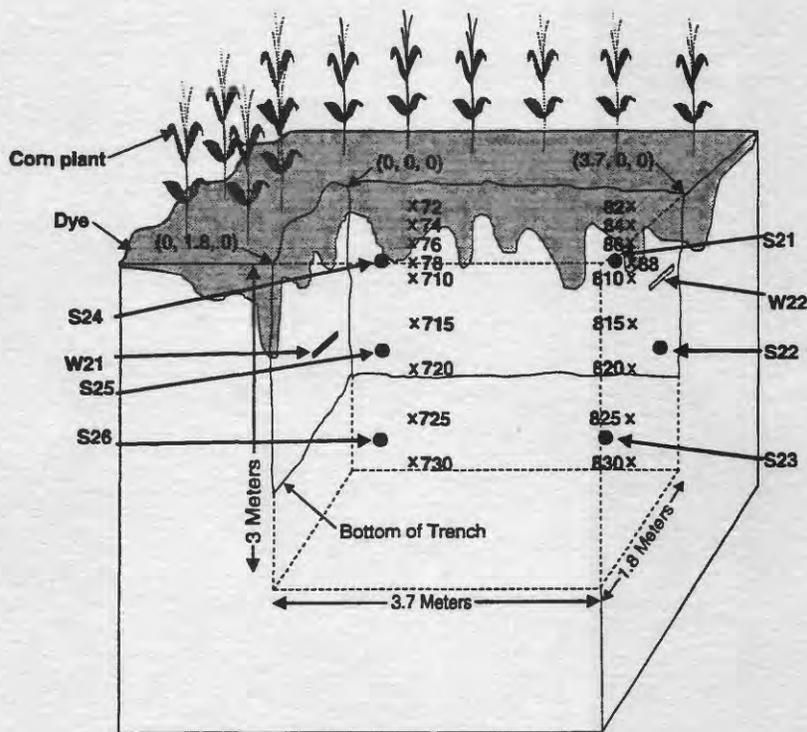


Hydrogeologic and Water-Quality Data Used to Evaluate the Effects of Focused Recharge on Ground-Water Quality Near Princeton, Minnesota, 1991-95

U.S. Geological Survey
Open-File Report 97-21



Three-dimensional view of instruments at the upland site

Prepared in cooperation with the
University of Minnesota Department of
Soil, Water, and Climate,
the U.S. Department of Agriculture,
Agricultural Research Service, and the
Minnesota Pollution Control Agency



Explanation for cover figure illustrating three-dimensional view of instrument locations at the upland site:

(0.35, 0.0, 1.8) X, Y, Z coordinate location, in meters
from point (0, 0, 0).

S24 ● Suction lysimeter and identifier.

W21 — Wick sampler and identifier.
Note: Wick sampler W22 is on a projected wall.

84 × Location of TDR probe and thermocouple, plus identifier.
Note: Left-most digit of the identifier for the
TDR probes and thermocouples is the string
number and the right-most one or two digits
corresponds to the depth below land
surface in tens of centimeters.

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R.W. Healy², H.W. Olsen², J.K. Böhlke³, B.R. Schroyer⁴, and P.D. Capel⁵

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Mounds View, Minnesota
1997

¹ U.S. Geological Survey, Mounds View, Minnesota

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Copy of the text in this report		report
Description of files on compact disk		readme
Air temperature data, 1992-95		airtemp
Precipitation data, 1992-95		precip
Well construction information for the upland and lowland sites		xyz
Geologic logs for the upland and lowland sites		geo
Moisture-retention data at the upland and lowland sites		mois-ret
Application rates for chemicals and irrigation water to the upland and lowland sites		chemrate
Results of monthly and quarterly chemical analyses for the upland and lowland sites, 1992-95		chem
Results of chemical analyses related to the 10/93 recharge experiment	chem1093	chem1093
Listing of instrument locations at the lowland site	lowland	r1instr
Soil analysis data at the lowland site	lowland	r1uzsum
Water-level data at the lowland site, 1992-95	lowland	r1watlev
Soil temperature data at the lowland site, 1992	lowland	r1tc92
Soil temperature data at the lowland site, 1993	lowland	r1tc93
Soil temperature data at the lowland site, 1994	lowland	r1tc94
Soil temperature data at the lowland site, 1995	lowland	r1tc95
Volumetric moisture content data at the lowland site, 1992	lowland	r1tdr92
Volumetric moisture content data at the lowland site, 1993	lowland	r1tdr93
Volumetric moisture content data at the lowland site, 1994	lowland	r1tdr94
Volumetric moisture content data at the lowland site, 1995	lowland	r1tdr95
Listing of instrument locations at the upland site	upland	r2instr
Soil analysis data at the upland site	upland	r2uzsum
Water-level data at the upland site, 1992-95	upland	r2watlev
Soil temperature data at the upland site, 1992	upland	r2tc92
Soil temperature data at the upland site, 1993	upland	r2tc93

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Volumetric moisture content data at the upland site, 1993	upland	r2tdr93
Volumetric moisture content data at the upland site, 1994	upland	r2tdr94
Volumetric moisture content data at the upland site, 1995	upland	r2tdr95

Note: All of the files listed above are in Microsoft Excel (Windows95 version 7.0) format (with a '.xls' extension). The following versions of each file are also included on the compact disk in similarly named subdirectories: space-delimited (with a '.prn' extension); tab-delimited (with a '.txt' extension); comma-delimited (with a '.csv' extension); and lotus-123 (with a '.wk1' extension).

Conversion Factors, Vertical Datum, and Abbreviated Water-Quality Units

<u>Multiply</u>	<u>By</u>	<u>To obtain</u>
centimeters (cm)	0.3937	inches
centimeter per day (cm/d)	.3937	inches per day
centimeter per second (cm/s)	.0328	foot per second
centimeter per year (cm/yr)	.3937	inches per year
cubic centimeters (cm ³)	.0610	cubic inches
cubic meter per second (m ³ /s)	35.31	cubic foot per second
hectare (ha)	2.471	acres
kilograms per hectare (kg/ha)	.8924	pounds per acre
kilograms per square centimeter (kg/cm ²)	32.81	feet of water
kilometer (km)	.6215	mile
liter (L)	.2642	gallon
meter (m)	3.281	foot
meters per year (m/yr)	3.281	feet per year
millimeters (mm)	.0394	inches
square kilometer (km ²)	.3861	square mile
degrees Celsius (°C)	1.8(°C)+32	degrees Fahrenheit

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.

Use of brand names in this report is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.

Chemical concentrations are given in metric units. Chemical concentrations of substances in water are given in milligrams per liter (mg/L) or micrograms per liter (µg/L). Milligrams per liter is a unit expressing the concentration of chemical constituents in solution as weight (milligrams) of solute per unit volume (liter) of water. One thousand micrograms per liter is equivalent to one milligram per liter. For concentrations less than 7,000 mg/L, the numerical value is the same as for concentrations in parts per million.

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Olsen², J.K. Böhlke³, B.R. Schroyer⁴, and P.D. Capel⁵

Abstract

This study was part of the Management Systems Evaluation Area (MSEA) Program, a multi-scale, inter-agency initiative to evaluate the effects of agricultural systems on water quality in the midwest corn belt. The research was part of the U.S. Geological Survey Toxics Substances Hydrology Program. The research area was located in the Anoka Sand Plain about 5 kilometers southwest of Princeton, Minnesota. This report presents temperature, precipitation, soil-moisture, water-quality, and other data collected during 1991-95 to evaluate the effects of focused recharge on ground-water quality at the Princeton MSEA.

Introduction

The primary objective of this 4-year research study was to evaluate the effects of transient recharge, topography, and subsurface heterogeneities on the flux of water and agricultural chemicals to the water table (Delin and Landon, 1996a). The research was part of the Management Systems Evaluation Area (MSEA) Program, a multi-scale, inter-agency initiative to evaluate the effects of agricultural systems on water quality in the midwest corn belt (Anderson and others, 1991). The research area was at the MSEA which is near Princeton, Minnesota, in the Anoka Sand Plain, an area of glacial outwash covering about 4,400 km² (fig. 1). The research was conducted primarily by the Minnesota District of the U.S. Geological Survey (USGS), in cooperation with USGS researchers from Denver and Reston. This report presents data collected during 1991-95 including temperature, precipitation, well-construction, geologic logs, moisture-retention, water-level, soil-moisture, water-quality, and other data used to evaluate the primary research objective. Selected graphs are included as examples of the data collected.

Location and Description of Research Area

The Princeton MSEA was adjacent to a wetland located about 5 km southwest of Princeton, Minnesota and about 80 km northwest of Minneapolis and St. Paul (figs. 1 and 2). Topography is undulating at the 65 ha Princeton MSEA with a maximum elevation gradient of about 2 m over a horizontal distance of about 40 m (Delin and others, 1994). The area is drained primarily by Battle Brook, a tributary of the St. Francis River, which flows into the Mississippi River. Five cropped areas (fig. 2) were established in 1991 to evaluate the effects of selected farming systems on ground-water quality (Anderson and others, 1991).

The research summarized in this report was conducted primarily at an upland site (R2) and a lowland site (R1) within the northernmost cropped area (fig. 2), in which corn was grown continuously during the study. The saturated and unsaturated zones at both sites generally contained medium-to-very coarse sand and fine gravel with discontinuous layers of laminations and silty sand up to 20 cm thick (table 1). The upland and lowland sites were about 78 m apart and differed in land-surface elevation by 1.4 m (slope of about 0.02).

¹ U.S. Geological Survey, Mounds View, Minnesota

² U.S. Geological Survey, Lakewood Colorado

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⁴ Terracon Environmental, White Bear Lake, Minnesota

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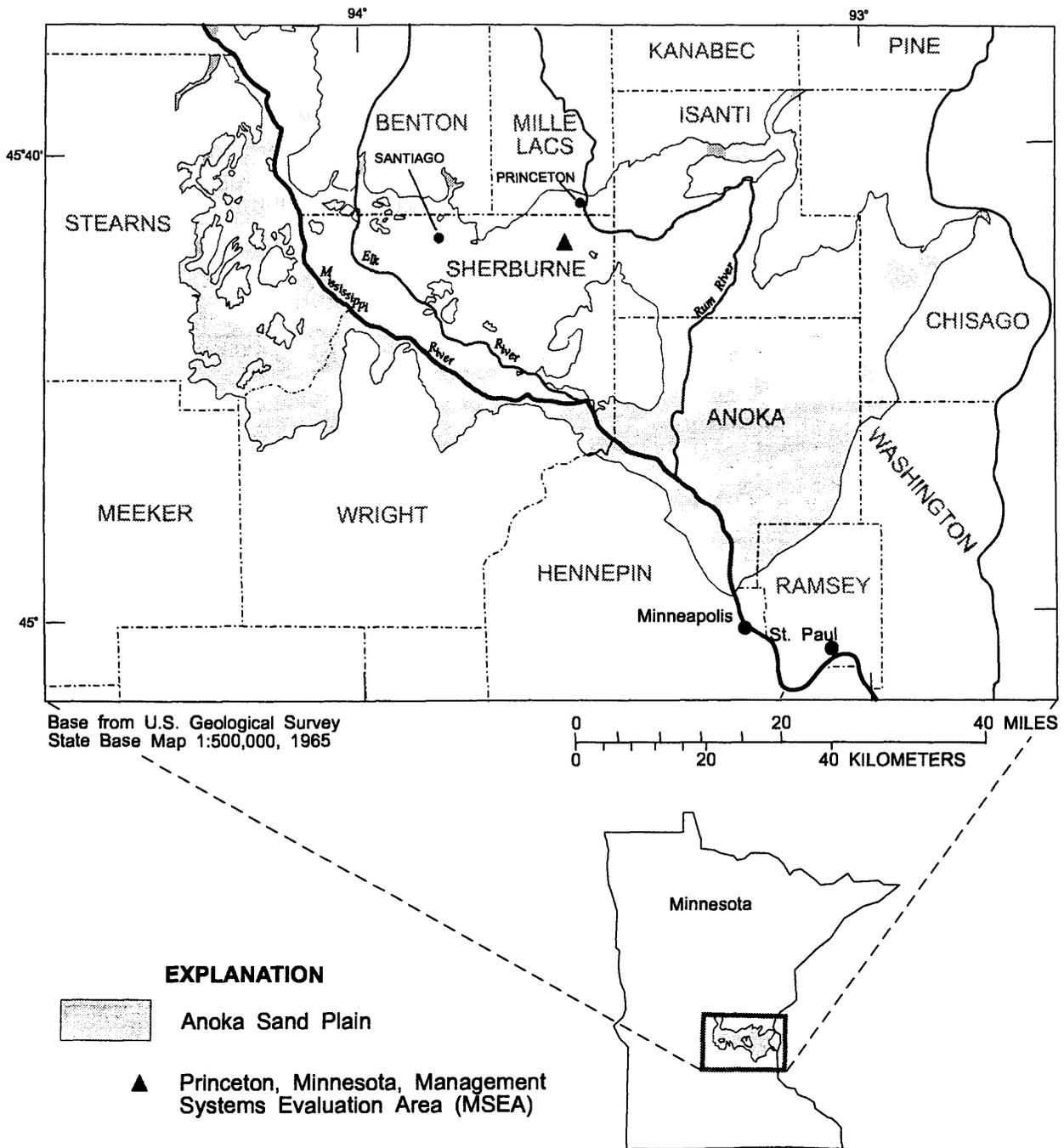
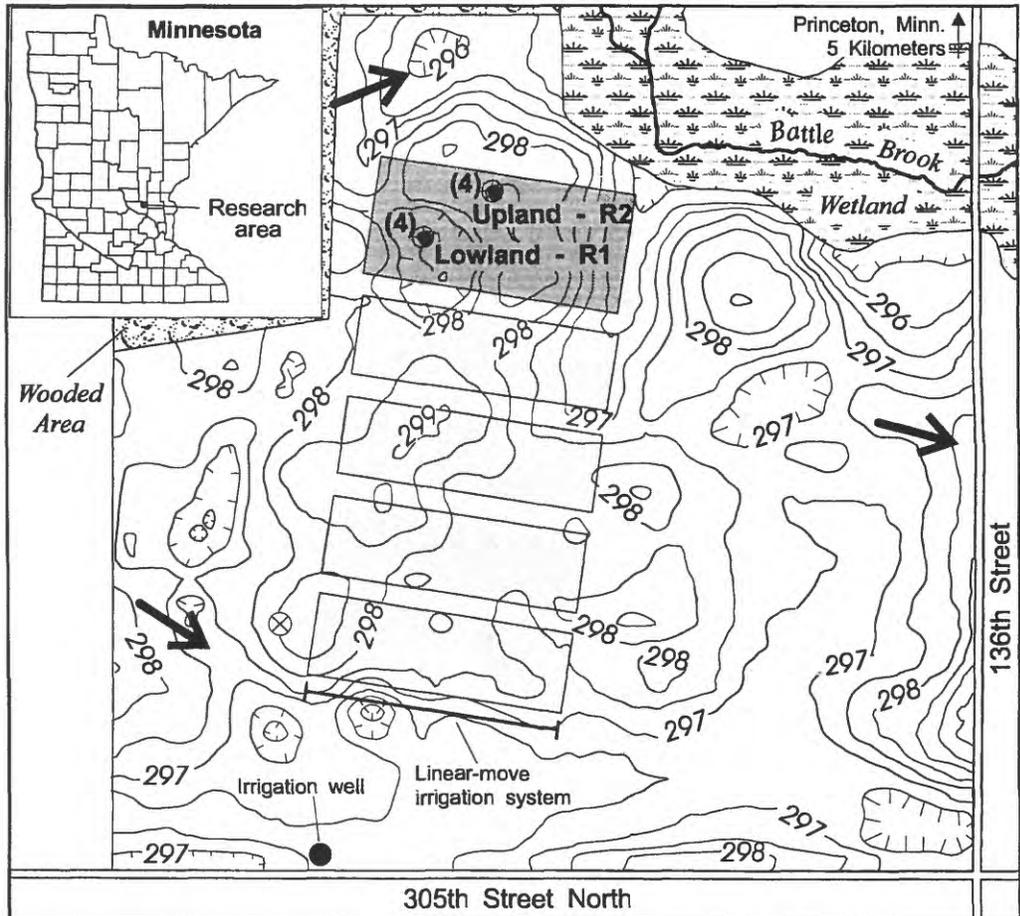


Figure 1.--Location of the Princeton, Minnesota, Management Systems Evaluation Area in the Anoka Sand Plain.



Base from U.S. Geological Survey
 Princeton 1:24,000 quadrangle, 1982
 Topographic data from J.E. Lucius, U.S.
 Geological Survey, Lakewood, Colorado

0 250 500 750 1000 FEET
 0 100 200 300 METERS

EXPLANATION

-  Cropped area
-  Research area
- Lowland - R1  Observation well and identifier, number in parentheses indicates number of wells at site
-  Multiport well
-  University of Minnesota climatological station
-  Average ground-water flow direction, 1992-95
-  — 297 — Topographic contour—Shows altitude of land surface. Hachures indicate depression. Contour interval 0.5 meters. Datum is sea level

Figure 2.--Layout of the research area at the Princeton, Minnesota, Management Systems Evaluation Area.

Table 1.—Geologic logs for the lowland (R1) and upland (R2) sites

Description	Depth to top of formation below land surface (meters)	Depth to bottom of formation below land surface (meters)	Formation thickness (meters)
Lowland (R1) site (land surface elevation = 296.4 meters)			
Sand, fine to medium, loamy, dark brown	0.0	0.8	0.8
Sand, medium to fine, dark brown to brown	.8	1.5	.7
Sand, medium to very coarse, some fine gravel and cobbles, brown	1.5	3.0	.8
Sand, medium to coarse, light brown	3.0	3.4	.4
Sand, medium to coarse, brown	3.4	3.5	.1
Sand, coarse to very coarse, brown	3.5	3.7	.2
Sand, coarse to very coarse, some fine gravel, brown	3.7	11.6	7.9
Sand, coarse to very coarse, some fine gravel, silty, brown	11.6	12.8	1.2
Sand, medium, silty, reddish gray	12.8	15.8	3.0
Sand, fine, silty, some cobbles, reddish gray	15.8	18.3	2.5
Till, clayey, reddish gray	18.3	18.9	.6
Static water level: 2.8 meters below land surface (2/8/92)			
Upland (R2) site (land surface elevation = 297.7 meters)			
Sand, fine to medium, loamy, dark brown	.0	.4	.4
Sand, fine to medium, brown	.4	.9	.5
Sand, fine to medium, light brown	.9	18.8	.9
Sand, fine to medium, brown	1.8	2.1	.3
Sand, medium to coarse, brown	2.1	2.4	.3
Sand, coarse to very coarse, brown	2.4	3.1	.7
Sand, medium to fine, brown	3.1	3.4	.3
Sand, coarse to very coarse, brown	3.4	4.0	.6
Sand, medium to coarse, gray	4.0	9.1	5.1
Sand, medium to coarse, reddish gray	9.1	11.3	2.2
Sand, medium to coarse, some fine gravel, reddish gray	11.3	14.9	3.6
Sand, fine to medium, silty, reddish gray	14.9	18.6	3.7
Till, clayey, reddish gray	18.6	19.2	.6
Static water level: 4.5 meters below land surface (2/8/92)			
Laminations at the upland site			
Varies between the 1.1- and 1.2-m depths	1.15	1.152	.002
Varies between the 1.22- and 1.3-m depths	1.25	1.252	.002
Varies between the 1.3- and 1.4-m depths	1.35	1.352	.002
Varies between the 1.6- and 1.68-m depths	1.60	1.610	.010
Varies between the 1.8- and 1.95-m depths	1.82	1.860	.040
Note: The laminations generally consist of dark brown, iron-cemented, fine to medium sand. The laminations are variable both in thickness and lateral extent. The listed thicknesses are minimum values with a maximum of up to 20 cm.			

The average horizontal hydraulic conductivity is about 0.04 cm/s. Based on this hydraulic conductivity and an average horizontal hydraulic gradient of 0.001, ground water generally moves from west-southwest to east-northeast at an average rate of about 8 cm/d (29 m/yr). Recharge generally ranged from 10 to 25 cm/yr during the study. The vertical hydraulic gradient (downward) beneath the area was about 0.0001 (Delin and others, 1994).

Methods of Investigation

The cropped area in which the upland and lowland sites were located (fig. 2) was planted in field corn during each year of the research study. The farming system for the entire cropped area consisted of full-width tillage, split-nitrogen application, and broadcast application of herbicides. Due to the above-ground instrumentation that prevented access of a tractor to each site, the herbicides and fertilizers were broadcast applied to both sites using a hand sprayer.

A linear-move irrigation system was used as necessary to supplement rainfall and to apply water during recharge experiments (fig. 2). The irrigation well was completed in a confined sand and gravel aquifer that is hydraulically separated from the surficial aquifer by a confining layer of clayey till about 15 m thick (Delin and others, 1994). The well was completed in this confined aquifer so that the hydraulic effects of pumping would be eliminated or minimized near the cropped areas. The effects of ground-water withdrawals from the irrigation well were not observed in the water levels or ground-water flow patterns of the surficial aquifer during the study.

Precipitation was measured at the upland and lowland sites using tipping-bucket rain gages. Climatological information was also recorded by the University of Minnesota at the Princeton MSEA (fig. 1) and by the National Weather Service at Santiago, Minnesota, 20 km west of the MSEA. Air temperature was measured at the upland and lowland sites using a thermistor.

A dye-tracing and trenching study was done at the upland and lowland sites to install instruments in the unsaturated zone and to collect soil samples for determining the unsaturated-zone properties (Delin and others, 1996). A 3 percent solution by volume of rhodamine WT ($C_{29}H_{29}N_2O_5Na_2Cl$) dye was applied uniformly to a 3.5 m by 6 m area at each site (fig. 3). About 12 liters of the dye solution was applied 8 times (at 10-day intervals) from July 5 through September 13, 1991 to ensure dye visibility and complete penetration through the unsaturated zone. Total rainfall from July 5

through October 22, 1991 was about 30 cm. Beginning on October 22, 1991 a trench, measuring approximately 3 m by 2 m, was dug in the center of each dye-application area (fig. 3). The depth of each trench was increased by intervals of 0.5 m to a total depth of 2.0 m. Each long wall of both trenches was directly beneath a corn row.

All of the unsaturated-zone instruments and soil samples were located within each trench based on an X,Y,Z coordinate system; the X direction was oriented approximately east-west and the Y direction was oriented approximately north-south (fig. 3). The origin of the coordinate system (location 0,0,0) was in the northwest corner of each trench. Some soil samples were further identified based on whether they were located on the north (A), east (B), south (C), or west (D) sides of each trench (fig. 3).

Soil samples, 20 cm³ in volume, were collected from the sides and bottom of each trench for measurements of grain-size distribution, bulk density, total organic-carbon content, volumetric moisture content, and dye fluorescence (files r1uzsum.xls and r2uzsum.xls on the compact disk). About 25 samples were collected at regularly spaced intervals of about 1.0 m horizontally and 0.5 m vertically from the northern and eastern walls of each trench. About 25 and 60 samples were collected from the southern and western walls of each trench, respectively, at irregular spacing to facilitate geostatistical analysis of the data. About 20 samples were collected at uniform spacing from the bottom of each 0.5-m depth interval in the trench to determine the three-dimensional distribution of dye.

