GROUND-WATER FLOW AND EFFECTS OF AGRICULTURAL APPLICATION OF SEWAGE SLUDGE AND OTHER FERTILIZERS ON THE CHEMICAL QUALITY OF SEDIMENTS IN THE UNSATURATED ZONE AND GROUND WATER NEAR PLATTEVILLE, COLORADO, 1985-89

by Neville G. Gaggiani

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 94-4037

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METRO WASTEWATER RECLAMATION DISTRICT,
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U.S. DEPARTMENT OF THE INTERIOR

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CONVERSION FACTORS, VERTICAL DATUM, AND ABBREVIATED WATER-QUALITY UNITS

Multiply	By	To obtain
acre	0.4047	hectare
foot (ft)	0.3048	meter
foot per day (ft/d)	0.3048	meter per day
foot per foot (ft/ft)	0.3048	meter per meter
foot per year (ft/yr)	0.3048	meter per year
inch (in.)	25.4	millimeter
inch per hour (in/h)	25.4	millimeter per year
inch per year (in/yr)	25.4	millimeter per year
mile (mi)	1.609	kilometer
pound (lb)	4.536	kilogram
square mile (mi^2)	2.590	square kilometer
ton, short	0.9072	megagram

Temperature in degree Fahrenheit (°F) may be converted to degree Celsius (°C) by using the following equation:

$$°C = 5/9\ (°F-32)$$

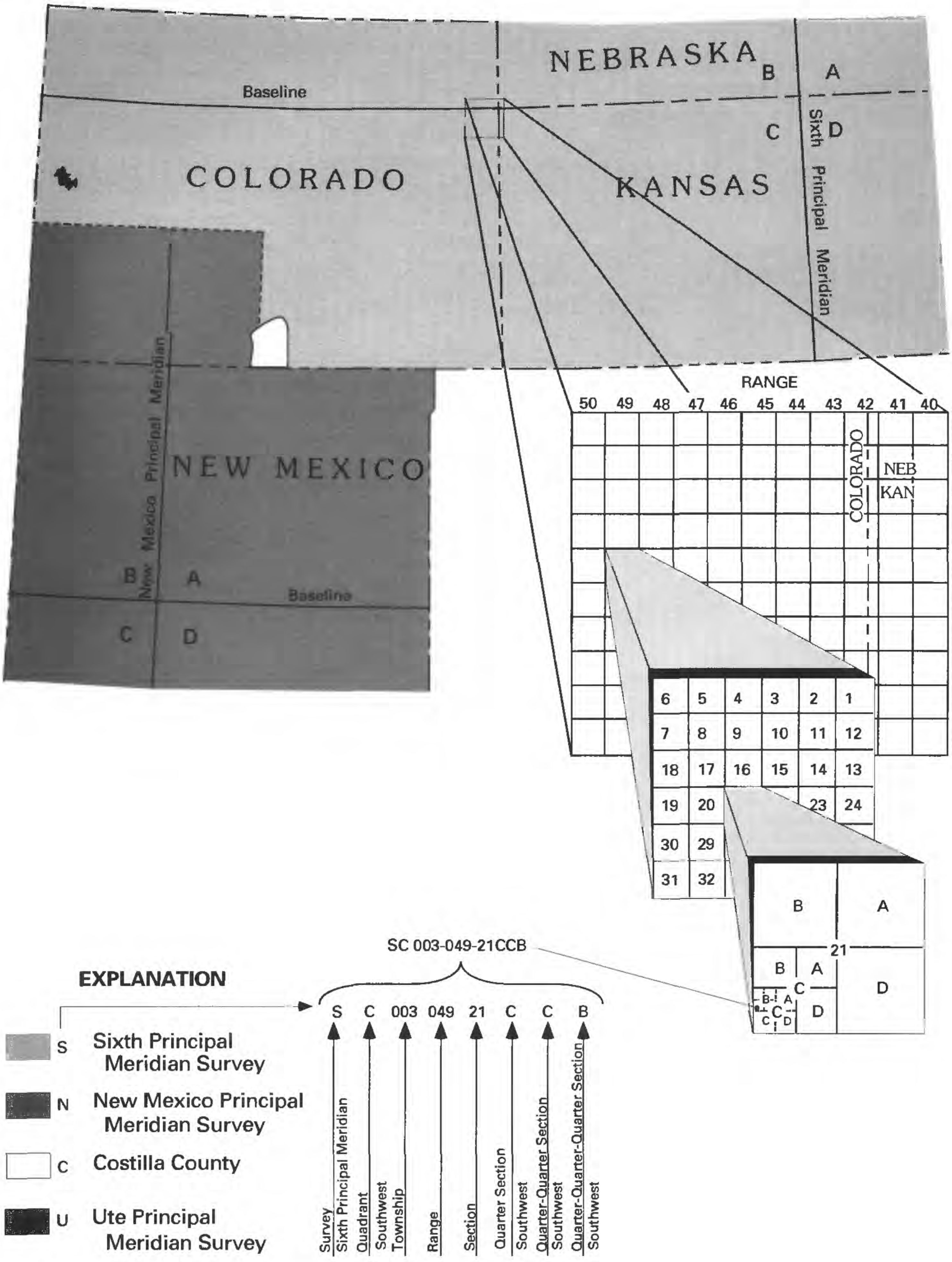
The following terms and abbreviations also are used in this report:

colony per one hundred milliliters (col/100 mL)
microgram per gram (µg/g)
microgram per liter (µg/L)
milligram per kilogram (mg/kg)
milligram per liter (mg/L)

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."

LOCAL WELL-NUMBERING SYSTEM

The well locations (local well number) in tables 1 and 2 (in the "Sampling Network" section) are based on the U.S. Bureau of Land Management system of land subdivision and show the location of the well by quadrant, township, range, section, and position within the section. A graphic illustration of this method of well location is shown in the following unnumbered figure. The first letter "S" preceding the location number means that the well is located in the area governed by the sixth principal meridian. The second letter indicates the quadrant in which the well is located. Four quadrants are formed by the intersection of the base line and the principal meridian—A indicates the northeast quadrant, B the northwest, C the southwest, and D the southeast. The first three numerals indicate the township, the second three the range, and the remaining two the section in which the well is located. The letters following the section number locate the well within the section. The first letter denotes the quarter section, the second the quarter-quarter section. The letters are assigned within the section in a counter-clockwise direction, beginning with (A) in the northeast quarter. Letters are assigned within each quarter section and within each quarter-quarter section in the same manner. Where two or more locations are within the smallest subdivision, consecutive numbers beginning with 1 are added in the order in which the wells were inventoried. For example, SC00304921CCB indicates a well in the northwest quarter of the southwest quarter of the southwest quarter of sec. 21, T. 3 S., R. 49 W. The "C" indicates the township is south of the base line and that the range is west of the principal meridian.



Well-numbering system.

Ground-Water Flow and Effects of Agricultural Application of Sewage Sludge and Other Fertilizers on the Chemical Quality of Sediments in the Unsaturated Zone and Ground Water Near Platteville, Colorado, 1985–89

By Neville G. Gaggiani

Abstract

About one-third of the municipal sewage sludge produced in the United States is used as a source of organic matter, nitrogen, phosphorus, and other nutrients for crop production in agricultural areas. The Metro Wastewater Reclamation District applies sewage sludge on selected agricultural land as part of its beneficial-reuse program. From fall 1985 through 1989, 6,431 dry tons of anaerobically digested sewage sludge were applied on about 1 square mile of sandy farmland near Platteville, Colorado. The sludge, which was injected or plowed about 6–10 inches into the soil, commonly is about 17 percent solids and has about 6 percent total nitrogen, analyzed by total kjeldahl nitrogen method, primarily in complex organic compounds. Data collected during 1985–89 were used to determine the rate and direction of ground-water flow and the effects of sewage sludge and other fertilizers on the quality of sediments in the unsaturated zone and ground water.

Ground water in the surficial aquifer in section 16 (T. 3 N., R. 66 W., Sixth Principal Meridian) generally moves northeastward at a velocity of about 0.01 foot per day (3 feet per year). Precipitation and irrigation water reaching the ground surface in section 16 infiltrates into the sandy soil and collects in temporary ponds. There is little or no runoff. Most water that infiltrates into the soil evaporates or is transpired by crops. The remaining water, if any, continues to move down to the saturated zone and recharges the surficial aquifer. Generally, there is little recharge by precipitation to the aquifer in this semiarid area. However, where irrigation water is applied or the water table is close to the surface, the surficial aquifer is recharged.

Nitrogen concentrations generally increased and trace-element concentrations changed minimally in the unsaturated zone in the irrigated part of section 16 after 4 years of applying sewage sludge and other fertilizers to the soil. Analyses of water samples from multilevel ground-water sampling devices indicate that nitrite plus nitrate as nitrogen concentrations changed with depth and time in the surficial aquifer. Most nitrogen probably moves vertically downward through the unsaturated zone with the water that infiltrates from irrigated areas and low, temporarily ponded areas. The nitrogen then moves laterally through the saturated zone. Trace elements probably have not moved into the ground water from the sewage sludge.

Mean nitrite plus nitrate as nitrogen concentrations in the surficial aquifer increased during the period of sewage-sludge application. However, the addition of commercial inorganic fertilizer during this period could have caused at least some of this increase. Areas having the largest concentrations of nitrite plus nitrate as nitrogen were in the northeastern and southwestern quarters of section 16.

INTRODUCTION

About 1.3 million dry tons, or 31 percent of the treated municipal sewage sludge produced in the United States in 1979, was applied to farmland as a source of organic matter, nitrogen, phosphorus, and other nutrients for crop production (U.S. Environmental Protection Agency, 1979, p. 18-2). Through this process, nutrients are recycled rather than wasted, and the need for commercially produced inorganic fertilizers is decreased. The Metro Wastewater Reclamation District (MWRD) in Denver, Colo., applies sewage sludge on selected agricultural land as part of its beneficial-reuse program. In addition to nutrients, sewage sludge also may contain trace elements that are harmful if allowed to leach into ground water used as a water supply for humans or animals (U.S. Environmental Protection Agency, 1983, p. 2-5). If the application of sludge is not managed properly, nutrients such as nitrate and trace elements such as cadmium and zinc could migrate into ground water and reach concentrations larger than recommended limits for drinking water. Because nitrite concentrations generally are less than the detection limit, the term nitrite plus nitrate as nitrogen will be referred to as nitrate in this report.

In 1985, the U.S. Geological Survey and the MWRD began a cooperative study of the effects on ground water of applying anaerobically digested sewage sludge at agronomic rates on about 1 mi^2 of sandy farmland near Platteville, Colo. (fig. 1). The objectives of this study were to determine (1) the rate, volume, and direction of ground-water flow, and (2) the effects of fertilizers such as sewage sludge, cattle and chicken manure, and inorganic fertilizer on chemical quality of sediments in the unsaturated zone and ground water.

Purpose and Scope

This report describes ground-water flow and the effects of the application of municipal sewage sludge, cattle and chicken manure, and commercial inorganic fertilizer on chemical quality of sediments in the unsaturated zone and on ground-water quality in the study area. The farmland near Platteville was chosen because it is underlain by an isolated sand aquifer. The sandy soil would enable water that had leached through sewage sludge and other fertilizers to move rapidly into the aquifer.

Monitoring wells (19 observation wells) in the surficial and bedrock aquifers were sampled for chemical analyses before and during the irrigation season each year. Also, water from several depths in the surficial aquifer was sampled for chemical analyses from four multilevel ground-water sampling devices. Water levels in the monitoring wells were measured monthly to determine water-level changes and to determine the direction of ground-water flow. Rainfall and snowfall were recorded by use of a recording precipitation gage. Sediment samples were obtained from several depths at five sites in the unsaturated zone for chemical analyses before and after the sludge was applied so that chemical changes could be determined. Wells were located so the effects on irrigated and nonirrigated farmland could be monitored. Water-quality samples were obtained from the monitoring wells before and after sludge was applied to the farmland. Soil moisture periodically was measured using three soil-moisture tubes in the unsaturated zone of the surficial aquifer, so that vertical movement of water could be monitored. Data were collected from 1985 through 1989. These data were used to determine the effects of sewage sludge, other organic fertilizers, and inorganic fertilizers on ground-water quality.

Acknowledgments

The author acknowledges the assistance of the land owner, Mr. Ray Olin, who avoided plowing-in obstructions such as observation wells and raingages, and endured truck traffic on his farmland.

DESCRIPTION OF STUDY AREA

The study area is in an agricultural area of the South Platte River valley about 35 mi northeast of Denver and about 2 mi east of Platteville (fig. 1). Sections 9 and 16 and parts of sections 8, 10, 15, and 17, T. 3 N., R. 66 W., Sixth Principal Meridian are within the study area.

The study area is characterized by low rolling hills and some sand dunes. The few trees, mostly cottonwood, grow in low spots where the water table is shallow enough for their roots to reach water and near the irrigation canals where there is water seepage during the summer. Crops are not grown in the low spots because water that collects in them creates temporary ponds or waterlogged soil. Cottonwoods have been removed from some of the low spots where only ponds or low, wet spots remain.

The farmland in section 16 received sewage sludge and other fertilizers. Farmland in sections 8, 9, 10, 15, and 17, which adjoin section 16, did not receive sewage sludge. Farming operations in the adjoining sections used mainly commercial inorganic fertilizers.

Climate

The study area is in the semiarid Great Plains of northeastern Colorado. The climate of the study area is semiarid; mean annual evaporation ranges from 50 to 60 in. and exceeds the mean annual precipitation of 12.6 in. (Hansen and others, 1978). The nearest weather station to the study area was at Ft. Lupton, which is about 10 mi south of the study area. During 1938–74, the minimum annual precipitation was 6.7 in., the maximum annual precipitation was 19.5 in.,

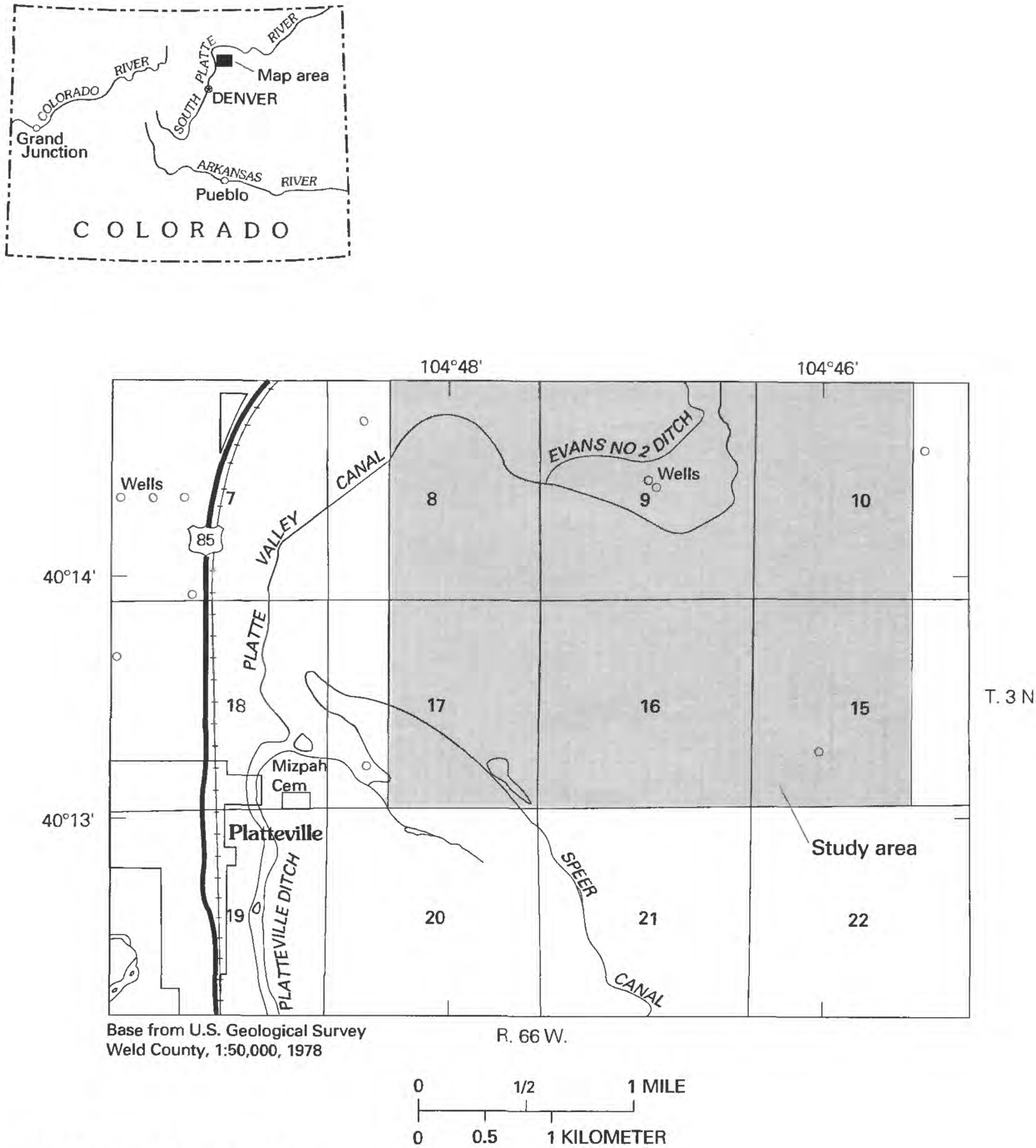


Figure 1. Location of study area.

and the mean annual precipitation was 12.6 in. (Hansen and others, 1978). The prevailing surface wind is from the south, and the temperature ranged from a maximum of 105°F in summer to a minimum of minus 37°F in winter. Precipitation records at Ft. Lupton indicate that 9.3 in. of the 12.6 in. mean annual precipitation was rainfall from April through September. The remainder of the precipitation was snowfall from October through May (Hansen and others, 1978). The mean annual snowfall depth at Ft. Lupton was 36.3 in.

Annual precipitation recorded in the study area ranged from 9.1 in. (1988) to 12.5 in. (1987) (fig. 2). The 1986–88 maximum annual precipitation of 12.5 in. in the study area was almost equal to the mean annual precipitation of 12.6 in. at the Ft. Lupton weather station. Most of the precipitation during the study period occurred during the second and third quarters (April through September) of each year (fig. 2). There were no precipitation data for the first two quarters of 1985 and the last quarter of 1989.

