FEASIBILITY OF ARTIFICIAL RECHARGE TO THE OAKES AQUIFER, SOUTHEASTERN NORTH DAKOTA: HYDROGEOLOGY OF THE OAKES AQUIFER

By Robert B. Shaver
and William M. Schuh

Water Resources Investigation No. 5
North Dakota State Water Commission

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SELECTED FACTORS FOR CONVERTING INCH-POUND UNITS TO METRIC UNITS

For those readers who may prefer to use metric (International System) units rather than inch-pound units, the conversion factors for terms used in this report are given below.

Multiply inch-pound unit	By	To obtain metric unit
Acre	0.4047	hectare
Acre-foot	0.0012	cubic hectometer
Cubic foot per second	28.3	liter per second
Foot	0.3048	meter
Foot per day	0.3048	meter per day
Foot per mile	0.1894	meter per kilometer
Foot squared per day	0.0929	meter squared per day
Gallon	3.785	liter
Gallon per minute	0.0631	liter per second
Gallon per minute per foot	0.0192	liter per second per meter
Inch	25.4	millimeter
Inch	2.54	centimeter
Mile	1.609	kilometer
Square foot	0.09294	square meter

To convert degrees Fahrenheit (°F) to degrees Celsius (°C), use the following formula: °C = (°F-32)x5/9.

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 "Mean Sea Level."

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ABSTRACT

In December 1984, the Garrison Diversion Unit Commission recommended that a feasibility study be initiated to assess artificial recharge to the Oakes aquifer, southeastern North Dakota. Under the artificial-recharge plan, the Oakes aquifer would function as a storage reservoir. Water would be diverted from the Missouri River to the James River and then into recharge facilities at selected sites in the aquifer. Withdrawals for irrigation would be from wells completed in the Oakes aquifer. To fulfill project irrigation requirements, the Oakes aquifer must (1) sustain a minimum withdrawal rate of 100 cubic feet per second for 60 days (11,900 acre-feet), (2) pose no water-quality limitations for irrigation, and (3) have initial surface infiltration rates of at least one foot per day.

The area of the Oakes aquifer most feasible for the development of both a well field to supply 11,900 acre-feet of water in 60 days and surface recharge facilities is within the channel-fill deposits near sec. 13, T. 129 N., R. 59 W. An aquifer test conducted using an irrigation well completed in the channel-fill deposits in this area, indicated a transmissivity of 94,000 feet squared per day. Individual well yields of about 2,000 gallons per minute are attainable. A surface-infiltration test conducted in sands overlying the channel-fill deposits in this area, indicated an initial infiltration rate of 2.5 feet per day, sufficient to support large-scale surface artificial recharge facilities. Although ground-water quality in the Oakes aquifer is variable, ground water in the channel-fill deposits is suitable for irrigation use. A finite-difference model of the Oakes aquifer indicates that the channel-fill deposits near sec. 13, T. 129 N., R. 59 W. could sustain withdrawals required to meet periods of peak irrigation demand in the West Oakes and West Oakes extension irrigation development tracts of the Garrison Diversion Unit.

INTRODUCTION

In 1957, the U.S. Bureau of Reclamation redesigned the Pick-Sloan Missouri River Basin Plan enacted by Congress in the Flood Control Act of 1944. Under the redesigned plan, 1,007,120 acres of land were to be irrigated in central and eastern North Dakota using Missouri River water diverted eastward from the Garrison Reservoir. The plan designated 108,000 acres of land to be irrigated in the Oakes area, southeastern North Dakota.

In 1965, Congress enacted legislation to authorize construction of the 250,000-acre Garrison Diversion Unit as the initial stage of the ultimate 1,007,120-acre project. The 1965 authorization designated 45,980 acres to be irrigated in the East and West Oakes irrigation development tracts of the Garrison Diversion Unit. Missouri River water would be diverted eastward to the James River via the McClusky, New Rockford, Sykeston, and James River feeder canals. Because channel capacity of the James River was insufficient to meet peak irrigation demands for the East and West Oakes irrigation development tracts, the U.S. Bureau of Reclamation proposed construction of Lake Taayer Reservoir.

The Garrison Diversion Unit, as authorized in 1965, raised important issues of environmental, economic, and international concern. As a result, in accordance with Public Law 98-360, sec. 207, enacted by Congress July 16, 1984, a 12-member commission was appointed by the Secretary of the Interior to "examine, review, evaluate, and make recommendations with regard to the contemporary water development needs of the State of North Dakota." Concerning irrigation in the Oakes area, the Garrison Diversion Unit Commission recommended the following in December 1984:

(1) Reduce the 45,980 acres to be irrigated under the 1965 authorization to 23,660 acres (West Oakes = 19,660 acres; West Oakes extension = 4,000 acres);
(2) deauthorize construction of Lake Taayer Reservoir; and
(3) initiate a feasibility study to assess artificial recharge to the Oakes aquifer as an alternative to a surface reservoir (Garrison Diversion Unit Commission, 1984).

Under the proposed artificial-recharge plan, the Oakes aquifer would function as a storage reservoir. Water would be diverted from the Missouri River to the James River and then into recharge facilities at selected sites in the aquifer. Withdrawals for irrigation would be from wells completed in the Oakes aquifer.

In July 1985, the North Dakota State Water Commission and the U.S. Geological Survey entered into a cooperative agreement with the U.S. Bureau of Reclamation to investigate the feasibility of artificial recharge to the Oakes aquifer. The feasibility study was divided into two phases. Phase I involved defining the geometric, hydraulic, and hydrochemical properties of the Oakes aquifer. Field work was initiated in August 1985 and completed in April 1986. Results of Phase I of the artificial-recharge feasibility study are described in two parts. Part I (this report) describes the hydrogeology of the Oakes aquifer. Part II presents the ground-water data, which consists of lithologic logs of test holes and wells (volumes 1A and 1B), water-level measurements (volume 2), and water-quality analyses (volume 2).

Phase II of the artificial-recharge feasibility study involves selection, construction, maintenance, and performance evaluation of surface-recharge test facilities in the Oakes aquifer. Water used to perform the recharge tests will be diverted from the James River. The objectives of phase II will be to assess reduction in infiltration rate due to clogging and to evaluate operational and maintenance methods that reduce clogging. Field work was initiated in May 1986 and terminated in the fall of 1987.

PURPOSE AND SCOPE

The purpose of this report is to describe the hydrogeology of the Oakes aquifer in southeastern North Dakota, with special emphasis on identifying areas of the Oakes aquifer that (1) can sustain a minimum withdrawal rate of 100 cubic feet per second for 60 days (11,900 acre-feet), (2) pose no water-quality limitations for irrigation, and (3) have initial surface infiltration rates of at least one foot per day.

Specific objectives of this report are to describe (1) Composition and geometry of the Oakes aquifer, (2) occurrence and movement of ground water in the aquifer, (3) aquifer hydraulic properties, (4) aquifer water quality, and (5) the effect on water levels in the aquifer of continuously withdrawing water at a rate of 100 cubic feet per second for 60 days. Aquifer composition and geometry and occurrence and movement of ground water were determined by evaluating test-drilling data and water-level data obtained at observation wells. Aquifer hydraulic properties were estimated from lithologic logs of test holes or were determined by evaluating aquifer-test data at selected sites. Surface infiltration rates and infiltration rates below the root zone were determined by evaluating infiltration-test data. Water quality was determined by analyzing water samples collected from observation wells. A finite-difference digital model of the Oakes aquifer was developed to estimate the effect of continuously withdrawing 100 cubic feet per second for 60 days.

ACKNOWLEDGMENTS

Thanks are extended to the following North Dakota State Water Commission personnel: Jon C. Patch for conducting aquifer tests, Allen E. Comeskey for supervising test drilling and for test-hole logging, Garvin O. Muri for chemical analyses of water samples, and Milton O. Lindvig for scheduling drilling activities. Thanks are extended also to Michael D. Sweeney, Soils Science Department, North Dakota State University, for sampling with the Gidding probe, describing soil samples, and digging pits at infiltration-test sites. Recognition is due to the U.S. Bureau of Reclamation for supplying drill-hole logs and observation-well, water-level, and water-chemistry data; to commercial drilling companies that provided well logs; and to landowners who allowed access to their lands.

LOCATION-NUMBERING SYSTEM

The location-numbering system used in this report is based on the public land classification system used by the U.S. Bureau of Land Management. The system is illustrated in figure 1. The first number denotes the township north of a base line, the second number denotes the range west of the fifth principal meridian, and the third number denotes the section in which the well or test hole is located. The letters A, B, C, and D designate, respectively, the northeast, northwest, southwest, and southeast quarter section, quarter-quarter section, and quarter-quarter-quarter section (10-acre tract). For example, well 130-059-15DAA is located in the NE1/4 NE1/4 SE1/4 sec. 15, T. 130 N., R. 59 W. Consecutive terminal numerals are added if more than one well or test hole is located within a 10-acre tract.

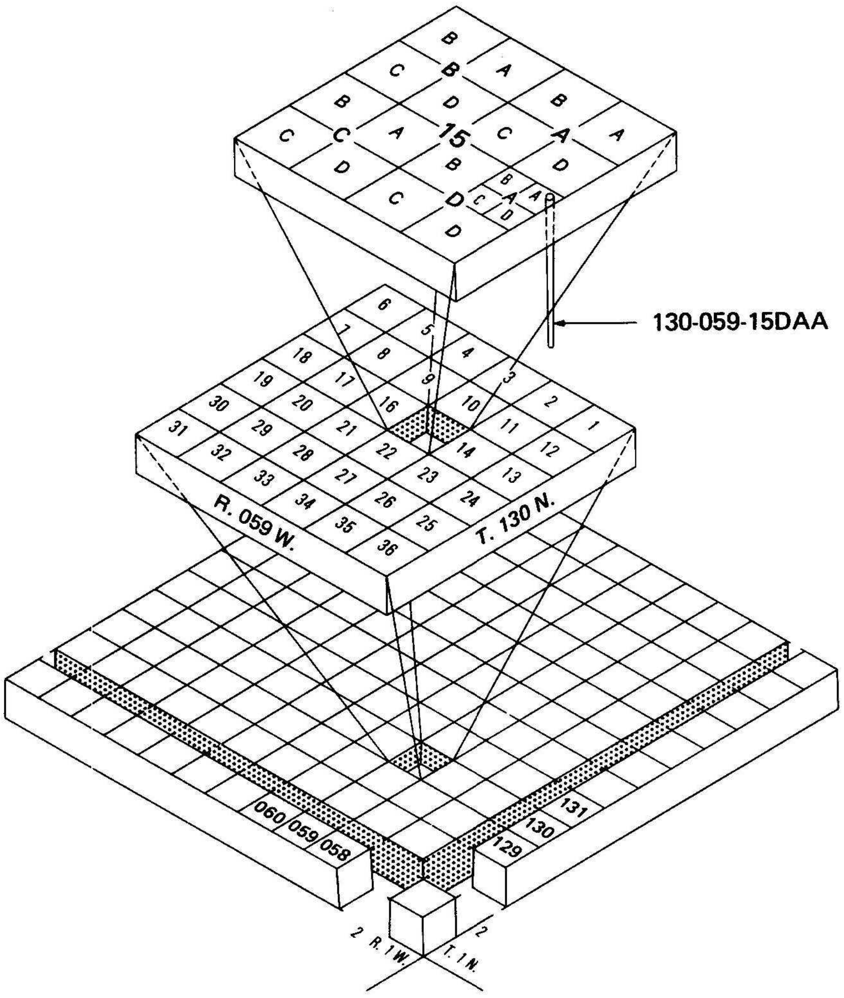


Figure 1.—Location-numbering system.

PREVIOUS WORK

The geology and water resources of the Edgeley and LaMoure areas were described by Hard (1929). Rasmussen (1947) and the U.S. Bureau of Reclamation (1953a, 1953b) described the geology and ground-water resources of the glacial Lake Dakota area in Dickey and Sargent Counties. Soil surveys of the study area were completed by Larsen and others (1964) and Thompson and Sweeney (1971).

The geology and ground-water resources of Dickey and LaMoure Counties were described in a three-part report. Part I (Bluemle, 1979a) described the geology of Dickey and LaMoure Counties, part II (Armstrong and Luttrell, 1978) presented the ground-water data, and part III (Armstrong, 1980) described the ground-water resources.

The geology and ground-water resources of Ransom and Sargent Counties also were described in a three-part report. Part I (Bluemle, 1979b) described the geology of Ransom and Sargent Counties, part II (Armstrong, 1979) presented the ground-water data, and part III (Armstrong, 1982) described the ground-water resources. Williams (1984) described the hydrogeochemistry of a closed topographic trough in the Oakes aquifer southeast of Oakes.

TEST-DRILLING, WELL-CONSTRUCTION, AND WATER-LEVEL MEASUREMENT METHODS

Test-drilling data used in this report were provided by the North Dakota State Water Commission, the U.S. Bureau of Reclamation, and commercial well-drilling firms. The locations of all test holes and wells in the study area are shown on plate 1. The North Dakota State Water Commission has been measuring water levels in observation wells completed in the Oakes aquifer monthly since 1975. Water levels were measured to the nearest 0.01 foot using a chalked steel tape. The U.S. Bureau of Reclamation has been measuring water levels in its observation-well network monthly since 1966. Water levels were measured to the nearest 0.10 foot using a steel tape with a popper. Water-level data from both the North Dakota State Water Commission and U.S. Bureau of Reclamation observation-well networks are in North Dakota State Water Commission Water-Resources Investigation No. 6, Vol. 2 (Shaver and Hove, 1990).

The North Dakota State Water Commission used a forward mud rotary rig to drill all test holes. The U.S. Bureau of Reclamation used a forward mud rotary rig to drill all test holes completed from 1950 to 1954 and a truck-mounted solid-stem spiral power auger to drill all test holes from 1966 to 1986. Most commercial test holes and wells were drilled using forward mud rotary rigs. Occasionally, a reverse hydraulic rotary rig was utilized.

For the Dickey-LaMoure and Ransom-Sargent Counties ground-water studies, the North Dakota State Water Commission constructed observation wells using 20-foot lengths of 1.25-inch diameter acrylonitrile-butadiene-styrene (abs) or 1.5-inch diameter polyvinyl-chloride (pvc) plastic casing. The well screen was 1.25- or 1.5-inch diameter abs plastic or 1.25-inch diameter galvanized steel. Screen lengths generally were from 3 to 6 feet, and slot size generally was 0.018 inch. A check valve was attached to the bottom of each screen. The plastic casing, well screen, and check valve were assembled prior to insertion into the drill hole. After insertion, the hole was backwashed through the screen to clean the formation. After backwashing, the hole was blown with air to collapse the formation around the screen. The remaining annular area was backfilled with drill cuttings.

The North Dakota State Water Commission installed a network of piezometer nests for the hydrogeochemical study conducted by Williams (1984). Each piezometer was constructed using 20-foot lengths of 2-inch diameter pvc plastic casing and variable lengths of 1.5-inch diameter pvc plastic screen. Slot size of the screen was 0.010 inch. A check valve was attached to the bottom of each screen. After the casing, screen, and check-valve assembly was inserted into the drill hole, the hole was backwashed through the screen to clean the formation. After backwashing, silica sand was placed around the screened interval using a tremie pipe. A cement slurry was injected into the annulus from the top of the sand pack to land surface.

During the fall of 1985, the North Dakota State Water Commission drilled additional test holes and constructed additional observation wells to further define the occurrence, movement, and quality of ground water in the Oakes aquifer. Observation wells were constructed using 20-foot lengths of 2-inch diameter pvc plastic casing and variable lengths of 2-inch diameter pvc plastic screen. Slot size of the screen was 0.018 inch. A check valve was attached to the bottom of each screen. After the casing, screen, and check valve assembly was inserted into the drill hole, the hole was backwashed through the screen to clean the formation. After backwashing, the hole was blown with air to collapse the formation around the screen. The remaining annular space was backfilled with drill cuttings.