Thirty-two undisturbed soil cores were collected from the west wall of each trench and at several depths beneath the corn rows and furrows for measurements of saturated hydraulic conductivity (files r1uzsum.xls and r2uzsum.xls on the compact disk). Most of these samples were obtained by pushing a 5-cm inside diameter (i.d.) by 4-cm-long thin-wall brass tube horizontally into the trench wall. Three vertically oriented cores were also obtained adjacent to three of the horizontally oriented cores, to estimate the vertical hydraulic conductivity. Saturated hydraulic conductivities (horizontal and vertical) were measured in a triaxial system by the constant-flow method (Olsen and others, 1988 and 1991). Effective stresses were varied between 0.35 and 2.81 kg/cm². Each sample also was analyzed for grain-size distribution and bulk density.

About 80 undisturbed cores were collected from the two trenches for measurements of moisture-retention

EXPLANATION

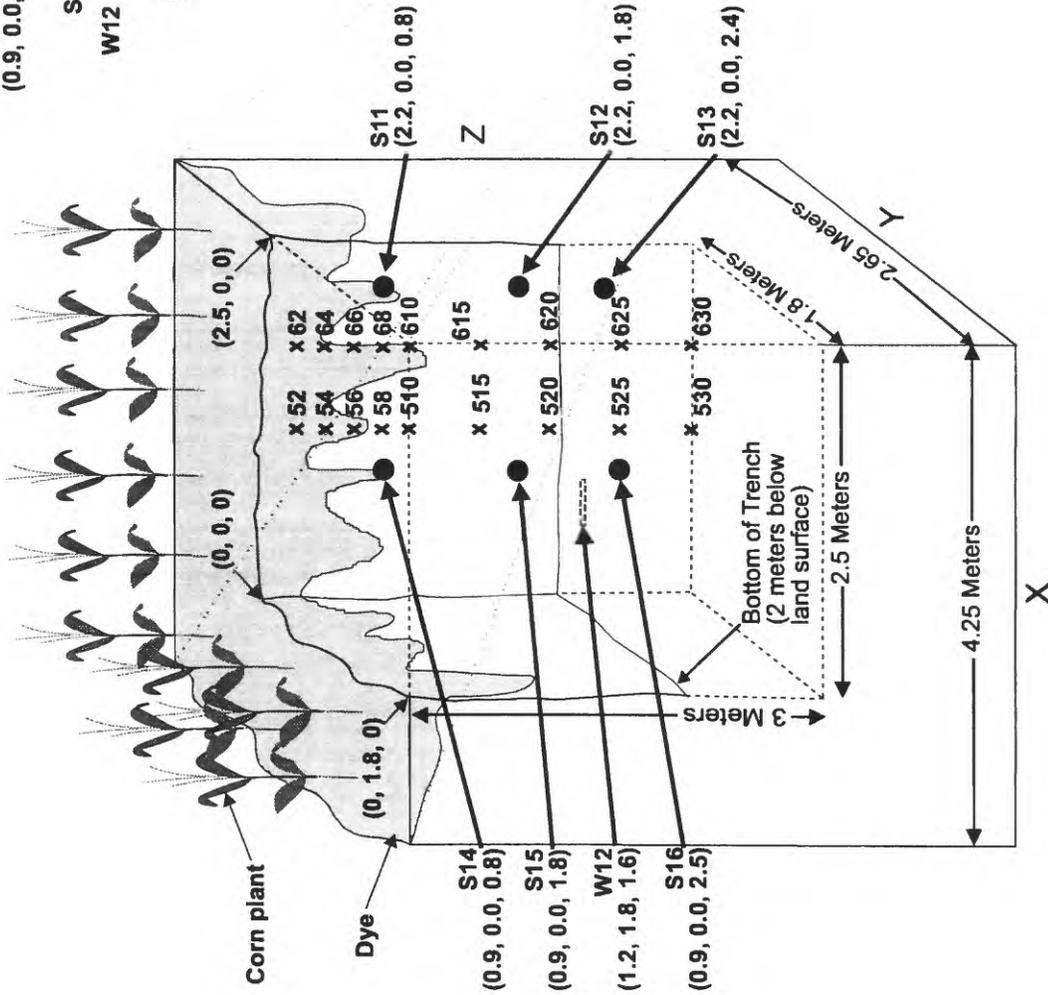
(0.9, 0.0, 0.8) X, Y, Z coordinate location, in meters from point (0, 0, 0).

S14 ● Suction lysimeter and identifier.

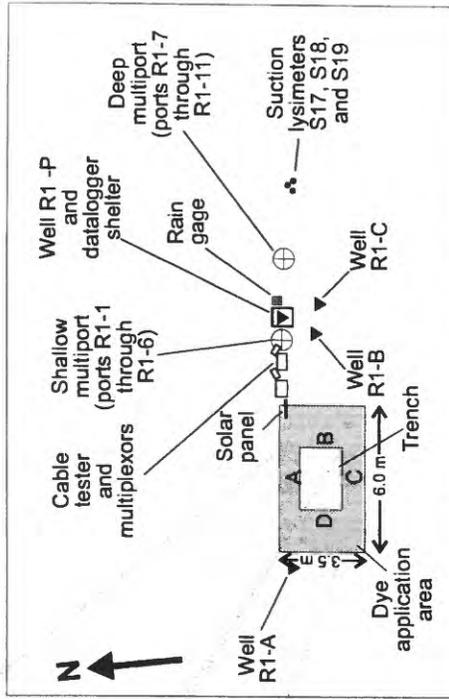
W12 ◻ Wick sampler and identifier.
Note: the wick sampler is on wall C.

64 x Location of TDR probe and thermocouple, plus identifier.
Note: Left-most digit of the identifier for the TDR probes and thermocouples is the string number and the right-most one or two digits corresponds to the depth below land surface in tens of centimeters.

A Identifier on Planimetric View corresponding to A - north, B - east, C - south, and D - west sides of the trench.



Three-Dimensional View



Planimetric View

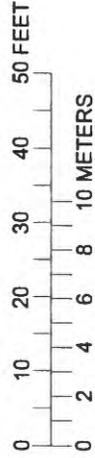
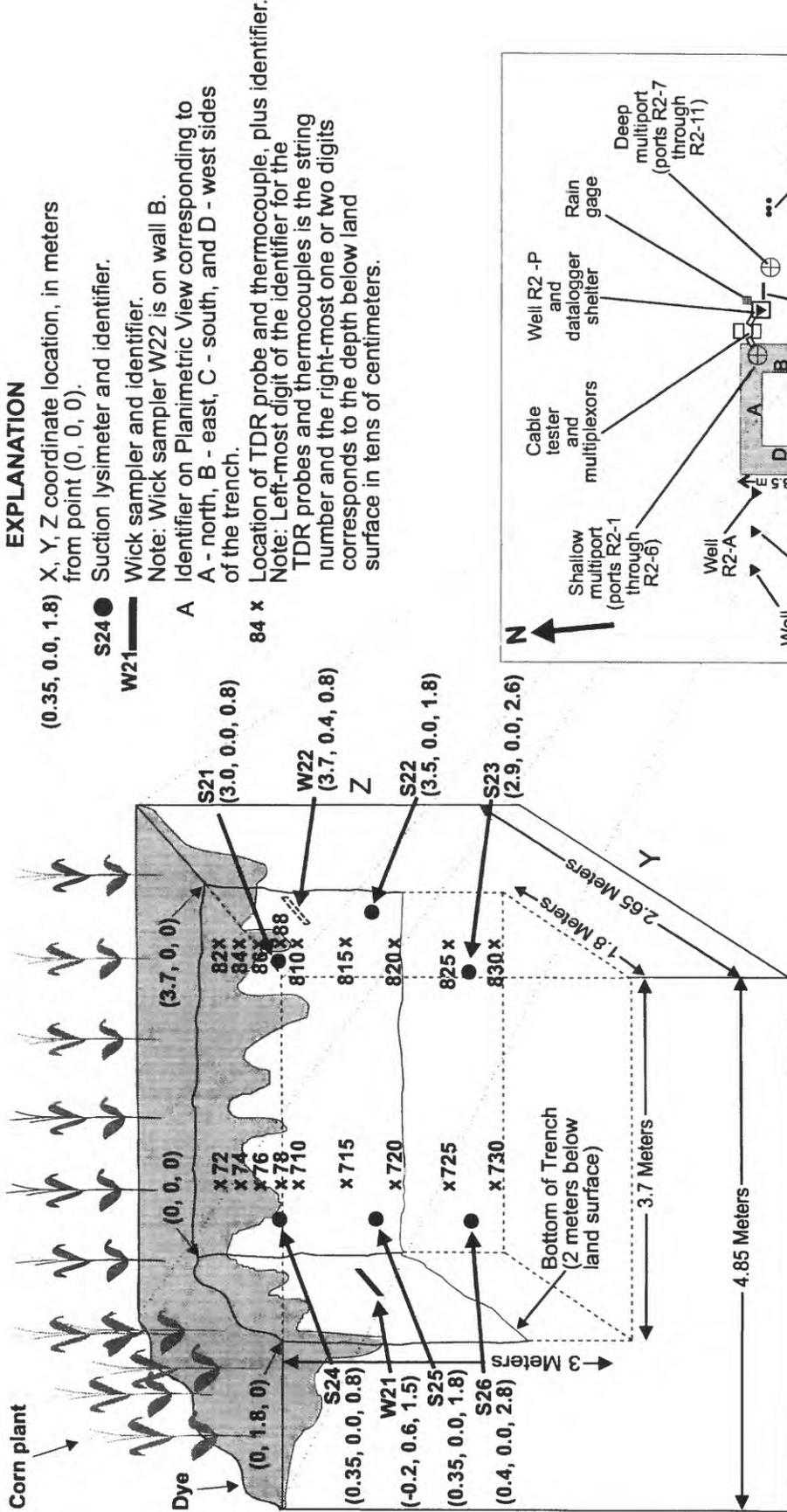


Figure 3a.--Three-dimensional and planimetric views of instrument locations at the lowland (R1) site.



EXPLANATION

- (0.35, 0.0, 1.8) X, Y, Z coordinate location, in meters from point (0, 0, 0).
 - S24 ● Suction lysimeter and identifier.
 - W21 — Wick sampler and identifier.
 - A Identifier on Planimetric View corresponding to the trench.
 - 84 x Location of TDR probe and thermocouple, plus identifier.
- Note: Wick sampler W22 is on wall B.
 Note: Left-most digit of the identifier for the TDR probes and thermocouples is the string number and the right-most one or two digits corresponds to the depth below land surface in tens of centimeters.

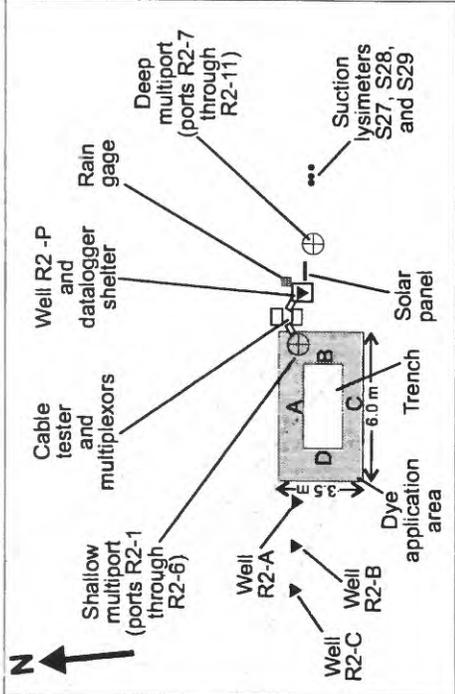


Figure 3b.--Three-dimensional and planimetric views of instrument locations at the upland (R2) site.

characteristics (file mois-ret.xls on the compact disk). These samples were obtained by pushing a 5-cm i.d. by 4-cm-long thin-wall steel tube into the wall of the trench. The cores were placed in Tempe cells and moisture retention was determined at tensions of 25, 50, 75, 100, 125, 150, 175, and 400 cm of water according to the method of Richards (1980).

Most of the unsaturated-zone instruments were installed in two vertical profiles within the trench at each site following the dye-tracing study, based on the presence or absence of dye. One vertical profile of instruments at each site was installed where the dye was more evident and is termed a preferential flow zone in this report. A second vertical profile of instruments at each site was installed where the dye was less evident and is termed a retarded flow zone in this report.

Thermocouples and time-domain reflectometry (TDR) probes were installed at depths of 0.2, 0.4, 0.6, 0.8, 1.0, 1.5, 2.0, 2.5, and 3.0 m in the unsaturated zone (fig. 3). TDR is a technique in which electronic pulses are transmitted through a coaxial cable that is attached to a fixed-length probe embedded in the soil (Topp and others, 1980). The resultant waveform is affected by the moisture content of the soil surrounding the probe. Because the dielectric constant of water is much higher than that of most other materials, a signal in moist soil will propagate more slowly than in the same soil when dry. Thus, the moisture content can be calculated by measuring the waveform propagation time over the fixed-length probe. The left-most digit of the identifier for the thermocouples and TDR probes (fig. 3) is the string number and right-most one or two digits corresponds to the depth below land surface in tens of centimeters. For example, identifier 68 corresponds to string number 6 located 80 cm below land surface at the lowland site. In the files included on the compact disk, prefixes have been added to each of these identifiers corresponding to the thermocouples (TC68, for example) and the TDR probes (TDR68, for example). A reference TDR probe within a 5.08-cm i.d. by 15-cm long polyvinyl chloride (PVC) pipe was installed at both sites to provide a constant measurement of volumetric moisture content for reference purposes.

In addition to the above-described installation, thermocouples were also installed adjacent to sampling ports 1 through 6 in the multiport wells (MPORTs) (Delin and Landon, 1996b). These thermocouples are labeled TC1 through TC6 for both the upland and lowland sites in each of the files included on the compact disk. A reference thermistor was also installed on the datalogger at both the upland and lowland sites.

The thermocouple and TDR signals were multiplexed before being recorded by a central datalogger (fig. 3). All of the electronic equipment at each site was powered by a solar panel. The scan interval of data collection by the dataloggers was varied during the study. During recharge experiments, a scan interval of 15-60 minutes typically was used. During the remainder of the study, scan intervals typically ranged from 1 to 4 times per day.

Suction lysimeters were installed at the upland site at depths of 0.8 m (S21 and S24), 1.8 m (S22 and S25), 2.6 m (S23), and 2.8 m (S26) (fig. 3). At the lowland site, suction lysimeters were installed at depths of 0.8 m (S11 and S14), 1.8 m (S12 and S15), 2.4 m (S13), and 2.5 m (S16). Suction lysimeters were also installed in an area about 10 meters east of each trench (fig. 3). At the upland site, these suction lysimeters were installed at depths of 0.8 m (S27), 1.8 m (S28), and 2.8 m (S29). At the lowland site, these suction lysimeters were installed at depths of 0.8 m (S17), 1.8 m (S18), and 2.8 m (S19). The suction lysimeters were constructed of Teflon with a porous ceramic cup. Wick samplers were installed at depths of 0.8 m (W22) and 1.5 m (W21) at the upland site and at the 1.6-m depth (W12) at the lowland site. The wick samplers were constructed of fiberglass attached to a glass plate, based on the design of Brown and others (1986).

A water-table well (R1-A or R2-A) was installed upgradient of each trench to facilitate collection of samples to determine concentrations of agricultural chemicals in shallow ground water (fig. 3). A second water-table well (R1-P or R2-P) was installed downgradient of each trench. Water levels were measured in these wells using a shaft encoder and float assembly connected to a datalogger. Two additional observation wells were screened about in the middle (R1-B or R2-B) and at the bottom (R1-C or R2-C) of the saturated zone at both sites. All of the observation wells were constructed of 5.1-cm i.d. galvanized-steel casing with 15- or 60-cm long stainless-steel screens (file xyz.xls on the compact disk). The observation wells were installed through the annulus of 10.2-cm i.d. hollow-stem augers. The augers were then removed and the natural formation below the water table was allowed to collapse around the casing. Above the water table, a mixture of bentonite and native material was used to backfill the annulus to prevent the vertical movement of water and agricultural chemicals down the borehole. Soil temperature, precipitation, soil moisture, and ground-water levels were continuously recorded at both sites with a datalogger.

A deep and a shallow MPORT was installed at both the upland and lowland sites (fig 3). Each shallow

MPORT consisted of six 0.6-cm i.d. stainless-steel tubes (ports R1-1 through R1-6 and R2-1 through R2-6) housed in a 5.1-cm i.d. PVC casing; each tube had a 3-cm long screened interval (port) external to the PVC casing (file xyz.xls on the compact disk). The shallow-sampling ports were installed at 50-cm intervals with the uppermost port 50 cm above the water table at the time of installation, to allow sample collection if the water table rose. The deep MPORTs (ports R1-7 through R1-11 and R2-7 through R2-11) were constructed similarly to the shallow MPORTs except that the interval between each sampling port varied from 1 to 2 m. The number 6 and 7 sampling ports at each site were located within about 50 cm of each other vertically. The MPORTs were installed through the annulus of 10.2-cm i.d. hollow-stem augers. The augers were then removed and the natural formation was allowed to collapse around the MPORT. The MPORTs were used to collect water samples to evaluate ground-water quality.

Water samples were collected monthly from selected wells, unsaturated-zone samplers, and MPORTs and during infiltration experiments conducted at the upland and lowland sites. Samples of the irrigation water or precipitation were also collected periodically and during infiltration experiments. Sample-collection and laboratory-analysis quality-assurance/quality-control protocols were followed and are described in detail by Delin and others (1994) and Larson and others (1996). Specific conductance, pH, temperature, dissolved-oxygen concentration, and oxidation reduction potential (ORP) of ground water were measured in a flow-through cell isolated from the atmosphere during pumping at each sampling site. Water samples were collected after these properties stabilized. Alkalinity titrations were performed in the field within 4 hours of sample collection.

Recharge experiments were conducted several times during the study to evaluate how differences in ground-water recharge and water movement through the unsaturated zone could be attributed to differences in topography and soil physical and hydraulic properties. Most experiments began by applying about 2-6 cm of water with the linear-move irrigation system. The movement of wetting fronts through the unsaturated zones were evaluated using the TDR system. Water samples were collected from the suction samplers, wick samplers, water-table wells, and the MPORTs before and numerous times during each experiment. The TDR system was also used during natural precipitation events to evaluate the effects of topography on recharge and water movement through the unsaturated zone.

As part of the recharge research, the average recharge in the upper several meters of the saturated zone was determined based on chlorofluorocarbon CCl_2F_2 (CFC-12) age-dating techniques. Water samples were collected from selected MPORT locations at the upland and lowland sites during 1993 and 1994. These samples were analyzed for CFC-12 concentrations in the U.S. Geological Survey Kinetic Modeling Laboratory, Reston, Virginia using the methods of Busenberg and Plummer (1992).

As part of the recharge research and evaluation of unsaturated-zone residence times, precipitation and water from sampling locations in the unsaturated and saturated zones were also analyzed periodically for oxygen ($\delta^{18}\text{O}$), hydrogen (δD), and sulfur ($\delta^{34}\text{S}$) stable isotopic compositions. These samples were analyzed using mass spectroscopy in the U.S. Geological Survey Isotope Fractionation Laboratory, Reston, Virginia.

Most analyses for dissolved major cations and anions were completed by the Geochemistry Laboratory in the Department of Geology and Geophysics at the University of Minnesota, Minneapolis, Minnesota; cations were analyzed using inductively-coupled plasma-mass spectroscopy (ICPMS) and anions were analyzed using ion chromatography (IC). Analytes measured by ICPMS included calcium, magnesium, sodium, potassium, silica, iron, manganese, strontium, and barium. Analytes measured by IC included sulfate, fluoride, chloride, bromide, nitrate nitrogen, nitrite nitrogen, and orthophosphate. Anion samples were also collected on a monthly basis and analyzed using ion chromatography by Richard B. Wanty (U.S. Geological Survey, Geologic Division) at his research laboratory in Denver, Colorado. Nutrient analyses were completed by the Research Analytical Laboratory in the Department of Soil, Water, and Climate at the University of Minnesota, St. Paul, Minnesota. Nutrient analytes included nitrite plus nitrate nitrogen, ammonium nitrogen, and total Kjeldahl nitrogen (ammonium plus organic nitrogen).

Analyses for selected herbicides and herbicide metabolites were completed at a U.S. Geological Survey laboratory in Navarre, Minnesota using gas chromatography/mass spectrometry (GC/MS) (Larson and others, 1996). Herbicide analytes included atrazine (2-chloro-4-ethylamino-6-isopropylamino-s-triazine), alachlor (2-chloro-2'-6'-diethyl-N-(methoxymethyl)-acetamide), metolachlor (2-chloro-N-(2-ethyl-6-methylphenyl)-N-(2-methoxy-1-methylethyl)acetamide), and metribuzin (4-amino-6(1,1-dimethylethyl)-3-(methylthio)-1,2,4-triazin-5(4H)-one); atrazine metabolites de-ethylatrazine

(DEA) (2-amino-4-chloro-6-(isopropylamino)-s-triazine) and de-isopropylatrazine (DIA) (2-amino-4-chloro-6-(ethylamino)-s-triazine); and alachlor metabolite 2,6-diethylaniline. Compound-specific reporting and detection limits were determined for each of the analytes (table 2). The detection limit was defined as the minimum concentration at which the analyte could be routinely identified by GC/MS. The reporting limit was defined as the concentration at which the analyte could be reliably and consistently quantified by GC/MS. In the concentration range between the detection limit and the reporting limit there was a significant possibility of false negatives (the presence of an analyte that was not identified). Concentrations greater than or equal to the detection limit, but less than the reporting limit, indicated trace concentrations of the analytes. The trace concentrations indicated that the analytes were present but at a lower confidence level than for concentrations greater than the reporting limit. The trace concentrations were used in computing the sum of atrazine plus atrazine-metabolites DEA and DIA, the ratio of DEA to atrazine (DAR), the ratio of DIA to DEA (D²R), and the ratio of DIA to atrazine (DIAR).

Table 2.—Laboratory detection and reporting limits for gas chromatography/mass spectrometry analyses of herbicide concentrations in water from the Princeton, Minnesota, Management Systems Evaluation Area (Larson and others, 1996).
[µg/L, micrograms per liter]

Herbicide or herbicide metabolite	Detection limit (µg/L)	Reporting limit (µg/L)
Atrazine	0.01	0.04
De-ethylatrazine	.03	.06
De-isopropylatrazine	.06	.08
Alachlor	.01	.04
2,6-diethylaniline	.01	.04
Metolachlor	.01	.04
Metribuzin	.03	.06

A recharge experiment was conducted in October 1993 to evaluate the effects of a catastrophic recharge event on the transport of agricultural chemicals through the unsaturated and saturated zones. About 15 cm of water was applied to both sites during the experiment using multiple lawn sprinklers. The tracers fluoride, chloride, bromide, nitrate nitrogen, sulfate, iodide, atrazine, and alachlor were applied prior to the test.