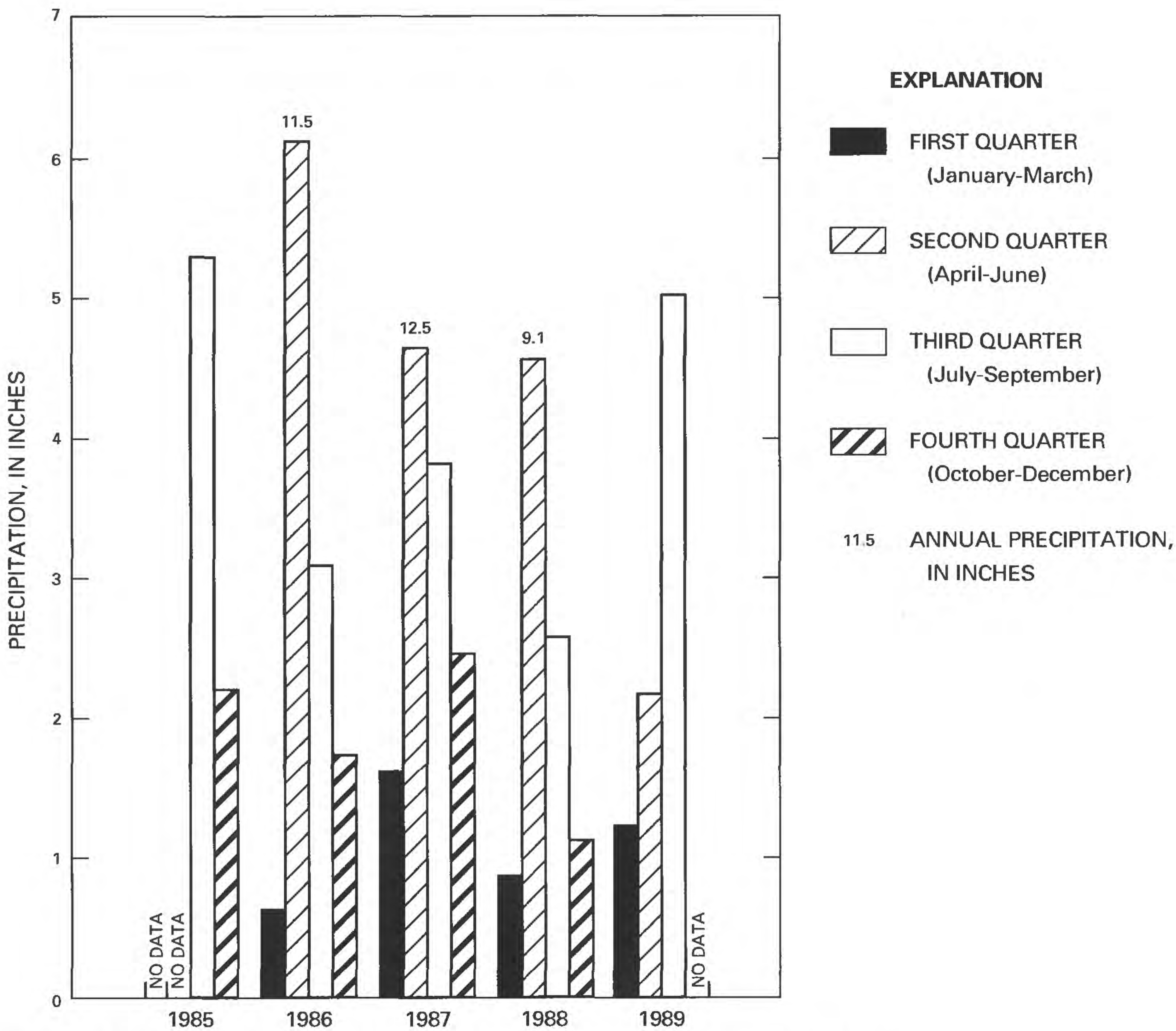


Figure 2. Quarterly precipitation in the Platteville, Colorado, area, July 1985–September 1989.

Geology

The study area is about 50 mi east of the Continental Divide in the Great Plains and overlies the sedimentary bedrock of the Denver-Cheyenne Basin. Bedrock in the study area is the Laramie Formation, which is one of the formations in the basin that contains coal and lignite deposits (Gaggiani and others, 1987).

Geology in the study area includes eolian and alluvial deposits and the bedrock Laramie Formation (fig. 3). Eolian deposits of sand or silt (loess) are present at the surface of most of the area and are underlain in some places by alluvial deposits. Bedrock crops out in several places but mostly underlies the alluvial or eolian deposits.

The fine to coarse eolian sand contains silt in places and ranges from grayish-yellow to grayish-orange. Soister (1965) indicates that the eolian sand probably was carried by the wind from the upper, fine-grained part of the alluvial valley fill about 7 mi northwest of the study area. Loess in the study area is pale yellowish-brown to grayish-orange and consists of sandy and clayey silt and some silty fine sand; locally, the loess may contain some pebbles or small cobbles. Pebbles and small cobbles probably are colluvial and are derived locally from older alluvial deposits. Soister (1965) also indicates that the loess probably is present below the eolian sand.

Lithologic logs of the eolian deposits in section 16 indicate that clay is present in most of the sand aquifer (figs. 4 and 5). The quantity of clay generally increases with depth. The thickness of the eolian deposits increases to the north and ranges from about 5 ft at well 1 to more than 20 ft at well 14 (fig. 4). The thickness of the eolian deposits generally increases to the east and ranges from about 15 ft at well 9 to about 45 ft at well 6 (fig. 4).

Alluvial deposits are present in the study area only in sections 8, 9, and 10 (fig. 3). The deposits are grayish-yellow to grayish-orange and consist of sand and silt and contain some clay, scattered pebbles, and gravel lenses. Well 16 probably is completed at the edge of the alluvial aquifer. The eolian deposits overlie the alluvial deposits at or near the edge of section 16. These two deposits form the surficial aquifer discussed in this report.

Bedrock is the Laramie Formation and generally consists of shale and very fine- to medium-grained calcareous sandstone, siltstone, clay, carbonaceous shale, and coal in evenly stratified beds commonly 1 to a few feet thick (Soister, 1965). The Laramie Formation crops out in parts of all sections in the study area except for section 9 (fig. 3).

The surface of the bedrock in section 16 slopes generally to the northeast (fig. 5). Bedrock is exposed at the surface in a small area in the southern part of section 16 and a small area at the northwestern boundary. The narrow depression in the bedrock surface in the northeastern quarter of the section may be the remnant of a paleochannel.

Soils

Soils in the study area are part of a region of sands to clay loams that are moderately to well drained and are present south of the South Platte River in northeastern Colorado (Crabb, 1980). These soils formed in eolian deposits and in mixed alluvium and eolian deposits.

There are three types of sandy soils in section 16 (fig. 6). Soils in the northern half of section 16 are predominantly Valent sand and Vona loamy sand; permeability is rapid (6.0 to 20 in/h) to moderately rapid (2.0 to 6.0 in/h), and the thickness of the surface layer of soil ranges from 6 to 12 in. Soils in the southern half of section 16 are predominantly Olney loamy sand, 1 to 3 percent slope; permeability is moderate (0.6 to 2.0 in/h), and the thickness of the surface layer of the soil ranges from 9 to 12 in. (Crabb, 1980). Runoff from these soils is minimal because the slope of the land surface is less than 9 percent, and precipitation readily infiltrates the sandy soil.

Agricultural Practices

The study area is located on benchland outside the flood plain of the South Platte River. After irrigation canals were built in the late 1800's, the benchland was cultivated, and wheat, potatoes, barley, corn, oats, and alfalfa were grown (Boyd, 1890). Currently (1992), nonirrigated and irrigated crops are grown in the area. Section 16 has been farmed by the present owner since the late 1960's.

Land Use

The sandy soil of the study area is used for nonirrigated and irrigated agriculture (fig. 7). Locations of crops grown in section 16 during 1985–89 are shown in figure 8. Nonirrigated wheat, fertilized only with sewage sludge, was grown in the northern half of section 16 throughout the study period. Irrigated corn, fertilized with sewage sludge and anhydrous ammonia during the study period, was grown in most of the southern half of the section. Part of the area irrigated

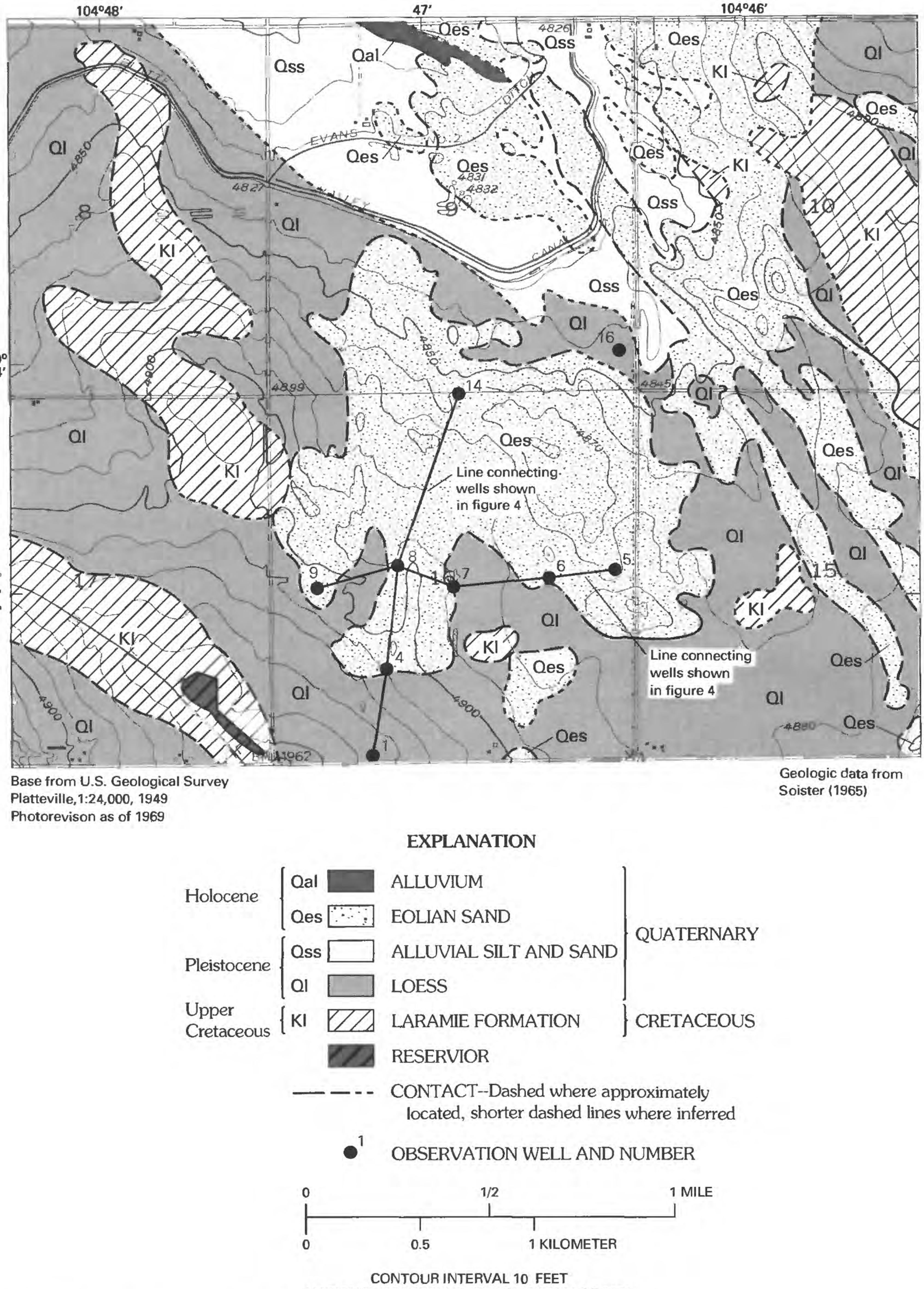


Figure 3. Geology in the study area and location of selected wells.

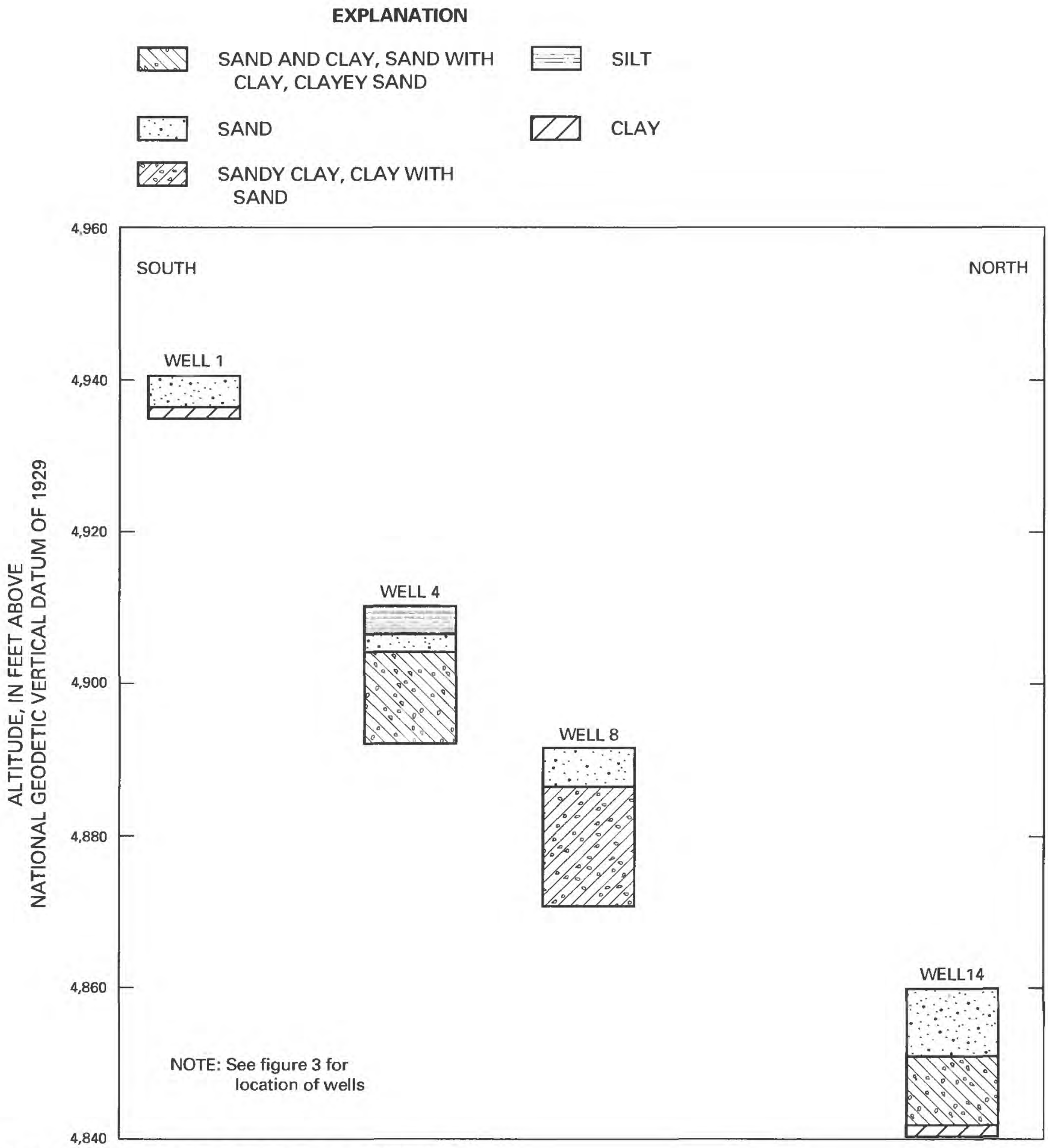


Figure 4. Lithologic logs of selected wells in the study area.

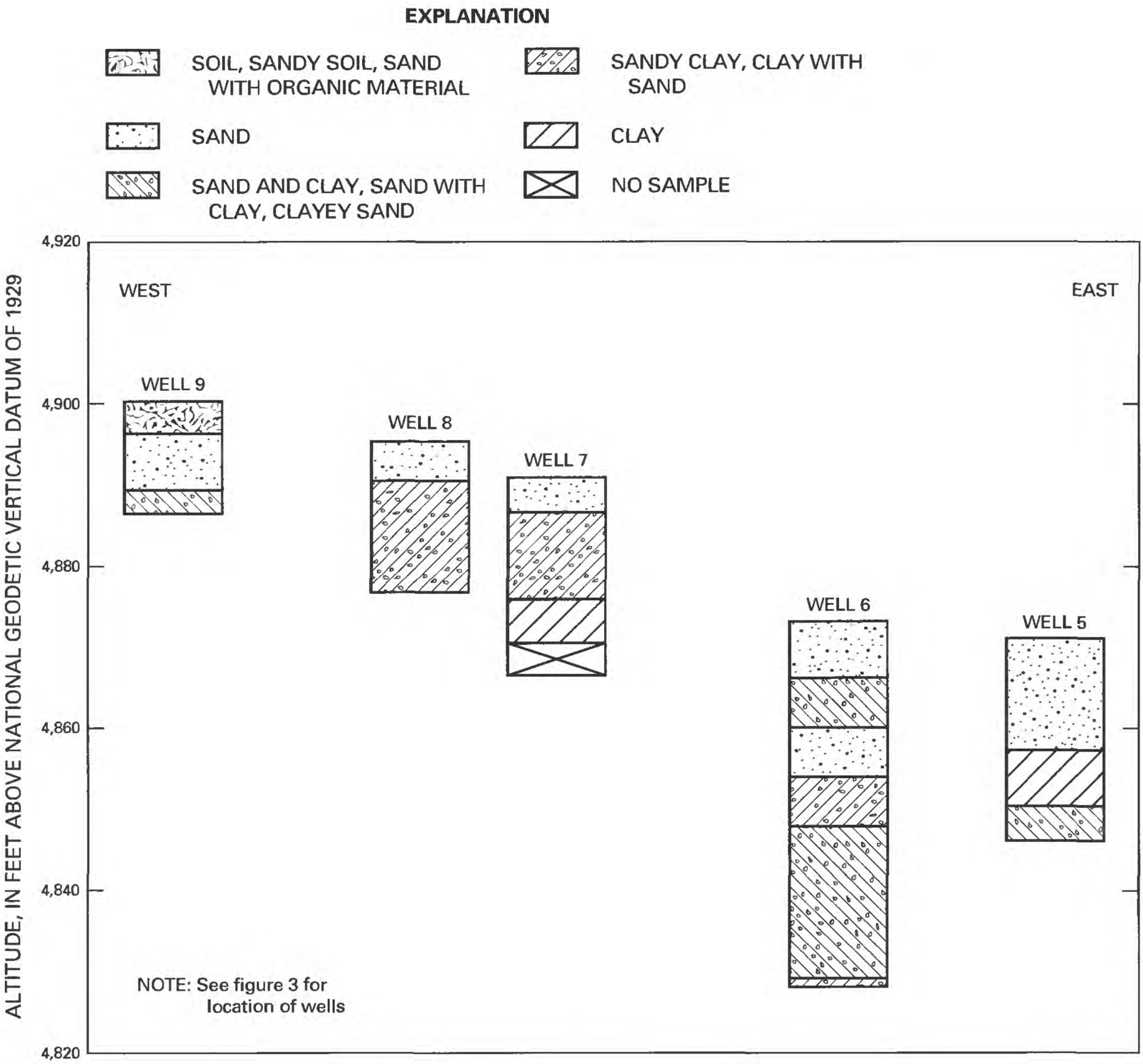


Figure 4. Lithologic logs of selected wells in the study area--Continued.

