. That is, there is no flow of water into or out of the section, except in directions co-planar to the section. As will be discussed subsequently, this assumption has important bearing on the model results.

Several computer simulations were made using different upper boundary conditions; each simulation consisted of constant-flux nodes at this boundary. Two basic hypotheses were tested: (1) The flux into the simulated region was uniform along the length of the region, and (2) the flux varied along that length. Total flow into the simulated region (total annual recharge at the site discretized along the length of the model section) ranged from 0.1 to 350 mm/yr. The lower value was unrealistically low for an annual recharge rate, whereas the upper value was unreasonably high; the actual recharge rate should lie between these values.

Figure 46 shows the results of one simulation. For this particular simulation, which produced the best overall fit, the total flow through the upper boundary was 1 mm/yr. Inflow was unequally apportioned between the Radnor Till Member (0.4 mm/yr) and the Peoria Loess (2.2 mm/yr). As with this simulation, better fits were generally achieved when incoming fluxes were varied across the length of the section. As can be seen by comparing figure 46 with figures 40 and 41, the simulated results for the northern half of the area matched the observed conditions well. The match in the southern half of the area, however, was poor. This same trend, the northern half having a much better fit than the southern half, was apparent in all simulations. In general, the simulated pressure heads were much higher than the actual data indicate in the southern half of the modeled area. In fact, the Toulon Member and Hulick Till Member in that area are shown to be completely saturated, whereas the data show that much of the Hulick Till Member and all but a small part of the Toulon Member in this area are unsaturated throughout the year.

One reason for the poor fit in the southern region of the modeled area may be that, in actuality, there is water flow out of the vertical section in that area. This is most easily explained by the lateral movement of water

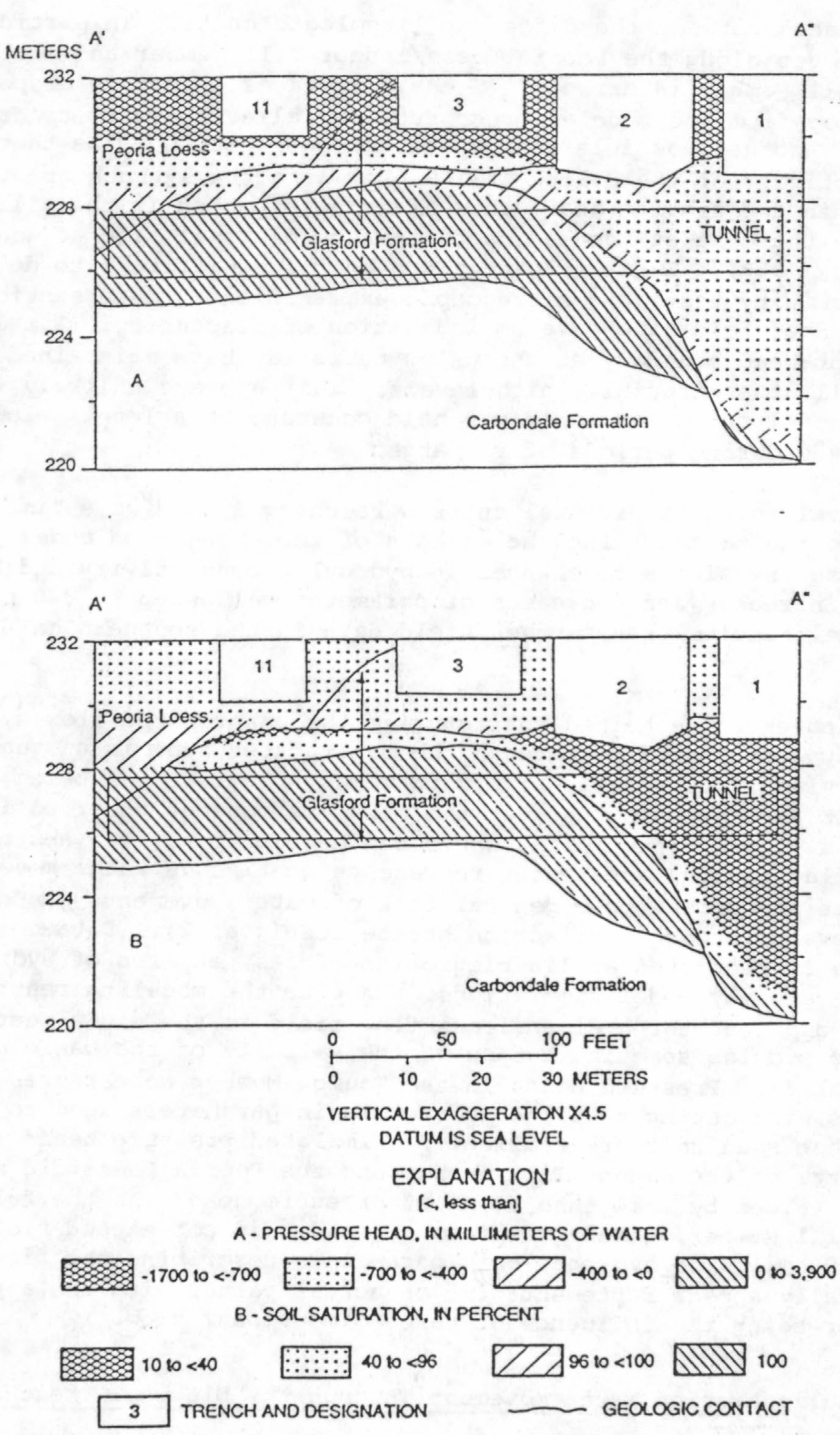


Figure 46.--Simulated pressure head (A) and soil saturation (B) in subtrench glacial deposits in geologic section A'-A". See figures 3 and 4 for location of line of section and figure 12 for designation of geologic units.

along the interfaces between the different lithologic units. In particular, water probably moves along the Peoria Loess/Radnor Till Member and Toulon Member/Hulick Till Member interfaces. These interfaces appear to slope to the east and west away from the modeled cross section, allowing water to drain out of the section. Another possible reason for the poor fit could be that the hydraulic conductivity of the Hulick Till Member is actually much greater than the values used in the simulations. This might be expected if the till were fractured, as is the case at the radioactive-waste disposal site at West Valley, New York (Prudic, 1986). These fractures can be quite difficult to detect; hydraulic-conductivity tests and microscopic examination of thin sections from the till at the Sheffield site gave no indication of fracturing. Finally, the use of a constant-head boundary at the water table may have maintained pressure heads in the till at artificially high levels. This appears unlikely, however, because in the model the water table was held constant at a level below that generally observed during periods of recharge.

Parameter values for individual units were changed, one at a time, and new simulations were run to determine the effects of the changes on model results. The model was most sensitive to changes in hydraulic conductivity and recharge rate; however, increases and decreases of parameter values up to 900 percent produced no model results that matched field data in the southern half of the site.

The modeling exercise helped characterize the unsaturated flow system (goal 1). It appears that flow through the unsaturated zone is unequally distributed, moving through a flow field that must be viewed as being three-dimensional. It also appears that, at the moisture content observed in the Toulon Member, a significant flux of water can be occurring; the absence of pressure-head fluctuations apparently represents continuous water movement at a very slow rate as opposed to a general lack of water movement. Model results were used in developing data-collection strategies (goal 2). Data-collection activities were concentrated at lithologic interfaces, an area of hydrologic importance indicated by model simulations. Despite the modeling restrictions imparted by an apparent three-dimensional flow field in the study section, the simulations did provide some indication of the validity of the basic hydrogeologic data (goal 3). Pressure heads in the Toulon Member were representative of field values, indicating that the hydrogeologic parameters used to describe the Toulon Member sand unit are realistic. Simulated pressure heads in the unsaturated parts of the Radnor Till Member and the Peoria Loess did not exceed existing field values by more than 50 mm of pressure head. In the fully saturated Hulick Till Member, simulated pressure heads did not exceed field values by more than 300 mm. The hydrogeologic parameters describing the fine-grained deposits generally appear representative of actual values with the apparent source of error being the influence of three-dimensional flow.

Conceptualization of Water Movement Through the Disposal Trenches

Waste containment and burial techniques suggest the disposal trenches should be highly permeable. The large variety of types and sizes of waste containers, and their sometimes random burial arrangement, would suggest that numerous voids and open channels between the waste containers exist in the trenches. It is likely that some voids would be filled during construction of trench covers, as loose sediment filtered down between the waste and less supportive containers were compacted by the addition of overburden and movement of construction equipment. On the basis of records of waste and trench volumes (Kahle and Rowlands, 1981), it has been estimated that voids within the trenches ranged from 36 to 67 percent following burial. The collapse of trench surfaces also indicates that a substantial amount of void volume remained following trench construction, and that new voids are created as waste containers deteriorate and adjacent trench sediments settle into the newly created voids.

The potential for substantial void volumes suggests that the trenches may be hydraulically similar to karstic limestone deposits or fractured rocks having large secondary permeability. Large voids and channels within the trenches may be hydraulically similar to solution cavities or fractures that, under saturated conditions, could act as conduits for movement of large quantities of water. Saturated hydraulic conductivities may range from about $1x10^3$ to $1x10^7$ mm/d in karst limestone and from about $1x10^1$ to $1x10^5$ mm/d in fractured igneous or metamorphic rock (Freeze and Cherry, 1979, p. 29). At unsaturated conditions, large air-filled voids may actually inhibit the flow of water by providing nearly infinite resistance to water movement along "fractures." Water movement would be limited to flow across local "bridges" of sediment and water connecting individual "fracture blocks" (isolated waste containers and trench-fill sediments). The phenomenon of water movement through unsaturated fractured rock is more fully explained by Wang and Narasimhan (1985), Montazer and Wilson (1985), and Evans and Huang (1983) and is comparatively illustrated in figure 47 with randomly buried waste containers.