Similar to the other tests, water samples were collected from the suction samplers, wick samplers, water-table well, and the multiport wells before and numerous times during each experiment. Each water sample was analyzed for fluoride, chloride, nitrate nitrogen, bromide, sulfate, atrazine, alachlor; atrazine metabolites de-isopropyl hydroxy atrazine (DIHA) (2-hydroxy-4-ethylamino-6-amino-1,3,5-triazine), didealkyl atrazine (DDA) (2-chloro-4,6-diamino-1,3,5-triazine), de-ethyl hydroxy atrazine (DEHA) (2-hydroxy-4-amino-6-isopropylamino-1,3,5-triazine), de-isopropyl atrazine (DIA), de-ethyl atrazine (DEA), hydroxy atrazine (HA) (2-hydroxy-4-ethylamino-6-isopropylamino-1,3,5-triazine); alachlor metabolites alachlor-oxanilic acid (A-OA) (2-[(2',6'-diethylphenyl)(methoxymethyl)amino]-oxoacetic acid), alachlor-ethane sulfonic acid (A-ESA) (2-[(2',6'-diethylphenyl)(methoxymethyl)amino-]-2-oxoethane sulfonic acid), demethoxymethyl alachlor (A-DMM) (2-chloro-2',6'-diethyl-acetanilide), and 2,6-diethylaniline (2,6 DiEA). A detailed description of the laboratory methods for this catastrophic recharge experiment is presented by Schroyer and Capel (1996).

Description of Graphs

Graphs are included in this report to illustrate some of the types of data collected during the study from 1992-95. The air temperature data (fig. 4) and the precipitation data (fig. 5) were measured at the University of Minnesota climatological station at the Princeton MSEA (fig. 2). The data from this climatological station were more complete than the climatological data from the upland and lowland sites. Where necessary, however, the University of Minnesota data were supplemented by precipitation measurements from the upland and lowland sites. Precipitation data for November through March of each year were measured by the National Weather Service (National Oceanic and Atmospheric Administration, electronic commun., 1996) at Santiago, Minnesota, about 20 km west of the research site (fig. 1). Other graphs of data collected during 1992-95 at the upland and lowland sites include: water-level hydrographs (fig. 6), soil temperature from selected depths (figs. 7-10) and volumetric moisture content from selected depths (figs. 11 and 12).

Graphs of selected ground-water-quality data collected during 1991-95 include chloride concentrations (figs. 13 and 14), nitrate nitrogen concentrations (figs. 15 and 16), and atrazine concentrations (figs. 17 and 18). Chemical concentrations in both the unsaturated and saturated zones are included in each graph. The water-table hydrograph is included as the upper boundary of the saturated zone, and reflects periods during which

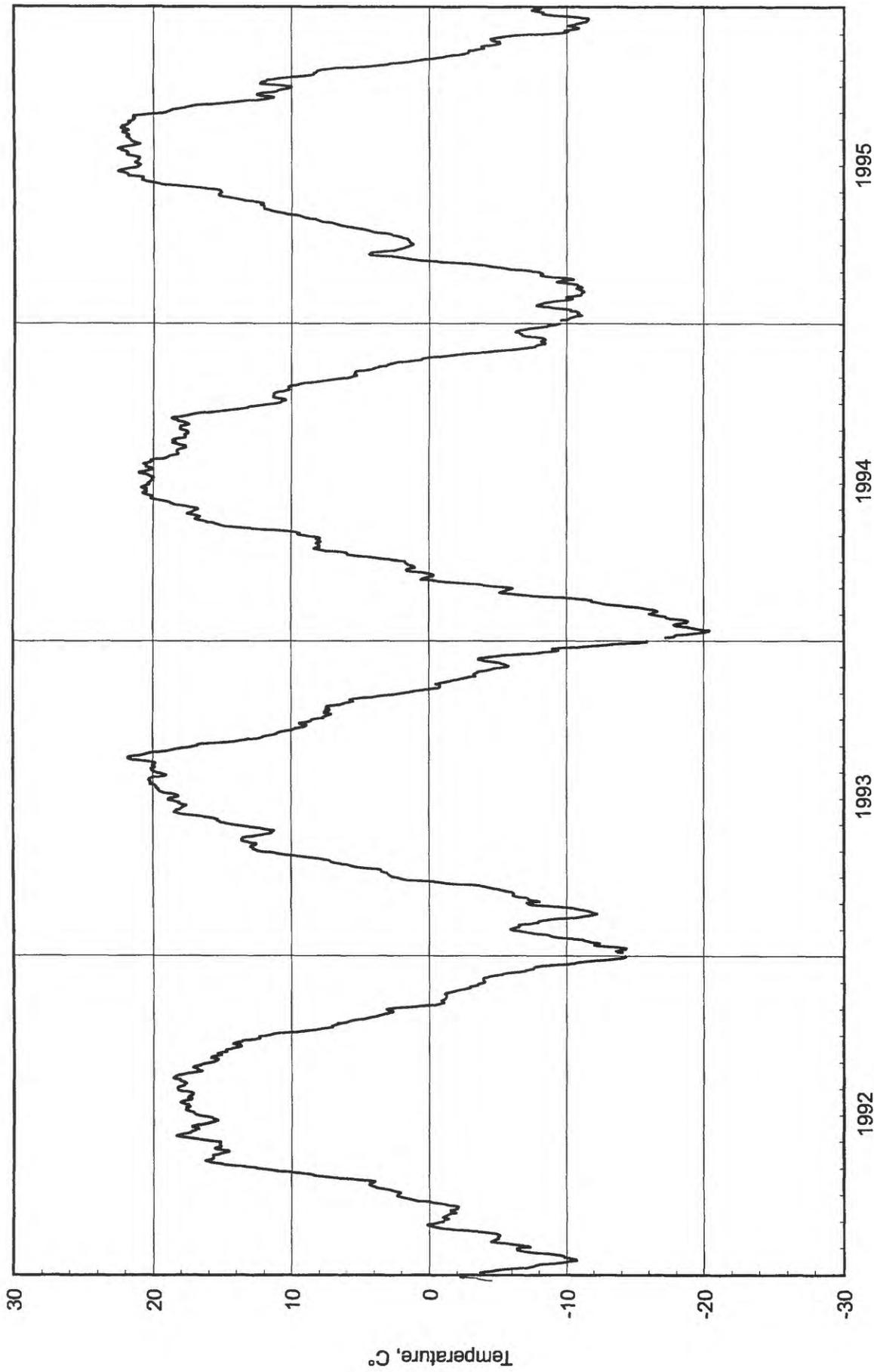


Figure 4.--Air temperature at the Princeton, Minnesota, Management Systems Evaluation Area, 1992-95.

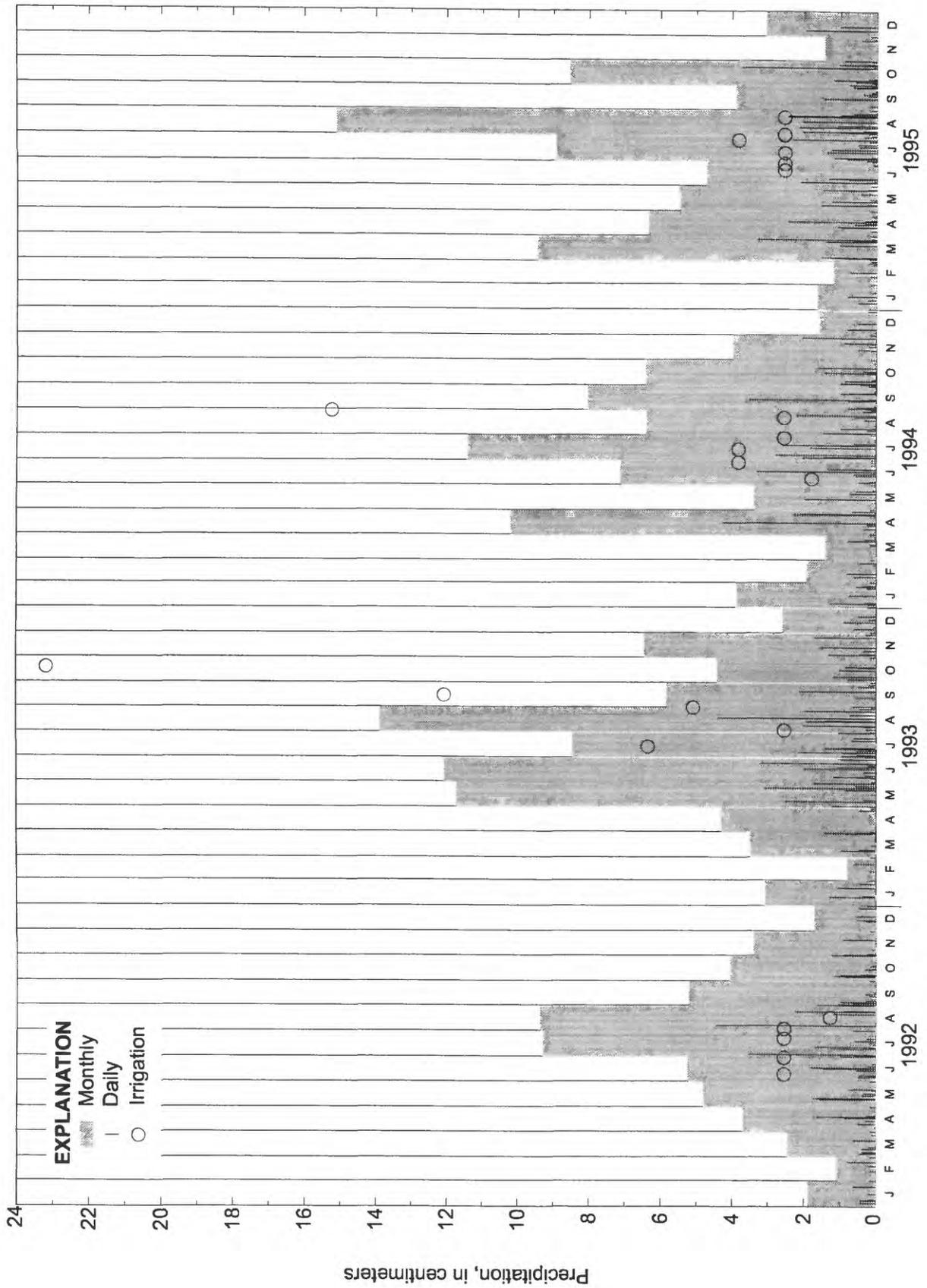


Figure 5.--Precipitation at the Princeton, Minnesota, Management Systems Evaluation Area, 1992-95.

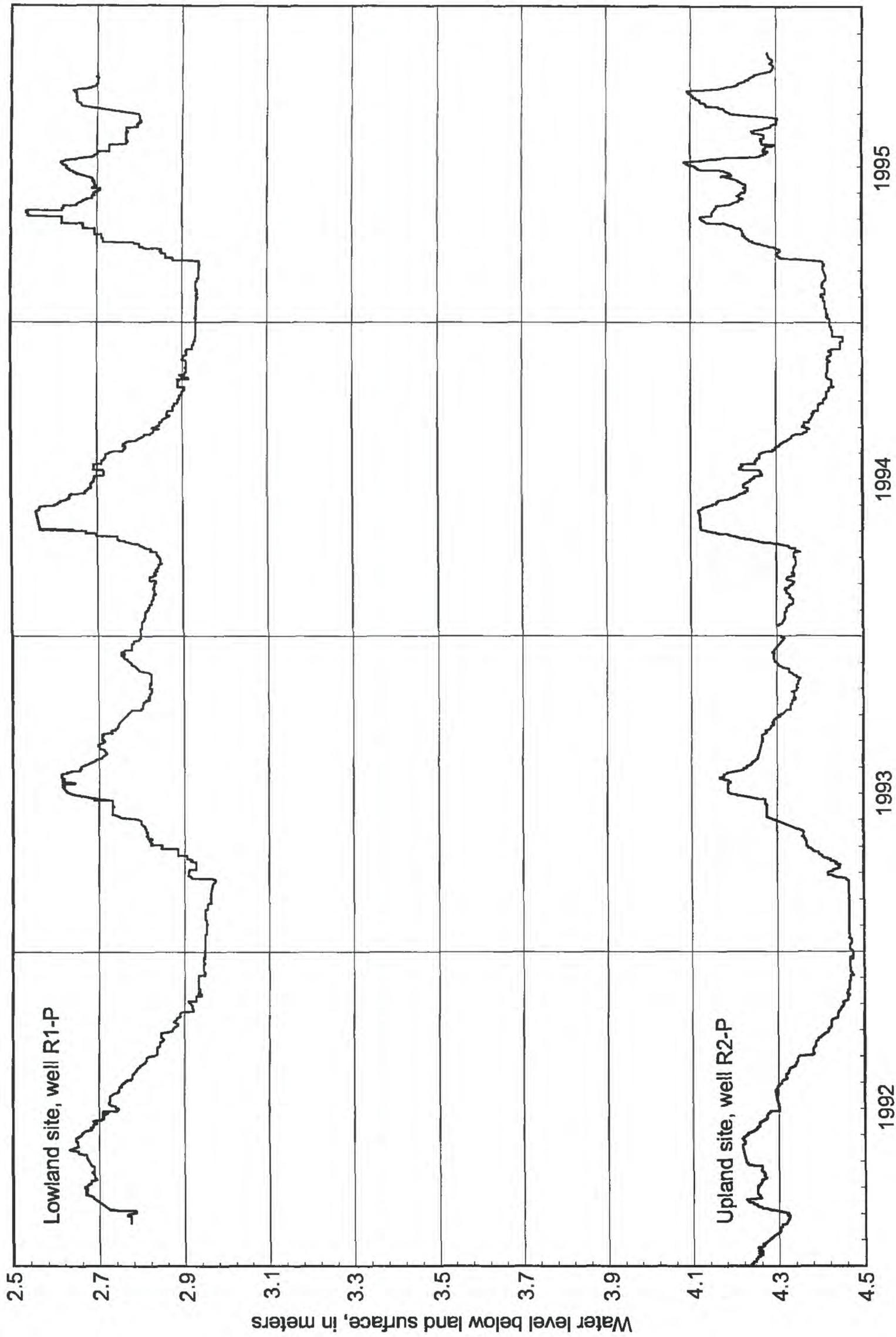


Figure 6.--Water-level hydrograph for the upland and lowland sites, 1992-95.

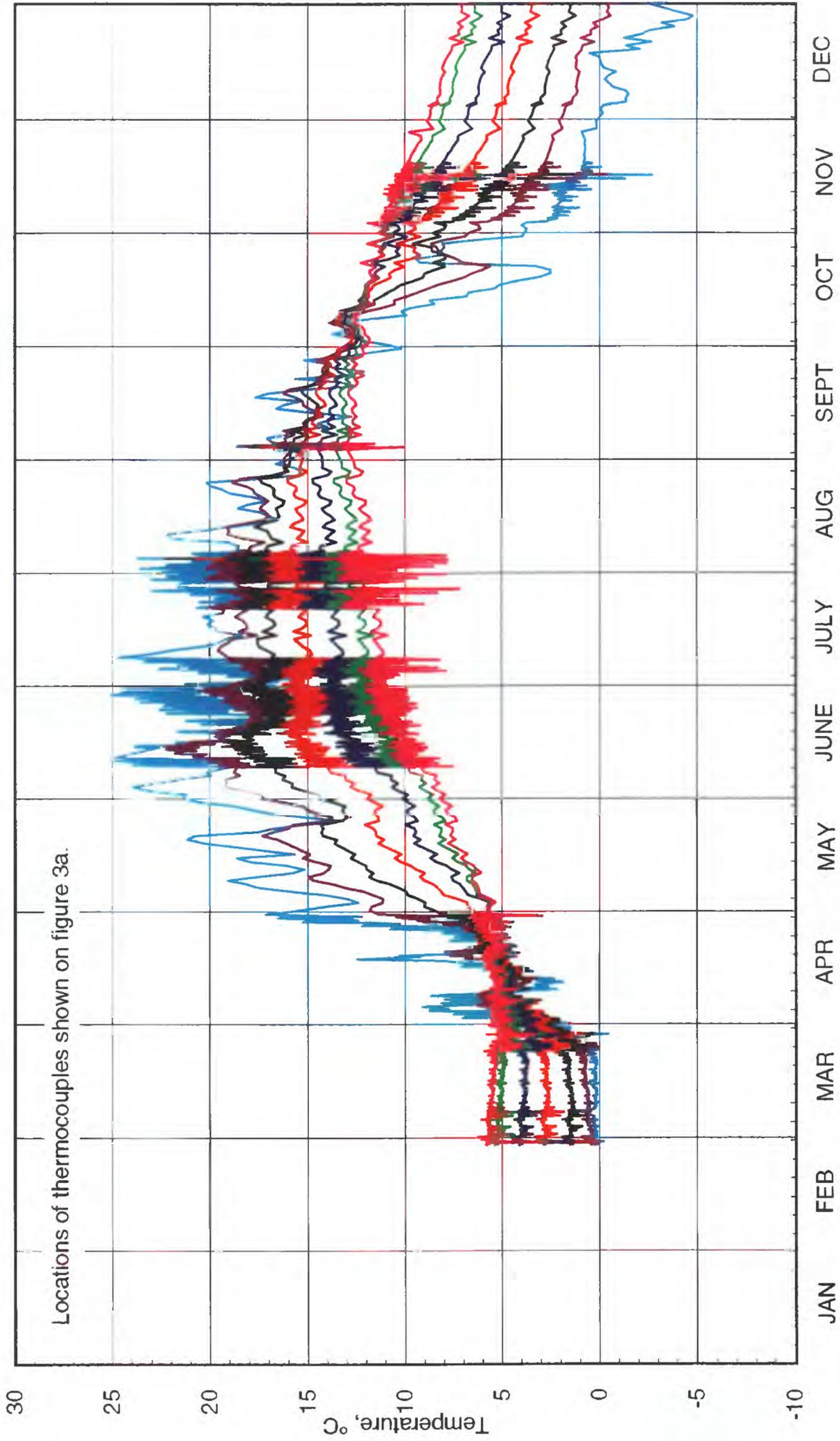


Figure 7a.--Soil temperature from selected depths at the lowland site during 1992.

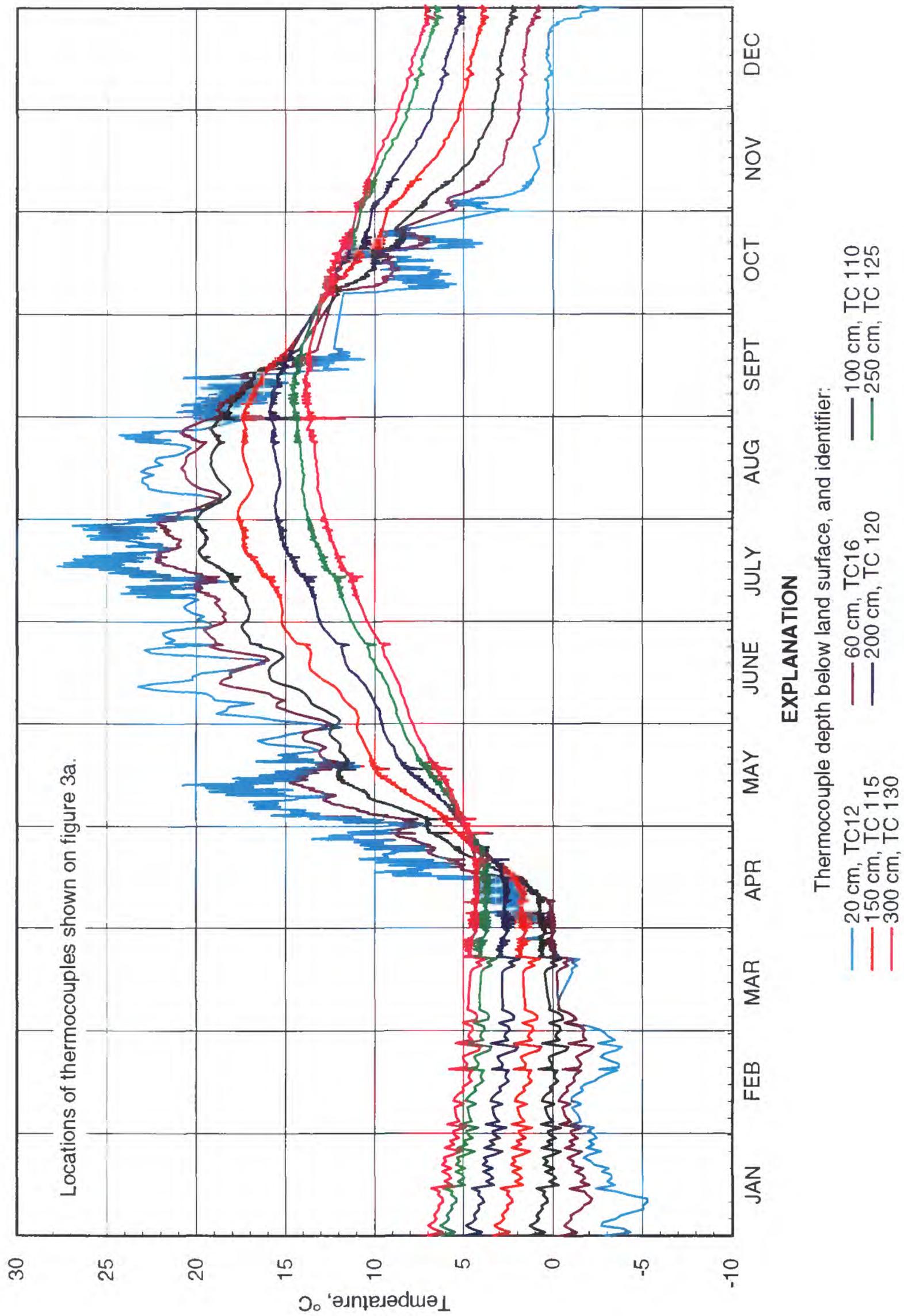


Figure 7b.--Soil temperature from selected depths at the lowland site during 1993.