Piezometers were constructed at sites where the aquifer consisted of sand and gravel layers separated by a confining bed. At these sites, the drill hole was not blown with air to collapse the formation around the screen. Instead, the well screen was packed with silica sand, and a cement slurry was injected into the well annulus from the top of the sand pack to at least the top of the confining bed.

During 1966 and 1967, the U.S. Bureau of Reclamation installed an observation-well network in the Oakes aquifer. Test holes were drilled using a truck-mounted solid-stem spiral power auger. Well casing was 3-inch diameter galvanized steel downspout. The entire length of downspout used in construction of the observation well had been perforated with a hand drill, and the bottom of the downspout was left open. The downspout casing was jetted into the aquifer to the desired depth.

In 1979, the U.S. Bureau of Reclamation installed a second observation-well network in the Oakes aquifer that in part, replaced some of the older downspout wells. The new wells were spaced at 0.5-mile intervals in a square grid pattern within a 5,000-acre test plot of the proposed West Oakes irrigation development tract of the Garrison Diversion Unit. For the most part, wells were installed at section corners, section centers, and half-section locations.

In 1983, the U.S. Bureau of Reclamation installed a third observation-well network in the Oakes aquifer to replace the remaining older downspout wells. The new wells also were spaced at 0.5-mile intervals in a square grid pattern. The wells were located between the 5,000-acre test plot and the North Dakota-South Dakota State line.

Both of the replacement observation-well networks were completed using 2-inch diameter pvc plastic casing and variable lengths of 1.5-inch diameter pvc plastic screen. Slot size of the screen was 0.010 inch. A check valve was attached to the bottom of each screen. The casing, screen, and check-valve assembly was jetted into the aquifer to the desired depth.

Beginning in 1972, State law required commercial well drillers to submit completion reports of test holes and wells completed in North Dakota. The completion reports, submitted to the State Board of Water Well Contractors, provide additional lithologic data within the study area. Summaries of all North Dakota State Water Commission, U.S. Bureau of

Reclamation, and commercial well driller completion reports are in North Dakota State Water Commission Water-Resources Investigation No.6, Vols. 1A and 1B (Shaver and Hove, 1990).

DESCRIPTION OF THE STUDY AREA

PHYSIOGRAPHY

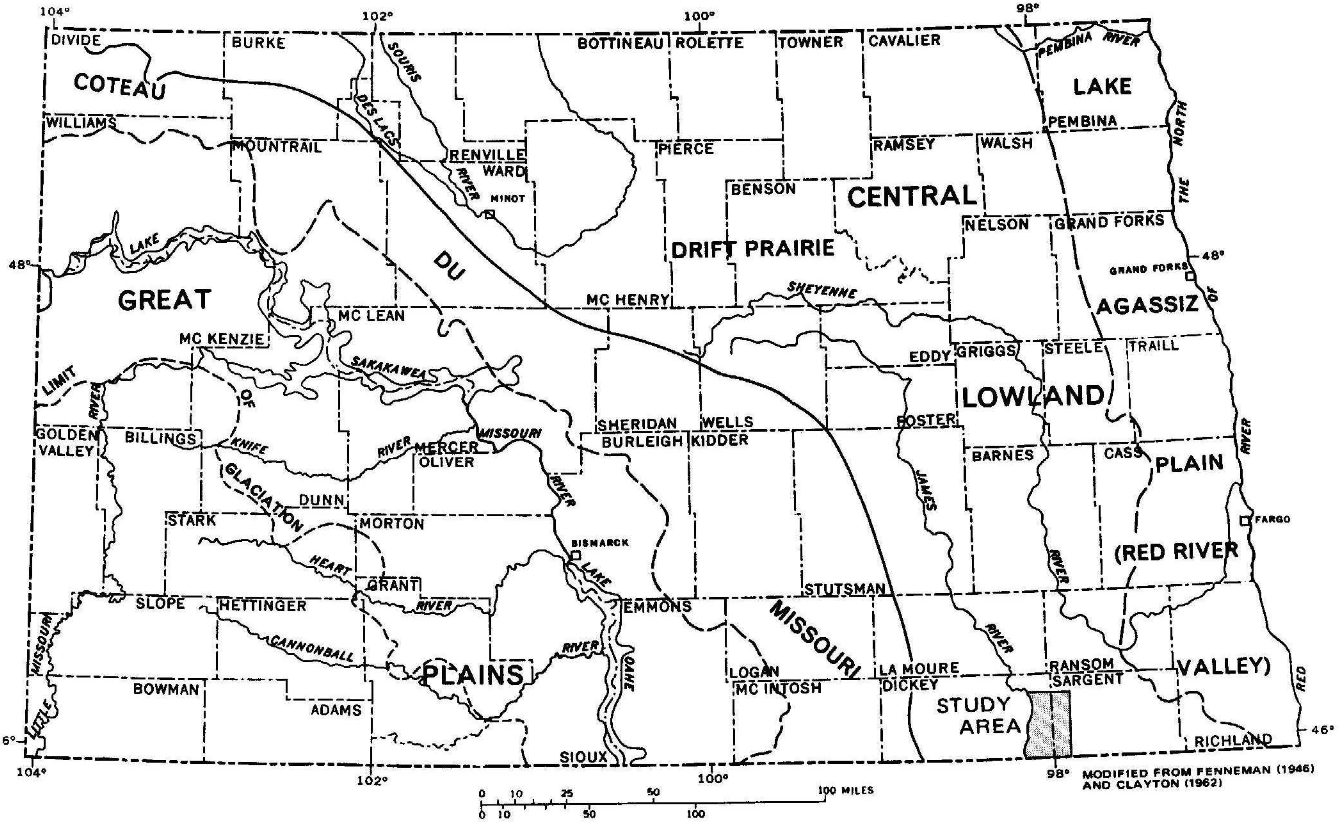
The study area is located in southeastern North Dakota in the Dakota Lake Plain district of the Central Lowland physiographic province (fig. 2). The study area is flanked on the west by the James River, on the northwest by Bear Creek, on the northeast by a drift plain, and on the east by a moraine.

On most maps included in this report, the southern boundary of the study area is the North Dakota-South Dakota State line. The ground-water model of the Oakes aquifer required extending the southern boundary of the study area into South Dakota. Therefore, those maps pertinent to the model (land-surface topography, hydraulic conductivity, and aggregate thickness) extend 2 miles south of the State line.

A generalized land-surface topography map of the study area was prepared from U.S. Geological Survey 7 1/2-minute topographic quadrangles using land-surface altitudes shown at section corners, section centers, and half-section locations (pl. 2). The study area occupies a flat lake plain. Relief generally is less than 10 feet per mile. Locally, the topography is hummocky because of scattered sand dunes and blowouts (fig. 3). The highest altitude is 1,475 feet above sea level on a hill east of the lake plain in sec. 4, T. 130 N., R. 58 W. The lowest altitude is 1,277 feet above sea level in sec. 12, T. 128 N., R. 61 W., in the southwestern part of the study area. Runoff from the lake plain is minor as indicated by the lack of surface drainage.

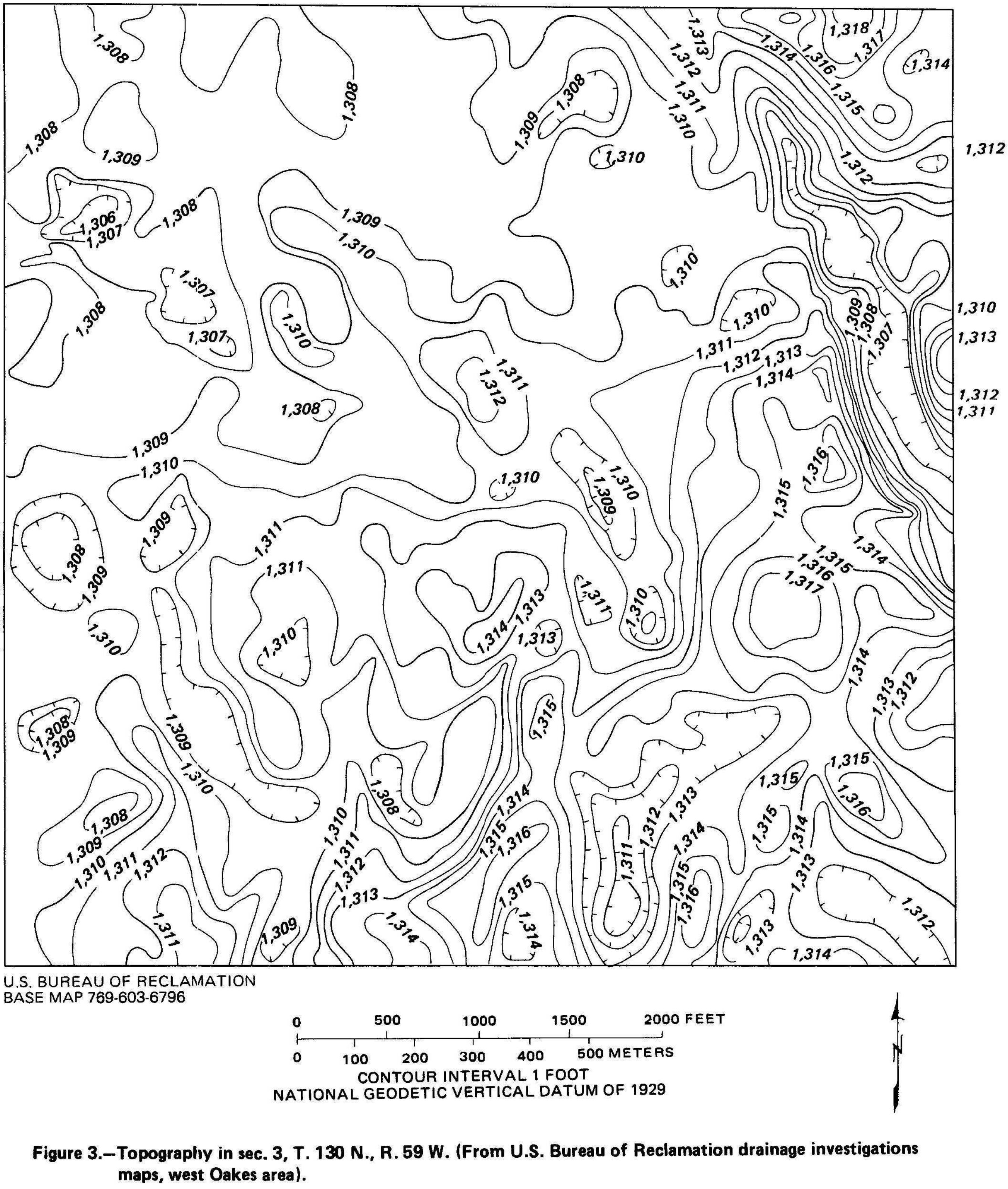
Climate

Climate of the study area is semiarid to subhumid. Mean annual precipitation at Oakes from 1931 through 1948, and 1951 through 1974, is 19.21 inches (U.S. Department of Commerce, Weather Bureau, 1960, 1965; U.S. Department of Commerce, Environmental Data Service, 1962-75). Annual precipitation ranged from 9.14 inches in 1936 to 29.64 inches in 1960. From 1975 to 1986, annual climatologic data for the Oakes station are incomplete.



MODIFIED FROM FENNEMAN (1946) AND CLAYTON (1962)

Figure 2.—Physiographic divisions in North Dakota and location of study area.



U.S. BUREAU OF RECLAMATION
BASE MAP 769-603-6796

Figure 3.—Topography in sec. 3, T. 130 N., R. 59 W. (From U.S. Bureau of Reclamation drainage investigations maps, west Oakes area).

About 70 percent of the precipitation generally falls from April through August (fig. 4) when it is most needed for germination and growth of crops. Most summer precipitation is from thunderstorms and is extremely variable (Armstrong, 1980).

Mean annual temperature at Oakes from 1951 through 1980 is 40.9°F (U.S. Department of Commerce, Environmental Data Service, 1982). From 1931 through 1984, the maximum recorded temperature was 115°F on July 6, 1936, and the minimum recorded temperature was -46°F on February 16, 1936. The average number of days between the last freeze (32°F) in the spring and the first freeze in the fall ranges from about 120 to 130 (Armstrong, 1980).

Geology

Surficial Geology

The study area is located on the lake plain of ancestral glacial Lake Dakota. Glacial Lake Dakota flooded part of southeastern Dickey and southwestern Sargent Counties when the late-Wisconsin glacier melted from the area (Bluemle, 1979a, 1979b).

The Oahe Formation and the Coleharbor Group are exposed within the study area (fig. 5). The Oahe Formation of Holocene age consists of clay, silt, sand, and gravel deposits. Three main textural facies are included in the formation (Bluemle, 1979a, 1979b): (1) Clay, (2) bouldery gravelly clay, and (3) sand and silt.

The clay facies occupies ponds and sloughs that are located in the northeast part of the study area near Lake Taayer. The sediment consists of dark-colored organic clays having minor amounts of silt and fine sand.

The bouldery gravelly clay facies consists of colluvial materials that were deposited by slopewash, slumping, sliding, and earth creep and commonly is found along fronts of steep slopes. This facies is not exposed in the study area.

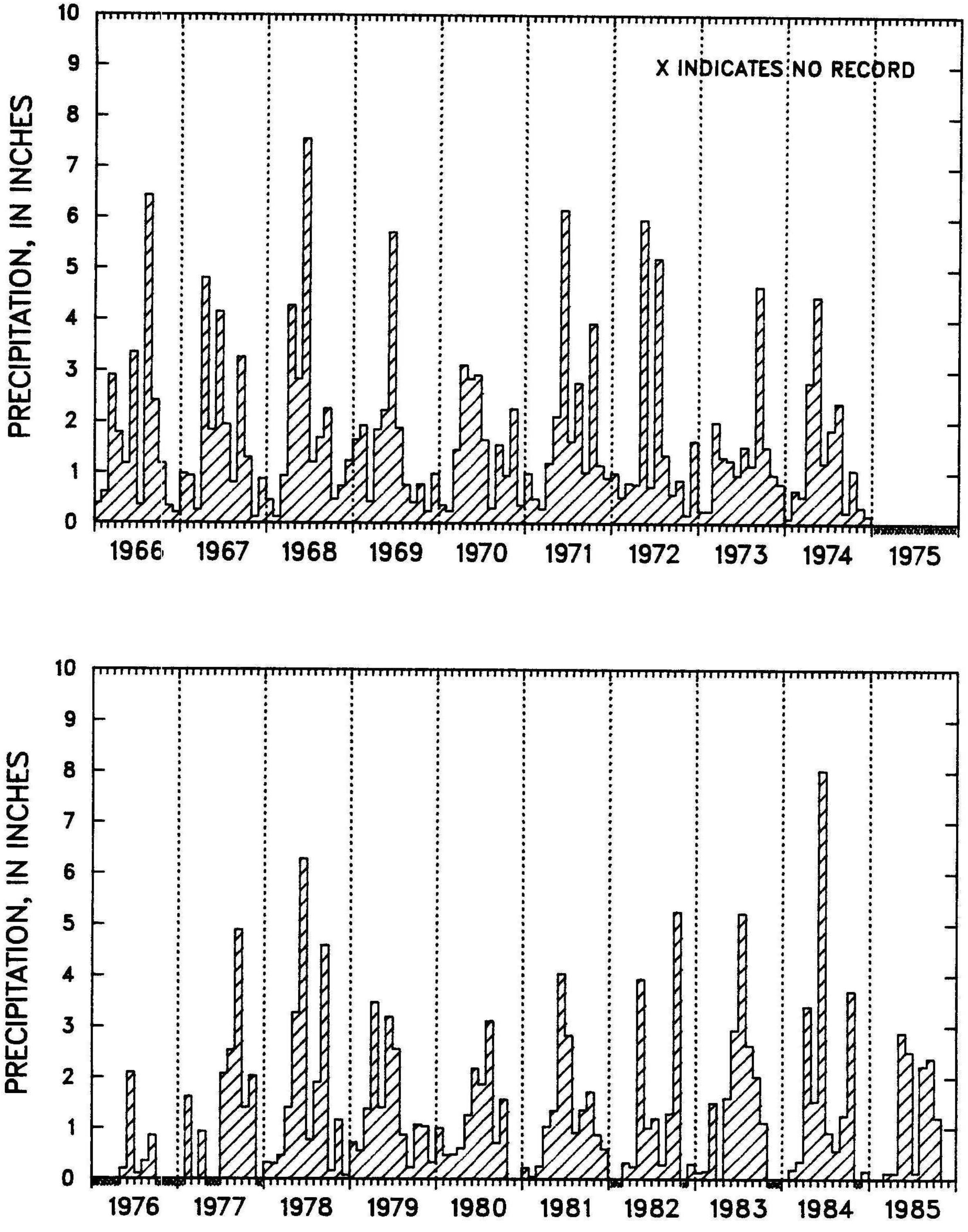


Figure 4.--Precipitation at Oakes, 1966-85.