Collapse holes in trench covers behave like sink holes in karstic deposits, allowing points for rapid infiltration. The potential hydrologic impact of collapse holes is exemplified by an observation made following a 3-hour rain in November 1985 that produced a total of 11 mm of precipitation. Surface runoff at a rate of about 10 liters per minute was observed flowing into a 7.0 m^3 hole with an orifice area of 2.9 m^2 (square meters), on the eastern end of trench 25c (figs. 2 and 48). Because the trench covers were saturated by 30 mm of precipitation the previous day, it is likely that much of the rainfall from the 3-hour storm was surface runoff. A total of about 1,700 liters was estimated to have entered the collapse hole during the rainfall. Under conditions such as this, parts of the trench were certainly saturated; hence, flow through the trench could have occurred quite rapidly through any existing voids.

The relative rate at which water moves through disposal trenches can be determined by comparing the velocity of water movement through the entire thickness of the unsaturated zone (including trench cover, trench, and subtrench sections) with velocities in the trench cover and subtrench sections of the unsaturated zone. Estimates of average velocities through the entire thickness of the unsaturated zone are based on time-of-travel of water between trench-cover and subtrench locations during the period of annual ground-water recharge. A soil-saturation tracking method was used to determine the time-of-travel. Using moisture probe and tensiometer data from 1983 and 1984, times of maximum soil saturation were determined at three locations: within the soil

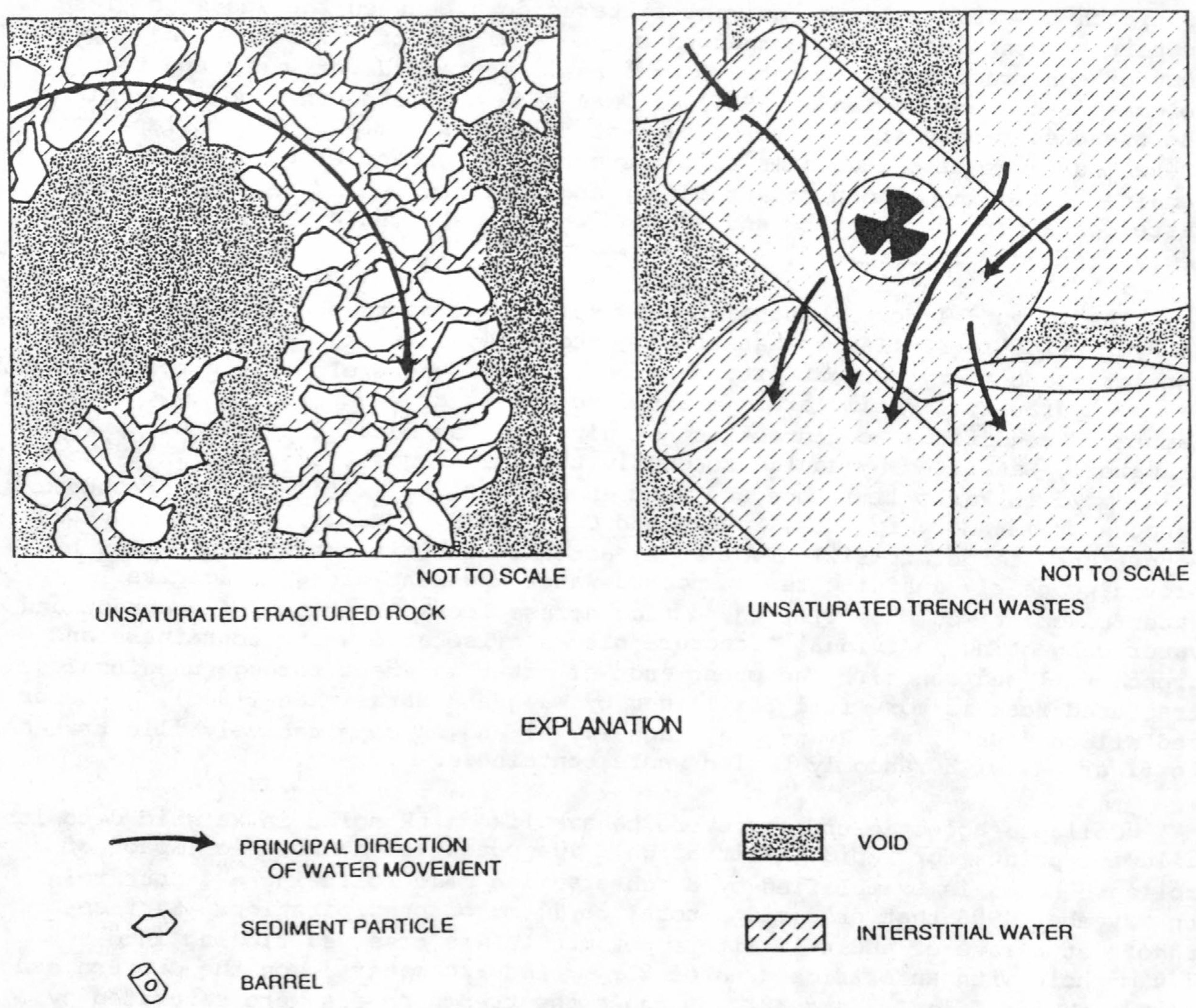


Figure 47.--Water movement through unsaturated fractured rock and unsaturated trench wastes. Modified from Wang and Narasimhan, 1985, figure 1.

Figure 48.--Surface-water drainage into a trench-cover collapse hole, November 1985.

cover of trench 2 (location A); within the Toulon Member and Hulick Till Member below trench 2 (location B); and within the Hulick Till Member below trench 11 (location D) (fig. 49). To estimate velocities, the average vertical thickness of the unsaturated zone was divided by the time lapse between maximum saturation at land surface and maximum saturation below the trenches.

Velocity estimation by this method required the following assumptions: (1) Water from surficial deposits completes its migration to the saturated zone in one wetting cycle, with soil-water storage in the unsaturated waste-burial horizon limited to a maximum of 1 year; (2) water moves through the unsaturated zone along a vertical linear path; (3) saturation data obtained from the cover of trench 2 (location A, fig. 49) can be regionalized to all surface locations; and (4) the time of maximum saturation at the selected subtrench locations can be uniquely determined. Field data are not available to verify all of the assumptions, especially assumption 1. Assumption 2 may be valid for flow through the trenches, but flow-simulation results indicate that its validity is less likely where flow occurs through layered geologic units.

Time-of-travel through the 7-m-thick trench 11 section (C to D, fig. 49) was estimated to be 54 days in 1983 and 66 days in 1984, yielding estimated velocities of 130 mm/d and 110 mm/d, respectively. Time-of-travel through the 14-m-thick trench 2 section (A to B, fig. 49) was 41 days (340 mm/d) in 1983 and 74 days (190 mm/d) in 1984.

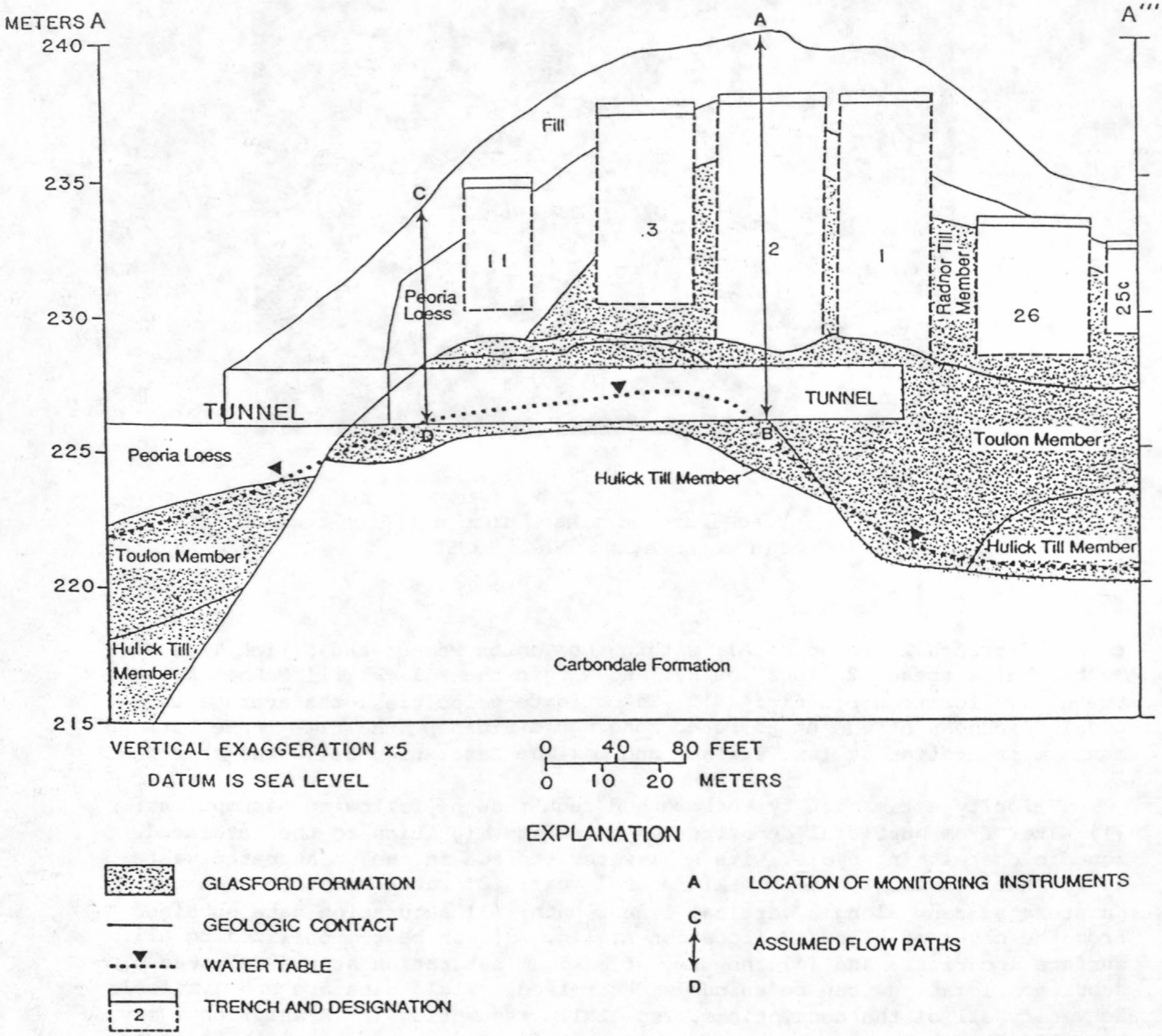


Figure 49.--Soil-saturation monitoring locations and assumed flow paths used to estimate flow rates through the unsaturated zone in geologic section A-A'''. See figures 3 and 4 for location of line of section.