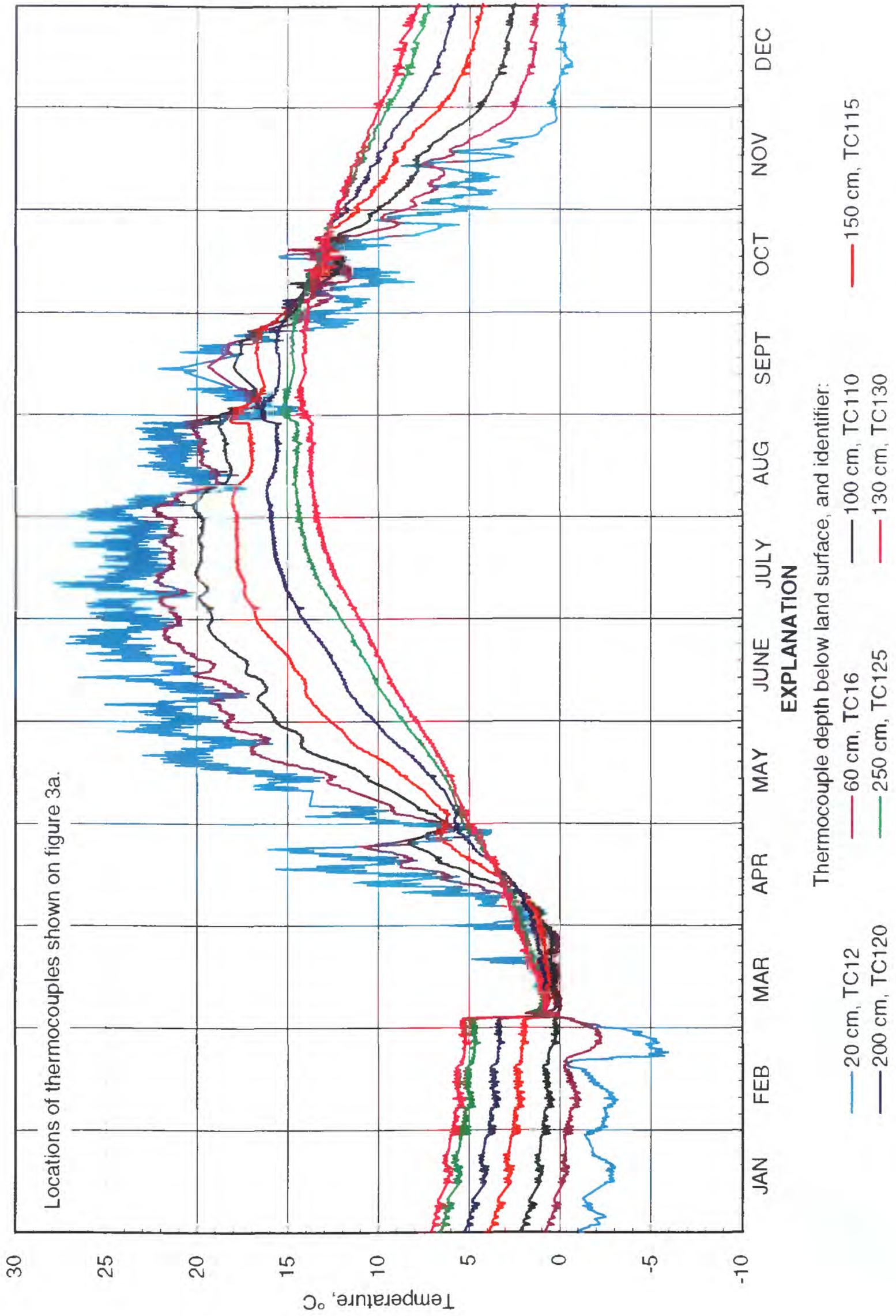
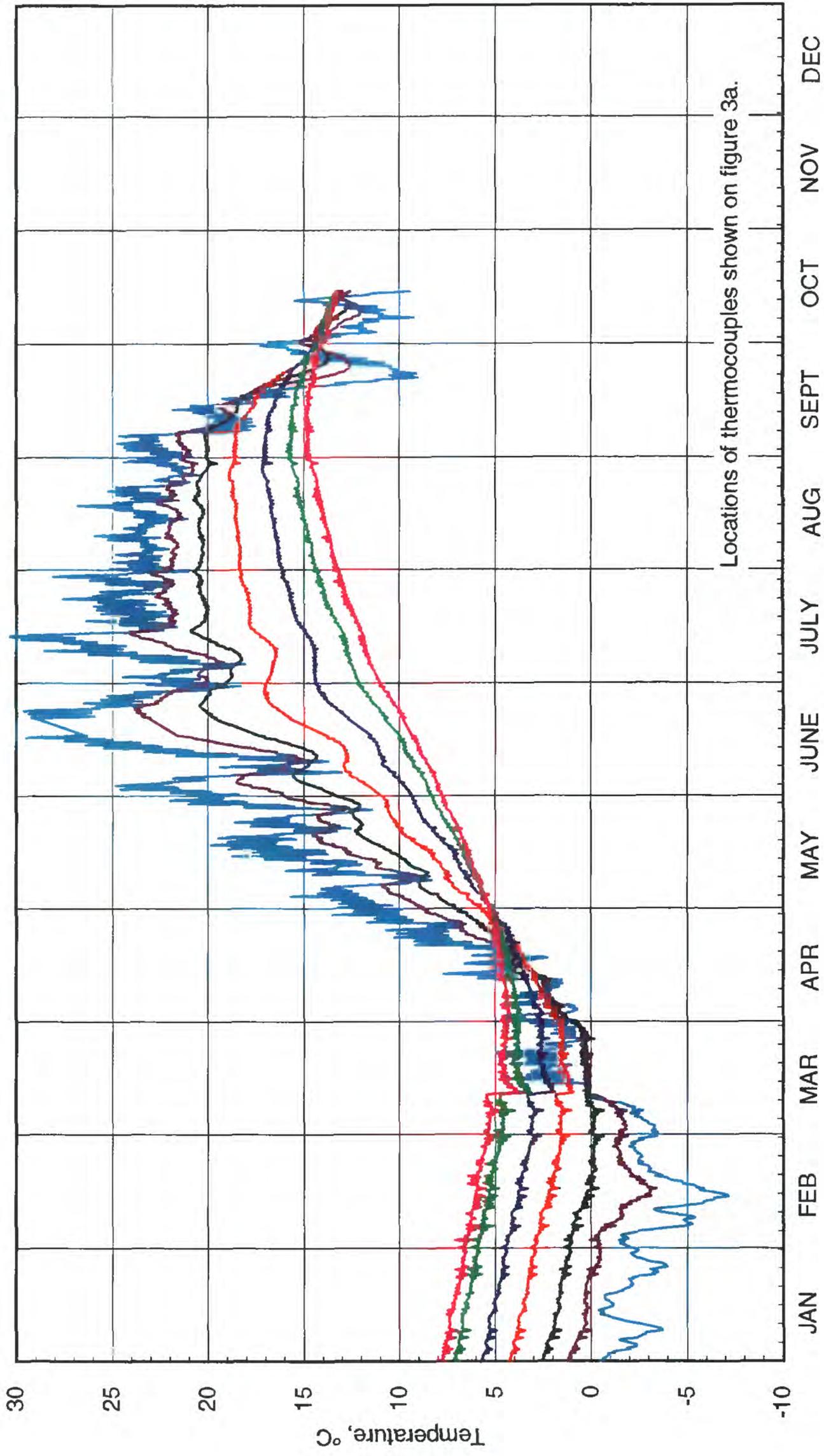


Figure 7c.--Soil temperature from selected depths at the lowland site during 1994.



EXPLANATION

Thermocouple depth below land surface, and identifier:

- 20 cm, TC12 — 60 cm, TC16 — 100 cm, TC110 — 150 cm, TC115
- 200 cm, TC120 — 250 cm, TC125 — 300 cm, TC130

Figure 7d.--Soil temperature from selected depths at the lowland site during 1995.

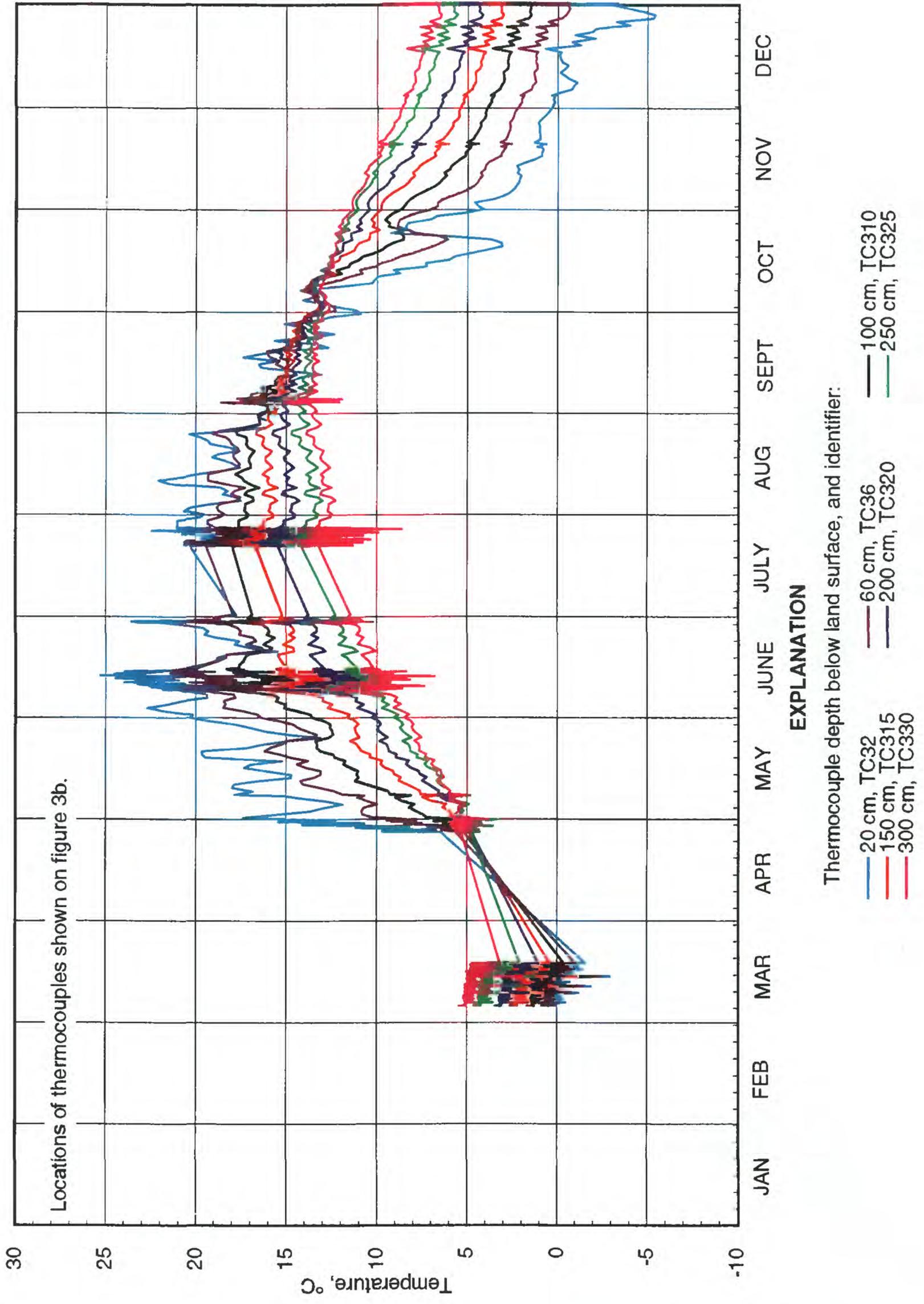


Figure 8a.--Soil temperature from selected depths at the upland site during 1992.

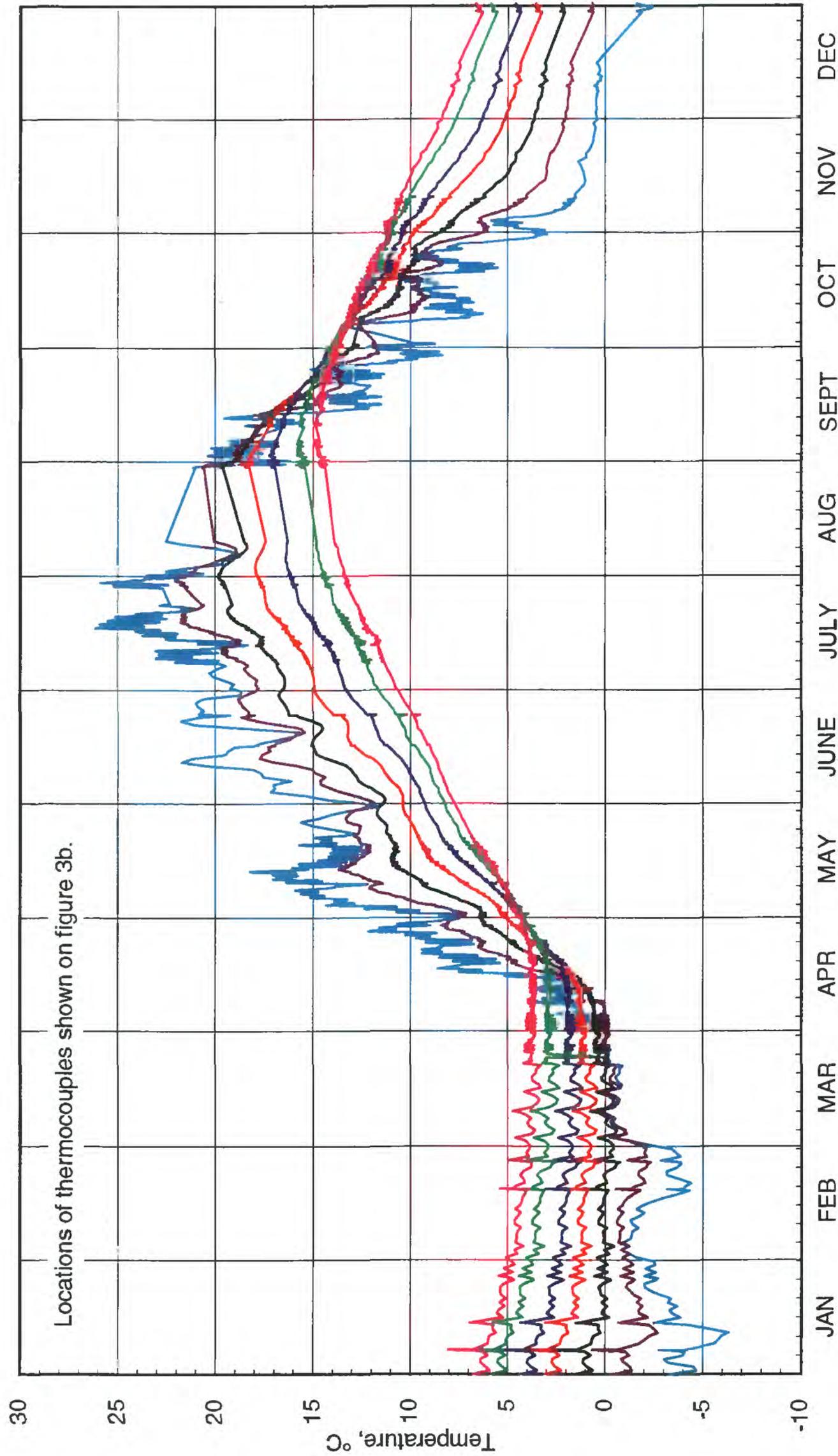
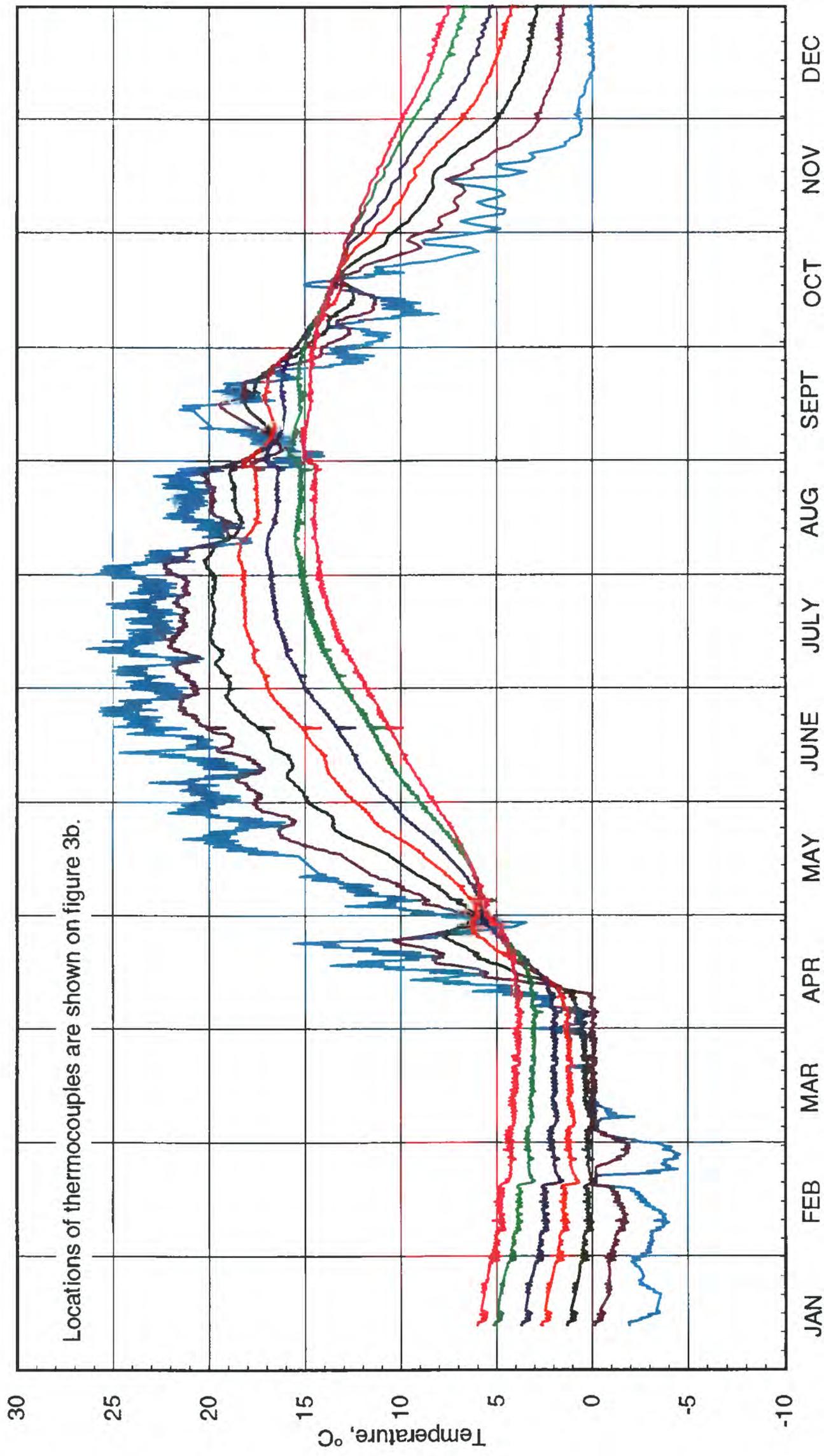


Figure 8b.—Soil temperature from selected depths at the upland site during 1993.



EXPLANATION

Thermocouple depth below land surface, and identifier:

- 20 cm, TC32
- 60 cm, TC36
- 100 cm, TC310
- 150 cm, TC315
- 200 cm, TC320
- 250 cm, TC325
- 300 cm, TC330

Figure 8c.--Soil temperature from selected depths at the upland site during 1994.

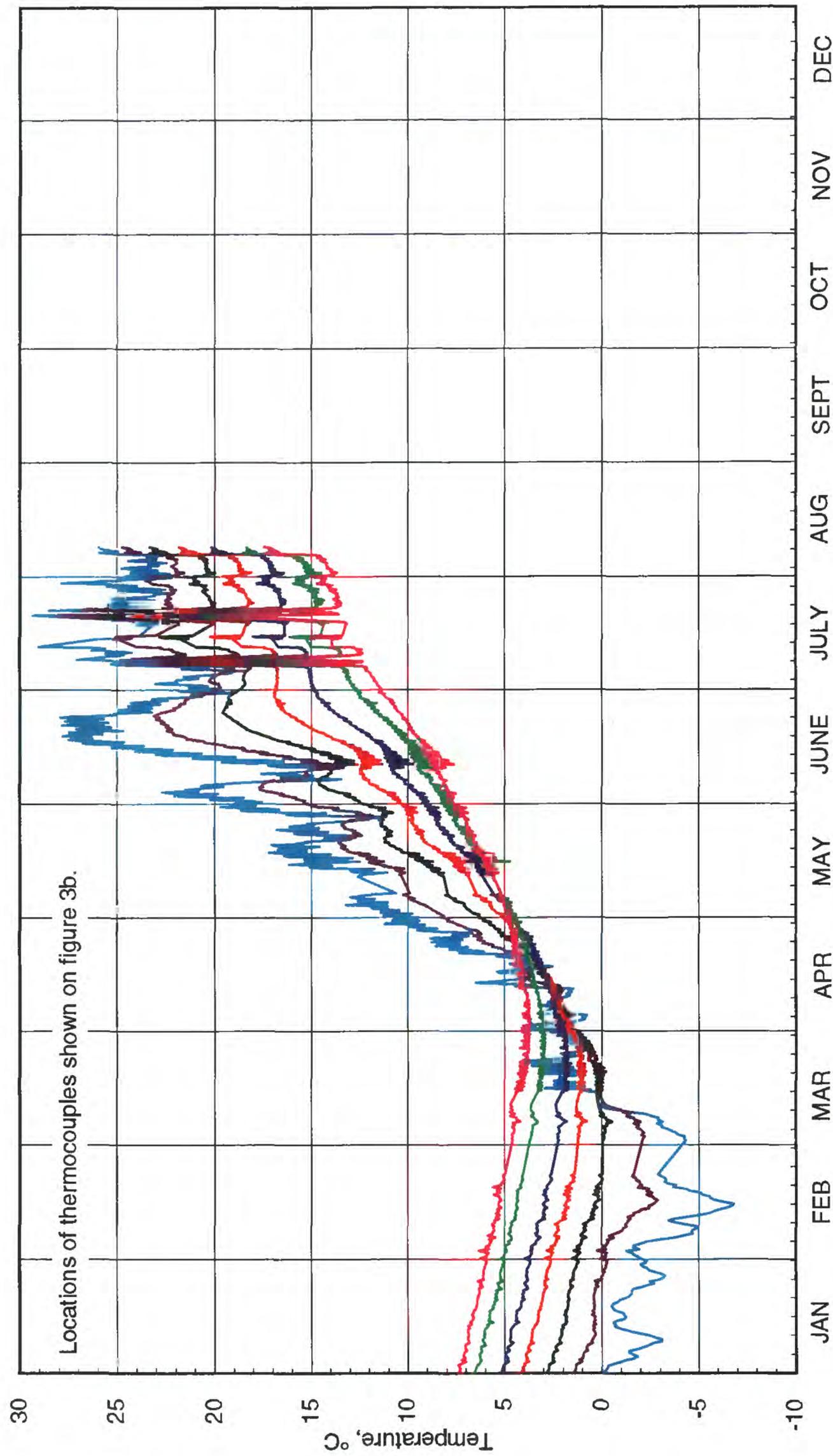


Figure 8d.--Soil temperature from selected depths at the upland site during 1995.

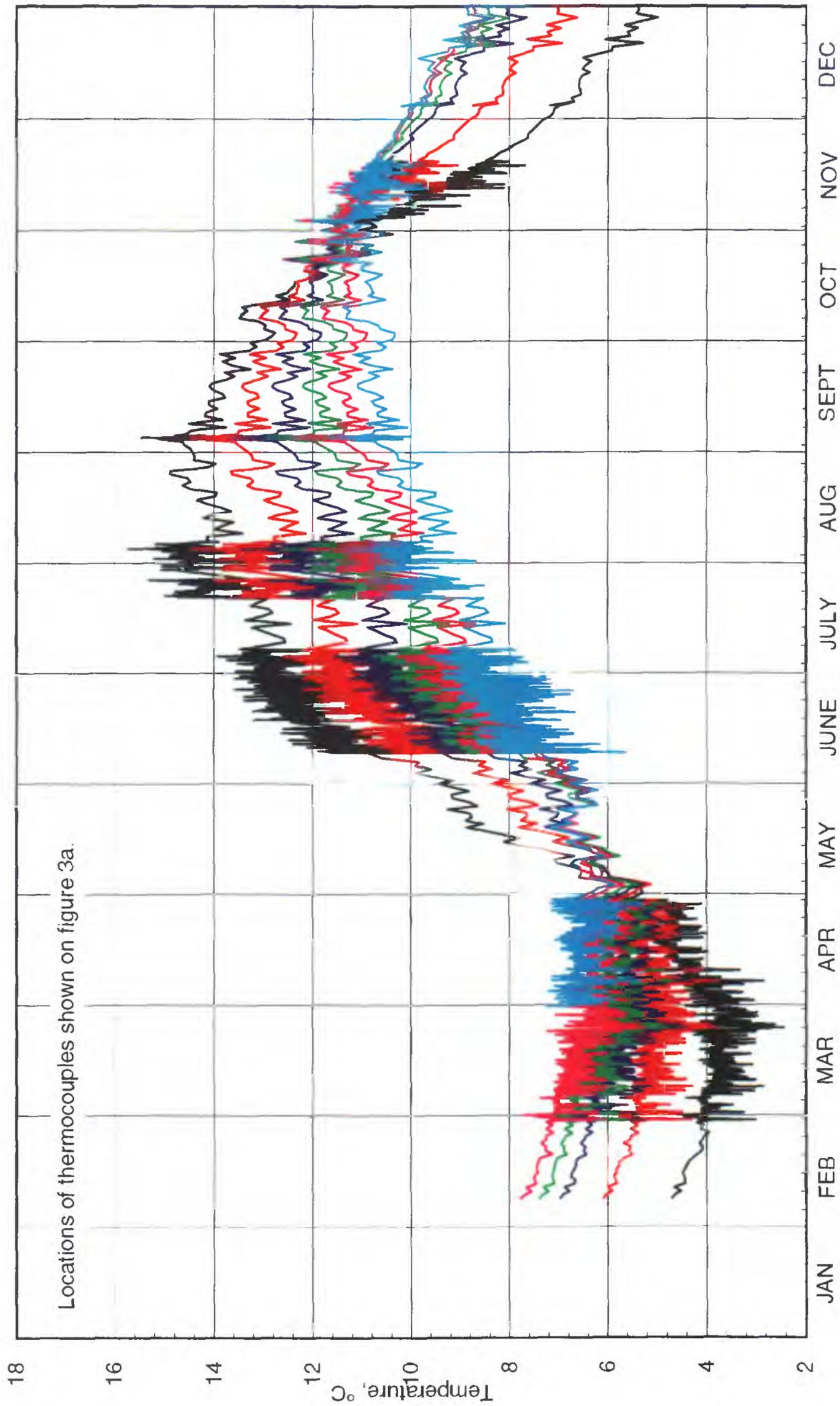


Figure 9a.--Soil temperature from the upper 2 meters of the saturated zone at the lowland site during 1992.