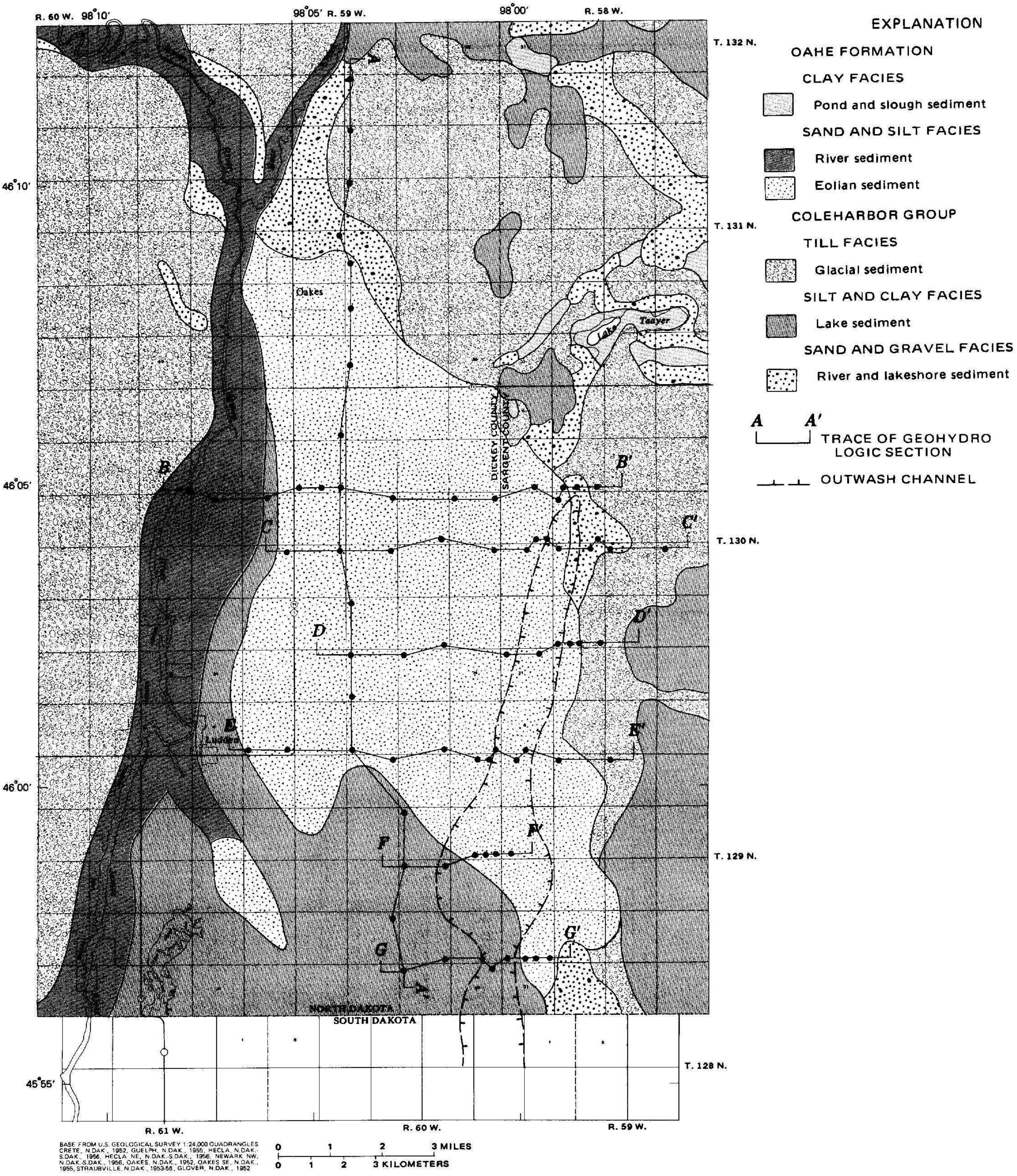


Figure 5.–Surficial geology, location of geohydrologic sections, and location of buried channel. (After Bluemle, 1979a, 1979b).

The sand and silt facies consists of river and eolian sediment. The river sediment is composed of clay, silt, and sand that occupies the flood plain of the James River valley along the western margin of the study area. The eolian sediment is composed of fine sand and silt that covers much of the lake plain of glacial Lake Dakota. The eolian deposits range in thickness from less than 1 foot to about 50 feet near sec. 30, T. 130 N., R. 58 W. The eolian deposits are the only Holocene surficial deposits that are part of the Oakes aquifer. The Oakes aquifer is a hydrostratigraphic unit that is defined later in the text.

The Coleharbor Group of Pleistocene age consists of three main textural facies (Bluemle, 1979a, 1979b): (1) Till, (2) silt and clay, and (3) sand and gravel. The till facies occur in upland areas along the western, northern, and eastern margins of the study area. They consist of a poorly sorted mixture of angular to well-rounded boulders, cobbles, pebbles, and sand in a matrix of cohesive silt and clay. The till is composed of a heterogeneous mixture of igneous and metamorphic rocks, carbonates, and shale. Igneous and metamorphic rocks were derived from the Precambrian Canadian Shield. Carbonates were derived from Paleozoic rocks of the northern Red River valley. Shale was derived from the Cretaceous, Pierre, and Niobrara Formations that unconformably underlie the Pleistocene drift in and around the study area.

The silt and clay facies occur primarily in the southern part of the study area and consist of laminated sandy silt and clay. The facies are glaciolacustrine in origin.

The sand and gravel facies occur in the northern and eastern parts of the study area. The facies consist of moderately well sorted, crossbedded sand and gravel associated with uncollapsed flood plains (Bluemle, 1979a, 1979b).

Subsurface Geology

In descending order throughout most of the lake plain in the study area, the stratigraphic section consists of sand and gravel, silt and clay, till, and bedrock shale (pls. 3 and 4). The sand and gravel, silt and clay, and till facies compose the previously described Coleharbor Group. The sand and gravel deposits are glaciofluvial and glaciolacustrine.

Near Oakes, stratified sand and gravel deposits form a deltaic complex up to about 80 feet thick (pl. 5). The deltaic sand and gravel deposits are composed of quartz, shale, lignite, Canadian shield silicates, and carbonates. The black noncalcareous shale probably is derived from the Pierre Formation. The deltaic sand and gravel deposits grade into lacustrine sand south of Oakes. Medium sand predominates in the central part of the lake plain. South of Ludden, the medium sand grades into fine to very fine silty sand, clayey silt, and silty clay. The lacustrine sand is composed of quartz, lignite, Canadian shield silicates, and carbonates. Thickness of the lacustrine sand ranges from less than 1 foot on the flanks to 60 feet at test hole 130-059-14DDD. Average thickness of the lacustrine sand is about 35 feet.

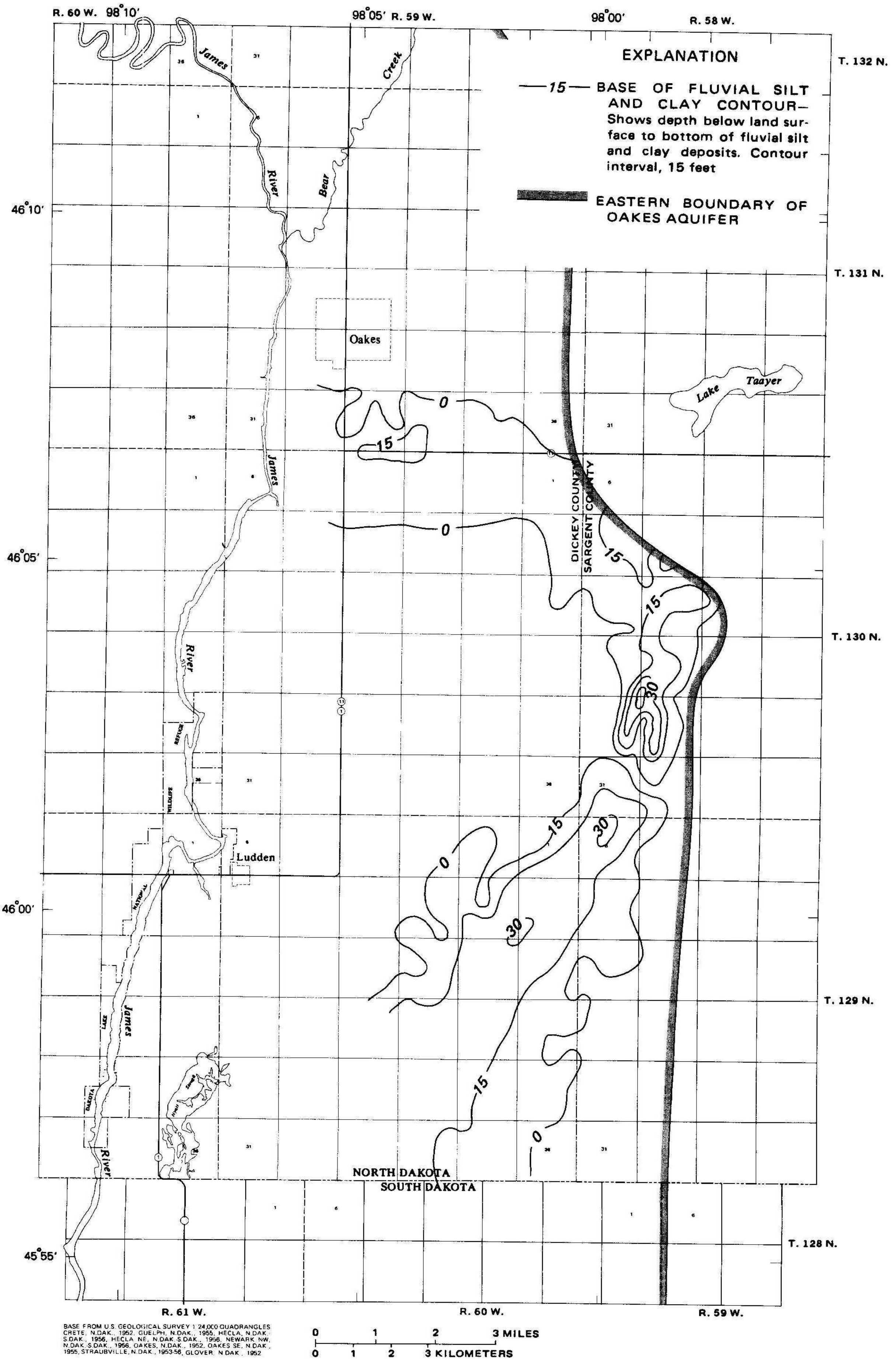
Channel-fill deposits consisting of stratified very fine sand to coarse cobbly gravel occur in a channel along the eastern margin of the lake plain (fig. 5). The channel trends north-south and varies in width from 0.5 to 2 miles. Depth ranges from less than 1 foot on the flanks to 197 feet at test hole 130-058-30DDD. The channel-fill sand and gravel is subangular to well-rounded and is composed of shale, quartz, carbonates, and Canadian shield silicates. The shale consists, in part, of subangular pebbles locally derived from the Niobrara Formation. In some areas, the channel-fill deposits are overlain by a fluvial silt and clay sequence (pl. 4, secs. D-D′ and E-E′). In other areas, the fluvial silt and clay sequence is absent (pl. 4, sec. F-F′).

A buried-valley deposit consisting of stratified very fine sand to coarse cobbly gravel and containing occasional thin silt and clay layers occurs in the northern part of the study area (pl. 3, sec. A-A′). The sand and gravel is subangular to well rounded and is composed of Canadian shield silicates, carbonates, shale, and minor amounts of lignite. The buried-valley deposit is part of the Spiritwood aquifer buried-valley complex that occurs in eastern North Dakota.

Minor deposits of sand and gravel also occur as lenses scattered throughout the till. The sand and gravel lenses are composed primarily of carbonates and shale.

A sequence of lacustrine clayey silts and silty clays underlies the deltaic and lacustrine sands throughout much of the study area. In areas where the lacustrine silt and clay are absent, the deltaic and lacustrine sands are underlain by till.

A sequence of fluvial deposits consisting of clayey silts and silty clays occurs in the northern, eastern, and southern parts of the study area (fig. 6). The fluvial silt and clay deposits are not shown extending to the southwest near the southern boundary of the study area. In this area, the fluvial silt and clay deposits intersect lacustrine silt and clay deposits making differentiation difficult.



BASE FROM U.S. GEOLOGICAL SURVEY 1:24,000 QUADRANGLES CRETE, N.DAK., 1952, GUELPH, N.DAK., 1955, HECLA, N.DAK.-S.DAK., 1956, HECLA NE, N.DAK.-S.DAK., 1956, NEWARK NW, N.DAK.-S.DAK., 1956, OAKES, N.DAK., 1952, OAKES SE, N.DAK., 1955, STRAUBVILLE, N.DAK., 1953-56, GLOVER, N.DAK., 1952

Figure 6.—Depth below land surface to bottom of fluvial silt and clay deposits.

Most of the fluvial silt and clay deposits are buried by a surficial layer of Holocene eolian fine sand and silt. Thickness of the eolian fine sand and silt layer ranges from less than 1 foot in the northern and southern parts of the study area to about 20 feet in the eastern part of the study area.

Throughout most of the study area, till underlies the lacustrine sand, silt, and clay deposits. Till is absent in places along the eastern margin of the study area where the outwash channel is incised into the bedrock shale (pl. 4, secs. D-D′ and G-G′).

The Niobrara Formation of Cretaceous age unconformably underlies the Pleistocene deposits of the Coleharbor Group in the north, central, and southeastern parts of the study area and conformably underlies the Pierre Formation in the southwestern part of the study area. The Niobrara Formation is a brown shale containing light-gray calcareous inclusions. Samples from the formation strongly effervesce in dilute hydrochloric acid leaving a dark-brown residue. The Niobrara Formation is a marine sediment.

The Pierre Formation of Cretaceous age unconformably underlies the Pleistocene deposits of the Coleharbor Group in the southwestern part of the study area. The Pierre Formation is a dark-black shale containing occasional light-gray bentonite layers. The shale is noncalcareous and has a smooth greasy texture. The Pierre Formation is a near-shore marine sediment.