For comparative purposes, velocities were computed using two variations of the described saturation-tracking method. In the first variation, velocities were estimated using the time span between the initial increase in soil saturation near land surface in the spring and the subsequent initial increase in soil saturation below the trenches. The data available allowed computation of a 1984 rate only. Velocities of 40 mm/d for the trench 2 section and 160 mm/d for the trench 11 section were estimated. The second variation was based on the time span between the return to minimal soil saturation near land surface in the fall and the subsequent return to minimal soil saturation below the trenches. Velocities estimated by this method were 130 mm/d in 1983 and 170 mm/d in 1984 for the trench 2 section and 40 mm/d in both 1983 and 1984 for the trench 11 section. Velocities computed by the second method were more consistent from year to year than those computed by the first method, apparently because fall meteorologic patterns are less variable than spring meteorologic patterns. As previously discussed, soil-saturation conditions in the spring are strongly dependent on highly variable snowmelt patterns. Of the three methods of estimating velocities of water movement, only the second method produced velocities that were faster in the trench 11 section than in the trench 2 section; there is no obvious explanation for this. It should also be noted that, of the three velocity-estimating methods, only the third method represents drying sediments. Hysteresis, therefore, could account for the difference between the estimates of this method and the estimates of the other two methods.

Velocities of water movement were estimated to be 10 to 100 mm/d through the Toulon Member and about 1 mm/d through the Hulick Till Member. Estimated velocities through the entire unsaturated zone ranged from 40 to 340 mm/d. If the velocity of water movement through the entire unsaturated zone exceeds the velocity through the subtrench subsections of the unsaturated zone, as generally indicated, then the velocity through the trenches should exceed the velocity through the entire unsaturated zone.

The maximum residence time of soil water in the unsaturated zone (and, therefore, in contact with trench wastes) was assumed to be 1 year, as dictated by the annual cycle of water movement. In actuality, a number of years may be required for an individual water molecule to migrate through the entire thickness of the unsaturated zone. Soil water moving through the subtrench may actually represent water that has remained in unsaturated storage through multiple wetting cycles, moving further downward toward the saturated zone each year. A piston-like flow mechanism (Levin and Verhagen, 1985, p. 242) would explain this process. Water entering the unsaturated zone at land surface, instead of continuously moving downward, would displace water already present in the unsaturated zone. The newly infiltrating water would then go into storage as the older water displaces water immediately below it. This process of displacement would continue until the bottom parcel of water in the unsaturated zone is "pushed" into the saturated zone. This process appears to be unlikely because seasonal fluctuations in pressure head (and thus soil-moisture content), as observed in this study, would not be readily apparent. During seasonal recharge periods, each parcel of stored water would merely replace an underlying parcel, exhibiting a minimal net change in water content at any given location.

Saturated conditions were not detected in the four study trenches and leachate did not accumulate in the tunnel sumps. Instruments in the Toulon Member indicated only small flow gradients immediately below trenches 1 and 2. The absence of water in the trench sumps should be expected under unsaturated conditions. The coarse-grained sediments (gravel and rock) in the French drains (which direct water to the sumps) act as a capillary barrier to water movement because, at the observed moisture contents, the hydraulic conductivity of the surrounding fine-grained sediments is greater than that of the French-drain sediments. Foster and others (1984, p. 17, 21) report that, with the exception of trench 18 (fig. 2), which may have been partially constructed below the water table, and trenches in which runoff entered by way of collapse holes in 1979, saturated conditions have not been detected and, under present conditions, are not expected to occur in any of the trenches at the Sheffield site.

Probable flow paths through the part of the unsaturated zone between the trench covers and the tunnel (which includes the trenches) are illustrated in figure 43. Water infiltrating the surficial veneer of clayey-silt fill and the permeable Peoria Loess beneath the swales may either enter trenches through the trench walls, moving downward through the waste material, or continue percolating downward through the intertrench loess deposits.

Water that percolates downward through trenches or the homogeneous deposits of Peoria Loess has the potential to move relatively unimpeded until vertical flow is restricted by the underlying Radnor Till Member. The inhibiting effect of this poorly conductive till unit on vertical flow is suggested by both theoretical and physical evidence. Characteristic curves (fig. 30) for the Peoria Loess and the Hulick Till Member indicate that the hydraulic conductivity of the loess deposits is greater than that of the clay-rich till deposits throughout the range of observed liquid pressures. Vertical flow, therefore, should be inhibited by the underlying Radnor Till Member. With vertical flow restricted, soil water should move laterally within the Peoria Loess along the sloping interface with the Radnor Till Member. The large pressure-head and water-table fluctuations recorded in the southern end of the tunnel, below trench 11, appear to support this hypothesis (fig. 40). Numerous vertical flow paths through the Peoria Loess apparently merge as flow is concentrated along the Peoria Loess/Radnor Till Member interface. The inhibiting effect of the Radnor Till Member on vertical flow is further indicated by the stable pressure heads observed in the till unit below the base of trench 3 (fig. 40) and the inverse relation of water-table response to precipitation and till-unit thickness (table 5 and fig. 38). Where the till unit is absent in well sections, water-table rises were more pronounced; where the till unit is present, the water-table rises were more subdued.

The dome-shaped structure of the Radnor Till Member (figs. 12 and 20) suggests that water movement along the sloped surface of the unit should occur in all directions from the crest of the dome. Because excavation has generally restricted the unit to narrowly confined intertrench areas, most flow along the surface of the till unit, with the exception of flow to the south toward trench 11, may be diverted into adjacent disposal trenches.

Near the bases of disposal trenches 1, 2, 3, and 11, flow follows three apparent paths as it approaches the Toulon Member. Although undetected by the unsaturated-zone monitoring instruments, rapid water movement may occur through

Table 5.--Stratigraphy at selected piezometer and well locations in and adjacent to the tunnel

[All values in meters]

Lithologic unit	Depth[1]	Thickness[2]	Lithology
	PZ1 (Land surface altitude: 233.0; Altitude of terminus of borehole: 224.3)		
Fill	1.9	1.9	Clayey silt
Peoria Loess	5.4	3.5	Silt
Hulick Till Member[3]	6.3	.9	Clayey silt
Carbondale Formation	9.5	[4]3.2	Silty clay
	PZ2 (Land surface altitude: 236.9; Altitude of terminus of borehole: 224.8)		
Fill	3.2	3.2	Clayey silt
Peoria Loess	7.9	4.7	Silt
Toulon Member[3]	8.9	1.0	Silty sand
Hulick Till Member	11.0	[4]2.1	Clay silt
Carbondale Formation	17.0	[5]6.0	Silty clay
	PZ3 (Land surface altitude: 239.3; Altitude of terminus of borehole: 224.8)		
Fill	2.6	2.6	Clayey Silt
Peoria Loess	5.6	3.0	Silt
Radnor Till Member[3]	10.3	4.7	Clayey silt
Toulon Member	10.7	.4	Silty sand
Hulick Till Member	13.0	[4]2.3	Clayey silt
Carbondale Formation	3.7	[5].7	Silty clay

Table 5.--Stratigraphy at selected piezometer and well locations in and adjacent to the tunnel--Continued

Lithologic unit	Depth[1]	Thickness[2]	Lithology
	PZ4 (Land surface altitude: 239.4; Altitude of terminus of borehole: 221.6)		
Fill	3.5	3.5	Clayey silt
Peoria Loess	5.0	1.5	Silt
Radnor Till Member	10.7	5.7	Clayey silt
Toulon Member	16.9	[4]6.2	Sand
Carbondale Formation	17.2	[5].3	Silty clay
	502 (Land surface altitude: 233.9; Altitude of terminus of borehole: 220.8)		
Fill	0.2	0.2	Silty sand
Peoria Loess	2.7	2.5	Clayey silt
	4.6	1.9	Silt
Radnor Till Member	6.6	2.0	Clayey silt
Toulon Member	7.1	.5	Sand-silt-clay
	11.7	[4]4.6	Sand
Hulick Till Member	12.6	[5].9	Sand-silt-clay
Carbondale Formation	13.1	[4].5	Silty clay
	505 (Land surface altitude 234.1; Altitude of terminus of borehole: 224.3)		
Fill	0.2	0.2	Clayey silt
Peoria Loess	2.3	2.1	Clayey silt
	3.5	1.2	Silt
Roxana Silt	4.1	.6	Silt
Radnor Till Member	4.5	.4	Sand-silt-clay
Hulick Till Member	6.7	2.2	Clayey silt
	9.5	[4]2.8	Sand-silt-clay
Duncan Mills Member	9.8	.3	Silty clay

Table 5.--Stratigraphy at selected piezometer and well locations in and adjacent to the tunnel--Continued

