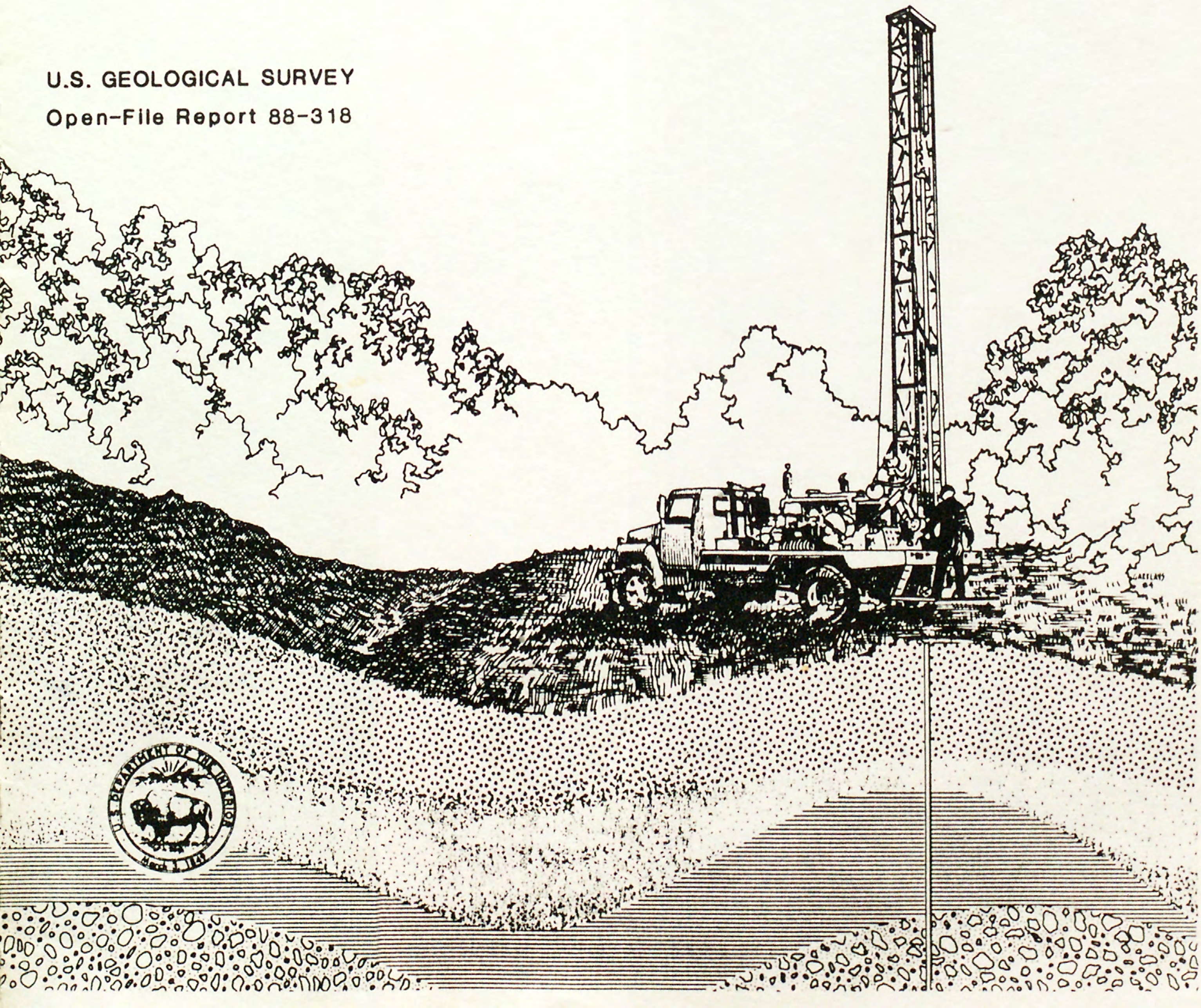
RESULTS OF HYDROLOGIC RESEARCH AT A LOW-LEVEL RADIOACTIVE-WASTE DISPOSAL SITE NEAR SHEFFIELD, ILLINOIS

U.S. GEOLOGICAL SURVEY
Open-File Report 88-318



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Edited by Barbara J. Ryan

U.S. Geological Survey Open-File Report 88-318

Urbana, Illinois

May 1989

DEPARTMENT OF THE INTERIOR

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U.S. GEOLOGICAL SURVEY

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The following factors may be used to convert the metric (International System) units in this report to inch-pound units, unless noted otherwise.

Multiply metric unit	by	To obtain inch-pound unit
	Length	
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Area	
hectare (ha)	2.471	acre
square meter (m^2)	10.76	square foot (ft^2)
square meter (m^2)	0.0002471	acre
square kilometer (km^2)	0.3861	square mile (mi^2)
	Volume	
liter (L)	0.2642	gallon (gal)
cubic meter (m^3)	35.31	cubic foot (ft^3)
	Mass	
gram (g)	0.03537	ounce, avoirdupois (oz)
gram (g)	0.002205	pound, avoirdupois (lb)
kilogram (kg)	2.205	pound, avoirdupois (lb)
megagram (Mg)	1.102	ton, short
	Mass per unit area	
megagram per hectare (Mg/ha)	0.4464	ton (short) per acre (ton/acre)
	Mass per unit volume	
gram per cubic centimeter (g/cm^3)	0.00006244	pound per cubic foot (lb/ft^3)
kilogram per cubic meter (kg/m^3)	0.06244	pound per cubic foot (lb/ft^3)
	Velocity	
meter per second (m/s)	3.281	foot per second (ft/s)
meter per second (m/s)	2.237	mile per hour (mi/h)
meter per day (m/d)	3.281	foot per day (ft/d)

CONVERSION FACTORS AND ABBREVIATIONS

Multiply metric unit	by	To obtain inch-pound unit
Flow		
cubic meter per second (m^3/s)	35.31	cubic foot per second (ft^3/s)
Hydraulic conductivity		
centimeter per second (cm/s)	328.1	foot per second (ft/s)
meter per second (m/s)	3.281	foot per second (ft/s)
meter per day (m/d)	3.281	foot per day (ft/d)
meter per year (m/yr)	3.281	foot per year (ft/yr)
Pressure		
pascal (Pa)	0.0002953	inch of mercury (in. Hg)
pascal (Pa)	0.0075006	Torr
kilopascal (kPa)	0.2953	inch of mercury (in. Hg)
kilopascal (kPa)	10.00	millibar (mb)
Energy per unit area time		
Watt per square meter (W/m^2)	0.0006452	Watt per square inch (W/in^2)
Chemical concentration		
microgram per liter (μg/L)	1.000	part per billion (ppb)
milligram per liter (mg/L)	1.000	part per million (ppm)

Milligrams per liter (mg/L) x F1 = milliequivalents per liter (meq/L);
milligrams per liter (mg/L) x F2 = millimoles per liter (mmols/L)

	F1	F2
Bicarbonate (HCO_3^-)	0.01639	0.01639
Calcium (Ca^{++})	.04990	.02495
Chloride (Cl^-)	.02821	.02821
Iron (Fe)	---	.01791
Magnesium (Mg^{++})	.08229	.04114
Silica (SiO_2)	---	.01664
Sodium (Na^+)	.04350	.04350
Strontium (Sr^{++})	.02283	.01141
Sulfate (SO_4^{--})	.02082	.01041
Zinc (Zn^{++})	.03059	.01530

CONVERSION FACTORS AND ABBREVIATIONS

Multiply metric unit	by	To obtain inch-pound unit
Temperature		
degree Celsius (°C)	°F = 1.8 x °C + 32	degree Fahrenheit (°F)
Radiometric concentration[1]		
nanocuries per gram (nCi/g)	37.01	Becquerel per gram (Bq/g)
nanocuries per liter (nCi/L)	37.01	Becquerel per liter (Bq/L)

NOTATION FOR SELECTED RADIONUCLIDES

Notation	Isotope	Radioactive half-life
^{3}H	tritium (hydrogen-3)	12.43 years
^{14}C	carbon-14	5,370 years
^{222}Rn	radon-222	3.82 days
^{226}Ra	radium-226	1,600 years
^{230}Th	thorium-230	77,000 years
^{233}U	uranium-233	161,500 years
^{235}U	uranium-235	711,841,000 years
^{239}Pu	plutonium-239	24,400 years

ALTITUDE DATUM

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

[1]Because there are no commonly used inch-pound units for radiometric concentration, a conversion factor for Becquerels has been included.

RESULTS OF HYDROLOGIC RESEARCH AT A LOW-LEVEL RADIOACTIVE-WASTE DISPOSAL SITE NEAR SHEFFIELD, ILLINOIS

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ABSTRACT

Ten years of hydrologic research have been conducted by the U.S. Geological Survey at a commercial low-level radioactive-waste disposal site near Sheffield, Illinois. Research included studies of microclimate, evapotranspiration, and tritium release by plants; runoff and land modification; water movement through a trench cover; water and tritium movement in the unsaturated zone; gases in the unsaturated zone; water and tritium movement in the saturated zone; and water chemistry. Implications specific to each research topic and those based on overlapping research topics are summarized as to their potential effect on the selection, characterization, design, operation, and decommissioning processes of future low-level radioactive-waste disposal sites.

Unconsolidated deposits at the site are diverse in lithologic character and are spatially and stratigraphically complex. Thickness of these Quaternary deposits ranges from 3 to 27 meters and averages 17 meters. The unconsolidated deposits overlay 140 meters of Pennsylvanian shale, mudstone, siltstone, and coal.

Approximately 90,500 cubic meters of waste were buried from August 1967 through August 1978, in 21 trenches that were constructed in glacial materials by using a cut-and-fill process. Trenches generally were constructed below grade and ranged from 11 to 180 meters long, 2.4 to 21 meters wide, and 2.4 to about 7.9 meters deep.

Research on microclimate and evapotranspiration at the site was conducted from July 1982 through June 1984. Continuous measurements were made of precipitation, incoming and reflected solar (shortwave) radiation, incoming and emitted terrestrial (longwave) radiation, horizontal windspeed and direction, wet- and dry-bulb air temperature, barometric pressure, soil-heat fluxes, and soil temperature. Soil-moisture content, for this research phase, was measured approximately biweekly. Evapotranspiration rates were estimated by using three techniques--energy budget, aerodynamic profile, and water budget. Although monthly totals for each method differed, estimated annual evapotranspiration averages ranged from 630 to 693 millimeters or about 70 percent of precipitation.

Tritium concentrations in leaf water from on-site plants were determined for 125 vegetation samples collected during the summers of 1982 through 1986. Concentrations varied significantly among some locations and plant types.

Tritium concentrations ranged from the detection limit of 0.2 to 1,330 nanocuries per liter, with alfalfa (Medicago sativa) having the highest concentrations, followed by brome grass (Bromus inermis), and then red clover (Trifoleum pratense); these variations in concentration are most likely a result of root depth.

Runoff and sediment transport were measured from July 1982 through December 1985 in four basins--three comprising almost two-thirds of the 8.1-hectare site and one comprising a 1.4-hectare undisturbed area. Volumes and equivalent weights of collapses were estimated from records of site surficial conditions from October 1978 through December 1985. Runoff showed a direct relation to degree of land modification; lowest mean yields were measured at the undisturbed area, and highest mean yields were measured from the basin composed wholly of trench and intertrench areas. Sediment yield measured onsite averaged 3.4 megagrams per hectare. A total of 315 collapse cavities, corresponding to a cumulative volume of about 500 cubic meters, were documented. Most collapses were recorded after periods of rainfall or snowmelt when soil moisture was near maximum. Almost two-thirds of the collapses, corresponding to 63 percent of the cumulative cavity volume, occurred during February through April.

Data for the study of water movement through a trench cover were collected from July 1982 through June 1984. Pressure-head data were collected at four different clusters at depths ranging from 50 to 1,850 millimeters within a selected trench cover. Soil-moisture content for this research phase was measured weekly with a gamma-attenuation moisture probe. The amount of water stored within the trench cover fluctuated in an annual cycle. Moisture contents were greatest in late March or early April, decreased steadily from late spring through the summer, reached a minimum in late August or early September, and then increased gradually from midfall through the winter. Depths of wetting-front movements were a function of initial soil-moisture content and total storm precipitation. Seepage to the trench was estimated by use of four different methods: the Darcy method, the zero-flux phase method, the surface-based water-budget method, and the ground-water based water-budget method. Estimates by the different methods differed considerably.

Investigation of the unsaturated zone at the site began in 1981 and is ongoing (1987). Water movement was measured along a generalized vertical section through four trenches. A 120-meter-long, 2-meter-diameter horizontal tunnel provided access below the trenches. The timing of water movement varied temporally and spatially. Vertical flow was inhibited at interfaces between lithologic units of contrasting hydraulic conductivities. Data also indicate that water movement through the sand of the Toulon Member of the Glasford Formation occurs along localized partially saturated to saturated flow paths. Average velocities of water movement through the extent of the unsaturated zone, as estimated by a saturation-tracking method, ranged from 0.04 to 0.34 meter per day.

Tritium concentrations in the unsaturated zone varied spatially reflecting the heterogeneity of wastes in the overlying trenches and local hydrogeologic conditions. Tritium concentrations at all lysimeter locations increased with time; however, the increases usually were of small magnitude. Tritium concentrations increased abruptly, from five to nine times previous concentrations, at only 3 of 14 locations.

Gas samples were collected from a network of soil-gas piezometers located in the undisturbed unsaturated zone near a waste trench at approximately 70-day intervals during 1984-86. Relative proportions of nitrogen, oxygen plus argon, carbon dioxide, methane, ethane, propane, butane, tritiated water vapor, ^{14}carbon dioxide, and ^{222}radon were converted to partial pressures, based on a mean atmospheric pressure of 98.6 kilopascals. Methane and ^{14}carbon dioxide were identified as originating in the waste and having mean partial pressures that generally decreased with horizontal distance from the trench and with vertical distance to the land surface. Partial-pressure gradients for other radioactive gases were not detected in the gas-sampling network; definable gradients may occur much nearer to the waste source.

Ground-water flow has been studied at the site since 1976. The spatial, stratigraphic, and lithologic complexity of the unconsolidated deposits that compose the shallow aquifer result in the free water surface intersecting nine different lithologic units at the site. Saturated hydraulic conductivities of these units range from about 4×10^{-12} to 8×10^{-6} centimeters per second. Three ground-water basins were defined within the shallow aquifer, with flow generally from west to east. Ground-water velocities are highly variable. A tracer test conducted in a pebbly-sand unit resulted in velocities in the range of 640 to 770 meters per year. Estimated velocities for the other units ranged from 2 to 490 meters per year.

Tritium was detected in observation wells on-site in 1976 and off-site in 1982. Concentrations ranged from the analytical detection limit of 0.2 to over 300 nanocuries per liter. Seasonal variations in tritium concentrations were observed in most wells, and dilution caused by infiltrating rainfall was observed.

Water-chemistry research included the collection and analysis of precipitation, geologic materials, and unsaturated- and saturated-zone water, both on-site and off-site, and in all geologic units, during 1978 to 1984. Precipitation was a calcium-zinc-sulfate type water. Calcium and bicarbonate were the most abundant cation and anion, respectively, in the geologic materials. Mean dissolved organic carbon and tritium concentrations (45 milligrams per liter and 290 nanocuries per liter, respectively) were greater in samples from six lysimeters located directly below waste trenches and one located within a trench, than in samples from all other lysimeters (8.4 milligrams per liter and 17 nanocuries per liter, respectively). Water in the saturated zone was generally a magnesium-bicarbonate type. Tritium was the only radionuclide detected in the saturated zone.

INTRODUCTION

Shallow burial has been the predominant means of disposing of low-level radioactive wastes[1] in the United States. Low-level radioactive wastes generated by the Federal Government have been disposed of at six major and several minor Department of Energy sites; wastes from private sources have been buried at six commercial repositories (fig. 1). As a result of the Low-Level Radioactive Waste Policy Act (Act) (Public Law 96-573--December 22, 1980) and the Low-Level Radioactive Waste Policy Amendments Act of 1985 (Public Law 99-240--January 15, 1986), each State is responsible for the disposal of wastes generated within its borders. In order to comply with the Act, most States have entered into compacts with neighboring States. These compacts allow low-level radioactive wastes from all States within the compact region to be disposed of at one site.

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[1]The term low-level radioactive waste has, over the years, been assigned a variable and imprecise definition. Currently (1988), low-level radioactive waste is defined in terms of what it is not. It is not high-level waste[2]; spent fuel[3]; transuranic waste[4]; or uranium mill tailings[5]. It includes a variety of radioactive materials, some of which are very radioactive and may include significant quantities of fission products with half-lives in excess of 25 years. Low-level radioactive wastes consist of a wide variety of materials including sludges, ion-exchange resins, clothing, tools, animal carcasses, instruments, glassware, piping, valves, paper, sweepings, and general trash.

[2]High-level waste is the liquid waste resulting from the operation of the first cycle solvent extraction system, or equivalent, and the concentrated waste from subsequent extraction cycles, or equivalent, in a facility for reprocessing irradiated reactor fuel, and solids into which such liquid waste has been converted. High-level waste is intensely radioactive, generates much heat through the decay of fission products, and is potentially the most dangerous type of nuclear waste.

[3]Spent fuel is the irradiated nuclear fuel removed from a commercial reactor or special fuels from a research reactor. Spent fuel is intensely radioactive and generates much heat. It contains all of the fission products present in high-level waste, plus the unused uranium and plutonium that would be recovered by reprocessing, plus the gaseous radionuclides that are released by reprocessing.

[4]Transuranic (TRU) waste is waste contaminated with alpha-emitting radionuclides having an atomic number greater than 92 with half-lives greater than 20 years in concentrations greater than 100 nanocuries per gram. Transuranic waste is generated primarily by defense activities during the reprocessing of irradiated materials and the fabrication of nuclear weapons by using plutonium.

[5]Uranium mill tailings are the residues remaining after the milling of uranium ore. They are produced in large volumes and contain low concentrations of naturally occurring long-lived radionuclides, including thorium-230 and radium-226, which decay into the radioactive gas radon-222.

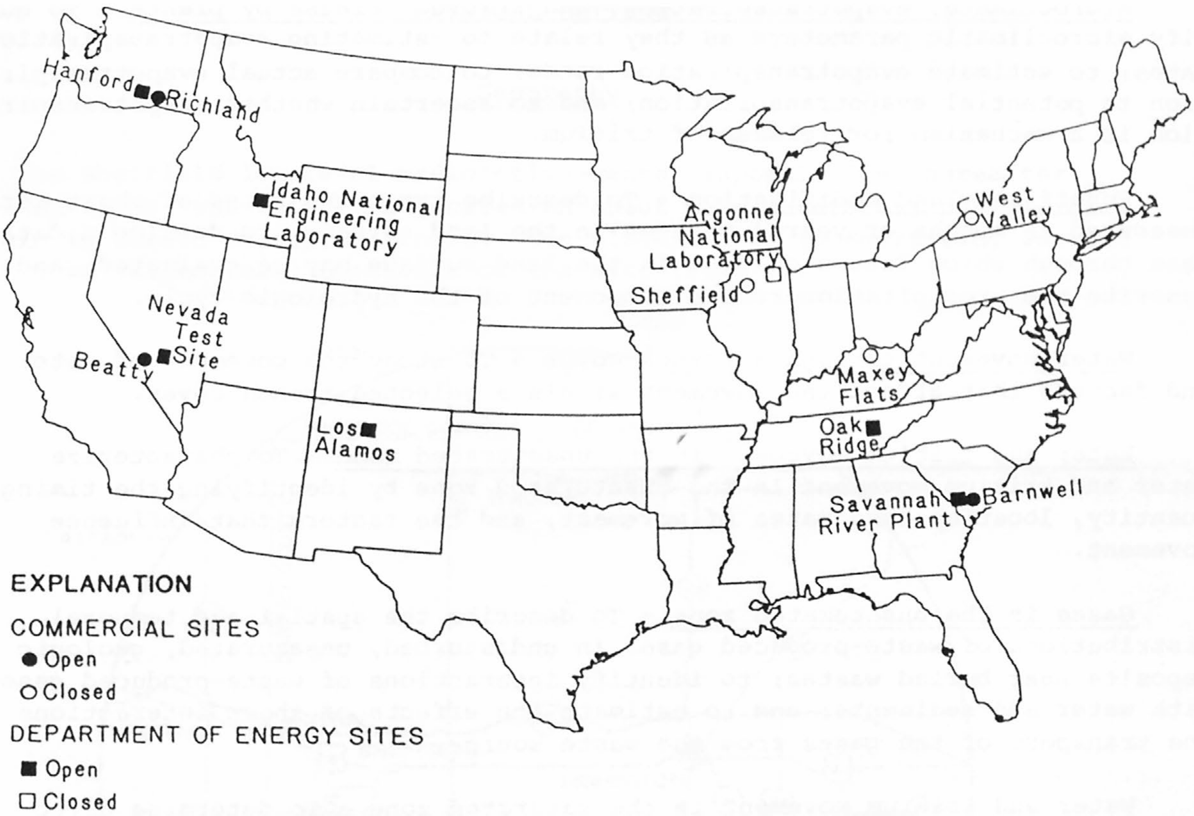


Figure 1.--Location of principal low-level radioactive-waste disposal sites in the United States.

Purpose and Scope

The purpose of this report is to present results and implications of approximately 10 years of hydrologic research conducted by the U.S. Geological Survey at a commercial low-level radioactive-waste disposal site.

Hydrologic research at the site located near Sheffield, Illinois, has included studies of microclimate, evapotranspiration, and tritium release by plants; runoff and land modification; water movement through a trench cover; water and tritium movement in the unsaturated zone; gases in the unsaturated zone; water and tritium movement in the saturated zone; and water chemistry.

The 10 years of research at the Sheffield site were conducted in increments with individual investigations not necessarily conducted in the order in which they are presented in this report. The order in which the investigations are presented, however, encourages a process-oriented view of the research that approximates the manner in which water moves through the hydrologic cycle. Each investigation's primary objectives were as follows:

Microclimate, evapotranspiration, and tritium release by plants - To quantify microclimatic parameters as they relate to estimating evapotranspiration rates; to estimate evapotranspiration rates; to compare actual evapotranspiration to potential evapotranspiration; and to ascertain whether evapotranspiration is a mechanism for release of tritium.

Runoff and land modification - To describe types and rates of short-term (measured in months or years) changes in the land surface; to develop a data base through which future changes in the land surface may be evaluated; and to describe the precipitation-runoff component of the hydrologic cycle.

Water movement through a trench cover - To study the movement of water and factors that affect the movement within a selected trench cover.

Water and tritium movement in the unsaturated zone - To characterize water and tritium movement in the unsaturated zone by identifying the timing, quantity, location, and rates of movement, and the factors that influence movement.

Gases in the unsaturated zone - To describe the spatial and temporal distributions of waste-produced gases in undisturbed, unsaturated, geologic deposits near buried wastes; to identify interactions of waste-produced gases with water and sediments; and to estimate the effects of those interactions on the transport of the gases from the waste source.

Water and tritium movement in the saturated zone - To determine directions and rates of water and tritium movement in the shallow saturated zone, and factors that affect this movement.

Water chemistry - To describe the chemistry of precipitation, geologic materials, and water in the unsaturated and saturated zones; to identify techniques useful for obtaining representative samples of water from the unsaturated zone; to support, through statistical analyses and geochemical modeling, the identification of naturally occurring geochemical reactions; and to investigate the effect of wastes on water chemistry.

Implications specific to each research topic are presented along with results of investigations. These specific implications and implications based on overlapping research topics also are summarized at the end of the report as to their potential effect on the selection, characterization, design, operation, and decommissioning of future low-level radioactive-waste disposal sites. Although some of the implications appear obvious after 10 years of research, the value of presenting them cannot be underestimated.

Acknowledgments

The authors extend their appreciation to the site operator for the assistance given over the years. The U.S. Nuclear Regulatory Commission is recognized for their cooperation and funding during selected phases of the study. Additionally, both the Illinois Department of Nuclear Safety and Illinois State Geological Survey are recognized for their assistance during this research effort.

PHYSICAL SETTING

Geography

The Sheffield low-level radioactive-waste disposal site (hereafter referred to as "the site") is located on about 8 ha (hectares) of rolling terrain in Bureau County, Illinois. The closest town is Sheffield, located about 5 km (kilometers) northeast of the site (fig. 2).

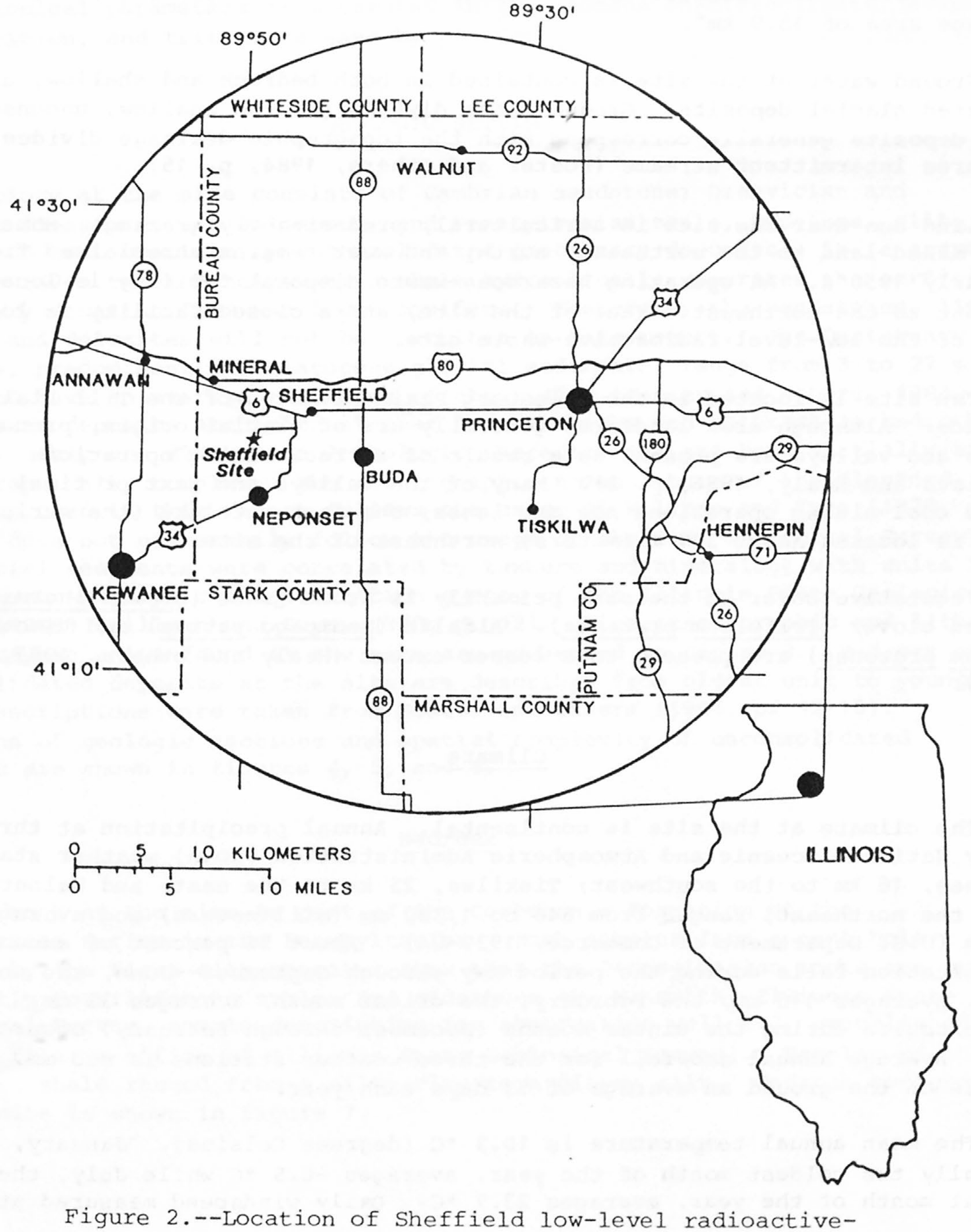


Figure 2.--Location of Sheffield low-level radioactive-waste disposal site.

Bureau County is approximately 2,250 km^2 (square kilometers) in area. In 1980, the County's population was approximately 39,100 with 13,200 living in urban areas and 25,900 living in rural areas (U.S. Department of Commerce, 1983, table B, p. 130-143). Sheffield has a population of approximately 1,000. The area is sparsely populated with 17 residences within 3-km radius of the site (Foster and others, 1984, p. 4).

The site is located in the Upper Mississippi River Basin. Three small intermittent streams, the headwater tributaries of Lawson Creek, drain the site. Lawson Creek, located approximately 1.6 km east of the site, has a drainage area of 15.9 km^2.

Ground water at the site is contained in both bedrock and shallow, unconsolidated glacial deposits. Ground-water divides for the shallow, unconsolidated deposits generally correspond with the topographic drainage divides of the three intermittent streams (Foster and others, 1984, p. 15).

Land use near the site is agricultural, predominantly grazing. Some strip-mined land to the northeast, north, and west remains unreclaimed from the early 1950's. An operating hazardous-waste disposal facility is located adjacent to the northwest corner of the site, and a closed facility is located north of the low-level radioactive-waste site.

The site is located in the Galesburg Plain Division of the Till Plains Province. Although area landforms generally are of glacial origin, pronounced ridges and valleys are present as a result of surface-mining operations (Garklavs and Healy, 1986, p. 3). Many of the valleys and last or final cuts of the coal-mining operations now are lakes; one last-cut lake (the strip-mine lake) is located about 300 m (meters) northeast of the site.

Vegetative cover at the site primarily is brome grass (*Bromus inermis*) and red clover (*Trifoleum pratense*). Alfalfa (*Medicago sativa*) and timothy (*Phleum pratense*) are present to a lesser extent (Healy and others, 1987, p. 11).

Climate

The climate at the site is continental. Annual precipitation at three nearby National Oceanic and Atmospheric Administration (NOAA) weather stations (Kewanee, 16 km to the southwest; Tiskilwa, 23 km to the east; and Walnut, 31 km to the northeast) ranged from 646 to 1,330 mm (millimeters) and averaged 890 mm (U.S. Department of Commerce, 1939-84). About 56 percent of annual precipitation falls during the period May through September--June, the wettest month, averages 116 mm, and February, the driest month, averages 33 mm. Most precipitation during the winter months (December through February) occurs as snow. Average annual snowfall for the three weather stations is 850 mm, and snow is on the ground an average of 53 days each year.

The mean annual temperature is 10.3 °C (degrees Celsius). January, generally the coldest month of the year, averages -6.5 °C while July, the warmest month of the year, averages 23.7 °C. Daily windspeed measured at

Moline Airport (68 km west of the site) for the period June 1, 1981, through December 31, 1983, averaged 4.7 m/s (meters per second) (Healy and others, 1987, p. 4). The predominant wind directions were south-southwest and west-northwest. Average relative humidity at Moline for the above-mentioned period was 71 percent and fluctuated little throughout the year.

Yearly average pan evaporation for April through October, from 1963 through 1983, at a NOAA station at the Hennepin, Illinois, powerplant (39 km east of the site), was 1,140 mm. The month with the highest average pan evaporation was July. A more detailed and site-specific presentation of meteorological parameters is presented in the section on microclimate, evapotranspiration, and tritium release by plants.

GEOLOGIC SETTING

Geology at the site consists of Cambrian sandstone; Ordovician and Silurian limestones and dolomites; and Pennsylvanian shale, mudstone, siltstone, and coal overlain by unconsolidated Quaternary deposits. It is assumed that the 140-m thick Pennsylvanian shale hydraulically separates the surficial Quaternary deposits from the lower aquifers. Therefore, the sandstones, limestones, and dolomites will not be described in this report. The Quaternary deposits, predominantly Pleistocene glacial sediments, range from 3 to 27 m thick and have an average thickness of about 17 m (Foster and others, 1984, p. 12). These deposits are thinnest near bedrock highs and thickest in bedrock valleys. They are diverse in lithologic character and are both spatially and stratigraphically complex. The stratigraphic nomenclature of the Glasford Formation used in this report follows the usage of Willman and Frye (1970, p. 52) and does not necessarily follow the usage of the U.S. Geological Survey. The glacial sediments were correlated by texture and mineralogy with units in the rock-stratigraphic classification system of the Illinois State Geological Survey (ISGS) (Willman and Frye, 1970, p. 12). Time-stratigraphic and lithostratigraphic units found at the site are presented in figure 3. Bedrock and unconsolidated deposits at the site are described from oldest unit to youngest unit; descriptions were taken from Foster and others (1984, p. 12-15). Locations of geologic sections and spatial complexity of unconsolidated deposits are shown in figures 4, 5, and 6.

Bedrock

Bedrock at the site is part of the Carbondale Formation of the Desmoinesian Series in the Pennsylvanian. Rock samples from a test hole drilled by the first site operator show that the Pennsylvanian rocks are predominantly fossiliferous shales and mudstones (H. W. Smith, Illinois State Geological Survey, sample description for observation well B-2, unpublished data on file in office of Illinois State Geological Survey). Samples of the weathered shale ranged from a silty clay to a clayey silt. Bedrock topography at the site is shown in figure 7.

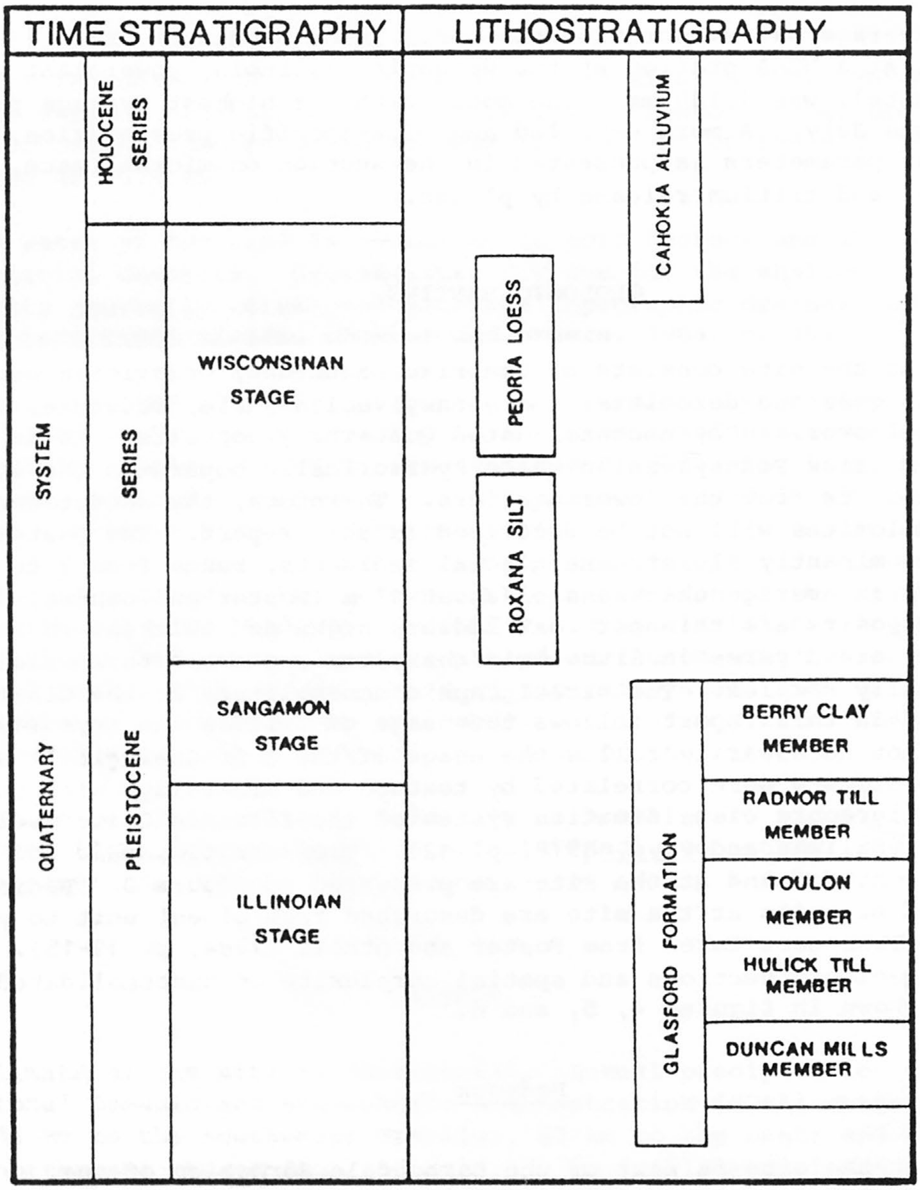


Figure 3.--Time-stratigraphic and lithostratigraphic units at the site (modified from Willman and Frye, 1970).

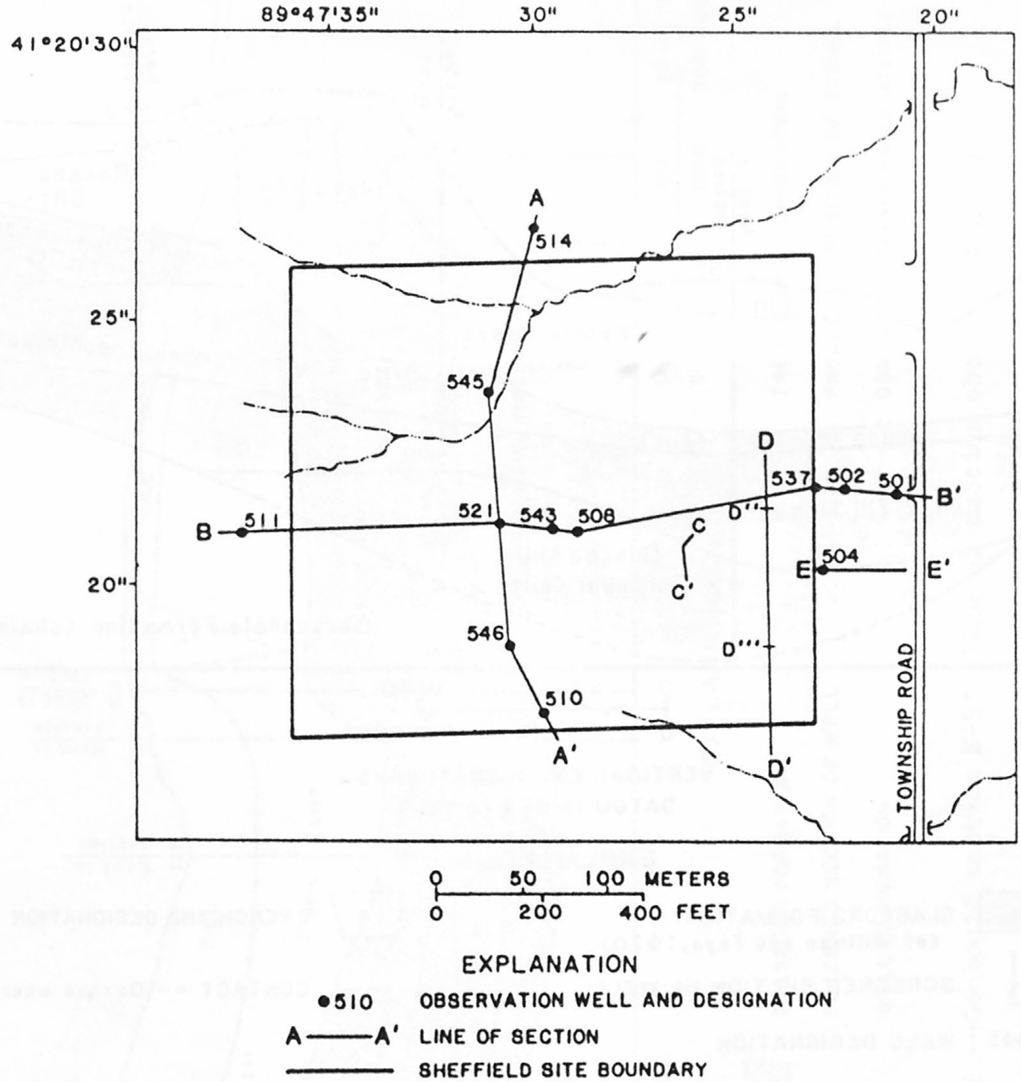


Figure 4.--Location of geologic sections.

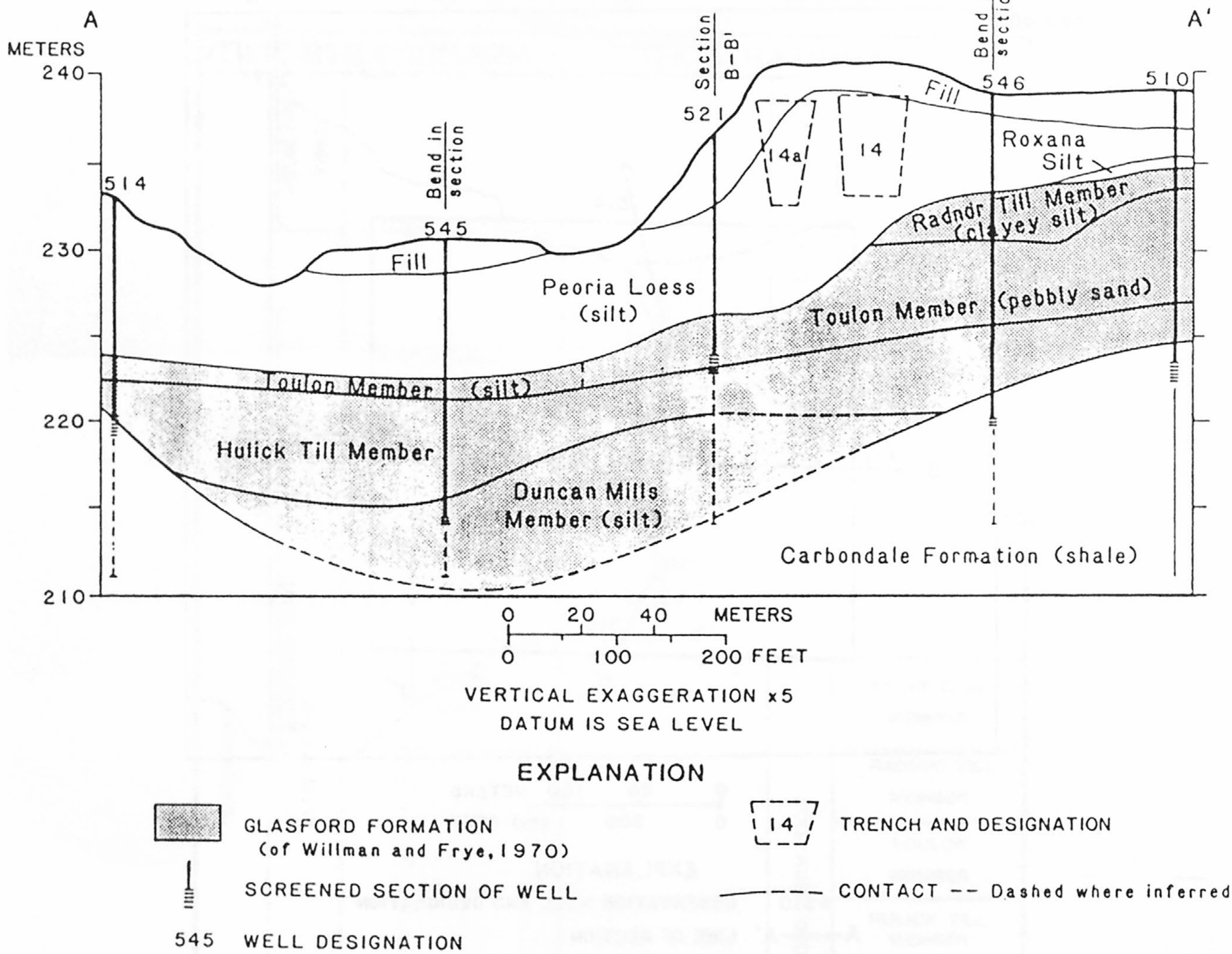


Figure 5.--Geologic section A-A' (line of section shown in fig. 4).