GROUND-WATER HYDROLOGY

Composition and Geometry of the Oakes Aquifer

The Oakes aquifer, named by Armstrong (1980), consists of four depositional facies that are grouped together into one hydrostratigraphic unit. The depositional facies include: (1) Deltaic sand and gravel, (2) lacustrine sand, (3) channel-fill sand and gravel, and (4) eolian sand. The composition and geometry of the four depositional facies were described previously in the geology section of this report.

Occurrence and Movement of Ground Water

For the most part, the Oakes aquifer is unconfined. Parts of the outwash channel along the eastern margin of the lake plain are overlain by a sequence of fluvial clayey silts and silty clays. In these areas, water in the channel-fill deposits occurs under leaky confined conditions.

A water-table map was prepared using water-level measurements made in both the U.S. Bureau of Reclamation and the North Dakota State Water Commission observation-well networks during May 1986 (pl. 6). In general, the water-table map indicates that regional ground-water flow is from east to west toward the James River valley. Discharge from the Oakes aquifer westward to the James River is negligible. Recent James River valley flood-plain deposits that consist of sandy silty clay truncate the western flank of the Oakes aquifer. North Dakota State Water Commission test hole 130-059-05BAA began flowing shortly after drilling was completed (C.A. Armstrong, verbal commun., 1986). The lithologic log indicates sand (Oakes aquifer) from 20 to 26 feet below land surface. The sand is overlain by sandy silty clay (James River valley flood-plain deposits) and underlain by silty sandy pebbly clay (till). The increased hydraulic gradient along the western flank of the study area is caused by truncation of the Oakes aquifer by small-transmissivity flood-plain deposits of the James River.

North of Oakes there is a dearth of observation wells and associated water-level data. In this area, available test-drilling data indicate the Oakes aquifer probably consists of isolated, saturated sand-and-gravel zones. The large hydraulic gradient between observation wells 131-059-15AAA2 and 131-059-22CBB2 supports the conclusion that the Oakes aquifer is discontinuous in the northern part of the study area.

Throughout much of the study area, depth to the water table is less than 8 feet. Scattered sand dunes and blowouts cause a hummocky land-surface topography. Thin, shallow water-table aquifers in areas of hummocky topography are conducive to development of numerous localized flow systems in which underflow may be insignificant. Within each local flow system, recharge is from direct infiltration of precipitation and local runoff that occurs primarily during the spring. Discharge primarily is from evapotranspiration that occurs during the summer. Thus, movement of ground water is largely vertical, and flow paths are relatively short. The configuration of the water table in the southwestern part of the study area supports the occurrence of numerous localized flow systems in the Oakes aquifer (pl. 6).

Hydraulic Properties of the Oakes Aquifer

Aquifer Tests

Since 1969, five aquifer tests were conducted using large-diameter, large-capacity production wells completed in the Oakes aquifer (fig. 7). Four of the tests were conducted by the North Dakota State Water Commission and one was conducted by the U.S. Department of Agriculture, Agricultural Research Service, in cooperation with the U.S. Geological Survey.

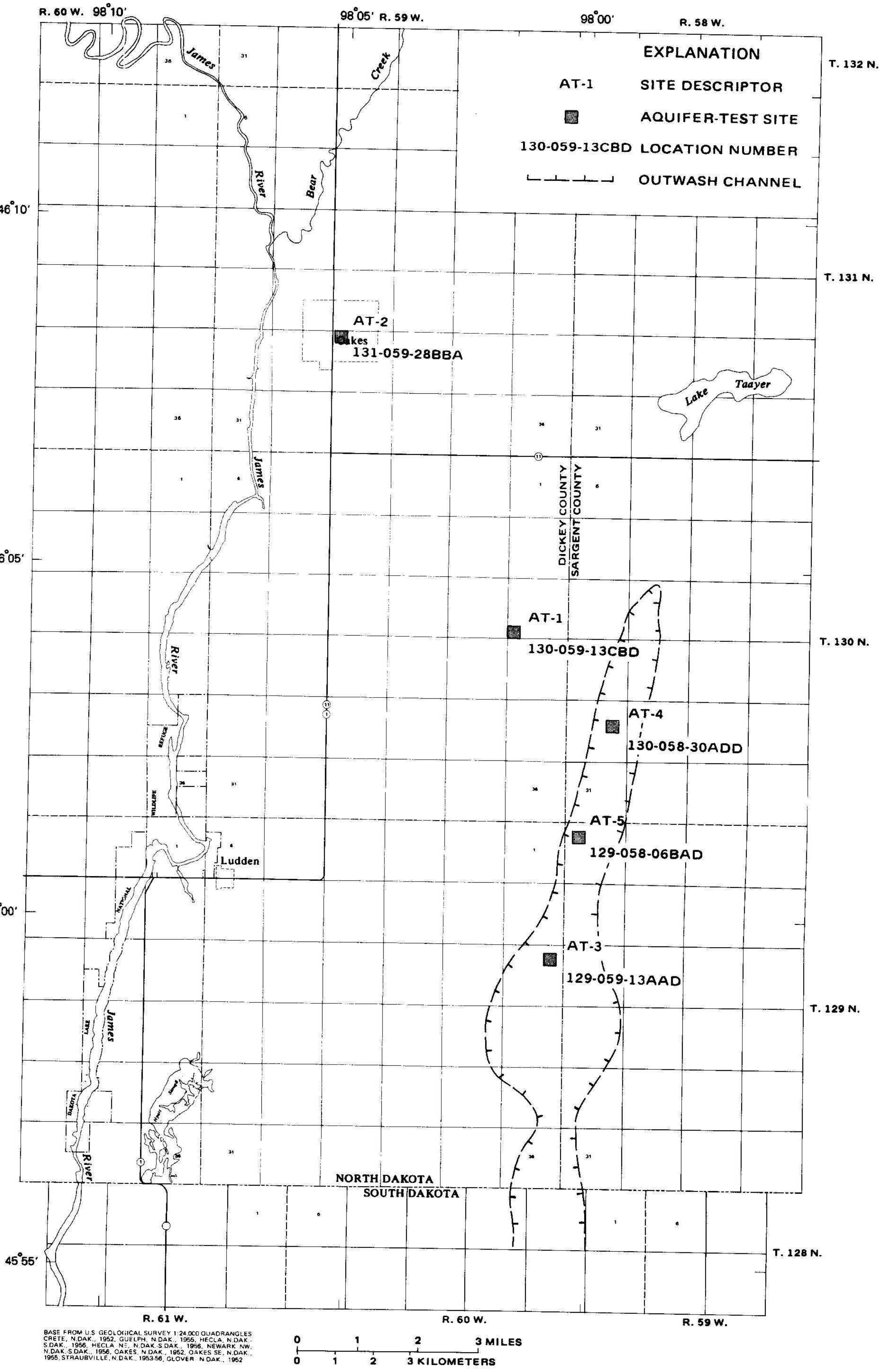
Aquifer-test site AT-1

During November 1969, the Agricultural Research Service conducted an aquifer test using a production well located at 130-059-13CBD1 (fig. 8). The well was installed to control water-table depths under agricultural test plots (Follet and others, 1974). The production well was constructed using 16-inch diameter steel casing from land surface to a depth of 35 feet. A 16-inch diameter, 40-slot screen was installed from 35 to 55 feet below land surface, and the well was gravel packed. The driller's log of the production well indicates topsoil from 0 to 1 foot below land surface, fine sand from 1 to 20 feet, fine to medium sand from 20 to 35 feet, and medium sand from 35 to 55 feet. Clay occurs below 55 feet. Deposits in the test area are uniform in thickness and grain size (E.J. Doering, verbal commun., 1986). Therefore, the driller's log of the production well is considered representative of the test area.

Water levels were measured in the production well and in four observation wells (fig. 8). The static water level in the production well was 5.7 feet below land surface. The production well was pumped continuously for 24 hours at a rate that varied from 254 to 292 gallons per minute. The average pumping rate was about 270 gallons per minute. The specific capacity of the production well after 24 hours of pumping was 20.1 gallons per minute per foot of drawdown.

The production well taps the bottom one-half of the aquifer (fig. 9). The aquifer is unconfined within the area of influence of the production well. The production well was not pumped at a constant rate for the entire length of the aquifer test.

A log-log composite time divided by distance squared (t/r^2) versus drawdown plot (fig. 10) was analyzed using the Prickett method (Prickett, 1965). Measured values of drawdown



BASE FROM U.S. GEOLOGICAL SURVEY 1:24,000 QUADRANGLES CRETE, N.DAK., 1952, GUELPH, N.DAK., 1955, HECLA, N.DAK.-S.DAK., 1956, HECLA NE, N.DAK.-S.DAK., 1956, NEWARK NW, N.DAK.-S.DAK., 1956, OAKES, N.DAK., 1952, OAKES SE, N.DAK., 1955, STRAUBVILLE, N.DAK., 1953-56, GLOVER N.DAK., 1952

Figure 7.—Location of aquifer-test sites.

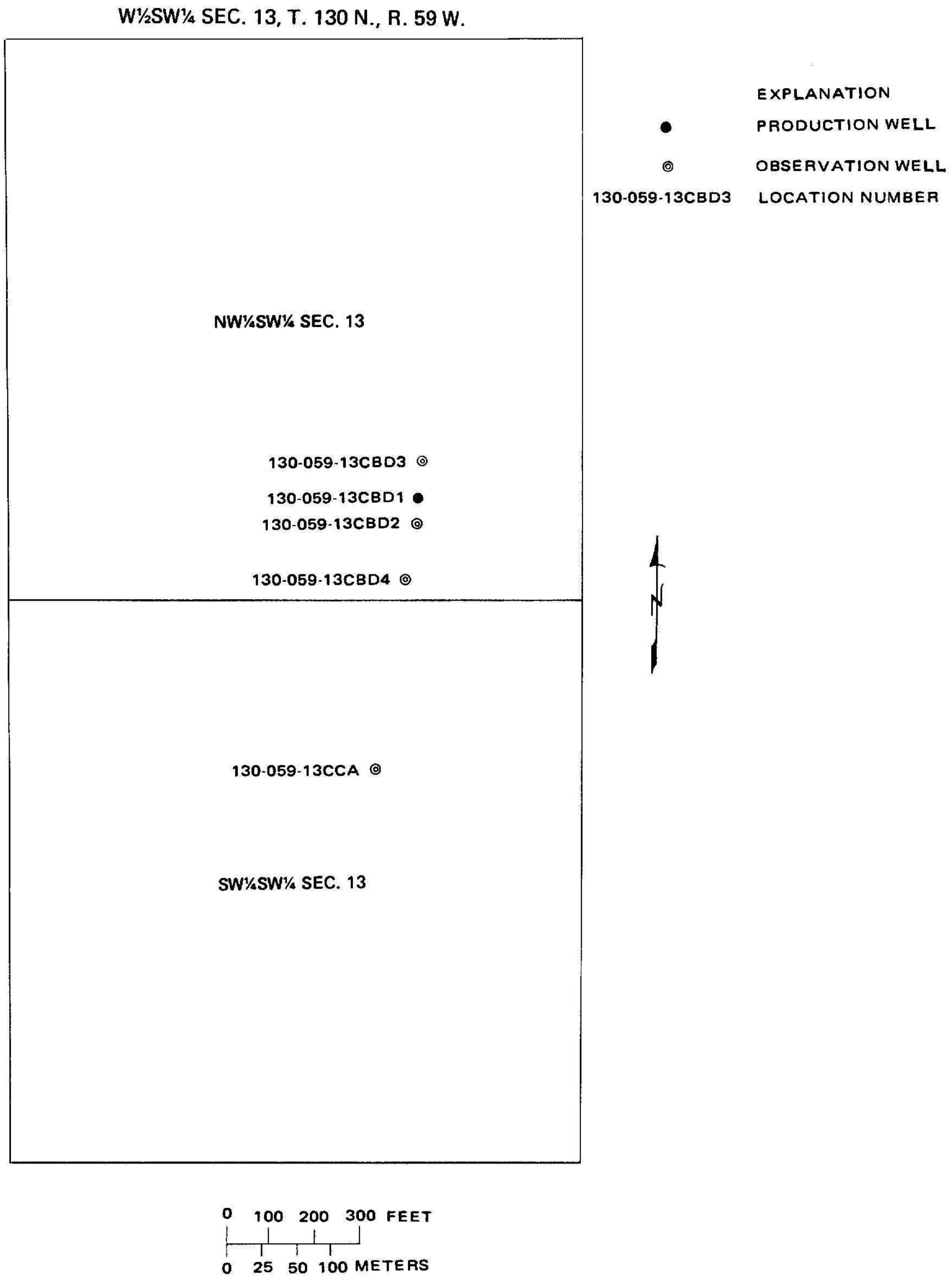


Figure 8.—Location of production well and observation wells at aquifer-test site AT-1.

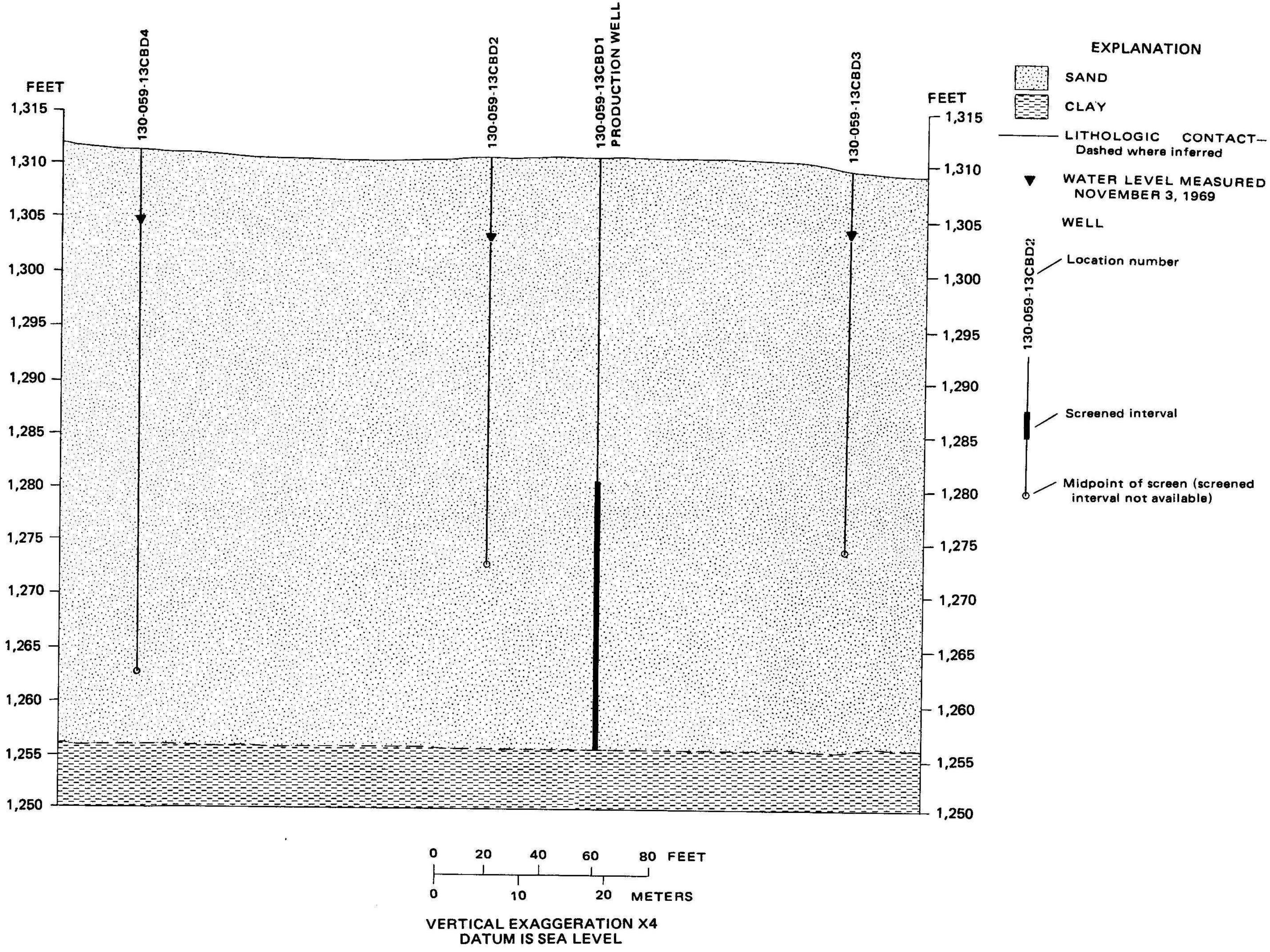


Figure 9.—Geohydrologic section showing the Oakes aquifer at aquifer-test site AT-1.