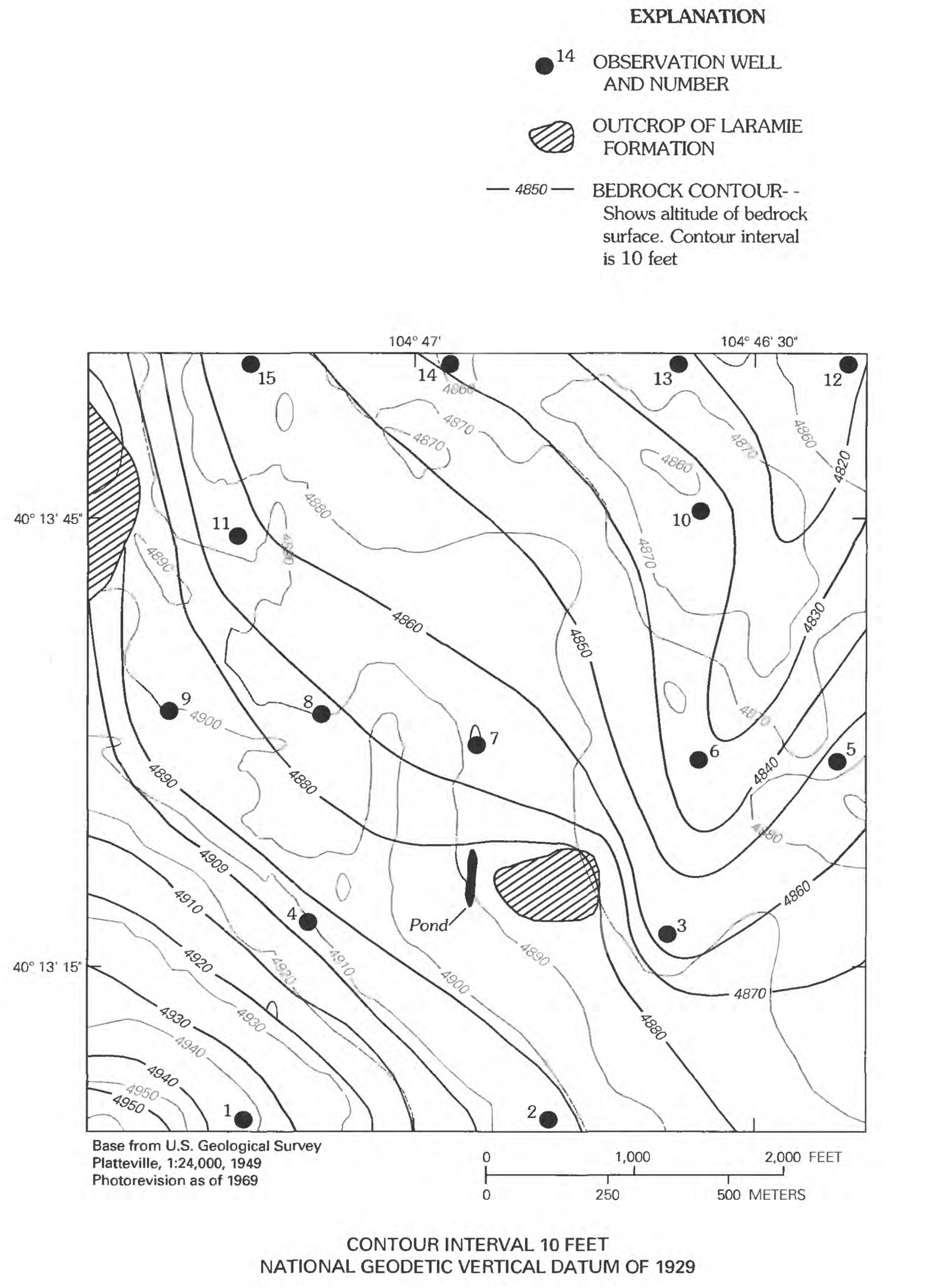
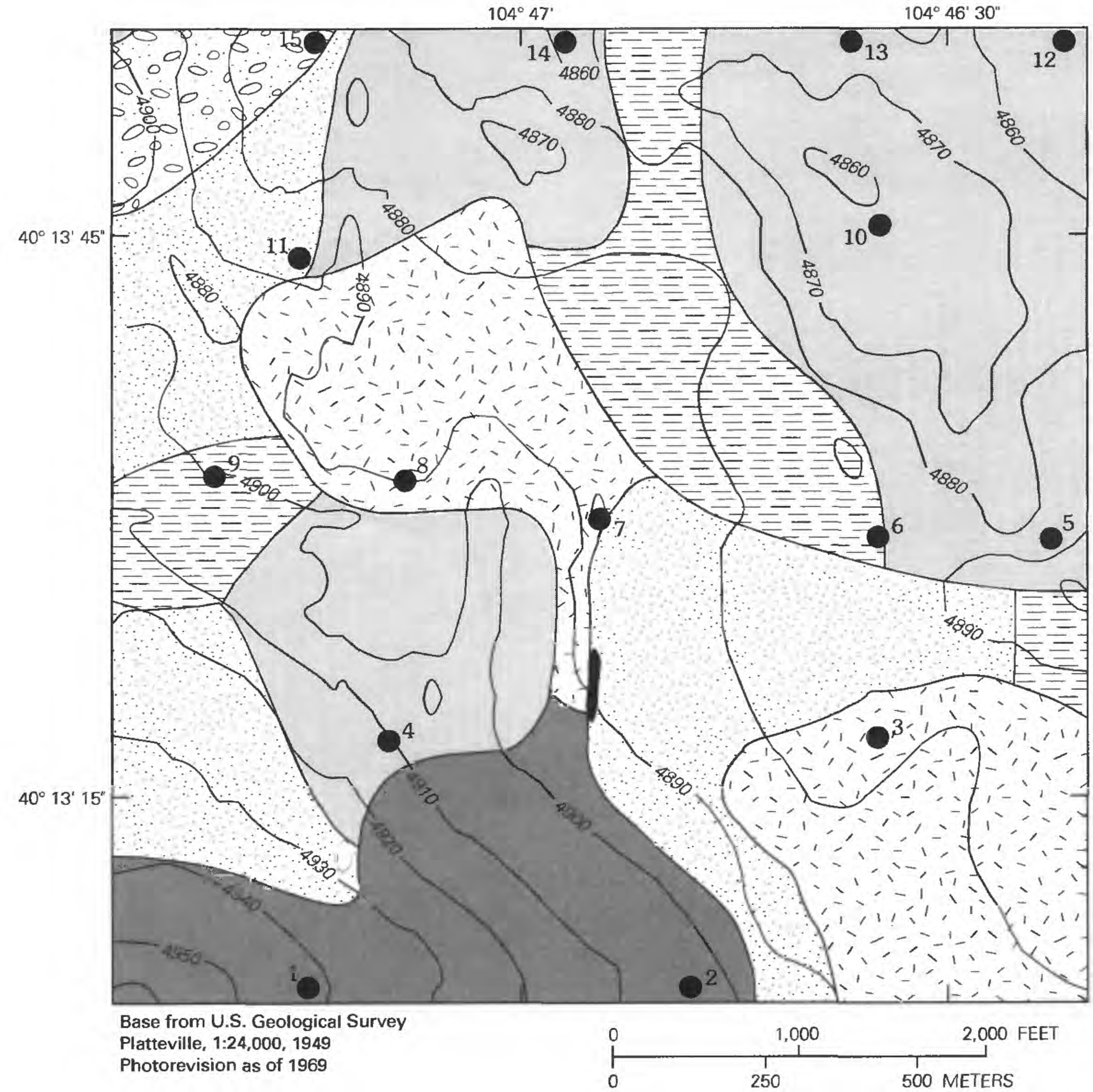


Figure 5. Altitude of the bedrock surface in section 16.



CONTOUR INTERVAL 10 FEET
NATIONAL GEODETIC VERTICAL DATUM OF 1929

Figure 6. Soils in section 16.

EXPLANATION

OLNEY LOAMY SAND, 1-3 percent slope, permeability and available water capacity is moderate.
surface layer - grayish brown loamy sand (9 inches)
subsoil - yellowish brown and very pale brown sandy clay loam (15 inches)
substratum - pale brown calcareous fine sandy loam (60 inches)

OLNEY LOAMY SAND, 3-5 percent slope, permeability and available water capacity is moderate.
surface layer - grayish brown loamy sand (7 inches)
subsoil - yellowish brown and very pale brown sandy clay loam (14 inches)
substratum - very pale brown calcareous fine sandy loam (60 inches)

OLNEY FINE SANDY LOAM, 1-3 percent slope, permeability and available water capacity is moderate.
surface layer - grayish brown fine sandy loam (10 inches)
subsoil - yellowish brown and very pale brown sandy clay loam (14 inches)
substratum - very pale brown calcareous fine sandy loam (60 inches)

VALENT SAND, 0-3 percent slope, permeability is rapid, available water content is moderate.
surface layer - brown sand (8 inches)
underlying material - brown sand (60 inches)

VALENT SAND, 3-9 percent slope, permeability is rapid, available water capacity is moderate.
surface layer - brown sand (6 inches)
underlying material - brown sand (60 inches)

VONA LOAMY SAND, 0-3 percent slope, permeability is moderately rapid, available water capacity is moderate.
upper surface layer - grayish brown loamy sand (6 inches)
lower surface layer - grayish brown fine sandy loam (6 inches)
subsoil - brown and lightly yellowish brown fine sandy loam (16 inches)
substratum - sandy loam (60 inches)

●1 OBSERVATION WELL AND NUMBER

Figure 6. Soils in section 16--Continued.

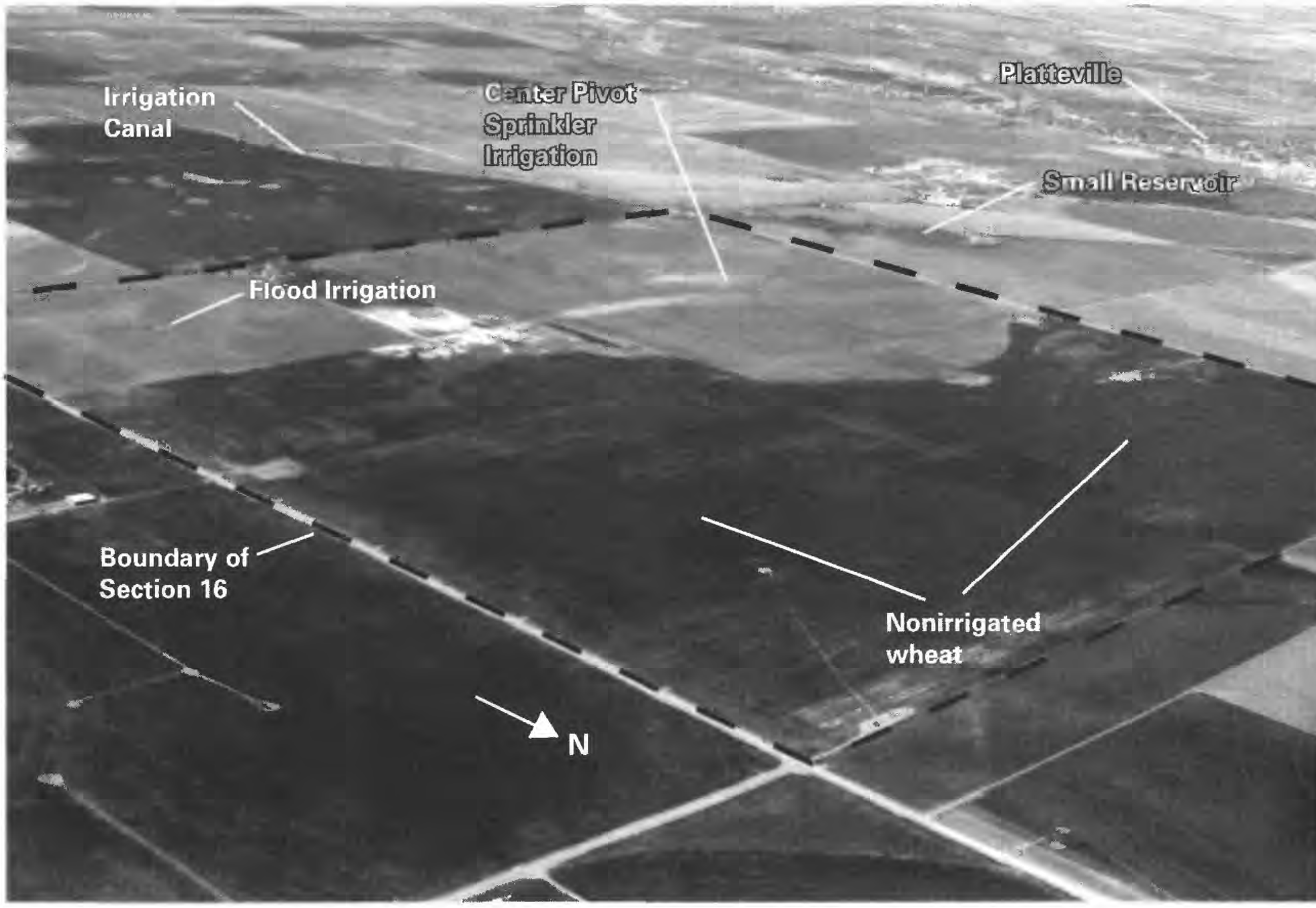


Figure 7. Aerial photograph of the study area, April 1988 (view looking southwest).

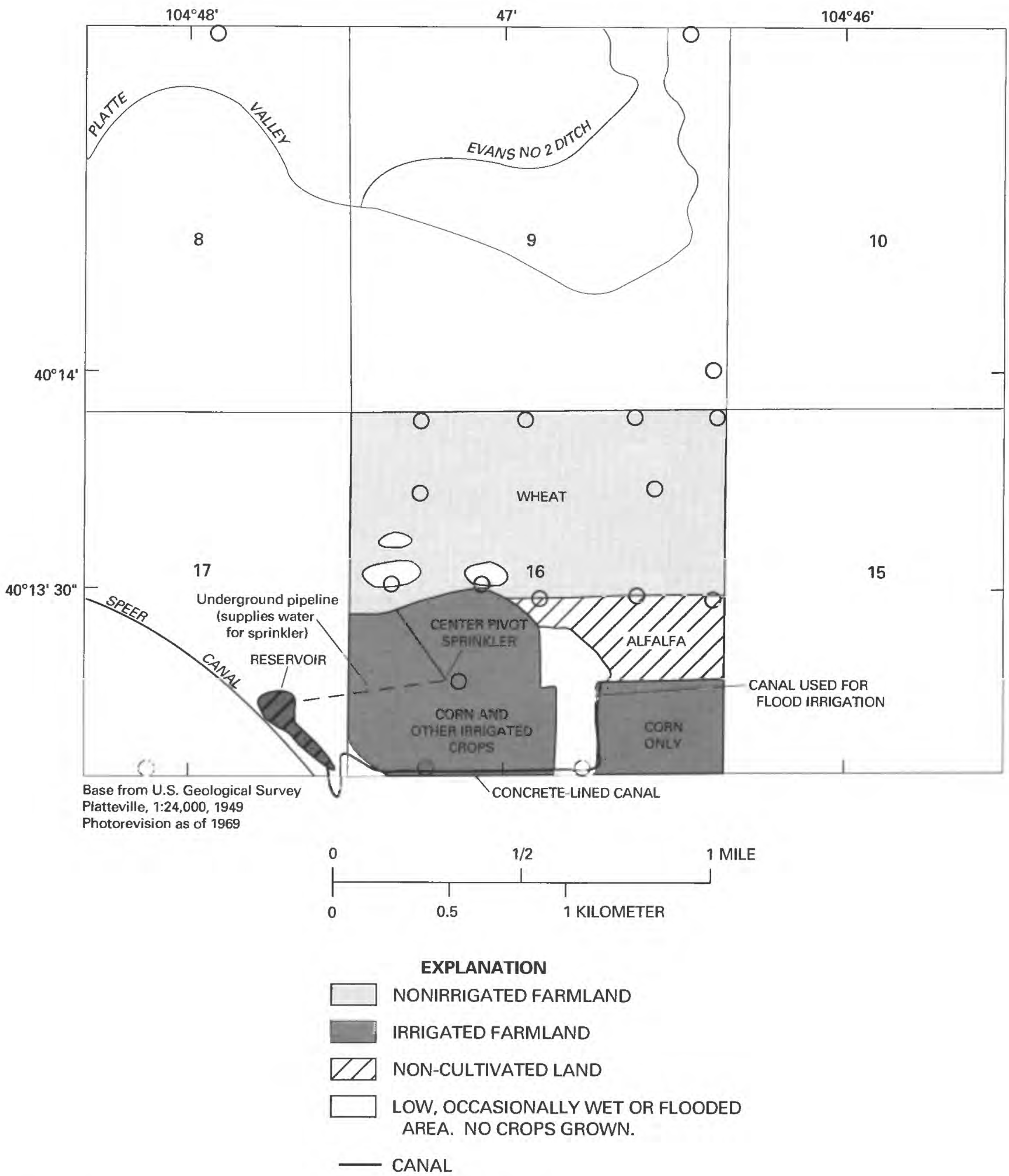


Figure 8. Land use and crops grown on section 16, 1985–89.

by the center-pivot sprinkler was used to grow crops other than corn. Alfalfa was grown in the part of the southeastern quarter of section 16 that was not cultivated or irrigated (fig. 8).

Nonirrigated and irrigated crops have different growing seasons. Nonirrigated wheat is planted in fall and harvested in summer. Corn is planted in spring and harvested in late summer. The area in the southeastern quarter of section 16 between the irrigated corn and the wheat is not tilled, fertilized, or irrigated. Alfalfa grown in this area is harvested two or more times per year for hay.

During the winter, when no crops are grown, cattle are kept in parts of section 16. The stubble of the corn and wheat fields provide feed, and the small ponds in the south-central part of section 16 provide water.

Water Use

Precipitation is the source of water for wheat and alfalfa, and a nearby irrigation canal is a source of water for corn and other irrigated crops (fig. 8). Ground water in the surficial aquifer in section 16 cannot be pumped in enough quantity to be used for irrigation.

Irrigation water in the nearby irrigation canal comes from the South Platte River and is stored in a small reservoir near the southwestern corner of section 16 (figs. 7 and 8). Center-pivot-sprinkler irrigation is used in the southwestern quarter of the section (fig. 9). Water for the center-pivot sprinkler is supplied by an underground pipeline from the small reservoir (fig. 8). The flood-irrigated area in the southeastern corner of section 16 is supplied water by a small concrete-lined irrigation canal (figs. 8 and 9).

Fertilizer Use

Fertilizers used on irrigated crops in section 16 before sewage-sludge application were anhydrous ammonia and cattle and chicken manure (Ray Olin, oral commun., 1987). For about 20 years before sewage-sludge application, the yearly quantity of fertilizer applied to section 16 was about 150 lb nitrogen, 50 lb phosphorus, and 20 lb potassium per acre on the irrigated areas. An undetermined quantity of nitrogen fertilizer in pellet form occasionally was used on nonirrigated wheat.

Sewage sludge was the major source of fertilization for section 16 beginning in fall 1985 to the end of the study period. Anhydrous ammonia was applied from 1987 to 1989 in addition to the sewage sludge. The anhydrous ammonia was applied directly to the soil or mixed with the irrigation water. The other farms in the sections surrounding section 16 did not use sewage sludge as a fertilizer.

The application of sewage sludge on selected farms involves fertilization of crops at agronomic rates. The agronomic rate of sewage application, which varies with the crop, is intended to provide only enough nutrients for the crop, thus minimizing the potential for leaching to ground water. Nitrogen in the sludge primarily is in the form of organic nitrogen and ammonia. The 6- to 10-in. injection depth enables aerobic conditions to dominate, and bio-oxidation of organic nitrogen compounds and ammonia to nitrate can be expected.

Beginning in fall 1985 through 1989, MWRD applied 6,431 dry tons of sewage sludge to section 16 (William Martin, Metro Wastewater Reclamation District, written commun., 1988, and oral commun., 1990). Sewage sludge was applied in the spring and sometimes in the fall on the southeastern and southwestern quarters of section 16. Sewage sludge was applied on the northern half of section 16 in late summer or fall, before winter wheat was planted.

During 1985–86, the method that was used to incorporate the sewage sludge into the soil was injection of liquid sludge about 6 to 10 in. into the soil by using a Terragator (fig. 10). The liquid sludge was transported by tanker truck and transferred to the Terragator (fig. 10). Sludge with about 17 percent total solids and about 6 percent total kjeldahl nitrogen, which is referred to as sludge cake, was applied during 1987–89. Constituents commonly present in sewage sludge applied by MWRD to section 16 are nitrogen, phosphorus, potassium, cadmium, copper, lead, nickel, and zinc (William Martin, Metro Wastewater Reclamation District, written commun., 1988). Zinc is the trace element present in the largest concentration. The sludge cake was transported by large dump trucks and was applied directly to the soil and plowed in. A dark strip of farmland in the irrigated southwestern quarter of section 16 indicates where sewage sludge is being spread on the surface (fig.11).