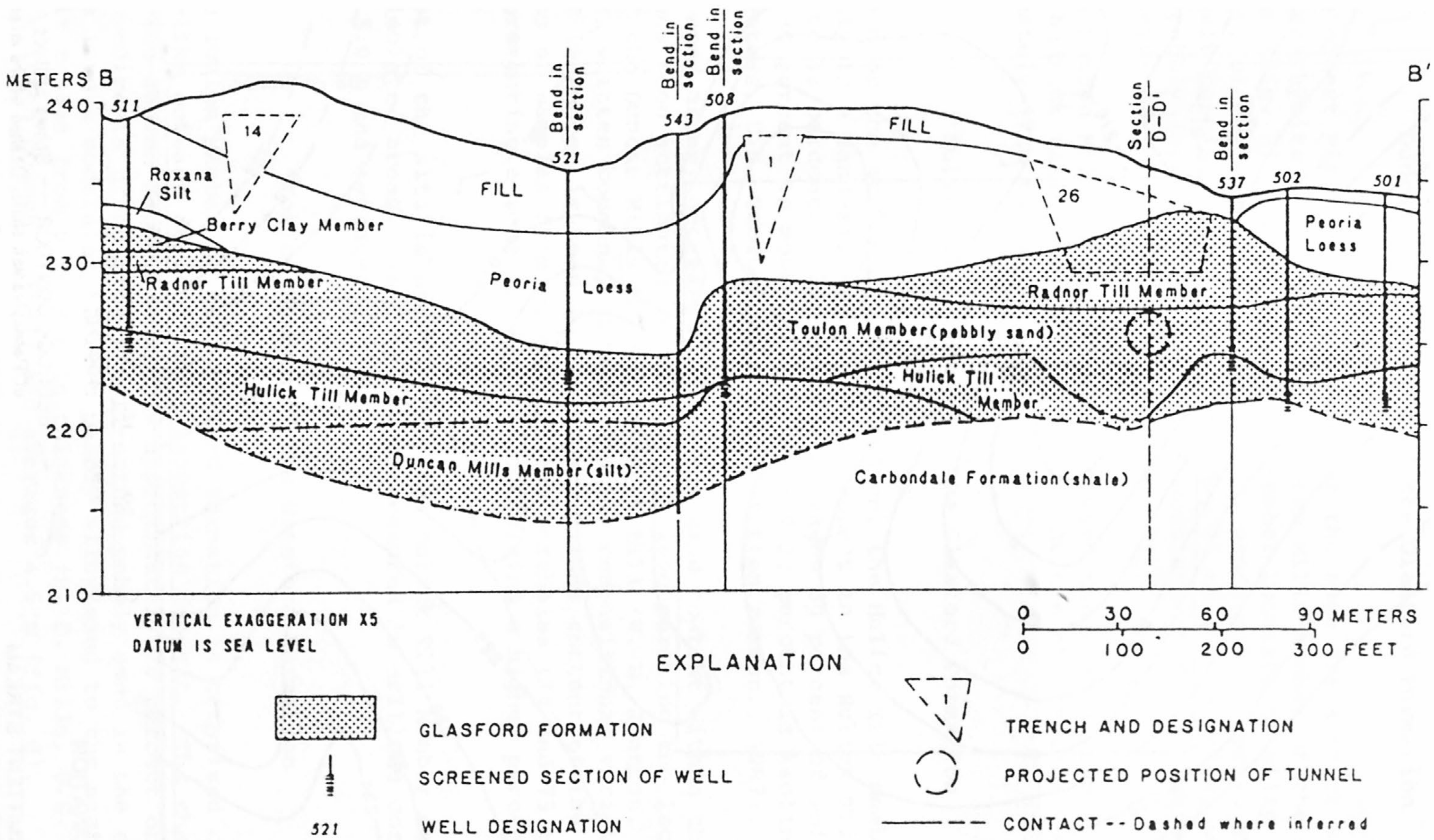


Figure 6.--Geologic section B-B' (line of section shown in fig. 4).

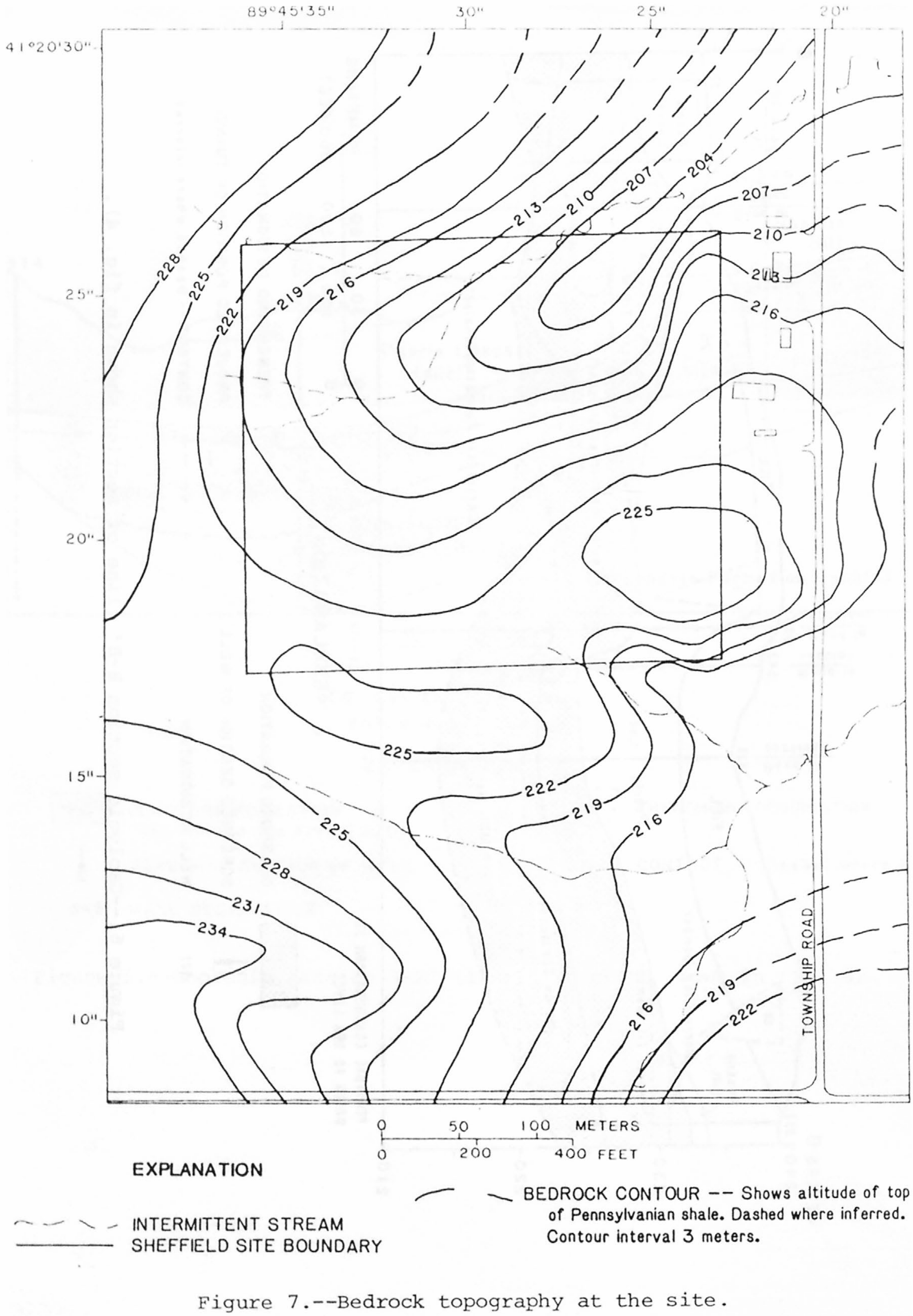


Figure 7.--Bedrock topography at the site.

Unconsolidated Deposits

Duncan Mills Member of the Glasford Formation

The oldest Pleistocene sediments at the site are a thick sequence of lacustrine-rhymite sediments of the Duncan Mills Member of the Glasford Formation (fig. 3). The Duncan Mills Member consists of silty clay interbedded with silt, clayey silt, and a few pebbly, sandy silt layers. The lower part of the deposit consists of clayey-silt beds, 25 to 450 mm thick, with interbedded coarse, pebbly layers. The upper part consists of finely laminated silts and silty clays.

The Duncan Mills Member thickens toward the northeast corner of the site where a bedrock valley deepens (fig. 7). At one observation well, the unit is approximately 17 m thick.

Hulick Till Member of the Glasford Formation

Based on the grain-size distribution, the Hulick Till Member (fig. 3) predominantly is a sand-silt-clay. Sand content in the Hulick Till Member ranges from 16 to 33 percent. Clay content averages 30 percent of which 43 percent is illite, 30 percent is montmorillonite, and 27 percent is kaolinite and chlorite (C. A. Peters, U.S. Geological Survey, written commun., 1987).

In some areas, decreased illite and sand content within the Hulick Till Member has been attributed to the glacier incorporating the lacustrine sediments of the Duncan Mills Member into the till (W. H. Johnson, University of Illinois, written commun., 1979). Another compositional variation in the Hulick Till Member is seen in the higher illite content of the clay-sized fractions of samples from cores from two boreholes (74 and 75 percent), probably representing a zone in the till containing a higher percentage of shale bedrock.

Most of the site is underlain by the Hulick Till Member except for a few, small, isolated areas. Till thickness measured in drilling cores ranged from 0.08 to 5.0 m and averaged 2.0 m.

Toulon Member of the Glasford Formation

The Toulon Member of the Glasford Formation is comprised of two units--a channel-like outwash deposit and a lacustrine deposit. The channel-like outwash of the Toulon Member underlies approximately 70 percent of the site. The outwash sediments grade from a well-sorted pebbly sand in the eastern half of the site into a moderately sorted pebbly-silty sand to the west. The pebbly-sand unit ranges from 0 to 8 m in thickness (P. C. Mills, U.S. Geological Survey, written commun., 1987) and averages 4.5 m (fig. 8).

A structure-contour map (fig. 9) of the upper surface of the pebbly-sand unit shows it dipping to the northeast from near the southwestern corner of the site. The pebbly sand probably covered all or most of the site up to an altitude of at least 232 m at one time. The present upper surface of the pebbly

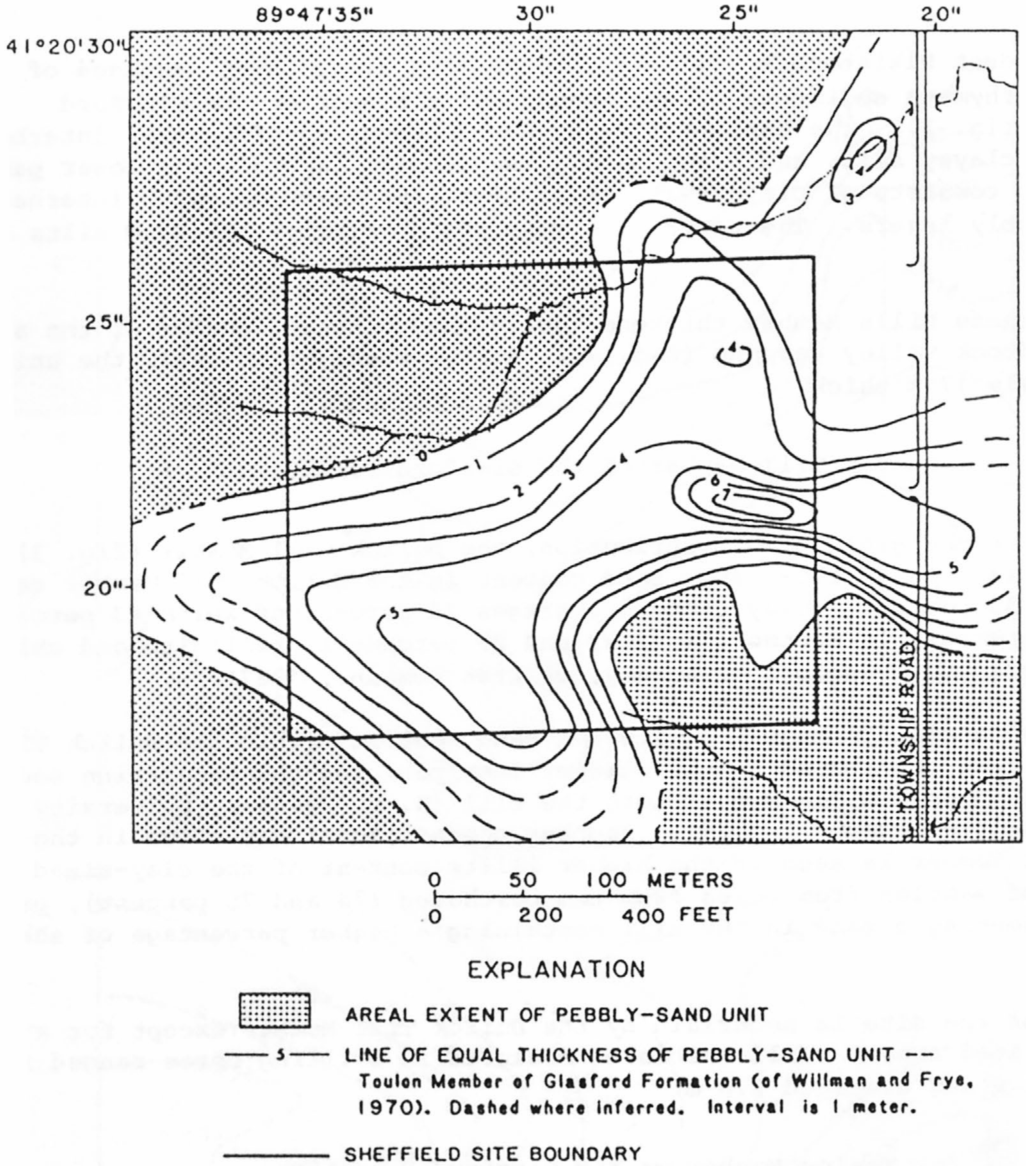


Figure 8.--Thickness of pebbly-sand unit of Toulon Member of Glasford Formation.

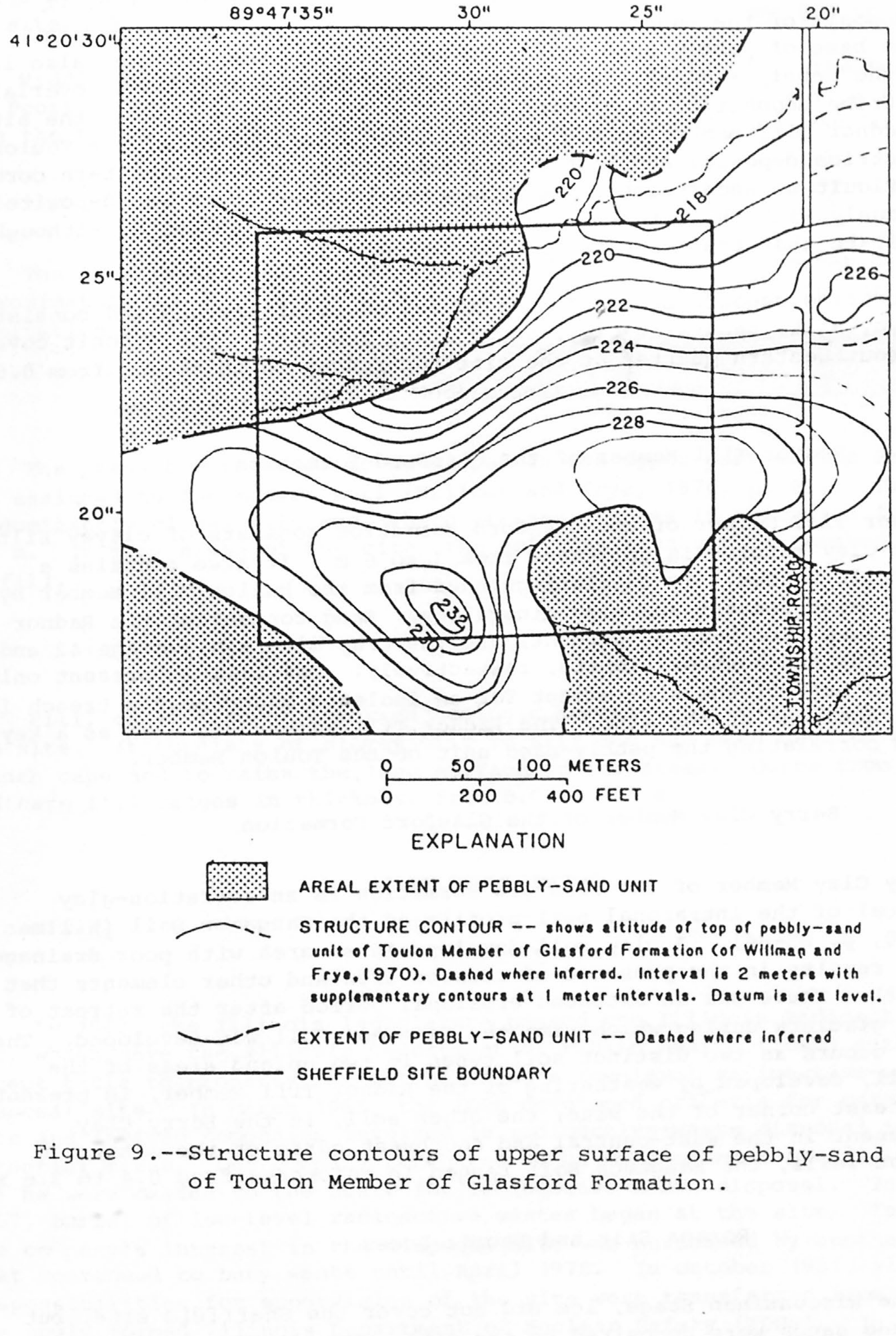


Figure 9.--Structure contours of upper surface of pebbly-sand unit of Toulon Member of Glasford Formation.

sand developed during an erosional period prior to the deposition of the younger Pleistocene deposits overlying the unit. The pebbly sand apparently is absent in the northwest and much of the southeast area of the site. A lacustrine deposit of the Duncan Mills Member was used as a marker bed to establish the base of pebbly sand on the western side of the site and also in correlating the pebbly-sand unit across the site. The pebbly sand is overlain by the lacustrine deposit of the Toulon Member on the western side of the site and by the Radnor Till Member on the eastern side. The absence of the Toulon Member (lacustrine deposit) and Radnor Till Member near the northeastern corner makes it difficult to ascertain if the pebbly-sand outwash here was deposited contemporaneously with the outwash on the southern half of the site, although the data indicate that the deposits are continuous.

The lacustrine deposit of the Toulon Member is fossiliferous and consists of silt, clayey silt, sand-silt-clay, sandy silt, and marl. The deposit covers most of the southwestern quarter of the site and ranges in thickness from 0.6 to 1.8 m.

Radnor Till Member of the Glasford Formation

The Radnor Till Member of the Glasford Formation consists of clayey silt and sand-silt-clay ranging in thickness from 1 to 6 m. It also contains a few sand and silt lenses. It is distinguished from the Hulick Till Member by differences in sand content and clay mineralogy. Sand content of the Radnor Till Member ranges from 6 to 46 percent, and the clay minerals average 42 and 44 percent illite and montmorillonite, respectively. The till is present only in the southern half of the site except for an isolated mound near a trench in the northwest quadrant of the site. The Radnor Till Member was used as a key marker bed in correlating the pebbly-sand unit of the Toulon Member.

Berry Clay Member of the Glasford Formation

The Berry Clay Member of the Glasford Formation is an accretion-gley deposit, typical of the intrazonal soil profile of the Sangamon Soil (Willman and Frye, 1970, p. 85-86). A gley soil develops in an area with poor drainage. The condition results in the presence of reduced iron and other elements that mottle the soil. There was an extended erosional period after the retreat of the Illinoian glaciers during which time the Sangamon Soil was developed. The Sangamon Soil occurs as two distinct soil types in two upland areas of the site. One soil, developed by weathering of the Radnor Till Member, is present near the southeast corner of the site; the other soil, in the Berry Clay Member, is present in the west-central and southwest parts of the site. In cores from test wells, the Sangamon Soil ranged in thickness from 0.4 to 3.6 m.

Roxana Silt and Peoria Loess

During the Wisconsinan Stage, ice did not cover the Sheffield site, but eolian silts and sands were deposited on the site. The silts originated from lake deposits along the Mississippi River (Willman and Frye, 1970, p. 36) and the sands from nearby outwash deposits.

Lower Wisconsinan eolian silts are assigned to the Roxana Silt (fig. 3). The Roxana Silt is largely loess but contains layers of clayey silt and sand-silt-clay. Two deposits of Roxana Silt are located in the southern third of the site. The thickness of Roxana Silt in cores ranged from 0.4 to 2.2 m.

Middle to upper Wisconsinan eolian silts are assigned to the Peoria Loess. The Peoria Loess covers the entire site, ranging in thickness from 0.6 to 9 m, with the thicker accumulations found near the north and west boundaries.

Cahokia Alluvium

The Cahokia Alluvium is present near the northeastern corner of the site. Approximately 0.6 m of sandy silt was penetrated in the drilling of a single observation well.

Modern Soil

The present soil cover is developed in the upper part of the Peoria Loess and assigned to the Modern soil (Willman and Frye, 1970, p. 89). This soil is predominantly clayey silt and, where present, ranges in thickness from 0.6 to 2.7 m. In many areas of the site, the soil has been either removed or covered by fill.

Fill

Fill, consisting of reworked geologic deposits, is the youngest unit on the site. It consists of clayey silt to silt and has been used to build trench caps and to raise the land surface in low areas. Cores from wells indicate fill ranges in thickness from 0.6 to 7.1 m.

SITE DEVELOPMENT

History

In 1963, the Illinois legislature passed the Illinois Radioactive Waste Act, which gave the Illinois Department of Public Health (IDPH) authority to accept title to property for establishing a low-level radioactive-waste disposal site. In March 1965, the IDPH developed criteria for establishing a site and invited companies involved in radioactive-waste disposal to propose potential sites. One company purchased 27 ha of land near Sheffield of which 8.1 ha were deeded to the State for radioactive-waste disposal. In August 1967, burial of low-level radioactive wastes began at the site. In March 1968, the company's interest in the disposal site was purchased by another company that continued to bury waste until April 1978. In October 1981, all State responsibilities for supervision of the site were transferred from the IDPH to the newly formed Illinois Department of Nuclear Safety (IDNS). In 1987, the U.S. Nuclear Regulatory Commission (the Federal agency responsible for site supervision) granted IDNS regulatory responsibility for the site (Agreement between the United States Nuclear Regulatory Commission and the State of Illinois for Discontinuance of Certain Commission Regulatory Authority and Responsibility within the State pursuant to Section 274 of the Atomic Energy Act of 1954, as amended, May 18, 1987, effective June 1, 1987).

Waste Trenches

Low-level radioactive wastes are buried in 21 trenches at the site (fig. 10) that were constructed in unconsolidated glacial materials. Trench dimensions ranged from 11 to 180 m long, 2.4 to 21 m wide, and 2.4 to about 7.9 m deep. Nineteen of the trenches were constructed at or below the natural grade of the land surface. By late 1976, all available space meeting an IDNS requirement that at least 3.1 m separate the base of a trench and the top of the saturated zone had been exhausted. Two trenches were subsequently constructed partly above the existing land surface to allow for the 3.1 m separation. Walls for the above-grade trenches were constructed by importing clayey-silt fill from nearby surface deposits and compacting the material layer upon layer.

A typical trench has sloped walls (fig. 11), a lengthwise sloping floor with a 0.6 m by 0.6 m rock-filled French drain connected to a sump at the low end of the trench. A pipe extends from the sump to land surface to allow for monitoring access and leachate removal. Some trenches were covered with a compacted layer of clayey silt from nearby surface deposits; all trenches were capped by a mound of clayey silt and silt. Swales exist between adjacent trench covers.

Although records are incomplete, it is estimated that a total of about 90,500 m^3 (cubic meters) of waste were buried including about 60,000 curies of by-product material, 13.6 kg (kilograms) of plutonium-239, 0.002 kg of uranium-233, 41 kg of uranium-235, and 270,845 kg of source material (Illinois Department of Nuclear Safety, written commun., 1979). Buried wastes are contained in steel drums, wooden crates, miscellaneous plastic containers, concrete casks, and cardboard cartons. Contents of the containers include such items as scintillation liquids (generally solidified), ion-exchange resins, decontamination solutions, contaminated and activated metals, laboratory supplies from hospitals, glassware, building materials, experimental animal carcasses, protective clothing, tools, and paper.

Arrangement of containers in the trenches varied from orderly placement to random disposal. Records of the arrangement methodology are limited. Figure 12 illustrate variations of container arrangement; relative trench dimensions also are evident. Waste-burial records compiled by Kahle and Rowlands (1981) indicate that the ratio of waste volume to trench volume ranges from 36 to 67 percent. The filled trenches at the site contain numerous voids that result from the use of a wide variety of waste containers and burial arrangements, incomplete backfilling, and collapse of waste containers.

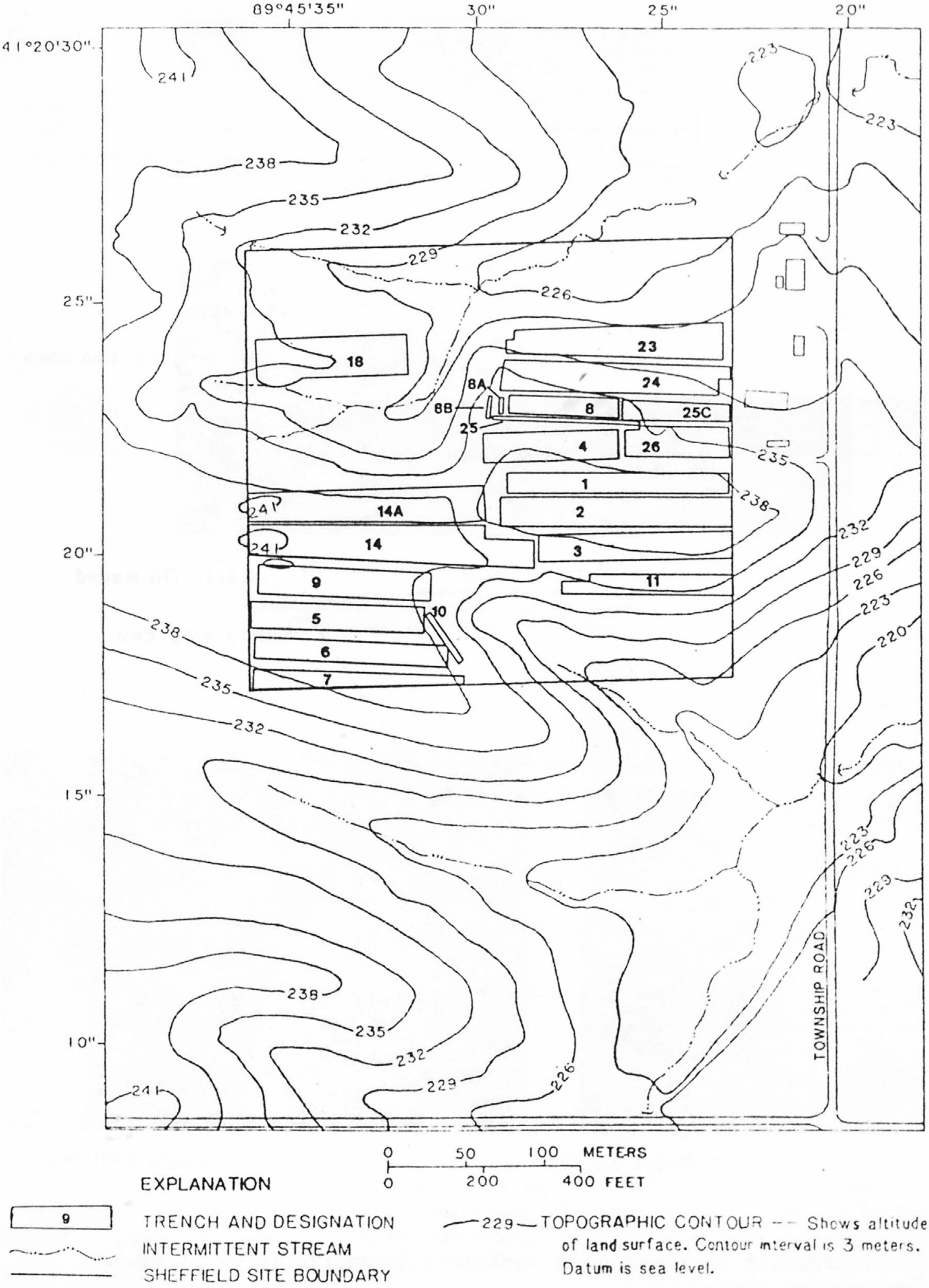


Figure 10.--Location of trenches.

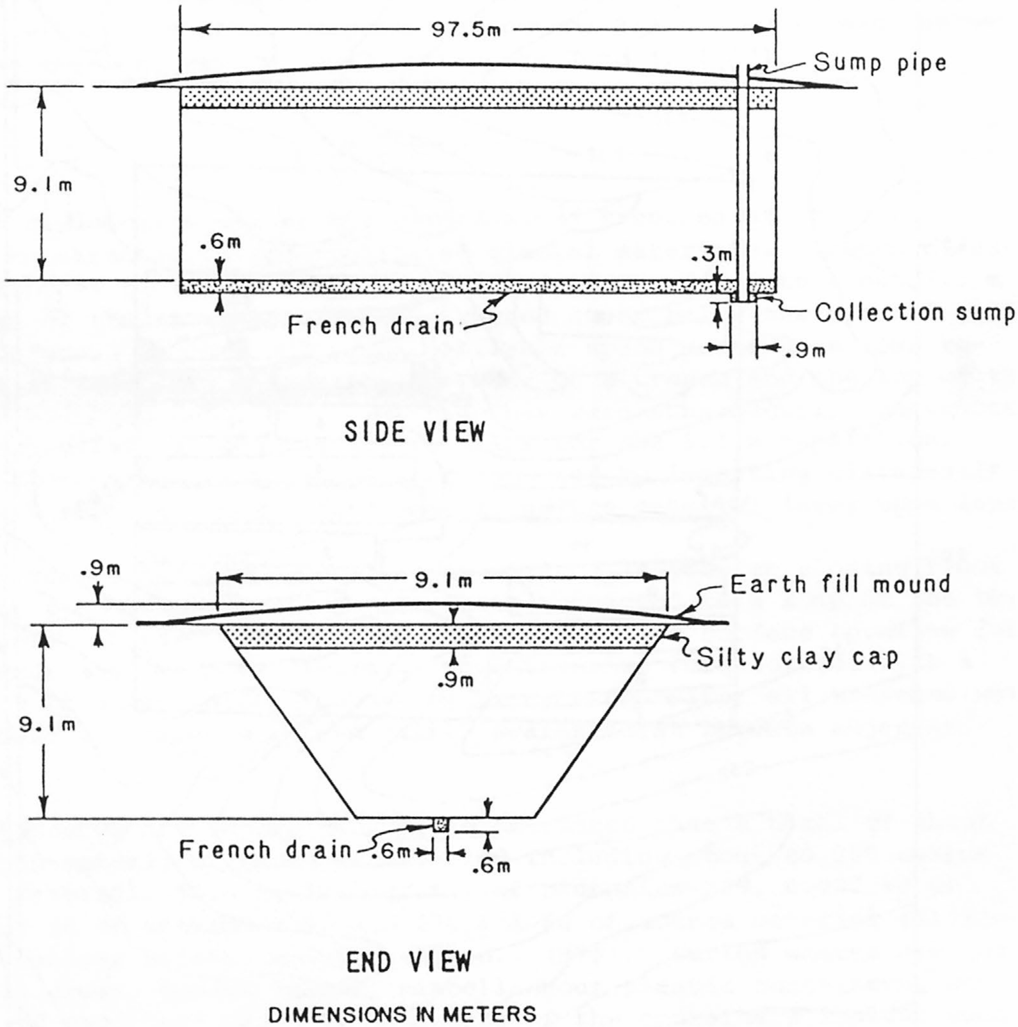
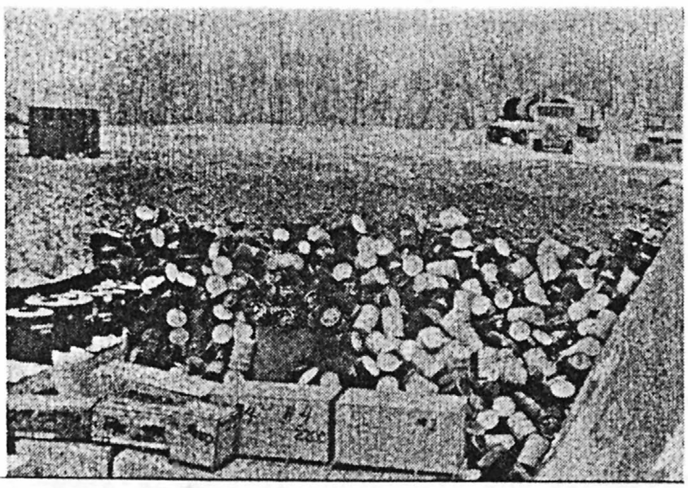
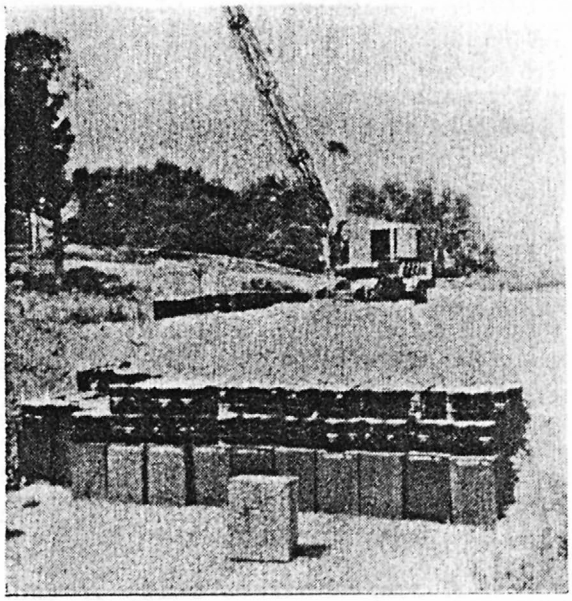


Figure 11.--Side and end views of a typical trench.

12.a Trench 11 undated, US Ecology



12.b Unidentified trench



12.c Trench 18 July 1976

Figure 12.--Variations of container arrangement in trenches.

Management Practices

For the purpose of this paper, site-management practices can be divided into two categories. The first category, routine maintenance, includes the following activities: periodic visual inspections, mowing vegetation, and inspecting for water in trench sumps. The second category, remedial measures, generally pertains to reducing erosion and includes the following activities: filling collapse holes, rills, and gullies; and maintaining slope stability by planting grasses and laying geotechnical fabric where needed.

HYDROLOGIC RESEARCH

In 1976, the U.S. Geological Survey began a study of the mechanisms and pathways by which radionuclides might move at the Sheffield low-level radioactive-waste site. Because it was anticipated that water would play a primary role in mobilizing and transporting radionuclides from the trenches, the following aspects of the hydrologic environment were investigated in the ensuing years: microclimate and evapotranspiration, surface hydrology, unsaturated-zone hydrology, saturated-zone hydrology, and water chemistry. As previously mentioned, these research topics were not investigated in the order presented. The order of presentation, however, approximates the manner in which water moves through the hydrologic cycle and, therefore, encourages a process-oriented view of radionuclide transport.

Three additional topics--tritium release by plants, water movement through a trench cover, and gases in the unsaturated zone--represent research that was conducted in the later phases of the U.S. Geological Survey's involvement at the site. The results and implications of each of these research topics need to be considered in the selection, characterization, design, operation, and eventual decommissioning processes of future low-level radioactive-waste disposal sites.

Microclimate, Evapotranspiration, and Tritium Release by Plants

by M. Peter deVries and Richard W. Healy

Introduction

A comprehensive study of the microclimate and evapotranspiration of vegetated trench covers was conducted from July 1982 through June 1984 at the site. A presentation of theory, methods, and results of the 2-year study can be found in Healy and others (1986 and 1987). The objectives of this research were to (1) quantify microclimatic characteristics as they relate to estimating evapotranspiration rates, (2) estimate evapotranspiration rates, (3) compare actual evapotranspiration to potential evapotranspiration rates, and (4) ascertain whether evapotranspiration is a mechanism for release of tritium. Included here is a description of the microclimate and estimates of evapotranspiration at the site for the period of data collection. The detailed microclimatic description serves to characterize the site so that it may be compared with other existing and potential waste sites. Also, wherever possible, comparison is drawn between the climatic data collected at the site and data from nearby NOAA stations to give an indication of the adequacy of commonly available measurements in characterizing climate-dependent variables at potential sites. Evapotranspiration rates are summarized on an annual basis for each of three different estimation methods, as are computed values for potential evapotranspiration. Finally, data indicating that evapotranspiration acts as a mechanism for tritium release are presented.

Evapotranspiration is the loss of water from soil and plants to the overlying atmosphere through evaporation and plant transpiration. Most precipitation in Illinois is eventually evapotranspired. Jones (1966, p. 12) estimated that annual evapotranspiration, in northern Illinois, ranges from 635 to 760 mm or approximately 71 to 85 percent of the long-term average-annual precipitation of 890 mm for the Sheffield area. Hence, quantification of the hydrologic budget in this area requires an accurate estimate of evapotranspiration.

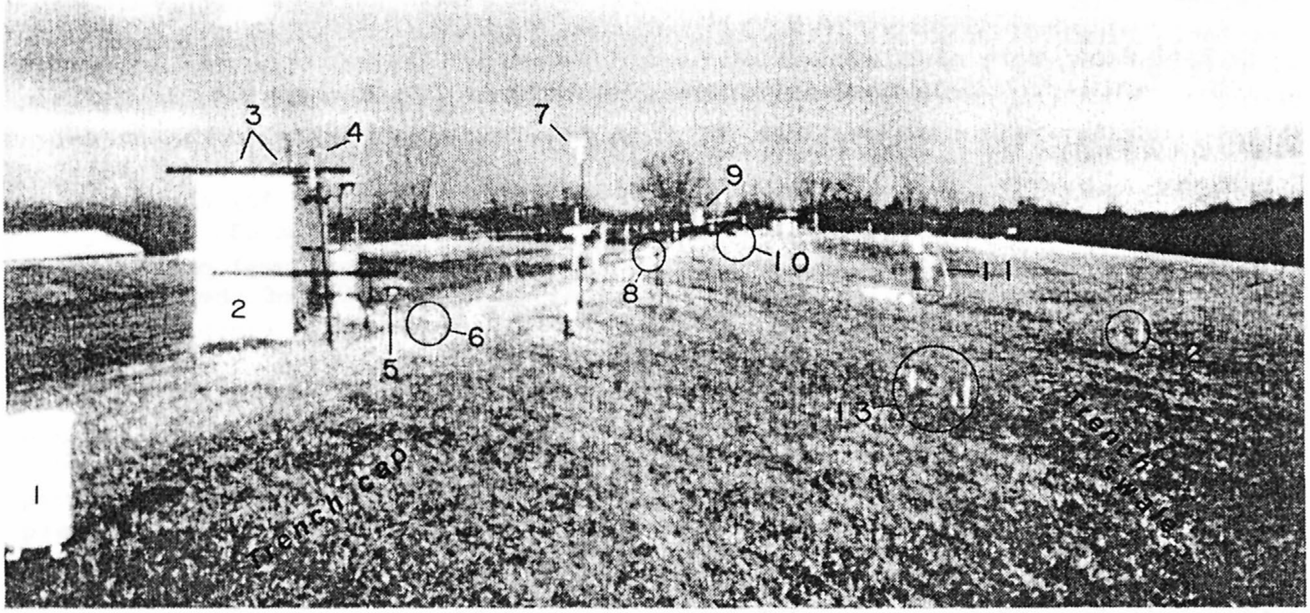
Because plants can often transpire more than their own weight of water in a day, and because the water content of plants changes only within narrow limits from day to day, transpiration cannot be maintained without uptake of water from the soil. Thus, water uptake and transpiration can be regarded as two related characteristics in a process in which large amounts of water are transferred from the soil through plants to the air, with a change from the liquid to vapor phase in the leaf (Rutter, 1975, p. 126). It is by this process that tritium enters the atmosphere at the site.

Microclimate

In order to fully characterize the microclimate of the trenches and to obtain data for evapotranspiration calculations, continuous measurements were made of precipitation, incoming and reflected solar (shortwave) radiation, incoming and emitted terrestrial (longwave) radiation, horizontal windspeed and direction, wet- and dry-bulb air temperature, barometric pressure, soil-heat fluxes, and soil temperature. Figure 13 shows instrumentation arrangement on-site. Windspeed and air temperature were measured at heights of 0.5 and 2.0 m (additionally at 1.0 m after September 1983). Soil-moisture content was measured about biweekly with a gamma-attenuation probe. Long-term climatic data from the three nearby NOAA stations were available only for precipitation and temperature.

Precipitation

From July 1, 1982, through June 30, 1983, a total of 928 mm of precipitation fell, whereas from July 1, 1983, through June 30, 1984, the total was 968 mm, resulting in an annual average of 948 mm. The long-term average for the NOAA station at Kewanee, 16 km southwest of the site, is 890 mm per year. Precipitation occurred on 112 days during the 2-year period. Much of the precipitation occurred during heavy thunderstorms. Of the 2-year total of 1,897-mm precipitation, 47 percent fell during 20 rainstorms, each of which



Trench 2, looking east, Spring 1984

EXPLANATION

1. Rain gage
2. Shelter housing data-loggers and telemetry
3. Incoming long-wave and short-wave radiometers
4. Wind-direction sensor
5. Wet- and dry-bulb psychrometer
6. Subsurface temperature probe and heat-flux disks
7. Wind-speed sensor
8. Moisture probe access tubes
9. Infrared surface-temperature sensor
10. Reflected long-wave and short-wave radiometers
11. Plot runoff and sediment collector
12. Lysimeter cluster
13. Tensiometer cluster

Figure 13.--Instrumentation for measurements of trench cap microclimate, runoff, and soil-moisture movement.

produced more than 25 mm of rain. This is slightly different than long-term trends that indicate, on the average, that 60 percent of annual precipitation in this part of Illinois falls in storms totaling 3 to 25 mm. The largest storm during the period of study occurred on July 6-7, 1982, when 108 mm of rain fell during a 30-hour period.

During the winter of 1982-83, 406 mm of snowfall, containing 40 mm of water, was measured at the NOAA station in Walnut (31 km from the site). Snow was on the ground for a total of 18 days. The winter of 1983-84 was much more severe; a total of 726 mm of snow, containing 69 mm of water, remained on the ground for 65 days.

Radiation

Incoming solar (shortwave) radiation averaged 156 W/m^2 (Watts per square meter), or approximately 65 percent of clear-sky radiation. Average reflected shorewave radiation was 40 W/m^2. There were a total of 117 clear-sky days (when measured shortwave radiation exceeded 90 percent of clear-sky solar radiation). For the same time period, Moline airport (65 km west of the site) reported 160 clear-sky days. Clear days were most common during the months of June, July, and August.

The ratio of reflected to incoming shortwave radiation is termed the surface albedo. Values for albedo at the site ranged from about 0.20, during the summer, to about 0.95, following a fresh snow. During spring and summer, while vegetation was predominantly green, the daily albedo was fairly constant at about 0.21. During fall, this value increased slightly as the vegetation turned brown.

Terrestrial (longwave) radiation is energy given off by the earth's surface and overlying air in direct proportion to the fourth power of their absolute temperature. Monthly incoming longwave radiation ranged from 245 W/m^2 during the winter months to 400 W/m^2 during the summer months. Monthly emitted longwave radiation ranged from 285 W/m^2 during the winter months to 480 W/m^2 during the summer months. Average monthly net longwave radiation was -47 W/m^2.

Net radiation is the total of incoming shortwave and longwave radiation minus the reflected shortwave and outgoing longwave radiation. Its magnitude is usually greater than all the other elements in the energy-balance equation. Net radiation averaged 69 W/m^2. Daily values ranged from -90 to 350 W/m^2. Monthly average net radiation ranged from a low of -9 W/m^2 in December to a high of 170 W/m^2 in July.