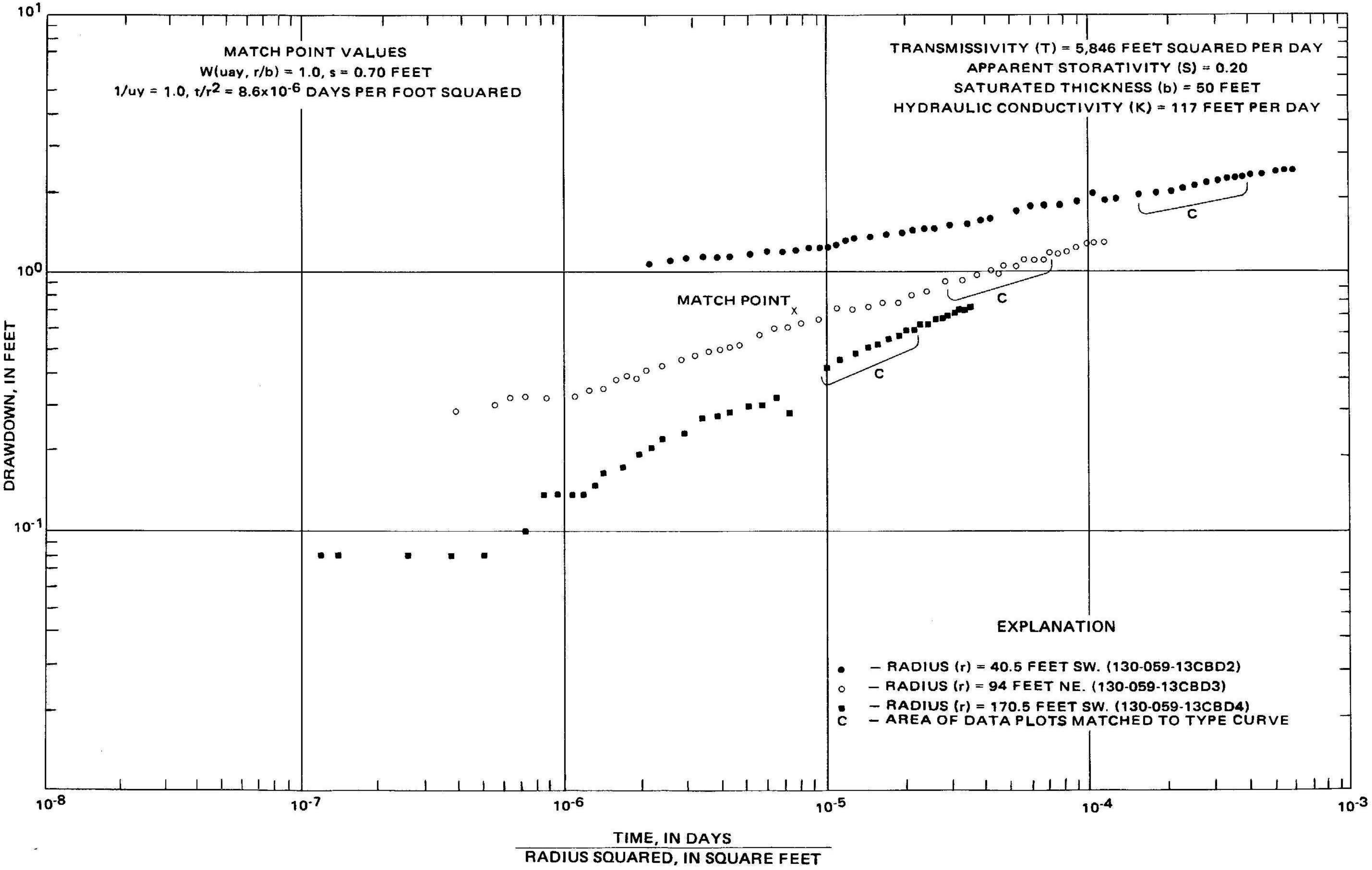


Figure 10.—Logarithmic composite t/r2 versus drawdown plot at aquifer-test site AT-1.

were corrected for decreasing transmissivity with time due to dewatering using the method of Jacob (1963, p.247).

The effects of partial penetration may have been significant at observation well 130-059-13CBD3 (r = 40.5 feet) because the well is located less than a distance of twice the saturated aquifer thickness (100 feet) from the production well. The screened interval of the production well is the bottom one-half of the aquifer. The midpoint of the screen in observation well 130-059-13CBD3 is 8 feet below the midpoint of the aquifer. Because (1) the screened interval of the production well is the bottom one-half of the aquifer, (2) the screened interval of observation well 130-059-13CBD3 is 8 feet below the midpoint of the aquifer, (3) the observation well is close to a distance of one aquifer thickness from the production well, and (4) the aquifer is not strongly anisotropic, the effects of partial penetration at observation well 130-059-13CBD3 are considered negligible.

The variable pumping rate caused significant changes in the temporal drawdown distribution. The effect of variable pumping on drawdown is most evident in the production well (fig. 11). There were 4 periods when a constant pumping rate was maintained (areas A through D, fig. 11).

The method of Prickett (1965) was applied to area C for each observation well shown on the composite t/r^2 versus drawdown plot. Area C represents the pumping period beginning at 360 minutes and ending at 900 minutes. Throughout this time period, the average pumping rate was 270 gallons per minute and varied less than ±5 percent.

Transmissivity calculated from the composite t/r^2 versus drawdown plot, using the method of Prickett was 5,850 feet squared per day and apparent storativity was 0.20. Based on a saturated thickness of 50 feet, the average hydraulic conductivity of the aquifer in the test area is 117 feet per day. A delay index ranging from about 440 to 660 minutes was calculated using the Prickett method. This range of values is typical for fine sand. The upper part of the aquifer that was dewatered during the aquifer test consists of fine sand.

The average calculated time at which delayed gravity drainage ceased to effect the drawdown at observation wells 130-059-13CBD2, CBD3, and CBD4 is about 2,000 minutes. Because this time is greater than the duration of the aquifer test, the actual storativity is probably slightly larger than the calculated apparent storativity.

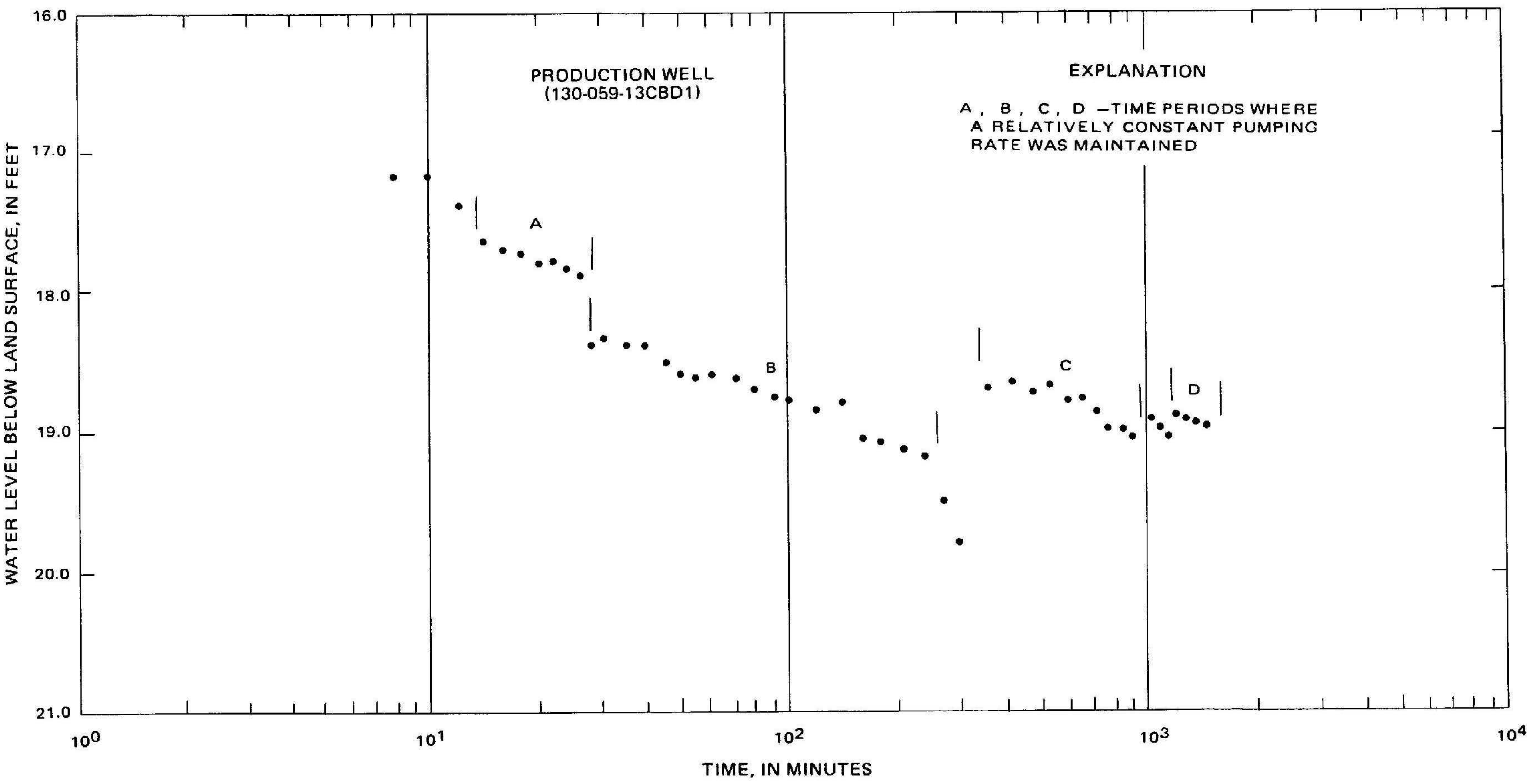


Figure 11.—Semilogarithmic time versus drawdown plot of the production well showing the effects of a variable pumping rate.

Based on a saturated thickness of 50 feet, a specific capacity of 20.1 gallons per minute per foot drawdown, and a pumping level not exceeding two-thirds of the saturated thickness, maximum individual well yields of about 700 gallons per minute are attainable in this area of the aquifer. The absence of confining beds in this area is conducive to development of surface recharge facilities (pits, ponds).

Aquifer-test site AT-2

During August 1983, the North Dakota State Water Commission conducted an aquifer test using a ground-water heat-pump source well located east of the Oakes Public School at 131-059-28BBA1 (fig. 12). The production well was constructed using 12-inch diameter steel casing from land surface to a depth of 50 feet. A 12-inch diameter, 60-slot stainless steel screen was installed from 50 to 70 feet below land surface, and the well was gravel packed. The driller's log of the production well indicates sand and gravel from 0 to 30 feet below land surface and sand from 30 to 68 feet (fig. 13). A cobble-boulder layer occurs from 68 to 70 feet below land surface. Till occurs below 70 feet.

Water levels were measured in the production well and in four observation wells (fig. 12). Continuous water-level recorders were installed on the four observation wells. Water levels in the production well were measured using a chalked steel tape. The static water level in the production well was 17.73 feet below land surface. The production well was pumped continuously for 4,200 minutes at a constant rate of 845 gallons per minute. The specific capacity of the production well after 4,200 minutes of pumping was 26.6 gallons per minute per foot of drawdown. Water was discharged into a storm sewer located about 700 feet west of the production well.

A log-log composite t/r^2 versus drawdown plot was analyzed using the Theis method (fig. 14). Measured values of drawdown were corrected for decreasing transmissivity with time due to dewatering using the method of Jacob (1963, p.247). The time versus drawdown data show the effects of delayed yield from gravity drainage, partial penetration and anisotropy. The composite t/r^2 versus drawdown plot shows the effect of delayed yield from gravity drainage for the first 2,500 minutes of the test. After 2,500 minutes, the effects of delayed yield are negligible.

The minor separation of the drawdown plots between observation wells 131-059-28BBB3 and 131-059-28 BBA2 at later times on the composite t/r^2 versus drawdown plot is probably

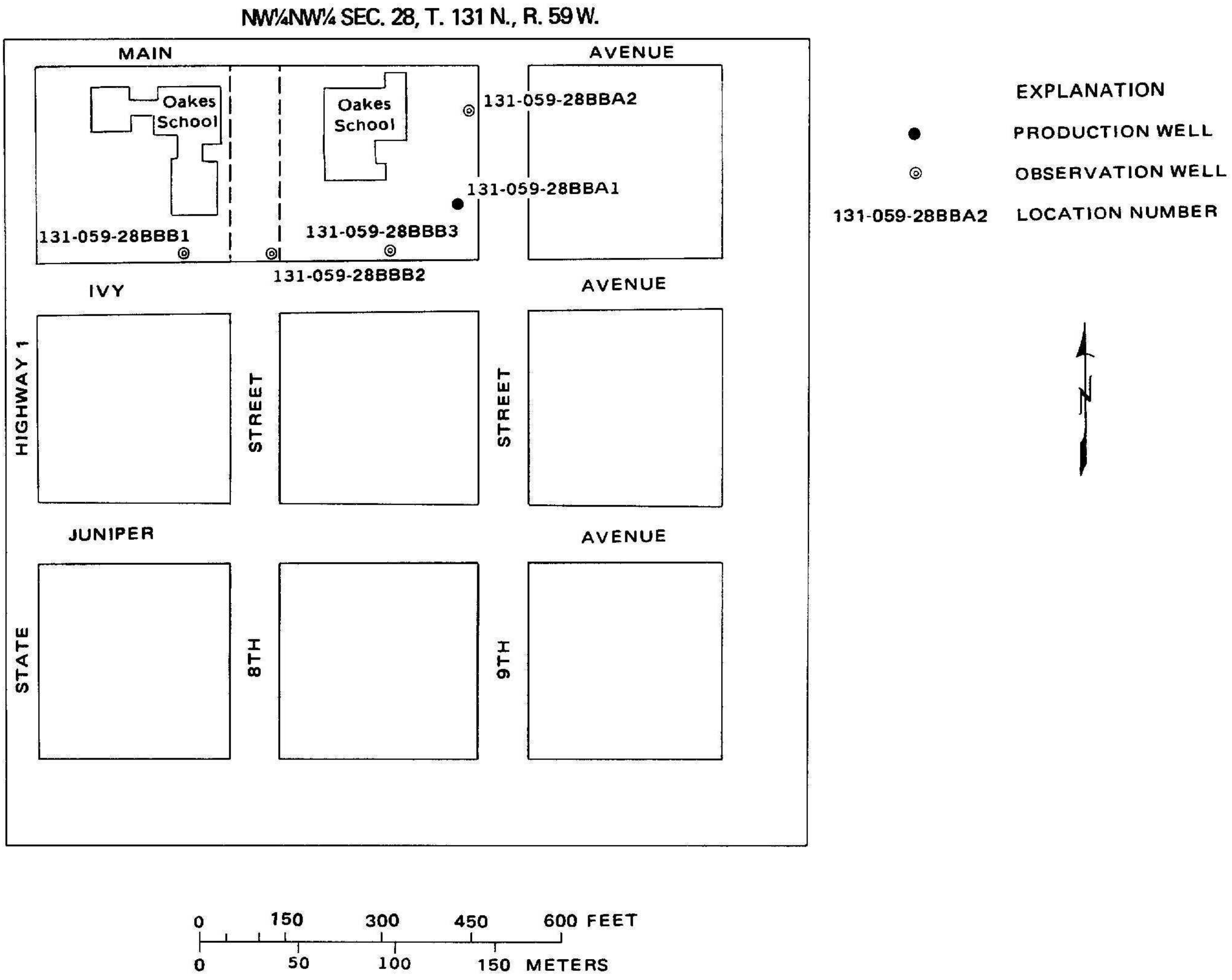


Figure 12.—Location of production well and observation wells at aquifer-test site AT-2.