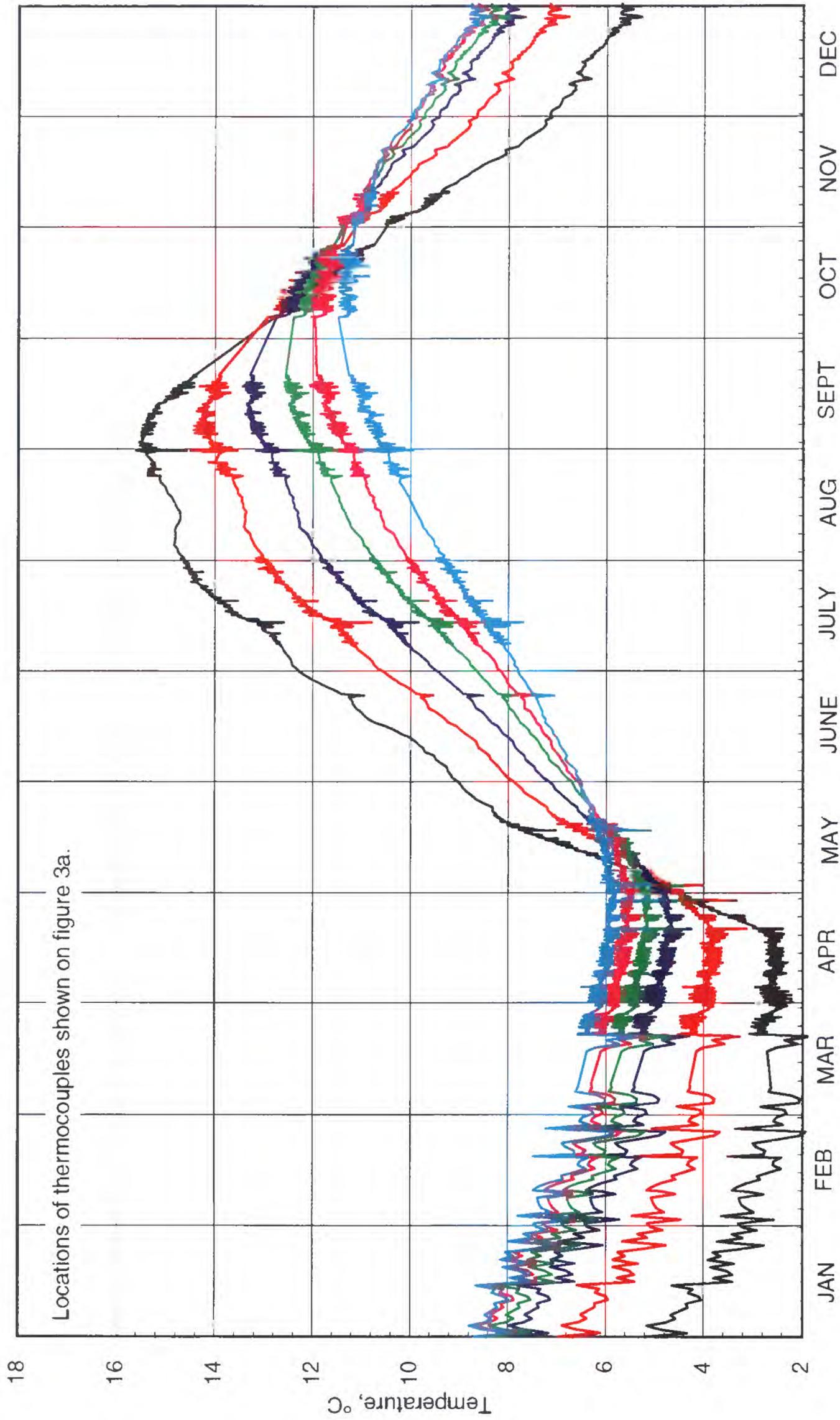
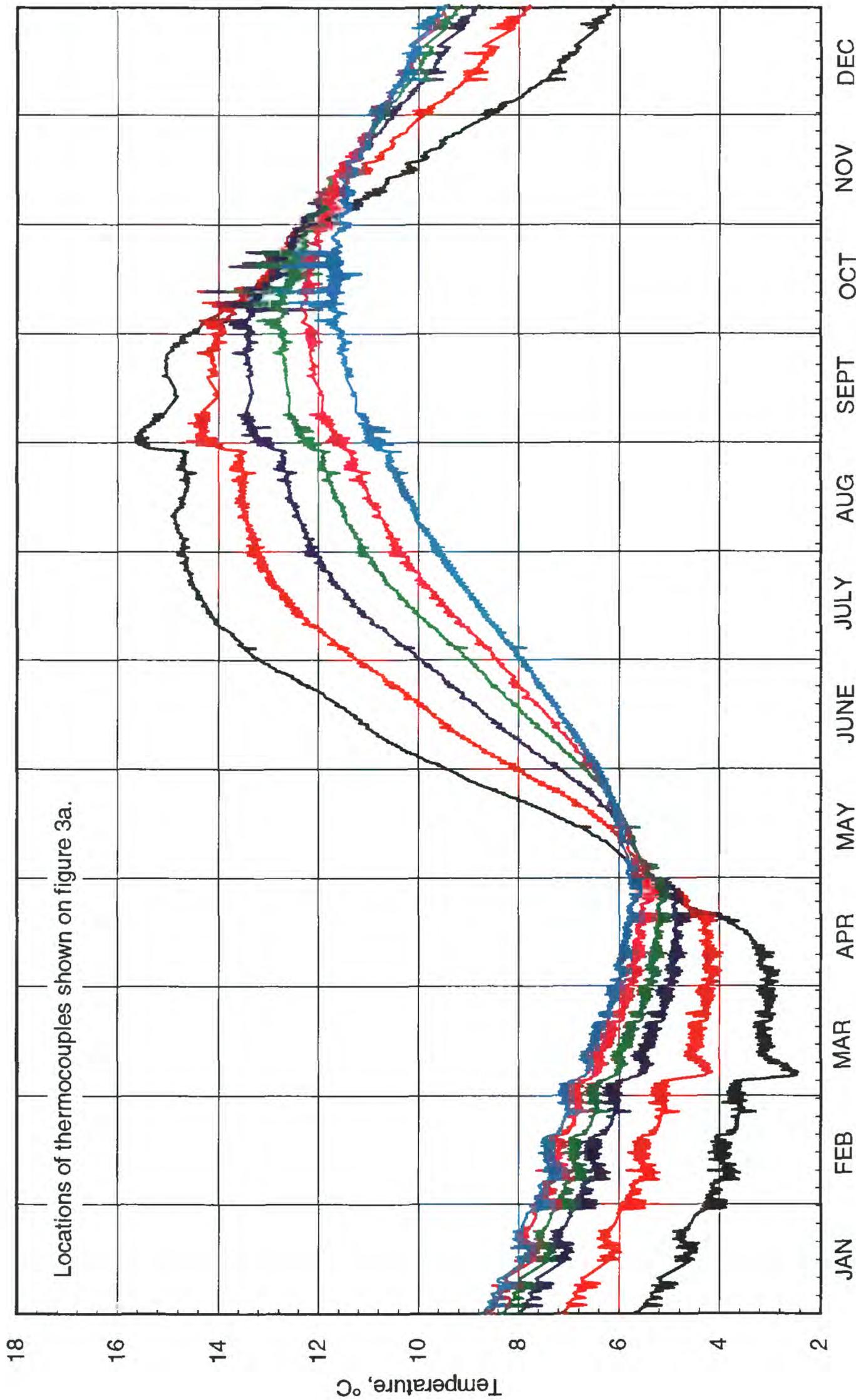


Figure 9b.--Soil temperature from the upper 2 meters of the saturated zone at the lowland site during 1993.



EXPLANATION

Thermocouple depth below land surface, and identifier:

- 220 cm, TC1 — 270 cm, TC2 — 320 cm, TC3 — 370 cm, TC4 — 420 cm, TC5 — 470 cm, TC6

Figure 9c.--Soil temperature from the upper 2 meters of the saturated zone at the lowland site during 1994.

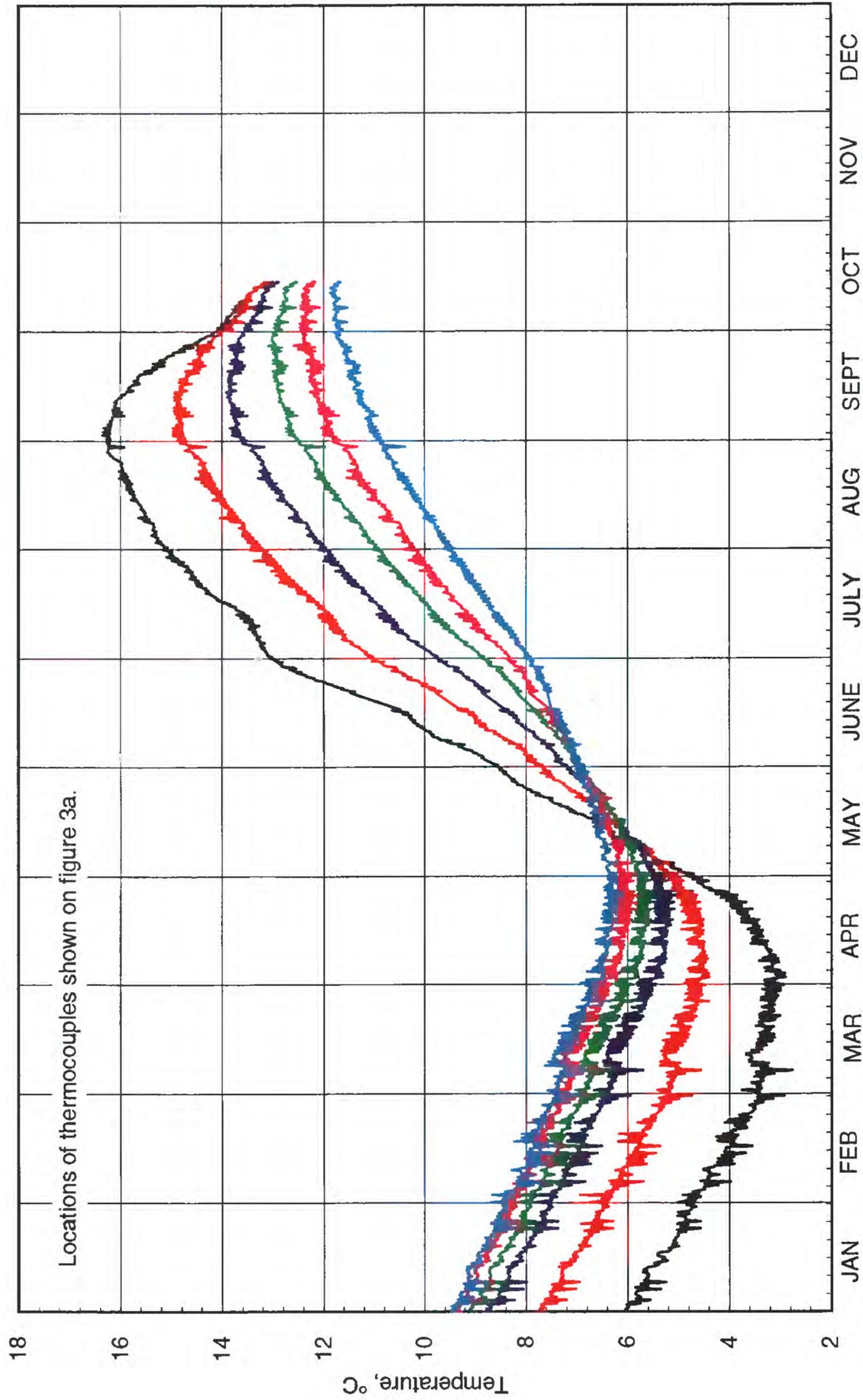


Figure 9d.--Soil temperature from the upper 2 meters of the saturated zone at the lowland site during 1995.

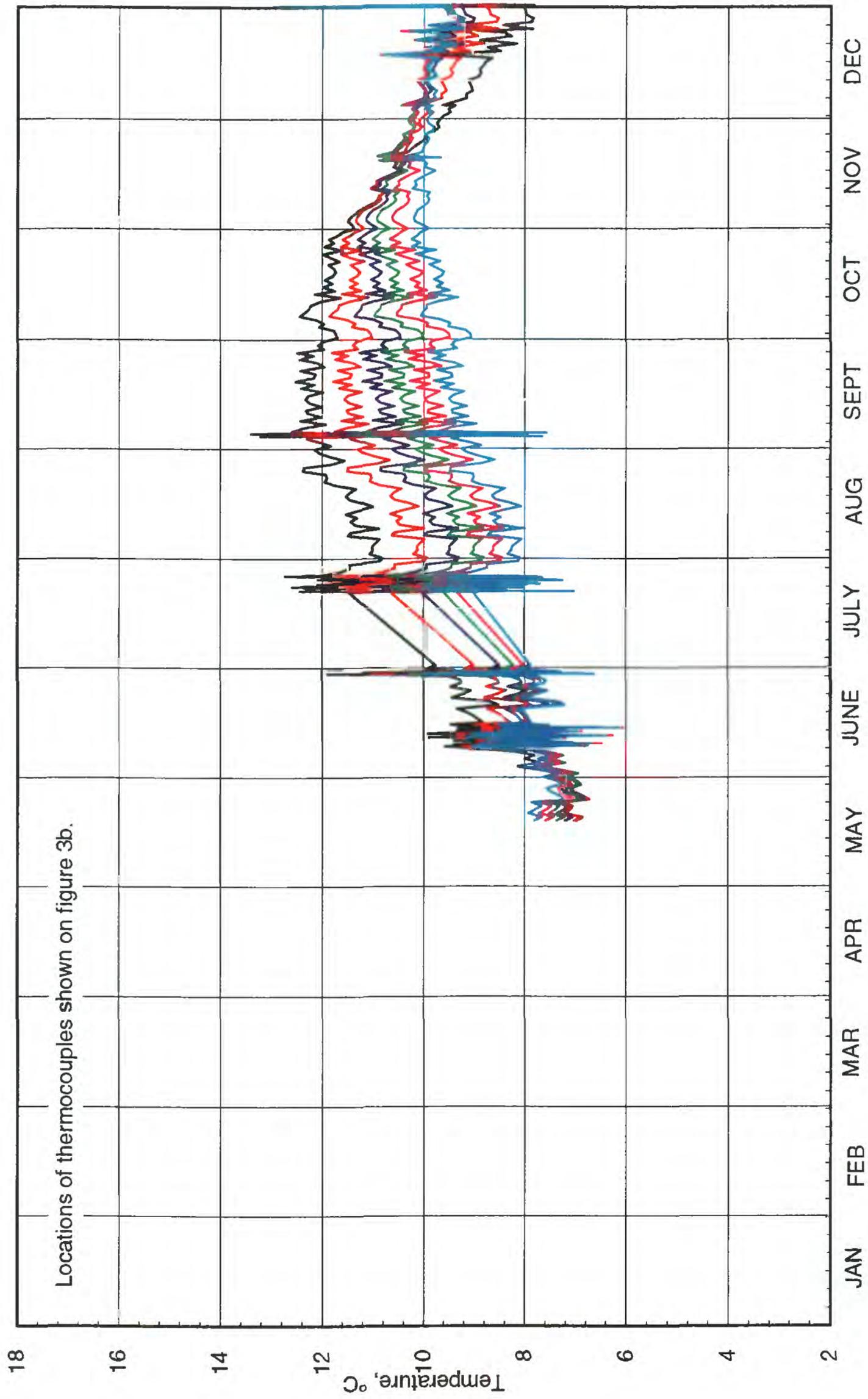


Figure 10a.--Soil temperature from the upper 2 meters of the saturated zone at the upland site during 1992.

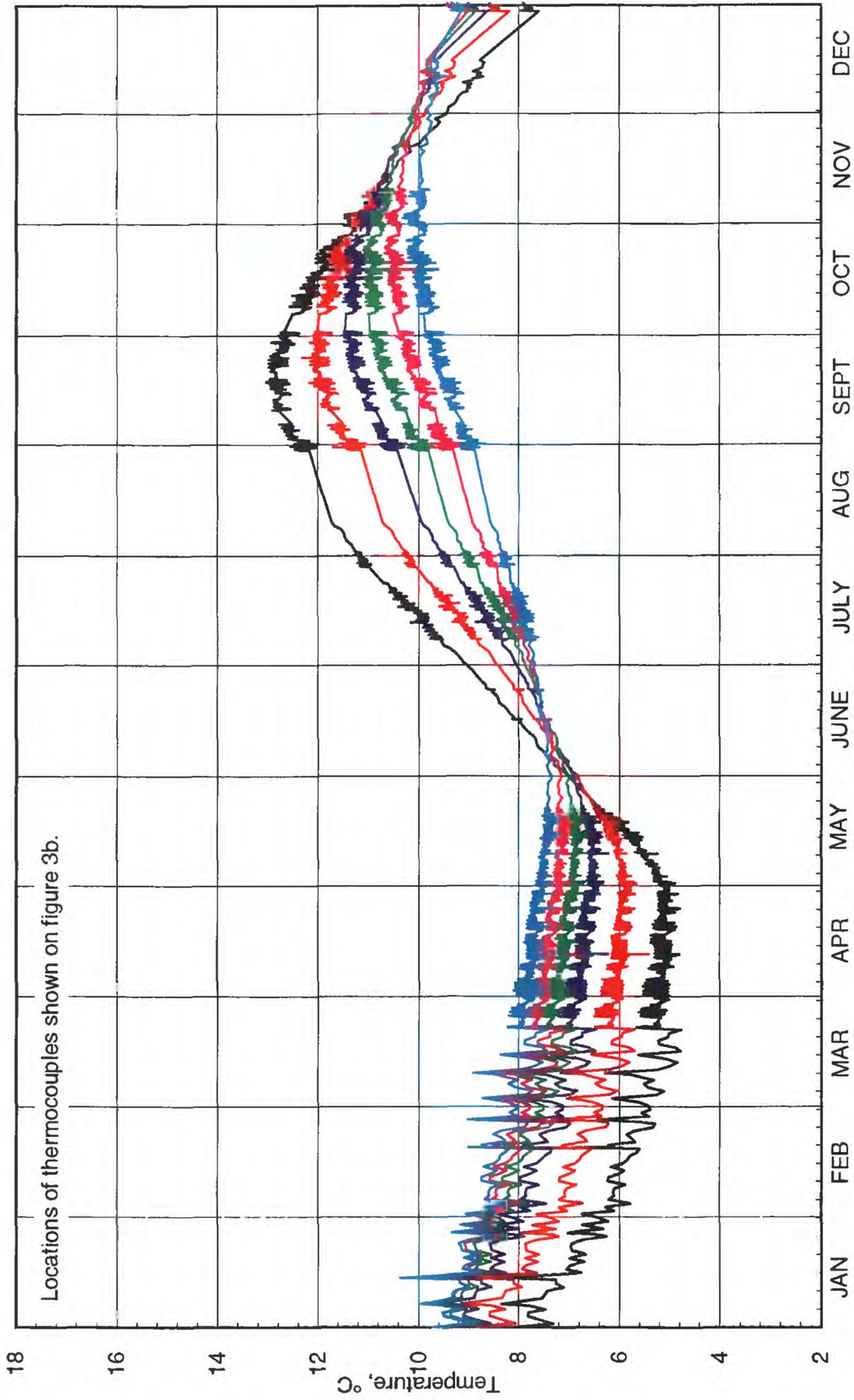


Figure 10b.--Temperature from the upper 2 meters of the saturated zone at the upland site during 1993.