Lithologic unit	Depth[1]	Thickness[2]	Lithology
		512 (Land surface altitude: 223.9; Altitude of terminus of borehole: 215.1)	
Peoria Loess	1.6	1.6	Clayey silt
	3.7	2.1	Silty sand
	6.7	[4]3.0	Silt to clayey silt
Toulon Member	6.9	[5].2	Clayey silt
	7.2	[5].3	Silty clay
	7.3	.1	Coal
	7.9	.6	Pebbly, silty sand
Carbondale Formation	8.8	.9	Siltstone
		524 (Land surface altitude: 226.5; Altitude of terminus of borehole: 216.7)	
Peoria Loess	1.7	1.7	Clayey silt
	4.1	2.4	Silt
Toulon Member	6.7	2.6	Silt
	7.2	.5	Sand-silt-clay
	7.3	[4].1	Silt
	7.8	[5].5	Sandy silt
	8.2	[5].4	Silt
	8.7	[5].5	Silt
Hulick Till Member	9.2	.5	Sand-silt-clay
Carbondale Formation	9.8	.6	Silty clay

[1]Depth from land surface to base of unit.
[2]Thickness of unit.
[3]of the Glasford Formation.
[4]Partially screened.
[5]Fully screened.

the bases of trenches 1 and 2, which are finished in the sand unit, or through the French drain of trench 11. The most substantial volumes of water appear to enter the Toulon Member by way of direct (vertical) and indirect (lateral) flow routes through the Peoria Loess, south of trench 3. Limited water movement may occur through the low-permeability Radnor Till Member deposits below trench 3 or between trenches 1, 2, and 3.

TRITIUM DISTRIBUTION AND MOVEMENT THROUGH THE UNSATURATED ZONE

Assessment of the distribution of radionuclides in the unsaturated and saturated zones provides a basis for determining (1) the effectiveness of shallow-land burial in containing radioactive-waste materials; (2) the relation between water movement and radionuclide migration; and (3) the environmental factors that influence water and radionuclide migration. Spatial and temporal distributions were determined by analyzing soil and water samples for radionuclide activity.

This study focused specifically on the relation between tritium distributions and trends in soil-water movement because tritium is the most mobile radionuclide (moving as water) and apparently the only radionuclide (or only readily detectable radionuclide) to migrate beyond the immediate boundaries of the disposal trenches. Radioassay of soil and water samples indicated that tritium was present above its background concentration (200 pCi/L); no abnormally high alpha, beta, or gamma activity was detected. The State also reports that no radionuclides other than tritium have been confirmed to be in concentrations above background in ground-water samples from beyond the trench boundaries (Dave Flynn, Illinois Department of Nuclear Safety, oral commun., 1987). Carbon-14, however, has been reported in gas samples from the Toulon Member (R.G. Striegl, U.S. Geological Survey, oral commun., 1987). Striegl notes that for carbon-14 to be present in gaseous carbon dioxide it also must be present in the dissolved carbon present in the calcium magnesium bicarbonate soil water at the site. Distribution of gas-phase radionuclides are described by Striegl (1988a). The presence of carbon-14 in soil water was not evaluated in the present study because the lysimeters used in the study could not produce the volume of water required for carbon-14 analysis.

Tritium concentrations in vacuum-lysimeter samples from trench-cover deposits ranged from 200 to 1,400,000 pCi/L and averaged 132,000 pCi/L (Peters, 1985). Excluding lysimeter LYS88, where the highest concentrations were recorded, the average tritium concentration was 21,000 pCi/L. Tritium concentrations in subtrench vacuum-lysimeter samples ranged from 200 to 450,000 pCi/L and averaged 70,000 pCi/L. Tritium concentrations in water from the two gravity lysimeters near trench 11 ranged from 42,000 to 150,000 pCi/L and averaged 69,000 pCi/L. Tritium concentrations in pore water from unsaturated soil cores ranged from 400 to 390,000 pCi/L and averaged 51,000 pCi/L. The maximum tritium concentration detected in the tunnel area, 10,000,000 pCi/L, was observed in a single water sample obtained below trench 11 during instrument installation. Tritium concentrations in ground water from piezometers directly beneath the disposal trenches ranged from 1,700 to 250,000 pCi/L and averaged 75,000 pCi/L. Tritium concentrations in ground water from observation wells adjacent to the tunnel and trenches ranged from 200 to 130,000 pCi/L and averaged 24,000 pCi/L. The reduced tritium concentrations at the well locations adjacent to the tunnel suggest that ground-water migration of tritium in the direction of these wells is limited or that tritium concentrations in these outlying areas are diluted by tritium-free ground water.

Foster and others (1984, p. 33-34) reported that elevated concentrations of chloride, silica, alkalinity, and calcium were often associated with mobilized tritium. This association was not detected by Peters (U.S. Geological Survey, oral commun., 1986); however, a relation between tritium and dissolved organic carbon (DOC) was found. Concentrations of DOC were quite variable in the tunnel area, ranging from 5.8 to 70 mg/L (milligrams per liter) and averaging 27.5 mg/L. Highest concentrations were observed in locations below trenches 2 and 3.

Tritium concentrations in soil cores from trench covers generally increased from land surface downward to the trenches. Seasonal increases in concentrations were detected at several locations, with highest concentrations occurring during the late summer and early fall when evapotranspiration rates are traditionally high and the moisture content in the upper soil zone is low (figs. 50 and 39). This seasonal increase apparently reflects rewetting of the soil zone by tritium-enriched soil water moving upward from the trenches. Upward movement of soil water also was evidenced by tritium detected in vegetation samples from the site. Tritium concentrations in vegetative samples from the trench covers ranged from 200 to 160,000 pCi/L and averaged 6,100 pCi/L (M. P. deVries, U.S. Geological Survey, written commun., 1985). The highest tritium concentrations were observed in alfalfa samples; alfalfa has deeper root systems when compared to other vegetation at the site.

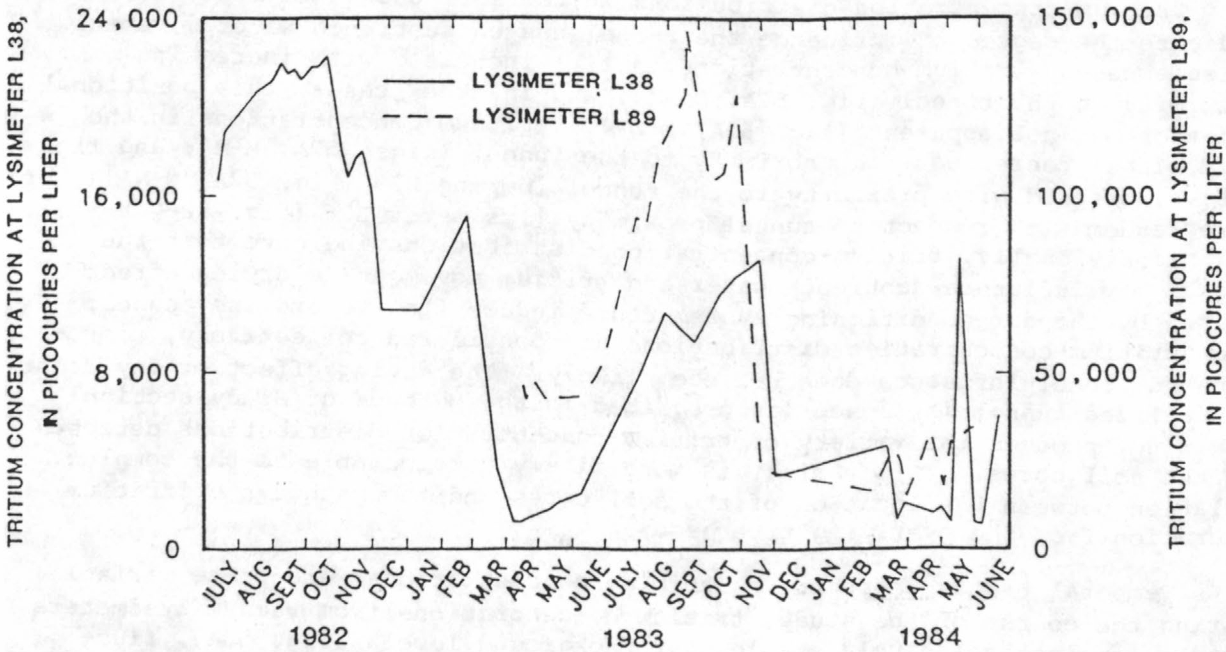


Figure 50.--Tritium-concentration trends at two trench-cover vacuum-lysimeter locations, July 1982 through June 1984.

Tritium concentrations varied spatially in the subtrench geologic deposits (figs. 51 and 52). Tritium concentrations of vacuum-lysimeter samples were generally greater below trenches (average concentration, 91,000 pCi/L) than below intertrench sediments (average concentration, 3,300 pCi/L), and greater in the Toulon Member (average concentration, 110,000 pCi/L) than in the Hulick Till Member (average concentration, 59,000 pCi/L) of the Glasford Formation. Average tritium concentrations near the sloping Toulon Member/Hulick Till Member interface were more than twice as great as concentrations away from the interface (88,000 and 31,000 pCi/L, respectively). The lowest tritium concentrations were detected beneath the surface high in the Hulick Till Member. Tritium concentrations in water from soil cores indicated similar distributions with average concentrations of 64,000 pCi/L in the Toulon Member and 20,000 pCi/L in the Hulick Till Member. Soil-core samples also showed that tritium concentrations generally increased with proximity to the trenches in the Hulick Till Member (80 percent of the samples) and decreased with proximity to the trenches in the Toulon Member (89 percent of the samples).