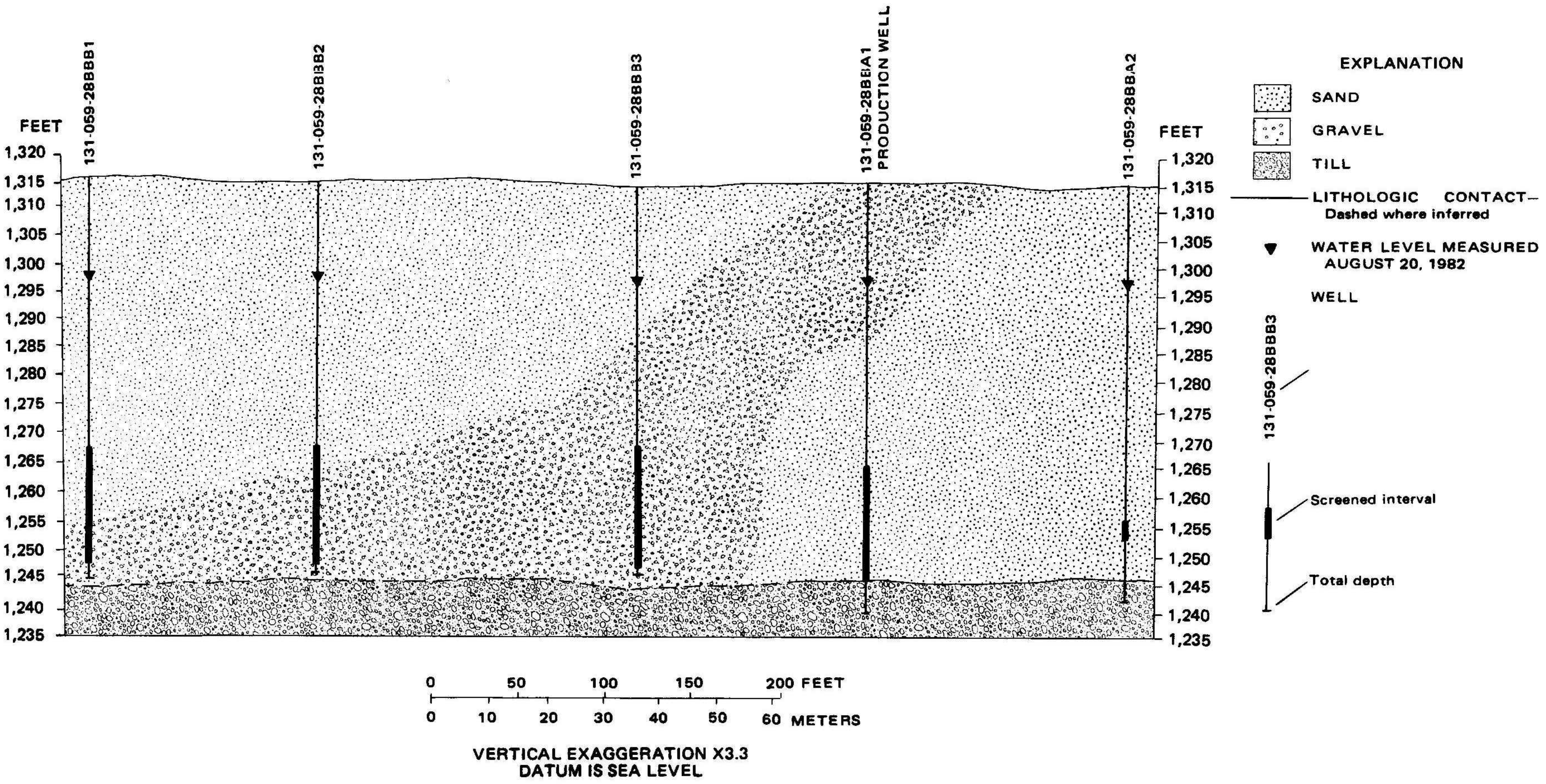


Figure 13. —Geohydrologic section showing the Oakes aquifer at aquifer-test site AT-2

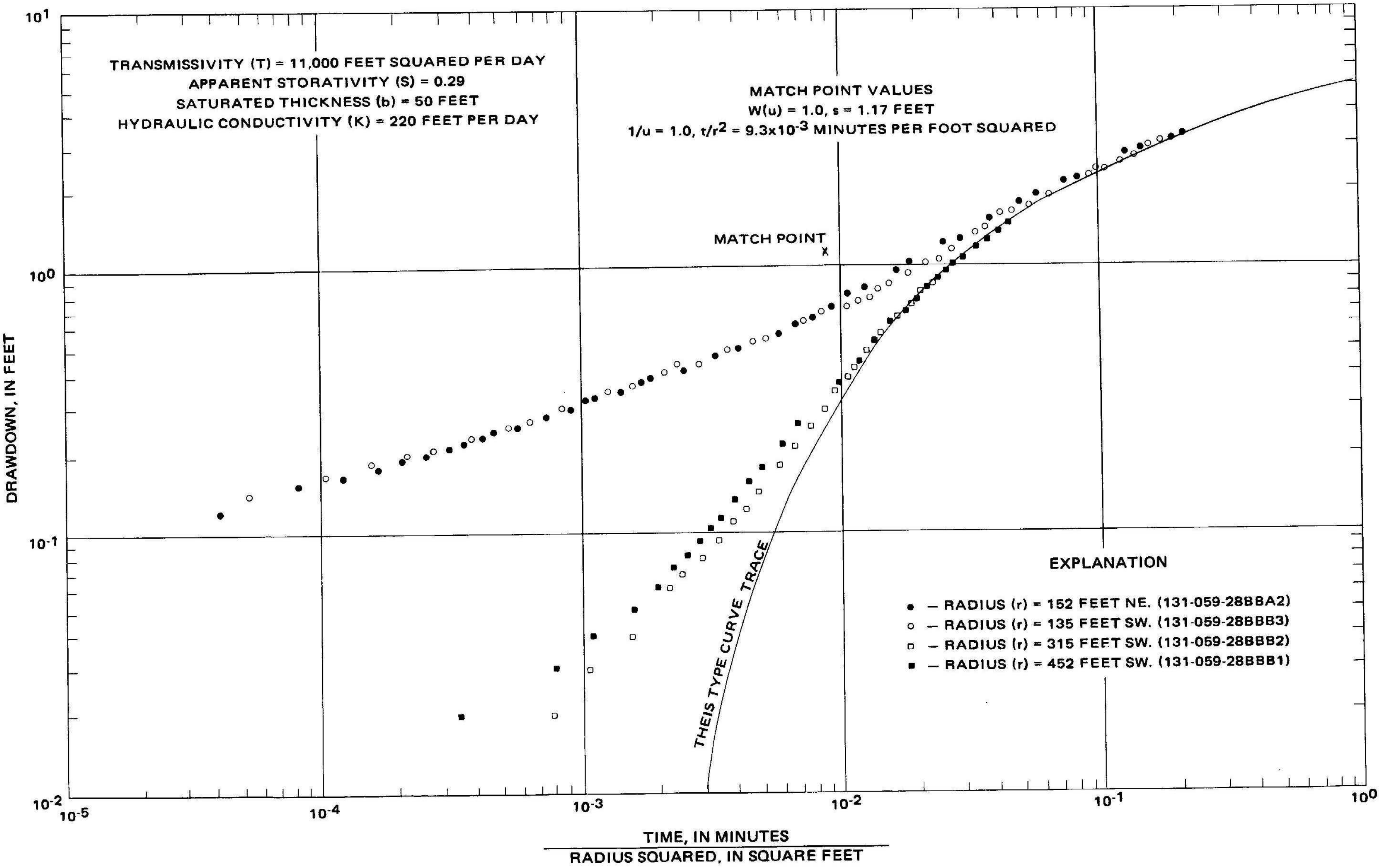


Figure 14.—Logarithmic composite t/r^2 versus drawdown plot at aquifer-test site AT-2.

due to the effects of partial penetration or anisotropy or both. The effects of partial penetration and anisotropy are considered negligible because the individual data plots merge to form a single curve that matches a segment of the Theis curve.

Transmissivity calculated by the Theis method using the composite t/r^2 versus drawdown plot was 11,000 feet squared per day, apparent storativity was 0.29, and hydraulic conductivity was 220 feet per day.

Based on a saturated thickness of 50 feet, a specific capacity of 26.6 gallons per minute per foot of drawdown, and a pumping level not exceeding two-thirds of the saturated thickness, maximum individual well yields of about 900 gallons per minute are attainable in this area of the aquifer. The absence of confining beds in this area is conducive to development of surface recharge facilities (pits, ponds). However, the size of individual surface recharge facilities would be limited because of the degree of urbanization.

Aquifer-test site AT-3

During September 1985, the North Dakota State Water Commission conducted an aquifer test using an irrigation well located at 129-059-13AAD6 (fig. 15) as the production well. The production well was constructed using 16-inch diameter steel casing from land surface to a depth of 95 feet. A 14-inch diameter, stainless steel screen was installed from 95 to 115 feet below land surface. Slot size was 0.150 inch from 95 to 100 feet below land surface and 0.125 inch from 100 to 115 feet below land surface. The driller's log of the production well indicates fine sand from 0 to 29 feet below land surface, gray sandy till from 29 to 58 feet, and gravel containing occasional coarse sand lenses from 58 to 115 feet. Based on data from North Dakota State Water Commission drilling activities near the production well, the till interval reported by the driller probably is a layer of lacustrine silt and clay. A geohydrologic section of the test area is shown in figure 16.

Water levels were measured in the production well, an irrigation well, and 11 observation wells (fig. 15). Continuous water-level recorders were installed on seven observation wells completed within 1,400 feet of the production well. Water levels in the production well, the irrigation well, and the four observation wells without continuous recorders were measured twice daily using a chalked steel tape. The static water level in the production well was

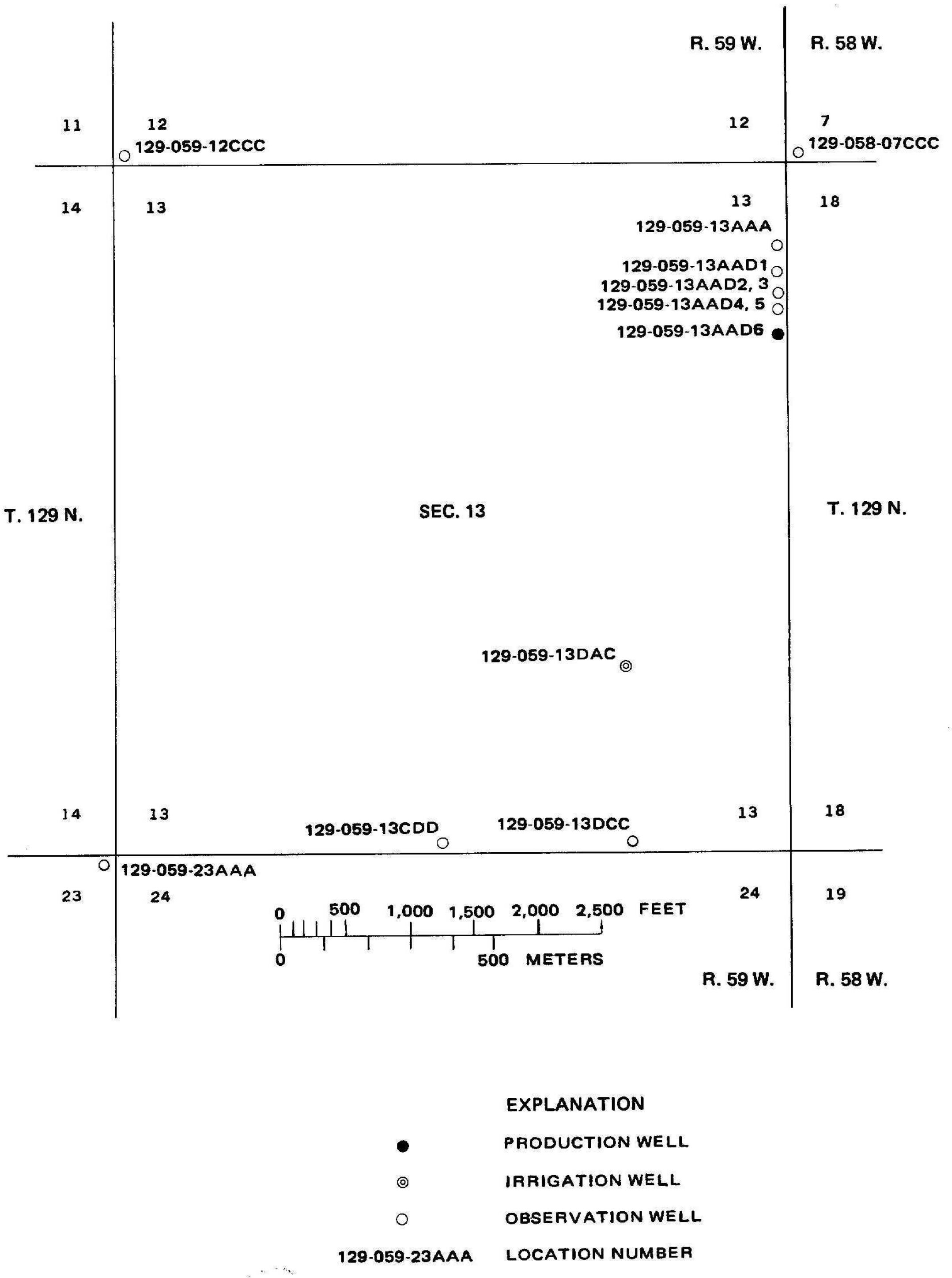


Figure 15.—Location of production well, irrigation well, and observation wells for which water levels were measured at aquifer-test site AT-3.