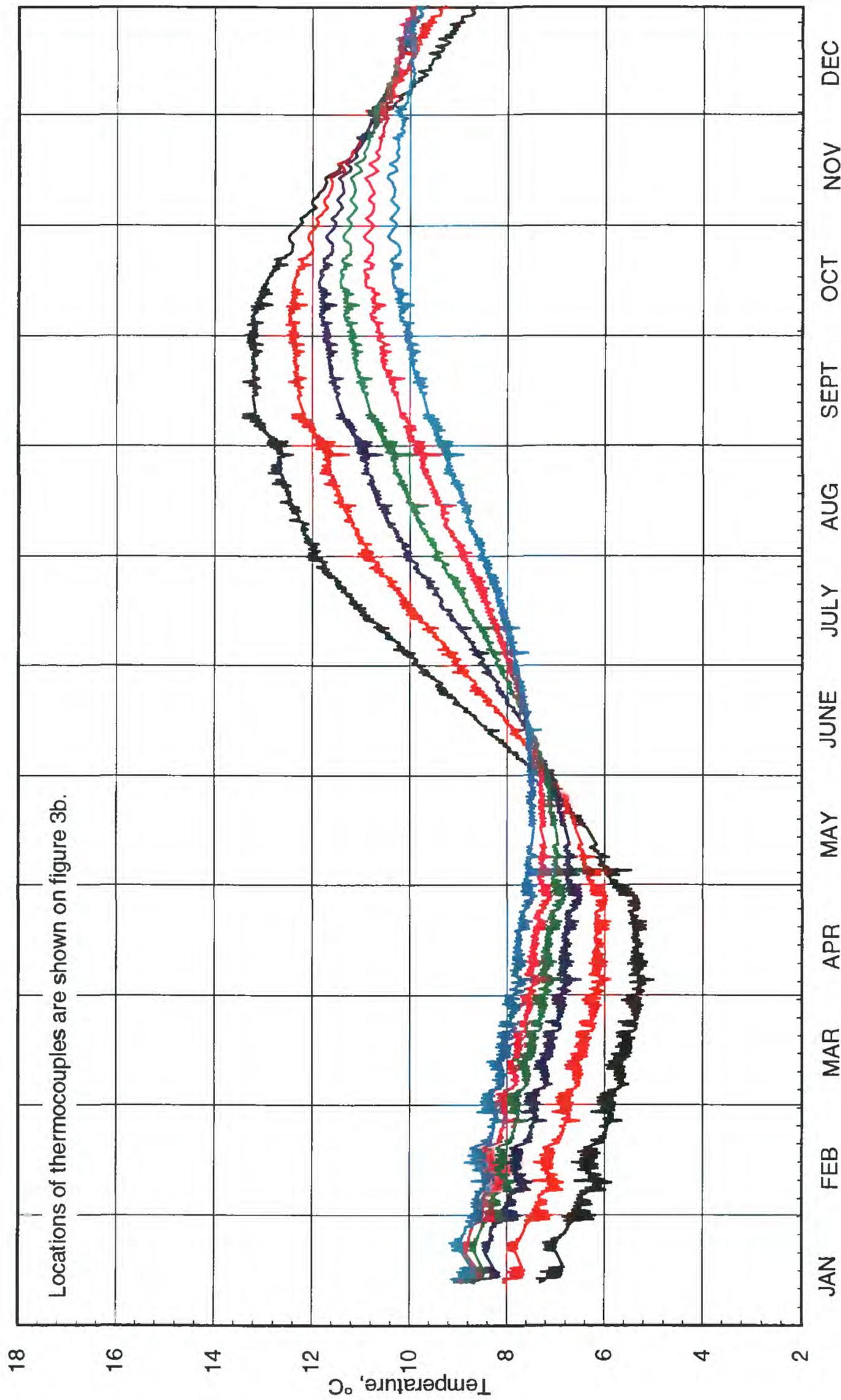
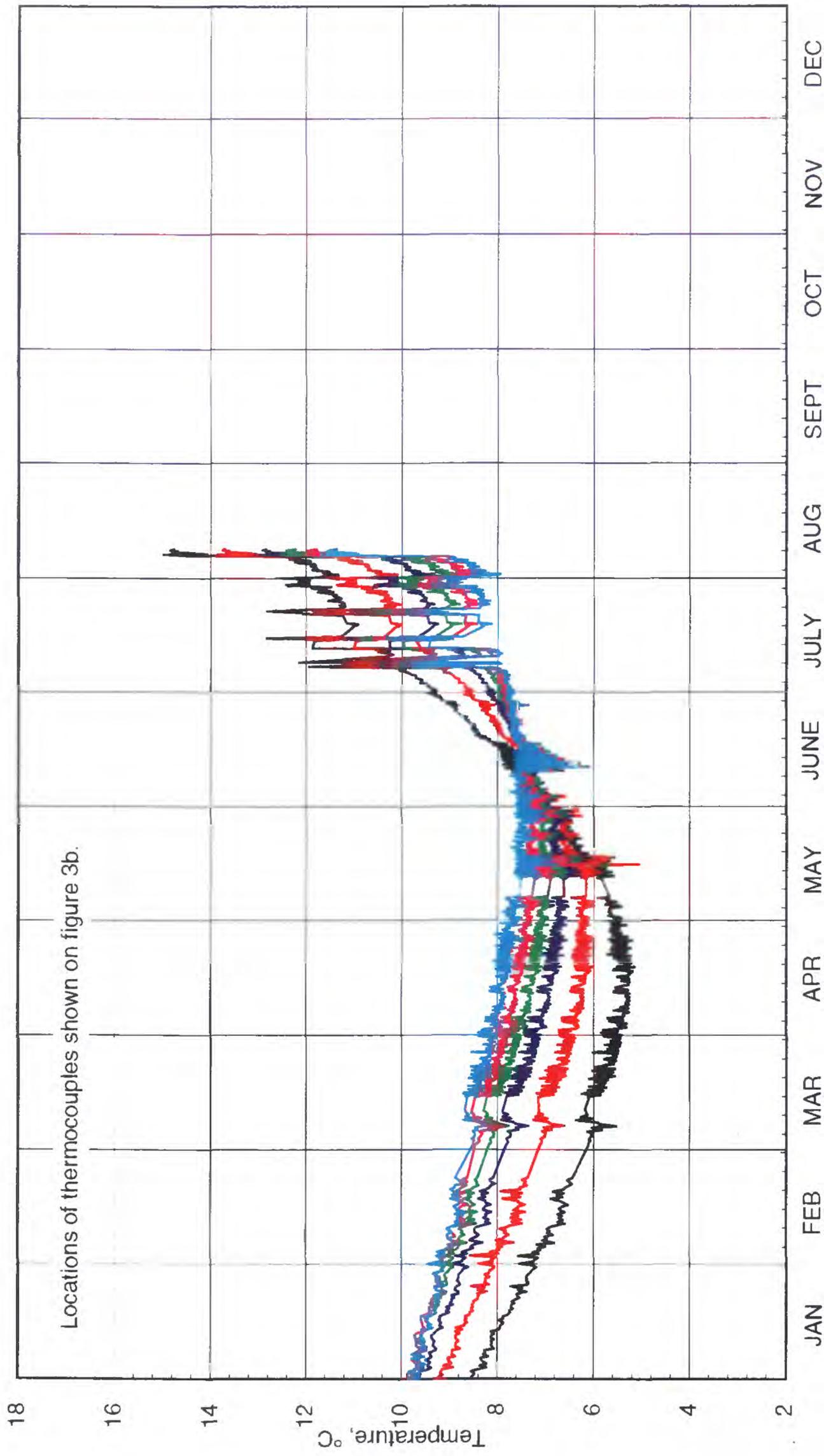


Figure 10c.--Soil temperature from the upper 2 meters of the saturated zone at the upland site during 1994.



EXPLANATION

Thermocouple depth below land surface, and identifier:

- 410 cm, TC1 — 460 cm, TC2 — 510 cm, TC3 — 560 cm, TC4 — 610 cm, TC5 — 660 cm, TC6

Figure 10d.--Soil temperature from the upper 2 meters of the saturated zone at the upland site during 1995.

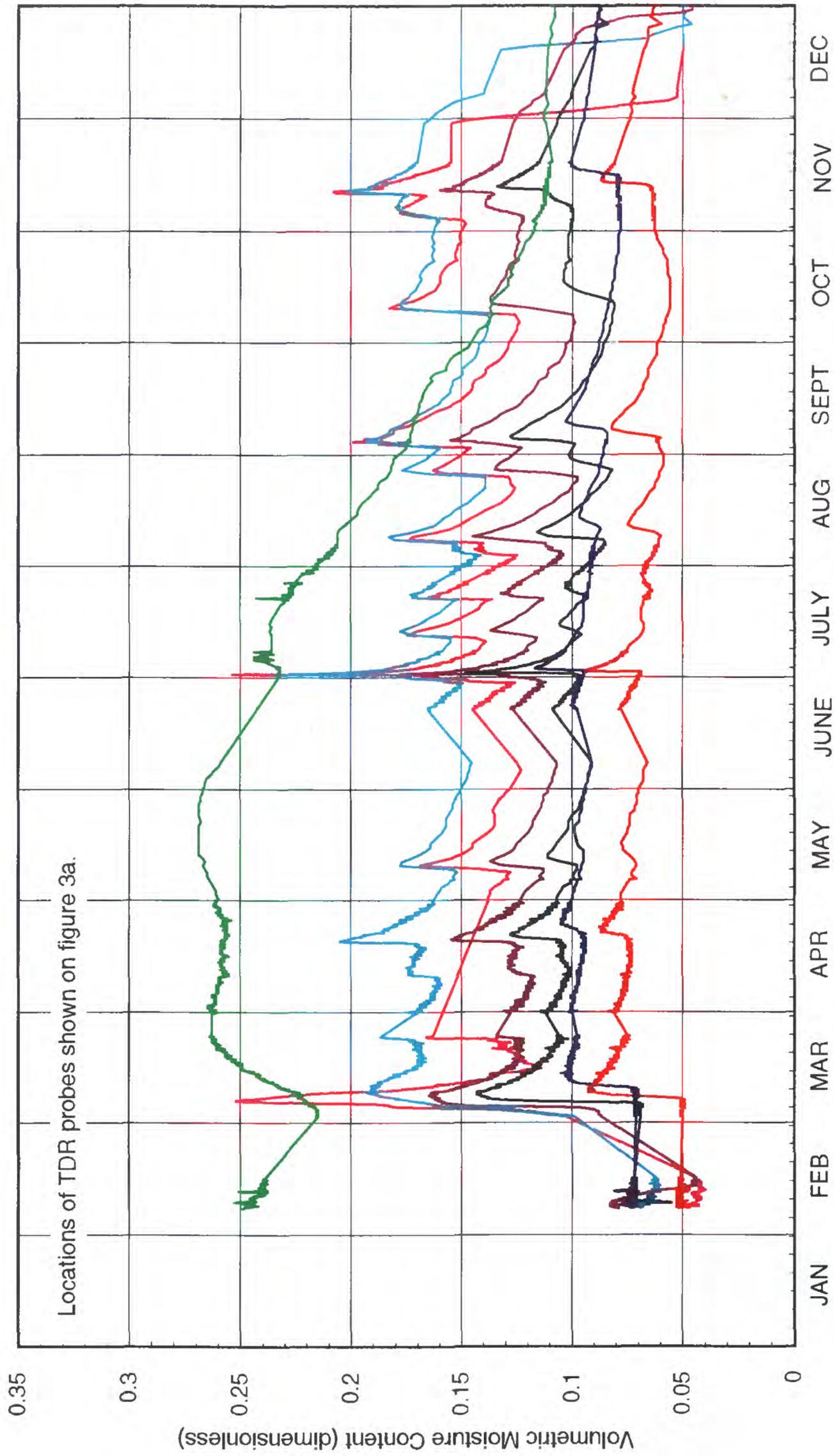
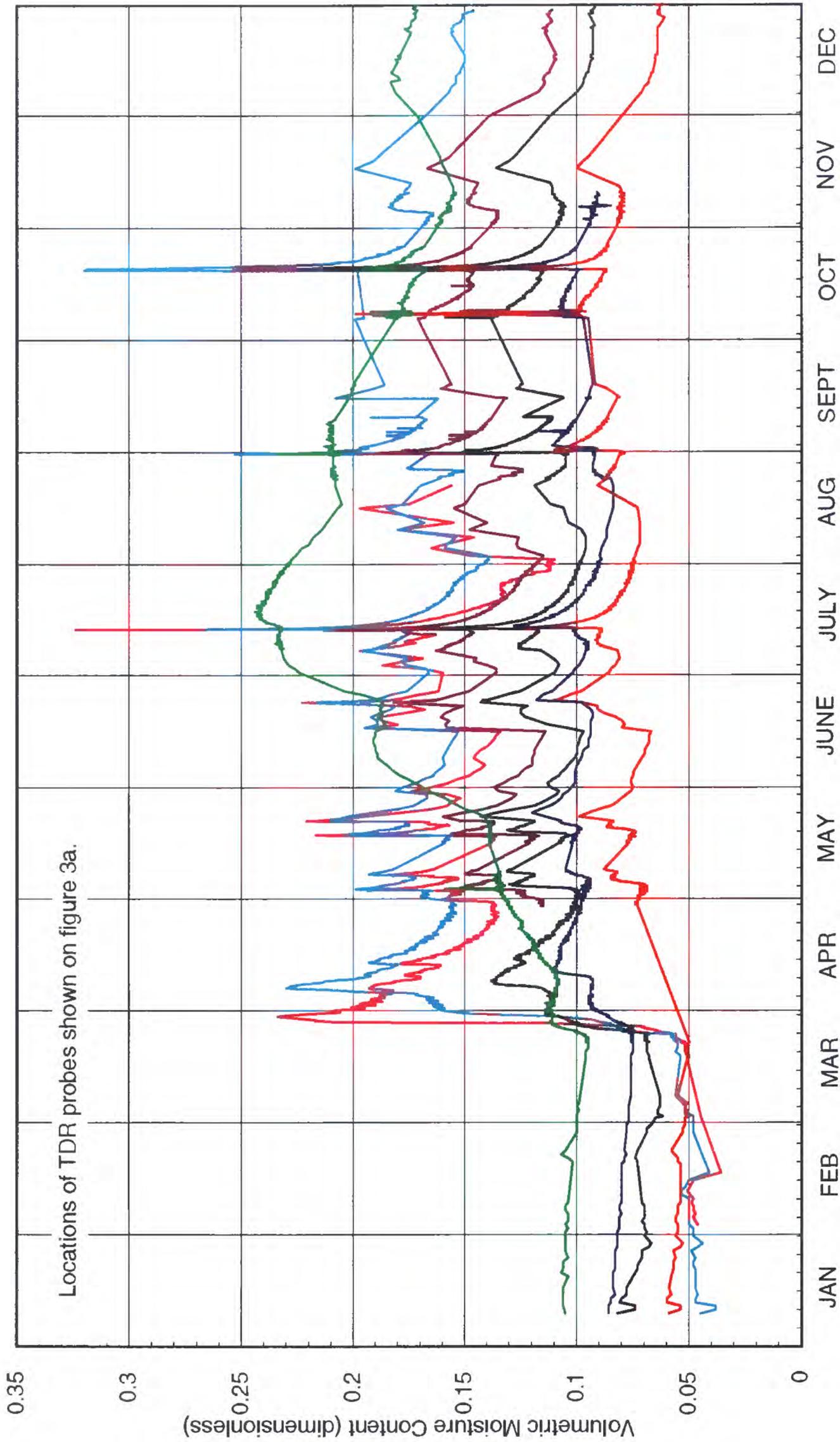


Figure 11a.--Volumetric moisture content from selected depths at the lowland site during 1992.



EXPLANATION

TDR probe depth below land surface, and identifier:

- 20 cm, TDR 52 — 40 cm, TDR 54 — 60 cm, TDR 56 — 100 cm, TDR 510 — 150 cm, TDR 515
- 200 cm, TDR 520 — 250 cm, TDR 525

Figure 11b.--Volumetric moisture content from selected depths at the lowland site during 1993.

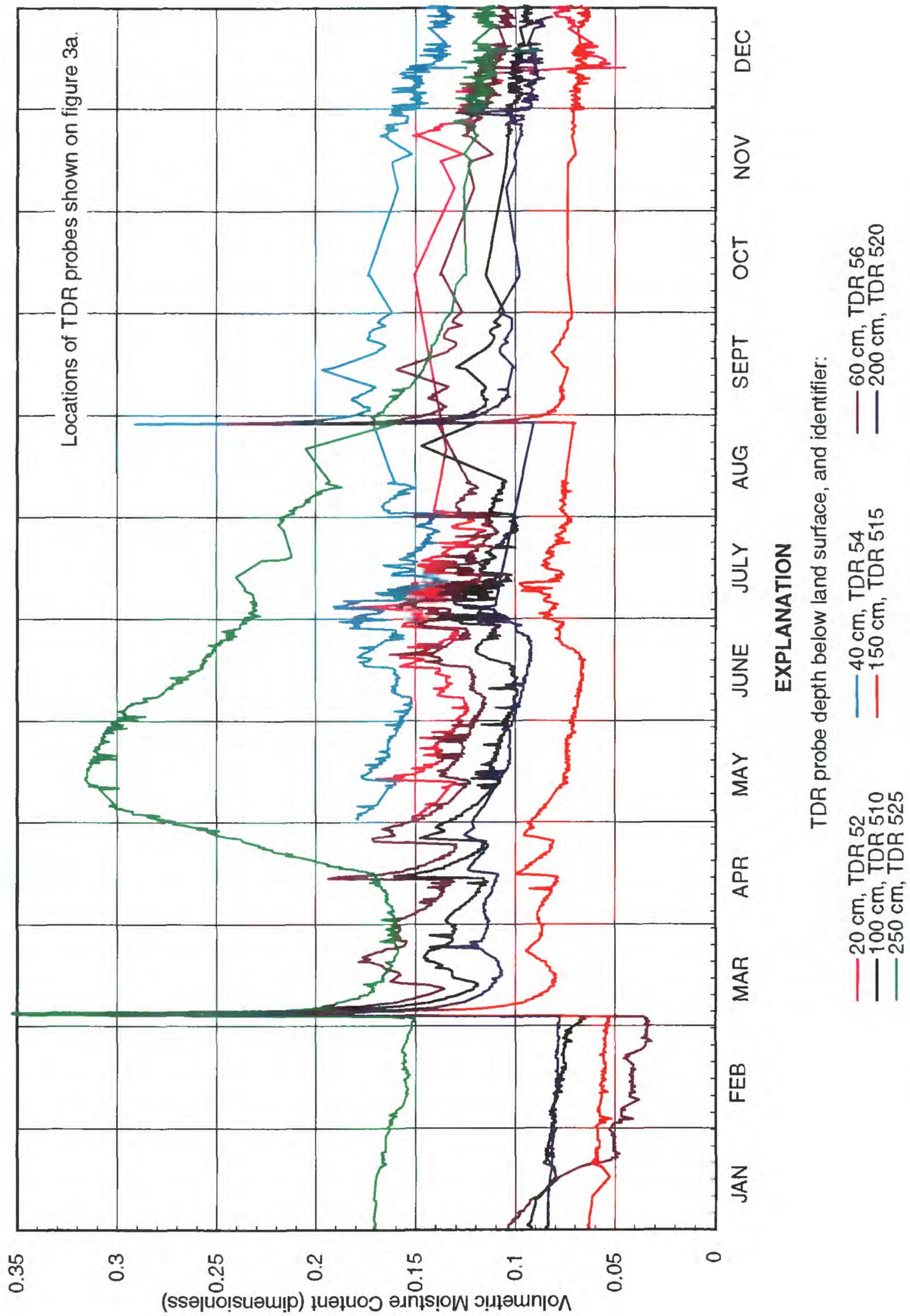
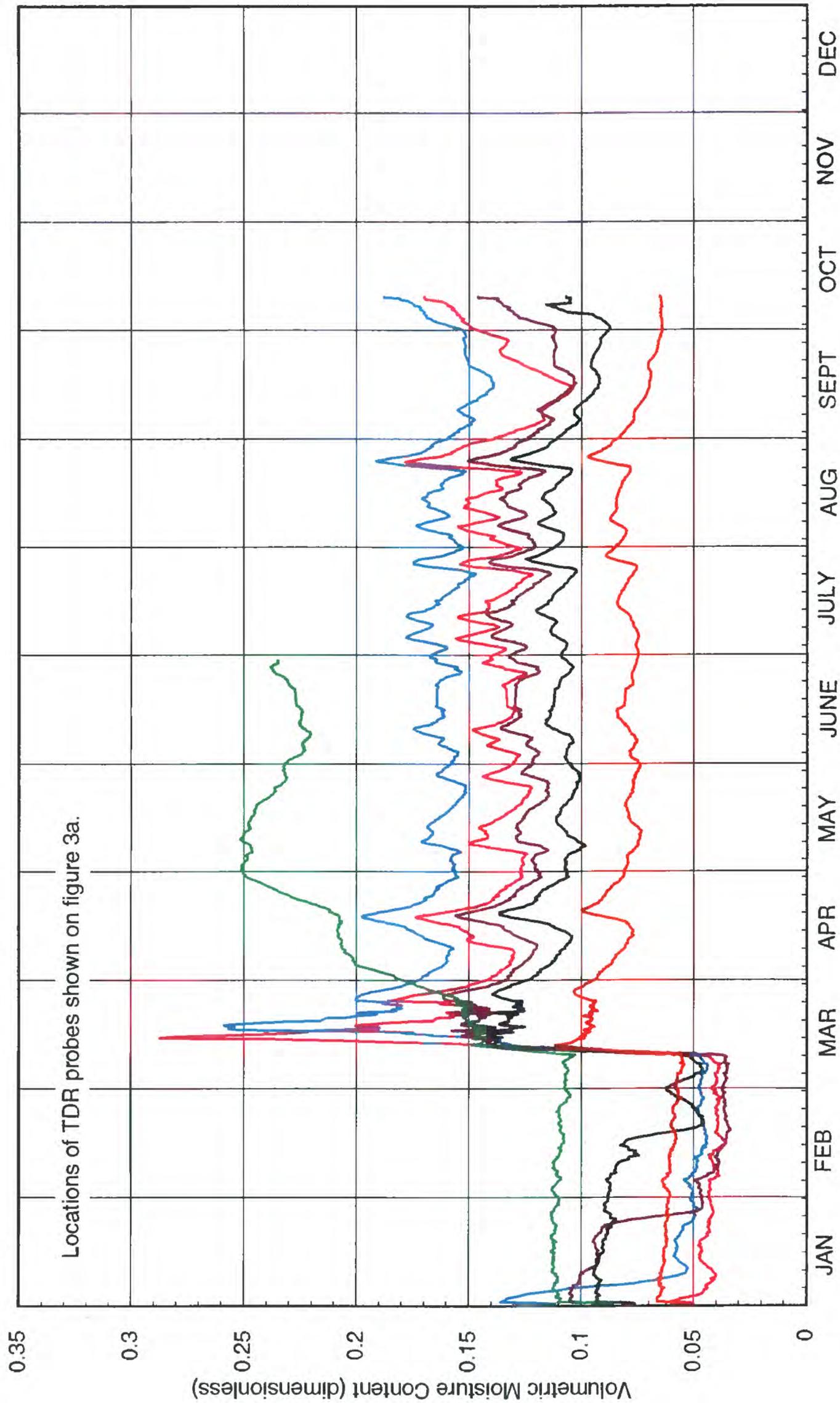


Figure 11c.--Volumetric moisture content from selected depths at the lowland site during 1994.



EXPLANATION

TDR probe depth below land surface, and identifier:

- 20 cm, TDR 52
- 40 cm, TDR 54
- 60 cm, TDR 56
- 100 cm, TDR 510
- 150 cm, TDR 515
- 250 cm, TDR 525

Figure 11d.--Volumetric moisture content from selected depths at the lowland site during 1995.