The distributions of tritium concentrations result from the heterogeneity of the waste materials and the heterogeneity of the hydrogeologic burial environment. The increased tritium concentrations above and decreased concentrations below interfaces of coarse- and fine-grained sediments emphasize the influence of sediment interfaces on water and tritium movement through the unsaturated zone. The greater tritium concentrations in the Toulon Member than in the Hulick Till Member, and the trend of increasing concentrations with increasing distance from the trench bases in the Toulon Member, indicate that water movement through the sand unit may be more pronounced than indicated by the pressure-head data and that water and tritium movement may be more rapid through the sand unit than through the less permeable till unit.

Tritium-concentration distributions in the soil cores (fig. 52) also may indicate the degree of influence the tunnel has on subtrench water movement. In some cases, tritium concentrations in till increased with increasing proximity to the tunnel (fig. 52A, J-J'), and in other cases, this positional relation was not apparent (fig. 52A, L-L'). Tritium concentrations in the sand either decreased with proximity to the tunnel (figs. 52A, M-M'; and fig. 52B), increased with proximity to the tunnel [boring B79 (fig. 52A, N-N')], or were random with respect to tunnel proximity [lysimeter L66 (fig. 52B, K-K')]. Taken individually, tritium-concentration distributions indicate that the tunnel may influence subtrench water and tritium movement; a drying affect caused by the air-conditioning system could induce flow toward the tunnel. When tritium-concentration distributions are considered collectively, a pronounced tunnel influence does not seem likely. The drying affect or any other generalized tunnel influence (as described in the Methods of Study section) would not produce the variety of tritium-concentration distributions detected in the soil cores. This variety is more likely attributable to the complex relation between the location of the soil cores and the pathways of tritium migration from the overlying trenches.

Temporal trends in subtrench tritium concentrations were quite variable. During the course of the study, tritium concentrations from vacuum lysimeters either remained relatively stable near background levels (fig. 53A), fluctuated randomly (fig. 53B), increased steadily (fig. 53C), increased abruptly (fig. 53D), or fluctuated seasonally (fig. 54). Short- and long-term temporal variations were detected.

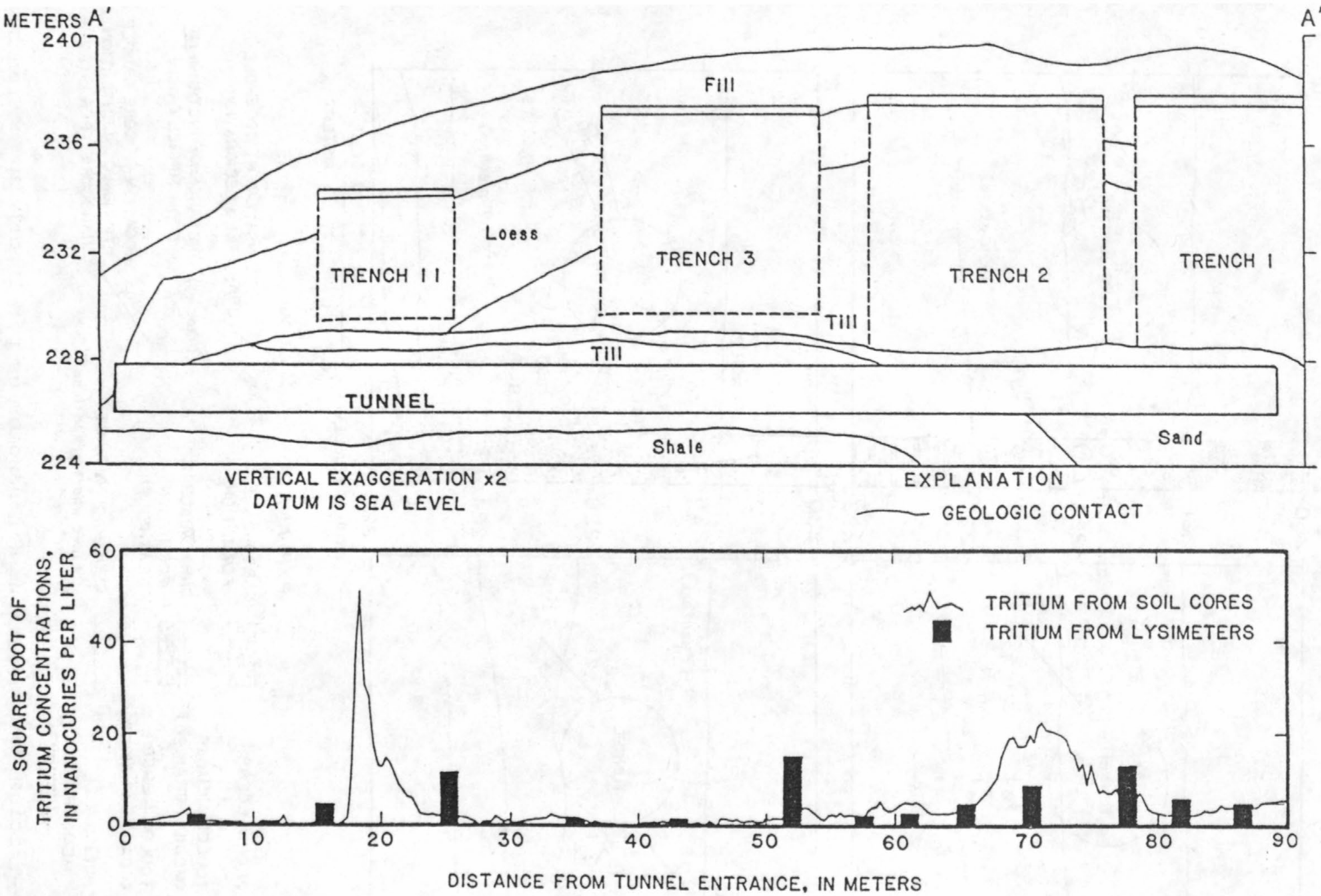


Figure 51.--Tritium concentrations from individual soil cores (1978-79) and average concentrations from vacuum lysimeters (1982-84) in geologic section A'-A". See figures 3 and 4 for line of section. Modified from Foster and others, 1984, figure 38.

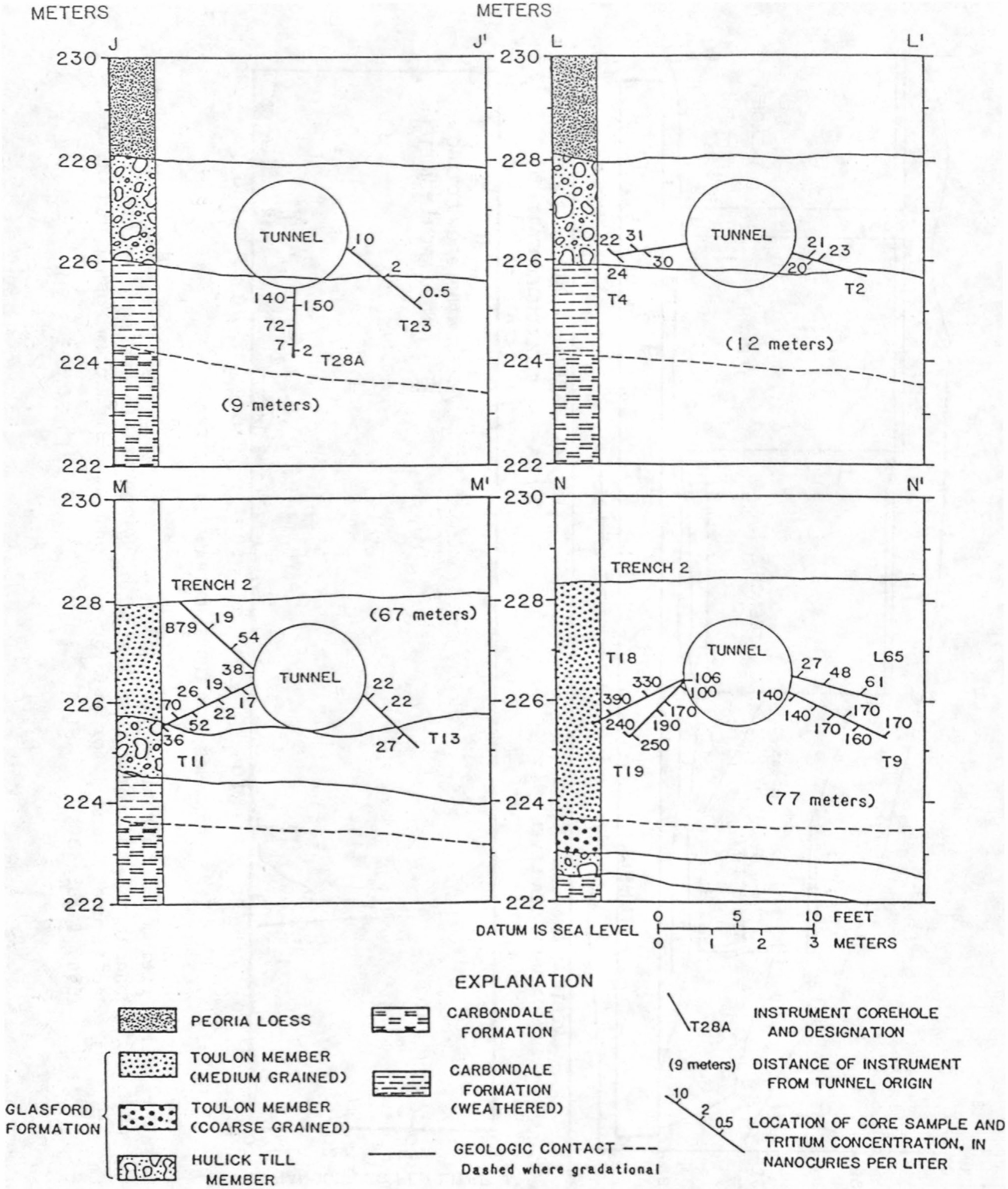


Figure 52.--Tritium concentrations (in nanocuries per liter) in subtrench soil cores in geologic sections J-J', L-L', M-M', N-N', O-O', and K-K'. See figure 3 for location of lines of section.