SAMPLING NETWORK

The ground-water sampling network consisted of 19 observation wells and 5 multilevel ground-water-sampling devices (MLGWSD) (fig. 12 and tables 1 and 2). The MLGWSD is described in Johncox and Gaggiani (1991). Well 3 was destroyed by farming operations in 1985. A water-level measurement was made before the well was destroyed, but no water samples for chemical analyses were obtained from well 3. Observation wells used during this study included 15 U.S. Geological Survey-installed surficial aquifer wells in section 16; 1 surficial-aquifer irrigation

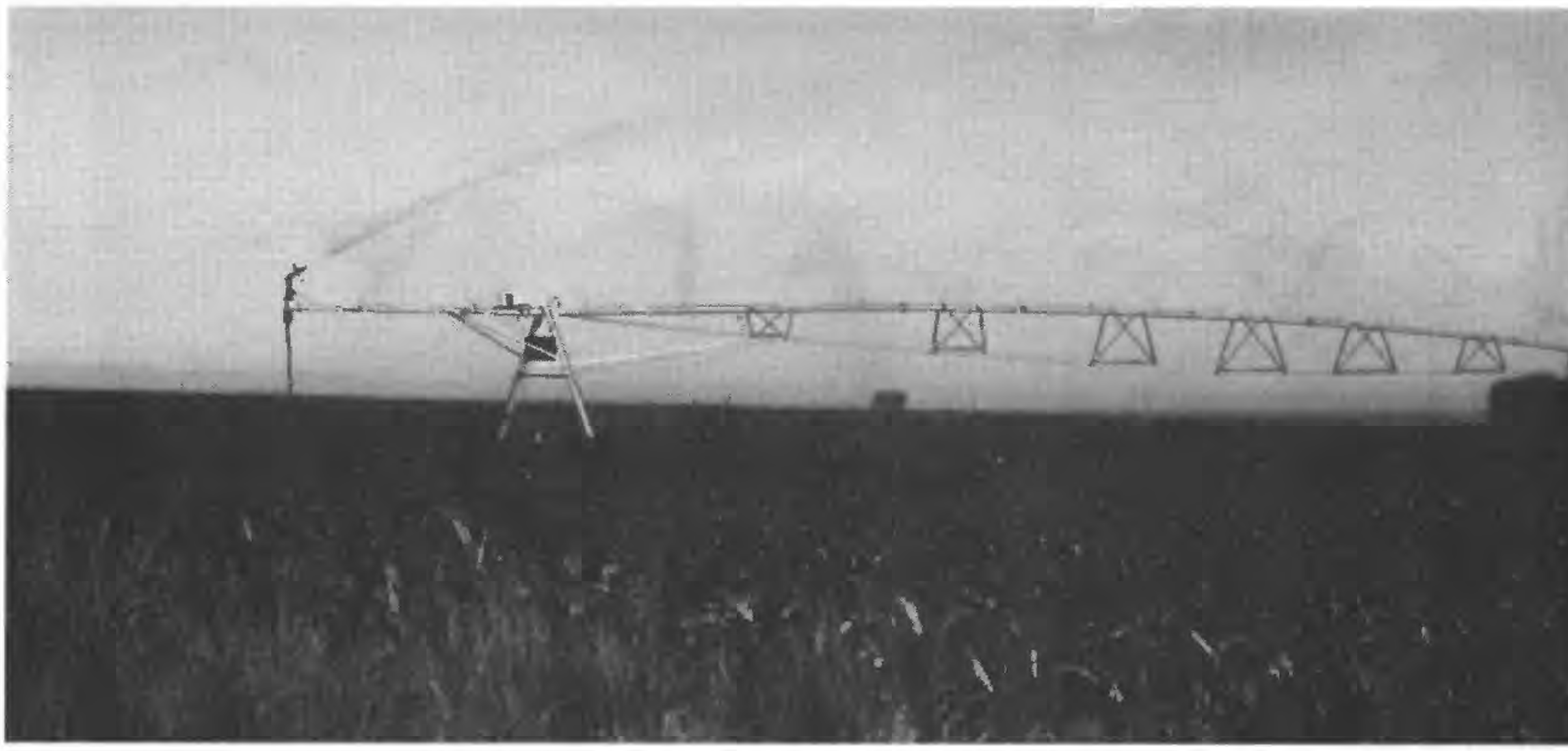


Figure 9. Center-pivot-sprinkler irrigation (upper photo) and flood irrigation (lower photo), July 1986.

Figure 10. Transfer of sewage sludge to a Terragator (upper photo) and Terragator injecting sewage sludge into soil (lower photo), October 1985.

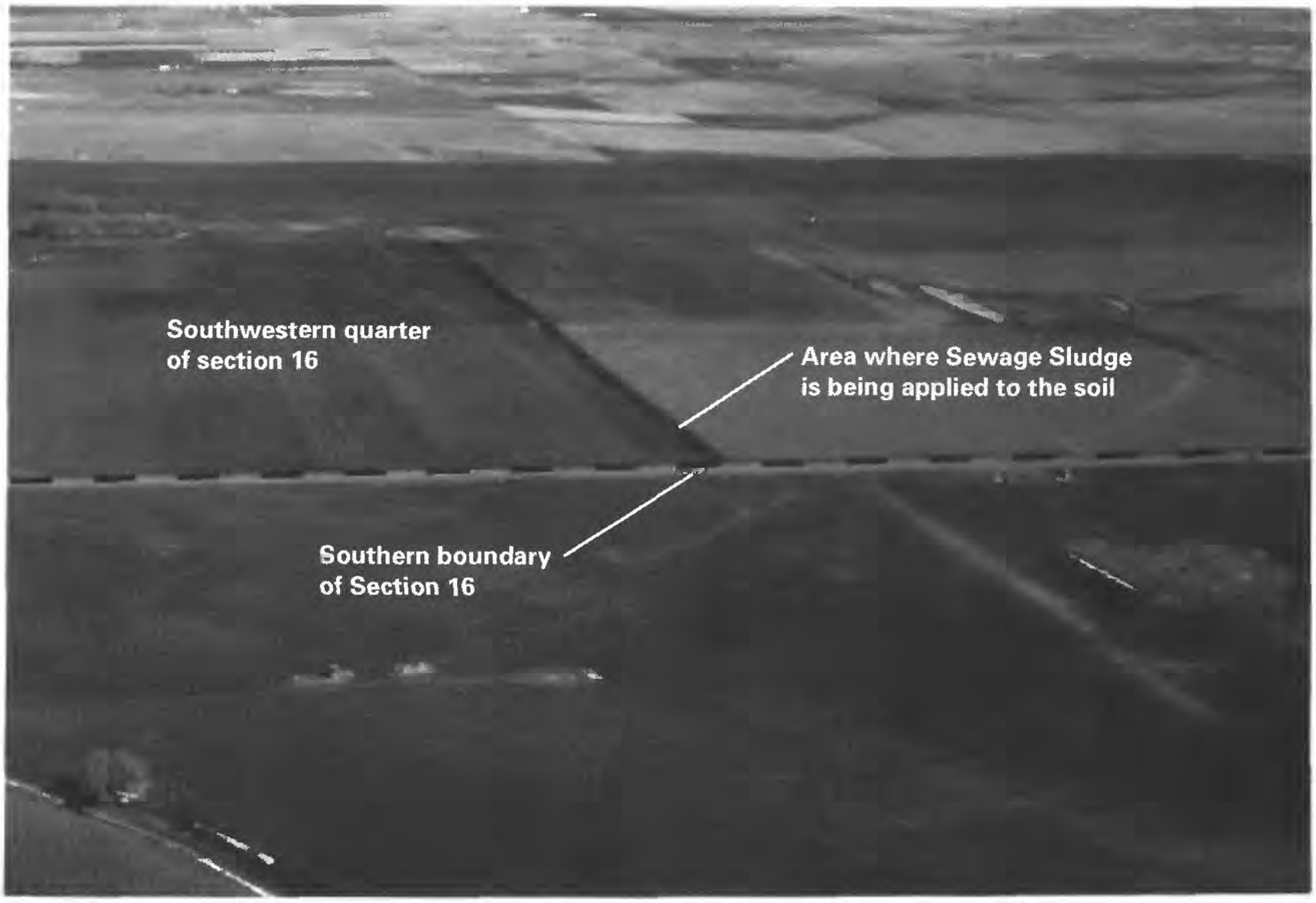


Figure 11. Southwestern quarter of section 16 and area where sewage sludge is being applied to the soil, February 1990.

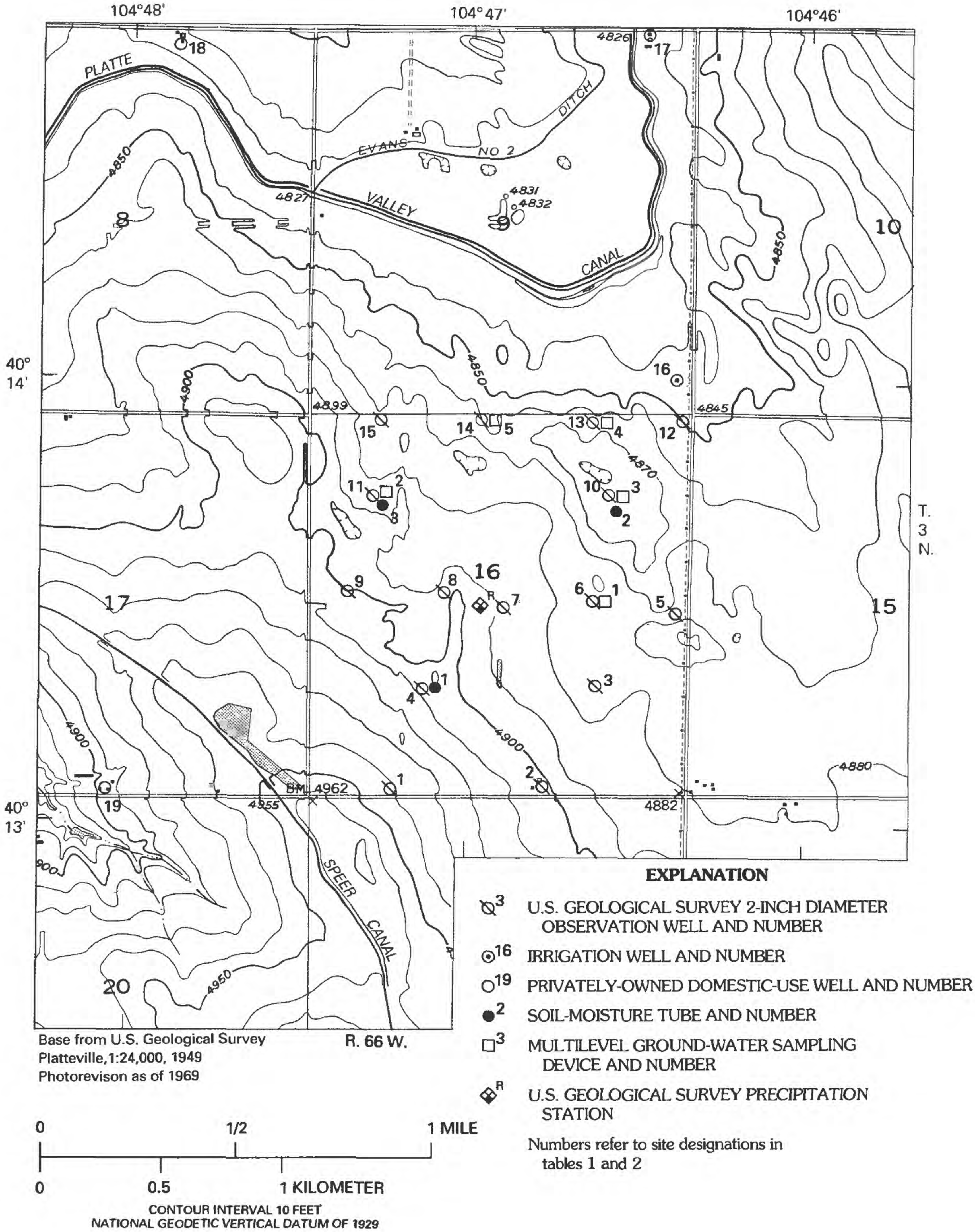


Figure 12. Locations of observation wells, multilevel ground-water sampling devices, and soil-moisture tubes.

Table 1. Observation wells used for water-quality sampling near Platteville, Colorado

[NGVD, National Geodetic Vertical Datum of 1929; Surficial-E, surficial aquifer mostly composed of eolian deposits; Surficial-A, surficial aquifer mostly composed of alluvial deposits; all wells are U.S. Geological Survey wells unless otherwise noted]

Site designation (see fig. 12)	Local well number[1]	Well depth (feet)	Land surface altitude (feet above NGVD of 1929)	Aquifer sampled
1	SB00306616CDD	6	4,942	Surficial-E
2	SB00306616DCC	9	4,903	Surficial-E
[2]4	SB00306616CAC	18	4,909	Surficial-E
5	SB00306616DAA2	24	4,875	Surficial-E
6	SB003066162DAB	45	4,877	Surficial-E
7	SB00306616CAA	25	4,890	Surficial-E
8	SB00306616BDC	19	4,890	Surficial-E
9	SB00306616BCC	14	4,900	Surficial-E
10	SB00306616AAC	30	4,862	Surficial-E
11	SB00306616BBD	27	4,888	Surficial-E
12	SB00306616AAA	30	4,849	Surficial-E
13	SB00306616AAB	39	4,860	Surficial-E
14	SB00306616BAA	20	4,859	Surficial-E
15	SB00306616BBA	14	4,871	Surficial-E
[3]16	SB0030669DDD	52	4,845	Surficial-A
[4]17	SB0030669AAA	346	4,837	Bedrock
[4]18	SB0030668ABA	330	4,812	Bedrock
[4]19	SB00306617CDD	331	4,895	Bedrock

[1] System of numbering wells is described in "Local Well-Numbering System" section.

[2] No water-quality samples collected from site 3 because well was destroyed.

[3] Irrigation well.

[4] Domestic well.

Table 2. Multilevel ground-water sampling devices used near Platteville, Colorado

[MLGWSD, multilevel ground-water sampling device; Surficial-E, surficial aquifer mostly composed of eolian deposits]

Site designation (see fig. 12)	Local well number[1]	Sampling depths (feet below land surface)	Aquifer sampled
MLGWSD-1	SB00306616DAB2	20, 25, 30, 34	Surficial-E
MLGWSD-2	SB00306616BBD2	11, 16, 21, 25	Surficial-E
MLGWSD-3	SB00306616AAC2	11, 16, 21, 25	Surficial-E
MLGWSD-4	SB00306616AAB2	22, 27, 32, 36	Surficial-E
MLGWSD-5	SB00306616BAA2	5, 10, 15, 19	Surficial-E

[1] System of numbering wells is described in "Local Well-Numbering System" section.

well in section 9; and 3 bedrock domestic-use wells in sections 8, 9, and 17.

Three soil-moisture tubes and a precipitation station also were installed in the study area (fig. 12). The 2-in. aluminum soil-moisture tubes were 10-ft deep. A neutron soil-moisture probe was inserted into these tubes to measure the water content of the unsaturated zone. The precipitation station consisted of a weighing-bucket gage that recorded rain and snow volumes and a tipping-bucket gage that recorded only rainfall volumes.

Samples from eolian deposits consisting of sand, silt, clay, and associated moisture were obtained for chemical analyses from several depths at five locations in the unsaturated zone. Locations of the unsaturated-zone sampling sites are shown in figure 13 and listed in table 3. One unsaturated-zone site (UZ–1) was sampled in 1985 and in 1988; the other four sites were sampled only in 1988. The sampling network and methods used for sampling the unsaturated zone and surficial aquifer are described in detail in Johncox and Gaggiani (1991).

Table 3. Sampling sites in the unsaturated zone near Platteville, Colorado

[UZ, unsaturated zone]

Site designation (see fig. 13)	Depth of samples collected from UZ (feet below land surface)
UZ–1	0, 1.5, 3.5, 5.5
UZ–2	0, 1.5, 3.5, 5.5
UZ–3	0, 1.5, 3.5, 5.5
UZ–4	0, 1.5, 3.5
UZ–5	0, 1.5, 3.5, 5.5

GROUND-WATER FLOW

Precipitation or irrigation water reaching the land surface in section 16 infiltrates into the sandy soil and collects in temporary ponds. There is little or no runoff. Most water that infiltrates into the soil evaporates and is transpired by crops. The remaining water, if any, continues to move down to the saturated zone and recharges the aquifer. Generally, there is little recharge to the aquifer by precipitation in this semiarid area. However, where irrigation water is applied or the water table is close to the surface, the aquifer is recharged. Water levels in observation wells, soil-moisture measurements, precipitation quantities, and physical properties of soil cores were used to describe the movement of water through the unsaturated zone and surficial aquifer.

Unsaturated Zone

Data from the soil-moisture tubes (fig. 14) indicate that the moisture content in the unsaturated zone in the irrigated area (soil-moisture tube 1) was larger and varied more with depth and time compared to the moisture content in the unsaturated zone in areas of nonirrigated farming (soil-moisture tubes 2 and 3). There was more water in the irrigated unsaturated zone than in the nonirrigated unsaturated zone because of the additional water applied by the center-pivot sprinkler. The volumetric soil-water content at soil-moisture tube 1 ranged from about 5 to 13 percent by volume at 1 ft below land surface to about 21 to 35 percent by volume at 7 ft below land surface. Soil-moisture tube 2 was located in an area used for growing nonirrigated wheat. The volumetric soil-water content at soil-moisture tube 2 ranged from about 7 to 12 percent by volume at a depth of 1 ft below land surface to about 16 to 27 percent by volume at a depth of 10 ft below land surface; a dryer zone that consistently contained less water than the zones above or below it was detected at a depth of 6 ft below land surface. The volumetric soil-water content at soil-moisture tube 3, also located in an area used for growing nonirrigated wheat, ranged from about 4 to 8 percent by volume at 1 ft below land surface to about 16 to 26 percent by volume at 10 ft below land surface. At soil-moisture tube 3, there was little variation in water content to a depth of 8 ft below land surface. Water content in the unsaturated zone was largest during October 1987 at all measured soil-moisture sites (fig. 14).

The water balance in the unsaturated zone of section 16 was estimated by using the following equation:

$$\text{Precipitation} + \text{Irrigation} = \text{Change in water storage} + \text{Evapotranspiration} + \text{Percolation} \qquad (1)$$

Precipitation (9.1 in.) and irrigation water (24 in.) were applied to the land surface during 1988. The amount of irrigation water applied was calculated using time of pumping and measured flow rate. Evapotranspiration (29 in.) was estimated by using the Blaney-Criddle method for estimating evapotranspiration (Sellers, 1965). Temperature data were from a weather station in Greeley (National Oceanic and Atmospheric Administration, 1988). Healy and others (1989), after monitoring water content of the unsaturated zone at a site weekly to biweekly for 2 years, concluded that the annual change in storage in the unsaturated zone over a 1-year period was negligibly small. During Healy's study, the moisture content in the unsaturated zone varied directly with precipitation

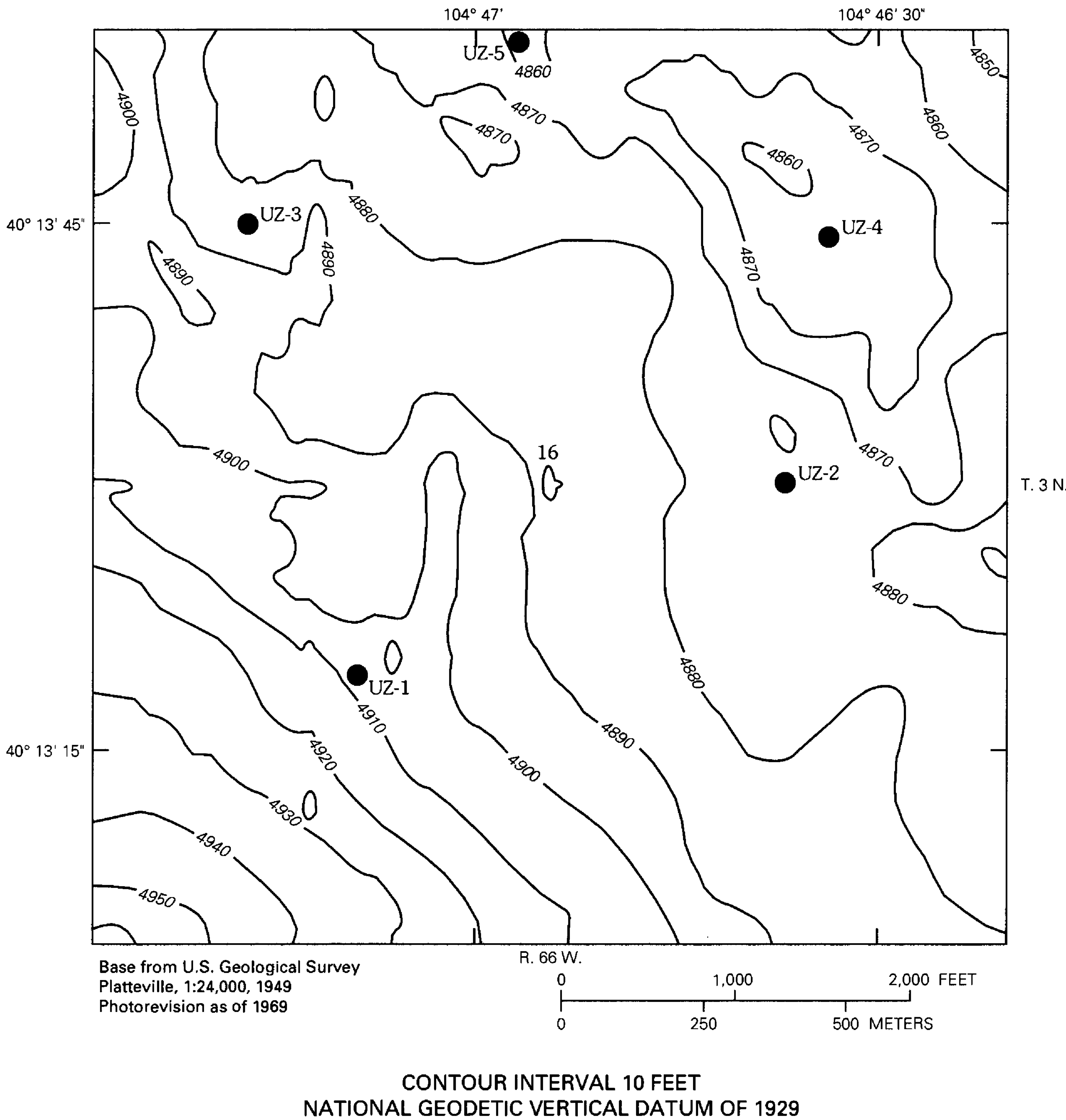


Figure 13. Locations of sampling sites in the unsaturated zone.