Wind

Surface winds predominantly were from the south-southeast for the 2-year study period. This direction is slightly different from the prevailing winds, from the south-southwest and west-northwest, measured at the Moline Airport.

Mean monthly windspeed at the 2-m height during the 2-year study period was 3.9 m/s. Daily average windspeed ranged from less than 1 to 10.2 m/s, whereas hourly averages ranged from less than 1 to 15.0 m/s. Windspeeds were significantly higher during the winter months (November through March) than the other months, averaging 4.3 and 3.6 m/s, respectively.

By using the Monin-Obukhov length (Monin and Obukhov, 1954) as an index for atmospheric stability, neutral conditions only existed around dawn and dusk. Stable conditions always existed during the night, and unstable conditions usually were present during the day.

Air temperature

The average temperature at the Sheffield site over the 2-year study period was about 10.8 °C. Daily averages ranged from a low of -26 °C on December 25, 1983, to a high of 32 °C on July 22, 1983. July was the warmest month while December and January were the coldest. In general, the study period was similar to the long-term NOAA average of 10.3 °C at Walnut.

Water-vapor pressure

Average monthly water-vapor pressures at the 0.5 m height above land surface for March through November ranged from a low of 0.6 kPa (kilopascals) in March to a high of 2.3 kPa in July. Values for some winter months were not determined due to instrument limitations. Water-vapor pressure followed the same monthly pattern as air temperature, reaching maximum values in July and August.

Soil-heat flux and soil temperature

Monthly soil-heat fluxes reached a maximum in June and July and a minimum in November and December. During the 2-year study period, the maximum monthly heat flux was 23.4 W/m^2 in July 1983, and the minimum was -13.0 W/m^2 in November 1982. From February through August, flux values were positive, indicating that the soil was gaining heat. Soil-heat flux was negative from September through January, indicating the release of heat.

Annual trends in soil-heat flux were supported by the soil-temperature profiles. Soil temperature was measured at seven depths ranging from 0.02 to 1.0 m. Daily average temperatures over the 2-year study period, at a depth of 0.1 m, ranged from a low of -5 °C on February 6, 1984, to a high of 28 °C on July 22, 1983. Daily averages at the 1.0-m depth ranged from a low of 1.7 °C on February 22, 1984, to a high of 21.9 °C on August 30, 1983. During the winter of 1982-83, the ground did not freeze to the 0.3-m depth. In contrast, during the 1983-84 winter, the ground was frozen at the 0.3-m depth from January 14 through March 23.

Soil-moisture content

Figure 14 shows the amount of water stored in the top 1.75 m of a trench cover from November 1982 through June 1984. The amount of water stored in a trench cover was greatest in early spring (March and April) when evapotranspiration rates were low and the ground had thawed. Soil-moisture content was at a minimum in September. Figure 15 shows the change in volumetric moisture content, with respect to depth, on specific days during the year. When evapotranspiration began to increase in midspring, water was readily available from near-surface storage. As the season progressed, water was drawn from deeper depths. This trend was reversed in the fall when evapotranspriation was decreasing; then, the moisture content of the soils tended to decrease with depth. Fluctuations in soil-moisture content were greatest near land surface and decreased with depth. At a depth of 0.5 m, moisture content ranged from 0.03 to 0.42 (saturation). At a depth of 1.5 m, the range was much smaller--about 0.27 to 0.37.

Evapotranspiration

Evapotranspiration rates during this study were estimated using three techniques: energy-budget, aerodynamic-profile, and water-budget. It is advantageous to use more than one technique because of inherent inaccuracies in each. The three techniques are briefly described here; for a complete description of each, the reader is referred to Healy and others (1987, p. 11-23).

The energy-budget or Bowen-ratio method for estimating evapotranspiration is based on the principle of conservation of energy. The primary source of available energy at the earth's surface is solar radiation. This energy is used to heat the soil surface, heat the air, and evapotranspire water. Energy absorbed by snowmelt and photosynthesis, and energy stored within the plant canopy are ignored in the Bowen-ratio method. Only vertical fluxes are measured; horizontal fluxes are considered negligible. Use of this method requires determination of net radiation, soil-heat flux, barometric pressure, and vertical gradients of air temperature and water-vapor pressure.

The aerodynamic-profile method is based on the assumption that turbulent transfer is described by the same equations that govern molecular transfer. Molecular processes in the laminar boundary layer are responsible for all vertical transfer of heat, water vapor, and momentum. However, this layer is so thin that it is virtually impossible to measure fluxes across it. Beyond this layer, transfer is by turbulent processes. In order to solve the equations for vertical fluxes of sensible heat, latent heat, and momentum, it is necessary to account for bouyancy effects by using stability functions. In this study, the Monin-Obukhov length (Monin and Obukhov, 1954) was determined for that purpose. The use of the aerodynamic-profile method requires determination of vertical profiles of horizontal windspeed, vapor pressure, and temperature.

The water-budget method for estimating evapotranspiration is based on the principle of conservation of mass. The amount of water evapotranspired is equal to the difference between any inputs from precipitation and reductions

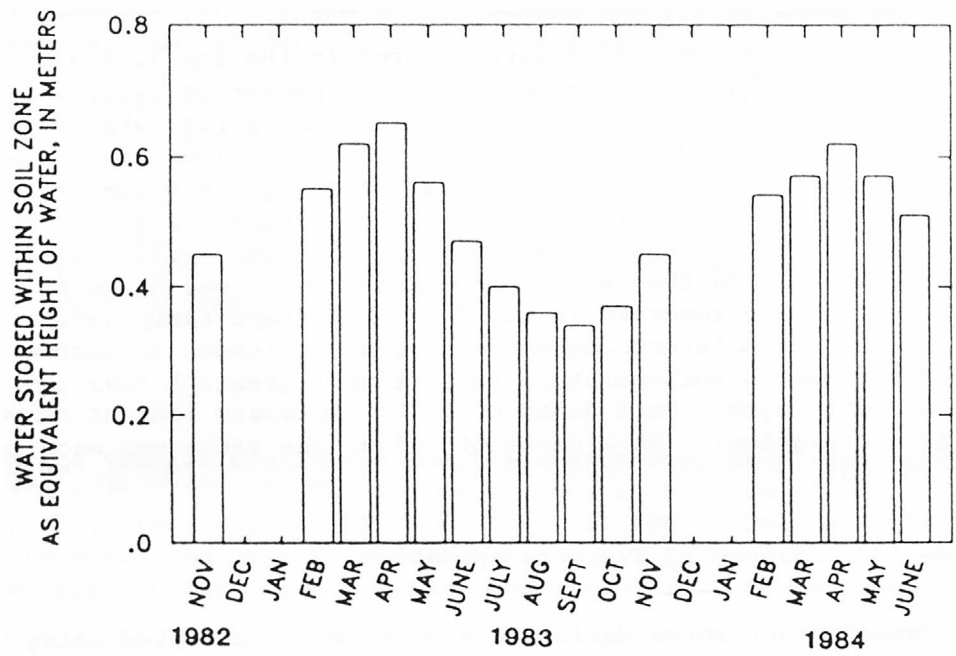


Figure 14.--Change in amount of water stored within the top 1.75 meters of a trench cover at the site.

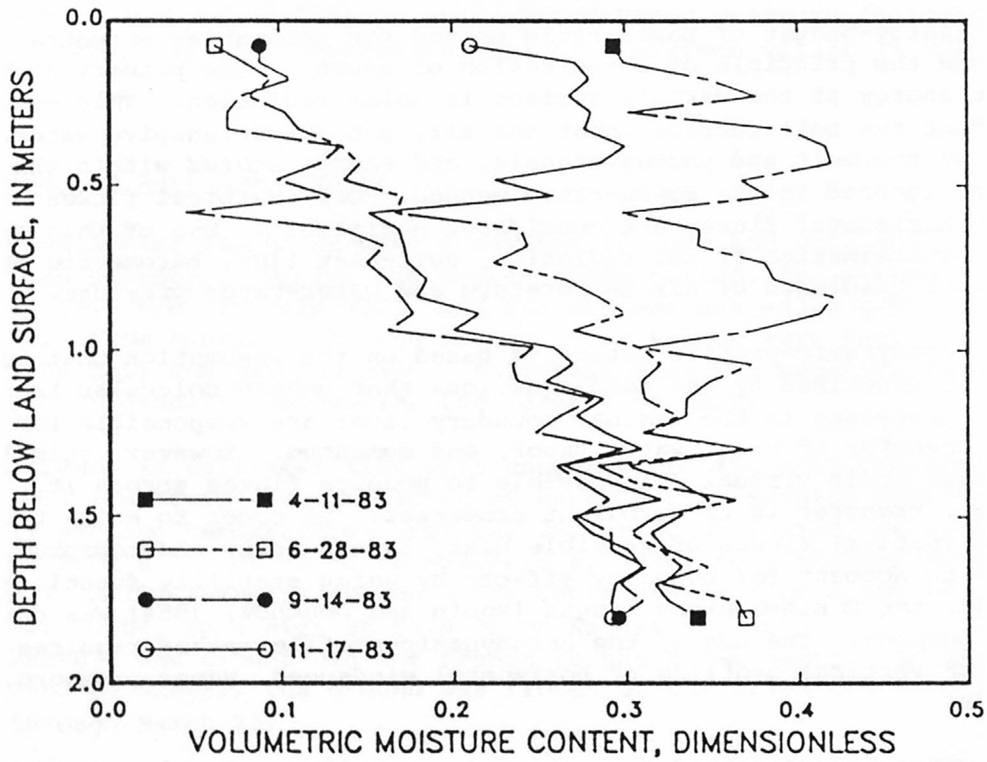


Figure 15.--Change in volumetric soil-moisture content with depth during 4 days at the site.

by runoff, downward drainage, and increases in the volumetric soil-moisture content in the soil zone. The use of this method requires the measurement of volumetric soil-moisture content, precipitation, runoff, and pressure heads at different depths within the soil zone.

The evapotranspiration cycle as determined by the Bowen-ratio method is shown in figure 16. Low rates occur in early March and increase to a maximum in July. Rates then declined steadily, dropping to about zero by late November. From July 1982 through June 1983, 622 mm of water were estimated to have evapotranspired. A total of 674 mm was estimated for the period July 1983 through June 1984. Annual average evapotranspiration for the 2 years was 648 mm.

Estimates of daily evapotranspiration by the Bowen-ratio method ranged from a low of near zero during winter months to a maximum of approximately 6 mm for a few summer days. Nighttime evapotranspiration rates were close to zero but could be either positive or negative (indicating condensation).

By using the aerodynamic-profile method, evapotranspiration for July 1982 through June 1983 was estimated to be 599 mm. For July 1983 through June 1984, 660 mm of water were estimated to have evapotranspired. The estimated annual average for the 2-year period was 630 mm. This is about 3 percent lower than that estimated by the Bowen-ratio method. Monthly totals of evapotranspiration estimates for the period of record are shown in figure 16. On a monthly and daily basis, there was good agreement between the two methods.

Figure 16 also shows monthly evapotranspiration estimates by the water-budget method for April 1983 through June 1984. It was not possible to estimate evapotranspiration on a daily basis by the water-budget method because some characteristics were not measured daily. A total of 655 mm of evapotranspiration was estimated for the period July 1983 through June 1984. Evapotranspiration during November through March was assumed to be zero because the rates of evapotranspiration for these months were too low to accurately estimate due to instrument limitations; sublimation was not measured. By including estimates averaged from the energy-budget and aerodynamic-profile methods for March and November, the yearly evapotranspiration total was 693 mm. This total is only 3 and 6 percent higher than the totals estimated by the energy-budget and aerodynamic-profile methods, respectively, for the same period. Some monthly totals from each method, however, were significantly different. Estimates for June, July, and August were, on the average, 20 percent higher by the water-budget method than by the other two methods; all methods matched well for the remaining months. Subsequent mention of monthly evapotranspiration totals will refer to the average value obtained by the three methods.

The average annual evapotranspiration estimate (657 mm) for the three methods was equivalent to 70 percent of precipitation; 60 percent of net radiation; and 32 percent of solar radiation. Figure 17 shows the monthly difference between precipitation and evapotranspiration. Generally, evapotranspiration exceeded precipitation for the months of May through August. The trend in this ratio shows good agreement with the trend in soil-moisture content within the trench cover (figs. 14 and 15).

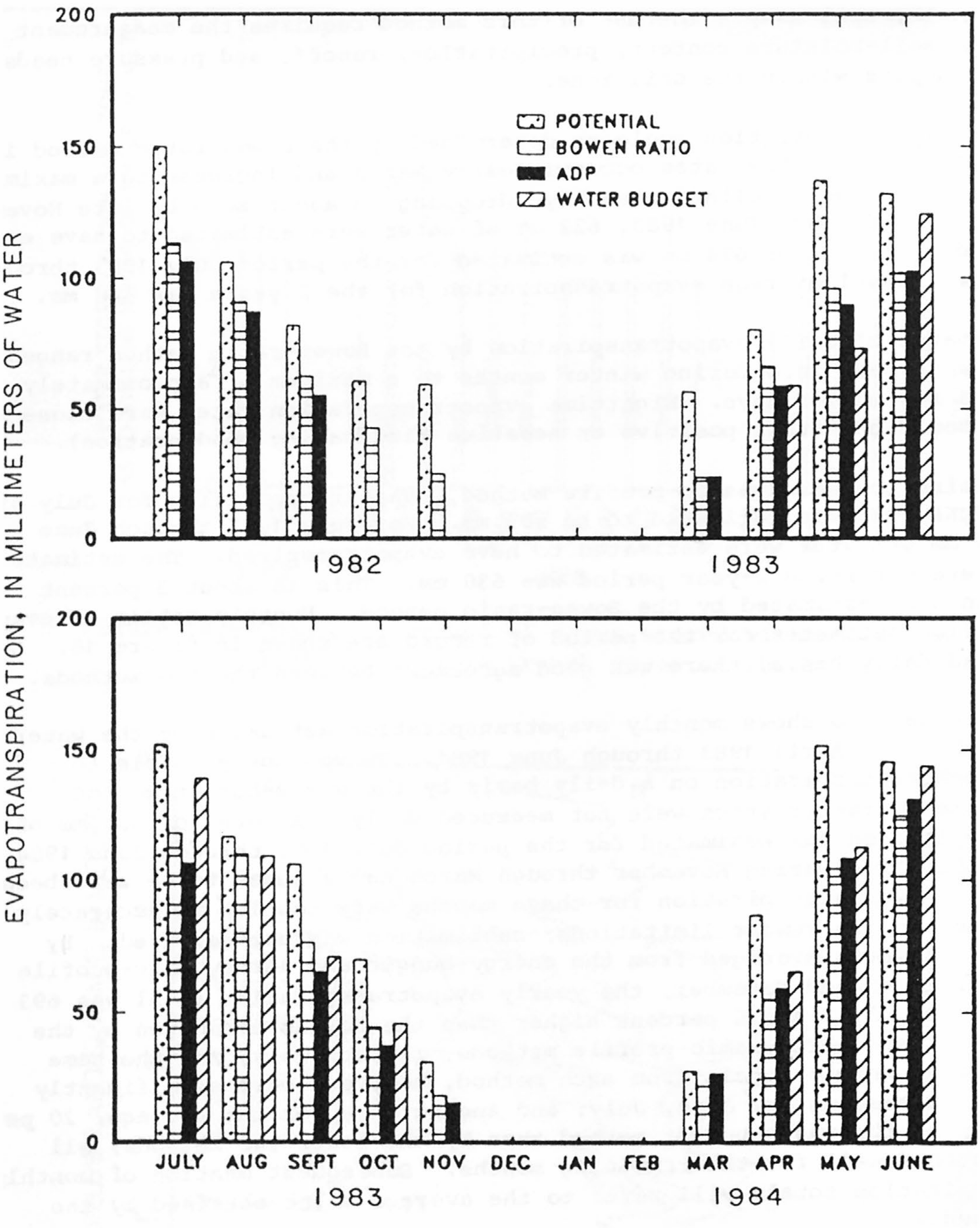


Figure 16.--Monthly evapotranspiration estimates.

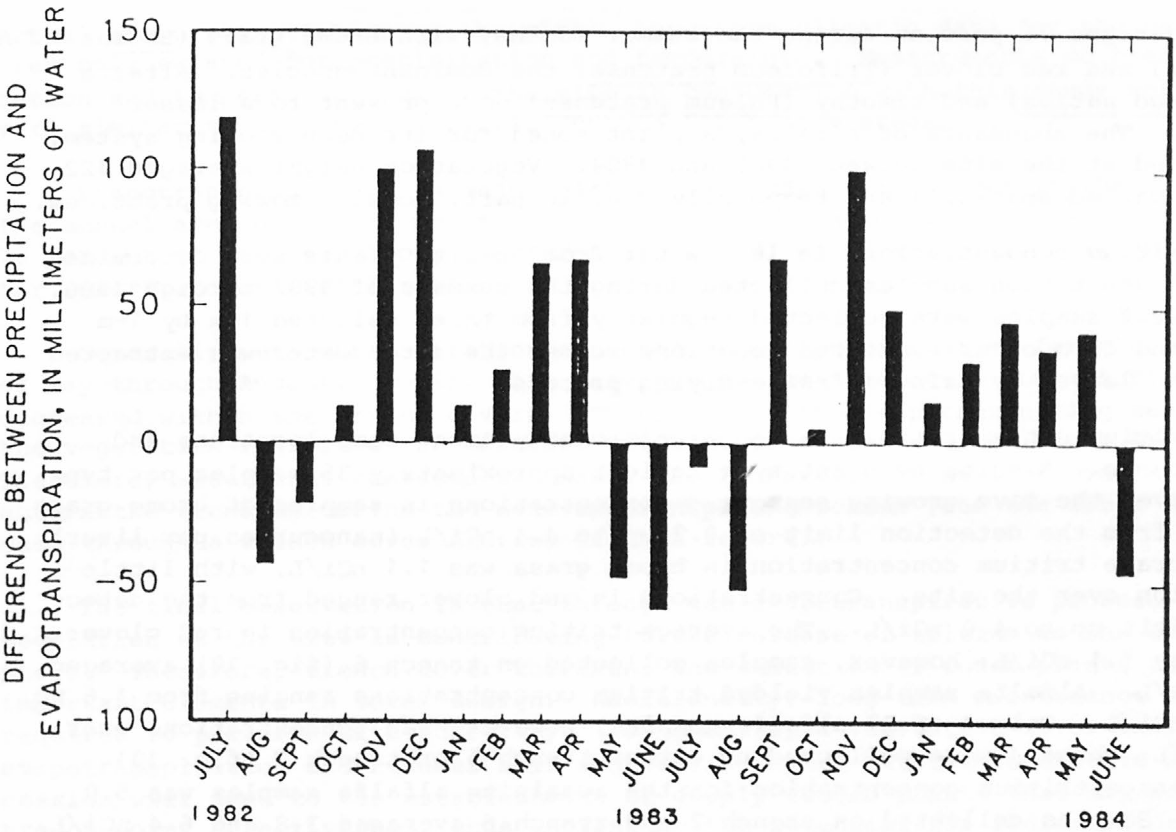


Figure 17.--Monthly difference between precipitation and evapotranspiration.

Potential evapotranspiration (PET) is the maximum rate at which evapotranspiration can occur if it were not limited by available soil moisture. The Penman (1948) method was used in this study for estimating PET. The Penman method is one of the more popular methods for determining PET and, as such, may serve as a good index for comparisons with other locations. The use of this method requires measurements of net radiation, soil-heat flux, windspeed, barometric pressure, and vertical gradients of air temperature and water-vapor pressure. In calculating the daily PET values, the empirical wind function proposed by van Bavel (1966) and a daytime-nighttime weighting scheme recommended by Tanner and Pelton (1960) were incorporated into the Penman method.

Potential evapotranspiration for July 1982 through June 1983 was estimated at 864 mm. For July 1983 through June 1984, the estimate was 888 mm. Figure 16 shows monthly averages for the period of record. Actual evapotranspiration averaged 75 percent of potential evapotranspiration.

Tritium Release By Plants

The trench covers and adjoining areas were seeded shortly after the site closed. Annual vegetation surveys have shown vegetative cover density at the site averages 76 percent during the summer months, with brome grass (Bromus inermis) and red clover (Trifoleum pratense) the dominant species. Alfalfa (Medicago sativa) and timothy (Phleum pratense) were present to a lesser degree. The abundance of alfalfa, a plant noted for its deep rooting system, increased at the site between 1982 and 1984. Vegetation height averaged 122 mm but varied spatially and temporally due, in part, to site mowing practices.

Tritium concentrations in leaf water from on-site plants were determined for 125 vegetation samples collected during the summers of 1982 through 1986. Plant-leaf samples were collected regularly from three selected 1-m by 1-m plots and from other scattered locations across the site; water was extracted from the leaves by using a freeze-drying process.

Tritium concentrations varied significantly among some locations and plant types. Results by plant type reflect approximately 35 samples per type taken over the five growing seasons. Concentrations in samples of brome grass ranged from the detection limit of 0.2 up to 4.4 nCi/L (nanocuries per liter). The average tritium concentration in brome grass was 1.1 nCi/L, with little variation over the site. Concentrations in red clover ranged from the detection limit up to 4.0 nCi/L. The average tritium concentration in red clover also was 1.1 nCi/L; however, samples collected on trench 6 (fig. 10) averaged 2.0 nCi/L. Alfalfa samples yielded tritium concentrations ranging from 1.6 to 1,330 nCi/L. Only 4 of 27 alfalfa samples, however, had concentrations over 14 nCi/L; those 4 were collected on either trench 5 or trench 7 (fig. 10). The average tritium concentration for the remaining alfalfa samples was 5.0 nCi/L. Samples collected on trench 2 and trench 6 averaged 3.8 and 6.4 nCi/L, respectively.

Although the data are limited, results of tritium concentrations from 125 leaf-water samples collected on-site are as follows:

(1) Concentrations differed among species at the same location. Alfalfa had the highest concentrations, followed by brome grass and then red clover. This is most likely a function of root depth.

(2) For some species, tritium concentrations varied significantly with location during a single sampling period. Alfalfa displayed the greatest areal variations in concentration with variations of as much as 1,328 nCi/L. This may be related to areal variations in cover thickness (thin covers allow longer root systems to contact buried wastes), variable activity of wastes, and(or) the differential degradation of the waste packaging.

(3) Based on a total of about 3 ha of filled trench area, 657 mm of evapotranspired water, 99 percent of site vegetation with concentrations of tritium in the leaf water of 1.1 nCi/L, and the remaining 1 percent (alfalfa), averaging 5.0 nCi/L tritium, the estimated release of tritium through evapotranspiration is about 23 microcuries per year.

Implications

There are several implications of the research regarding microclimate, evapotranspiration, and tritium release by plants at the site. Measurement of microclimatic characteristics at the site was necessary in order to quantify actual evapotranspiration at the site. Long-term climatic data for the nearby area only existed for precipitation and temperature. Measurements of precipitation and temperature made at the site in conjunction with this study were very similar to long-term climatic records for nearby areas.

Evapotranspiration is a major part of the hydrologic budget at the site. The annual average of 657 mm of actual evapotranspiration was equivalent to 70 percent of precipitation. Therefore, only 291 mm of water was available for runoff and(or) infiltration.

Generally, evapotranspiration exceeded normal precipitation for the months of May through August. During this same period, soil-moisture content steadily decreased within the trench covers. Thus, during the evapotranspiring season, the vegetation inhibited the downward movement of water into the waste trenches. Therefore, water that contacts the waste and recharges the aquifer generally enters the trenches during the nonevapotranspiring season (see the water movement through a trench cover section of this report).

The final observation is that through the evapotranspirative process some vegetation at the site is contributing to the release of tritium to the atmosphere. Therefore, trench cover thickness and selection of cover plants are important elements in cover design. Additionally, long-term maintenance is required to preserve site integrity. For example, a vegetative cover increases evapotranspiration and reduces soil erosion; however, natural vegetative succession will lead to the establishment of deeply rooted plants that may reduce trench-cover effectiveness, thus increasing the potential for radionuclide releases to the atmosphere.

Runoff and Land Modification

by John R. Gray

Introduction

Runoff and land modification were investigated at the site to describe types and rates of short-term (measured in months or years) changes in the land surface, to develop a data base through which future changes in the land surface may be evaluated (contents of the data base provide the foundation for this discussion), and to describe the precipitation-runoff component of the hydrologic cycle. Processes relating to runoff, sediment transport, and collapse were evaluated at the site and at a nearby undisturbed area. Runoff was measured to provide one component of the hydrologic budget and to provide data for computations of sediment transport. Sediment transport was computed to estimate fluvial erosion from the site. Collapse and erosion were studied because they compose the bulk of landform modifications presently affecting the site. Similar types of measurements were made at the undisturbed area to provide a reference to processes occurring on-site.

Precipitation, runoff, and sediment transport were measured in four basins--three comprising almost two-thirds of the 8.1-ha site area and one comprising the 1.4-ha undisturbed area--from July 1982 through December 1985 (fig. 18). Runoff and sediment transport from four small plots (fig. 18) averaging 10.6 m^2 (square meters) in size also were measured. Two of the plots were located on trench covers; the other two occupied parts of the undisturbed basin. The small plots were designed to compare processes related to runoff and sediment transport from trench covers to parts of the undisturbed basin.

Volumes and equivalent weights of collapses were estimated from records of site surficial conditions for the period October 1978 through December 1985. Site inspections were performed by the site operator at least monthly and more often during and following periods of rainfall or snowmelt. Information on inspection sheets usually included approximate dimensions and locations of collapse cavities relative to trench boundaries. An estimate of borrow-material volume used to fill cavities also was occasionally noted. Masses of collapsed material were computed from cavity volumes and a mean bulk density for site surficial material of 1,560 kg/m^3 (kilograms per cubic meter).

Runoff

Precipitation measured at the site from January 1982 through December 1985 averaged 895 mm annually; this amount was close to the long-term annual mean of 690 mm.

Runoff was generally confined to a period during and immediately following rainfall or snowmelt. Mean annual runoff from site basins was 144 mm (16 percent of precipitation) compared to 38 mm (1.2 percent of precipitation) from the undisturbed area. The ratio of runoff to precipitation at the site averaged 0.09 and 0.25 during the growing (May through October) and dormant seasons (November through April), respectively. Runoff showed a direct relation to degree of land modification; lowest mean yields (1.2 percent of precipitation) were measured at the undisturbed area, and highest mean yields (26 percent of precipitation) were measured from the site basin comprised wholly of trench and intertrench areas. No relation was observed between mean runoff and mean basin slope, most likely because of the overwhelming relation between runoff and degree of land modification.

Two principal differences exist between the site surface and adjacent undisturbed lands: (1) The site surficial material has a comparatively high bulk density (1.58 versus 1.43 g/cm^3 (grams per cubic centimeter) for the undisturbed area) resulting from inadvertent compaction by heavy machinery during, and subsequent to, waste burial, and (2) although predominant vegetation types differ between the site and undisturbed lands, site vegetation tends to be shorter (0.1 versus 0.5 m) and less dense (73 versus 98 percent coverage) than off-site vegetation. On-site conditions (denser surficial materials and less vegetation) should favor runoff over infiltration. Additionally, sparse vegetation offers comparatively little resistance to flow, allowing precipitation falling on trench areas to run off quickly and, therefore, permitting comparatively little water to infiltrate.

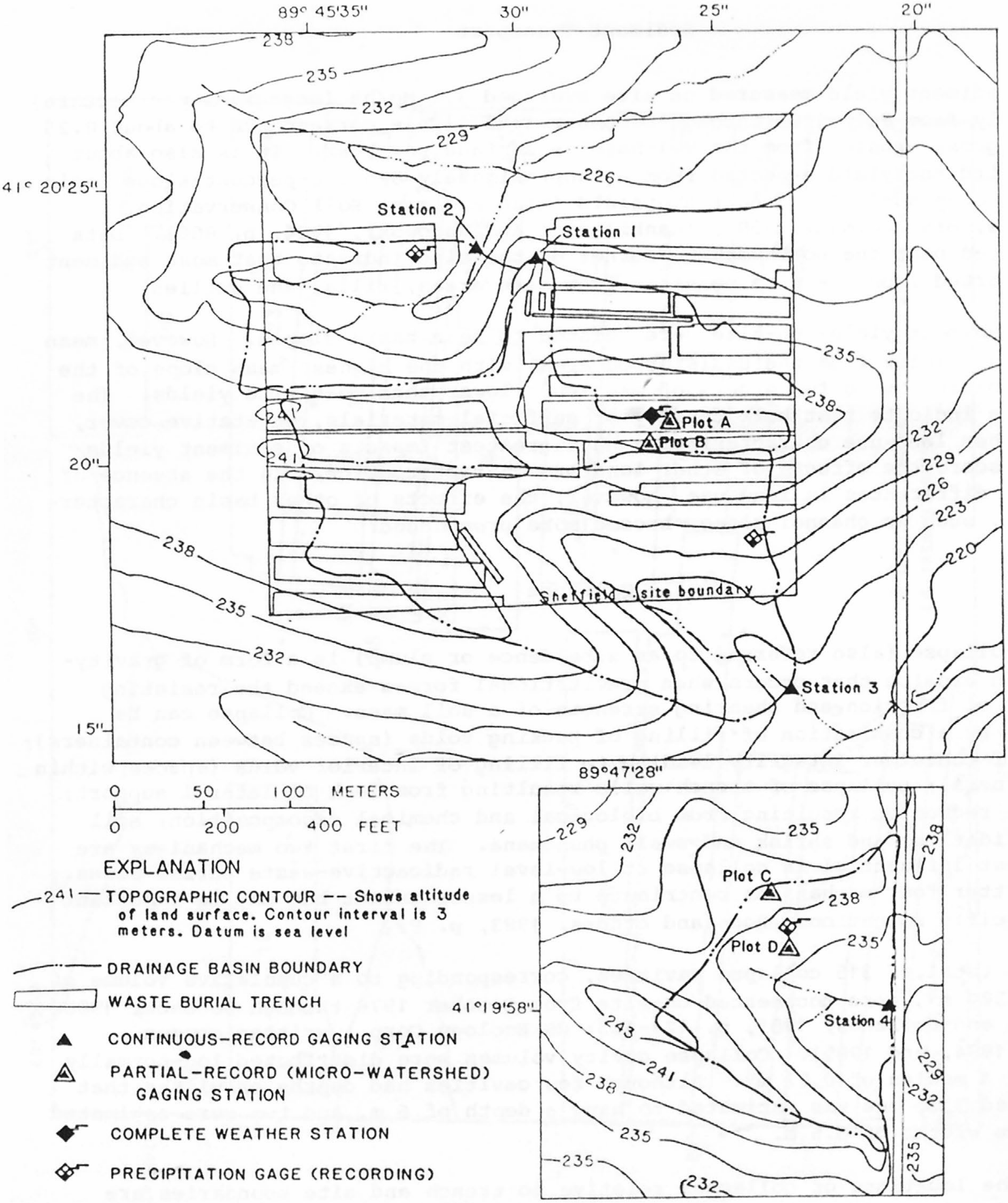


Figure 18.--Topography and surface drainage divides at and adjacent to the site.

Sediment Transport

Sediment yield measured on site averaged 3.4 Mg/ha (megagrams per hectare) annually from July 1982 through December 1985. This corresponds to about 0.25 mm of gross erosion from the 8.1-ha site surface per year. It is also about one-third the yield expected from an approximately 8-ha, 8-percent-slope basin in row-crop agriculture near Sheffield (Alan Madison, Soil Conservation Service, oral commun., 1985; Khanbilvardi and Rogowski, 1984, p. 866). Data collected near the northwestern corner of the site indicate that most sediment transported from the site emanated from bare areas, rills, and gullies.

Sediment yields on-site were related to mean basin slopes. However, mean sediment yields from the undisturbed area, with the highest mean slope of the gaged basins, were two orders of magnitude lower than mean site yields. The results indicate that bulk density of surficial materials, vegetative cover, and other land-use characteristics have greatest impacts on sediment yields and obscure the effects of other landform characteristics. In the absence of marked differences in land use, however, the effects of other basin characteristics, such as channel slope, become more pronounced.

Collapse

Collapse (also referred to as subsidence or slump) is a form of gravity-induced erosion that occurs when gravitational forces exceed the resisting forces of friction and shearing strength of a soil mass. Collapse can be caused by a combination of filling of packing voids (spaces between containers); loss of container integrity leading to filling of interior voids (spaces within containers); collapse of trench walls resulting from lack of lateral support; volume reduction resulting from biological and chemical decomposition; soil consolidation; and shrink and swell phenomena. The first two mechanisms are the most influential in collapse at low-level radioactive-waste burial sites. The latter four mechanisms contribute to a lesser extent but may be important in specific situations (Roop and others, 1983, p. 8).

A total of 315 collapse cavities, corresponding to a cumulative volume of about 500 m^3, were documented on-site from October 1978 through December 1985 (Kahle and Rowlands, 1981, p. 124-165; US Ecology Corp., written commun., 1983, 1984, and 1985). Collapse cavity volumes were distributed log-normally around a median of 0.22 m^3. Although few cavities had depths or widths that exceeded 3 m, one was estimated to have a depth of 6 m, and two were estimated to have widths of 5.5 m.

The locations of collapses relative to trench and site boundaries are shown in figure 19. Sixty-two percent of the collapses occurred in swales between trenches or near trench boundaries. The remainder occurred in earth-material covers over trench interiors. Some trenches were more susceptible to collapse than others. About two-thirds of the cumulative cavity volume was associated with five trenches (Nos. 1, 7, 10, 14A, and 24).

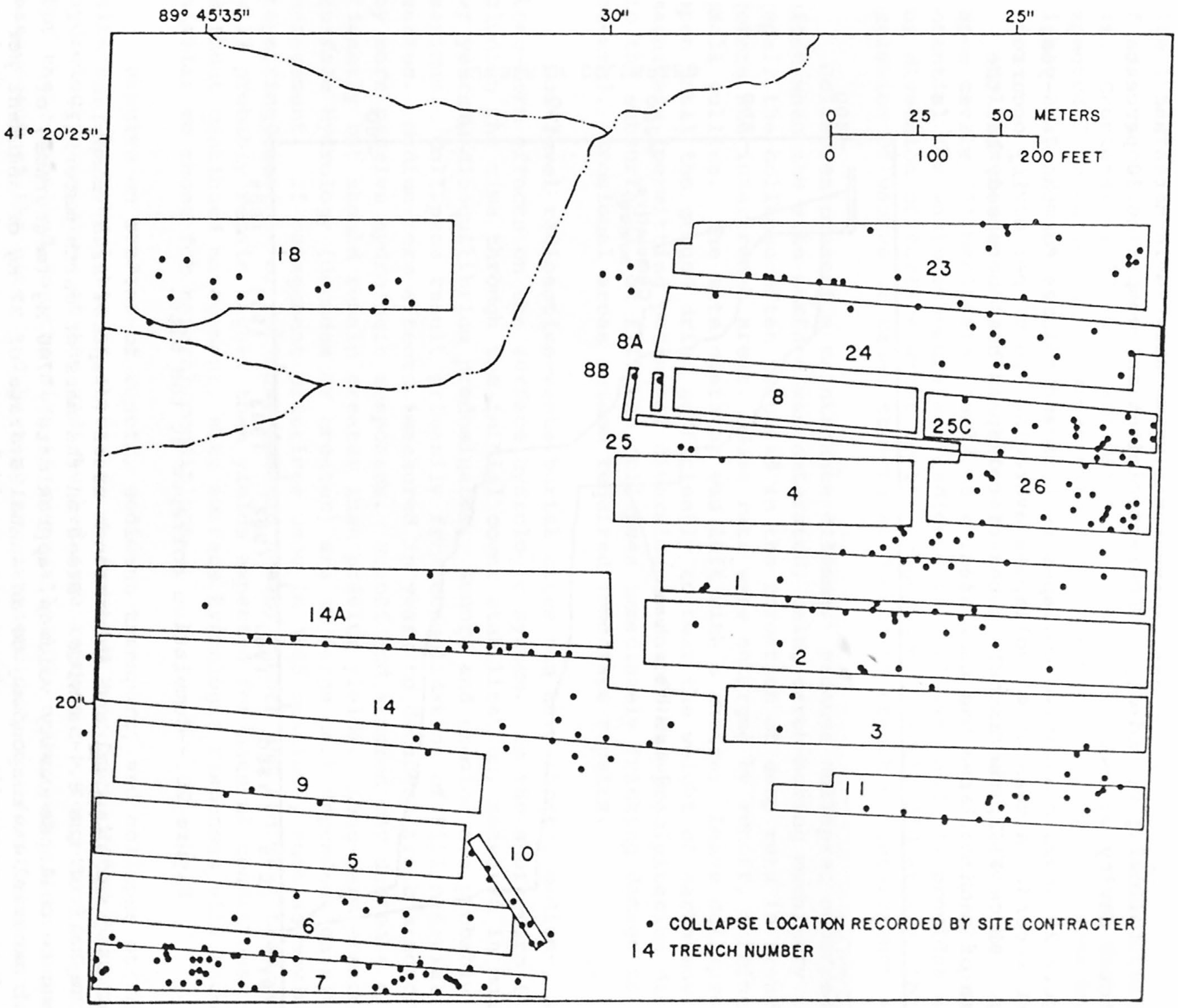


Figure 19.--Locations of collapses and trenches at the site,
October 1978 through September 1985.

Most collapses were recorded following periods of rainfall or snowmelt when soil moisture was near maximum. Almost two-thirds of the collapses, corresponding to 63 percent of the cumulative cavity volume, occurred in the months of February through April. Three cavities documented in March and April 1979, following record-high winter precipitation, comprised 30 percent of the total cavity volume.

Figure 20 shows cumulative collapse numbers and volumes for the 7.25-year period of record. A mean of 43 collapses averaging 1.6 m^3 per cavity occurred annually. Since 1982, the annual number of collapses has increased, but the mean size of each collapse has decreased.

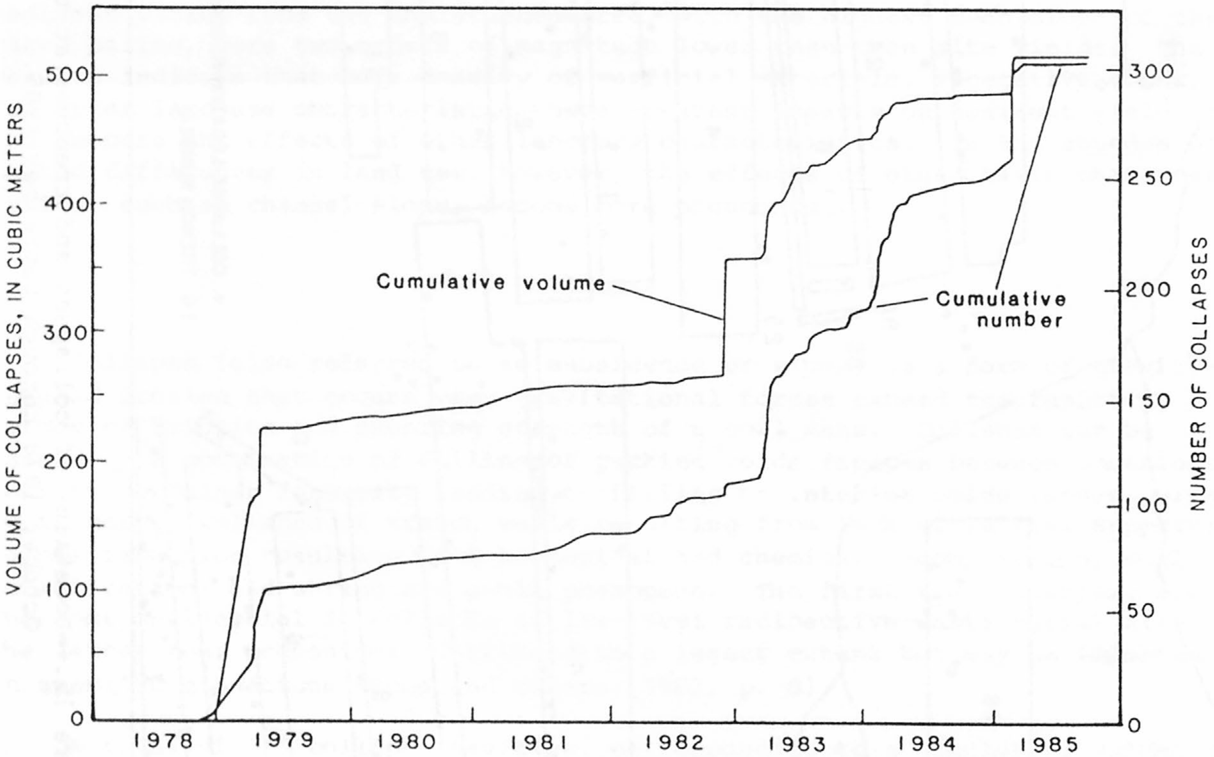


Figure 20.--Cumulative collapse at the site.

Land used for disposal and intertrench areas (disposal area) comprise almost one-half of the 8.1-ha site. Based on the mass of earth material equivalent to collapse cavity volumes, approximately 780 Mg (megagrams) of surficial material corresponding to an annual average of 27 Mg of sediment per hectare of trench area have collapsed during the study period. This mass, if distributed evenly over the disposal area, would correspond to a 1.8-mm reduction in the land surface altitude.

Implications

Of the two types of landform modifications analyzed, collapse and erosion, site integrity was affected most by collapse. Estimates of downward movement of soil by collapse exceeded mean site erosional yields by a factor of about six. Erosional yields were estimated to be only about one-third of that expected from agricultural areas with similar topographies in the area but higher than from undisturbed areas.

Collapses compromise trench-cover and intertrench stability. Each collapse cavity (1) manifests itself as a failure in cover material, (2) provides potential for waste exposure and radionuclide release, and (3) provides a sink for diversion of surface water to the subsurface. Rarely did erosion threaten isolation of wastes or cause structural damage to trench or intertrench areas.

Collapses present a maintenance dilemma. Because collapses occurred most often when the site surface was saturated, using earth-moving machinery to repair the collapse often resulted in the formation of deep ruts in trench covers and intertrench areas. Some ruts were enlarged by runoff, forming small gullies. The site operator was left with a choice: Leave collapses open until the ground dried sufficiently to bear the weight of earth-moving machinery (permitting potential diversion of runoff and precipitation directly to the subsurface), or fill the collapses immediately (risking damage to trench covers). Erosional areas seldom required immediate repairs.

Low-level radioactive-waste burial sites can have short-, medium-, and long-term effects on the surface hydrologic system. In the short term (including the time through the initial cover stabilization, measured in months or years), disequilibrium predominates. Runoff and erosion are probably near maximum. Collapses result primarily from consolidation of fill material around wastes. Medium-term effects (measured in years to decades) are characterized by more passive hydrologic responses. Runoff and erosion may decrease significantly but should remain greater than presite yields. Long-term effects on surface hydrology (decades or greater) are in large part dependent on site management. If management practices used in 1985 continue, such as mowing and repairing erosion- or collapse-damaged areas, runoff and sediment transport will probably remain higher than yields expected for natural conditions. Without continued management, site surface hydrologic responses will become similar to those for natural conditions.

Results on studies of runoff, sediment transport, and collapse at the site are characteristic of short- to medium-term hydrologic effects. Surface hydrologic responses at the undisturbed area represent a long-term endpoint for those expected for the site if eventually left unmanaged. With continued management of the site, and barring any extraordinary modifications to the surface or trench contents, the following is likely: (1) Mean annual runoff and sediment transport per unit precipitation will gradually decrease but will probably remain greater than those at the undisturbed area. Precipitation not forming runoff will result in greater infiltration. (2) Mean collapse volumes will generally diminish due to more complete waste degradation and compaction. However, collapses will likely be associated with precipitation and snowmelt during the dormant season for years to come.