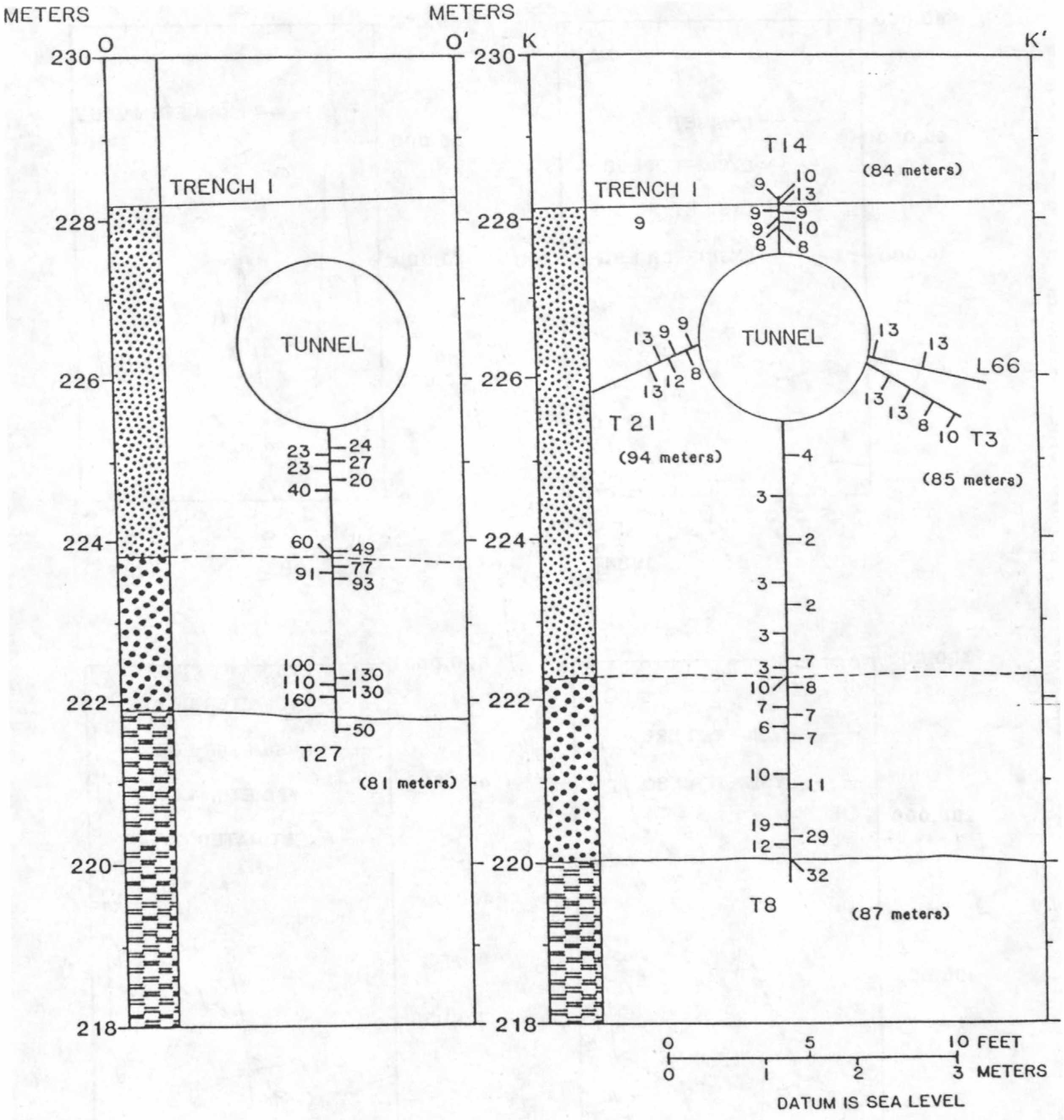


Figure 52.--Continued.

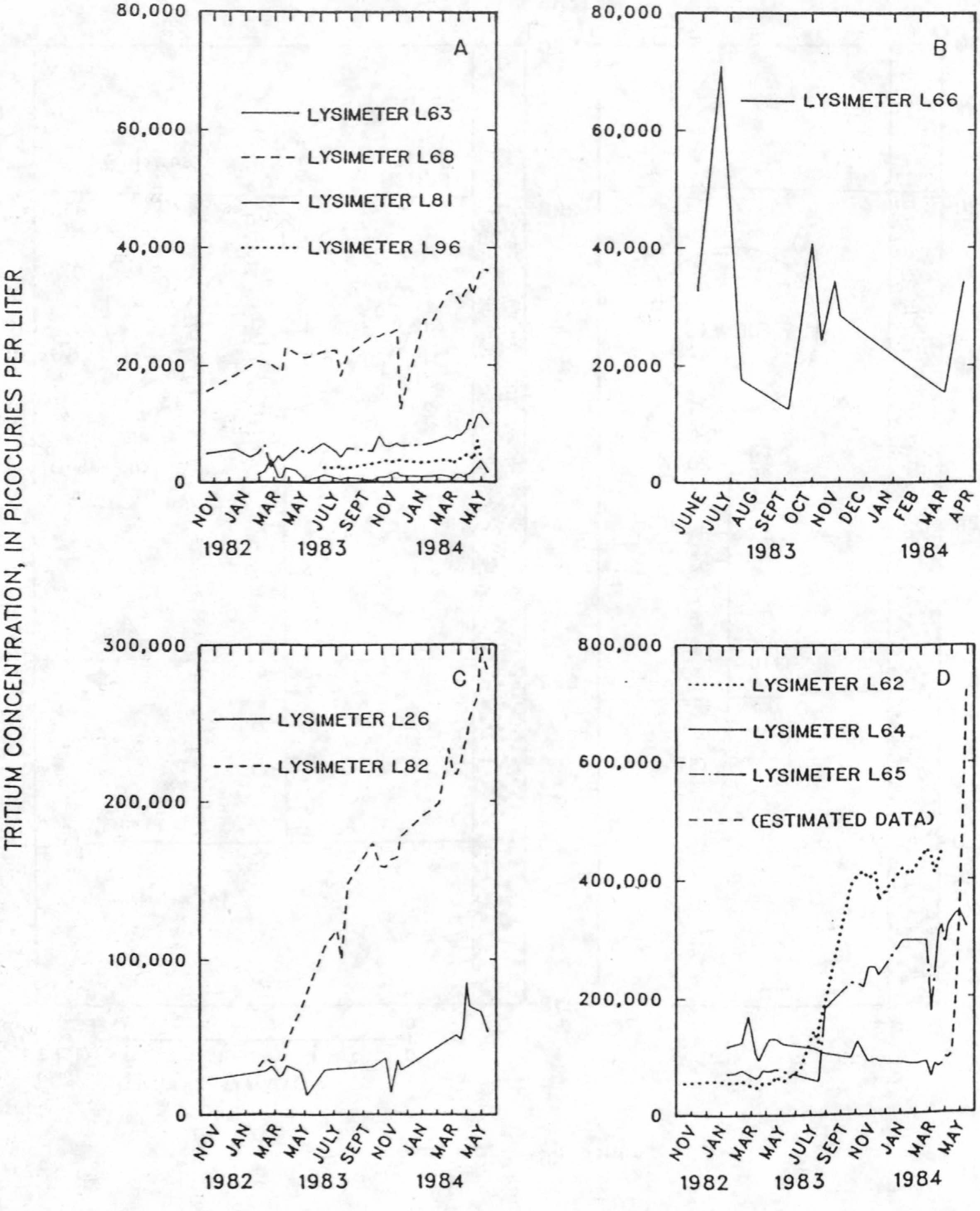


Figure 53.--Temporal trends in tritium concentrations at selected subtrench, vacuum-lysimeter locations, 1982-84: A, Relatively stable; B, Randomly fluctuating; C, Steadily increasing; D, Abruptly increasing.