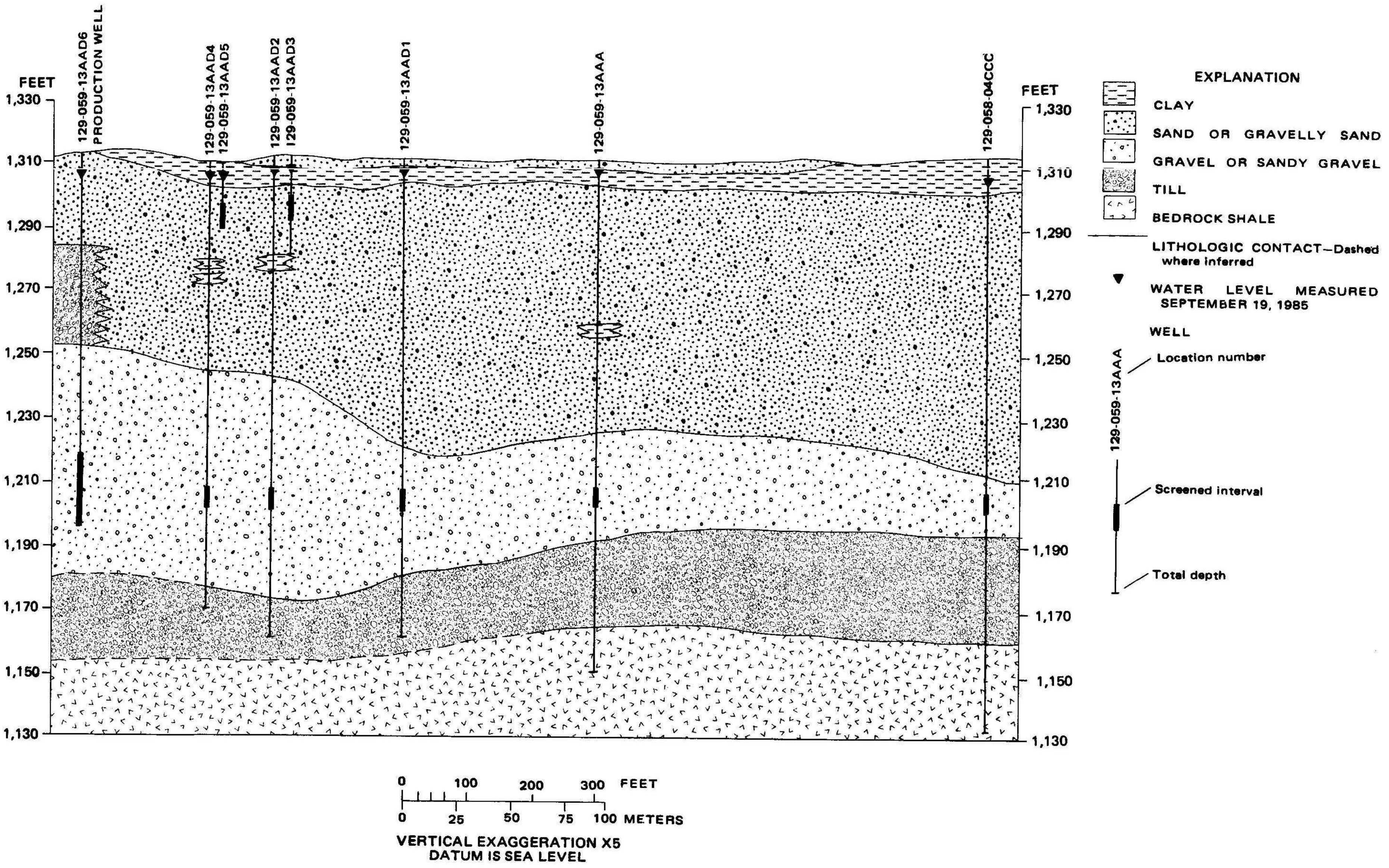


Figure 16. — Geohydrologic section showing the Oakes aquifer at aquifer test site AT-3.

7.5 feet below land surface. Except for a 10-second shutoff period that occurred about 20 minutes after the test was started, the production well was pumped continuously for 6,000 minutes at a constant rate of 780 gallons per minute. The specific capacity of the production well after 6,000 minutes of pumping was 215 gallons per minute per foot of drawdown. Water was discharged through a low-pressure center-pivot irrigation system in the NE1/4 of sec. 13.

A log-log composite t/r^2 versus drawdown plot was analyzed using the Theis method (fig. 17). The composite t/r^2 versus drawdown plot shows the effect of delayed yield from gravity drainage for about the first 400 minutes of pumping. After about 400 minutes of pumping, the individual drawdown curves intersect and are displaced upward above the Theis curve. The upward displacement of each drawdown curve is probably caused by two parallel barrier boundaries. The production well is located near the center of an outwash channel that is about 5,000 feet wide in this area.

Because of delayed response that occurred during the first 50 minutes of pumping and boundary effects that occurred after about 400 minutes of pumping, late-time (after 500 minutes of pumping), semiiog distance versus drawdown plots were utilized to calculate transmissivity. Average transmissivity calculated from the 500-, 1,000-, 2,000-, 4,000-, and 6,000-minute distance versus drawdown plots is about 94,000 feet squared per day (fig. 18). Based on an average transmissivity of 94,000 feet squared per day and an average saturated thickness of 122 feet, hydraulic conductivity is about 770 feet per day.

Average apparent storativity calculated from semilog distance versus drawdown plots is 0.017. An apparent storativity of 0.022 was calculated by superimposing a Theis type curve on the log-log t/r^2 versus drawdown plot (fig. 17). Both apparent storativity values are small for an unconfined aquifer and large for a confined aquifer. Static water levels were near the base of the surficial silty clay layer prior to test initiation (fig. 16). The drawdown in each observation well after 6,000 minutes of pumping was less than 1 foot. It is probable that part of the area of influence converted from confined to unconfined conditions, and part of the area of influence remained confined. This could cause a shift to the left in the composite log-log t/r^2 versus drawdown plot, resulting in calculation of a small apparent storativity.

The smaller apparent storativity calculated from the semilog distance versus drawdown plots as compared to that

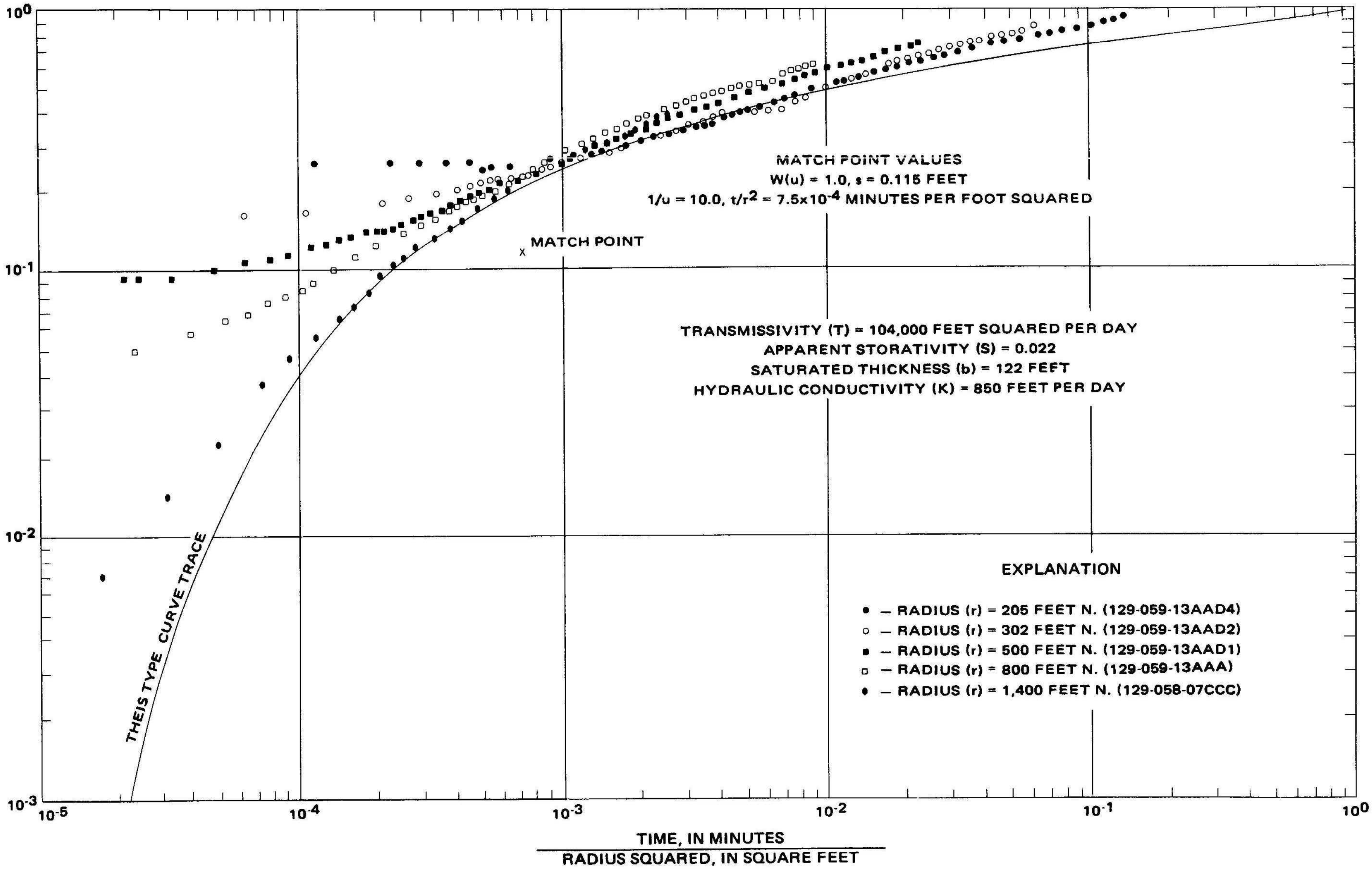
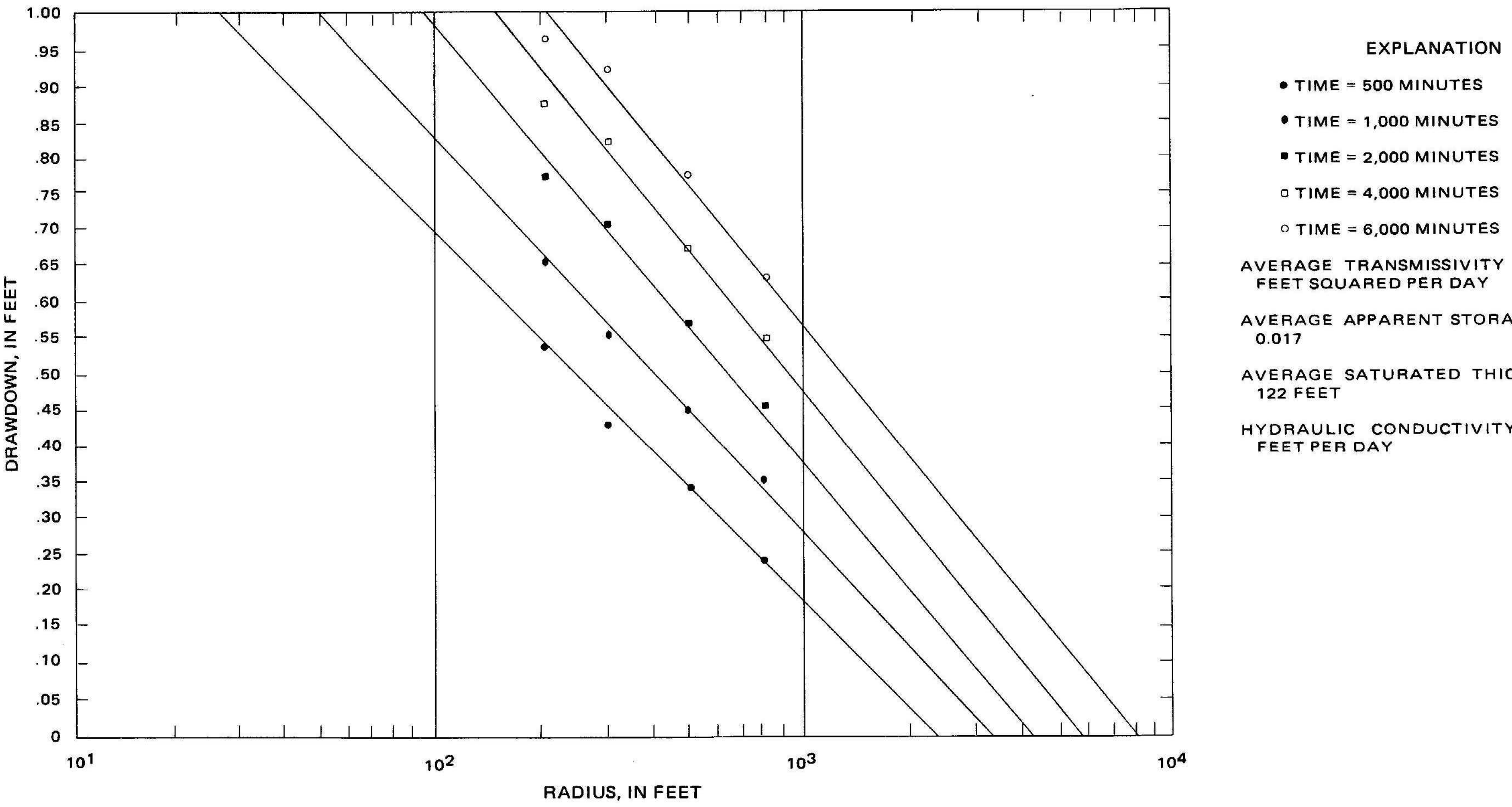


Figure 17.—Logarithmic composite t/r^2 versus drawdown plot at aquifer-test site AT-3.



AVERAGE TRANSMISSIVITY (T) = 94,000 FEET SQUARED PER DAY

AVERAGE APPARENT STORATIVITY (S) = 0.017

AVERAGE SATURATED THICKNESS (b) = 122 FEET

HYDRAULIC CONDUCTIVITY (K) = 770 FEET PER DAY

Figure 18.—Semilogarithmic distance versus drawdown plots for selected times at aquifer-test site AT-3.

calculated from the log-log t/r^2 versus drawdown plot could have been caused by a barrier boundary. The barrier boundary causes a downward displacement and a small increase in slope of semilog distance versus drawdown plots, resulting in an increased r_o value. The value r_o is defined by the intersection of the straight line fitted through the plotted points and the x-axis where drawdown equals zero. Since S is inversely proportional to r_o, an apparent storativity smaller than the actual storativity is calculated.

The apparent storativity values calculated using the aquifer-test data will be inadequate for use in predicting the drawdown distribution resulting from large-scale ground-water withdrawals in this area of the aquifer. In response to large-scale withdrawals, water levels will fall below the base of the surficial confining bed. Therefore, storativity will be significantly larger than the apparent storativity as calculated using the aquifer-test data. Based on previous experience in similar hydrogeologic settings, an estimated storativity of 0.20 is more appropriate for prediction of water-level response resulting from long-term, large-scale stress in this area of the aquifer.

Two pairs of observation wells were installed north of the production well. One pair, 129-059-13AAD4 and 129-059-13AAD5, was installed 205 feet north of the production well. Another pair, 129-059-13AAD2 and 129-059-13AAD3, was installed 302 feet north of the production well. At each site, one observation well was completed near the top of the aquifer and one observation well was completed near the base of the aquifer (fig. 16). After 6,000 minutes of pumping, the difference in drawdown between the shallow observation well at 129-059-13AAD5 and the deep observation well at 129-059-13AAD4 was 0.06 feet. After 6,000 minutes of pumping, the difference in drawdown between the shallow observation well at 129-059-13AAD3 and the deep observation well at 129-059-13AAD2 was 0.05 feet. The small difference in drawdown between the shallow observation well and the deep observation well at each of the two sites indicates a continuous interval of sand or gravel or both from 19 to 105 feet below land surface. The smaller drawdown in each of the two shallow wells as compared to the drawdown in each of the deeper wells is caused by the difference in flow-path length. Partial penetration and aquifer anisotropy combine to create a flow path between the shallow observation well at each site and the production well that is longer than the flow path between the deep observation well at each site and the production well. Because of assumed conversion from confined to unconfined conditions and the occurrence of a barrier boundary, it was not possible to calculate aquifer anisotropy using available analytical methods.

Data from aquifer-test site AT-3 indicate individual well yields in excess of 2,000 gallons per minute are attainable from properly completed production wells in this area of the aquifer. The absence of a thick surficial confining layer in this area is conducive to the development of surface recharge facilities (pits, ponds).