Water Movement Through a Trench Cover

By Richard W. Healy

Introduction

In order to study the movement of water and factors that affect the movement within a selected trench cover, soil-moisture tensiometers were installed in four different clusters at depths ranging from 50 to 1,850 mm along a transect (fig. 21). Readings were automatically made at preset time increments (usually 5 to 60 minutes) with the aid of pressure transducers and an analog data recorder. Soil-moisture content was measured weekly with a gamma-attenuation moisture probe. Access tubes for the probe were installed adjacent to tensiometer clusters. Details on installation and operation of the instruments are contained in Healy and others (1986). Data for this study were collected from July 1982 through June 1984. Table 1 contains a brief description of the different sediments that comprise the trench cover; locations of sediments are shown in figure 21.

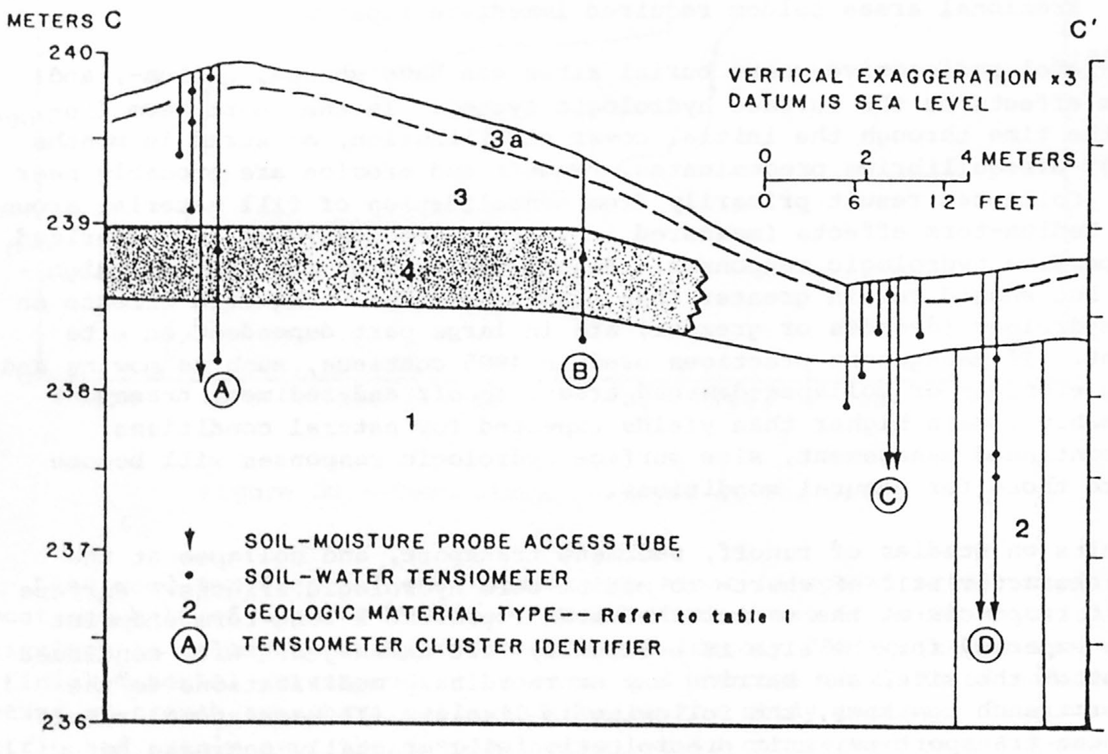


Figure 21.--Geologic section C-C' of trench cover showing instrumentation and soil types (line of section shown in fig. 4).

Table 1.--Properties of trench-cover sediments

[Locations of sediment types are shown in figure 21; g/cm^3, grams per cubic centimeter; cm/s, centimeter per second]

Type	Lithology	Bulk density (g/cm^3)	Saturated hydraulic conductivity (cm/s)	Description
1	Silt	1.25	2.2×10^{-4}	Trench backfill similar to type 2, but waste containers are present in some locations.
2	Silt	1.45	7.6×10^{-5}	Undisturbed lower part of Peoria Loess.
3	Clayey silt	1.65	3.9×10^{-5}	Soil developed in upper part of Peoria Loess; other sediments may be mixed in.
3a	Clayey silt	1.65	1.5×10^{-4}	A and B horizons of type 3.
4	Clayey silt	1.85	4.0×10^{-7}	Similar to type 3, only more compacted and slightly higher clay content.

Soil-Water Content and Tension

Collection of soil-water content and pressure-head (tension) data in the field allowed determination of the moisture-retention curves needed to calculate the flux of water through the trench cover. Figure 22 shows moisture-retention data derived from field data for three tensiometer locations. The data display significant hysteresis; different values of moisture content for a single pressure-head value depend on whether the soil is wetting or drying. Although inclusion of the effects of hysteresis in field studies has been shown to be advantageous (Royer and Vachaud, 1975), it is extremely difficult to accurately measure all the scanning curves between the primary wetting and drying curves. Therefore, hysteresis was neglected in this study and an average moisture-retention curve for each soil type was used in all calculations. This approach is similar to that used by Sammis and others (1982) and Sophocleous and Perry (1985).

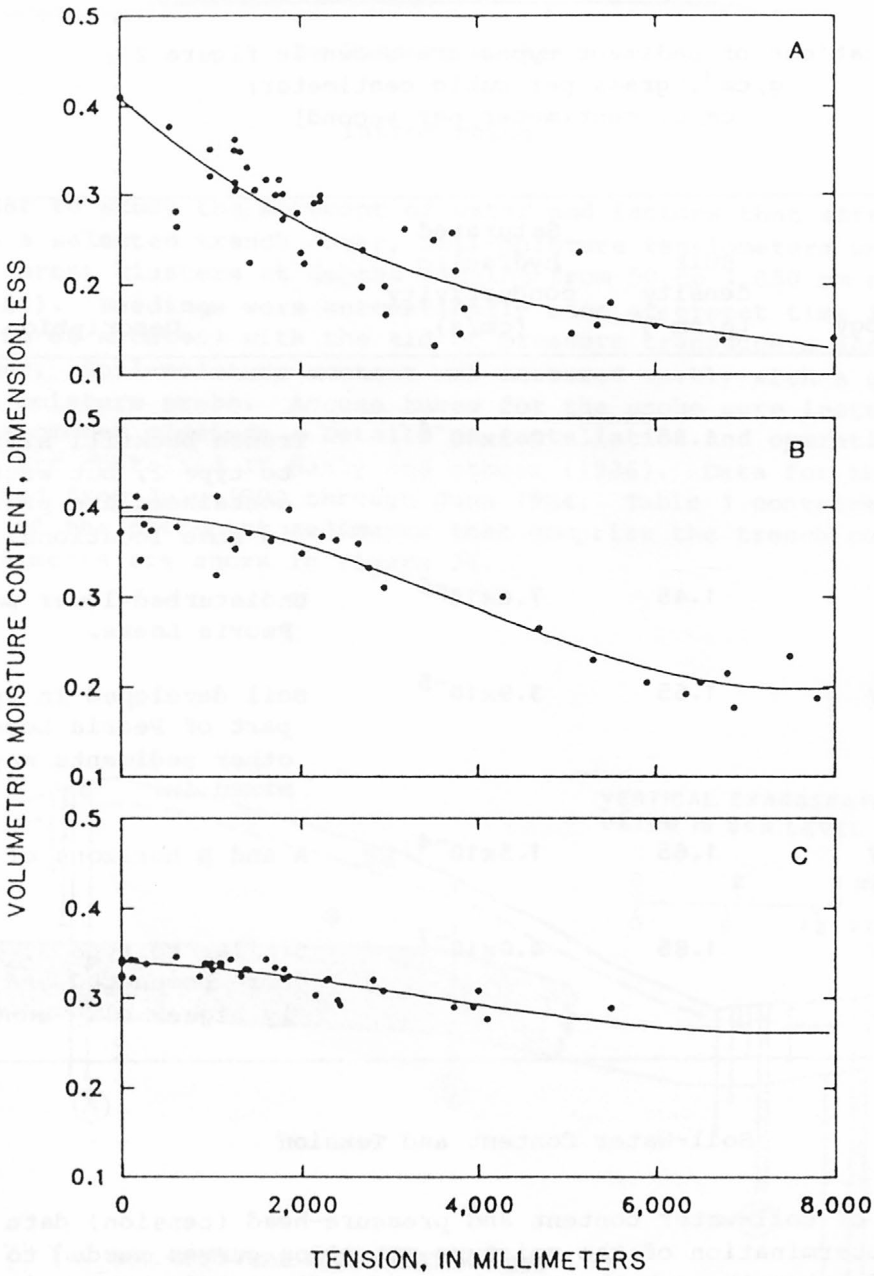


Figure 22.--Field-derived moisture-retention data.
A, Soil type 1--cluster C, 76-cm depth.
B, Soil type 3--cluster A, 86-cm depth.
C, Soil type 4--cluster A, 115-cm depth.

The amount of water actually stored within the trench cover varied in a cyclic manner, in response to precipitation and evapotranspiration (fig. 23). Precipitation was evenly distributed both temporally throughout the study period and spatially over the study area. Evapotranspiration rates were highest in June and July and were close to zero from November through March. These trends, and the fact that the fine sediments that comprise the trench cover are capable of holding a substantial amount of water, account for the cyclic trend in moisture content within the cover. Moisture contents were greatest in late March or early April, at the beginning of the evapotranspiration season. Moisture contents decreased steadily from late spring through the summer as mean evapotranspiration continued to exceed mean precipitation. The minimum moisture content was in late August or early September after which precipitation exceeded evapotranspiration. Moisture contents then increased gradually from midfall through the winter. Average daily pressure head (fig. 24) displays a trend similar to that of soil saturation. The range in variation of pressure head generally decreases with increasing depth. At depths less than 500 mm, tensions exceeded the upper limit that could be measured by tensiometers (about 9,000 mm) for some summer periods.

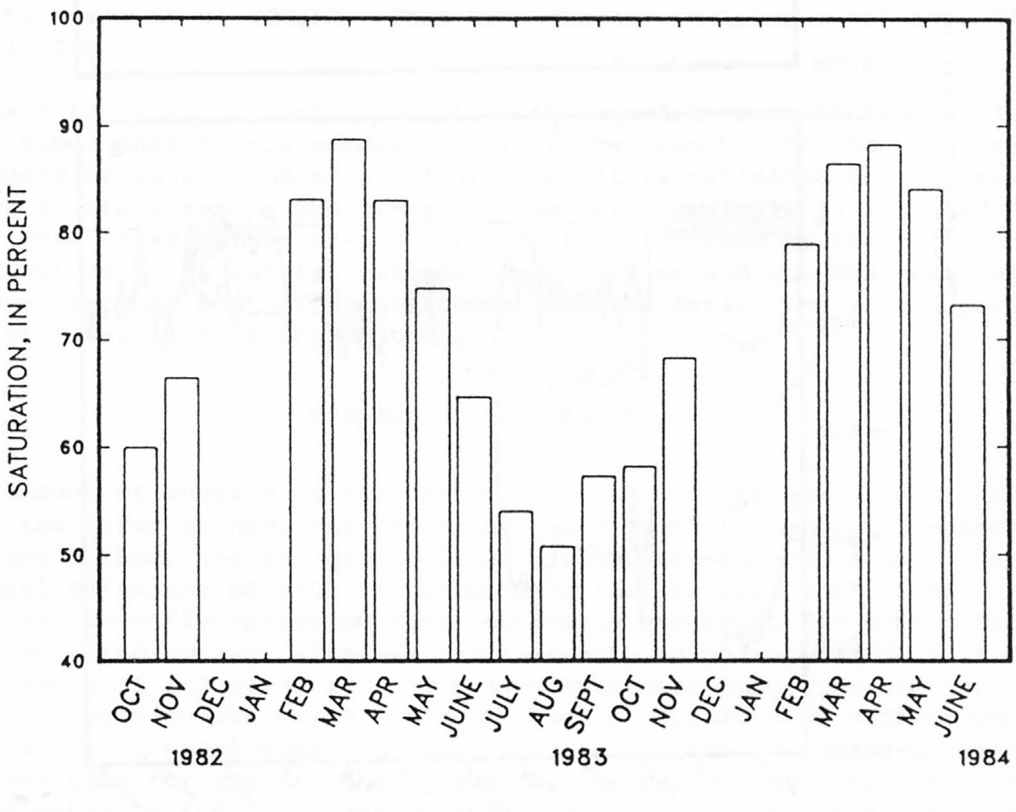


Figure 23.--Average monthly saturation of trench cover.

Wetting-Front Movement

The rate and total depth of wetting-front (defined for this report as the location where the change in pressure head with respect to depth is a maximum) movement varied throughout the study period. It was difficult to compare the

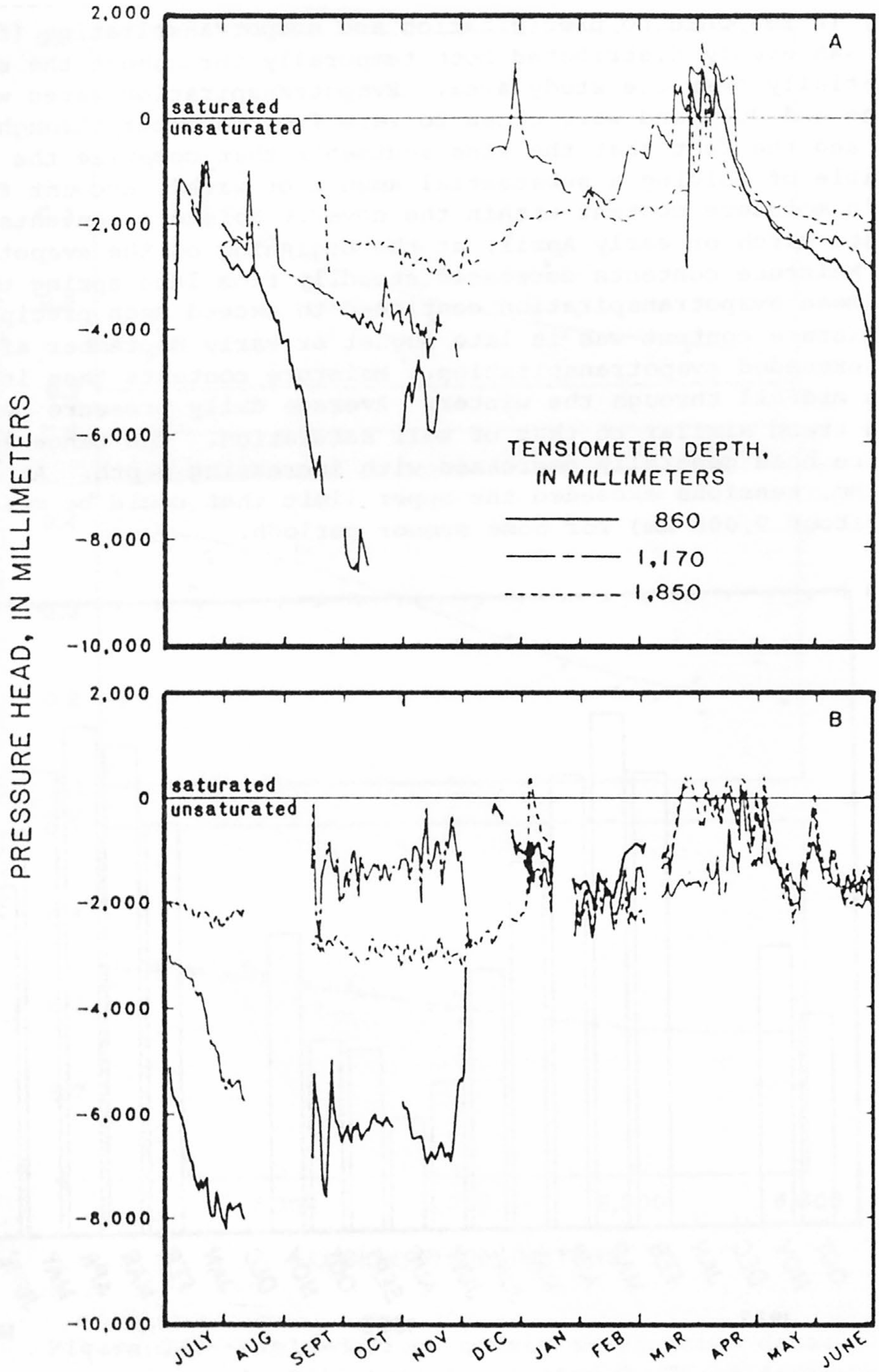


Figure 24.--Pressure head at cluster A for three depths.
A, July 1, 1982, to June 30, 1983.
B, July 1, 1983, to June 30, 1984.

rates of wetting-front movement among storms because of the variability of precipitation intensity both between and within individual storms. Total depths of wetting-front movements are shown in figure 25 as a function of initial soil-moisture content (in terms of percent saturation averaged over the thickness of the cover) and total storm precipitation. Initial moisture content was more important than total precipitation in controlling the depth of wetting-front movement at tensiometer cluster A, near the center of the trench (fig. 21), with equal amounts of precipitation producing deeper fronts for wet soils than for dry soils.

At tensiometer cluster C, near the edge of the trench (fig. 21), the depth of wetting-front movement was equally correlated with precipitation and initial soil-moisture content (fig. 25). It was found, in general, that wetting fronts from storms penetrated deeper and more quicky at cluster C than at cluster A. This is illustrated for a single storm in figure 26. There are two apparent reasons for these differences: (1) Surface drainage was much slower at cluster C than at cluster A--occasionally, ponding occurred at cluster C as well as in other swales between adjoining trench covers--and (2) the compacted layer (sediment type 4 in fig. 21), with its low permeability and the greater thickness of the cover at cluster A, offer much greater resistance to water flow than at cluster C.

Perhaps the item of most interest, with regard to wetting fronts, is the number of times that fronts actually entered the trench. Of the 87 storms that produced at least 5 mm of precipitation, it is estimated that 28 resulted in wetting fronts entering the trench at cluster C and only 11 resulted in wetting fronts entering the trench at cluster A. Because of the relation of wetting-front depth to initial soil-moisture content and the seasonal nature of moisture content, most of these storms occurred during the spring periods of high initial soil-moisture content.

Seepage to the Trench

The amount of seepage to the trench was estimated by using four different methods: the Darcy method, the zero-flux-phase method, the surface-based water-budget method, and the ground-water-based water-budget method. Table 2 shows annual estimates of each of the methods for the period of study. For the Darcy and zero-flux-phase methods, estimates are shown for both clusters A and C. A weighted average also was calculated by using weights of 0.75 for cluster A and 0.25 for cluster C. These weights were determined by the ratio of width of trench cover, which was occasionally inundated by surface ponding near cluster C, to total width of trench cover. Figure 27 shows cumulative seepage over time for the different methods. There is a significant difference in the estimates by the different methods. This illustrates the inherent difficulty in determining seepage to the trenches.

The nine-fold difference in seepage estimates, by the Darcy method, between clusters A and C during the 1982-83 period (fig. 28) is interesting. At cluster A, seepage was gradual, almost steady, from early winter to late spring; individual storms are very difficult to isolate. Seepage at cluster C was highly episodic, occurring mostly in response to individual storms. For

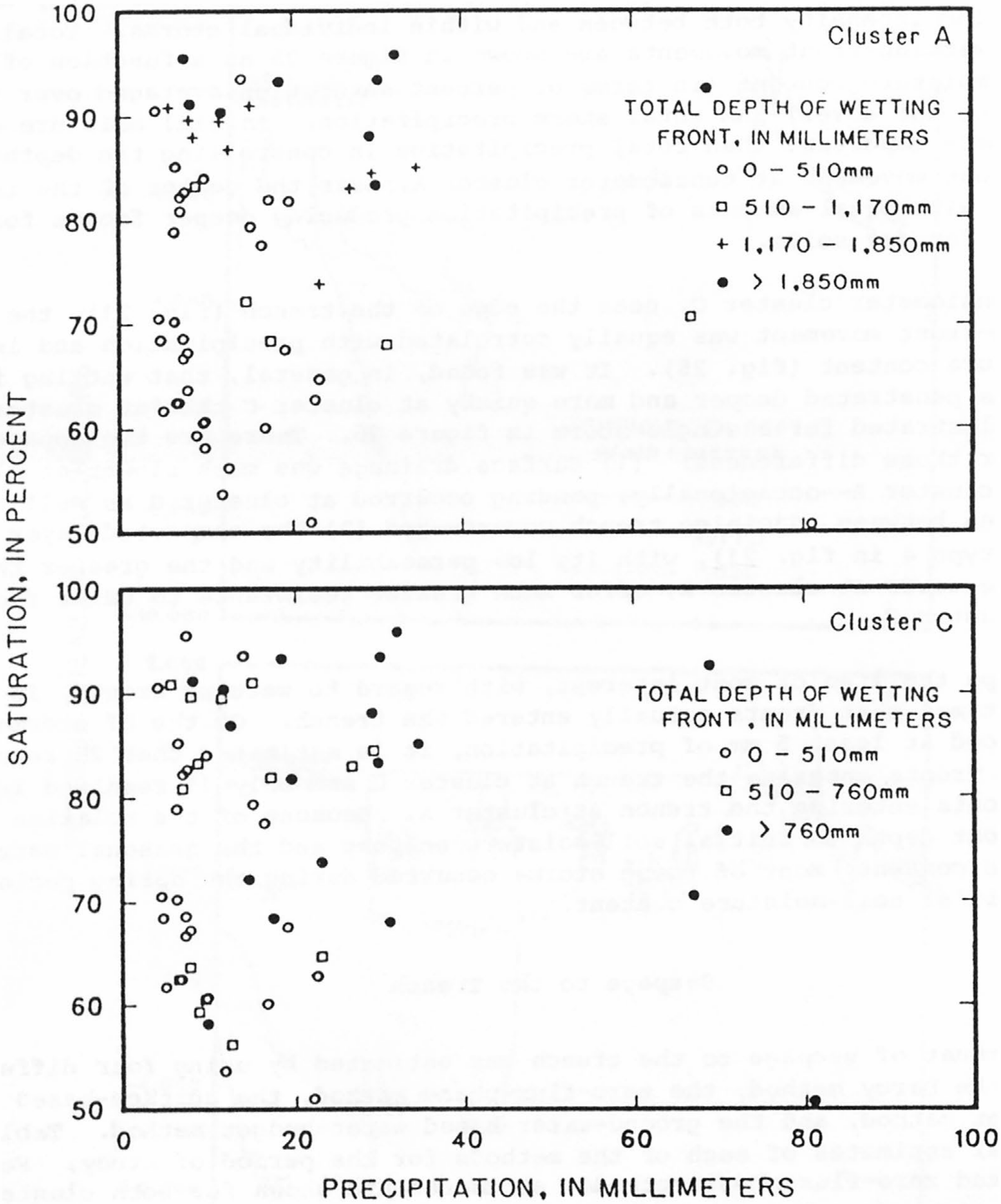


Figure 25.--Total depth of wetting-front movement as a function of initial soil saturation and total storm precipitation.

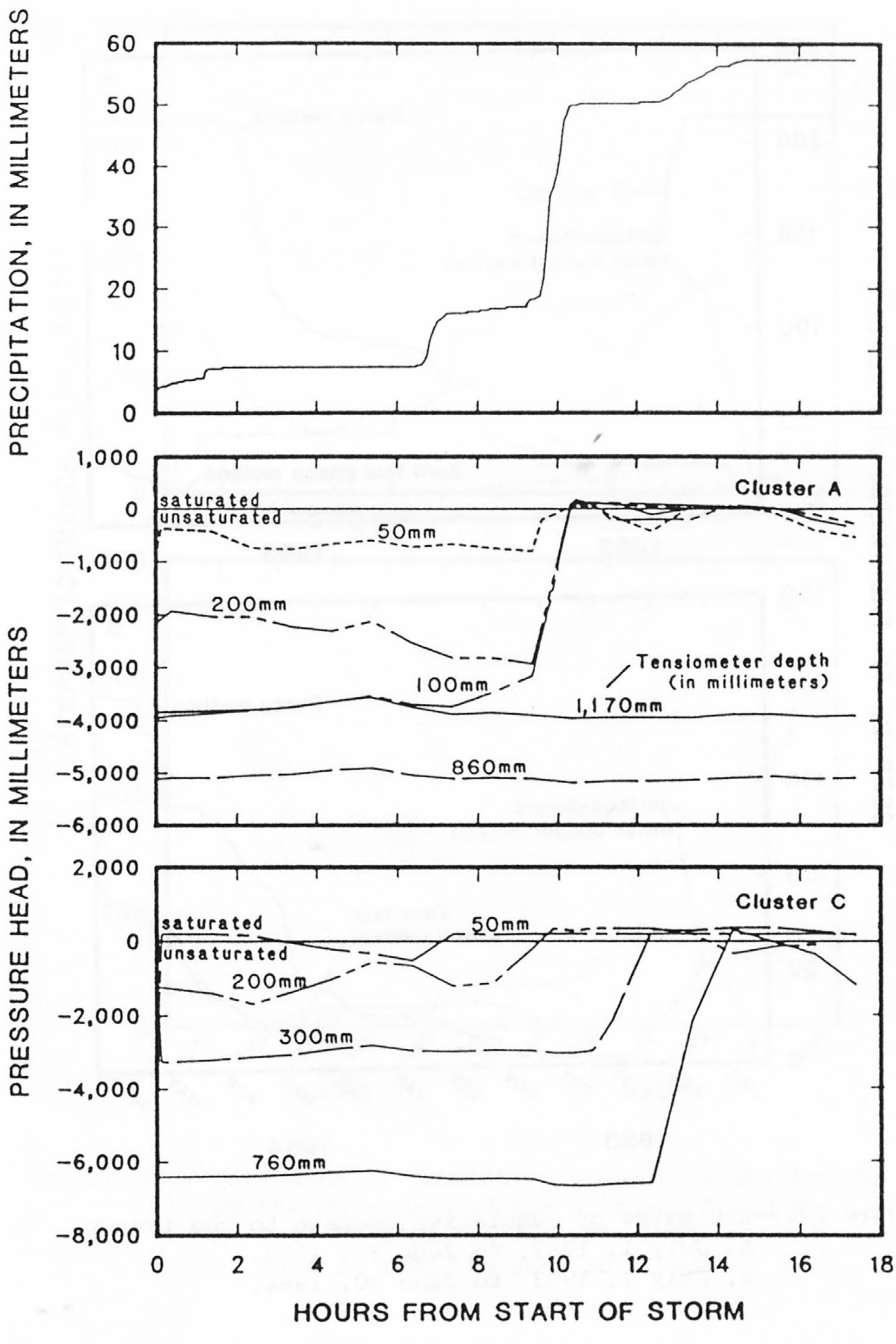


Figure 26.--Precipitation and pressure head at clusters A and C for the November 1, 1982, storm.

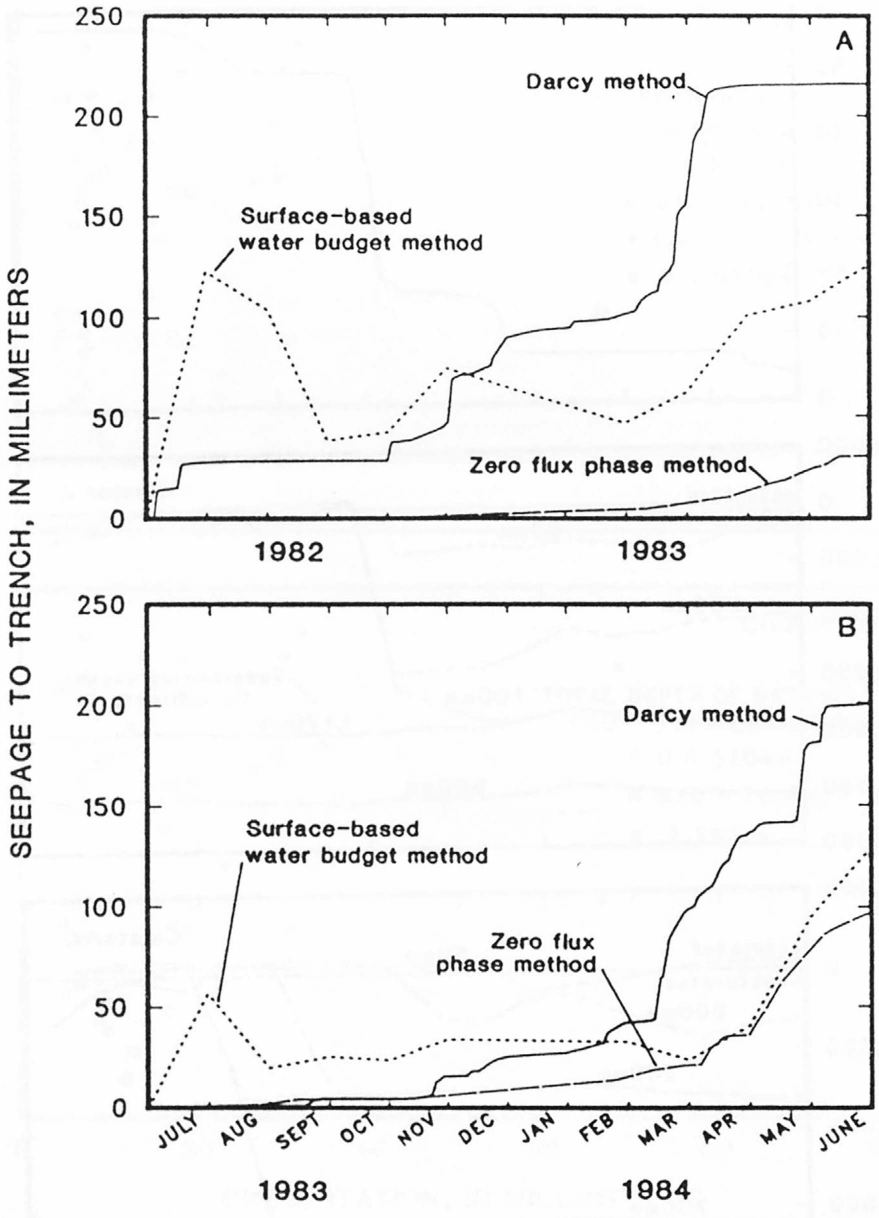


Figure 27.--Estimates of cumulative seepage to the trench.
A, July 1, 1982, to June 30, 1983.
B, July 1, 1983, to June 30, 1984.

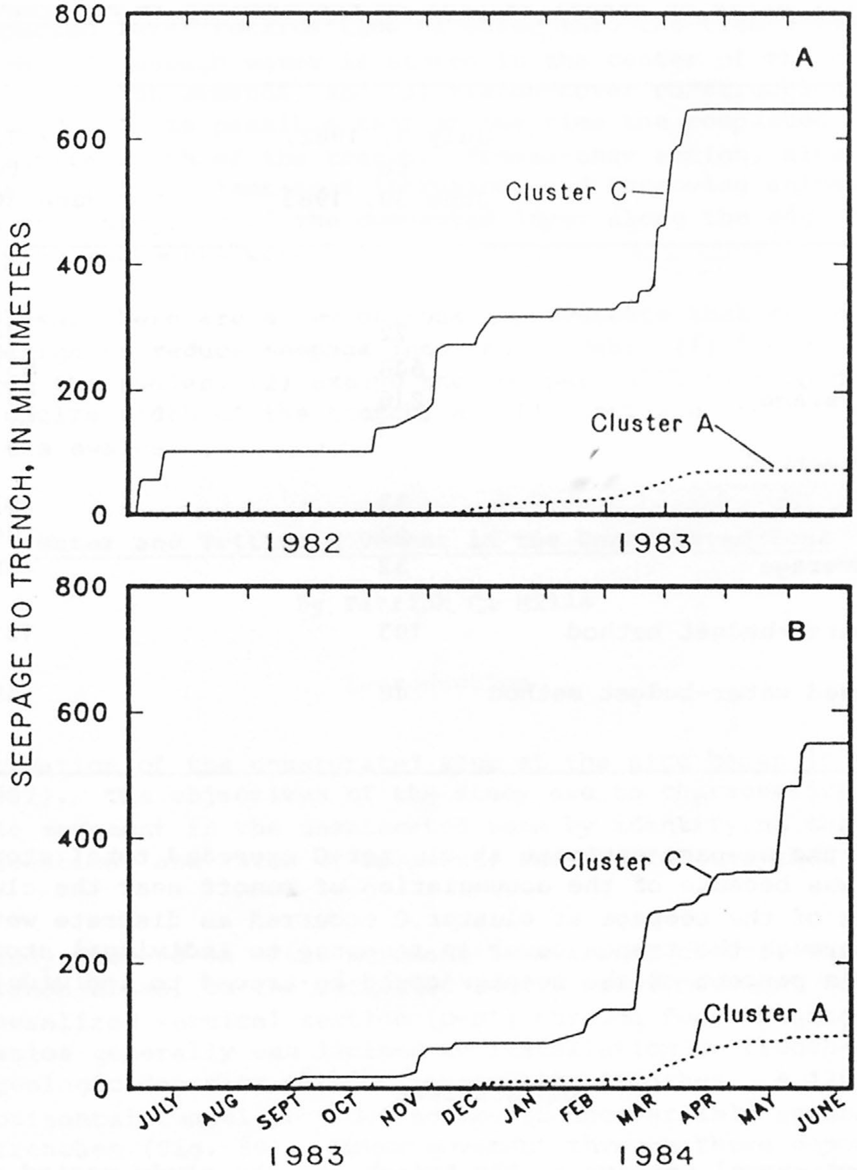


Figure 28.--Estimates of cumulative seepage to the trench by the Darcy method for clusters A and C. A, July 1, 1982, to June 30, 1983. B, July 1, 1983, to June 30, 1984.

Table 2.--Estimates of annual seepage to the trench, in millimeters

	July 1, 1982, to June 30, 1983	July 1, 1983, to June 30, 1984
Darcy method		
cluster A	72	84
cluster C	648	551
weighted average	216	201
Zero-flux-phase method		
cluster A	33	97
cluster C	27	99
weighted average	32	98
Surface-based water-budget method	103	121
Ground-water-based water-budget method	48	48

several storms, the seepage estimate at cluster C exceeded total storm precipitation. This was because of the accumulation of runoff near the cluster. About 84 percent of the seepage at cluster C occurred as discrete wetting fronts moving through the trench cover in response to individual storms. At cluster A, only a percent of the seepage could be traced to individual wetting fronts.

Implications

Estimates of annual seepage to the trench for the study period ranged from 5 to 22 percent of total precipitation. While this is a fairly wide range, it presents a measure by which alternative trench designs can be compared. However, because of the demonstrated difficulty in measuring seepage to the trench, it is questionable, if indeed a better designed cover could be constructed, whether or not its improvement could be demonstrated with the instruments used in this study.

Seepage to the trench is equivalent to ground-water recharge if it is assumed that there was no net change in the amount of water that was stored in the trench. Over a several-year period, this is probably a valid assumption. For the 2-year study period, the validity of the assumption could not be determined because soil-moisture content within the trench could not be measured.

The simple cover design used at the site has some favorable features: (1) The compacted layer retards flow of water into the trench near the center of the trench, (2) enough water is stored in the center of the cover to satisfy evapotranspiration demands, and (3) trench-cover construction is relatively straightforward. It is possible that at one time the compacted layer extended across the entire width of the trench. Freeze-thaw action, alternate periods of wetting and drying, plant-root intrusion, and burrowing animals could have compromised the integrity of the compacted layer along the edge of the trench where overlying sediments were thin.

Regardless, there are a few obvious improvements that could be made to the cover design to reduce seepage into the trench: (1) Improve surface drainage from the swales, (2) extend the low-permeability compacted layer across the entire width of the trench, and (3) increase the thickness of the cover over the swales.

Water and Tritium Movement in the Unsaturated Zone

by Patrick C. Mills

Introduction

Investigation of the unsaturated zone at the site began in 1981 and is ongoing (1987). The objectives of the study are to characterize water and radionuclide movement in the unsaturated zone by identifying the timing, quantity, location, and rates of movement; and the factors that influence movement.

The study focused on water movement from trench covers, through trenches and intertrench areas, to the saturated zone. Water movement was measured along a generalized vertical section (D-D') through four trenches (fig. 29). Instrumentation generally was limited to installation in trench-cover and subtrench geologic deposits without penetrating trenches. A 120-m-long by 2-m-diameter horizontal tunnel provided access to the variably saturated deposits below the trenches (fig. 30). Water movement through these deposits was monitored by soil-moisture tensiometers, gravity lysimeters, and piezometers. Soil-moisture tensions and water levels were monitored at intervals ranging from 5 minutes to 2 hours by using automatic data loggers. Water was collected by gravity lysimeters at daily to monthly intervals, depending on flow rates. Details of the study, including a description of the study area, the data-collection network, and results, are presented by Mills and Healy (1987). Healy and others (1986) provide a detailed description of the instrumentation used in the study.

Water Movement

The timing of water movement through the unsaturated zone below the trenches varied considerably from year to year and season to season. However, at no time was there a measurable response to individual rainstorms. Figure 31 shows pressure heads at selected locations in the subtrench sand and till

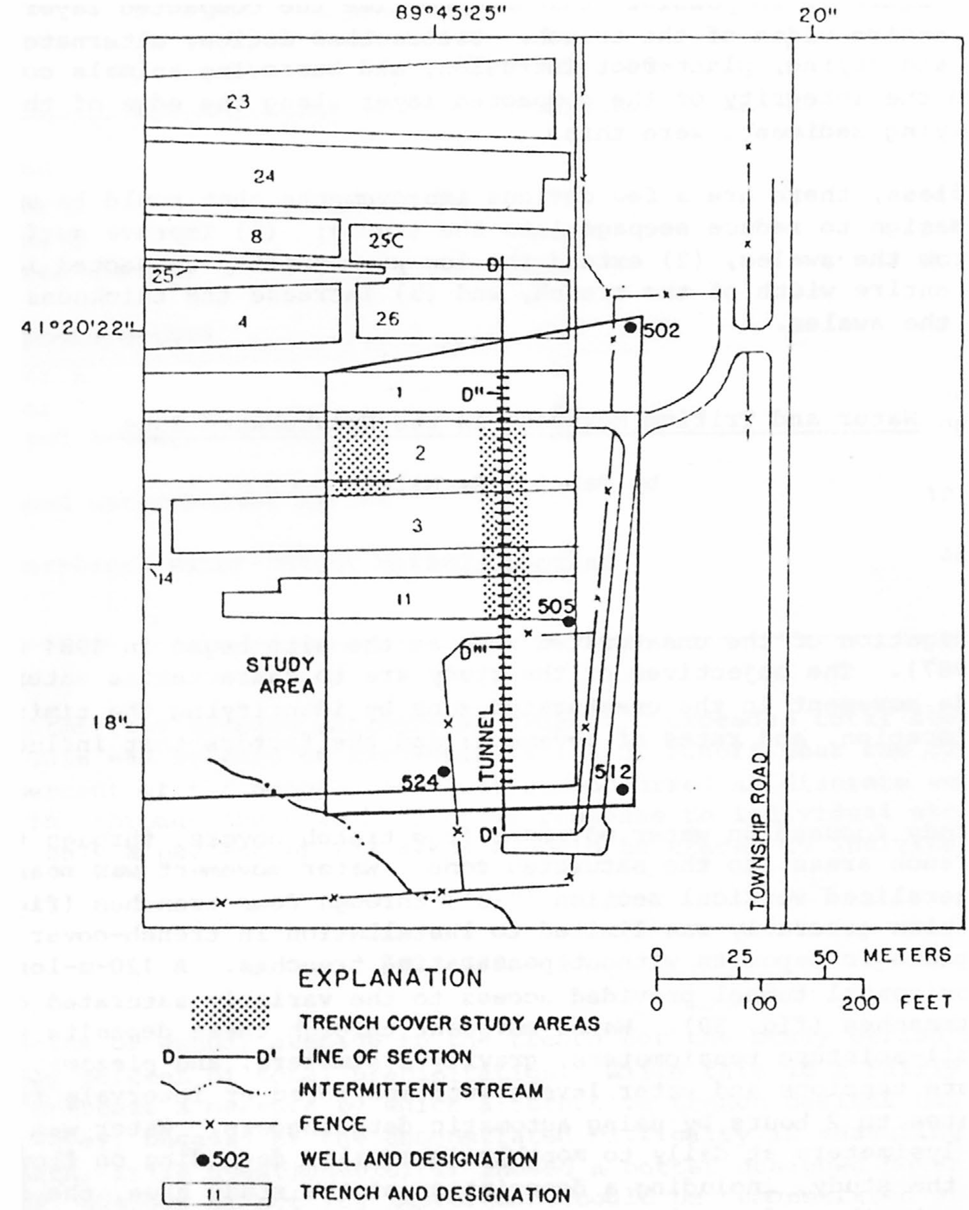


Figure 29.--Location of study area, observation wells, and line of section for the unsaturated-zone study at the site.

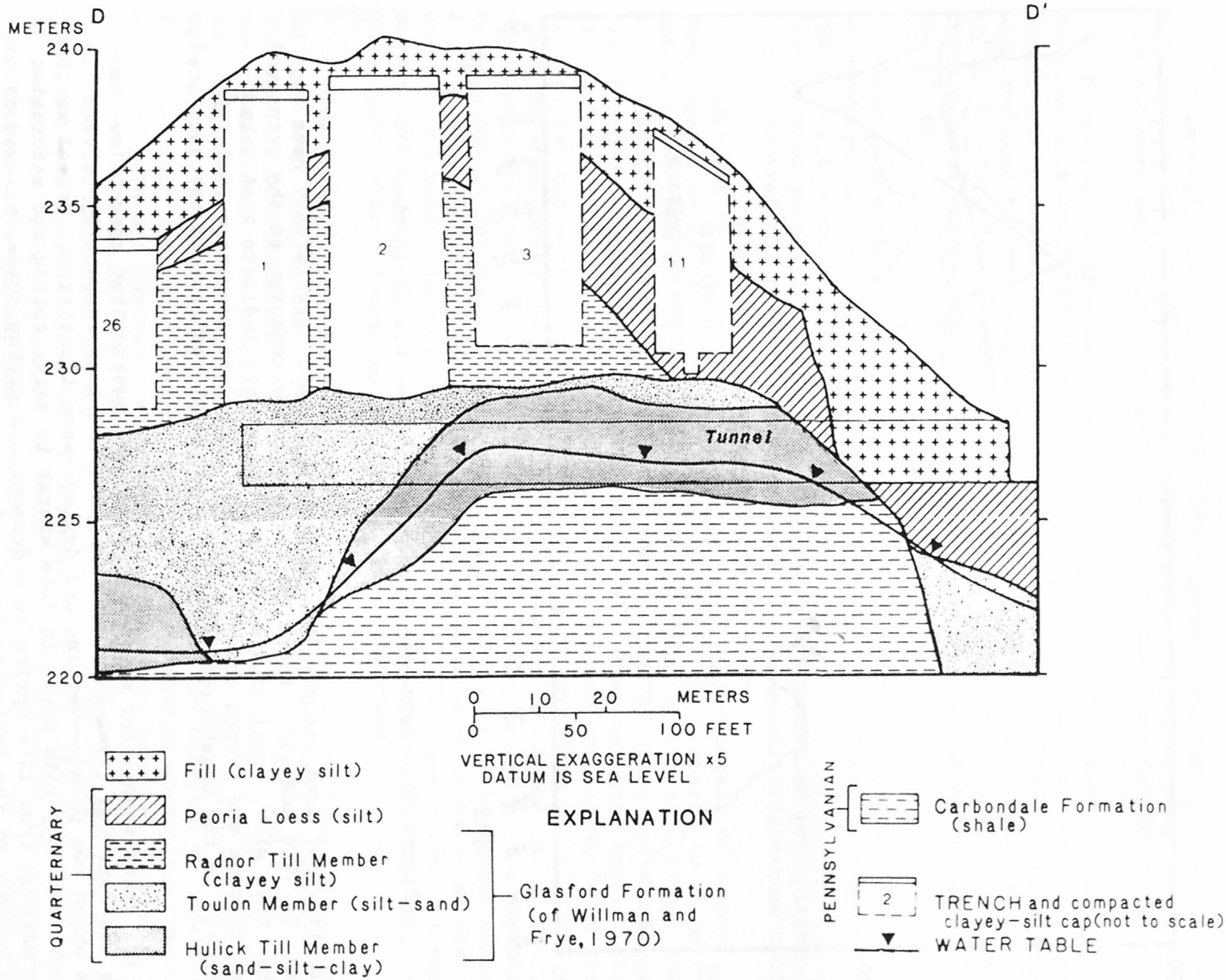


Figure 30.--Geologic section D-D' through tunnel-study area (line of section shown in fig. 29).