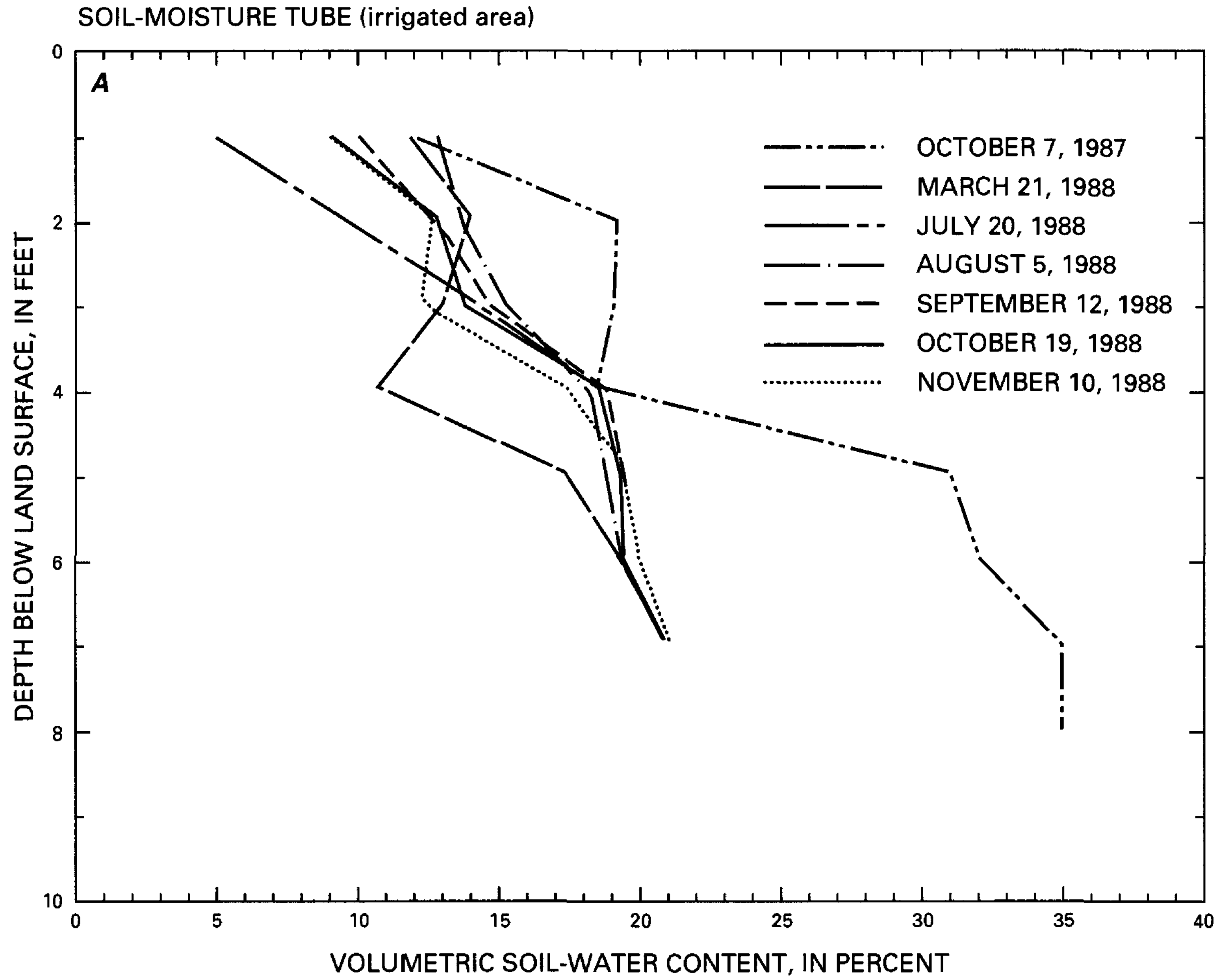


Figure 14. Soil-water content in the unsaturated zone.

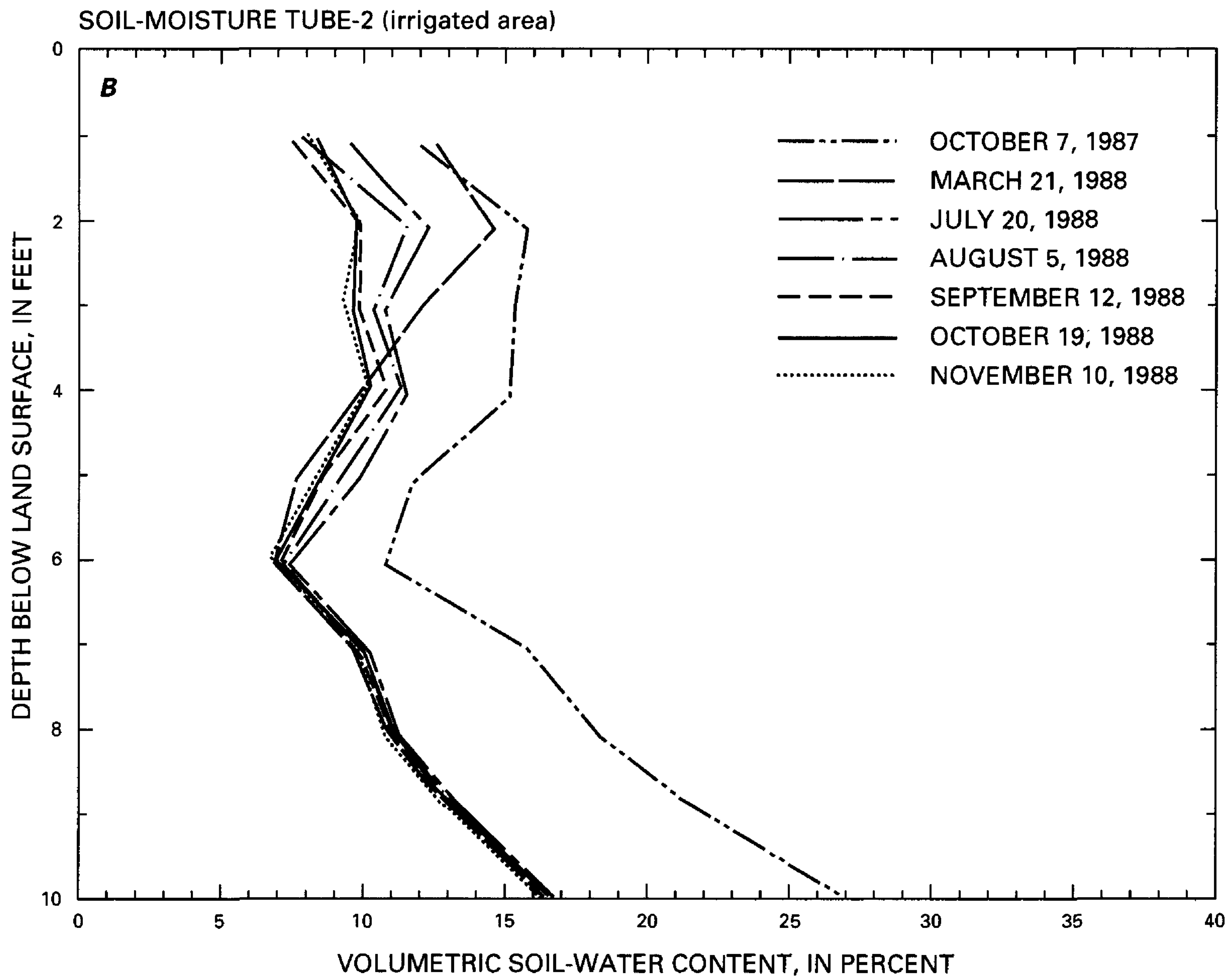


Figure 14. Soil-water content in the unsaturated zone--Continued.

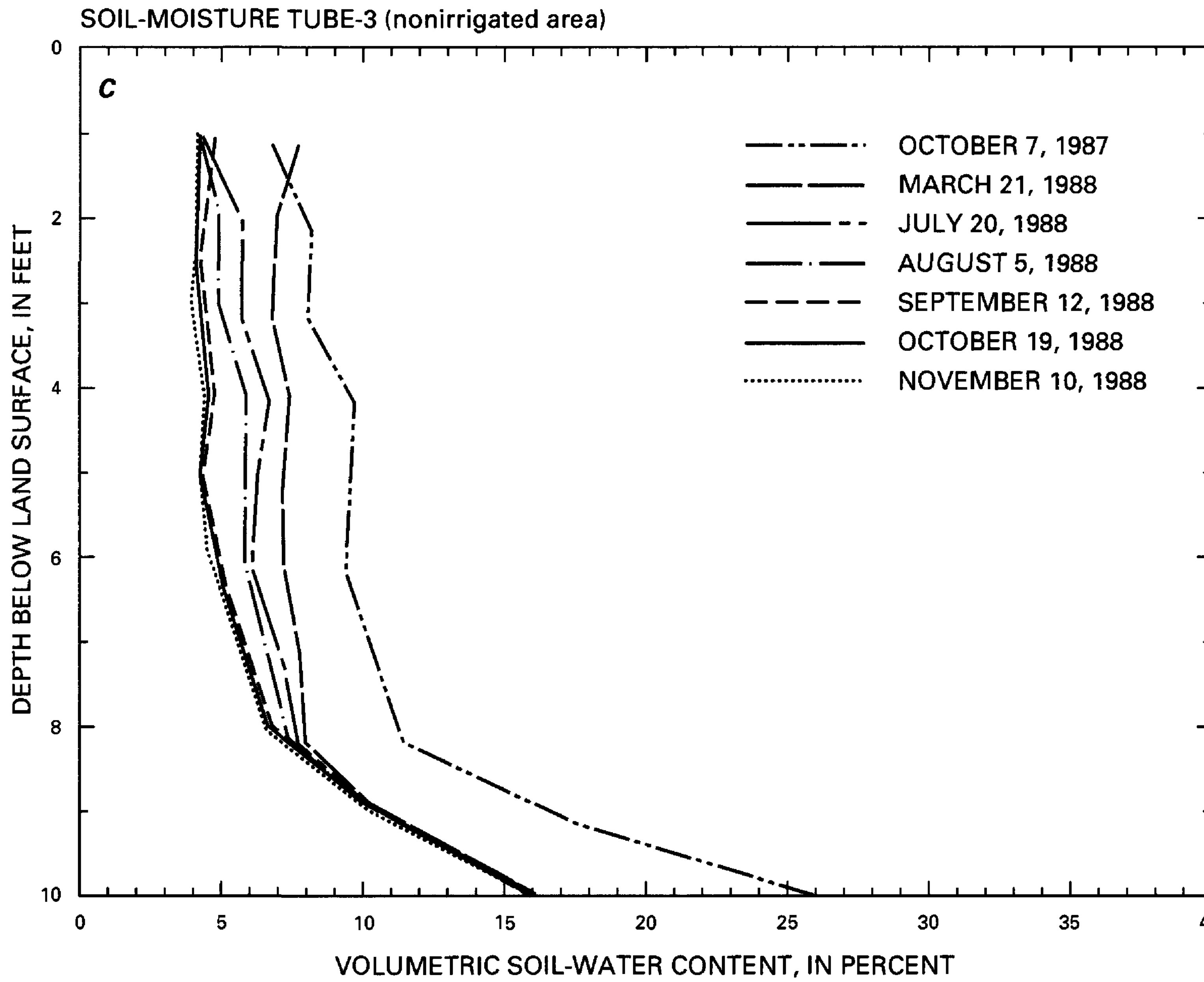


Figure 14. Soil-water content in the unsaturated zone--Continued.

and evapotranspiration, and the variations were noticeably different between the 2 years. Therefore, at Platteville, annual change in water storage is assumed to be zero (Healy and others, 1989).

During 1988, about 4 in. of water was calculated to infiltrate to the aquifer through the unsaturated zone in the irrigated southwestern quarter of section 16. The quantity of recharge to the aquifer was determined by solving equation (1) using the other known quantities for percolation. Most of the precipitation and irrigation and all of the estimated evapotranspiration occur from the beginning of May to the end of September (fig. 15).

Saturated Zone

Ground water in the surficial aquifer in section 16 generally flows to the northeast (fig. 16). Ponds were dug south of the center of section 16 so that water from ground-water seepage could be used by cattle during the winter. Occasional seepage of water to the land surface from the surficial aquifer occurs at places in section 16 where the water table is above the land surface (fig. 16). The occasionally wet or flooded areas are indicated in figure 8. Water-table contours in the northeastern quarter of section 16 indicate that there may be ground-water flow from the surficial aquifer outside of section 16 into the northeastern corner of section 16.

The saturated thickness of the surficial aquifer in August 1987 ranged from less than 5 ft near the southern, eastern, and western boundaries of section 16 to more than 20 ft near well 6 (fig. 17). Generally, the saturated thickness was less than 10 ft in most of the southern one-third of section 16 and increased to more than 10 ft in most of the northern two-thirds. The saturated thickness was largest in the north-central and northeastern parts of section 16.

Analysis of precipitation records and water-level hydrographs for selected observation wells (fig. 18) indicates that precipitation and other factors affected ground-water levels in section 16. Water levels rose in wells 2 and 7 shortly after some periods of intense precipitation (fig. 18) indicating that recharge can increase as a result of increased precipitation. For example, 1.25 in. of rainfall on April 1 and 2 was followed by a rise in water levels on April 14 at wells 2 and 7. The steady rise in water levels in some wells during the winter probably was caused by slow melting of the snowpack. The rise in water level through most of the study period in well 4 probably was caused by recharge from the center-pivot sprinkler. The water level in well 12 fluctuated about 7 to 10 ft each year because of intermittent pumping of nearby irrigation wells. Well 14 showed the smallest water-level variation, probably because the water level was not affected by irrigation or ground-water pumping, and evapotranspiration and recharge had less effect than in areas where the water table was closer to the land surface.

The velocity of ground-water flow is calculated from the following equation (Lohman, 1972, p. 10):

$$v = \frac{K \, dh/dl}{\Theta} \qquad (2)$$

where

v	= velocity, in ft/d;
K	= hydraulic conductivity, in ft/d;
dh/dl	= the hydraulic gradient, in ft/ft; and
Θ	= porosity, expressed as a decimal.

Hydraulic conductivity and porosity of the surficial aquifer were determined from core samples and well logs. Hydraulic-conductivity values from core samples ranged from about 0.0002 to 0.14 ft/d. The smallest hydraulic-conductivity value was from the nearly impermeable clay at the bottom of the surficial aquifer, and the largest value was from the lower part of the surficial aquifer above the clay layer. Hydraulic conductivity of 0.14 ft/d is used because this is most representative of the saturated zone of the surficial aquifer. This value is within the range reported by the U.S. Department of the Interior (1981, p. 29), which indicates that hydraulic-conductivity values for a mixture of sand, silt, and clay range from about 0.0005 to 0.5 ft/d. Porosity of the surficial aquifer (34 percent) was calculated from the mean dry density reported from analysis of core samples and the mean density of quartz and clay minerals. The gradient of the water table (0.017 ft/ft) was determined using the 4,940-ft and the 4,830-ft water-table contours during August 1987 (fig. 16). The equation yields a lateral velocity of ground-water flow in section 16 of about 0.01 ft/d (about 3.6 ft/yr).

CHEMICAL QUALITY OF SEDIMENTS IN THE UNSATURATED ZONE AND WATER IN THE SURFICIAL AND BEDROCK AQUIFERS

Samples for chemical analyses were collected from eolian deposits at selected depths in the unsaturated zone and from water in the surficial aquifer. Chemical analyses of samples obtained from the unsaturated zone are listed in table 4. Chemical analyses of water samples obtained from the surficial aquifer are listed in Johncox and Gaggiani (1991).

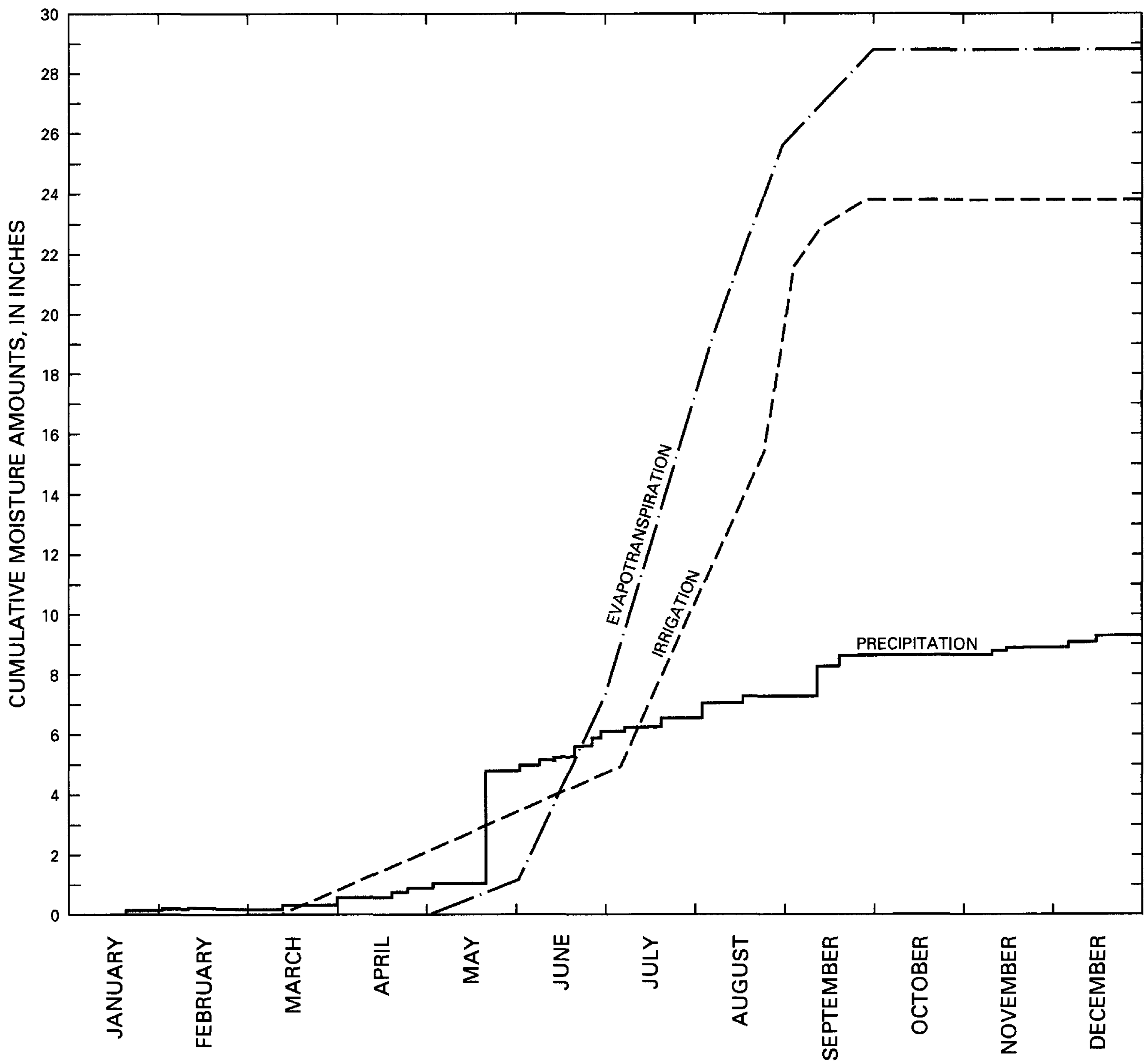


Figure 15. Evapotranspiration, irrigation, and precipitation in the southwestern quarter of section 16 in 1988.