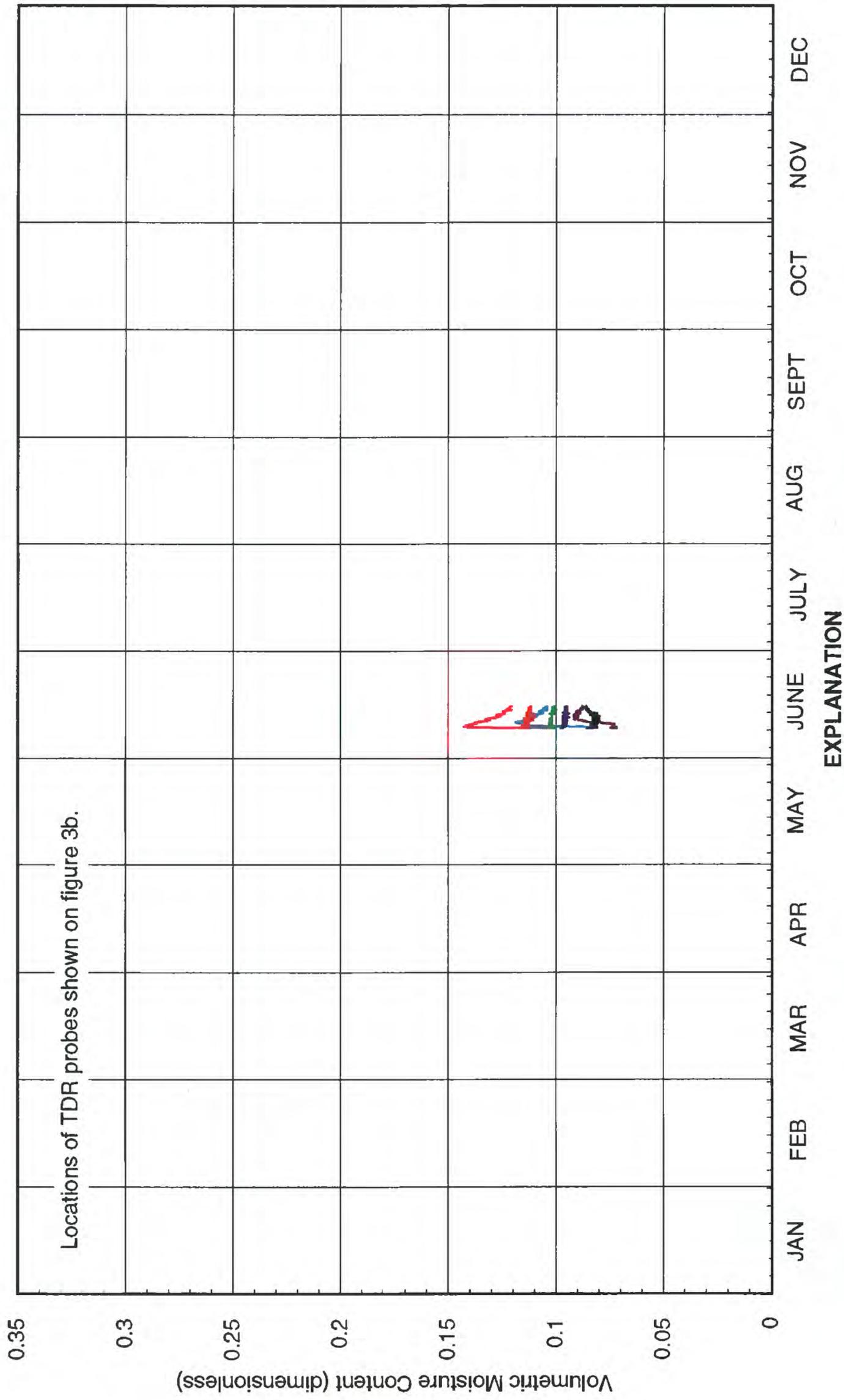
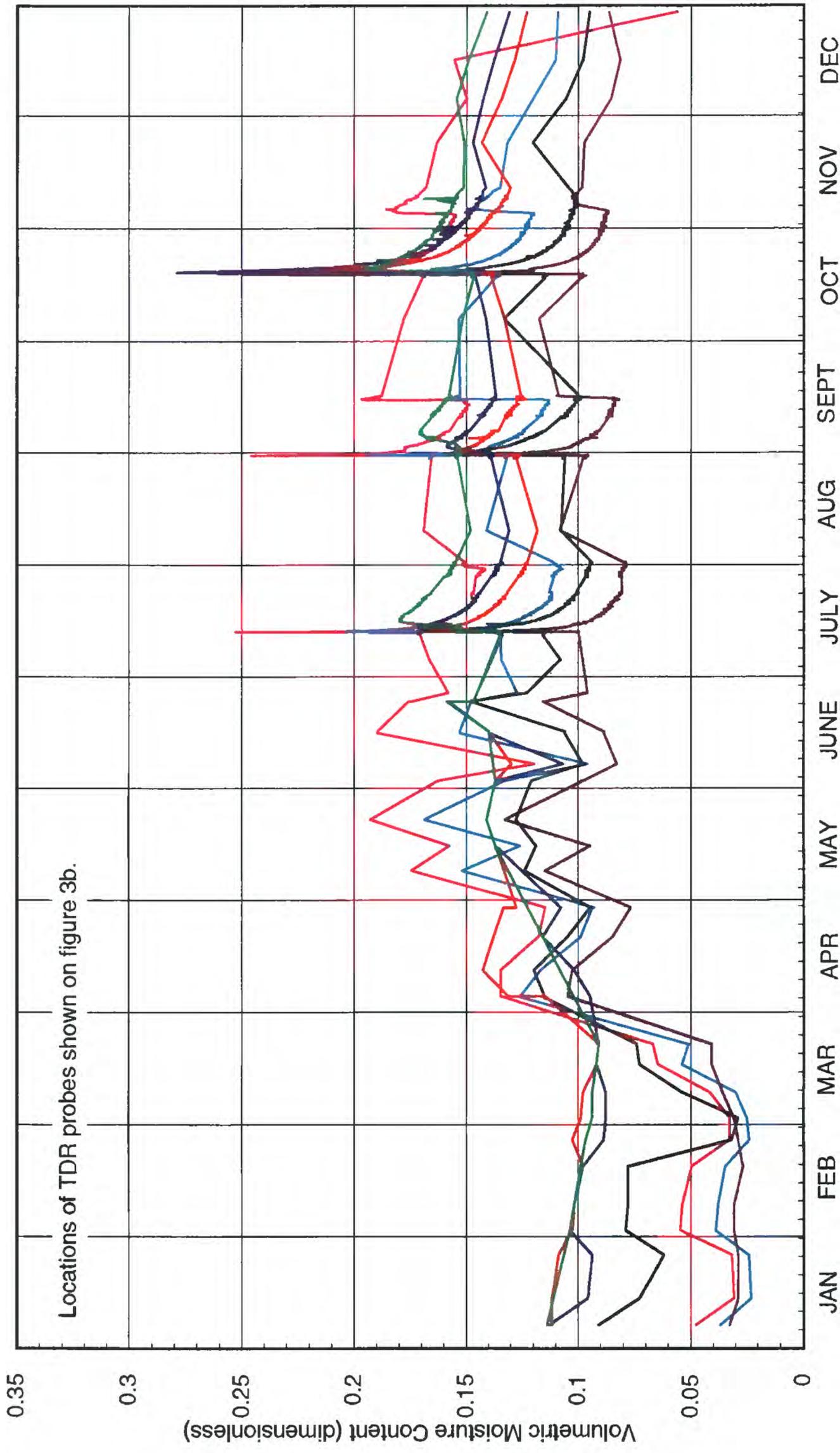


Figure 12a.--Volumetric moisture content from selected depths at the upland site during 1992.

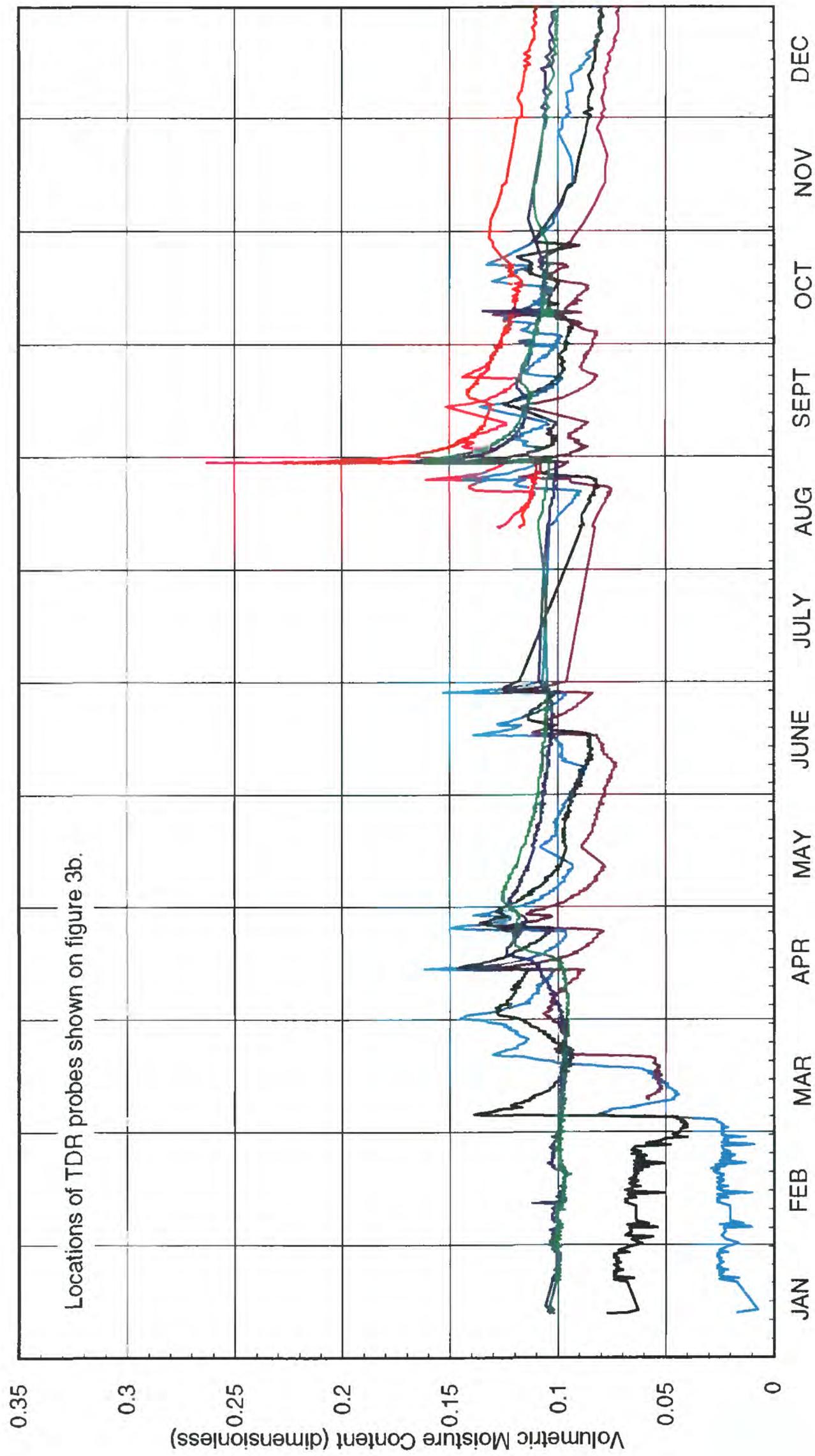


EXPLANATION

TDR probe depth below land surface, and identifier:

- 20 cm, TDR 72
- 40 cm, TDR 74
- 60 cm, TDR 76
- 100 cm, TDR 710
- 150 cm, TDR 715
- 200 cm, TDR 720
- 300 cm, TDR 730
- 730 cm, TDR 730

Figure 12b.—Volumetric moisture content from selected depths at the upland site during 1993.

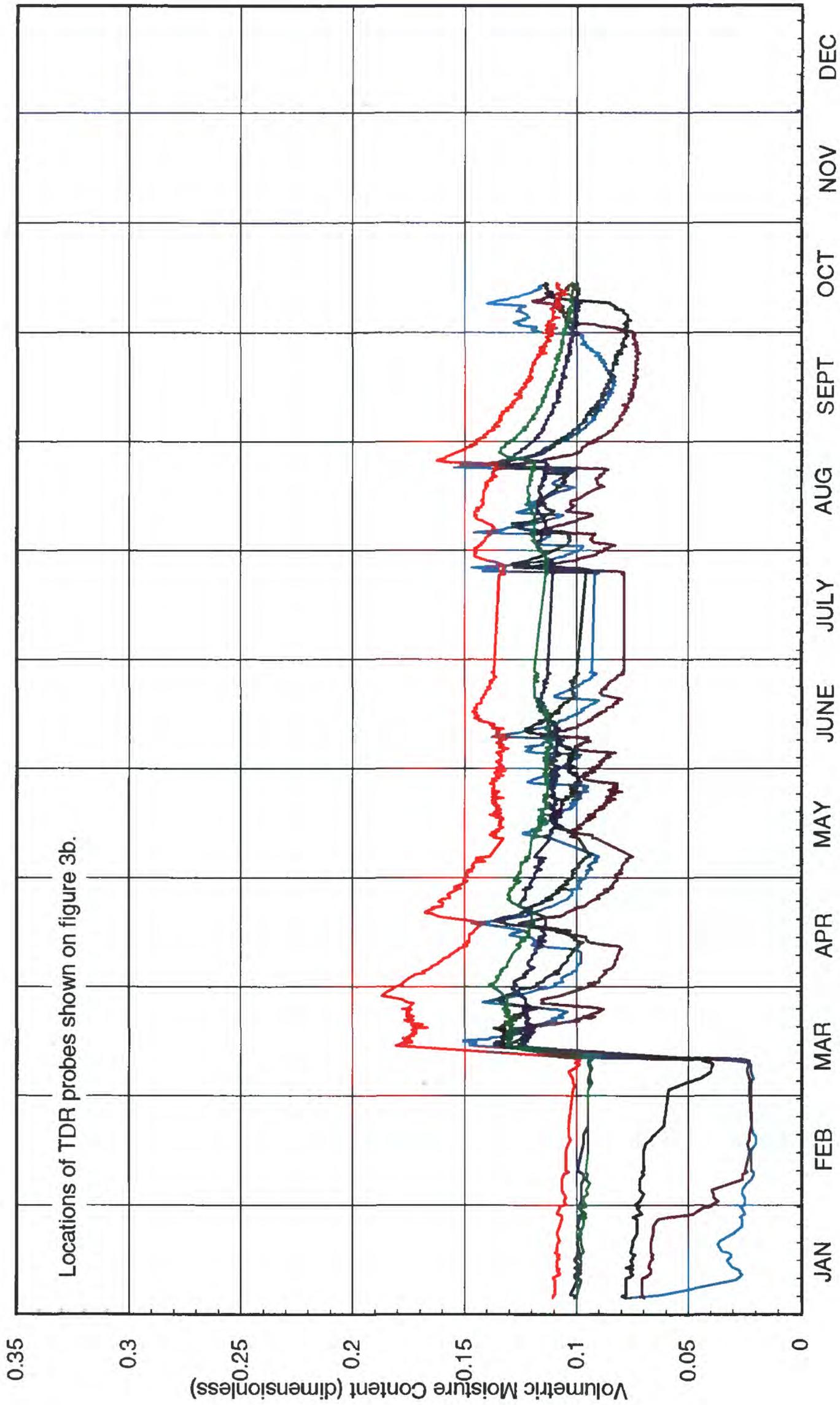


EXPLANATION

TDR probe depth below land surface, and identifier:

-
 20 cm, TDR 72
-
 40 cm, TDR 74
-
 60 cm, TDR 76
-
 100 cm, TDR 710
-
 150 cm, TDR 715
-
 200 cm, TDR 720
-
 250 cm, TDR 725

Figure 12c.--Volumetric moisture content from selected depths at the upland site during 1994.



EXPLANATION

TDR probe depth below land surface, and identifier:

- 40 cm, TDR 74
- 60 cm, TDR 76
- 100 cm, TDR 710
- 150 cm, TDR 715
- 200 cm, TDR 720
- 250 cm, TDR 725

Figure 12d.--Volumetric moisture content from selected depths at the upland site during 1995.

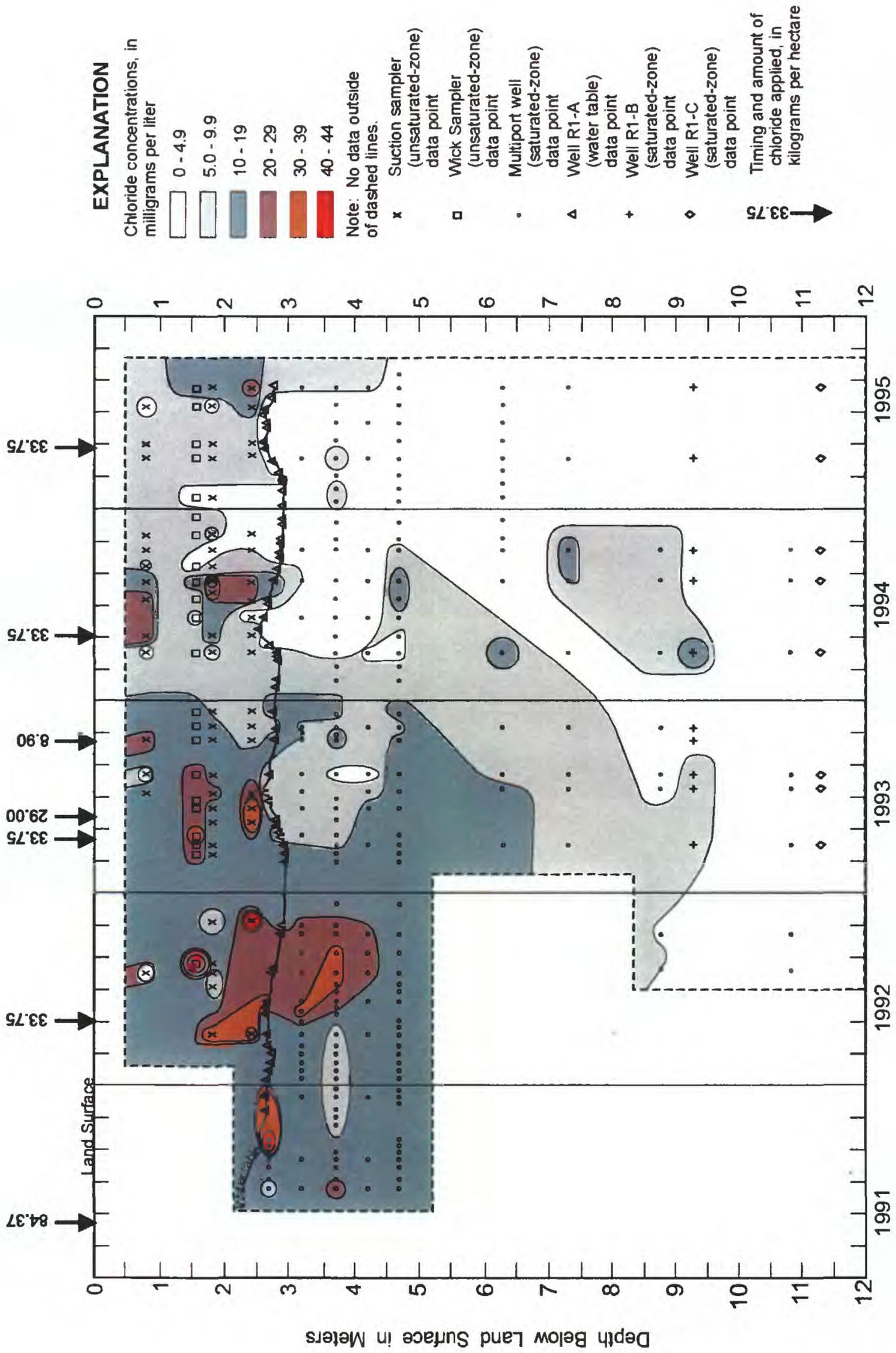


Figure 13.—Time series of chloride concentrations at the lowland site.

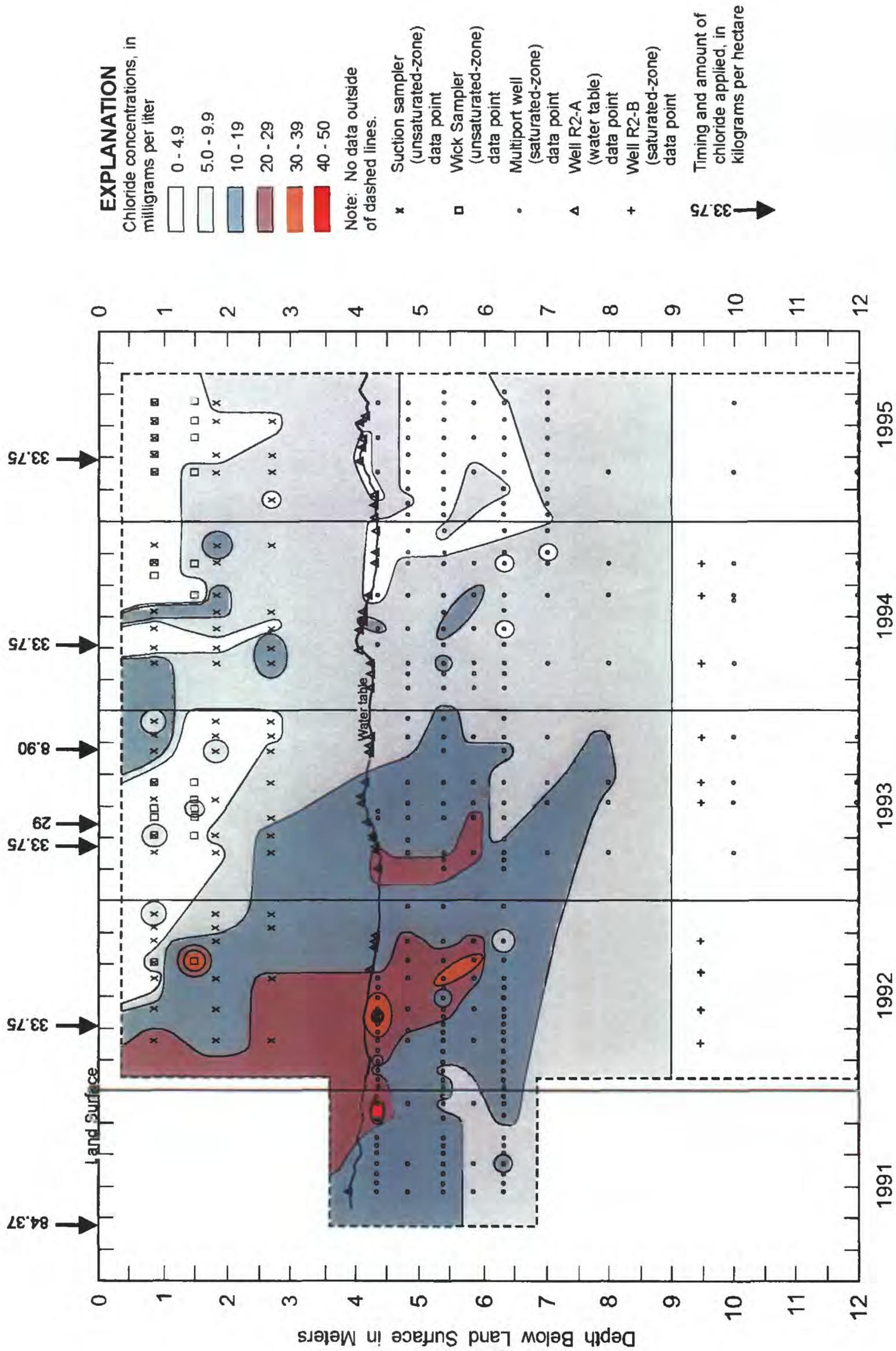


Figure 14.—Time series of chloride concentrations at the upland site.