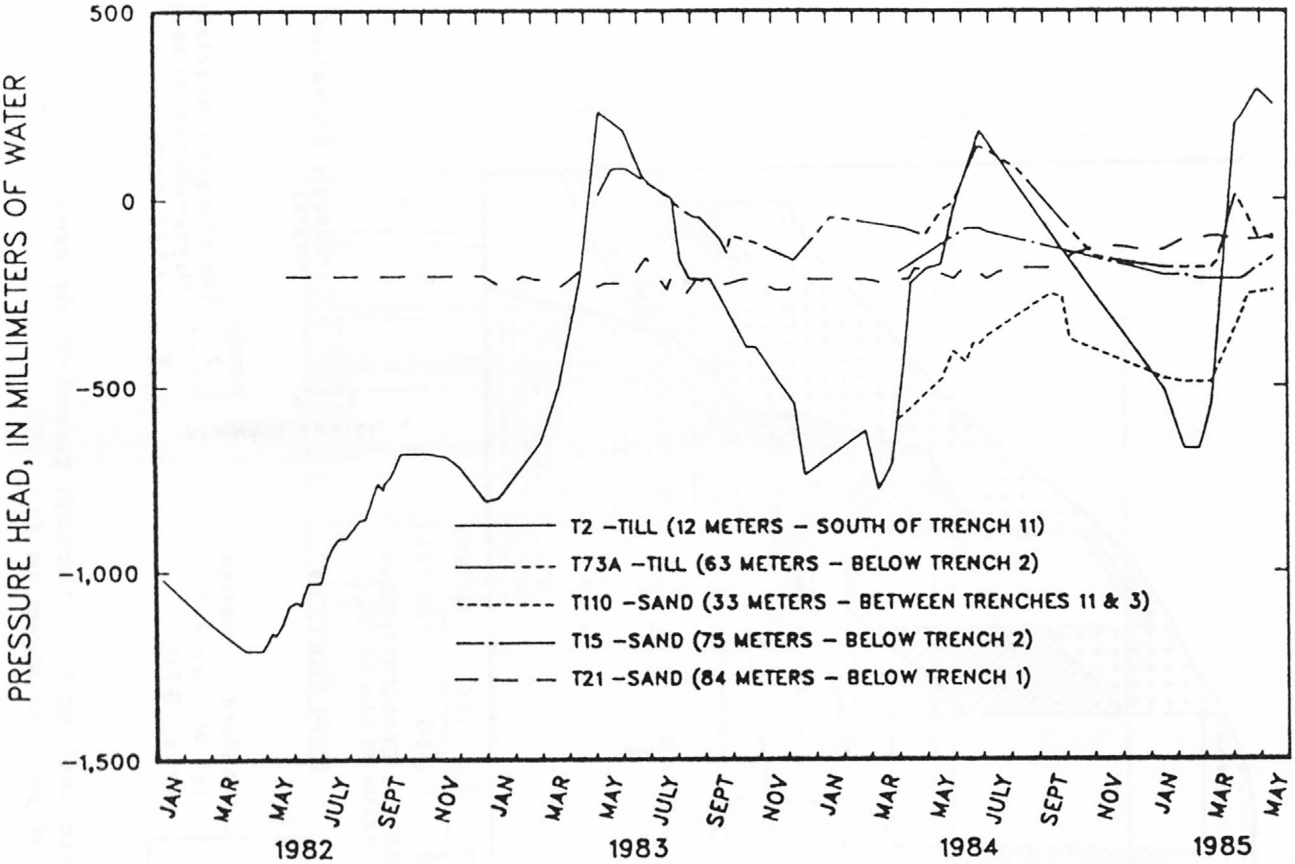


Figure 31.--Representative pressure-head trends in the subtrench sand and till deposits.

deposits (fig. 30) from January 1982 through May 1985. Preliminary data suggest that, in 1986 and 1987, there was no detectable recharge to the saturated zone other than slow, continuous drainage. These data indicate that water migrating through the trench covers primarily went into long-term (multiple-year) storage in the unsaturated zone for subsequent recharge to the saturated zone.

In the years when water movement through the unsaturated zone below the trenches was detected (1982-85), movement occurred in a seasonally related cycle in which two phases--wetting and drying--were identified. Annual wetting of the subtrench deposits began in late winter to early spring and saturation was at a maximum from late spring to midsummer. A drying phase followed as moisture content of the sediments decreased. Generally, drying continued to the beginning of the wetting phase in the subsequent annual cycle.

In one cycle (1983-84), there was evidence for an additional phase in which soil-moisture content and liquid pressure heads remained relatively constant between the end of drying in late fall (1983) and the beginning of wetting in early spring (1984) (fig. 31). During some fall periods, there also were indications of a second wetting phase. However, their short duration and weak magnitude made discrimination of the phase difficult.

Potential recharge to the trenches was estimated by a water-budget method based on data collected during a 2-year period beginning in July 1982. Average annual precipitation for the 2-year period was 948 mm. Annual evapotranspiration averaged 657 mm (Healy and others, 1987), and annual runoff averaged 160 mm (J. R. Gray, U.S. Geological Survey, written commun., 1986). Based on these average annual values, the estimated annual recharge to the subsurface was 132 mm.

Recharge estimates, however, were different for each year. The estimate of recharge for the period July 1982 to June 1983 was 95 mm, as compared to 168 mm for the annual period that followed. The variability of recharge rates from year to year was influenced by the timing and amount of precipitation and evapotranspiration, and the characteristics of the annual freeze-thaw cycle.

Additionally, to provide a general measure of the impact of trench construction on recharge, the site's water budget was compared to an approximated budget from an undisturbed basin 0.5 km south of the site (Gray, 1984, p. 534-539). In his collection of comparative precipitation and runoff data, Gray found no significant difference in precipitation measured between the site and the undisturbed basin. However, the average annual runoff at the undisturbed basin (11.4 mm) for the 2-year period beginning in July 1982 was about one-fourteenth the runoff at the on-site basin (160 mm) (J. R. Gray, U.S. Geological Survey, written commun., 1986). Comparison of the approximated annual water budget from the undisturbed basin with the budget estimated for the site indicates that there was over twice as much recharge at the undisturbed basin (280 mm) than at the site (132 mm). Compaction of trench covers during construction most likely reduced recharge to the trenches and underlying saturated zone.

Flow through trenches may be hydraulically similar to flow through karst or fractured-rock systems. Despite relatively high hydraulic conductivities in karst or some fractured-rock systems (ranging up to 10^{-2} and 1 cm/s (centimeter per second), respectively) (Freeze and Cherry, 1979, p. 29), trench voids may actually inhibit the movement of water through the unsaturated zone. Wang and Narasimhan (1985) discuss this phenomenon in relation to unsaturated fractured-rock systems. However, even under unsaturated conditions, locally saturated pathways can occur within the trenches. An example of this could be trench-cover collapse holes that provide preferential pathways for water to enter the trenches from the surface. During one 11-mm rainstorm in November 1985, surface water drained into a collapse hole (fig. 32) at a measured rate of 1.7×10^{-4} m^3/s (cubic meters per second). It is estimated that as much as 1,700 liters of water may have entered the trench through the collapse hole during the storm period (Mills and Healy, 1987). Under these conditions, some of the trench may have been saturated allowing rapid water movement through the voids.

Water movement below the trenches varied spatially, as indicated by pressure-head measurements in the Hulick Till and Toulon Members of the Glasford Formation. The range and spatial distribution of pressure heads in

November 1985

Figure 32.--Surface-water drainage into a collapse hole during a rainstorm in November 1985.

the wetting and drying phases are shown in figure 33. During the wetting cycle in 1984, pressure-head fluctuations averaged 430 mm in the Hulick Till Member and 190 mm in the Toulon Member.

Pressure-head and water-table fluctuations were greater in the layered till and sand deposits below trench 11 than in similarly layered deposits elsewhere in the study area (fig. 33). For example, in 1984, pressure-head fluctuations in the deposits below trench 11 averaged 820 mm, and water-level fluctuations averaged 1,270 mm. Below trenches 2 and 3 (20 to 50 m north of trench 11), pressure-head fluctuations averaged 200 mm, and water-level fluctuations averaged 230 mm.

Saturation values in the Hulick Till and Toulon Members (fig. 34) indicate that the total change over time in subtrench soil-water content was relatively small. Despite measured fluctuations in pressure head, the till deposits were consistently 99 to 100 percent saturated. Water content of the sand deposits changed little over time. In contrast to the till unit, however, water content in the sand was spatially variable. At the beginning of the wetting phase,

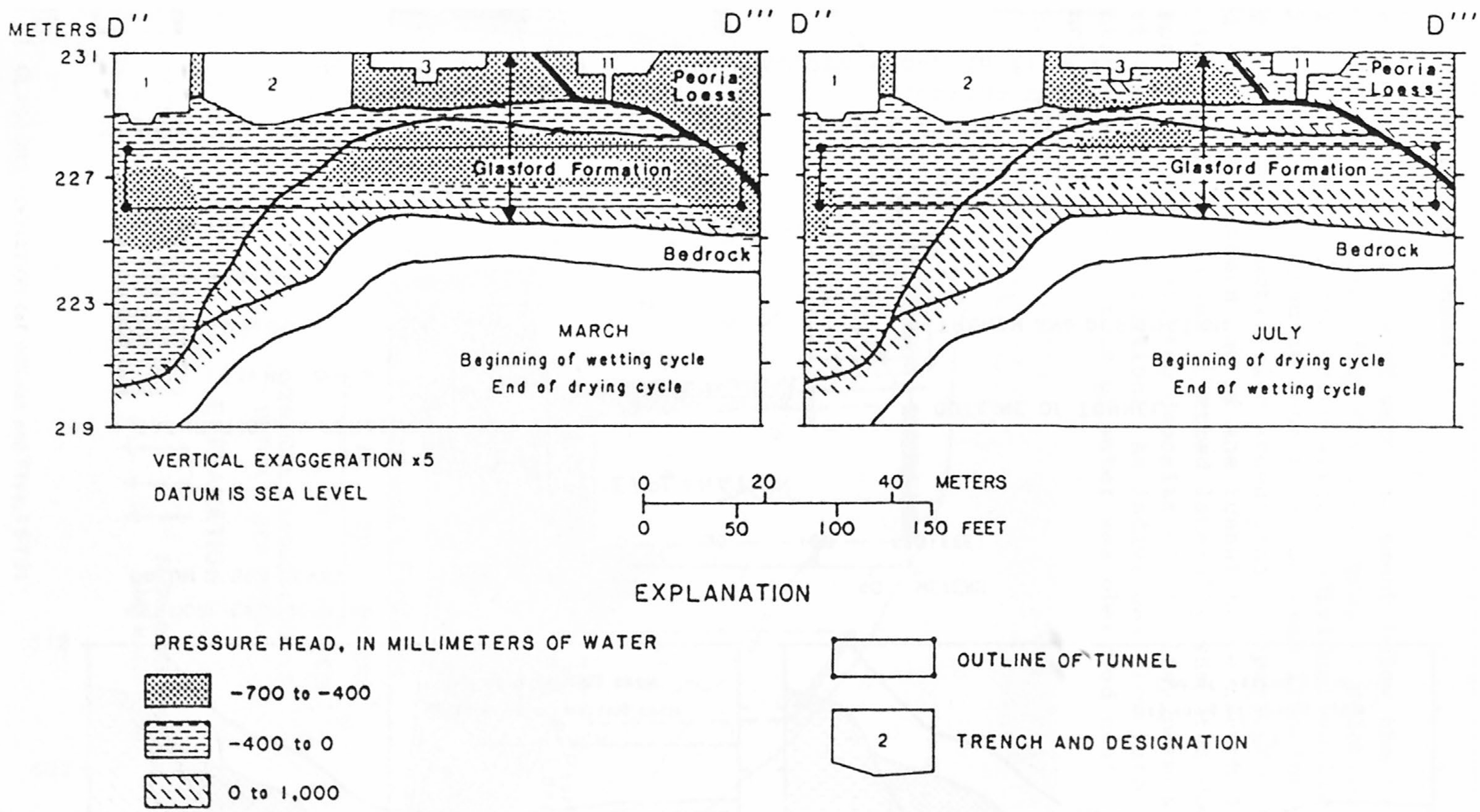


Figure 33.--Schematic section D"-D"' showing range and spatial distribution of subtrench pressure heads in March 1984 (drying phase) and July 1984 (wetting phase) (line of section shown in fig. 29).

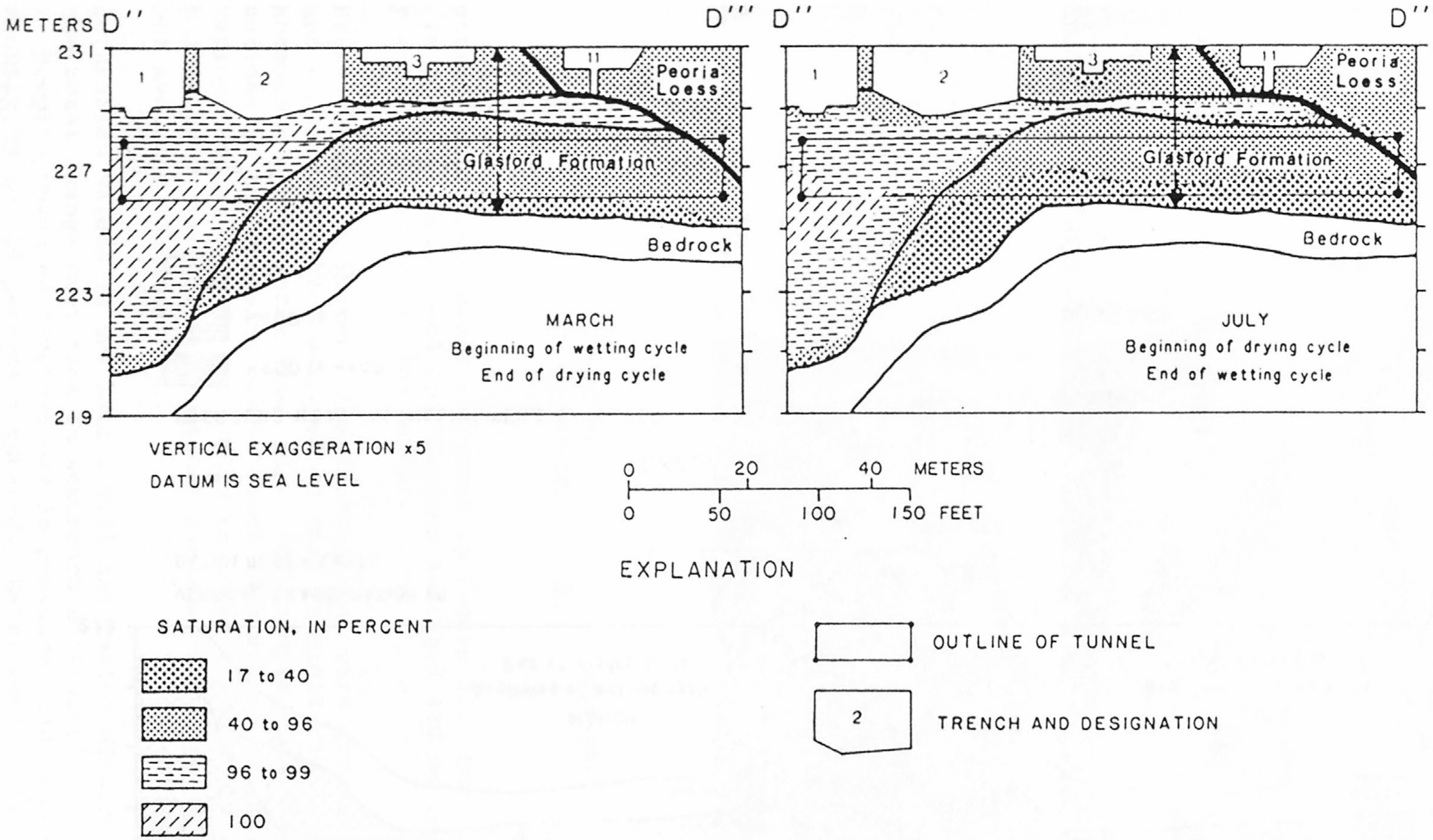


Figure 34.--Schematic section D"-D"' showing range and spatial distribution of subtrench soil saturation in March 1984 (drying phase) and July 1984 (wetting phase) (line of section shown in fig. 29).

saturation values in the sand unit ranged from 17 to 100 percent. The average saturation of the sand unit increased only 3 percent (from 42 to 45 percent) during the 1984 wetting phase.

The spatial variability of water movement below the trenches during wetting phases was influenced by the stratigraphic relation and the hydraulic conductivity of the geologic units within individual vertical sections. Vertical flow was inhibited at interfaces between lithologic units of contrasting hydraulic conductivities accounting, in part, for the influx of water detected near the southern end of the tunnel below trench 11 (fig. 35). Flow through the Peoria Loess was diverted laterally when the downward percolating water approached the underlying deposits of the less permeable Radnor Till Member of the Glasford Formation. As individual flow paths along the loess-till contact merged, an influx of water was observed near the southern end of the tunnel.

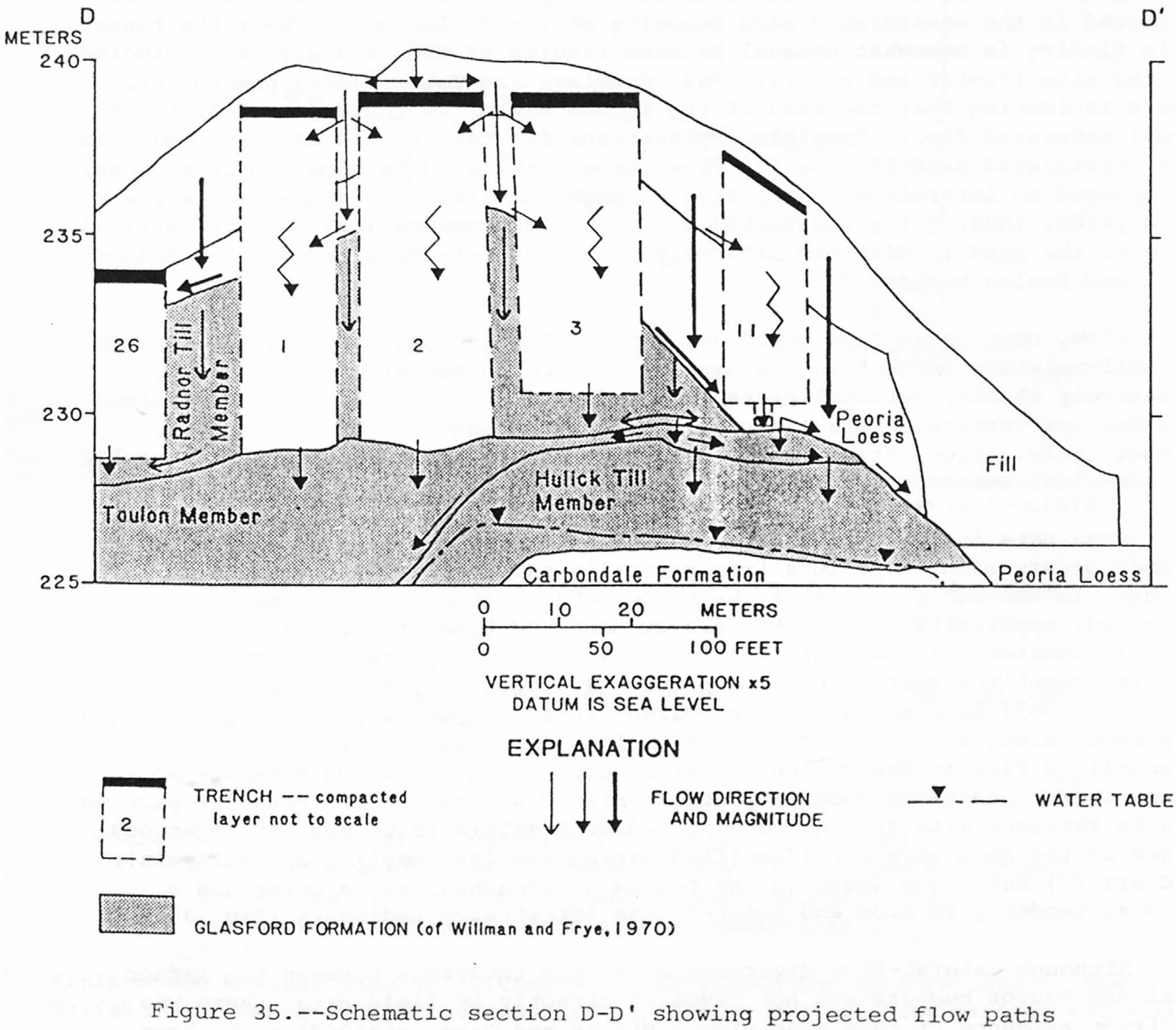


Figure 35.--Schematic section D-D' showing projected flow paths through the unsaturated tunnel-study section.

Inconsistencies in time-of-travel estimates for water movement through the study section support the role of geologic contacts in inducing lateral flow in the unsaturated zone. In 1983, the measured traveltime of water movement along a vertical section from land surface to below trench 11 was 13 days longer (153 compared to 140 days) than the traveltime along a 7-m shorter vertical section through trench 2. Assuming similar disposal characteristics (contents, arrangement of containers, and compaction of till material), the discrepency in traveltimes can be accounted for if flow through the trench 11 section was not strictly vertical, as would be the case if lateral water movement occurred along the sloping interface between the Peoria Loess and Radnor Till Member. Increased tritium concentrations detected immediately above the interface between the Toulon and Hulick Till Members and numerical computer simulation of water movement through the variably saturated geologic deposits below the trenches provide additional support for the influence of geologic contacts and their contrasting hydrogeologic properties on unsaturated flow.

Limited water movement (as indicated by pressure-head fluctuations) was detected in the unsaturated sand deposits of the Toulon Member near the tunnel. This finding is somewhat unusual because results of the saturated-zone studies at the site (Foster and others, 1984; Garklavs and Toler, 1985) present evidence indicating that the sand of the Toulon Member is the major conduit for local saturated flow. Possible explanations for the limited water movement in the unsaturated sand include (1) flow through the sand is slow and continuous, as opposed to intermittent; (2) flow through the sand is confined to narrow flow paths, thus, going undetected by tunnel instrumentation; and (3) vertical flow to the sand is diverted laterally above the interface between the Radnor Till and Toulon Members.

Slow, continuous flow would account for the lack of temporal fluctuation in soil-moisture content in the sand of the Toulon Member, and for small, relatively stable, vertical hydraulic gradients in the unit. Average minimum and maximum vertical hydraulic gradients for the unit were 1.09 and 1.62, respectively. Slow, steady-state water movement also was supported by results of numerical computer simulation.

Some data indicate that water movement through the sand of the Toulon Member occurs along very localized partially saturated to saturated flow paths. In the early phases of the study, channelized water movement was not detected, apparently because the arrangement and type of early instrumentation (small-diameter soil-moisture tensiometers and gravity-drain lysimeters) did not intercept the restricted flow paths. In laboratory tests, Palmquist and Johnson (1962) have shown that in coarse-grained deposits preferential flow may occur along narrow channels; the Toulon Member is a coarse-grained deposit. Channelized flow in the Toulon Member likely occurs (1) along heterogeneous zones where conditions such as particle-size distribution and granular packing are in variance with the surrounding sediment matrix (although heterogeneous zones in the sand were not identified during routine sampling and analysis); and(or) (2) below low areas in the bottom of trenches, where water has a natural tendency to flow and saturate the intratrench sediments (fig. 35).

Although lateral-flow diversion above the interface between the Radnor Till and Toulon Members was not revealed directly by field data, there was indirect evidence of this diversion. Miller and Gardner (1962) have shown that water movement may be impeded by the contrast in hydraulic conductivity at geologic contacts where fine-grained deposits overlie coarse-grained deposits. The retention characteristics of the Toulon Member and the Radnor Till Member are such that, at pressure heads below about -350 mm, the hydraulic conductivity of the sand of the Toulon Member is less than that of the clayey-silt deposits of the overlying Radnor Till Member. This situation can be seen in figure 36, which shows the moisture retention characteristics of the sand in the Toulon and Hulick Till Members (a deposit that is hydrogeologically similar to the Radnor Till Member). Thus, under all but near-saturated conditions, the unsaturated till may be a better conduit for water movement than the unsaturated sand. Foster and others (1984, p. 17) reported that this same phenomenon probably accounted for the lack of leachate in trench sumps at the site. The fine-grained deposits surrounding the French drains may be more conductive for water movement than the gravel-filled drains.

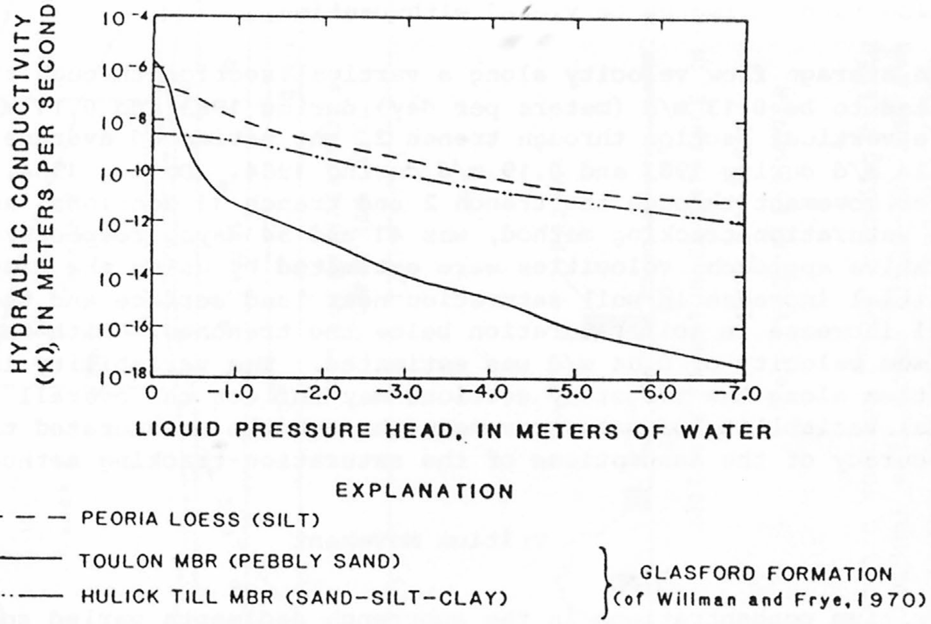


Figure 36.--Hydraulic conductivity as a function of liquid pressure head of three geologic units at the site.

Vertical flow velocities through the subtrench geologic deposits were calculated by using the following formula:

$$v = [K/\Theta]i, \qquad (1)$$

where v = average linear velocity (length per unit time),
K = unsaturated hydraulic conductivity (length per unit time),
Θ = volumetric moisture content (dimensionless), and
i = vertical hydraulic gradient (dimensionless).

Minimum and maximum flow velocities were calculated for 17 locations in the Hulick Till Member and 13 locations in the Toulon Member. The maximum velocity in the till was 3.9×10^{-3} m/d (meters per day) and in the sand was 6.6×10^{-1} m/d.

The average minimum and maximum flow velocities in the till were 5.0×10^{-4} m/d and 2.3×10^{-3} m/d, respectively. In the sand, the average minimum and maximum flow velocities were 6.7×10^{-2} and 1.7×10^{-1} m/d, respectively.

Velocities of water movement through trenches and surrounding geologic deposits were estimated by a saturation-tracking method, in which the vertical distance between two observation points was divided by the time lapse between maximum saturation at a trench-cover location and maximum saturation at a subtrench location. In using this method, the following assumptions were made: (1) Water stored in trench covers between wetting phases completes its migration to the saturated zone in one annual cycle; (2) there is no change in water storage between the upper and lower measuring points; (3) all unsaturated flow occurs vertically; and (4) the time of maximum saturation above and below the trenches can be determined. Because of the absence of the field data necessary to verify these assumptions, especially assumption 1, it is important that flow-rate estimates be viewed with caution.

An average flow velocity along a vertical section through trench 11 was estimated to be 0.13 m/d (meters per day) during 1983 and 0.11 m/d during 1984. Along a vertical section through trench 2, the estimated average flow velocity was 0.34 m/d during 1983 and 0.19 m/d during 1984. During 1984, the traveltime of water movement through the trench 2 and trench 11 sections, as determined by the saturation-tracking method, was 41 and 54 days, respectively. As a comparative approach, velocities were estimated by using the time span between the initial increase in soil saturation near land surface and the subsequent initial increase in soil saturation below the trenches. With this approach, a minimum velocity of 0.04 m/d was estimated. The variability in flow rates traveltime along the two study sections may reflect the overall spatial and temporal variability of water movement through the unsaturated trenches and(or) the accuracy of the assumptions of the saturation-tracking method.

Tritium Movement

Tritium concentrations in the subtrench sediments varied spatially (fig. 37) reflecting the heterogeneity of wastes in the overlying trenches and local hydrogeologic conditions. Although tritium concentrations at all lysimeter locations increased with time, the increases usually were of small magnitude. Tritium concentrations increase abruptly, from five to nine times previous concentrations, at only 3 of 14 locations (fig. 38). Although not directly attributable, these large increases in tritium concentration roughly coincided with heavy summer rains and the development of several collapses in the trench cover near the tunnel. Comparison of water samples collected from vacuum lysimeters between 1982 and 1984 with water samples extracted from soil cores during tunnel excavation in 1978 and 1979 (J. B. Foster, U.S. Geological Survey, written commun., 1979) showed an increase in average tritium concentration from 60 to 70 nCi/L.

Changes in tritium concentration indicate that tritiated water was migrating through the study section during the course of the study, although the actual relation between water movement and fluctuating tritium concentrations was difficult to define. Tritium concentrations fluctuated in phase

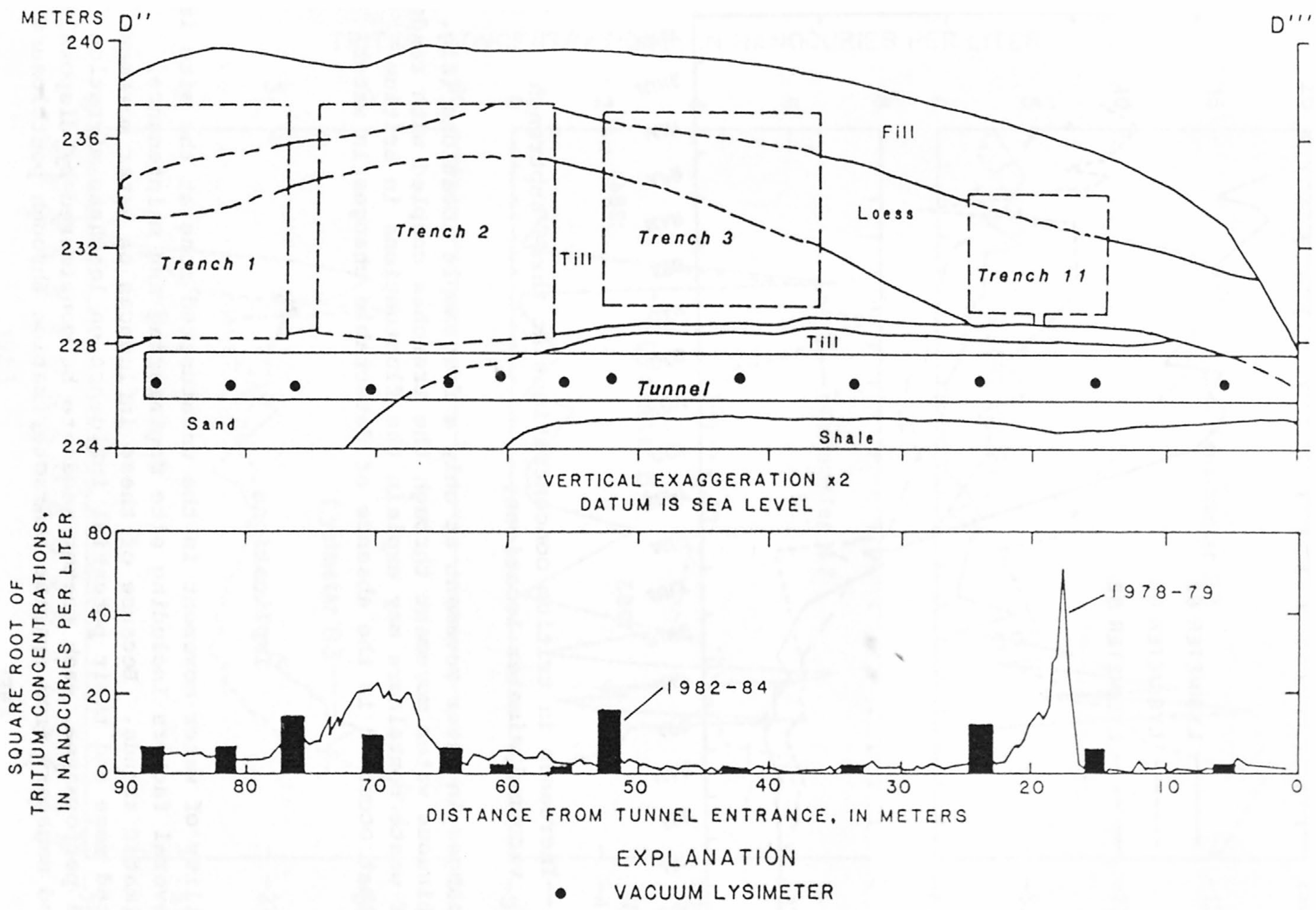


Figure 37.--Schematic section D"-D"' showing tritium concentrations from individual soil cores (1978-79) and average concentrations from vacuum lysimeters (1982-84) (line of section shown in fig. 29).

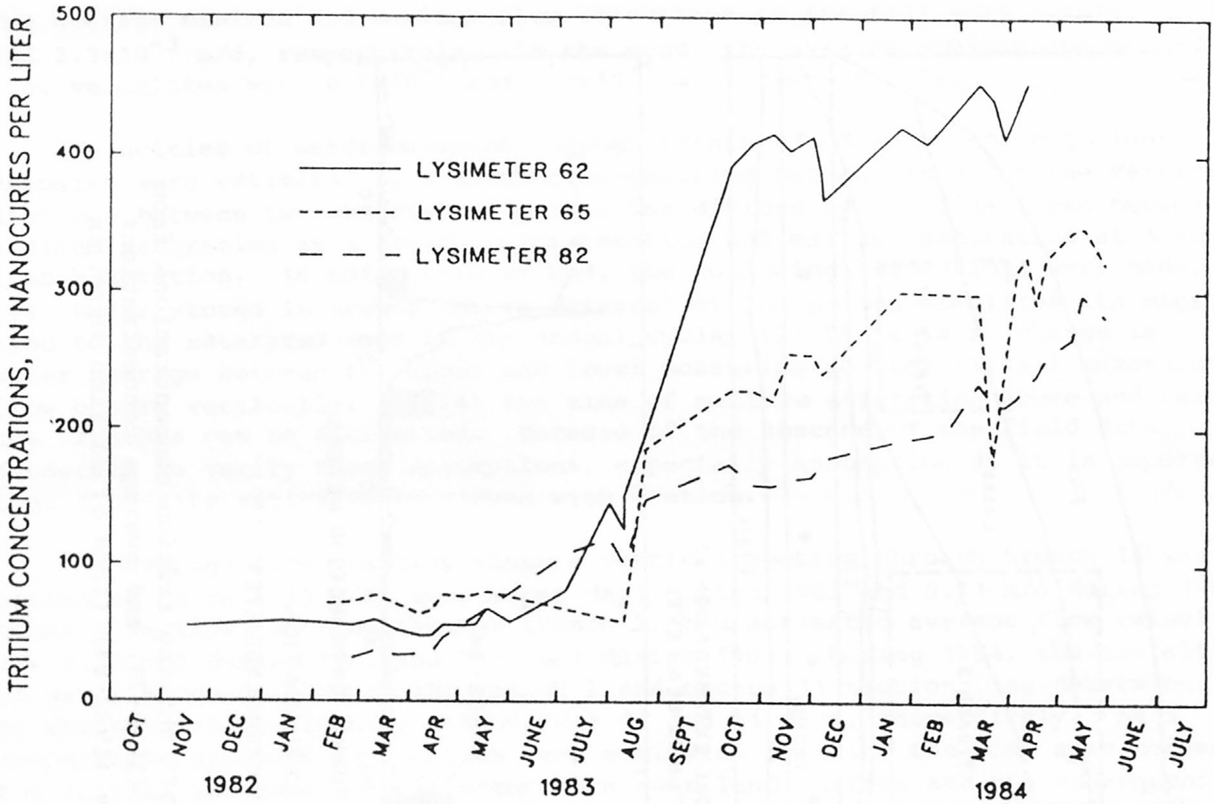


Figure 38.--Increases in tritium concentrations at three subtrench vacuum-lysimeter locations.

with seasonal changes in water movement at only a few sample locations (fig. 39). Slow, continuous water movement through the trenches coupled with random deterioration of waste containers may explain the fluctuations in tritium concentrations that occurred in the absence of detectable changes in water movement.

Implications

The variability of water movement in the unsaturated zone at the site is a function of several factors including site engineering and maintenance, geology, and climatic trends. Because of these influences on water movement in the unsaturated zone and their potential influence on leachate migration and overall site performance, each factor needs to be considered by disposal-site planners and managers from presite characterization through postclosure monitoring.

The complex relation between the natural hydrogeologic system and the engineered waste-burial system makes long-term monitoring and evaluation necessary to provide accurate assessment of current site performance and prediction of future site performance. A short-term study may not allow sufficient time to accurately characterize important influences on water movement and leachate migration, such as climatic trends or the processses of waste

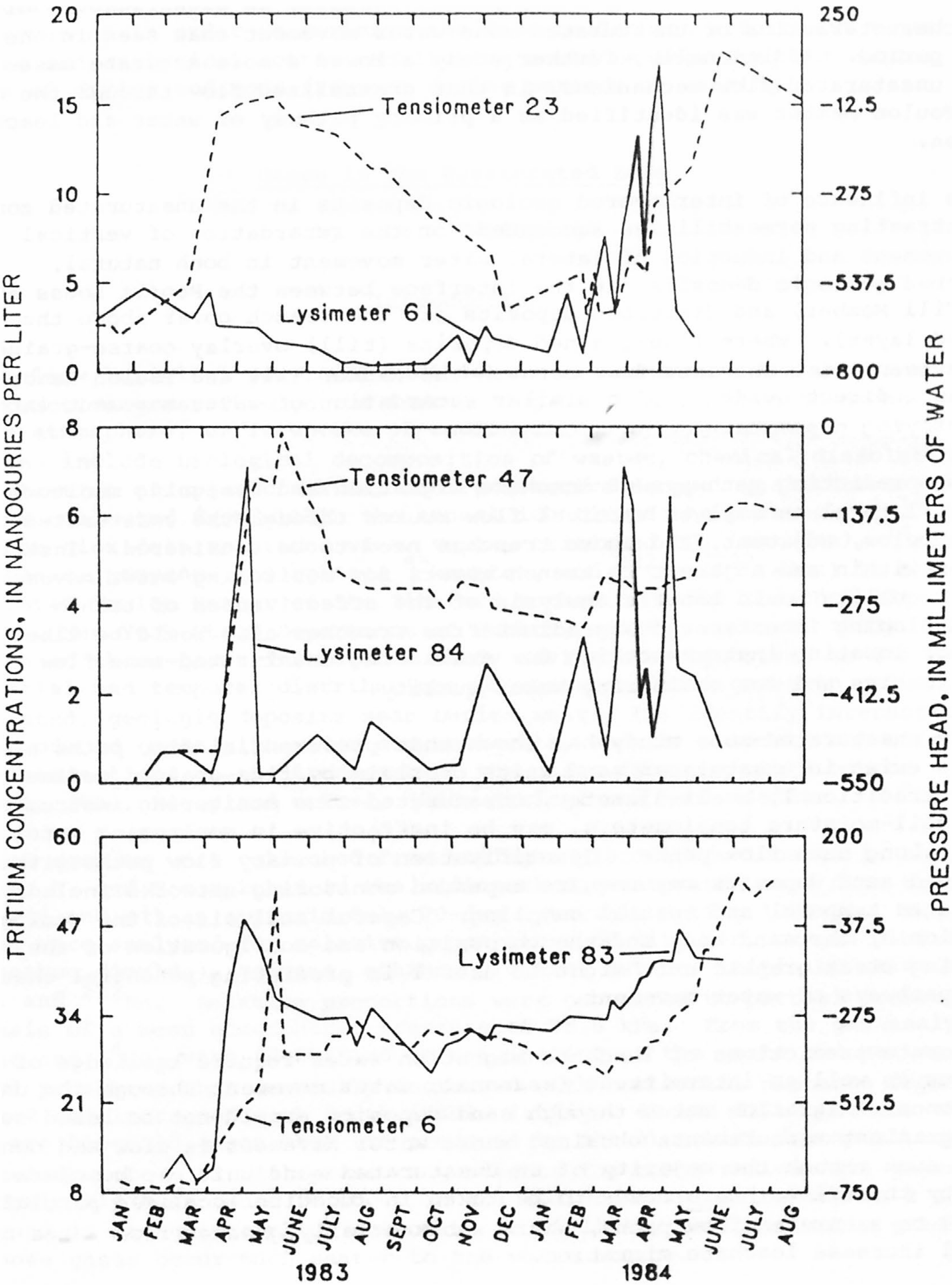


Figure 39.--Relation between subtrench tritium concentrations and seasonal trends in pressure head.

compaction and sediment redistribution within the trenches. Reduced amounts of annual rainfall in the latter study period resulted in significantly different characteristics of unsaturated-zone water movement than seen in the earlier period. Additionally, further study allowed a more accurate assessment of unsaturated-flow mechanisms, in that channelized flow through the sand of the Toulon Member was identified as a primary pathway of water and leachate migration.

The influence of interlayered geologic deposits in the unsaturated zone with contrasting permeabilities accounted for the retardation of vertical water movement and induction of lateral water movement in both natural, undisturbed geologic deposits (at the interface between the Peoria Loess and Radnor Till Member) and disturbed deposits (in the trench cover above the compacted layer). Where fine-grained deposits (till) overlay coarse-grained deposits (sand) (at the interface between the Radnor Till and Toulon Members), there was indirect evidence of a similar retardation of water movement into the underlying deposits.

When predicting pathways of leachate migration and designing monitoring networks, lateral as well as vertical flow routes through the unsaturated deposits below, adjacent, and above trenches need to be considered. Instrumentation within and adjacent to trench covers for monitoring water movement and water quality would benefit analysis of the effectiveness of trench covers. Sloping interfaces downgradient from trenches also would be likely places for locating instrumentation for evaluating unsaturated-zone flow characteristics and for monitoring water quality.

This unsaturated-zone study has shown that preferential flow paths are likely to exist in unsaturated sand units overlain by fine-grained sediments, and that traditional, small-diameter, unsaturated-zone monitoring instruments, such as soil-moisture tensiometers, may be ineffective in monitoring water movement along such flow paths. Identification of primary flow paths within unsaturated sand deposits may require expanded monitoring networks including concentrated temporal and spatial sampling. Careful analysis of the geologic composition of the sand body and the composition and configuration of the surrounding stratigraphic unit might be useful in predicting potential channelized pathways of water movement.

Accurate predictions of leachate migration rates require knowledge of the continuous as well as intermittent (seasonal) water movement through the unsaturated zones. Migration rates through sand deposits should not be based solely on head-gradient measurements obtained where water movement is slow and continuous, even though the majority of an unsaturated sand unit may be characterized by this flow. Care needs to be taken in locating localized partially saturated to saturated flow paths, where substantially greater flow rates may occur and increase leachate migration.