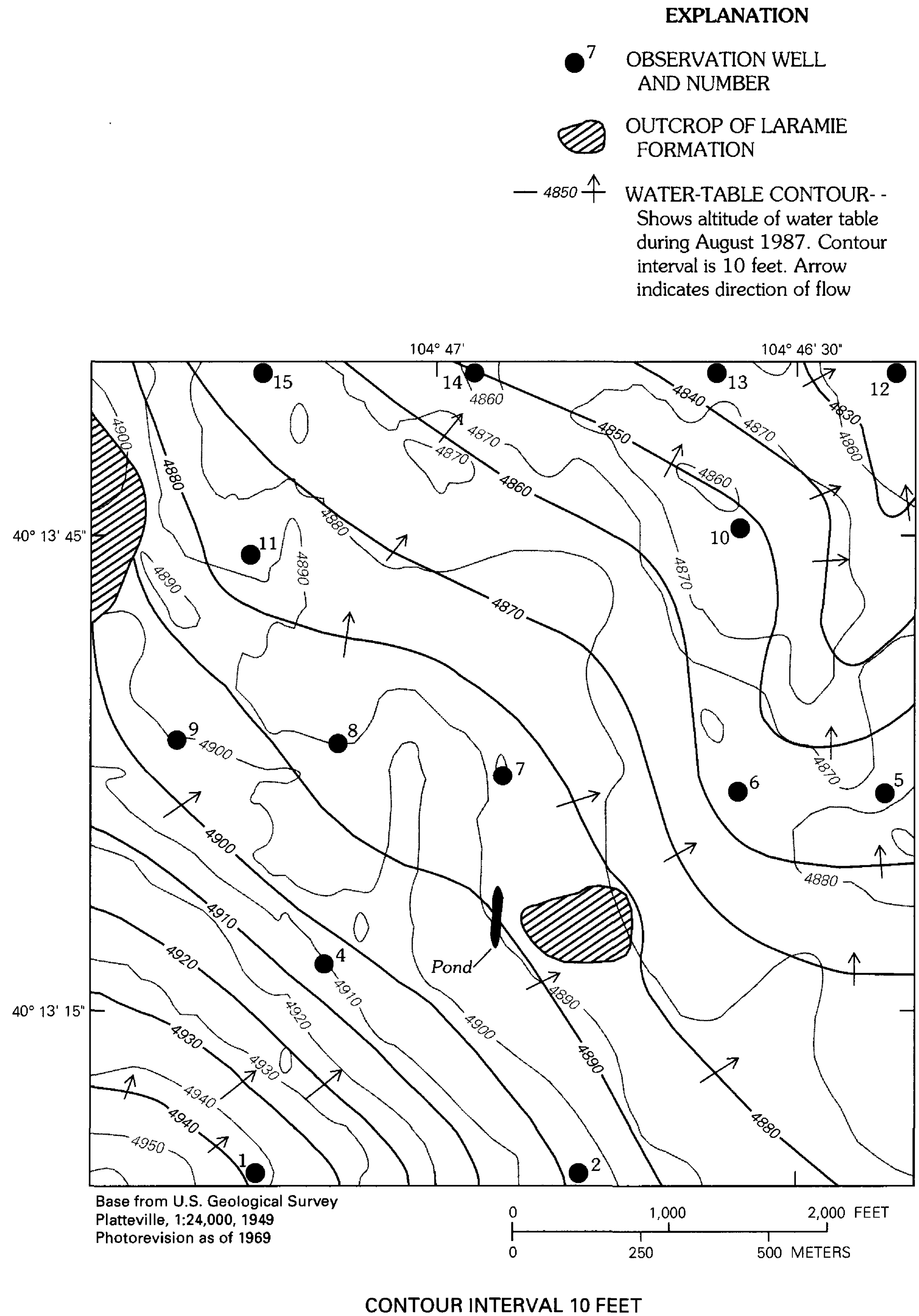
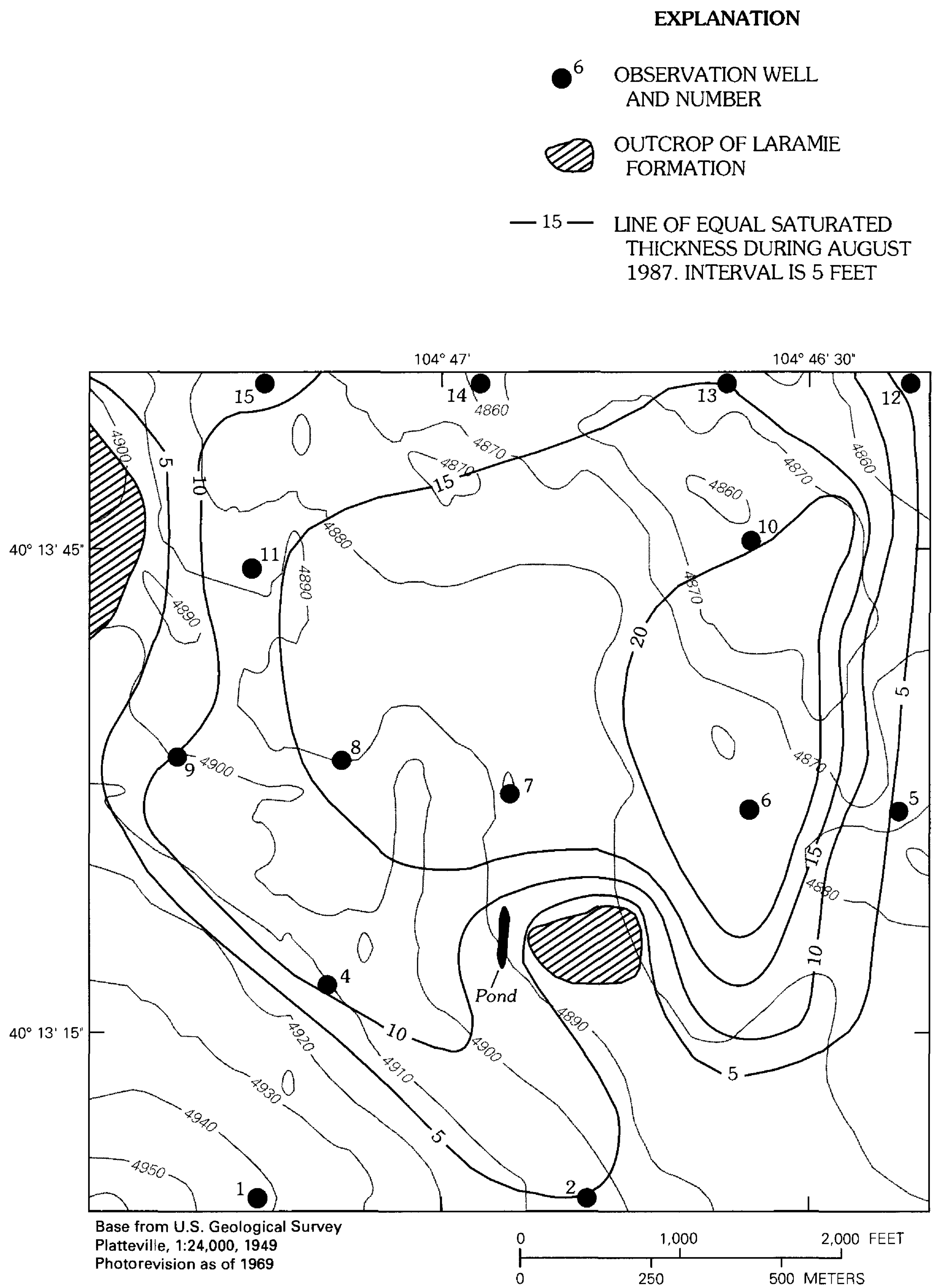


Figure 16. Water-level contours of the surficial aquifer and direction of ground-water flow, August 1987.



CONTOUR INTERVAL 10 FEET
NATIONAL GEODETIC VERTICAL DATUM OF 1929

Figure 17. Saturated thickness of the surficial aquifer, August 1987.

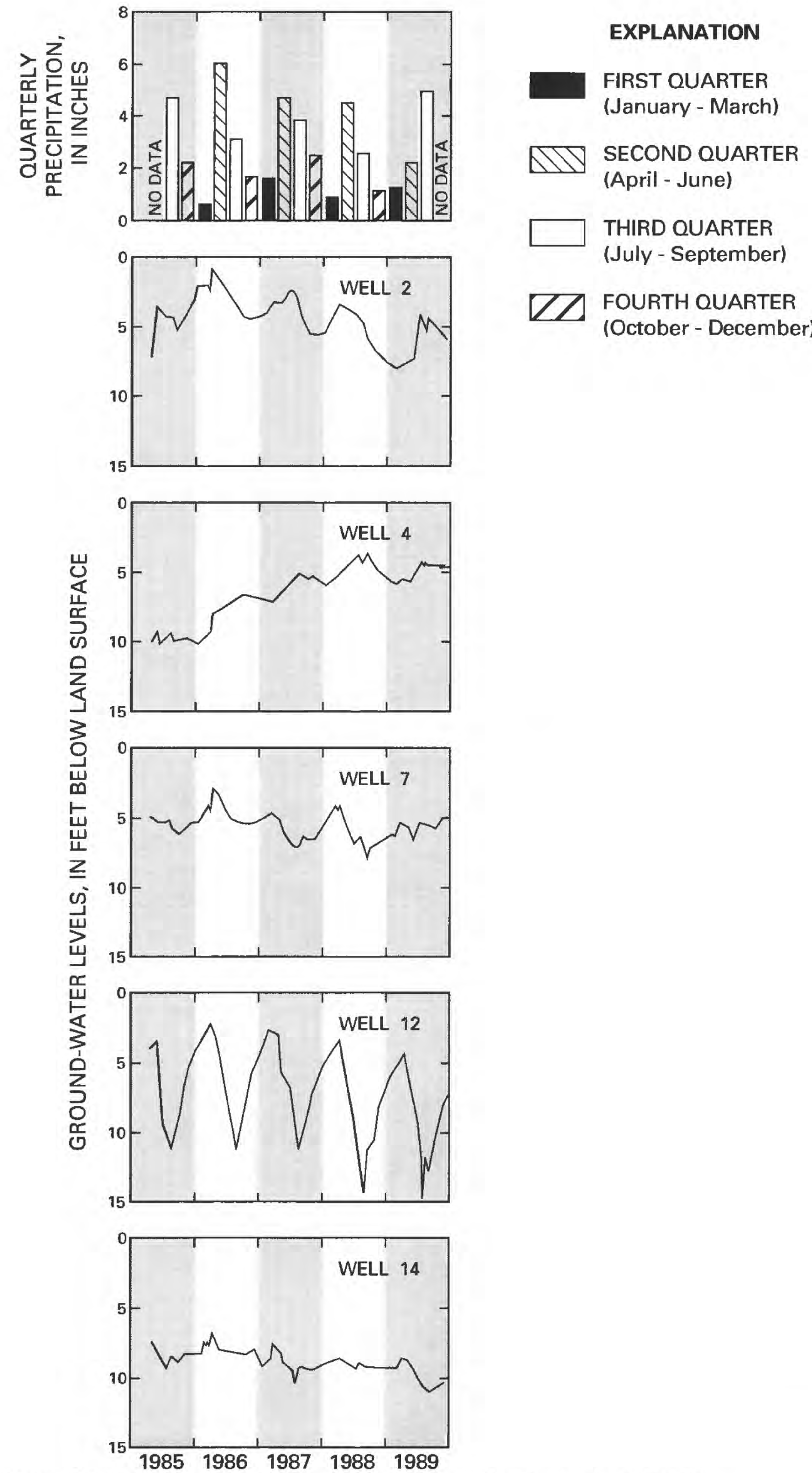


Figure 18. Quarterly precipitation and ground-water levels at selected wells.

Table 4. Chemical analyses of eolian deposits sampled from selected depths in the unsaturated zone near Platteville, Colorado

[NH_4, ammonia; mg/kg, milligram per kilogram; NO_2+NO_3, nitrite plus nitrate; µg/g, microgram per gram; <, less than]

Unsaturated zone sampling-site number (see fig. 13)	Date	Depth of sample (feet)	Nitrogen, NH_4 total (mg/kg as N)	Nitrogen, NH_4 plus organic total (mg/kg as N)	Nitrogen, NO_2+NO_3 total (mg/kg as N)	Phosphorus, total (mg/kg as P)	Arsenic, total (µg/g as As)	Cadmium, total recoverable (µg/g as Cd)	Chromium, total recoverable (µg/g as Cr)	Cobalt, total recoverable (µg/g as Co)	Copper, total recoverable (µg/g as Cu)	Iron, total recoverable (µg/g as Fe)	Lead, total recoverable (µg/g as Pb)	Manganese, total recoverable (µg/g as Mn)	Zinc, total recoverable (µg/g as Zn)	Mercury, total recoverable (µg/g as Hg)
UZ–1	04-25-85	1.5	3.5	340	12	400	1	<1	170	<10	<1	4,700	<10	110	20	0.01
	04-25-85	3.5	2.1	130	4.0	110	1	<1	140	<10	<1	4,000	<10	81	10	<0.01
	04-25-85	5.5	2.8	<20	4.0	62	2	1	150	<10	<1	3,300	<10	70	10	<0.01
	11-16-88	0.0	5.4	370	8.0	120	3	<10	2	<50	10	3,400	<100	69	30	0.03
	11-16-88	1.5	3.5	420	5.0	130	3	<10	3	<50	5	4,300	<100	100	20	<0.01
	11-16-88	3.5	9.9	90	4.0	<40	2	<10	3	<50	4	4,300	<100	83	10	<0.01
	11-16-88	5.5	8.3	80	26	57	1	<10	2	<50	4	3,300	<100	70	10	<0.01
UZ–2	11-16-88	0.0	9.3	170	40	130	2	<10	8	<10	6	6,700	<100	130	20	0.02
	11-16-88	1.5	7.2	80	4.0	140	2	<10	<1	<50	<1	1,600	<100	59	<10	<0.01
	11-16-88	3.5	3.9	190	5.0	50	1	<10	2	<50	3	2,400	<100	38	<10	<0.01
	11-16-88	5.5	4.3	210	7.0	63	1	<10	2	<50	4	3,600	<100	57	10	<0.01
UZ–3	11-16-88	0.0	9.5	80	5.0	<40	2	<10	2	<50	4	2,800	<100	50	20	<0.01
	11-16-88	1.5	2.8	170	4.0	220	2	<10	1	50	4	3,000	<100	49	10	<0.01
	11-16-88	3.5	1.2	210	3.0	<40	1	<10	3	<50	3	4,000	<100	56	10	<0.01
	11-16-88	5.5	0.8	80	<2.0	<40	1	<10	2	<50	4	3,200	<100	55	10	<0.01
UZ–4	11-16-88	0.0	8.8	370	5.0	170	3	<1	20	10	10	9,700	10	210	40	0.01
	11-16-88	1.5	3.5	40	3.0	100	3	<1	8	10	6	6,700	<100	100	20	<0.01
	11-16-88	3.5	8.7	40	<2.0	75	3	<10	10	10	10	9,000	<100	12	30	<0.01
UZ–5	11-16-88	0.0	6.4	330	34	91	1	<10	5	10	10	3,100	<100	94	30	0.04
	11-16-88	1.5	2.4	170	8.0	46	2	<10	3	<50	6	4,500	<100	93	20	<0.01
	11-16-88	3.5	1.9	130	31	<40	2	<10	5	<50	5	6,100	<100	160	20	<0.01
	11-16-88	5.5	4.0	120	21	130	2	<10	10	10	6	6,300	<100	160	20	<0.01

Conditions Before Sewage-Sludge Application (1985)

Samples of eolian deposits collected from the unsaturated zone at sampling site UZ–1 (fig. 14) in April 1985, before the application of sewage sludge, were analyzed for nutrients and trace elements (table 4). Most of the nitrogen detected in the unsaturated zone in 1985 was in the form of ammonia plus organic nitrogen (fig. 19). Nitrate was detected in the unsaturated zone but at concentrations substantially less than the concentrations of ammonia plus organic nitrogen. Concentrations of ammonia plus organic nitrogen at UZ–1 in 1985 decreased from 340 mg/kg at a depth of 1.5 ft to less than 20 mg/kg at a depth of 5.5 ft (fig. 19 and table 4). The location of site UZ–1 was under the center-pivot sprinkler. Anhydrous ammonia had been applied to the soil and mixed with the irrigation water in the sprinkler during farming activities.

The largest concentrations of iron, chromium, and manganese were detected in the eolian deposits in the unsaturated zone in 1985 at UZ–1 (table 4). Concentrations of chromium ranged from 140 µg/g at 3.5 ft to 170 µg/g at 1.5 ft; concentrations of iron ranged from 3,300 µg/g at 5.5 ft to 4,700 µg/g at 1.5 ft; and concentrations of manganese ranged from 70 µg/g at 5.5 ft to 110 µg/g at 1.5 ft. The toxic trace elements arsenic, cadmium, lead, and mercury were near or less than detection limits.

Ground water in the surficial aquifer in section 16, before application of sewage sludge, contained large concentrations of calcium, magnesium, sodium, sulfate, and dissolved solids (Johncox and Gaggiani, 1991). Concentrations of hardness as calcium carbonate ranged from 260 mg/L in well 6 to 3,900 mg/L in well 10; concentrations of dissolved solids ranged from 701 mg/L in well 14 to 12,100 mg/L in well 10. The predominant ions in the surficial aquifer were sodium and sulfate. Concentrations of sodium ranged from 89 mg/L in well 14 to 2,500 mg/L in well 10. Concentrations of sulfate ranged from 180 mg/L in well 4 to 7,000 mg/L in well 10. Well 10 was installed near a natural gas well.

Nitrate concentrations exceeded the 10 mg/L recommended limit for drinking water (U.S. Environmental Protection Agency, 1976) in 9 of the 14 surficial-aquifer wells sampled. Nitrate concentrations ranged from 0.36 mg/L in well 1 to 33 mg/L in well 6. Well 1 probably was not affected by fertilizers because it was upgradient from the fertilized area in section 16 and downgradient from nonirrigated wheat cultivated south of section 16. Wells 1 and 2 probably were not affected by farming activities south of section 16 because the surficial aquifer at the southern boundary of section 16 is thin and occasionally dry so that there is little or no flow from the south. The large concentrations of nitrate in other wells in the surficial aquifer in 1985 probably were caused by application of fertilizer other than sewage sludge to the soil because, according to the land owner, no sewage sludge had been previously applied.