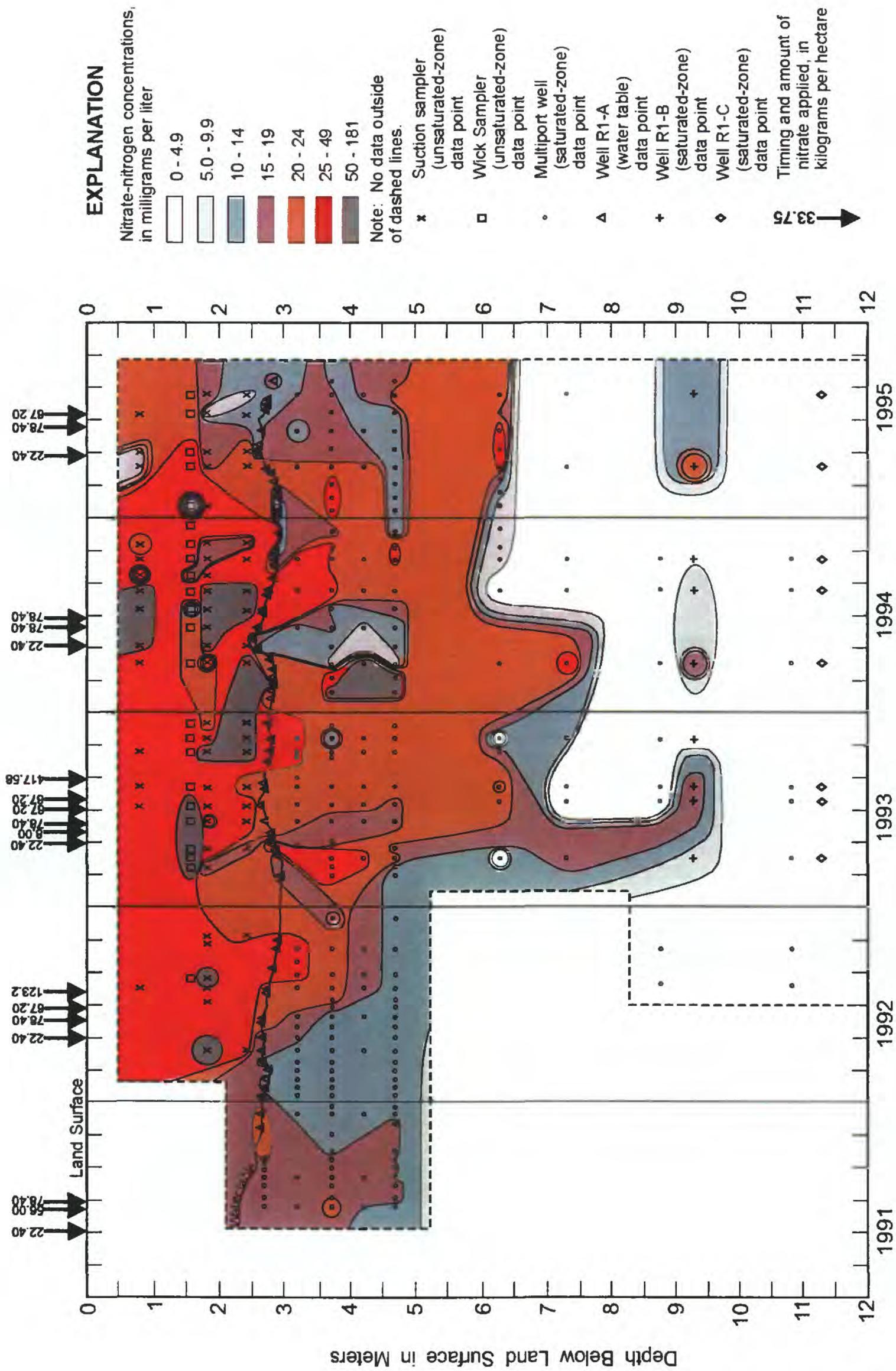


Figure 15.—Time series of nitrate-nitrogen concentrations at the lowland site.

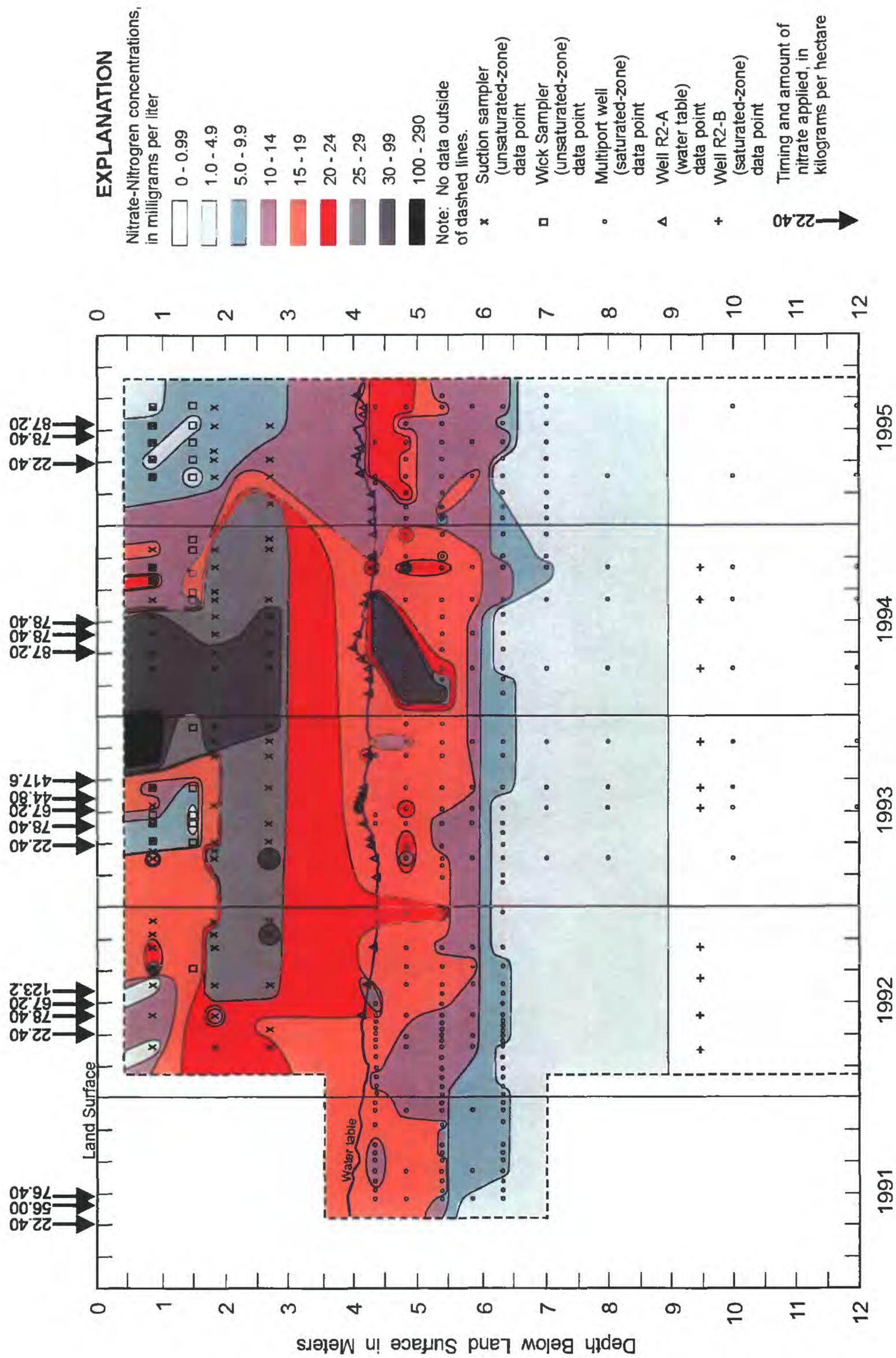


Figure 16.—Time series of nitrate-nitrogen concentrations at the upland site.

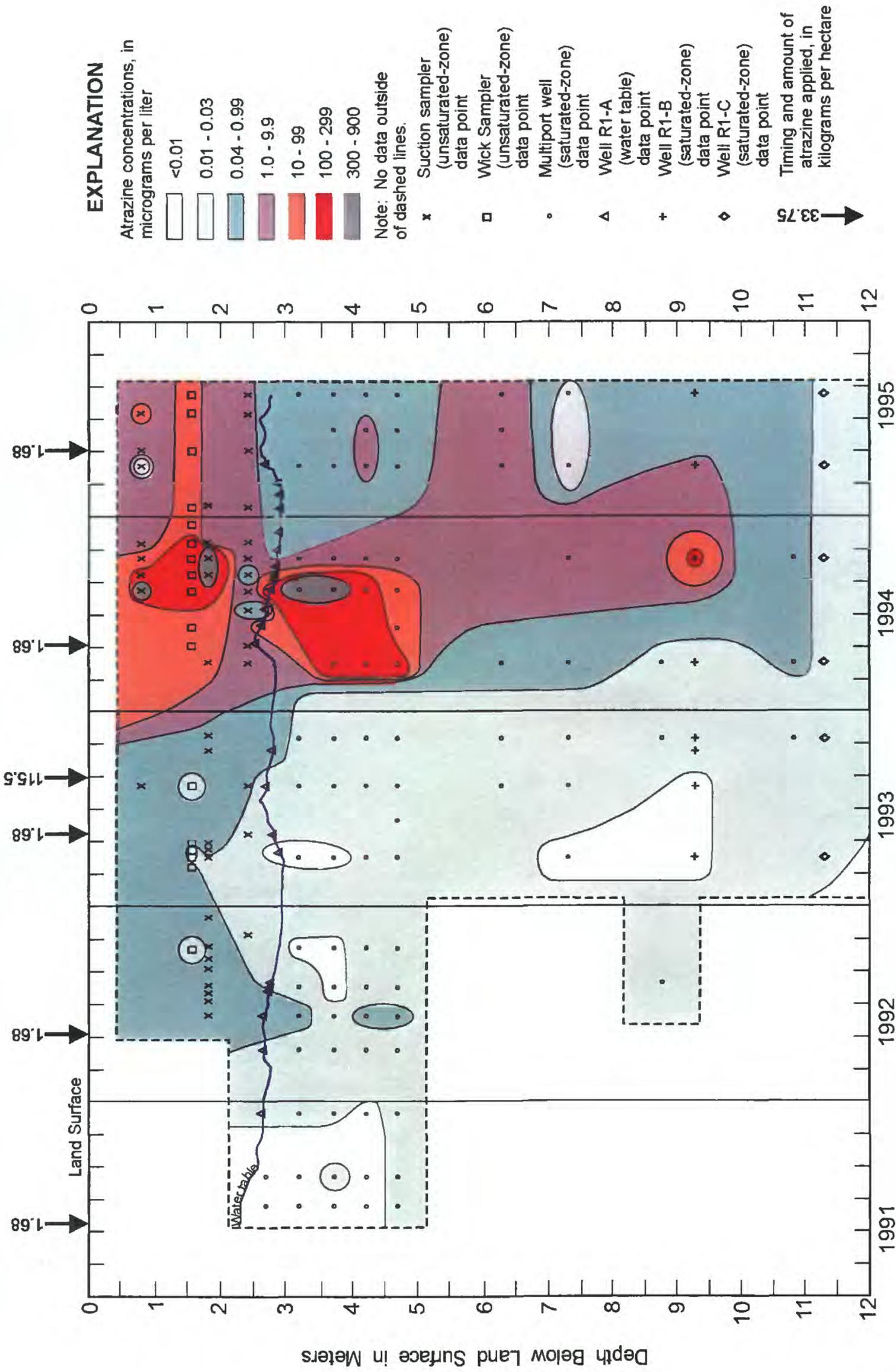


Figure 17.--Time series of atrazine concentrations at the lowland site.

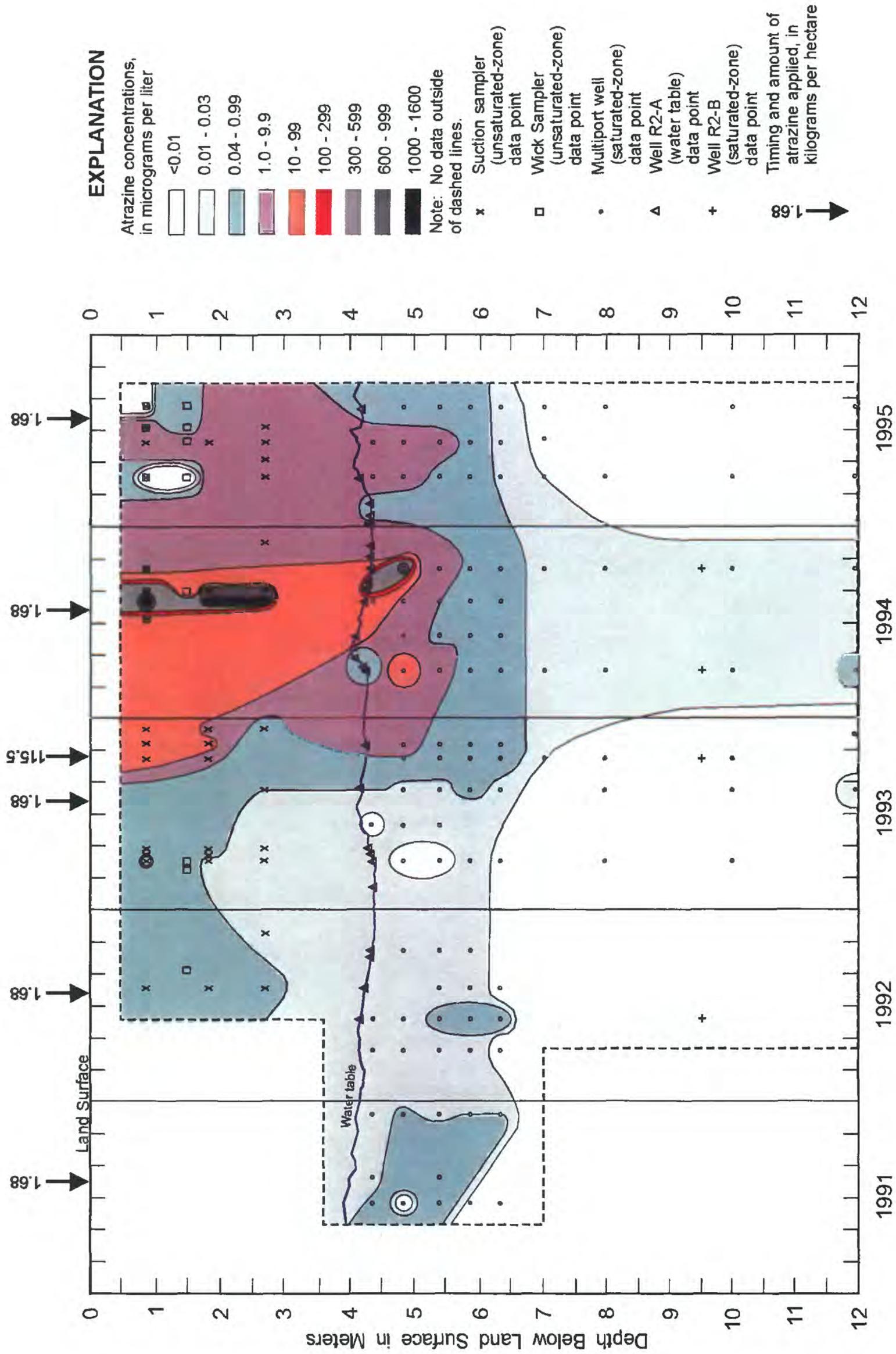


Figure 18.—Time series of atrazine concentrations at the upland site.

ground-water recharge occurred. Arrows at the top of each contoured graph show when chemicals were applied on the overlying cropped area. The vertical Y axis in figures 13-18 is depth below land surface and the horizontal X axis is time. Thus, the chemical concentrations are contoured in space (vertically) versus time (horizontally). Contour intervals were selected that best emphasize contrasts in constituent concentrations vertically in space and horizontally through time. Most of the closed contours are artifacts of the contour intervals selected. The contouring is somewhat subjective, however, due to the wide temporal (horizontal) spacing of the data points. The following assumptions were used in contouring the data shown in figures 13-18:

- The primary source of the varying chemical concentrations in ground water at each MPORT was varying chemical applications to the overlying and upgradient land areas (Delin and others, 1995).
- The primary mechanism transporting the chemicals to ground water was recharge. Recharge created a vertical component of ground-water flow that caused the water and chemicals to move by piston displacement through the unsaturated and saturated zones. Ground-water ages inferred from chlorofluorocarbon concentrations indicate that the magnitude of this vertical ground-water flow below the water table was 0.4 m/yr at the upland site and 0.7 m/yr at the lowland site.
- Chemical loading upgradient of each MPORT was areally uniform following a particular recharge event due to areally uniform land use.
- Chemical concentrations measured at each sampling port were related to chemical concentrations at shallower and deeper sampling ports. This assumption is plausible given the relatively low vertical rates of ground-water flow compared to the average horizontal rate of about 29 m/yr. It should be kept in mind, however, that water from each successively deeper sampling port had a recharge source area that was successively further upgradient from the MPORT.
- Chemical concentrations for each sampling period were related to chemical concentrations for earlier and later sampling periods. The average vertical and horizontal ground-water flow rates were slow enough that the chemicals in the upper part of the saturated zone were not flushed out of the profile before the next sampling.

Description of Files on Compact Disk

The data included on the compact disk are duplicated in several formats with an identical filename prefix. Files of a particular format are in separate directories. File formats include: Microsoft Excel workbook, or spreadsheet (Windows95, Version 7.0, file extension '.xls'); space-delimited text (file extension '.prn'); tab-delimited text (file extension '.txt'); comma-delimited text (file extension '.csv') extension; and Lotus-123 (file extension '.wk1'). At least one of the text versions should import into any software package. Files including data of relevance to both the upland and lowland sites are included at the root level on the compact disk. Files pertaining only to the upland site are included in the directory entitled 'upland' and have an 'r2' prefix. Files pertaining only to the lowland site are included in the directory entitled 'lowland' and have an 'r1' prefix. Following is a brief description of the types of information included in each file.

Included in the 'report' file is duplication of the text of this report in Microsoft Word format (Windows95, Version 7.0, file extension '.doc') and an ascii version (file extension '.txt'). A description of the files on the compact disk is included in the 'readme' file. Included in the 'precip' file is the hourly precipitation (when available), total daily, monthly, and annual precipitation, and irrigation water applied to the field during 1991-95. Also included is the source of the data, either the University of Minnesota climatological station, upland (R2), lowland (R1), or the National Weather Service at Santiago, Minnesota. An Excel chart (Windows95, Version 7.0) is included illustrating precipitation throughout the period of record. Air temperature recorded at the University of Minnesota climatological station during 1991-95 is included in the 'airtemp' file. Geologic logs for the upland and lowland sites, identical to table 1, are included in the 'geo' file.

Moisture-retention data from the upland and lowland sites is included in the 'mois-ret' file. It includes the X,Y,Z location of each sample, the van Genuchten alpha, n, and residual moisture content best fit values (Richards, 1980), plus the pressure head and volumetric moisture content derived from the laboratory analyses. Excel charts are included which graph the distribution of volumetric moisture content versus pressure head for each sample. A chart is also included showing the average and range of moisture-retention characteristics for the upland and lowland sites.

Well construction information for each of the wells at the upland and lowland sites is included in the 'xyz' file. Included is the date of installation, stickup height, depth

of the well screen below land surface, screen length, spacing between the MPORTs, and elevations for the measuring point, top, and bottom of the screen.

The amounts and times of fertilizer, herbicide, and irrigation water applied to the entire area in which the upland and lowland research sites are located (area E), as well as only to the upland and lowland sites, are summarized in the 'chemrate' file. Chemicals applied to the entire field include nitrogen (from ammonia fertilizer [urea], diammonium phosphate, and ammonium sulfate), potassium (from potassium chloride), chloride (from potassium chloride), magnesium (from potassium magnesium sulfate), phosphorus (from diammonium phosphate), sulfur (from zinc sulfate and ammonium sulfate), zinc (from zinc sulfate), atrazine, and alachlor. Additional chemicals applied only to the upland and lowland sites include nitrogen (from $\text{NO}_3\text{-N}$), fluoride (from potassium fluoride), iodide (from potassium iodide), and rhodamine WT. Chemicals applied only to the upland and lowland sites were generally used during recharge experiments as tracers of water and agricultural chemicals through the unsaturated and saturated zones.

Results of chemical analyses of water from the unsaturated and saturated zones at the upland and lowland sites are included in the 'chem' file. Please contact the authors for the most complete version of this file. The date and time each sample was collected are also included in the file. Results of the quality assurance analyses for the study are presented by Landon and others (1997).

Results of chemical analyses associated with the recharge experiment conducted in October 1993 are included in the 'chem1093' file. Included are tables of precipitation data, results of laboratory column experiments, and results of field tracer experiments. For the field experiments, data are included for water samples and for soil cores collected at the upland and lowland sites. Excel charts are included for some of the data which illustrate changes in selected chemical concentrations during the field tracer experiments. Charts showing vertical profiles for selected chemical concentrations in the soil cores are also included.

The X,Y,Z locations of the unsaturated-zone instruments installed at the upland and lowland sites are included in the 'r1instr' and 'r2instr' files, respectively. Also included in each file is information relevant to wiring the electronic equipment to the multiplexors and dataloggers.

Soil-analysis data are summarized in the 'r1uzsum' and 'r2uzsum' files, respectively. The data are sorted by trench face (A, B, C, D, or trench floor) and X,Y,Z location. In addition to the X,Y,Z location of each sample, each file lists the percent silt and clay content, d50 particle size, standard deviation of particle size, d10 particle size, rhodamine WT dye fluorescence, moisture content by weight, bulk density, volumetric moisture content, percent porosity, percent saturation, percent organic carbon content, saturated hydraulic conductivity (calculated by H.W. Olsen, U.S. Geological Survey, Golden, Colorado, written commun., 1992), saturated hydraulic conductivity based on d10 particle size, natural log of saturated hydraulic conductivity based on d10 particle size, and the van Genuchten alpha, n, and residual moisture content parameters. An 'X' is placed in cells where values were not calculated. Samples that were collected from a lamination at the upland site are labeled accordingly. Selected analyses were obtained from samples that were saturated with water. These samples have a 'water' label added to them.

Water-level data measured by steel tape and collected by the dataloggers during 1992-95 at the upland and lowland sites are included in the 'r1watlev' and 'r2watlev' files, respectively. The water-level data are listed both as elevations, depths below land surface, and depths below measuring point. Units of both feet and meters are included. Dates are listed both as month-day-year and Julian day. The stickup of each well and the battery voltage are also included. Where data were not recorded, the cells in the spreadsheet are left blank. A chart is included which illustrates water-level fluctuations throughout the period of record.

Temperature data are summarized in all of the files having 'tc' as part of their filename. Included are temperatures for the reference thermistor, saturated-zone thermocouples (TC1-TC6), and unsaturated-zone thermocouples. The reference thermistor was used for calibrating the thermocouple temperature measurements. At the upland site, the preferential flow zone thermocouples are labeled TC42-TC430 and the retarded flow zone thermocouples are labeled TC32-TC330. At the lowland site, the preferential flow zone thermocouples are labeled TC12-TC130 and the retarded flow zone thermocouples are labeled TC22-TC230. Where data were not recorded, the cells in the spreadsheet are left blank. Some of the temperature data are 'noisy', reflecting either electronic interference within the datalogger recording systems or diurnal temperature fluctuations. Selected sets of these 'noisy' data were smoothed in a separate section of the spreadsheet by creating a running average of the five

previous and five succeeding temperature measurements. Charts are included which illustrate temperature fluctuations throughout the period of record for both the original and the smoothed data.

TDR data are summarized in all of the files having 'tdr' as part of their filename. Included are volumetric moisture contents at the upland site for probes TDR72-TDR730 (retarded flow zone) and TDR82-TDR830 (preferential flow zone) and at the lowland site for probes TDR52-TDR530 (retarded flow zone) and TDR62-TDR630 (preferential flow zone). Volumetric moisture contents are also included for the reference TDR probes. Where data were not recorded, the cells in the spreadsheet are left blank. Columns are also included that provide an average volumetric moisture content for TDR probes in the upper 40 and 200 cm of the unsaturated zone. Charts are included which illustrate fluctuations in volumetric moisture content throughout the period of record.

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