Knowledge of the seasonal nature of water movement is helpful in tailoring water-quality sampling schedules to the timing of recharge. Although tritium migration also can be associated with slow, continuous (nonseasonal) gravity drainage through the unsaturated zone, leachate migration may be more significant during periods of accelerated water movement associated with seasonal recharge pulses. Schedules for monitoring water quality in the unsaturated zone could be adjusted to coincide with known or predicted temporal trends of water movement in order to maximize the data-collection effort and minimize sampling and analytical costs. Monitoring could be less frequent during periods of drying and more frequent during periods of wetting.

Gases in the Unsaturated Zone

by Robert G. Striegl

Introduction

Shallow burial of low-level radioactive wastes can result in transport of radioactive gases through the surrounding unsaturated zone to ground water and the atmosphere, or in uptake of radionuclides by organisms. Sources for the gases include biological decomposition of wastes, chemical dissolution, volatilization of organic wastes, and radioactive decay. Qualitative analyses of gases collected from within the tunnel identified the presence of $^{14}CO_2$ (^{14}carbon dioxide), tritiated water vapor, tritiated CH_4 (methane), ^{14}carbon-CH_4, ethane, propane, and butane; ^{85}krypton; and ^{222}Rn (^{222}radon) in the unsaturated Toulon Member of the Glasford Formation below trench 2 (fig. 30) (C. Kunz, New York State Department of Health, written commun., 1983). Identification of those gases initiated a study having the objectives to (1) describe the spatial and temporal distributions of waste-produced gases in undisturbed, unsaturated, geologic deposits near buried waste, (2) identify interactions of waste-produced gases with water and sediments, and (3) estimate the effects of those interactions on the transport of the gases from the waste source (Striegl, 1984; Healy and others, 1986; Striegl and Ruhl, 1986).

Gas samples were collected from soil-gas piezometers located in boreholes A, B, and C completed in the undisturbed unsaturated zone near trench 2 (figs. 40 and 41) at approximately 70-day intervals during 1984-86. The samples were analyzed for relative proportions of nitrogen, oxygen plus argon, CO_2 (carbon dioxide), methane, ethane, propane, butane, tritiated water vapor, $^{14}CO_2$, and ^{222}Rn. Relative proportions were converted to partial pressures on the basis of a mean atmospheric pressure of 98.6 kPa. From the gas analyses, methane and $^{14}CO_2$ were identified as originating at the waste and having mean partial pressures that generally decreased with horizontal distance from trench 2 and increased with depth (table 3; figs. 42 and 43). Methane and $^{14}CO_2$ are biogenic gases that are produced by the microbial decomposition of the buried waste. Partial-pressure gradients for other radioactive gases that had previously been found to occur in the Toulon Member below trench 2 were not found in the gas-sampling network. It is likely that definable gradients for those gases occur much nearer to the waste source.

Distribution

Methane is produced as an end product of microbial decomposition of waste under locally anaerobic conditions. Although not separated from other gases and counted, the methane produced is presumed to be enriched in ^{14}C and ^{3}H

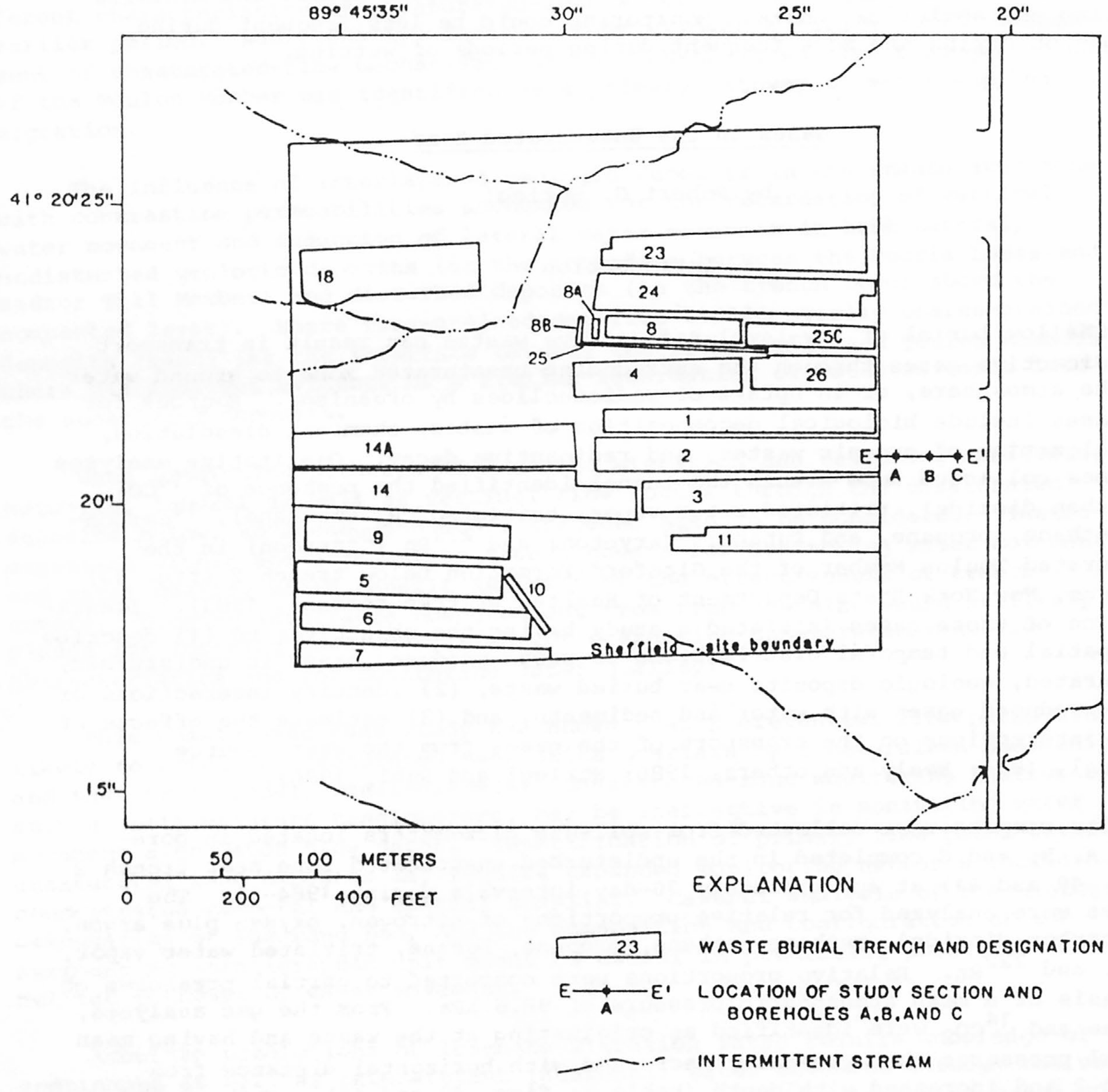


Figure 40.--Location of boreholes A, B, and C at the site.

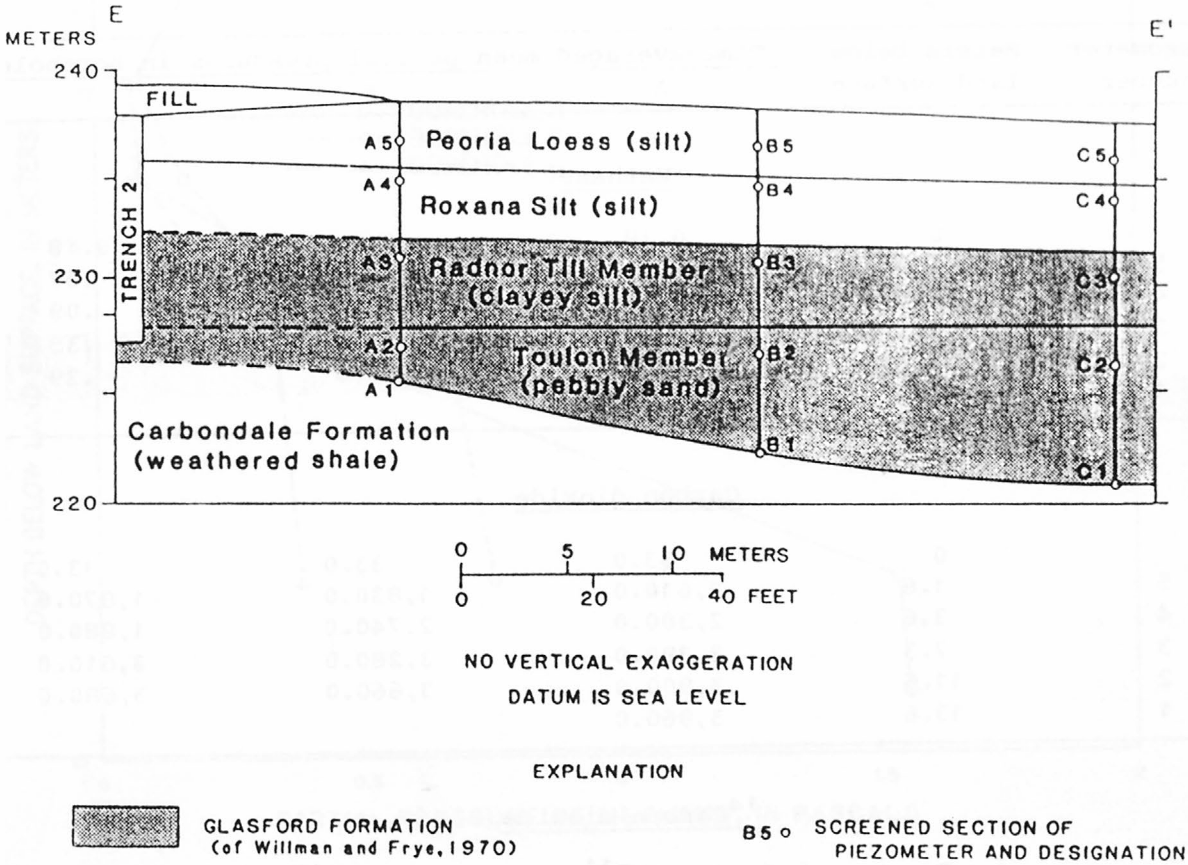


Figure 41.--Geologic section E-E' showing lithology of study section and location of soil-gas piezometers (line of section shown in fig. 40).

Table 3.--Time-averaged mean partial pressures of methane, carbon dioxide, and ^{14}carbon dioxide in the unsaturated zone, in pascals

Piezometer number	Meters below land surface	Time-averaged mean partial pressures in borehole A	B	C
		Methane		
	0	0.18	0.18	0.18
5	1.8	.08	.07	.07
4	3.6	.17	.08	.09
3	7.3	.47	.68	.35
2	11.6	1.54	.76	.39
1	13.6	1.56		
		Carbon dioxide		
	0	33.0	33.0	33.0
5	1.8	2,610.0	1,830.0	1,870.0
4	3.6	2,300.0	2,740.0	1,880.0
3	7.3	3,380.0	3,280.0	3,610.0
2	11.6	3,900.0	3,660.0	3,680.0
1	13.6	3,860.0		
		^{14}Carbon dioxide		
	0	3.96×10^{-11}	3.96×10^{-11}	3.96×10^{-11}
4	3.6	5.80×10^{-6}	3.54×10^{-7}	5.90×10^{-9}
3	7.3	1.19×10^{-5}	3.89×10^{-6}	7.45×10^{-7}
2	11.6	2.54×10^{-5}	7.88×10^{-6}	7.48×10^{-7}
1	13.6	2.03×10^{-5}		

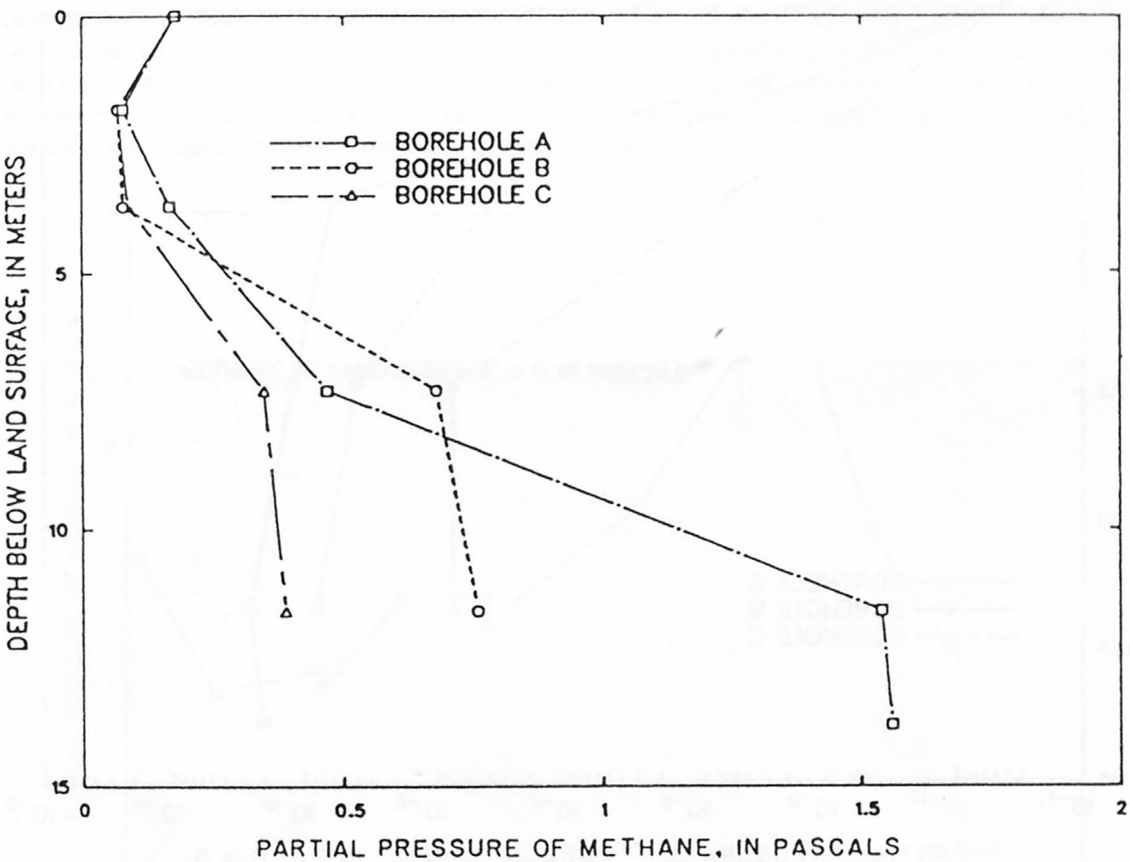


Figure 42.--Time-averaged mean partial pressures of methane at boreholes A, B, and C as a function of depth.

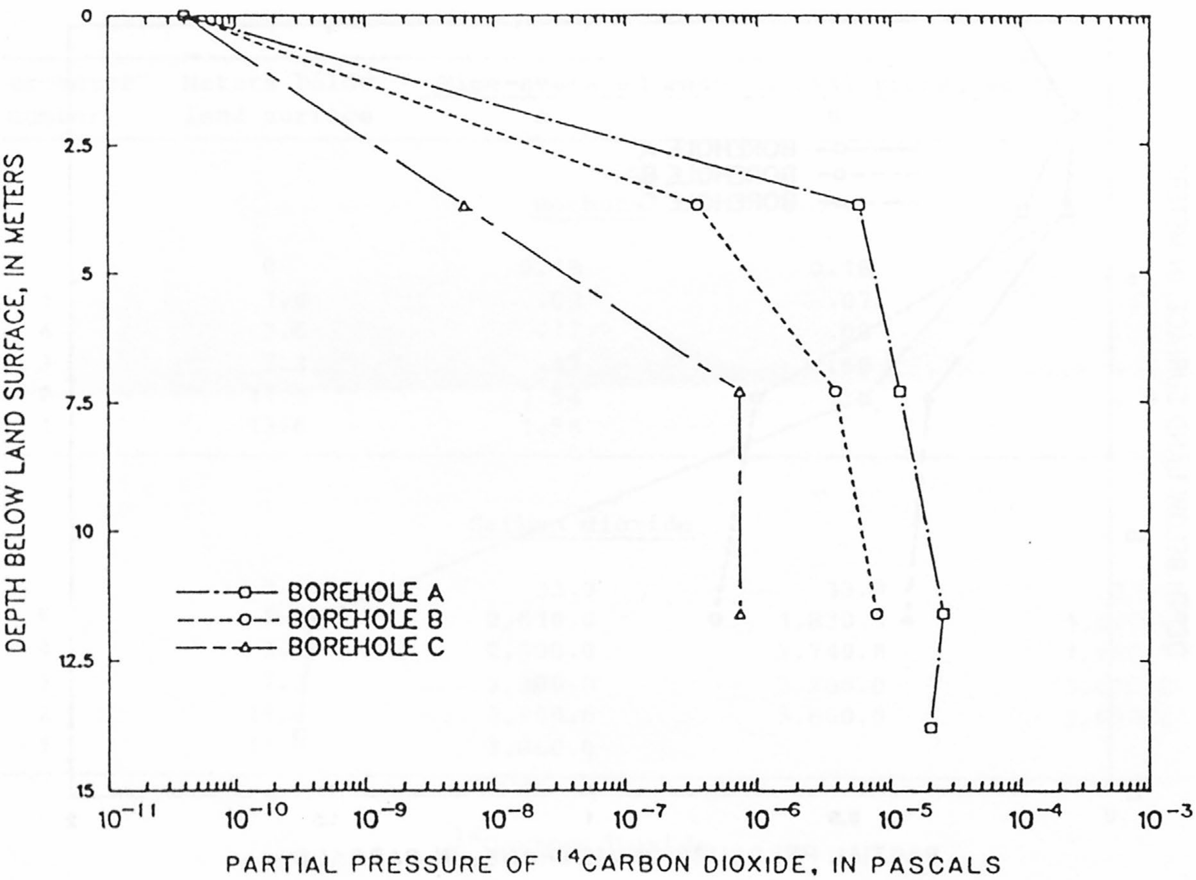


Figure 43.--Time-averaged mean partial pressures of ^{14}carbon dioxide at boreholes A, B, and C as a function of depth.

(tritium), having specific ^{14}C and ^{3}H activities that are similar to those of the waste source. Methane diffuses from the waste source to the surrounding aerobic environments, resulting in a gradient of methane partial pressures away from the source. The gradient is most evident in the Toulon Member (depths greater than 11.6 m below land surface) (table 3, fig. 42). Methane partial pressures appear to cycle annually, with peaks occurring during summer months (fig. 44). Production of methane, however, is apparently dominated more by source-related factors (container integrity and availability of material for microbrial decomposition) than by season.

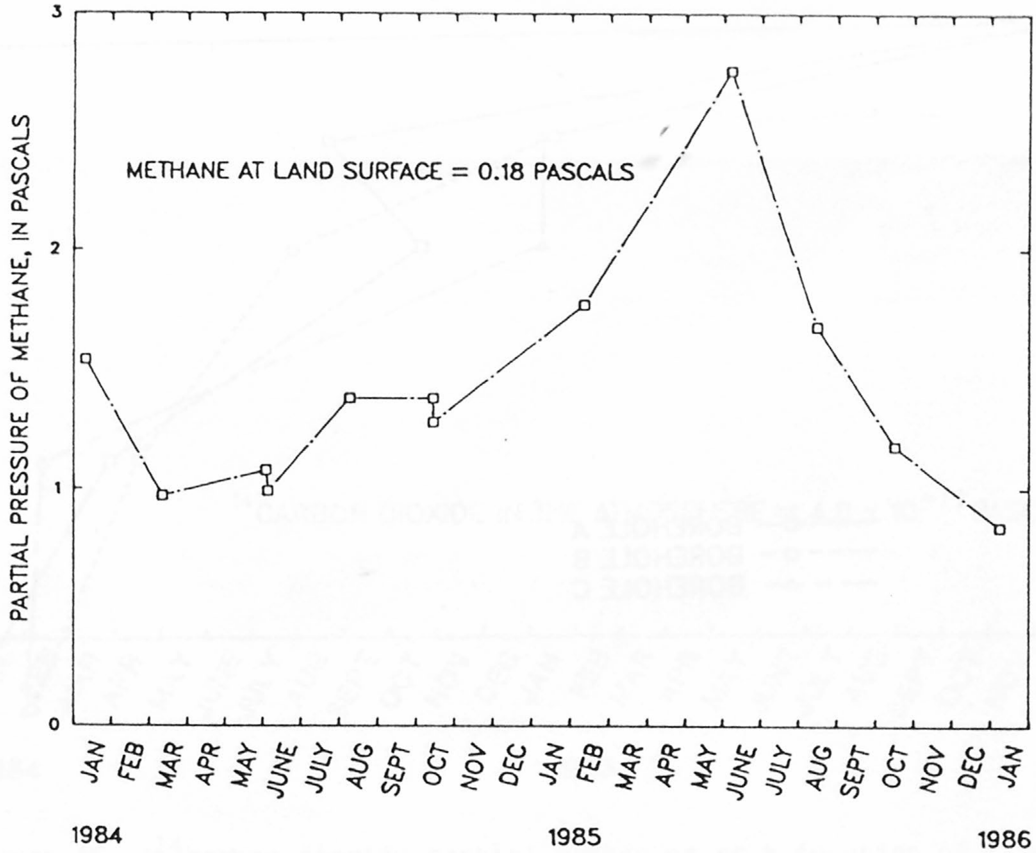


Figure 44.--Methane partial pressures as a function of time at borehole A, 11.6 meters below land surface.

Carbon dioxide is naturally produced in the unsaturated zone as an end product of the microbial decomposition of organic materials, by root respiration, and by the dissolution of carbonate minerals. Most CO_2 is produced in the root zone and diffuses from that location to the atmosphere and to underlying deposits. Production of carbon dioxide is seasonal. Greatest rates of production occur during the peak growing season for surface vegetation, and when warm, moist soil conditions enhance microbial production (Reardon and others, 1979; Thorstenson and others, 1983).

At the site, an additional source of CO_2 is the microbial decomposition of buried wastes in the trenches. It was hypothesized that the source of CO_2 from the trenches would be identifiable from CO_2 partial pressures in the gas-sampling network. However, quantitative isolation of the portion of CO_2 that was contributed from the waste material at each sampling location was not possible, and a pattern showing higher mean CO_2 partial pressures at borehole A than at boreholes B and C was not observed (table 3, fig. 45). Qualitatively, the presence of a CO_2 source at the trenches was suggested by the occurrence of annual peak partial pressures of CO_2 that usually were higher at borehole A than at boreholes B and C.

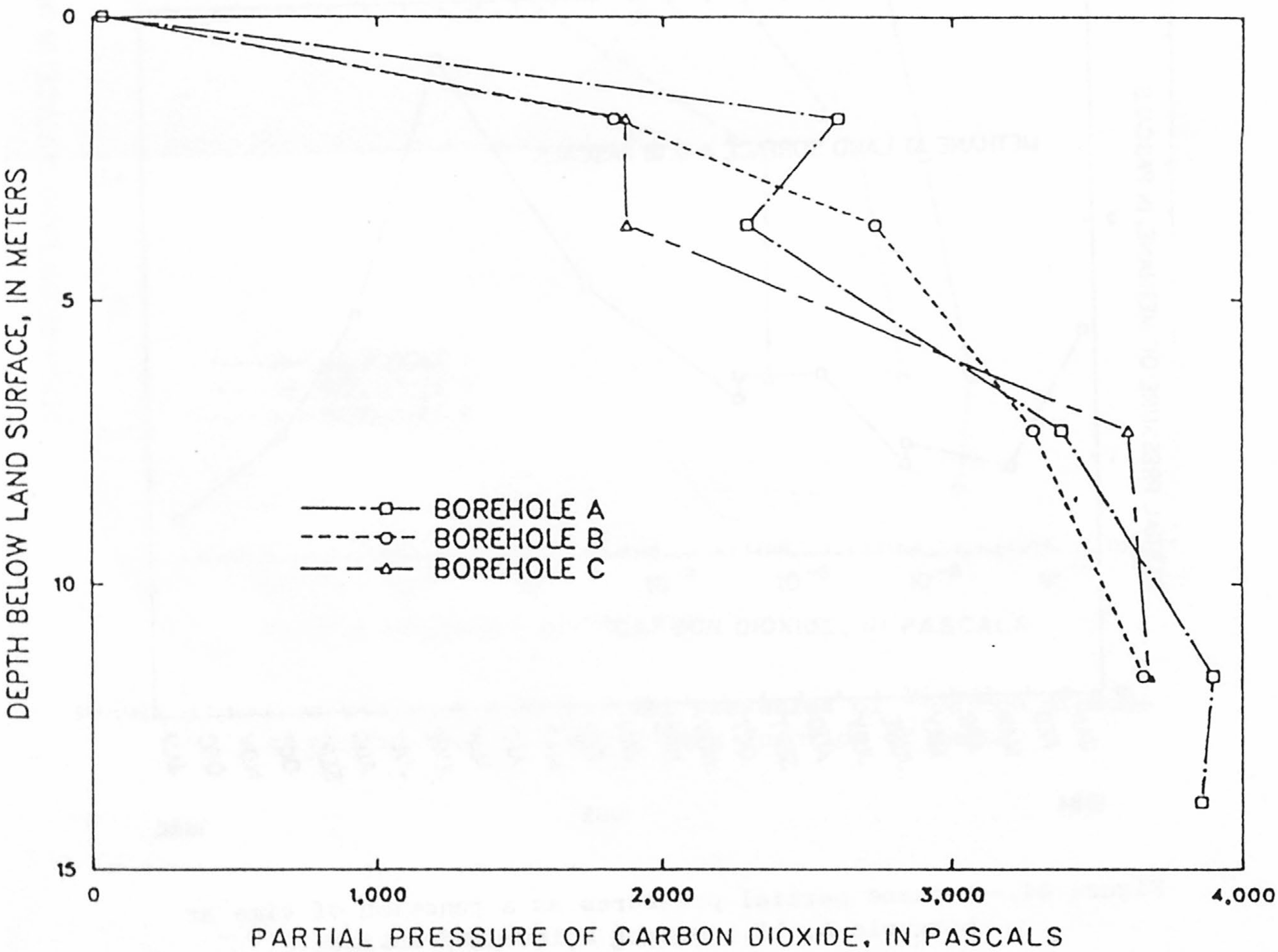


Figure 45.--Time-averaged mean partial pressures of carbon dioxide at boreholes A, B, and C as a function of depth.

Aerobic decomposition of organic wastes that contain ^{14}C produces $^{14}CO_2$ that diffuses from the waste source. The waste source was sufficient to create very high $^{14}CO_2$ partial pressures that sometimes exceeded atmospheric $^{14}CO_2$ partial pressures by factors greater than 10^6 at piezometers A1 and A2 (table 3, fig. 45). Consequently, $^{14}CO_2$ partial pressure gradients were large, having time-averaged partial pressures that decreased by a factor of 34 from piezometer A1 to piezometer C1 and by a factor of 64,000 from piezometer A1 to the land surface. The data suggest that $^{14}CO_2$ production occurs in an annual cycle with peaks in summer (fig. 46). However, as with methane, $^{14}CO_2$ production was strongly source-related and was apparently dominated by pulse-type releases from discrete sources. The magnitude of those types of releases was evidenced by a drop in $^{14}CO_2$ partial pressure by a factor of 10 or more at various depths at borehole A between August 1984 and February 1985.

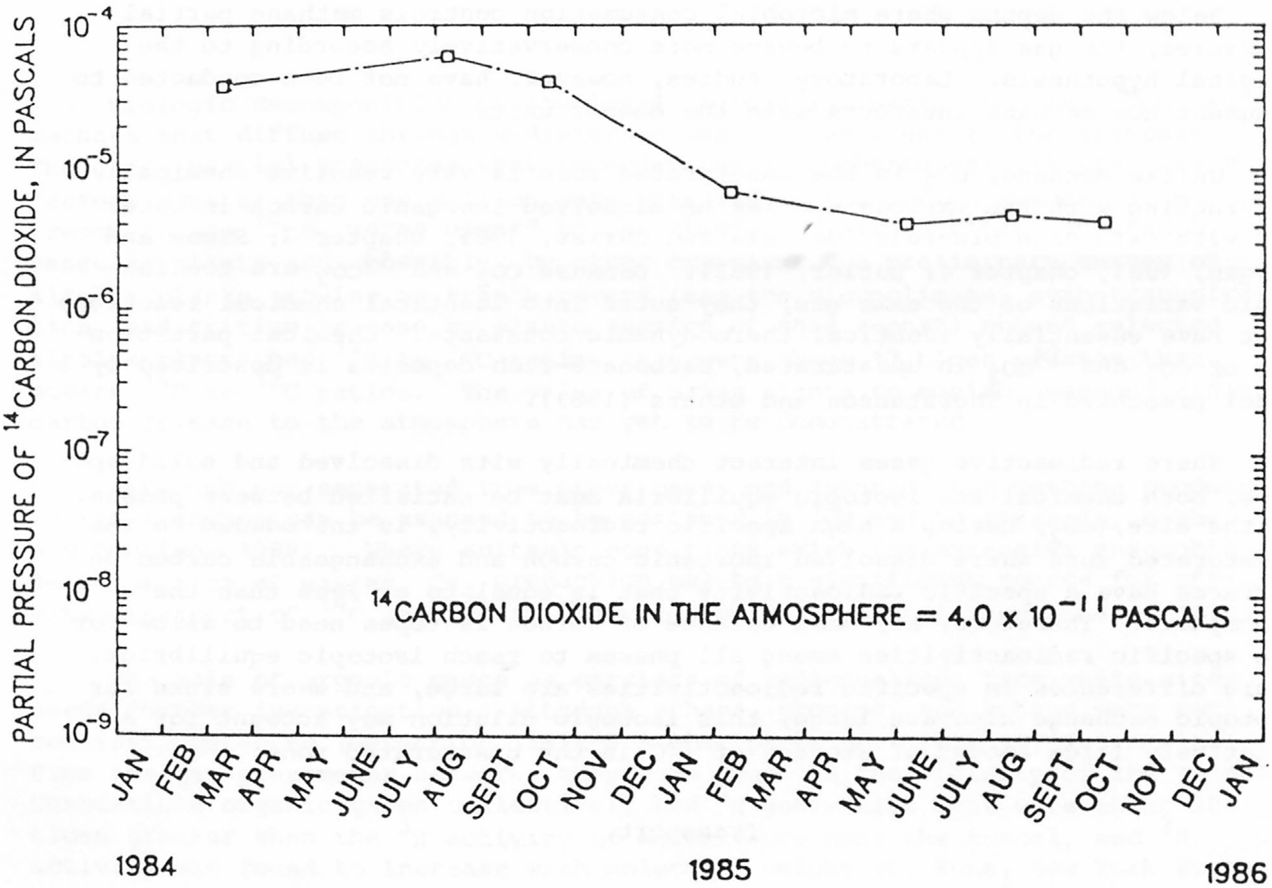


Figure 46.--^{14}carbon dioxide partial pressures as a function of time at borehole A, 11.6 meters below land surface.

Interactions

Gases moving through unsaturated geologic deposits may (1) pass through conservatively, (2) partition to water by means of physical interactions or chemical reactions, (3) partition to solids by means of physical interactions or chemical reactions, (4) be biologically or chemically converted to solutes, solids, or other gases, and (5) possibly decay radioactively. It was originally hypothesized that movement of methane through the unsaturated zone would be nearly conservative, the methane having nominal partitioning to water according to Henry's law (Stumm and Morgan, 1981, p. 179), and not entering into chemical or biological interactions that could be considered significant from a mass-balance perspective. Methane partial pressures in the soil zone are less than atmospheric indicating that soil bacteria consume methane from both the overlying atmosphere and from underlying geologic environments. Those bacteria, which have yet to be isolated, maintain mean methane partial pressures near the land surface at about one-third of the atmospheric methane partial pressure (table 3, fig. 42) and represent the major factor impeding the movement of methane from the waste source to the atmosphere.

Below the depths where microbial consumption controls methane partial pressures, the gas appears to behave more conservatively according to the original hypothesis. Laboratory studies, however, have not been conducted to document how methane interacts with the deeper units.

Unlike methane, CO_2 in the unsaturated zone is very reactive chemically, interacting with the various species of dissolved inorganic carbon in water and with carbonate minerals (Garrels and Christ, 1965, chapter 3; Stumm and Morgan, 1981, chapter 4; Butler, 1982). Because CO_2 and $^{14}CO_2$ are two isotopic variations of the same gas, they enter into identical chemical reactions that have essentially identical thermodynamic constants. Chemical partitioning of CO_2 and $^{14}CO_2$ in unsaturated, carbonate-rich deposits is described by a model presented in Thorstenson and others (1983).

Where radioactive gases interact chemically with dissolved and solid species, both chemical and isotopic equilibria must be satisfied between phases. At the site, CO_2, having a high specific radioactivity, is introduced to the unsaturated zone where dissolved inorganic carbon and exchangeable carbon on surfaces have a specific radioactivity that is equal to or less than the atmosphere. Therefore, any mass balance of carbon isotopes need to allow for the specific radioactivities among all phases to reach isotopic equilibrium. Where differences in specific radioactivities are large, and where sinks for isotopic exchange also are large, this isotopic dilution may account for a relatively large amount of storage of ^{14}C in the unsaturated zone.

Transport

Where partial pressures of gases produced in a trench are very small relative to total barometric pressure, it generally can be assumed that total gas pressures are isobaric at any given elevation and that transport of trace quantities of waste-produced gases is controlled by ordinary diffusion along partial-pressure gradients according to Fick's second law (Bird and others, 1960, p. 502). Diffusion of trace gases through the surrounding unsaturated zone is affected by pore-size distributions, air- and water-filled porosities, and by biological, chemical, and physical interactions that occur between gases, water, and solids (Millington, 1959; Evans, 1965; Lai and others, 1976; Weeks and others, 1982; Thorstenson and others, 1983).

Quantification of the impedance factors that affect diffusion allows construction of a general equation where the binary diffusion coefficient for the trace gas in air is adjusted to determine the effective diffusivity of the gas in the unsaturated zone (Weeks and others, 1982; Thorstenson and others, 1983). For the Sheffield case, the binary diffusion coefficient for methane was adjusted to account for tortuosity (Millington and Quirk, 1961), for partitioning to water according to Henry's law, and for biological consumption near the surface. The binary diffusion coefficient for CO_2 was adjusted to account for tortuosity (Millington and Quirk, 1961), for CO_2-water-calcite equilibria (Thorstenson and others, 1983), and for isotopic exchange with dissolved inorganic carbon and sorbed CO_2 on particle surfaces. Two-dimensional diffusion of the gases was numerically simulated by using a finite-difference code for gas diffusion (A. L. Ishii, U.S. Geological Survey, written commun., 1987).

Implications

Biologic decomposition of low-level radioactive waste produces $^{14}CO_2$ and methane that diffuse through undisturbed deposits adjacent to the trenches. The $^{14}CO_2$ partial pressures that exceeded the atmospheric partial pressure by factors greater than one million were measured in the Toulon Member, 12 m from trench 2. As $^{14}CO_2$ moves upward to the atmosphere, it is bioaccumulated by vascular plants and, possibly, by other organisms. A preliminary survey of alfalfa plants growing on trench covers (see the microclimate, evapotranspiration, and tritium release by plants section of this report) showed selected alfalfa plants had ^{14}C to ^{12}C ratios that were about 17 times greater than modern ^{14}C to ^{12}C ratios. The value of using plants to monitor gaseous radiocarbon release to the atmosphere has yet to be demonstrated.

Although not separated from other gases and counted, the methane produced in the trenches can be assumed to be enriched in ^{14}C and ^{3}H (Francis, Dobbs and Doering, 1980). Where suitable conditions exist for extensive anaerobic decomposition of wastes, CH_4 production may be a significant source for off-site transport of ^{14}C and ^{3}H (Lu and Matuszek, 1978; Husain and others, 1979).

The role of organic gases as carriers of radionuclides from waste sites needs further investigation. Although ethane, propane, and butane were not routinely detected [detection limit 0.5 ppm (parts per million)] in samples from the gas-piezometer network, they were found in the vicinity of the tunnel. Combustible organic gases collectively had ^{3}H activities that were about 30 times greater than the ^{3}H activity of water vapor near the tunnel, and ^{3}H activity was found to increase with molecular weight (C. Kunz, New York State Department of Health, written commun., 1983). Several volatile-organic compounds including alcohols, ketones, amines, aromatic hydrocarbons, ethers, and phenols have been identified in leachate from waste-disposal trenches at other sites (Francis and others, 1980). Those volatile compounds are likely to have gaseous-radioactive counterparts.

Water and Tritium Movement in the Saturated Zone

By Richard W. Healy, Barbara J. Ryan, and George Garklavs

Introduction

Ground-water flow has been studied at the site since 1976. The primary objectives of this research included determining the directions and rates of water and tritium movement in the shallow saturated zone, and factors that affect this movement. The early work by Foster and others (1984, 1984a, 1984b), describing the hydrogeologic setting of the site and an area east of the site, respectively, determined directions of ground-water flow and some factors that affected this flow. Later work by Garklavs and Toler (1985) and Garklavs and Healy (1986), by using tracer tests and digital modeling, respectively, determined rates of ground-water flow and additional factors that affect the flow.

Water Movement

Ground water is present in unconsolidated deposits and bedrock at the site. The unconsolidated or shallow aquifer is separated from the bedrock or deep aquifers by about 140 m of Pennsylvanian shale, mudstone, siltstone, and coal. The predominantly fine-grained bedrock is assumed to be relatively impermeable; therefore, the aquifer of interest generally has been the unconsolidated aquifer. However, the uppermost units of the bedrock may, in fact, be in hydraulic connection with the shallow aquifer system.

The unconsolidated deposits that comprise the shallow aquifer are spatially, stratigraphically, and lithologically complex (see previous description of site geology). Each unit has varying degrees of saturation and water-transmitting transmitting properties. Ground-water flow in the unconsolidated deposits is a complex phenomenon because of the irregular layering and vastly different hydraulic properties of the different lithologic units. Foster and others (1984) indicate that, beneath the site, the water table (or free-water surface) intersects nine different lithologic units. The saturated hydraulic conductivity for these units ranges from about 4×10^{-12} cm/s for the weathered shale to 8×10^{-6} cm/s for the pebbly sand of the Toulon Member. Garklavs and Healy (1986) grouped the lithologic units into elements in order to construct relatively simple conceptual and digital models of the study area.

Three ground-water basins (fig. 47) were defined within the shallow aquifer. The boundaries for each basin are ground-water divides with the exception of the eastern boundary for Basins I and II, which is the strip-mine lake, and the southern boundary for Basin III, which is an ephemeral stream.

Depth from land surface to the saturated zone ranges from 1.5 m in the valleys to 14 m at topographic highs; it averages approximately 7.5 m. Water-table fluctuations are related to periods of recharge that typically occur during spring months. Water-table altitudes generally are highest during spring months and, with the possible exception of one trench (trench 18), the water table remains below the trench bottoms.

Ground-water flow generally is from west to east, although some localized flow paths may trend north or south. All three ground-water basins ultimately drain to the strip-mine lake about 300 m northeast of the site (fig. 48). The only significant inflow to the shallow aquifer occurs as recharge derived from precipitation falling directly on the three basins. Garklavs and Healy (1986) used a ground-water-flow model to estimate a site-average recharge rate of about 48 mm/yr (millimeters per year). More recent work (R. W. Healy, U.S. Geological Survey, written commun., 1987) indicates that the recharge rate may be much higher (up to 200 mm/yr).

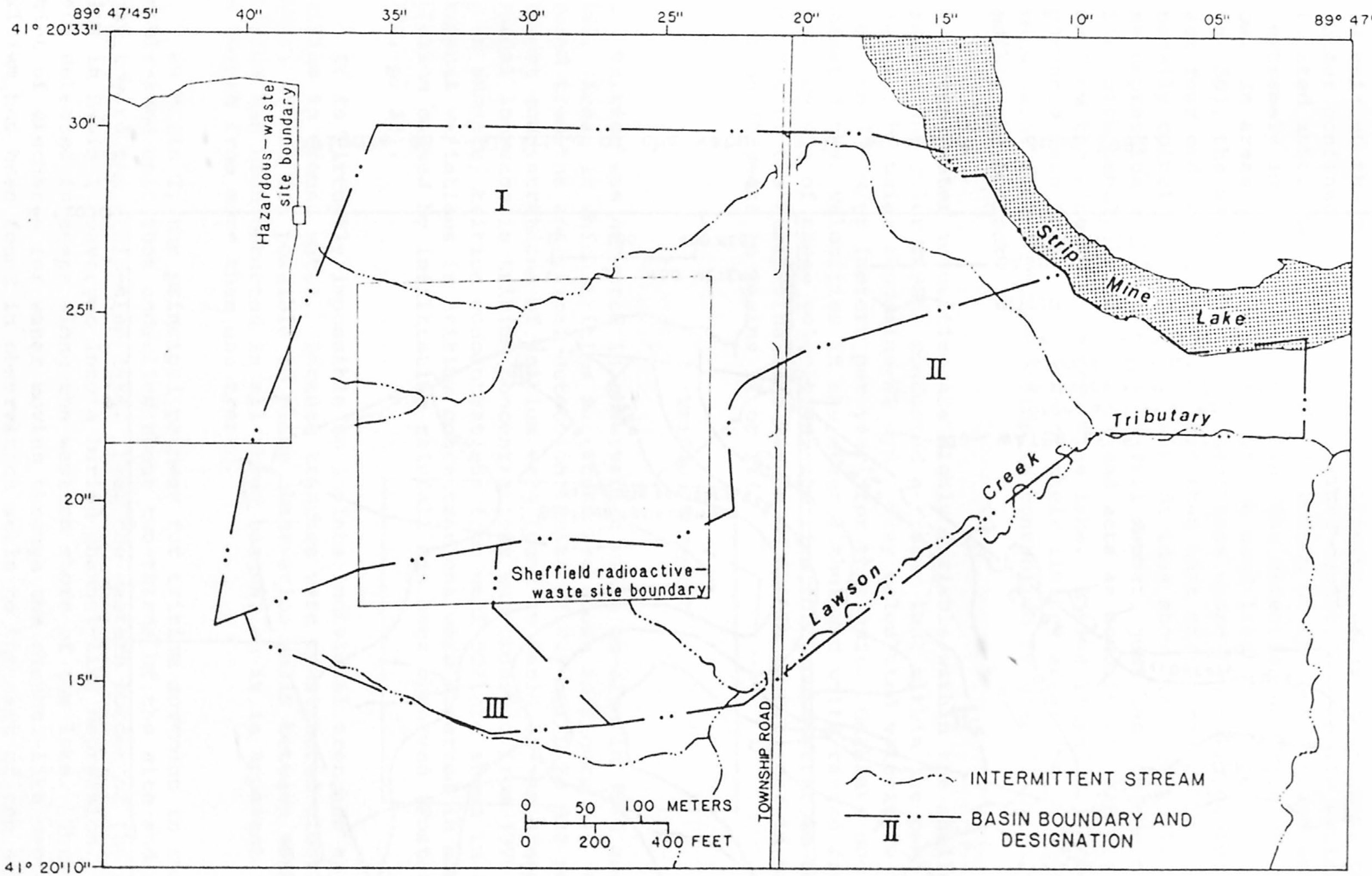


Figure 47.--Ground-water basins in study area.