The surficial aquifer in section 16 probably had been affected by fertilizers before sewage sludge was applied. In June 1985, 3 months before sewage-sludge application began, nitrate concentrations in water from a large part of the surficial aquifer in section 16 exceeded 10 mg/L. Large nitrate concentrations were detected in parts of the western half and the northeastern quarter of section 16.

Ground water in the bedrock aquifer (sampled from domestic bedrock wells 17, 18, and 19) had small concentrations of hardness as calcium carbonate, dissolved solids, and nitrate (Johncox and Gaggiani, 1991). Prior to the period of sludge application, concentrations of hardness as calcium carbonate ranged from 7.0 mg/L in well 19 to 42 mg/L in well 18; concentrations of dissolved solids ranged from 492 mg/L in well 19 to 782 mg/L in well 18; and concentrations of nitrate ranged from 0.04 mg/L in well 18 to 0.50 mg/L in well 19. The predominant ions were sodium and bicarbonate. Concentrations of sodium ranged from 200 mg/L in well 19 to 310 mg/L in well 18. Concentrations of bicarbonate ranged from 194 mg/L in well 19 to 432 mg/L in well 17.

During 1985, prior to sewage-sludge application, two bacteria samples were obtained from most observation wells. None of the samples contained fecal-coliform bacteria counts greater than the detection limit, but most samples contained fecal-streptococcal bacteria.

Conditions During Sewage-Sludge Application (1986–89)

Samples of eolian deposits from the unsaturated zone were obtained from the surface and from depths of 1.5, 3.5, and 5.5 ft at four of five sites in 1988. No samples were obtained from 5.5 ft at site UZ–4. Concentrations of nitrogen, phosphorus, and trace elements in the unsaturated zone from samples obtained in 1988 are listed in table 4. At the time of the 1988 sampling, sewage sludge had been applied on section 16 for 3 years.

Ammonia and organic nitrogen were the predominant forms of nitrogen in the unsaturated zone in

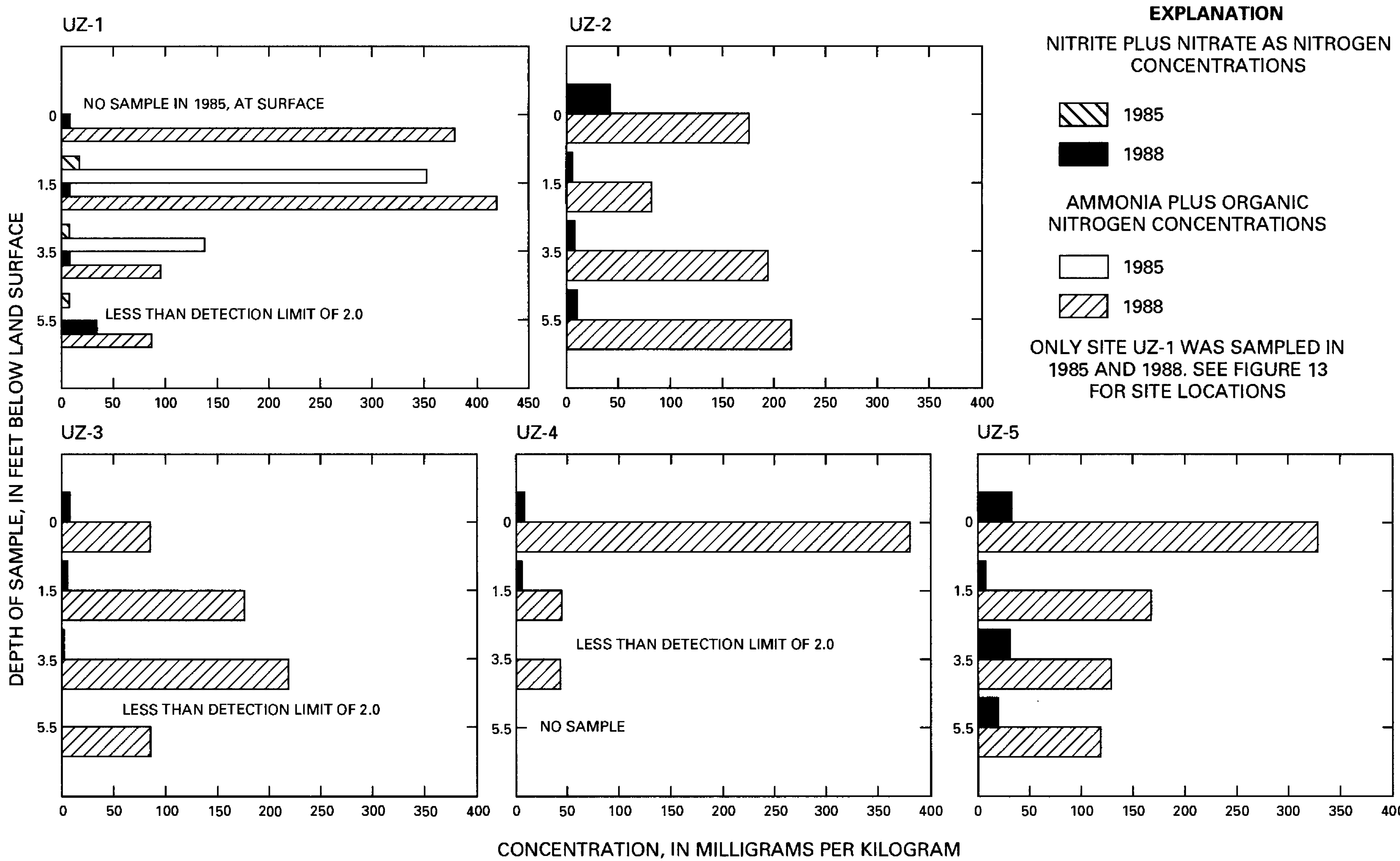


Figure 19. Concentrations of nitrite plus nitrate as nitrogen and ammonia plus organic nitrogen in the eolian deposits in the unsaturated zone.

1988. Concentrations of ammonia plus organic nitrogen generally decreased with depth at all the unsaturated-zone sampling sites except UZ–2 and UZ-3 (fig. 19), where concentrations generally increased with depth. The largest ammonia plus organic nitrogen concentrations were at and near the land surface at site UZ–1 in the irrigated southwestern quarter of section 16. The smallest concentrations were at depths of 1.5 and 3.5 ft at site UZ–4 in the northeastern quarter of section 16. Nitrate was only a small part of the total nitrogen concentration in the unsaturated zone.

Trace elements in the unsaturated zone sampled in 1988 generally were detected near or less than the detection limit except for chromium, copper, iron, and manganese (table 4). Concentrations of chromium at site UZ–1 ranged from 2 μg/g at the surface and 5.5 ft to 3 μg/g at 1.5 and 3.5 ft. Concentrations of chromium at the other sites did not exceed 20 μg/g. Concentrations of copper ranged from less than 1 μg/g at site UZ–2 (1.5 ft) to 10 μg/g at site UZ–1 (surface), site UZ–4 (surface and 3.5 ft), and at site UZ–5 (surface). Concentrations of iron ranged from 1,600 μg/g at site UZ–2 (1.5 ft) to 9,700 μg/g at site UZ–4 (surface). Concentrations of manganese ranged from 12 μg/g at site UZ–4 (3.5 ft) to 210 μg/g at site UZ–4 (surface).

At site UZ–1 in the unsaturated zone of the irrigated part of section 16, nitrogen concentrations generally increased and trace-element concentrations generally were the same from 1985 to 1988. Ammonia plus organic nitrogen concentrations increased from 1985 to 1988, ranging from less than 20 to 340 mg/kg in 1985 and from 80 to 420 mg/kg in 1988. Nitrate concentrations at 5.5 ft increased from 4.0 mg/kg in 1985 to 26 mg/kg in 1988. Chromium concentrations decreased, ranging from 140 to 170 μg/g in 1985 and from 2 to 3 μg/g in 1988. Copper concentrations increased slightly; all samples were less than 1 μg/g in 1985 and ranged from 4 to 10 μg/g in 1988.

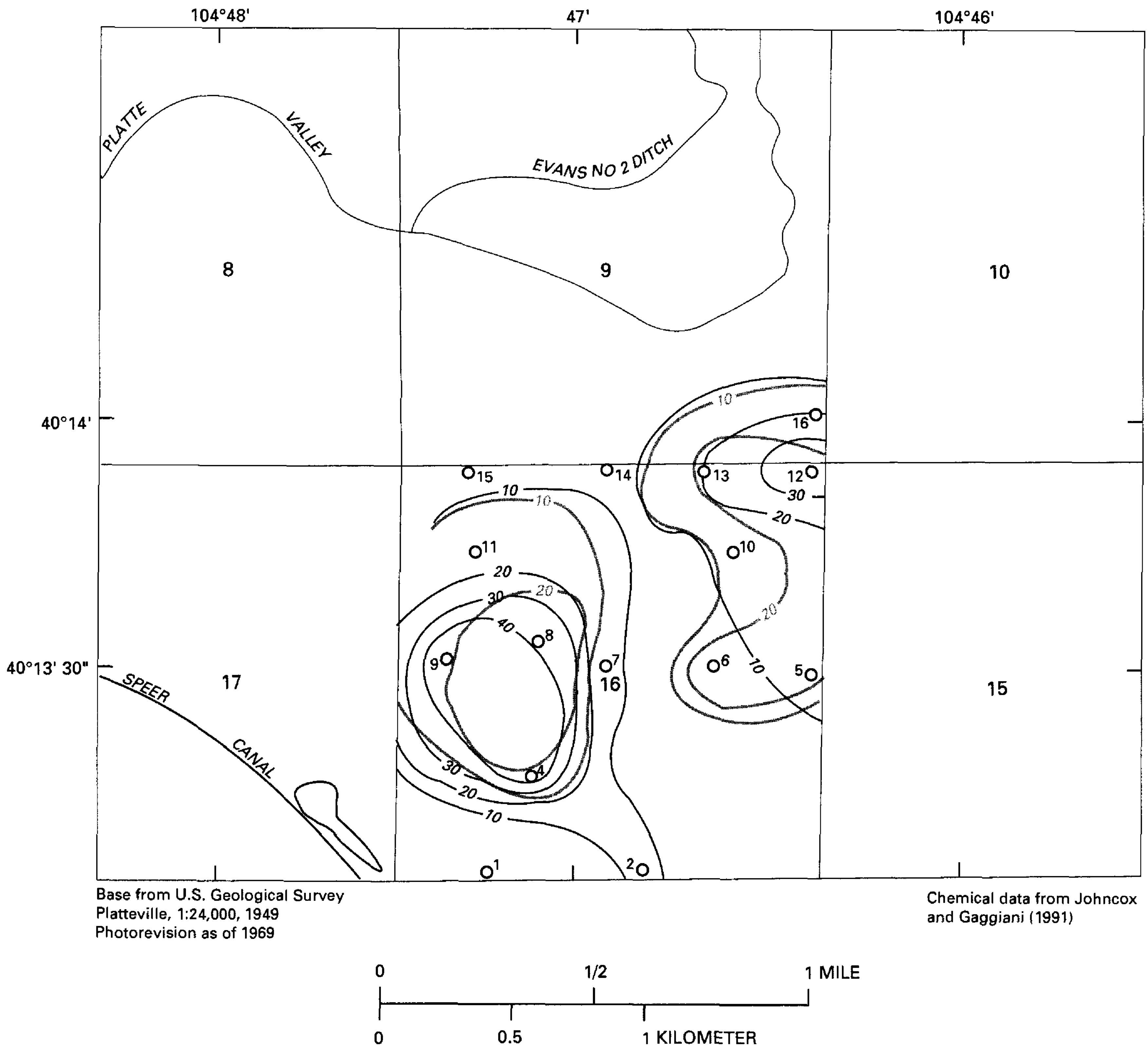
Ground water sampled from the surficial aquifer during the period of sewage-sludge application in section 16 (1986–89) contained large concentrations of calcium, magnesium, sodium, sulfate, and dissolved solids (Johncox and Gaggiani, 1991). In some areas, nitrate exceeded the 10-mg/L recommended limit for drinking water (U.S. Environmental Protection Agency, 1976). During 1986–89, concentrations of hardness as calcium carbonate ranged from 266 mg/L in well 13 to 4,300 mg/L in well 10; dissolved solids ranged from 714 mg/L in well 14 to 12,300 mg/L in well 10; and nitrate ranged from 0.04 mg/L in well 1 to about 92 mg/L in well 4. The predominant ions were sodium and sulfate. Sodium concentrations ranged from 82 mg/L in well 14 to 2,200 mg/L in well 10. Sulfate concentrations ranged from 140 mg/L in well 13 to 7,200 mg/L in well 10.

Compared to 1985, maximum concentrations of hardness, dissolved solids, sodium, and sulfate in samples obtained from wells in the surficial aquifer during 1986–89 decreased or remained about the same in wells along the southern boundary and the northern half of section 16 and increased in wells in the southwestern quarter and the center of section 16 (Johncox and Gaggiani, 1991). The increased concentrations could have been caused by irrigation water leaching these constituents out of the soil and into the surficial aquifer.

Lines of equal mean nitrate concentrations (1986–89) show the areal distribution of nitrate in the surficial aquifer in section 16 (fig. 20). The largest nitrate concentrations were in the southwestern and northeastern quarters of section 16. The remaining area in section 16 generally contained mean nitrate concentrations of less than 20 mg/L. The southwestern quarter contained an area of mean nitrate concentrations of more than 40 mg/L. One possible source of nitrate is cattle manure that was stored in this area before it was applied to irrigated farmland. Cattle manure was applied to section 16 as part of normal farming activities prior to sewage-sludge application. Large concentrations of nitrate in the northeastern quarter may originate from farming activities outside of section 16. The water-table contours (fig. 16) indicate that there is ground-water flow from the alluvial aquifer outside of section 16 into the northeastern corner of section 16.

Mean nitrate concentrations increased and large nitrate concentrations generally were more widespread in the surficial aquifer during 1986–89 compared to nitrate concentrations before sewage-sludge application in 1985 (fig. 20). Mean nitrate concentrations increased about 20 mg/L in the southwestern quarter of section 16 during sewage-sludge application. The area of nitrate concentrations greater than 10 mg/L increased in the western half and decreased in the northeastern quarter of section 16. Organic and inorganic fertilizers probably were the sources of these nitrate concentrations.

Variations in nitrate concentrations with depth and time were measured in water samples from the MLGWSD's in the surficial aquifer (figs. 12 and 21). Nitrate was the predominant form of nitrogen detected at all levels sampled in the surficial aquifer (Johncox and Gaggiani, 1991). Nitrate concentrations were smallest at sampling site MLGWSD–5 (ranging from 3 to 7.3 mg/L) and largest at MLGWSD–1 (ranging from 9.6 to 24 mg/L). During September 1987 through



EXPLANATION

—10— LINE OF EQUAL MEAN CONCENTRATION OF NITRITE PLUS NITRATE AS NITROGEN-- Tweleve samples obtained from most wells during 1986-89. Interval is 10 milligrams per liter.

—10— LINE OF EQUAL MEAN CONCENTRATION OF NITRITE PLUS NITRATE AS NITROGEN-- Two samples obtained from most wells during 1985. Interval is 10 milligrams per liter.

o1 OBSERVATION WELL AND NUMBER

Figure 20. Lines of equal mean concentrations of nitrite plus nitrate as nitrogen in the surficial aquifer.

September 1988, nitrate concentrations varied less than 5 mg/L at all depths sampled at MLGWSD–5 and varied more than 5 mg/L at all depths sampled at MLGWSD–1 and MLGWSD–2. Generally, concentrations were larger and varied more near the top of the surficial aquifer than near the bottom. MLGWSD–1 and MLGWSD–2 probably were affected by the recharge caused by the irrigation in the southeastern and southwestern quarters of section 16. MLGWSD–5 was only slightly affected by cultivation of nonirrigated wheat near the northern boundary of section 16.

Most nitrogen probably moves vertically downward through the unsaturated zone with the water that infiltrates from irrigated areas and low, temporarily ponded areas. The nitrogen then probably moves laterally through the surficial aquifer. The direction of nitrogen movement in the surficial aquifer in section 16 probably is controlled by the movement of ground water, which follows the slope of the land surface northeastward (figs. 16 and 17).

Nitrate concentrations increased in most of the surficial aquifer during the study period (fig. 22). The change in nitrate concentrations in samples collected in June 1985, prior to sewage-sludge application, compared to samples collected in August 1989, after 4 years of applying sewage sludge and other fertilizers to the soil, are indicated in figure 22. Increases in nitrate concentrations ranged from less than 5 mg/L near the southern and northern boundary of section 16 to 20 to 40 mg/L in the southwestern quarter and northeastern corner of section 16. The areas of smallest nitrate concentrations were the southern boundary of section 16, which is upgradient from fertilizer application in section 16, and the northern boundary of section 16, where nonirrigated wheat was grown.

Most trace elements (arsenic, cadmium, cobalt, copper, lead, mercury, and zinc) were detected in small concentrations; chromium, iron, and manganese were detected in larger concentrations, some exceeding the recommended drinking water limit (Johncox and Gaggiani, 1991). Chromium concentrations ranged from less than 20 μg/L in most of the wells to 280 μg/L in well 1. The recommended drinking water limit for chromium is 50 μg/L (U.S. Environmental Protection Agency, 1976). Iron and manganese were detected in concentrations ranging from less than 50 to 1,900 μg/L for iron and less than 40 to 2,700 μg/L for manganese. The recommended drinking water limit is 300 μg/L for iron and 50 μg/L for manganese (U.S. Environmental Protection Agency, 1976). Most trace elements detected in water from the surficial aquifer did not exceed the recommended drinking water limit and probably were not moving into the ground water from the sewage sludge. Gaggiani (1991) reported that trace elements did not leach into the shallow ground water at the Lowry sewage-sludge disposal area where 233,000 dry tons of sewage sludge had been disposed. If trace elements did not leach out of this large amount of sewage sludge into the shallow ground water, then trace elements probably did not leach out of the much smaller amount of sludge applied to section 16.

Fecal-coliform and fecal-streptococcal bacteria were detected in the surficial aquifer during sewage-sludge application (1986–89). Fecal-coliform bacteria were detected only in wells 2, 4, and 8. The largest concentration of fecal-coliform bacteria in the surficial aquifer was 82 col/100 mL in well 8. Fecal-streptococcal bacteria were detected in all observation wells in the surficial aquifer. The largest fecal-streptococcal bacteria concentration was 2,800 col/100 mL in well 2.

Lin and others (1974, p. 295) used the fecal-coliform/fecal-streptococci ratio to determine whether the bacterial contamination was primarily from a human source (ratios greater than 4) or from warm-blooded animals other than human (ratios less than 0.7). For example, mean bacterial concentrations for well 8 during the study period were about 11 col/100 mL for fecal-coliform bacteria and about 35 col/100 mL for fecal-streptococcal bacteria, which is a ratio of 0.31. Because the ratio was less than 0.7, the bacterial contamination at well 8 probably was caused by cattle that are kept on section 16 during the winter.

In the bedrock aquifer, during the period of sludge application, concentrations of hardness as calcium carbonate ranged from 7.0 mg/L in well 19 to 54 mg/L in well 18; concentrations of dissolved solids ranged from 472 mg/L in well 19 to 852 mg/L in well 18; and concentrations of nitrate ranged from less than 0.02 mg/L in well 18 to 0.77 mg/L in well 19. The predominant ions were sodium and bicarbonate. Sodium concentrations ranged from 170 mg/L in well 19 to 310 mg/L in well 18. Bicarbonate concentrations ranged from 162 mg/L in well 19 to 444 mg/L in well 17.