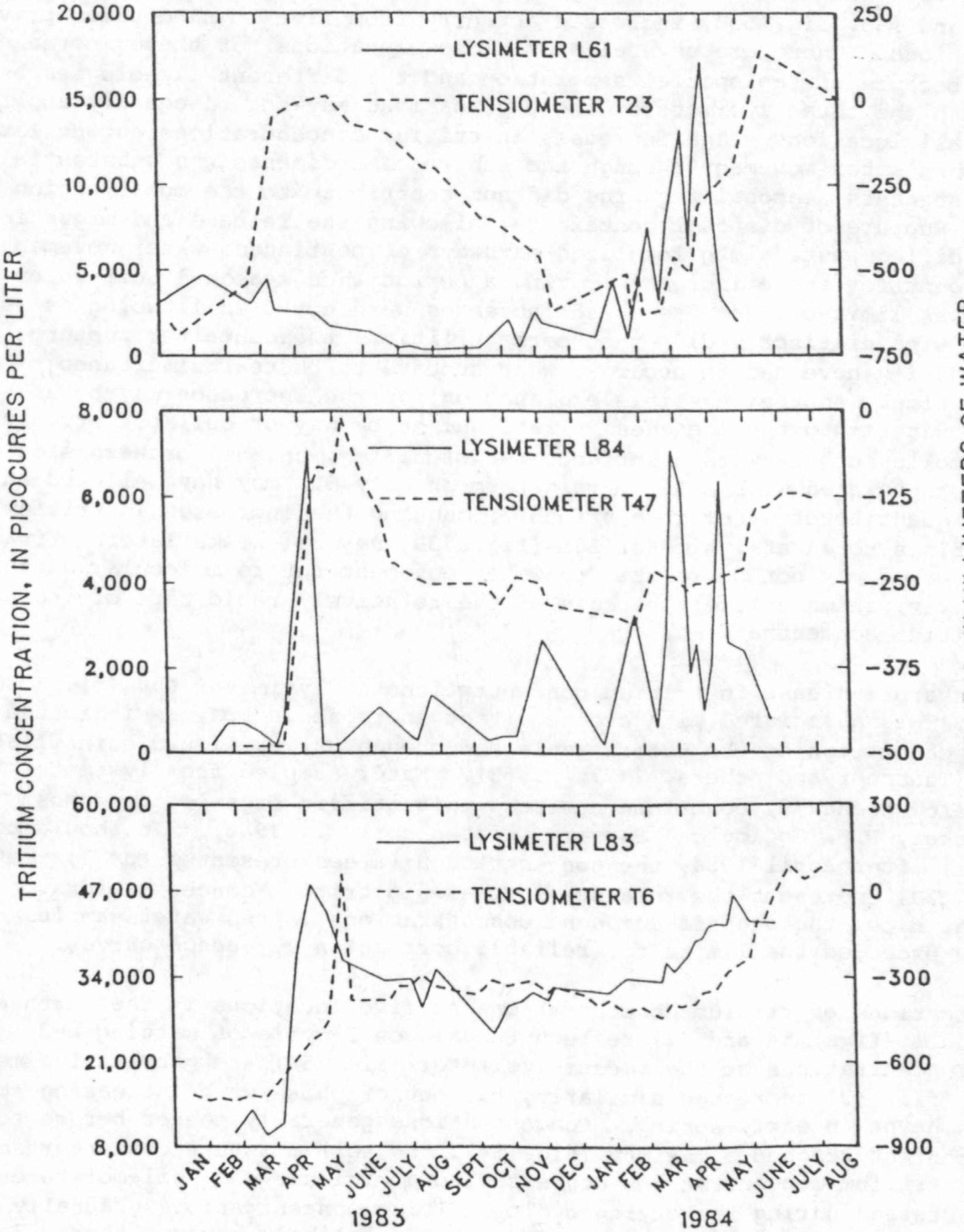


Figure 54.--Seasonal trends in pressure head and tritium concentration at three subtrench locations, January 1983 through August 1984.

In 1983, tritium concentrations at three lysimeter locations (L82, fig. 53C; L62 and L65, fig. 53D) increased abruptly from five to nine times previous concentrations. There are several possible explanations for these increases; however, because of the spatial separation and the different lithologies associated with the three lysimeters, the explanations may not be equally applicable at all locations. The increases in tritium concentrations during late summer, when water movement through the subtrench sediments was substantially reduced, suggests seasonal recharge did not contribute to the mobilization of tritium. Rupture of disposal containers, allowing the release and migration of unsolidified waste along localized pathways of continuous water movement, could account for these increases during a period when seasonal soil-water movement was limited. Because these increases were noted in lithologies (sand and till) with distinctly different permeabilities, the container ruptures may not necessarily have had to occur at what appears to be near simultaneous points in time. Another possible explanation for the increases may be an influx of water into the trenches in late summer by way of collapse structures. A 5.1-m^3 collapse hole with a surface area of 3.3 m^2, on the northern side of trench 2, associated with a 92-mm rainstorm on July 30, may have allowed an excessive quantity of water into trench 2, causing the increases in tritium concentrations noted at lysimeter L65 (fig. 53D) several weeks later. Finally, these increases may not be related to water movement but to molecular diffusion. This, however, seems unlikely because of the relatively rapid rate of increase in the tritium concentrations.

The sharp increase in tritium concentrations at lysimeter L64 (fig. 53D) in May 1984 was associated with a concomitant increase in DOC, as indicated by increased coloration of the water sample and quench during liquid scintillation analysis (Thatcher and others, 1977, p. 63). Water sampled from lysimeter L64, located below trench 2, contained numerous unidentified organic compounds (L. D. Becker, U.S. Geological Survey, written commun., 1986). It should be noted that, after April 1984, the concentration values presented for lysimeter L64 (fig. 53D) represent the relative increase in tritium concentrations. Before that date, the organic-compound concentrations in the water samples apparently exceeded the limits for reliable correction by quench curves.

Fluctuations of tritium concentrations at five locations in the north end of the tunnel (figs. 54 and 42) reflect the seasonal cycle of wetting and drying. Concentrations at the vacuum-lysimeter (fig. 54) and gravity-lysimeter locations (fig. 42) increased similarly, but out of phase with increasing soil-moisture content in early spring. Concentrations generally peaked before soil-moisture content reached a maximum (fig. 54). As soil-moisture content reached a maximum, tritium concentrations decreased to a minimum. As soil-moisture content decreased during the drying cycle, tritium concentrations gradually increased. Such a trend makes piston-flow theory unlikely because there should be no apparent seasonal increase and decrease in tritium concentrations. This pattern is more suggestive of a continuous migration of water, driven by seasonal increases in soil-moisture content near land surface. As water percolates downward, contaminated soil water in the vicinity of the wastes is carried downward with the leading edge of migrating water. As the center of the "uncontaminated" recharging water mass passes through the wastes, the contaminated soil water in the vicinity of the wastes is diluted and the tritium concentrations decrease.

Between 1982 and 1984, the average tritium concentration in the subtrench region increased from 28,000 to 100,000 pCi/L (C. A. Peters, U.S. Geological Survey, written commun., 1985); excluding lysimeters L62, L65, and L82, which exhibited large increases in tritium concentration, the average concentration increased from 21,000 to 27,000 pCi/L. If all tritium concentrations were corrected for radioactive decay over time, then the increase in concentrations would be even greater. When tritium concentrations from individual tunnel-area soil cores, as measured by Foster and others (1984) in 1978-79, are compared with the average tritium concentration from vacuum lysimeters, as measured by Peters in 1982-84 (fig. 51), a general increase in concentration (from 60,000 to 70,000 pCi/L) also is indicated. During 1978-79, there was a distinct bimodal distribution of tritium; highest concentrations were centered below trenches 2 and 11; by 1982-84, concentrations were distributed more evenly; notable increases in tritium concentrations occurred below trench 3.

Mean annual tritium flux of 3.4 mCi/yr (millicuries per year) through the unsaturated subtrench sediments in the 450-m^2 (5-m-wide zone along the length of the 90-m tunnel) study area is estimated by assuming (1) a constant soil-water tritium concentration of 70,000 pCi/L; (2) an equal distribution of 107 mm of annual recharge across the site; and (3) diffusion is negligible. It must be stressed that this is an estimate of tritium flux and that it is only applicable to the tunnel area. The average tritium concentration used in the estimate only represents samples from vacuum-lysimeter locations. As shown, soil-water samples obtained during instrument installation and from gravity lysimeters and sediment cores may vary considerably from the "vacuum-lysimeter" average. The recharge rate used in the estimate is a site-average value, and it does not specifically represent spatial variability of water movement through the tunnel area. Furthermore, this estimate neglects tritium flux by molecular diffusion resulting from concentration gradients (Freeze and Cherry, 1979).

Many questions remain about the exact nature of tritium migration through the unsaturated zone. Water moving through the unsaturated zone during the seasonally timed wetting phase probably initiates the migration of water stored in contact with waste material, as well as leaching tritium as it passes through the wastes. Tritium migration, however, also appears to occur in random pulses related to changing conditions within the trenches. Deterioration of waste containers or development of collapse holes in trench covers, for example, may cause additional tritium migration. Tritium also may move in the vapor phase, but Striegl and Ruhl (1986) saw little indication of this. The occurrence of tritium in the Toulon Member, where fluctuations in pressure head generally were not observed and where hydraulic gradients were small, provides some additional insight into the mechanics of tritium and water movement. The pressure-head and tritium data indicate, as did the previously discussed modeling results, that water and tritium movement through the sand unit generally is slow and continuous and, therefore, does not exhibit the seasonally timed pulses seen elsewhere in the tunnel area. It appears that localized preferential flow paths may exist within the sand unit; preferential pathways would allow more substantial movement of water and tritium than is presently detected in the unit and, thus, account for the higher tritium concentrations and more rapid tritium-migration rates in the sand unit compared to the till unit. Although water movement appears to be the primary mechanism for tritium migration, molecular diffusion also may be an important mechanism. This is especially true in the geologic units where water velocities are low, such as the Hulick Till Member. Unfortunately, because of the heterogeneity of the wastes in the trenches and the complexity of the flow paths, it is not possible to differentiate between the advective and diffusive components of transport.

SPATIAL AND TEMPORAL REPRESENTATIVENESS OF DATA FROM THE STUDY AREA

The area-averaged depth of water entering trench 2 in the study area was estimated to be approximately 107 mm/yr. The actual quantity of water entering individual trenches at the site differs somewhat from the study-area estimate as indicated by the spatial variability of unsaturated-zone water movement in the tunnel area. Although it is difficult to determine the exact amount of recharge to individual trenches, a qualitative comparison may be derived by examining (1) vegetative cover, (2) surface topography, (3) trench-cover characteristics, (4) trench contents, and (5) subsurface geology.

Differences in vegetation type and density may influence runoff and evapotranspiration, thus increasing or decreasing water available for recharge. Site surveys indicate that vegetative cover above the trenches generally is homogeneous (J. R. Gray, U.S. Geological Survey, oral commun., 1986). Vegetative cover, therefore, appears to have little effect on variations in infiltration into disposal trenches at the Sheffield site.

Surface topography can influence runoff and recharge. This appears to be especially true at the Sheffield site, where the topographic relief is as great as 14 m. However, studies indicate that the physical properties of trench covers exert a much stronger influence on runoff (and thus infiltration) than slope. Gray (1986, p. 3-98) reported that runoff from a high-slope trench crest was less than from a low-slope trench edge location, indicating the significance of the thick layer of moisture-absorbing fill above the compacted zone at the high-slope location.