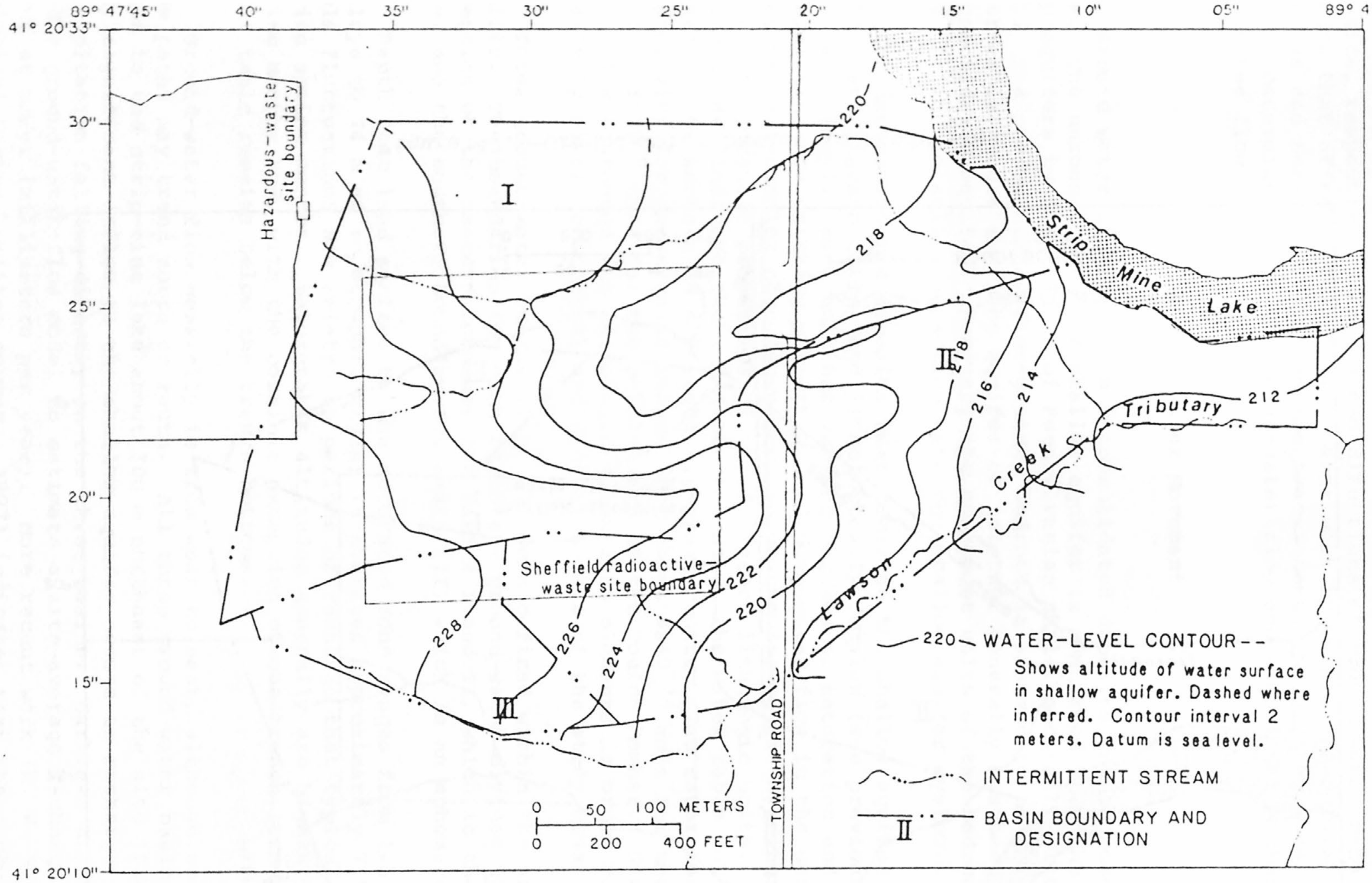


Figure 48.--Altitude of the water table measured in June 1982.

Basin I includes ground water lying beneath 80 percent of the site. Virtually all of the ground water within this basin flows through the pebbly sand unit of the Toulon Member. In different areas of Basin I, this unit may be under confined conditions, unconfined conditions, or lie entirely above the saturated zone. The altitude of the bottom of the pebbly-sand unit (fig. 49) is extremely important in controlling the direction and rate of ground-water flow. In areas where the bottom of the sand lies above the saturated zone (fig. 50), the water table is in sediments whose hydraulic conductivity is at least four orders of magnitude less than that of the sand. These areas generally coincide with ground-water divides shown in figure 47. A channel-like depression within the Hulick Till Member, just east of the site, is filled with pebbly sand (fig. 49) and acts as conduit for rapid ground-water flow from the site to the strip-mine lake. Basins II and III are of less importance than Basin I because of their limited areal extent at the site. Ground-water flow in these basins is controlled by glacial tills, outwash, and possibly the bedrock.

Ground-water velocities are highly variable within the shallow aquifer. Garklavs and Toler (1985) conducted a tracer test within the pebbly-sand unit (fig. 51) by using rhodamine-WT dye. They calculated velocities in the range of 640 to 770 m/yr (meters per year) for that unit. Garklavs and Healy (1986) estimated that velocities in the other lithologic units ranged from 2 to 490 m/yr. By use of these velocities, the time for ground water to travel from the site to the strip-mine lake may be as little as 0.2 year in Basin I or as great as 10 years in Basins II or III.

Tritium Movement

Tritium was detected in observation wells on-site in 1976 and off-site in 1982. Areas in which tritium was found are shown in figure 51. Concentrations ranged from the analytical detection limits of 0.2 nCi/L to 920 nCi/L. The highest concentrations of tritium were found in Basin II--an area in which a gradual increase in tritium concentrations was observed from 1976 to 1984. As an example, tritium concentrations from well 523 are shown in figure 52. Seasonal variations in tritium concentrations were observed in most wells, and dilution caused by infiltrating rainfall has been observed (Foster and others, 1984, p. 33).

It is virtually impossible to isolate individual trenches as sources of tritium in ground water. Because trenches were constructed close to each other, it was not possible to place observation wells between many of them. Tritium has been detected in all three basins, so it is apparent that tritium is moving from more than one trench.

In Basin I, the principal pathway for tritium movement is through the pebbly-sand unit that underlies about two-thirds of the site and extends eastward toward the strip-mine lake. Near the eastern border of the site, all flow in Basin I converges into a buried channel-like depression. Tritium has been detected in seeps along the western shore of the lake. These seeps are a point of discharge for water moving through the channel-like depression. No tritium has been found in observation wells to the east of the site in Basin I

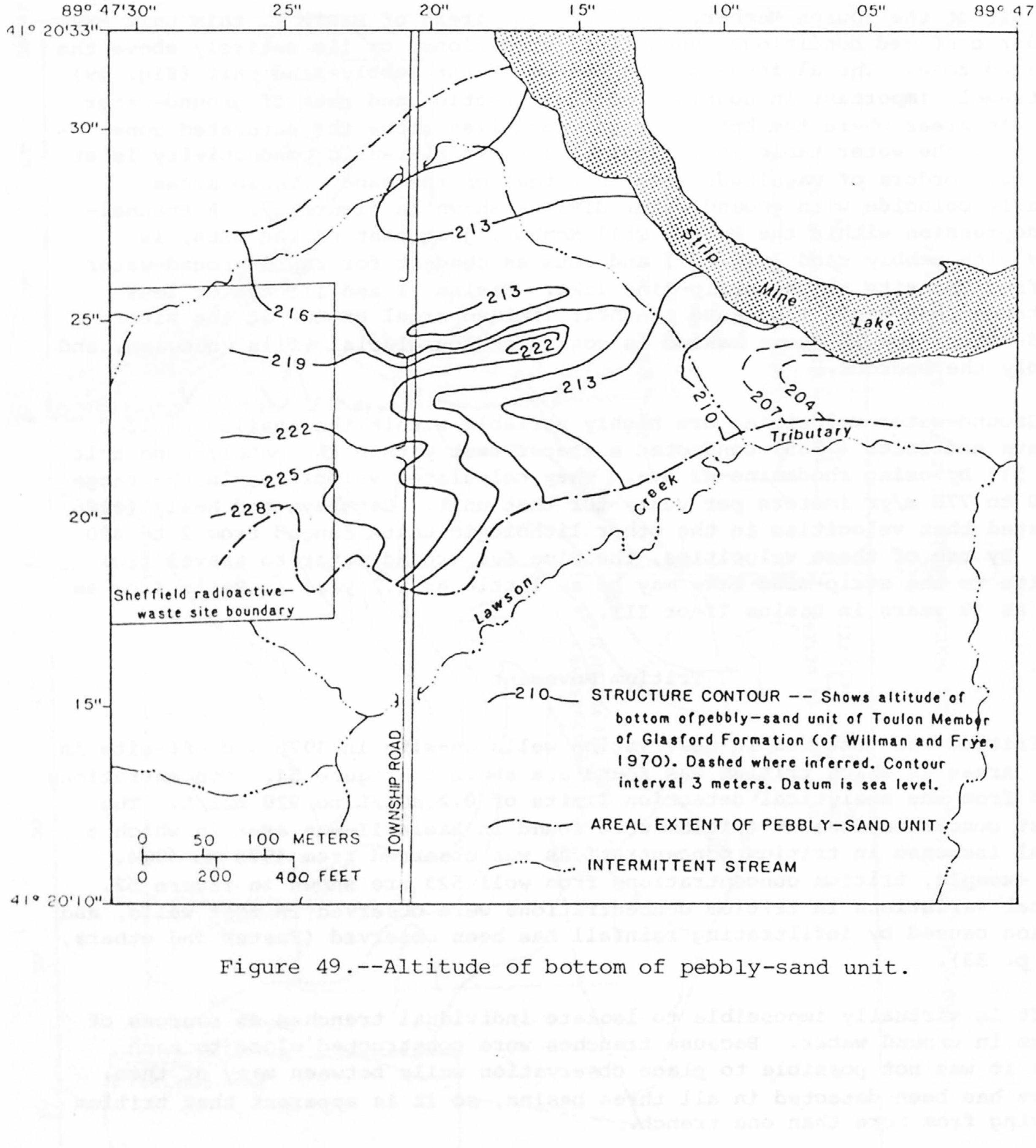


Figure 49.--Altitude of bottom of pebbly-sand unit.

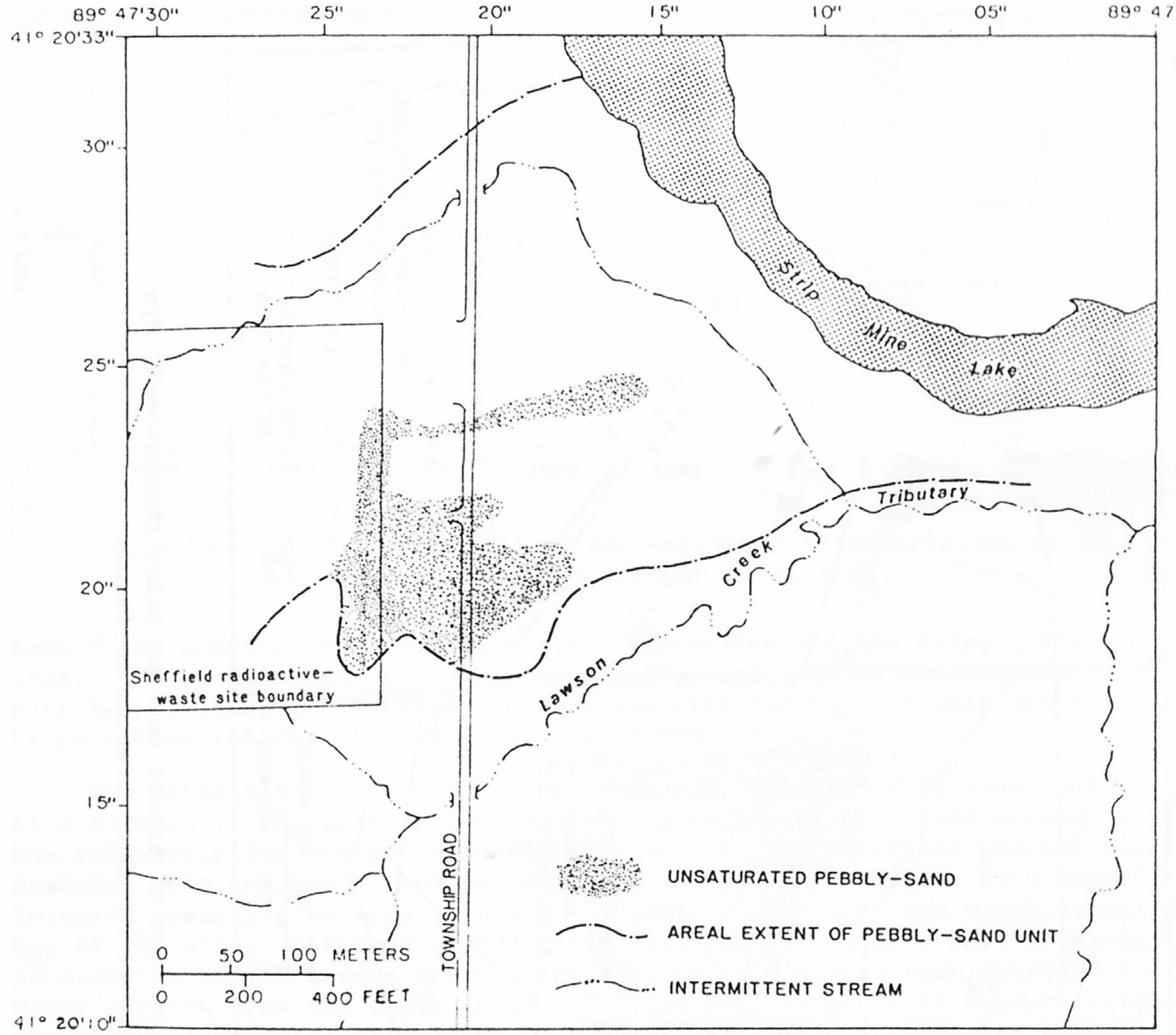


Figure 50.--Areas of unsaturated pebbly sand.

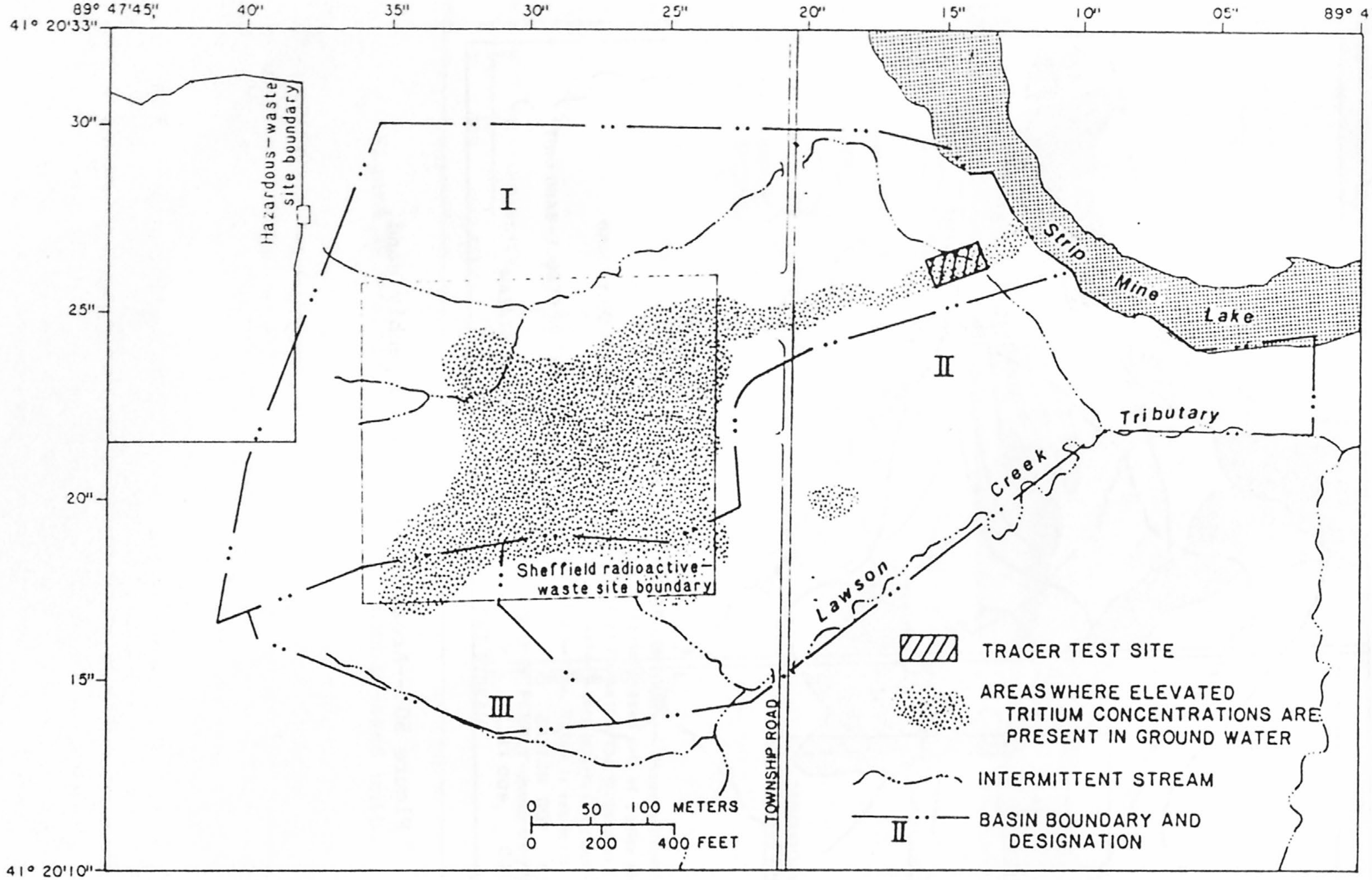


Figure 51.--Location of tracer test by using rhodamine-WT dye and areas where tritium is found.

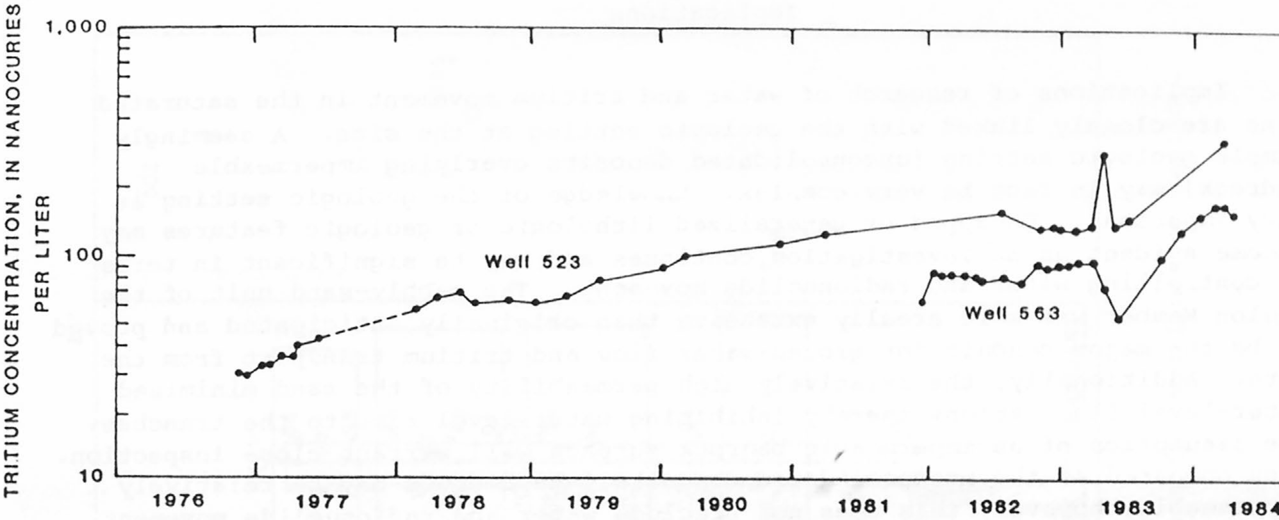


Figure 52.--Variation in tritium concentration in observation wells 523 and 563, October 1976 through April 1984.

beyond the confines of the channel-like depression and the seeps along the lake. The presence of the pebbly sand influences tritium concentrations on-site by providing rapid transport from the site to the east that generally keeps concentrations from increasing with time.

The materials that control ground-water flow in Basin II also control tritium movement. The principal water-bearing units are tills and outwash silts. The relatively low hydraulic conductivities of these materials prevent rapid drainage from the basin. Consequently, tritium concentrations have tended to increase gradually on-site in Basin II, particularly near the southeastern corner of the site. Although ground-water flow in the southern part of Basin II is directed toward Lawson Creek Tributary, no tritium has been detected in water samples from the creek (fig. 51). The higher hydraulic conductivity of the alluvial material is thought to provide sufficient dilution of tritium transport through the Hulick Till Member so as to render it undetectable near the creek.

Detection of off-site migration of tritium in Basin II is restricted to the area near observation well 602. It is hypothesized that ground-water flow and tritium movement may be occurring at the bedrock/till interface. The bottoms of the trenches in the southeastern corner of the site are close to the bedrock surface. Saturation at the bedrock surface would, in the presence of joints, fractures, or coal seams, allow movement of both ground water and tritium off-site.

Tritium migration from Basin III is difficult to define. The pebbly sand, where present, is saturated and is a likely unit for transport of tritium. Tritium has been detected in the pebbly sand in observation well 531. Because the pebbly-sand unit does not extend to the intermittent stream channel, the flow path for tritium from Basin III has not been determined. Flow may occur at the pebbly sand/till interface, or a bedrock/till flow path, similar to that in Basin II, may be present. Tritium has not been detected off-site in Basin III.

Implications

Implications of research of water and tritium movement in the saturated zone are closely linked with the geologic setting at the site. A seemingly simple geologic setting (unconsolidated deposits overlying impermeable bedrock) may in fact be very complex. Knowledge of the geologic setting is very important. Unmapped or generalized lithologic or geologic features may become evident as an investigation continues and may be significant in terms of controlling water and radionuclide movement. The pebbly-sand unit of the Toulon Member was more areally extensive than originally anticipated and proved to be the major conduit for ground-water flow and tritium transport from the site. Additionally, the relatively high permeability of the sand minimized water-level fluctuations thereby inhibiting water-level rise to the trenches. The assumption of an impermeable bedrock surface will warrant close inspection. When compared to the unconsolidated deposits, the bedrock may be relatively impermeable; however, this does not preclude water and radionuclide movement through the bedrock.

Another factor related to the relative permeabilities of the unconsolidated deposits and the bedrock is the issue of scale. Hydraulic properties for areal appraisals may be averaged without causing undue errors in the final prediction of avenues for water and radionuclide movement. Averaging hydraulic properties for smaller areas may, however, result in significant errors in identifying, or possibly the inability to identify, water and radionuclide pathways. The scale of the investigation, and the scale for which predictions will be made, need to be consistent.

Water Chemistry

by Charles A. Peters

Introduction

Waste disposal at the Sheffield site rearranged existing geologic materials and placed chemically reactive substances in the unsaturated zone. The behavior of these substances with both water and the geologic media provided a framework for a field investigation of the chemical and geologic factors that may influence radionuclide mobility at waste-disposal sites.

The objectives of this study were to (1) describe the chemistry of precipitation, geologic materials, and water in the unsaturated and saturated zones; (2) identify techniques useful for obtaining representative samples of water from the unsaturated zone; (3) support, through statistical analysis and geochemical modeling, the identification of naturally occurring geochemical reactions; and (4) investigate the effect of radioactive wastes on water chemistry.

The scope of the work included the collection and analysis of precipitation, geologic materials, and unsaturated- and saturated-zone water, both on-site and off-site, and in all geologic units, during 1978 to 1984. Water-chemistry data-collection sites are shown in figure 53.

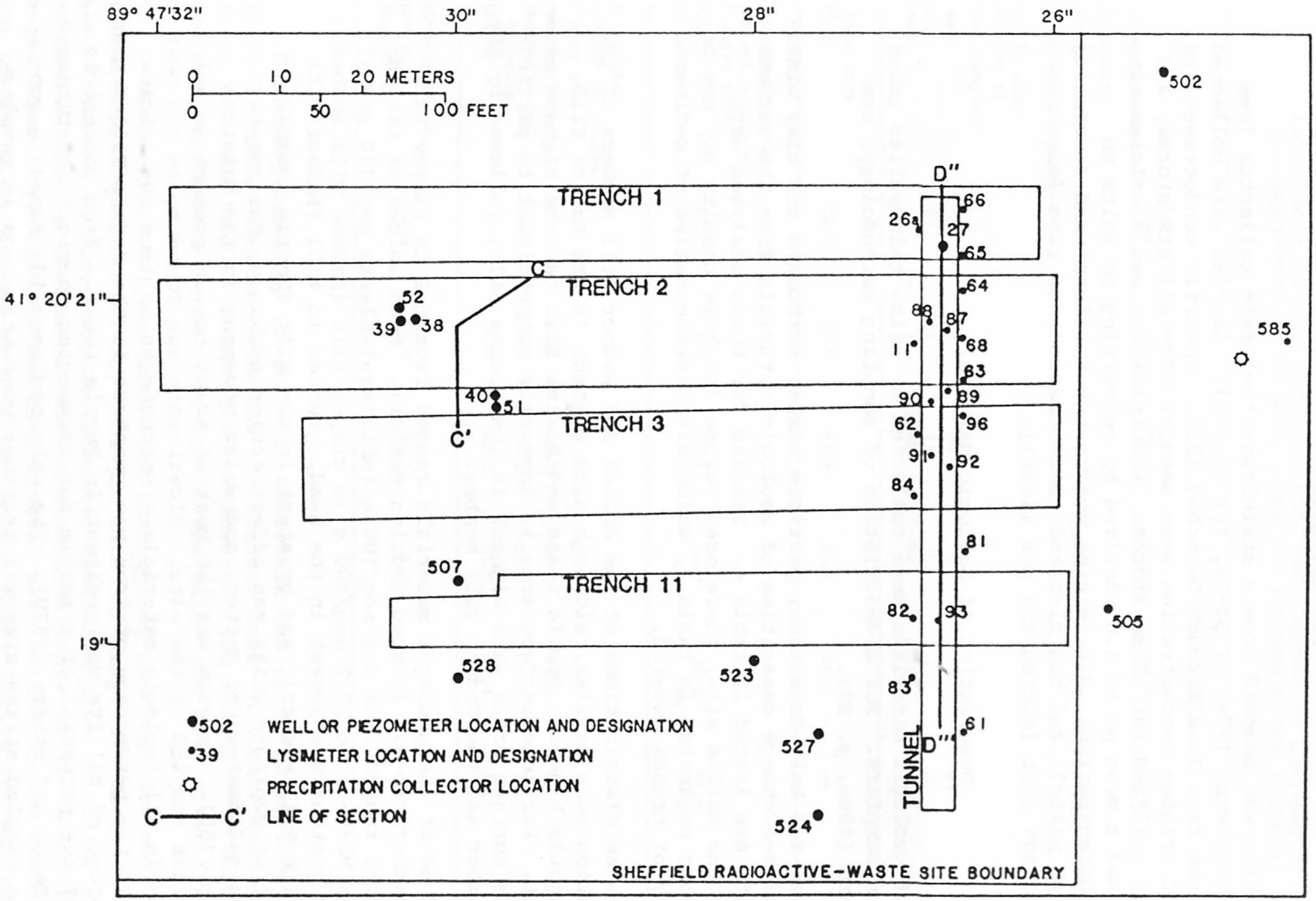


Figure 53.--Location of water chemistry data-collection sites and lines of section.

Precipitation

Precipitation was sampled from a stainless-steel rain collector (see Brackensiek and others, 1979, p. 32-36, for design). Samples were collected during six storms from June through December 1983. Specific conductance, pH, alkalinity, and tritium concentration were measured for all six storms, and major ions were analyzed for three storms. Precipitation was a calcium-zinc-sulfate type, had a mean pH of 4.6 (derived by converting pH units to hydrogen-ion concentrations, determining mean concentrations, and converting means back to pH units), and had elevated concentrations of zinc [mean concentration of 1,300 µg/L (micrograms per liter)].

Description of Geologic Materials

Samples of geologic materials were collected by using thin-walled tubes and split-spoon samplers. For a description of sampling methodology, see Healy and others (1986, p. 29).

Mean values for bulk densities, particle sizes, carbonate and clay mineralogy, and cation-exchange capacities of geologic materials from the various lithologic units are listed in table 4. Samples for these analyses were collected from the entire site; therefore, values for bulk density may not be the same as those presented in table 1, which are representative of sediments in the vicinity of trench cover 2.

Particle-size distributions of the Hulick and Radnor Till Members of the Glasford Formation were similar, although sand content in the Hulick Till Member was slightly higher. Peoria Loess and Roxana Silt had the highest percentage of silt. Particle surface area is inversely proportional to particle size. Particle surface areas were highest in the Roxana Silt, followed by the Hulick Till Member and the Radnor Till Member.

Values of pH of the geologic materials ranged from 6.2 in clayey silt (Hulick Till Member) to 8.4 in sand (Toulon Member). Mean values of cation-exchange capacity ranged from 4.4 meq/100 g (milliequivalents per 100 grams) in sand (Toulon Member) to 20.2 meq/100 g in clayey silt (Radnor Till Member). Organic-matter content was lowest in the sand, greater in till (Radnor Till Member and Hulick Till Member), and greatest in the silt (Peoria Loess). Organic content of geologic units can affect cation exchange, the sorptive capacity of the sediment-water system, and water movement in the material (Brady, 1974, p. 150). Calcium was the most abundant cation present in all geologic materials sampled at the site. Bicarbonate was found to be the most prevalent anion in all geologic materials. Percentages of iron and calcite differed widely; the percentage of iron was greatest in the Radnor Till Member, and the percentage of calcite was greatest in Peoria Loess. Iron content is an indicator of the potential of a medium for scavenging chemical constituents (Jenne, 1977; Means and others, 1978). The only radionuclide found in geologic materials sampled at the site was tritium; concentrations in samples from 21 vacuum-lysimeter locations ranged from 0.2 to 1,230 nCi/L and averaged 43 nCi/L. For the most part, tritium concentrations in all other geologic-material samples were similar; concentrations in four samples from a single location below trench 11 did range from 1,600 to 11,000 nCi/L and averaged 6,000 nCi/L.

Table 4.--Mean values of physical, chemical, and mineralogic properties of geologic materials

[g/cm^3, grams per cubic centimeter; m^2/g, meters squared per gram; meq/100 g, milliequivalents per 100 grams; a dash (--) indicates no data available]

			Glasford Formation					
	Peoria Loess	Roxana Silt	Radnor Till Member	Toulon Member	Hulick Till Member	Trench cover	Clayey silt cap	Trench fill
Bulk density (g/cm^3)	1.45	1.50	1.90	1.60	1.85	1.65	1.77	1.61
Particle size (percent of total sample)								
Clay	15	17	29	6	30	24	--	--
Silt	81	81	53	10	43	68	--	--
Sand	4	2	18	84	27	8	--	--
Surface area (m^2/g)	38.5	53.8	47.8	31.1	50.1	--	--	--
Carbonate minerals (percent by weight of <silt size)								
Total	21.7	4.0	10.6	6.0	16.0	16.0	--	--
Ca/Mg ratio	.14	.11	.12	.13	.26	.01	--	--
Clay minerals (percent by weight of clay size)								
Montomorillonite	57.7	81.8	43.7	16.5	29.8	69.3	--	--
Kaolinite and chlorite	15.0	8.0	14.3	20.6	26.8	13.7	--	--
Illite	27.1	10.3	42.0	61.5	43.4	17.0	--	--
Cation-exchange capacity (meq/100 g)	14.0	17.4	20.2	4.4	16.5	--	--	--

Buffering capacity of geologic materials can be inferred from their carbonate content. Peoria Loess had the highest bulk-carbonate content and the Roxana Silt and Toulon Member had the lowest. The Hulick Till Member had the greatest calcite-to-dolomite ratios in the silt- and clay-sized fractions.

Petrographic analyses indicated that quartz and the clay matrix were the predominant components in all geologic material sampled. Minerals in the clay-sized fraction included montmorillonite, kaolinite plus chlorite, and illite. Montmorillonite, a sodium-containing aluminosilicate of the smectite group, ranged from 17 percent of the clay-mineral part of the Toulon Member to 82 percent of the clay-mineral part of the Roxana Silt; illite ranged from 10 percent in the Roxana Silt to 62 percent in the Toulon Member; and kaolinite plus chlorite ranged from 8 percent in the Roxana Silt to 27 percent in the Hulick Till Member.

Cations and anions that were predominant in the geologic material also were predominant in water from the unsaturated zone. Differences in mineralogy among the various geologic units influenced water chemistry.

Unsaturated Zone

Porous-cup vacuum lysimeters (fig. 54) were used to collect water samples from the unsaturated zone. A hand pump was used to apply a vacuum to the system, and nitrogen gas was used to force samples out of the lysimeters. Nitrogen affects sample chemistry less than air (Claassen, 1982, p. 32). Water samples were filtered as they passed through the porous ceramic cup at the end of a lysimeter and, therefore, only dissolved fractions were measured. Details of construction and installation of vacuum lysimeters are described by Healy and others (1986, p. 28-29). Lysimeters for determining water chemistry in undisturbed sediments were installed in an off-site borehole, 30 m east of trench 2, at five depths and in four lithologic units (fig. 55).

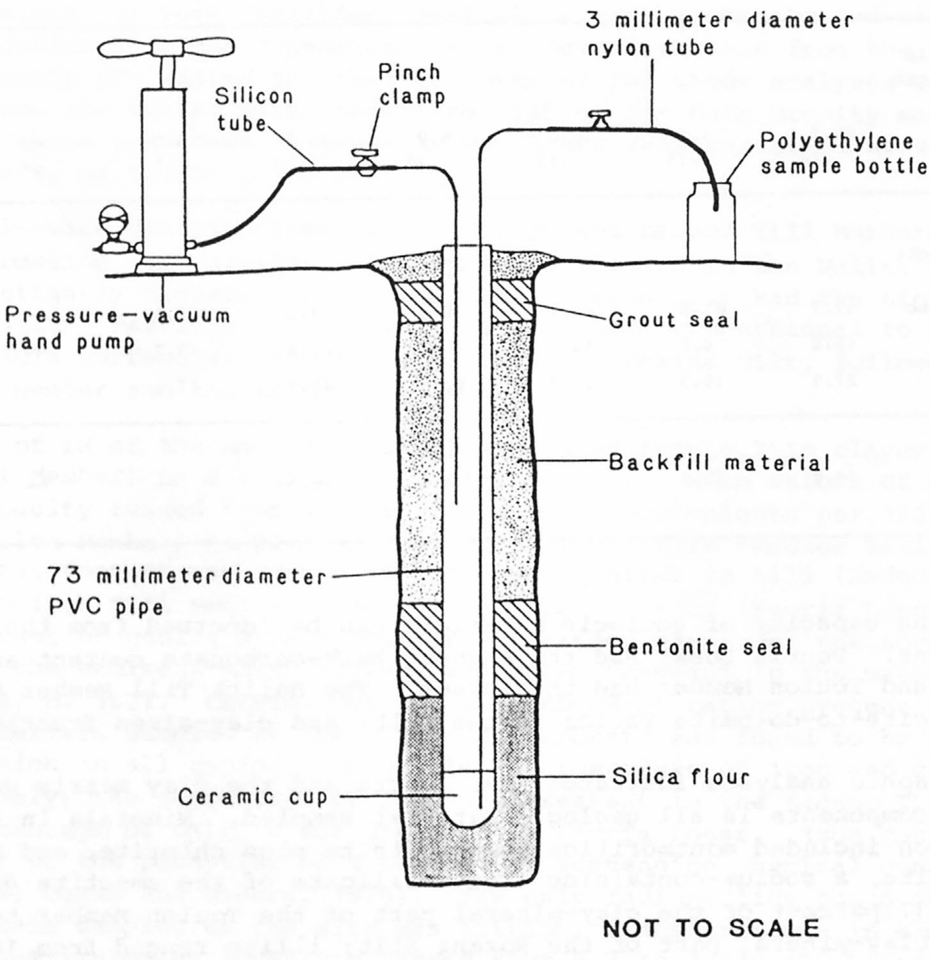


Figure 54.--Typical installation of a vacuum lysimeter.

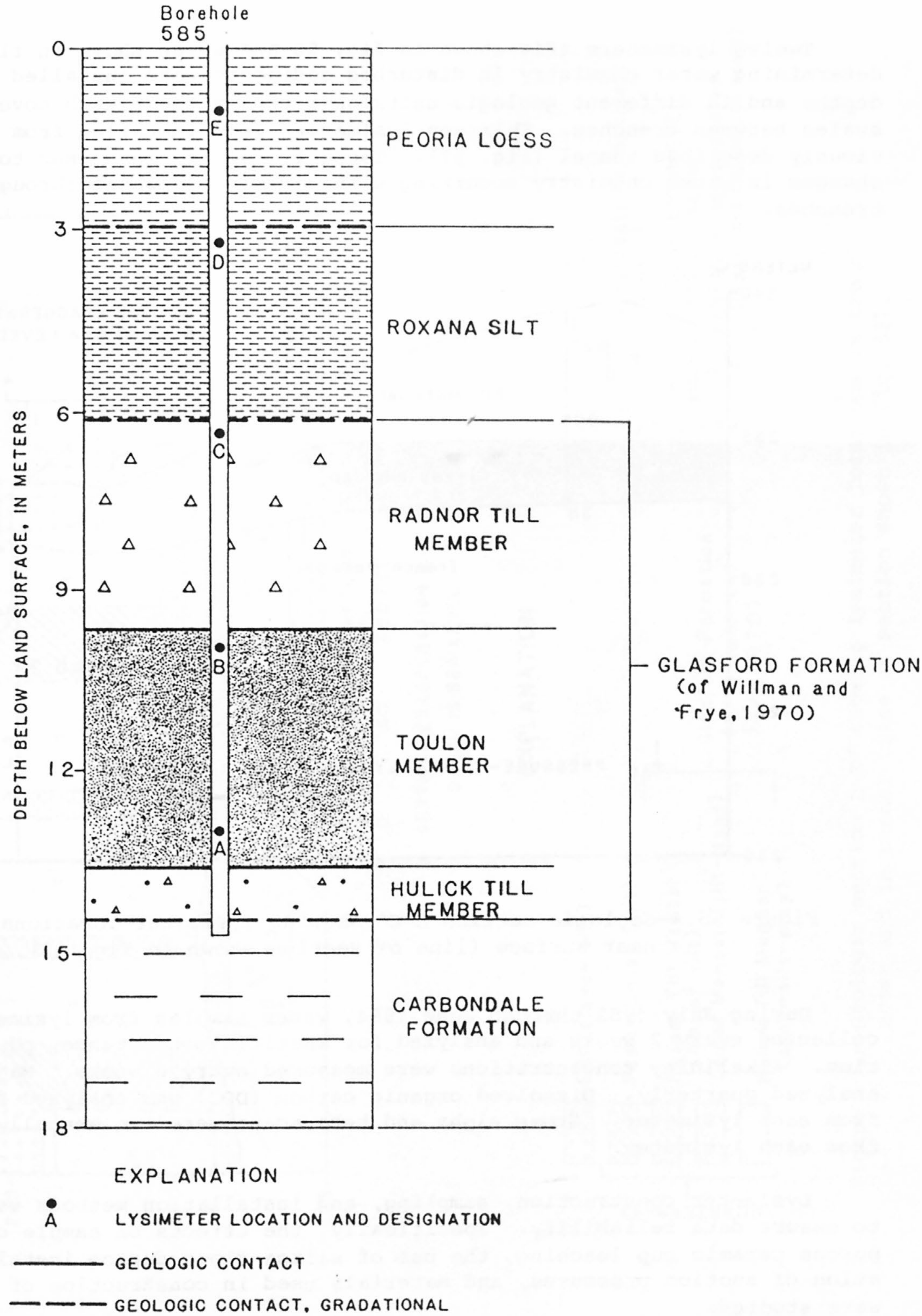


Figure 55.--Geologic section showing lysimeter locations at an off-site borehole.

Twelve lysimeters (fiv shown in fig. 56 and seven shown in fig. 57) for determining water chemistry in disturbed sediments were installed at different depths and in different geologic units on-site, in the trench covers, and in swales between trenches. Thirteen lysimeters were installed from the previously described tunnel (fig. 57). These lysimeters were used to define the changes in water chemistry occurring with movement of water through the waste trenches.

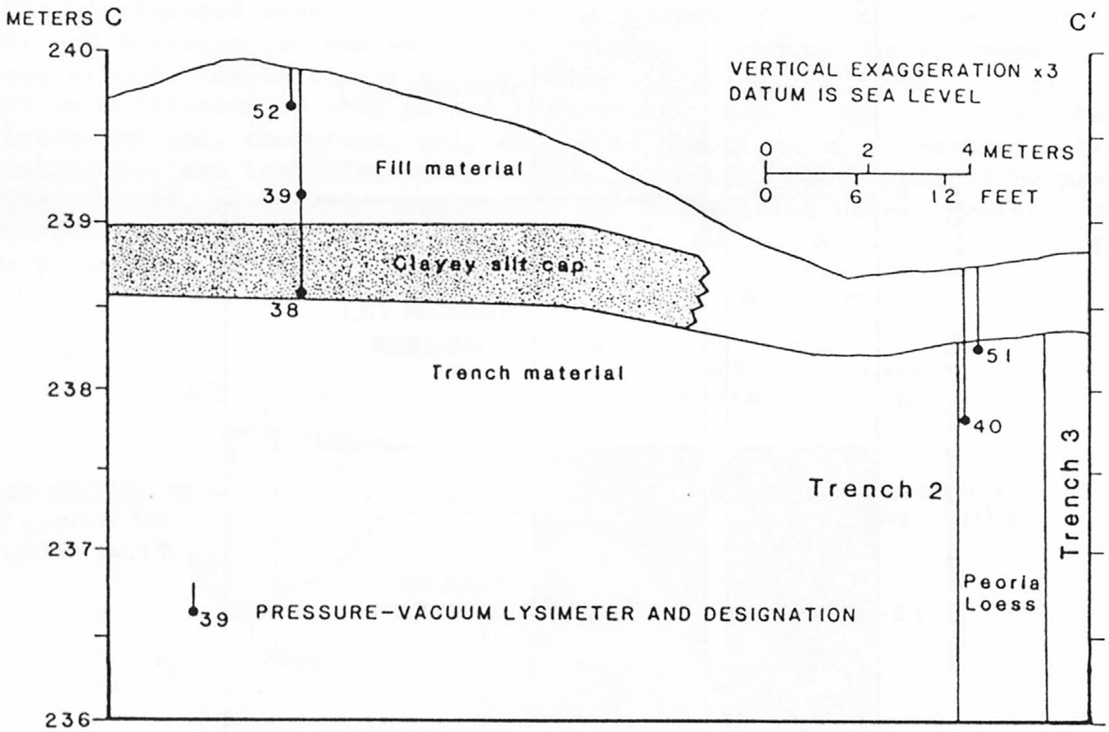


Figure 56.--Geologic section C-C' showing lysimeter locations on-site, near surface (line of section shown in fig. 53).

During July 1982 through June 1984, water samples from lysimeters were collected every 2 weeks and analyzed for specific conductance, pH, and tritium. Alkalinity concentrations were measured every 6 weeks. Major ions were analyzed quarterly. Dissolved organic carbon (DOC) was analyzed for one sample from each lysimeter. Gross alpha and beta scans were run annually on samples from each lysimeter.

Lysimeter construction, sampling, and installation methods were evaluated to ensure data reliability. Specifically, the effects on sample chemistry of porous ceramic cup leaching, the use of silica flour during installation, variation of suction pressures, and materials used in construction of lysimeters were studied.