The bedrock aquifer contained smaller concentrations of nitrate compared to the surficial aquifer, and there was little change in concentrations of nitrate in the bedrock aquifer from 1985 to 1986–89. Comparison between chemical data collected before and after sludge application indicates that there was little change in bedrock water quality during the study period.

Fecal-coliform and fecal-streptococcal bacteria also were detected in water samples collected from bedrock wells (wells 17, 18, and 19) used for domestic water supply. Well 17 contained 63 col/100 mL fecal-coliform bacteria in one sample, well 18 contained 3 col/100 mL fecal-streptococcal bacteria in one sample, and well 19 contained fecal-coliform and fecal-streptococcal bacteria in several samples during the study period.

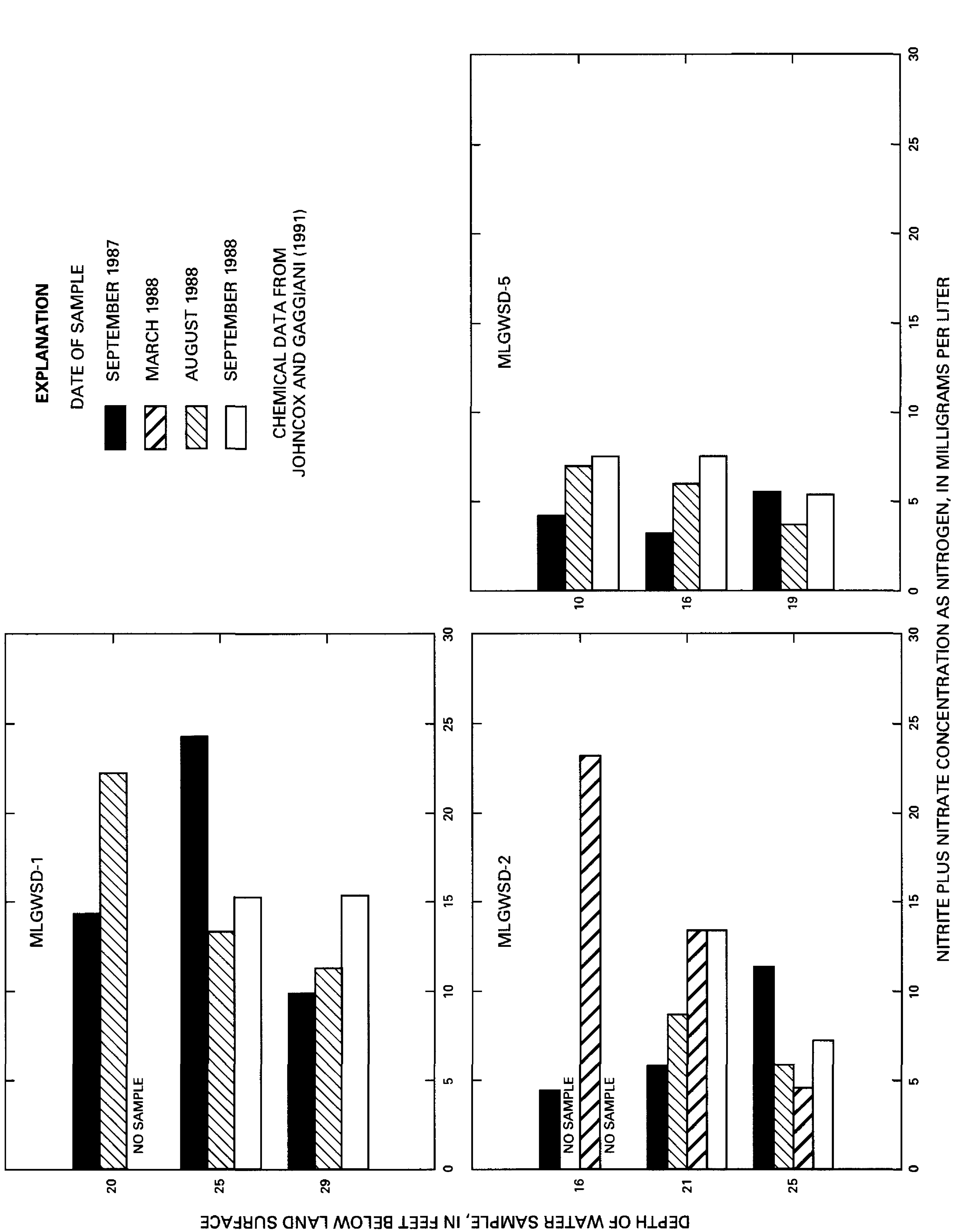
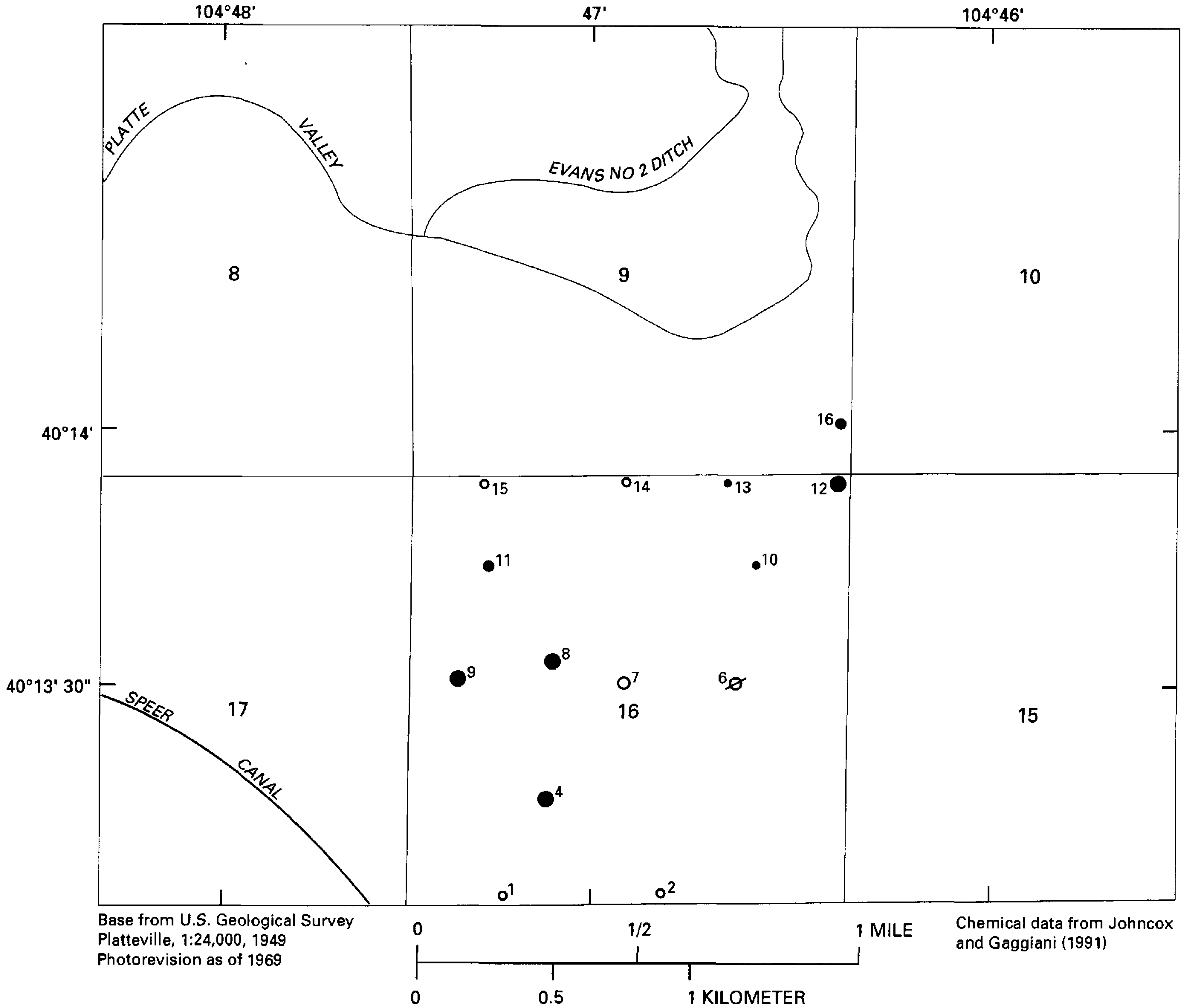


Figure 21. Concentrations of nitrite plus nitrate as nitrogen at several depths in the surficial aquifer.



EXPLANATION

OBSERVATION WELLS--Number is well number (see fig. 12). Symbol size indicates amount of change in nitrite plus nitrate concentrations in milligrams per liter (June 1985 to August 1989)

DECREASE--June 1985 value greater than 10

6 5 to 10

INCREASE--June 1985 value less than 10

1 Less than 5

7 5 to 10

INCREASE--June 1985 value greater than 10

10 Less than 5

11 5 to 10

4 20 to 40

Figure 22. Change in concentrations of nitrite plus nitrate as nitrogen in the surficial aquifer from June 1985 to August 1989.

CONDITIONS OBSERVED WITH APPLICATION OF SEWAGE SLUDGE AND OTHER FERTILIZERS TO FARMLAND

Overapplication of fertilizer on irrigated fields can cause degradation of ground-water quality. The relations among precipitation, irrigation, water levels, and nitrate concentrations in an irrigated area in the southwestern quarter of section 16 and in a nonirrigated area on the northern boundary of section 16 are shown in figure 23. No sludge was applied to the field around well 4 during the 1985 growing season; in well 4, water levels varied less than 1 ft and nitrate concentrations increased about 4 mg/L, probably as the result of infiltration from large precipitation in July. During 1986, irrigation water and sludge were applied

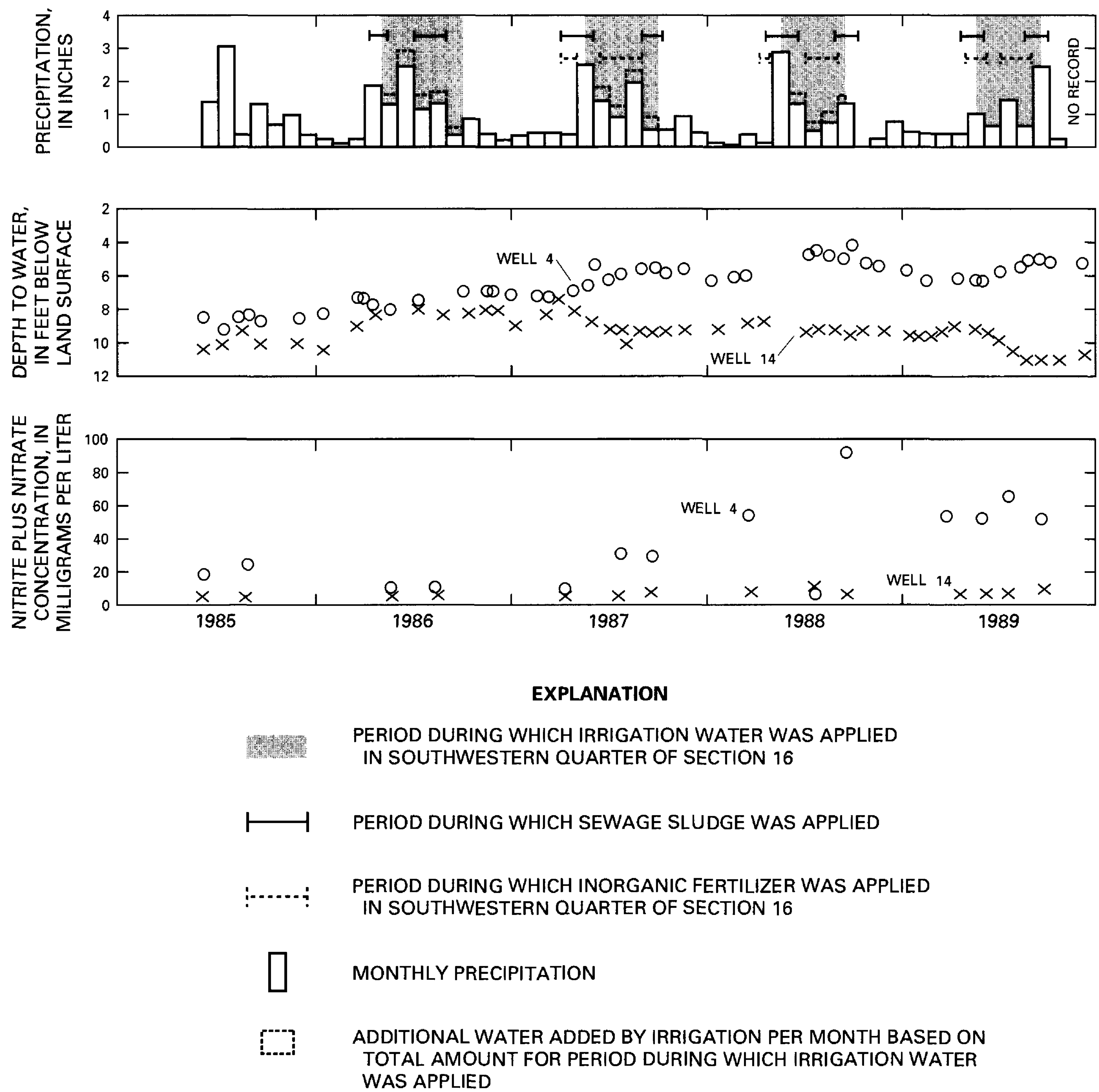


Figure 23. Relations among irrigation, fertilization, precipitation, water levels, and concentrations of nitrite plus nitrate as nitrogen in well 4 (irrigated farmland), and in well 14 (nonirrigated farmland).

to the field around well 4; in well 4, water levels rose about 3.2 ft and nitrate concentrations decreased about 10 mg/L compared to 1985. During 1987–89, irrigation water, sludge, and inorganic fertilizer were applied to the field around well 4; in well 4, mean water levels rose about 0.8 ft from 1987 to 1988 and about 2.5 ft from 1988 to 1989, and nitrate concentrations increased about 10 to 50 mg/L each year. The large increase in nitrate concentrations likely was caused by the combined application of sludge and inorganic fertilizer. Irrigated fields are more likely to affect ground-water quality because some irrigation water infiltrates and carries nitrogen compounds and other soluble compounds to the water table.

Water levels and water quality are less affected by land-use practices in nonirrigated areas. Well 14, for example, is downgradient from the nonirrigated northern half of section 16. Water-level changes in well 14 do not correlate well with periods of greater or lesser precipitation (fig. 23), indicating that little water percolates to the water table. Similarly, nitrate concentrations have remained less than 10 mg/L during 1986–89 when sludge was applied to the adjacent nonirrigated field. Because of minimal percolation, application of sludge caused minimal changes in ground-water levels and quality. Results of other studies (U.S. Environmental Protection Agency, 1983) indicate that application of sewage sludge to farmland at agronomic rates likely will have little or no effect on ground-water quality particularly in areas of low-permeability soil, deep water table, semiarid climate, and nonirrigated crops. Although the soil is permeable and the water table generally is more than 10 ft below the land surface, the northern, nonirrigated part of section 16 has shown few effects from sewage-sludge application. In the southwestern quarter of section 16, the permeable sandy soils, the water table less than 10 ft below land surface, and irrigated fields have enabled infiltration of applied water and dissolved constituents. Nitrate carried to the water table in this area likely was derived from applied sludge and commercial inorganic and organic fertilizer.

The following is a list of conditions observed with application of sewage sludge and other fertilizers.

1. Concentrations of nitrogen generally increased and concentrations of trace elements changed minimally in the unsaturated zone in the irrigated part of section 16 after 4 years of applying sewage sludge and other fertilizers to the soil.
2. In water from the surficial aquifer, concentrations of major anions and cations remained about the same in most of section 16 and increased in the southwestern quarter and center of section 16.
3. Concentrations of nitrate increased in the surficial aquifer in section 16 during sewage-sludge application. The largest mean 1986–89 nitrate concentrations were in the southwestern quarter, probably caused by irrigated agriculture practiced on that quarter of section 16.
4. Nitrate was the predominant form of nitrogen in the surficial aquifer in section 16. Concentrations of nitrate varied with depth and time in the surficial aquifer.
5. Large concentrations of nitrate existing before sewages sludge was applied indicate that the surficial aquifer probably already had been affected by fertilizers. The areas least affected by fertilizers were the southern boundary of section 16, which was upgradient from fertilizer application on section 16 and the nonirrigated northern part of section 16, which was in an area of nonirrigated wheat.
6. Most trace elements were detected in small concentrations; chromium, iron, and manganese were detected in larger concentrations, some exceeding the recommended drinking water limit. Trace elements probably did not leach out of the relatively small amount of sewage sludge applied.
7. The source of bacteria detected in the surficial aquifer probably was cattle, which were kept on section 16 during the winter.
8. Comparison between chemical data collected before and after sludge application indicates that there was little change in water quality in the bedrock aquifer during the study period.

SUMMARY

The Metro Wastewater Reclamation District applies sewage sludge on selected agricultural land as part of its beneficial-reuse program. Sewage sludge was applied on about 1 mi^2 of sandy farmland near Platteville, Colo. The sludge, which contained about 6 percent total nitrogen and about 17 percent solids, was injected or plowed about 6 to 10 in. into the soil. In addition to nitrogen, sewage sludge applied to section 16 also contained phosphorus, potassium, cadmium, copper, lead, nickel, and zinc. These constitu-

ents could be harmful if allowed to migrate in large concentrations into ground water used as a water supply for humans or animals. Data collected during 1985–89 were used to determine the rate and direction of ground-water flow and the effects of sewage sludge and other fertilizers on the quality of sediments in the unsaturated zone and ground water.

Ground water in the surficial aquifer in section 16 is recharged by precipitation and irrigation water and generally moves northeastward at a velocity of about 0.01 ft/d (about 3.6 ft/yr). Precipitation and irrigation water reaching the ground surface in section 16 infiltrates into the sandy soil and collects in temporary ponds. There is little or no runoff. Most water that infiltrates into the soil evaporates and is transpired by crops. The remaining water continues to move down to the saturated zone and recharges the surficial aquifer. Generally, there is little recharge by precipitation to the aquifer in this semiarid area. However, where irrigation water is applied or the water table is close to the surface, the surficial aquifer is recharged.

Mean nitrate concentrations in the surficial aquifer increased during the period of sewage-sludge application. However, the addition of commercial inorganic fertilizer during this period could have caused at least some of this increase. Areas having the largest concentrations of nitrate were in the northeastern and southwestern quarters of section 16.

Nitrogen concentrations generally increased and trace-element concentrations changed minimally in the unsaturated zone in the irrigated part of section 16 during the study period. Analyses of water samples from multilevel ground-water sampling devices indicate that nitrate concentrations changed with depth and time in the surficial aquifer. Most nitrogen probably moves vertically downward through the unsaturated zone with the water that infiltrates from irrigated areas and low, temporarily ponded areas. The nitrogen then moves laterally through the saturated zone to the northeast. Trace elements probably have not moved into the ground water from the sewage sludge.

The effects of application of about 6,431 dry tons of municipal sewage sludge as a fertilizer to less than 1 mi^2 of farmland were obscured by the effects of cattle and chicken manure and anhydrous ammonia that were applied to the area as fertilizer for 20 years prior to sewage-sludge application. The large increase in nitrate concentrations in the surficial aquifer during the study period likely was caused by the combined application of sewage sludge and inorganic fertilizer.

The effects of sewage sludge used as fertilizer were not separated from the effects of the other fertilizers used in the study area. In order to separate the effects of chemicals traditionally used by farms in the area from the specific effects of sewage sludge, another method of study will be required. One possible method is the use of a stable isotope of nitrogen, such as nitrogen-15, as a tracer. The nitrogen-15, which can be obtained commercially, could be applied to the soil near lysimeter and piezometer sites at the time of sewage-sludge application. The presence or absence of the nitrogen isotope in water from nearby sampling sites would indicate whether or not sewage sludge is affecting the unsaturated zone and water in the surficial aquifer.

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