The hydraulic conductivity and thickness of trench covers influence the fate of water movement into trenches. Sediments with low hydraulic conductivities (clayey silt versus silt) inhibit infiltration. This holds true for covers with consistently low hydraulic conductivities throughout their thickness, as well as covers that may have a layer of reduced permeability. Thicker trench covers may reduce runoff by absorbing more water than thinner covers but may reduce water movement into trenches because of a more substantial root zone and, thus, a better medium for subsequent atmospheric release by evapotranspiration compared to thinner areas.

Although not fully documented, there appears to be substantial difference in the construction of trench covers at the Sheffield site. Measured thicknesses of fill material used in site development and trench-cover construction range from 0.5 to 7 m. Porosities computed from bulk densities of trench-cover sediments sampled along a section through the eastern ends of trenches 11 to 23 ranged from about 30 to 45 percent at average depths of 0.15 and 0.40 m and from about 30 to 50 percent at an average depth of 0.75 m (J. R. Gray, U.S. Geological Survey, oral commun., 1986). Although a compacted zone was present in several trench covers in the study area, records indicate that no specific attempt at trench-cover compaction was made anywhere except at trenches 14, 14a, and 18 (A. Armbrust, US Ecology, Inc., oral commun., 1984).

Trenches that are filled with structurally strong waste containers arranged in an orderly fashion will contain fewer voids, will be less inclined to develop collapse structures, and will more greatly inhibit saturated water movement into and through trenches than will randomly buried wastes in structurally weak containers. Wastes at the Sheffield site are buried in a variety of manners within the trenches. Records compiled by Gray and McGovern (1986) indicate that collapse structures have developed in all trenches on-site, although 50 percent of those collapses occurred in four trenches (1, 7, 23, and 25c), all outside of the study area.

Variations in subsurface geology also contribute to variations in water movement within individual trenches. Interlayered geologic deposits with contrasting permeabilities inhibit vertical water movement between trenches and enhance lateral flow into the trenches. Disposal trenches at the Sheffield site generally are constructed entirely within the Peoria Loess, but there are exceptions. Some trenches in the southwestern corner and along the eastern boundary of the site also penetrate the Radnor Till Member; at least two trenches in the southeastern corner penetrate the Toulon Member.

The single annual recharge event observed in the tunnel area does not fully typify the timing of water movement through the unsaturated zone elsewhere on-site. Ground-water recharge occurs in more direct response to precipitation events at some localities than at others. Foster and others (1984, p. 21) reported water-level response times in the range of hours at wells both inside and outside the study area after a 140-mm rainfall in August 1979. This response to precipitation occurred following a historically large rainfall event and was most apparent in wells where the unsaturated zone is thin and consists of moderately permeable sediments. Similarly, in each case, there was a consistent direct correlation between depth to water and response time.

Although the presence of the Radnor Till Member of the Glasford Formation and the thickness of the unconsolidated deposits in the study area create hydrologic conditions that are unique to the study area, it should be noted that hydrologic conditions at trenches elsewhere on-site probably are equally unique. Nonetheless, the basic findings of the study are believed to be meaningful and applicable to the site as a whole. Even though factors such as geology and trench characteristics may vary locally, the mechanisms by which those factors influence water movement and leachate migration are universal. Understanding those mechanisms, as outlined in this report, provides a basis for improving the evaluation of local flow scenarios.

Precipitation and air temperature patterns at the Sheffield site for the period of study were similar to long-term (45-year NOAA record) trends for the area. Annual precipitation during the period of study varied no greater than 12 percent from the long-term annual mean; mean annual air temperature did not vary by more than 15 percent. This indicates that, for the most part, the hydrologic system described during the period of study generally reflects the system over the long term. However, the following points should be noted: (1) Within limits, climatic variability does occur at the site from year to year, and, as previously discussed, so do annual patterns of water movement; and (2) the disposal site is not a static system. Collapses, averaging 43 per year in the 7 years following termination of burial operations (Gray and McGovern, 1986, p. 744), and erratic increases in soil-water tritium concentrations reflect the continual structural and geohydrologic equilibration of the trenches. Some variability may, therefore, be expected between the hydrologic system described herein and the hydrologic system that exists over the long term.

SUMMARY AND CONCLUSIONS

Soil-water and tritium movement through the unsaturated zone was studied from 1981 to 1985 at a low-level radioactive-waste disposal site near Sheffield, Illinois. The study described the geologic and hydraulic properties of the sediments and trenches, and characterized the hydrogeologic, meteorologic, and waste-burial conditions that affect the timing, quantity, rate, and paths of water and tritium movement from land surface, through disposal trenches, to the saturated zone.

A horizontal tunnel, 2 m in diameter and 120 m long, provided access to unsaturated deposits beneath four disposal trenches. Soil cores were used to define trench locations, stratigraphy, and the properties of the geologic materials. Soil-moisture tensiometers and a nuclear soil-moisture gage were installed in the trench-cover and subtrench geologic materials to monitor soil-water movement. Vacuum and gravity lysimeters were used to collect soil water for tritium analysis. Piezometers and observation wells were used to monitor water level in the saturated zone. A cross-sectional, numerical, ground-water-flow model guided data collection and aided interpretation of subtrench water-movement data. Concurrent studies at the site provided precipitation, evapotranspiration, and runoff data for water-budget-based estimates of recharge to the disposal trenches.

Mean annual precipitation for 1982-85 was 871 mm. A water-budget analysis was performed for the 2-year period from July 1982 through June 1984. For that period, mean annual precipitation was 948 mm, providing an estimated 657 mm of evapotranspiration, 160 mm of runoff, and 107 mm of recharge to the disposal trenches.

Waste trenches were constructed in glacial and postglacial deposits ranging in composition from clayey silt to sand. Saturated horizontal hydraulic conductivities ranged from 4.8×10^{-1} mm/d in the Hulick Till Member to 3.4×10^{4} mm/d in the Toulon Member (sand), both in the Glasford Formation. Average soil saturation was about 99 percent in the Hulick Till Member and 25 percent in the Toulon Member during a period of minimum water movement through the subtrench geologic deposits. During a period of maximum percolation, average saturation was about 100 and 29 percent in the Hulick Till Member and Toulon Member, respectively.

Water movement through the unsaturated zone generally occurred in an annual cycle with a single, seasonally timed wetting (recharge) phase. Increased soil water in the trench covers in the spring, when precipitation exceeds evapotranspiration plus runoff, initiates the migration of stored water to the saturated zone. Soil-moisture content in the subtrench geologic deposits reached a maximum in early to midsummer, decreased through early fall, and was at a minimum through fall and winter. Of the components of the water budget, evapotranspiration contributed most to the temporal variability of water and tritium movement.

Water and tritium movement through the unsaturated zone was spatially variable and substantially influenced by the complex geology. Field data and computer simulation indicate that lateral flow occurs in the unsaturated zone along interfaces between lithologic units of contrasting permeability. Water movement through a trench cover was restricted by a compacted layer of clayey silt. Most water movement into a trench occurs along its edge where the cover is relatively thin, the compacted zone is absent, and swales between trenches enhance ponding. Pronounced water movement also was indicated along the southern edge of the Radnor Till Member of the Glasford Formation below trench 11, where flow is apparently concentrated along the sloping interface between that unit and the Peoria Loess. Limited temporal variation in water movement and small flow gradients (relative to the Hulick Till Member) were detected in the unsaturated sand of the Toulon Member; maximum gradients during the spring recharge period averaged 1.62 mm/mm. Time-of-travel of water moving from the trench covers to the saturated zone was estimated to be as rapid as 41 days (assuming water moves through the full thickness of the unsaturated zone in one recharge cycle).

Waste-disposal practices also contributed to the variability of water and tritium movement in the unsaturated zone. Trench-cover collapse holes resulting from inadequate compaction of wastes within the trenches provided preferential pathways for surface-runoff drainage into the trenches. Drainage into one collapse hole during a rainstorm was estimated to be 1,700 liters.

Tritium was the only radionuclide detected above background concentrations (200 pCi/L). Mean annual tritium flux below the four study trenches was estimated to be 3.4 mCi/yr. Tritium concentrations ranged from 200 to 10,000,000 pCi/L in the unsaturated zone and from 200 to 250,000 pCi/L in the saturated zone. Tritium concentrations were generally higher below trench bases (averaging 91,000 pCi/L) than below intertrench sediments (averaging 3,300 pCi/L), in the Toulon Member (averaging 110,000 pCi/L) than in the Hulick Till Member (averaging 59,000 pCi/L), and near the Toulon Member/Hulick Till Member interface (averaging 88,000 pCi/L) than away from the interface (averaging 31,000 pCi/L). Tritium movement occurred in association with the annual cycle of water movement, as well as independent of the cycle, as water continuously percolated past randomly deteriorating waste containers.

The higher concentrations of tritium in the Toulon Member and the trend of higher concentrations of tritium at greater distances from the trenches in the Toulon Member indicate that water movement through the unit may be more pronounced than indicated by the pressure-head data. Localized flow paths may have gone undetected by the soil-moisture tensiometers and small-diameter gravity lysimeters used in the study.

Although data have been collected from the unsaturated zone at the site for 5 years, comprehensive data have only been collected during three recharge periods (1983, 1984, and 1985). Data may be too sparse to draw firm conclusions about the role of the unsaturated zone in water and radionuclide migration and about how representative short-term climatic trends at the site are of long-term trends.

Many questions remain about the movement of water within the Toulon Member. Further study of water movement in the Toulon Member by using alternative monitoring methods may allow improvement in the characterization of water movement through the sand unit and in the definition of the fate of water and radioactive wastes contained in the disposal trenches.

Additional study also will further the understanding of the effects of the tunnel on water movement below the disposal trenches. Although preliminary studies indicate that the tunnel structure did not substantially alter natural pretunnel flow conditions, additional detailed study is needed to evaluate fully the tunnel's influence.

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