Vacuum lysimeters were determined to be an adequate means of collecting representative samples from the unsaturated zone. There were several constituents that showed possible effects due to lysimeter use. Increased levels were observed for silica; selected heavy metals showed either elevated levels (zinc

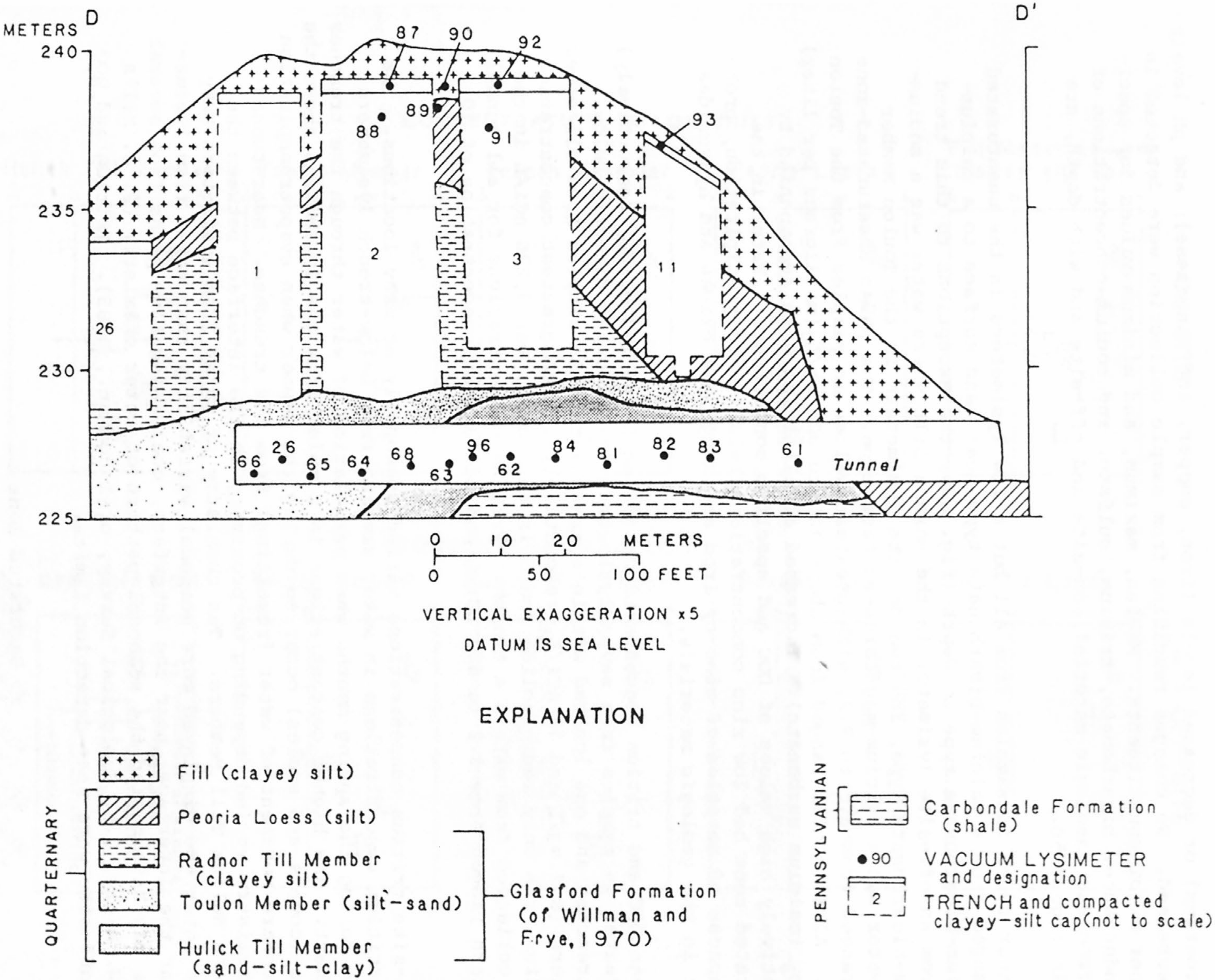


Figure 57.--Geologic section D-D' showing lysimeter locations in trench cover and in tunnel (line of section shown in fig. 53).

and strontium) or decreased levels (iron, copper, and manganese); and pH levels were decreased. No changes resulting from sample collection were detected in the other major constituents. Median, maximum, and minimum values for specific conductance, bicarbonate, tritium, sulfate, and sodium concentrations of water from each geologic material, on-site and off-site and with depth, are shown in figure 58.

Water types in samples from all but a few lysimeters in the unsaturated zone ranged from a calcium-bicarbonate type near land surface to a calcium-magnesium-bicarbonate type at depth (fig. 59); the exceptions to this trend were from an off-site lysimeter in the Roxana Silt where water was a sodium-calcium-bicarbonate type, and two on-site lysimeters in the Toulon Member where water was a calcium-magnesium-sulfate type. The pH in unsaturated-zone water ranged from 6.8 to 9.2, with greatest values in samples from the Toulon Member. Alkalinities ranged from about 100 to 800 mg/L (milligrams per liter) as $CaCO_3$ (calcium carbonate). Increased alkalinities were accompanied by comparatively high values of DOC and specific conductance. Water in the unsaturated zone had low zinc concentrations relative to precipitation, probably because of sorption of zinc by iron and manganese oxides and hydroxides present in the geologic materials.

Mean DOC and tritium concentrations (45 mg/L and 290 nCi/L, respectively) were greater in samples from seven lysimeters (six located directly below waste trenches and one located within a trench) than in samples from all other lysimeters (8.4 mg/L and 17 nCi/L, respectively). The greatest concentration of tritium, the only radionuclide found in the water, was 1,270 nCi/L in the sample collected from within a trench. Tritium concentrations for all tunnel lysimeters ranged from 0.2 to 450 nCi/L and had a mean concentration of 70 nCi/L.

On-site tritium concentrations varied seasonally at many locations. The higher tritium concentrations in water samples from below-trench lysimeters occurred during the spring months when percolation of water through the trenches was highest. The higher concentrations in samples from the lysimeters above the trenches (covers and swales) occurred during the summer when evapotranspiration caused upward movement of water (rewetting) from the trenches. Near-tunnel water chemistry varied depending on proximity to the interface between the Toulon and Hulick Till Members. The chemistry of water from lysimeters away from the interface displayed more seasonal variability than water from lysimeters near the interface; near the interface, coalescing flow paths from several trenches may have masked the seasonal pattern of water chemistry (P. C. Mills and R. W. Healy, U.S. Geological Survey, oral commun., 1985). Tritium and DOC values off-site were near detection limits.

Saturated Zone

Sixty-four wells at the site were sampled for water chemistry (fig. 60) (Foster and Erickson, 1980; Foster and others, 1984 and 1984b), and these data were used to define the chemistry of water in the saturated zone. Water samples were collected once or twice annually from 1978 through 1982 and were analyzed for major ions. Tritium concentrations were analyzed quarterly in 1982, 1983, and 1984.

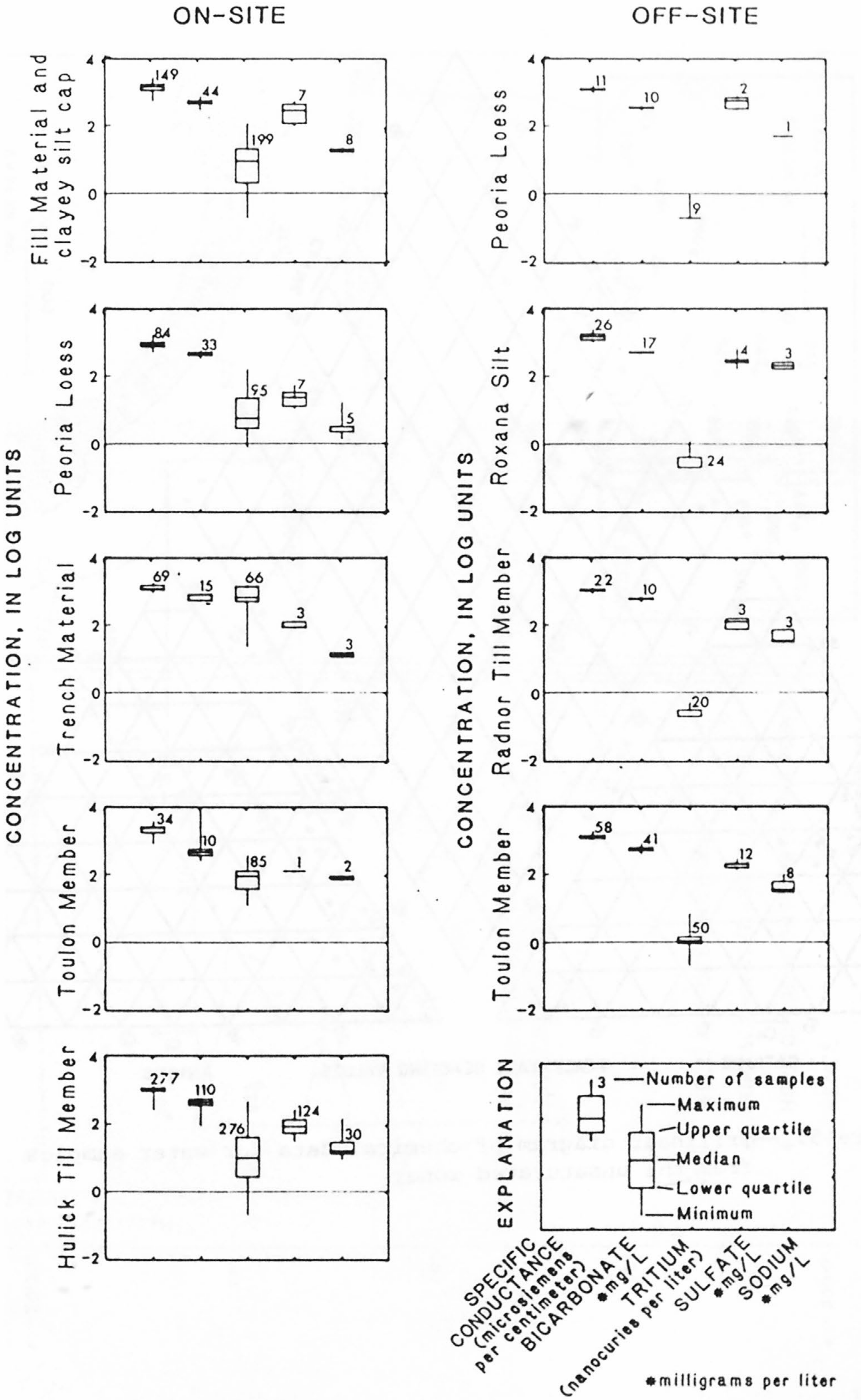


Figure 58.--Box and whisker plots for several constituents at each lithologic unit on-site and off-site.

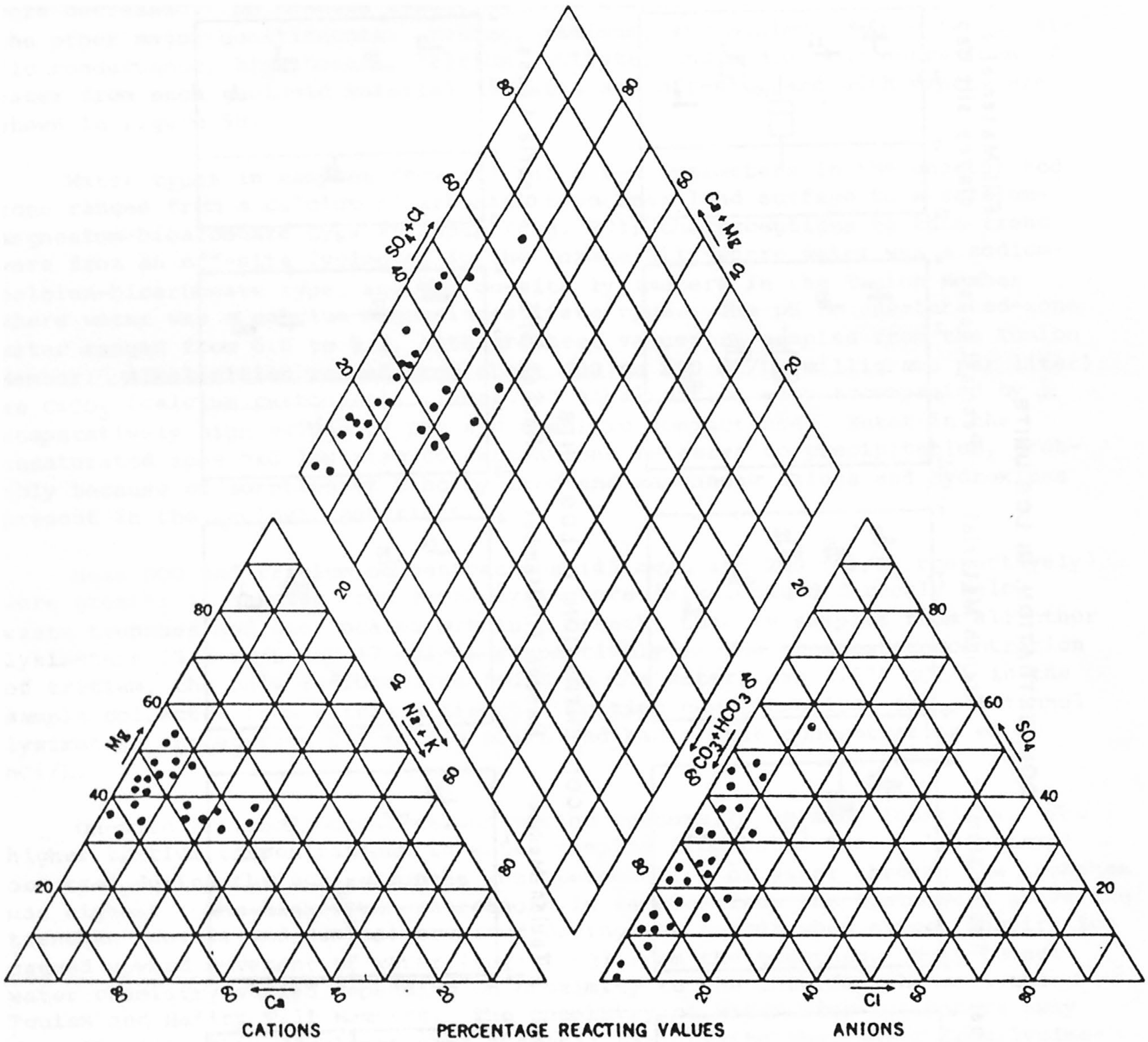


Figure 59.--Trilinear diagram of chemical data for water samples from the unsaturated zone.

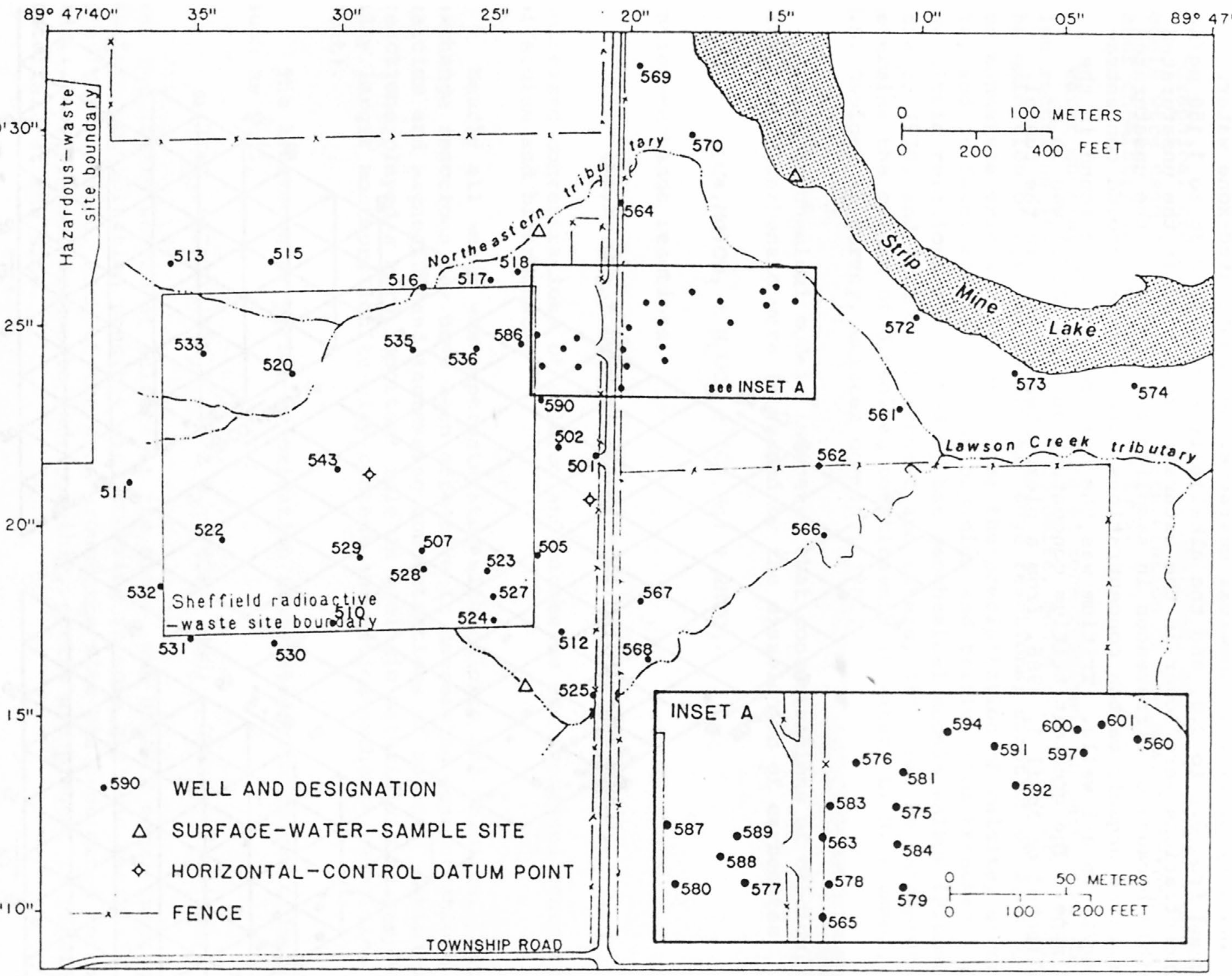


Figure 60.--Location of U.S. Geological Survey observation wells sampled for water chemistry.

Water in the saturated zone generally was a magnesium-bicarbonate type (fig. 61) and very similar in chemical character to unsaturated-zone water. The pH ranged from 6.2 to 9.0, and the alkalinity ranged from 36 to 1,150 mg/L. Silica concentrations were lower in the saturated zone than in the unsaturated zone possibly because of differences in sampling techniques in the unsaturated zone. Dissolved organic carbon concentrations were near background concentrations (3 mg/L) in all wells. Tritium was the only radionuclide found in the saturated zone. The greatest tritium concentration (920 nCi/L) was in a sample collected on April 1, 1986, from a piezometer located in the tunnel.

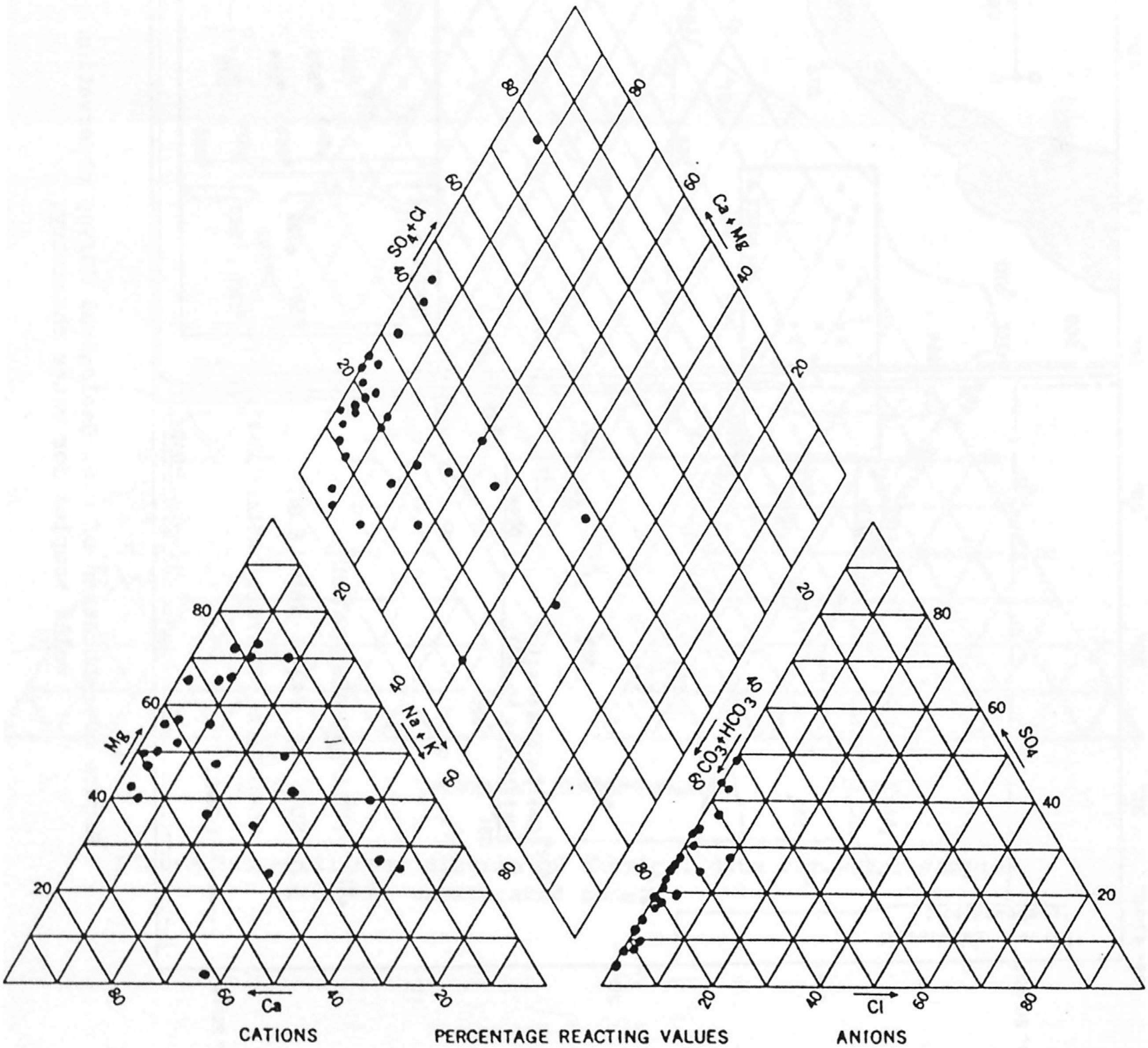


Figure 61.--Trilinear diagram of chemical data for water samples from the saturated zone.

Graphical techniques, statistical analyses, and geochemical equilibrium models were used to supplement interpretation of the spatial heterogeneity of water chemistry in the unsaturated zone.

Water chemistry in the unsaturated zone resulted, in part, from dissolution reactions involving calcite, dolomite, montmorillonite, and strontianite; the oxidation of pyrite; cation-exchange reactions; sorption of zinc by iron and manganese oxides and hydroxides; the precipitation of calcite, strontianite, and sulfate; and leaching of organics and tritium from trenches. Chemical equilibria relations calculated by the geochemical models WATEQF (Plummer and others, 1978) and BALANCE (Parkhurst and others, 1982) may be interpreted to determine the origin of dissolved constituents in water (L. N. Plummer, U.S. Geological Survey, written commun., 1982).

These geochemical models indicated that concentrations of calcium, magnesium, and bicarbonate were increased by the dissolution of carbonates

$$(Ca,Mg)CO_3 + H_2CO_3 = (Ca,Mg) + 2HCO_3. \qquad (3)$$

Cation-exchange reactions,

$$(Ca,Mg)CO_3 + H_2CO_3 + 2Naex. = (Ca,Mg)ex. + 2Na + 2HCO_3, \qquad (4)$$

decreased concentrations of calcium and magnesium and increased concentrations of sodium and bicarbonate.

Nearly all water was supersaturated with calcite and dolomite. Cation-exchange reactions may have been effective in decreasing concentrations of calcium and magnesium and increasing concentrations of sodium. Cation-exchange reactions played a more important role in geologic materials with proportionally larger montmorillonite-clay content and cation-exchange capacities (Roxana Silt).

The breakdown of pyrite by oxidation associated with biogenic deposits such as coal,

$$2FeS_2 + 8CaCO_3 + 5H_2O + 15/2\ O_2 = 8Ca + 4SO_4 + 8HCO_3 + 2FeO(OH), \qquad (5)$$

was the likely source of sulfate at the site. The BALANCE model indicated sulfate precipitation possibly was occurring in some geologic materials. As previously stated, much of the area around the site has been mined for coal. Additionally, coal fragments and, possibly, pyrite are present in glacial materials at the site.

Sodium and silica concentrations most likely were increased by the dissolution of aluminosilicate clays. Calculations with BALANCE indicate that dissolution reactions involving aluminosilicate (clay) minerals could cause increases in sodium and silica concentrations.

Effect of Waste Burial

The major difference between on-site and off-site inorganic water chemistry resulted from the removal of much of the Roxana Silt and Radnor Till Member units from on-site. Off-site, the Roxana Silt contributed significant quantities of sodium to solution from montmorillonite dissolution and associated cation-exchange reactions. The Radnor Till Member provided exchange surfaces for magnesium.

Analysis of variance indicated that sulfate concentrations on-site were associated with the amount of clayey materials present. The major differences in organic and radionuclide water chemistry were related to the proximity of lysimeters to sources of DOC and tritium available in the trenches. Water chemistry was more variable near major unsaturated-zone flow paths (fig. 35), most likely due to variable residence times. Tritium and DOC concentrations were higher beneath or within waste trenches than at other locations. The major effect of the trenches was to contribute tritium and DOC to the water.

Implications

Although difficult to obtain, because soil tensions inhibit the extraction of water, water-quality data from the unsaturated zone can provide an earlier detection of the release of contaminants from waste trenches than water-quality data from the saturated zone. Constituents released from the disposal trenches may not be limited to radionuclides. Inorganic and organic constituents mobilized from wastes in trenches were detected at the site. The apparent absence of radionuclides other than tritium, in both the unsaturated and saturated zones, may suggest that the clayey soils present at the site inhibit the migration of other radionuclides. Also, accurate records of the chemical and radionuclide contents of disposal trenches would indicate the presence of other radionuclides and constituents that might be expected to migrate from the trenches.

CONCLUSIONS

Implications of the hydrologic research conducted over the course of a decade at the Sheffield low-level radioactive-waste disposal site have been presented in discussions of each of the hydrologic research topics reported here. Implications of individual studies and those that can be made after consideration of results of all the studies are presented here according to their potential effect on the selection, characterization, design, operation, and decommissioning of future low-level radioactive-waste disposal sites.

Selection and Characterization

- A seemingly simple geologic setting can, in fact, be very complex. Unmapped or generalized lithologic features may become evident as construction or subsequent investigations continue. Lithologic features can be quite significant in terms of water and radionuclide movement both in the unsaturated and saturated zones.

- Hydraulic properties of a single geologic unit are easier to characterize than those of several geologic units. For example, layered, unsaturated deposits, with contrasting permeabilities, may retard vertical water movement but enhance lateral water movement, increasing the difficulty of predicting recharge rates and radionuclide transport.

- The assumption of an impermeable bedrock warrants close inspection during selection of future low-level, radioactive-waste disposal sites. When compared to overlying unconsolidated deposits bedrock may be relatively impermeable; however, this does not preclude water and radionuclide movement through the bedrock.

- Scale becomes a significant factor in predicting pathways for radionuclide transport. For an areal appraisal, hydraulic properties can be averaged without causing undue errors in the predictions. For a detailed site investigation, however, such averaging can mask actual pathways and create substantial errors in transport predictions. The scale for which predictions will be made needs to be similar to the scale of investigation.

- At the site, a pebbly-sand channel serves as a drain for ground-water flow and allows a slow but continuous release of relatively low tritium concentrations to a nearby strip-mine lake (the discharge area for shallow ground water). It is essential that long-term effects of a slow but continuous release of radionuclides to ground water be compared to rapid, but periodic, releases of radionuclides to ground water.

Design

- Documentation of trench-construction, waste-emplacement, and backfilling techniques should improve the accuracy of predicting potential pathways of water and radionuclide movement.

- A compacted layer in the trench cover reduces the flow of water into the trench. At Sheffield, a single-composition geologic material has been used. The flow retardation observed in the unsaturated-zone investigation at Sheffield, however, supports the use of alternating layers of materials with contrasting permeabilities for a trench cover.

- Trench-cover thickness is an important element in cap design. The compacted layer in the trench covers at Sheffield was closer to land surface at the edges of the trenches than in the middle. Intrusion by roots into the compacted layer along the trench edges increased the permeability of the compacted layer, allowing more water to enter the trenches along the edges than in the center of the trench.

- Constructing trench walls above land surface can lead to increased collapses of the walls and covers.

- o Although not done at Sheffield, the lining of trench floors with coarse-grained material overlain by fine-grained material would retard infiltration through the trench floor. Flow to the coarse-grained material could be diverted to a drain underlying a low area in the fine-grained material.

- o The use of culverts and geotechnical fabrics to control surface drainage can reduce soil erosion and infiltration of precipitation.

- o A vegetative cover reduces soil erosion, recharge to the saturated zone, and potential off-site migration of radionuclides. Interruption of the natural growth of vegetation that leads to deep rooting would minimize transpirative releases of radionuclides. Additionally, plant-root invasion of trench covers increases the permeability of the covers, allowing for increased infiltration of water. Freeze-thaw cycles, alternating periods of wetting and drying, and burrowing animals similarly affect trench covers.

- o Monitoring instrumentation needs to be incorporated into site design. Although more difficult to monitor because soil tensions inhibit the extraction of water, monitoring devices installed in the unsaturated zone beneath and adjacent to trenches can provide for the early detection of contaminants released from the trenches. When designing monitoring networks to assess site performance, a multidisciplinary approach is needed. Radionuclide transport at Sheffield occurred through water in the unsaturated and saturated zones, soil gases, and plants.

- o Monitoring devices installed in the unsaturated zone need to be designed to detect lateral as well as vertical flow paths above, adjacent to, and below the trenches. Sloping interfaces between deposits of contrasting permeabilities downgradient from trenches would be a likely place for instrument installation. It is important to recognize that radionuclides can migrate upward, downward, and laterally through the unsaturated zone before being released to the atmosphere or ground-water system.

- o Small-diameter monitoring instruments in the unsaturated zone may be ineffective in detecting individual flow paths in sand bodies; large-diameter gravity lysimeters that are sensitive to hydraulic conditions over larger areas may be more effective.

Operation

- o Accurate records that describe trench construction, dimensions, and contents are essential for evaluating disposal methodologies, determining potential contaminants, and monitoring water and radionuclide movement from the trenches.

- o Use of improved waste-burial procedures, including nonrandom burial and the use of stable waste containers and backfill material, can improve site performance. Random burial, unstable waste containers, and the absence of backfill material lead to differential compaction and settling, which results in surface collapse features near the trenches. Collapse features not only create preferential pathways for water movement but may expose wastes.

- o Early implementation of continuous, long-term monitoring is required to evaluate site performance. Effect of precipitation on the hydrologic regime at the site changes over time. Trench-cover collapse rates, erosion rates, and trench-cover effectiveness also can change, as can other natural or artificial events that change or affect the hydrologic regime.

- o It is desirable that water-quality-sampling schedules be tailored to predicted temporal trends of water movement in order to maximize the data-collection effort and minimize unnecessary sampling.

- o It would be desirable to include in the water-quality and soil-gas screening process other constituents besides radionuclides. Other inorganic and organic contaminants released from the waste can be as hazardous as the radioactive contaminants.

- o Measurements of microclimatic parameters will help determine the water balance for a disposal site.

Decommissioning

- o Long-term maintenance is required to preserve site integrity. Although erosion from the site may be controlled, locations of surface collapses are unpredictable and uncontrollable. Collapse features need to be filled to prevent preferrential pathways or induced infiltration of water. Trench-cover degradation caused by freezing and thawing, wetting and drying, and biointrusion are a significant, continuing concern.

- o A vegetative cover increases evapotranspiration and reduces soil erosion. However, interruption of the natural vegetative succession leading to the establishment of deeply rooted plants is necessary to maximize trench-cover effectiveness.

- o Precipitation that does not leave the site as runoff will result in greater infiltration to the site cover. In the growing season, added soil moisture from precipitation will evaporate or be transpired. In the dormant season, precipitation that infiltrates generally will recharge the aquifer.

SUMMARY

Shallow burial has been the predominant means of disposing of low-level radioactive wastes in the United States. As a result of the Low-Level Radioactive Waste Policy Act (Act) (Public Law 96-573--December 22, 1980) and the Low-Level Radioactive Waste Policy Amendments Act of 1985 (Public Law 99-240--January 15, 1986), each State is responsible for the disposal of wastes generated within its borders. To comply with the Act, many States are in the process of selecting new sites for the disposal of low-level radioactive wastes.

The report presents results and implications of approximately 10 years of hydrologic research conducted by the U.S. Geological Survey at a commercial low-level radioactive-waste disposal site near Sheffield, Illinois. Research at the site has included studies of microclimate, evapotranspiration, and tritium release by plants; runoff and land modification; water movement through a trench cover; water and tritium movement in the unsaturated zone; gases in the unsaturated zone; water and tritium movement in the saturated zone; and water chemistry. The order in which the research is discussed encourages a process-oriented view that approximates the manner in which water moves through the hydrologic cycle. The results and implications of this research, along with research conducted at other low-level radioactive-waste disposal sites, will be used to optimize the selection, characterization, design, operation, and eventual decommissioning of new disposal sites.

The Sheffield low-level radioactive-waste disposal site is located on about 8 ha of rolling terrain in Bureau County, Illinois. The area is sparsely populated with 17 residences within a 3-km radius of the site. Sheffield, the closest town, is located approximately 5 km northeast of the site and has a population of approximately 1,000. Climate at the site is continental. Annual precipitation at three NOAA weather stations within a 31-km radius of the site averaged 890 mm. The mean annual temperature is 10.3 °C.

Geology at the site consists of Cambrian sandstone; Ordovician and Silurian limestones and dolomites; and Pennsylvanian shale, mudstone, siltstone, and coal overlain by unconsolidated Quaternary deposits that range from 3 to 27 m thick. The Quaternary deposits, predominantly Pleistocene glacial sediments, are spatially, stratigraphically, and lithologically complex.

In August 1967, burial of low-level radioactive wastes began at the site and continued until April 1978. Wastes were buried in 21 trenches that were constructed in the unconsolidated glacial materials. Trench dimensions ranged from 11 to 180 m long, 2.4 to 21 m wide, and 2.4 to about 7.9 m deep. Trenches generally were constructed at or below the natural grade of the land surface. Some trenches were covered with a compacted layer of clayey silt from nearby surface deposits; all trenches were capped by a mound of clayey silt and silt. Swales separate adjacent trench covers.

It is estimated that about 90,500 m^3 of waste were buried at the site. A variety of containers was used and arrangement of containers in the trenches ranged from orderly placement to random disposal. The interiors of the trenches contain numerous voids that result from the use of a large variety of waste containers and burial arrangements, incomplete backfilling, and collapse of waste containers. Site-management practices consist of routine maintenance (periodic visual inspections and mowing vegetation) and remedial measures, such as filling collapse holes, rills, and gullies, planting grasses, and laying geotechnical fabric.

A study of the microclimate and evapotranspiration of vegetated trench covers was conducted from July 1982 through June 1984. Continuous measurements of precipitation, incoming and reflected solar radiation, incoming and emitted longwave radiation, horizontal windspeed and direction, wet- and dry-bulb air temperature, barometric pressure, soil-heat fluxes, and soil temperature were made. Soil-moisture content was measured about biweekly.

Evapotranspiration rates were estimated by using three techniques--energy budget, aerodynamic profile, and water budget. Monthly totals from each method were variable; however, annual estimates of evapotranspiration were similar (648 mm for the energy-budget method; 630 mm for the aerodynamic-profile method; and 693 mm for the water-budget method). Actual evapotranspiration averaged 75 percent of potential evapotranspiration.

Tritium release by plants was studied by using 125 vegetation samples collected during the summers of 1982 through 1986. Leaf water was extracted from the plant by using a freeze-drying process for determining tritium concentration. Concentrations differed significantly among some locations and plant types. Alfalfa had the highest concentrations, followed by brome grass, and then red clover; tritium concentration is most likely a function of root depth. Alfalfa displayed the greatest areal variation in concentration; this may be related to areal variations in trench cover thickness (thin covers allow longer root systems to contact buried wastes), variable activity of wastes, and(or) the differential degradation of waste containers.

Runoff and sediment transport were measured in four basins--three comprising almost two-thirds of the 8.1-ha site and one comprising a 1.4-ha undisturbed area--from July 1982 through December 1985. Runoff and sediment transport from four small plots that average 10.6 m^2 in area also were measured; two of the plots were located on trench covers and the other two occupied parts of the undisturbed basin. Volumes and equivalent weights of collapses were estimated from records of site surficial conditions from October 1978 through December 1985. Collapse and erosion comprise the bulk of landform modification presently affecting the site.

The ratio of runoff to precipitation averaged 0.09 and 0.25 during the growing season (May through October) and dormant season (November through April), respectively. Runoff increased in direct relation to degree of land modification; lowest mean runoff yields (1.2 percent of precipitation) were measured at the undisturbed area, and highest mean runoff yields (26 percent of precipitation) were measured at the site basin consisting wholly of trench and intertrench areas. Sediment yield on-site averaged 3.4 Mg/ha annually. This corresponds to about 0.25 mm of gross erosion from the 8.1-ha site per year. Most sediment transported from the site emanated from bare areas, rills, and gullies.

A total of 315 collapse cavities, corresponding to a cumulative volume of about 500 m^3, were documented on-site from October 1978 through December 1985. Although few cavities had depths or widths that exceeded 3 m, one was estimated to have a depth of 6 m, and two were estimated to have widths of 5.5 m. Sixty-two percent of the collapses occurred in swales between trenches or near trench boundaries; the remainder occurred in earth-material covers over trench interiors. Most collapses were recorded following periods of rainfall or snowmelt when soil moisture was near maximum.

Water movement within a selected trench cover was studied from July 1982 through June 1984. Pressure-head and moisture-content data were collected to construct moisture-retention curves needed to calculate the flux of water through the trench cover.

The amount of water stored within the trench cover varied in a seasonal manner, responding to precipitation and evapotranspiration. Moisture contents were greatest in late March or early April at the beginning of the growing season. Moisture contents decreased steadily from late spring through the summer as mean evapotranspiration continued to exceed mean precipitation. The minimum moisture content was in late August or early September after which precipitation exceeded evapotranspiration. Moisture contents then increased gradually from midfall through winter. Average daily pressure head in the unsaturated zone displays a trend similar to that of soil saturation. The range in variation of pressure head generally decreases with increasing depth.

Amount of seepage to the trench was estimated by using four different methods: the Darcy method, the zero-flux phase method, the surface-based water-budget method, and the ground-water-based water-budget method. Estimates from each method differed significantly, which illustrates the inherent difficulty in determining seepage to the trenches.

Investigation of water and tritium movement in the unsaturated zone at the site began in 1981 and is ongoing (1987). A 120-m-long by 2-m-diameter horizontal tunnel provided access to the variably saturated deposits below the trenches. Soil-moisture tensiometers, gravity lysimeters, and piezometers were used to monitor water movement.

Water movement varied considerably from year to year and season to season. However, at no time was there a measurable response to individual rainstorms. In the years when water movement was detected (1982-85), wetting of the sub-trench deposits began in late winter to early spring and saturation was at a maximum from late spring to midsummer. Drying of the subtrench deposits followed and continued to the beginning of the subsequent wetting phase. Spatial variability of water movement below the trenches was influenced by the stratigraphic relation and hydraulic conductivity of the geologic units. Vertical flow was inhibited at interfaces between units of contrasting hydraulic conductivities. Flow was diverted laterally when downward percolating water reached less permeable deposits. Data also indicate that water movement through the sand of the Pleistocene Toulon Member of the Glasford Formation occurs along very localized partially saturated to saturated flow paths.

Tritium concentrations in the subtrench sediments differed spatially, reflecting the heterogeneity of wastes in the overlying trenches and local hydrogeologic conditions. Tritium concentrations at all lysimeter locations increased with time; however, the increases usually were of small magnitude. Tritium concentrations increased abruptly, from five to nine times previous concentrations, at only 3 of 14 locations. Although not directly attributable, these large increases in tritium concentration coincided with heavy summer rains and the development of several near-tunnel collapses in trench covers.

Gases in the unsaturated zone at the site were collected from a soil-gas piezometer network at about 70-day intervals during 1984-86. Sources for the gases include biological decomposition of wastes, chemical dissolution, volatilization of organic wastes, and radioactive decay. Gases were analyzed for relative proportions of nitrogen, oxygen plus argon, carbon dioxide, methane, ethane, propane, butane, tritiated water vapor, ^{14}carbon dioxide, and ^{222}radon. Relative proportions were converted to partial pressures based on a mean atmospheric pressure of 98.6 kPa.

From the gas analyses, methane and ^{14}carbon dioxide were identified as originating at the waste and having mean partial pressures that generally decreased with horizontal distance from a trench and with vertical distance to land surface. Partial-pressure gradients for other radioactive gases that previously had been found to occur in the sand below a trench were not found in the gas-sampling network. It is likely that definable gradients for these gases occur much nearer to the waste source.

Ground-water flow has been studied at the site since 1976. Ground water is found in unconsolidated deposits and bedrock at the site; however, the unconsolidated or shallow aquifer is separated from the bedrock or deep aquifers by about 140 m of Pennsylvanian shale, mudstone, siltstone, and coal. Ground-water flow in the shallow aquifer is a complex phenomenon because of the spatial, stratigraphic, and lithologic complexity of the unconsolidated deposits. The free-water surface intersects nine different lithologic units. Ground-water flow generally is from west to east in three ground-water basins that have been defined in the shallow aquifer. Depth to the water table ranges from 1.5 m in the valleys to 14 m at topographic highs. Water-table altitudes generally are highest during spring months. With the possible exception of one trench, the water table remains below the trench bottoms. Ground-water velocities are highly variable within the shallow aquifer. A tracer test conducted in the pebbly-sand unit resulted in velocities ranging from 640 to 770 m/yr. Velocities in other lithologic units ranged from 2 to 490 m/yr.

Tritium was detected in observation wells on-site in 1976 and off-site in 1982. Concentrations ranged from the analytical detection limit of 0.2 nCi/L to 920 nCi/L. Seasonal variations in tritium concentrations were observed in most wells, and dilution caused by infiltrating rainfall was observed. Tritium was detected in all three basins, so it is apparent that tritium is moving from more than one trench.

Water-chemistry research included the collection and analysis of precipitation, geologic materials, and unsaturated- and saturated-zone water, both on-site and off-site, and in all geologic units, during 1978 to 1984.

Precipitation was a calcium-sulfate type, had a mean pH of 4.6, and had high (mean was 1,300 µg/L) concentrations of zinc. Values of pH of the geologic materials ranged from 6.2 in clayey silt (Hulick Till Member) to 8.4 in sand (Toulon Member). Mean cation-exchange capacities varied from 4.4 meq/100 g in sand to 20.2 meq/100 g in clayey silt. Organic matter content was lowest in the sand, greater in till, and greatest in the silt. Calcium was the most abundant cation present in all geologic materials sampled at the site. Bicarbonate was the most prevalent anion in all geologic materials.

Water types in samples from all but a few lysimeters in the unsaturated zone ranged from a calcium bicarbonate type near the land surface to a magnesium calcium bicarbonate type at depth. Alkalinities ranged from about 100 to 800 mg/L as $CaCO_3$. Mean DOC and tritium concentrations (45 mg/L and 290 nCi/L, respectively) were greater in samples from six lysimeters located directly below waste trenches and one located within a trench than in all other lysimeter locations. The greatest concentration of tritium, the only radionuclide found in the water, was 1,270 nCi/L.

Water in the saturated zone generally was a magnesium bicarbonate type and was very similar in chemical character to unsaturated-zone water. The pH ranged between 6.2 and 9.0; alkalinities ranged from 170 to 1,150 mg/L as $CaCO_3$. Dissolved organic-carbon concentrations were near background concentrations (3 mg/L) in all wells. Tritium was the only radionuclide found in the saturated zone.

Implications of the hydrologic research conducted at the site relate to specific investigations and also to overlapping research topics. Although some of the implications appear obvious after 10 years of research, the value of presenting them according to their potential effect on the selection, characterization, design, operation, and decommissioning processes of future low-level radioactive-waste disposal sites cannot be underestimated.

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