Aquifer test site AT-4

During October 1985, the North Dakota State Water Commission conducted an aquifer test using an irrigation well located at 130-058-30ADD7 (fig. 19). The production well was constructed using 12-inch diameter steel casing from land surface to a depth of 55 feet. A 12-inch diameter, 100-slot stainless steel screen was installed from 55 to 75 feet below land surface. The driller's log of the production well indicates fine sand from 0 to 55 feet below land surface, medium to coarse sand from 55 to 75 feet, and sandy clay from 75 to 77 feet. A geohydrologic section of the test area is shown in figure 20.

Water levels were measured in the production well, 5 irrigation wells, and 29 observation wells (fig. 19). Continuous water-level recorders were installed on 10 observation wells completed within 813 feet of the production well. Water levels in the remaining observation wells and the five irrigation wells were measured twice daily using a chalked steel tape. The static water level in the production well was 10.0 feet below land surface. The production well was pumped continuously for 6,000 minutes at a constant rate of 875 gallons per minute. The specific capacity of the production well after 6,000 minutes of pumping was 23.2 gallons per minute per foot of drawdown. Water was discharged through a center-pivot irrigation system located along the western border in the NE1/4 of sec. 30. The drawdown measured in the production well after 6,000 minutes of pumping and in the 10 observation wells equipped with continuous recorders is shown in table 1.

A log-log composite t/r^2 versus drawdown plot was analyzed using the Theis method (fig. 21). Analysis of the log-log composite t/r^2 versus drawdown plot indicates the following:

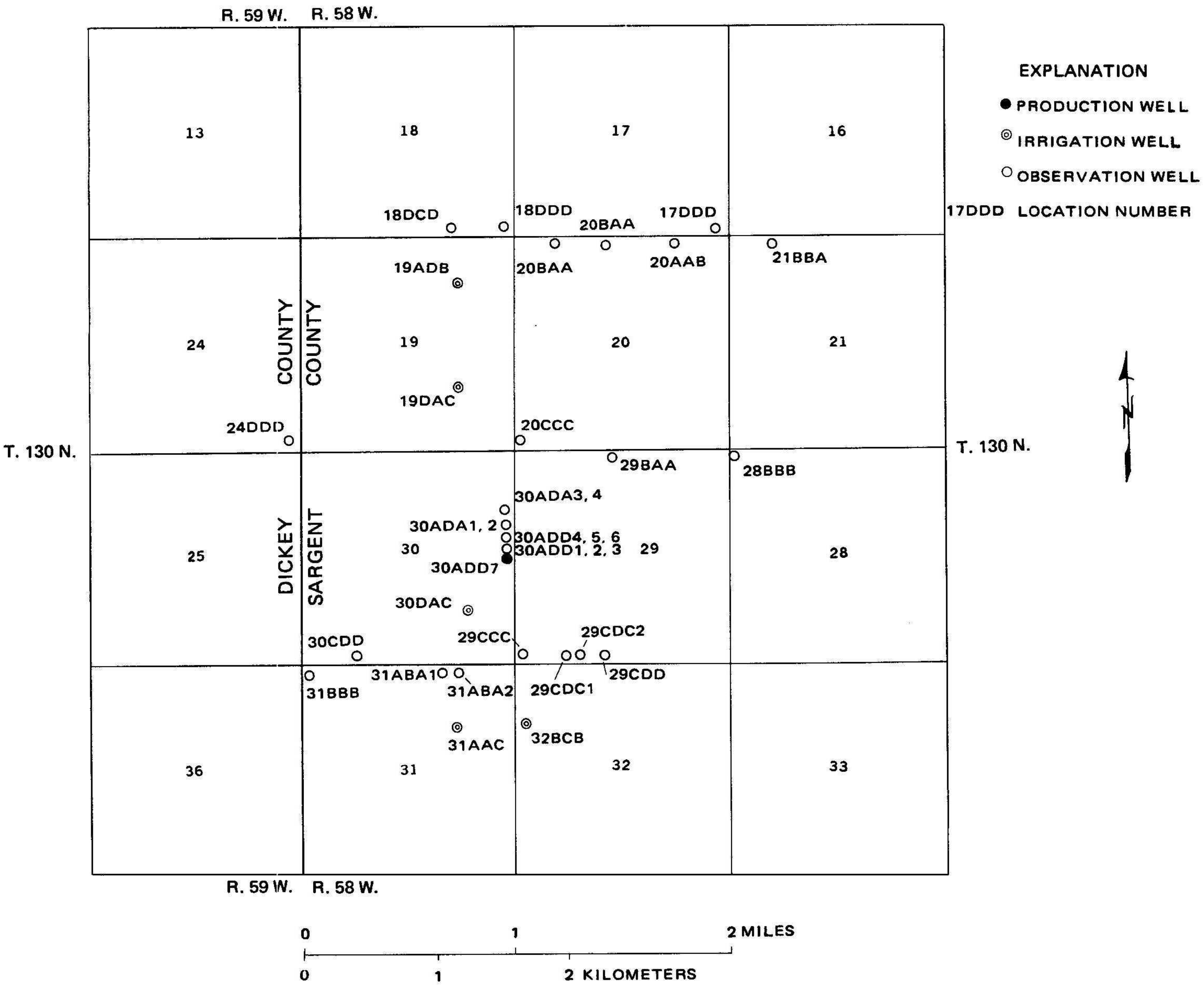


Figure 19.—Location of production well, irrigation wells, and observation wells for which water levels were measured at aquifer-test site AT-4.

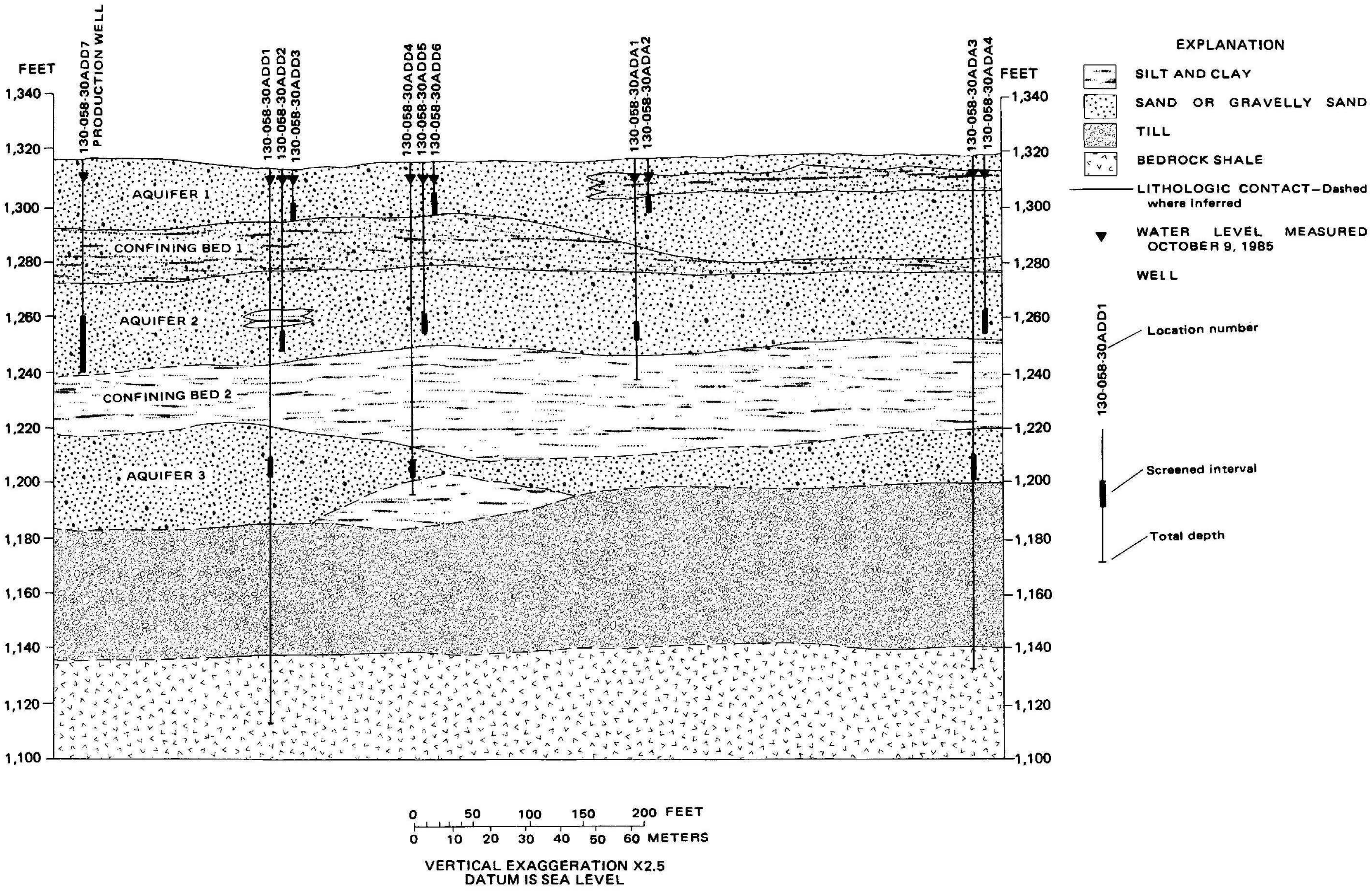


Figure 20.—Geohydrologic section showing the Oakes aquifer at aquifer-test site AT-4.

Table 1. -- Drawdown in production well and in selected observation wells after 6,000 minutes of pumping at a rate of 875 gallons per minute aquifer-test site AT-4

Type of well	Location	Radial distance and direction from production well to observation well, in feet	Screened interval, in feet below land surface	Drawdown after 6,000 minutes of pumping, in feet
Production	130-058-30ADD7	--	55 to 75	37.67
Observation	130-058-30ADD1	175 N.	105 to 110	.33
Observation	130-058-30ADD2	185 N.	60 to 65	5.43
Observation	130-058-30ADD3	196 N.	15 to 20	3.19
Observation	130-058-30ADD4	300 N.	108 to 113	.42
Observation	130-058-30ADD5	312 N.	56 to 61	3.27
Observation	130-058-30ADD6	323 N.	15 to 20	2.02
Observation	130-058-30ADA1	500 N.	60 to 65	2.34
Observation	130-058-30ADA2	512 N.	15 to 20	1.40
Observation	130-058-30ADA3	801 N.	110 to 115	.34
Observation	130-058-30ADA4	813 N.	60 to 65	1.34

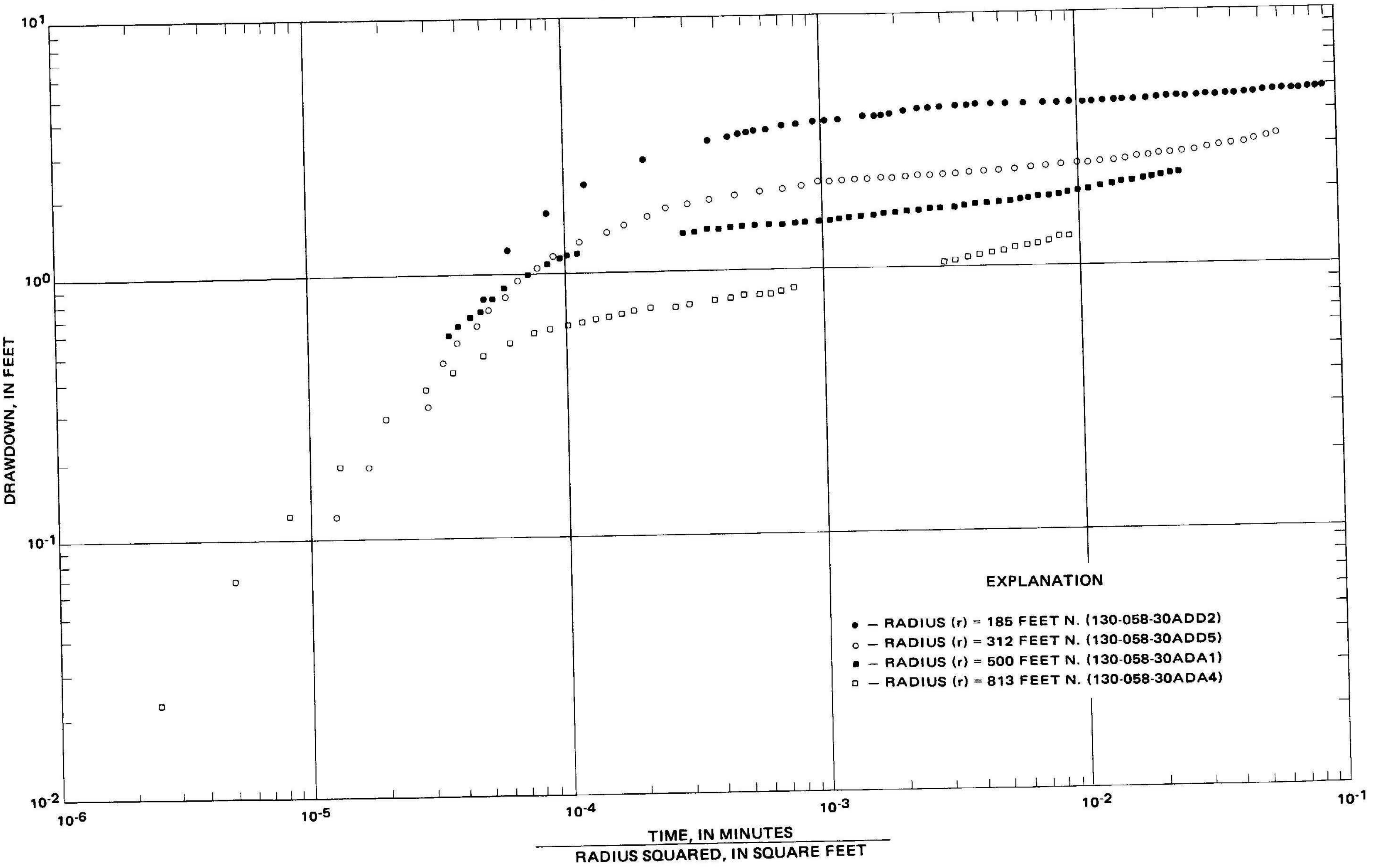


Figure 21.—Logarithmic composite t/r^2 versus drawdown plot at aquifer-test site AT-4.

1) For about the first 10 to 15 minutes of pumping, the individual drawdown plots are separated. After 10 to 15 minutes, the plots intersect. The separation and intersection of the drawdown plots probably is the result of a local decrease in transmissivity to the north within about 300 feet of the production well. An interval of clay and silt causes a decrease in transmissivity near observation well 130-058-30ADD2 (fig. 20). It is possible that this silt and clay layer thickens to the north toward piezometer 130-058-30ADD5. A decrease in transmissivity between piezometers 130-058-30ADD2 and 130-058-30ADD5 is also inferred by log-log distance versus drawdown squared plots (fig. 22). If a Theis type curve is matched to the drawdown points at piezometers 130-058-30ADD2 and 130-058-30ADD5, the drawdown points at 130-058-30ADA1 and 130-058-30ADA2 are above the Theis curve. If a Theis curve is matched to piezometers 130-058-30ADD5, 130-058-30ADA1, and 130-058-30ADA2, the drawdown point at 130-058-30ADD2 is above the Theis curve.

   The decrease in transmissivity between piezometers 130-058-30ADD2 and 130-058-30ADD5 is within 300 feet of the production well. Because the distance to piezometer 130-058-30ADD2 from the production well is large in relation to the distance to the decrease in transmissivity, the flow regime is probably not radial between the production well and piezometer 130-058-30ADD2.

2) After about 15 minutes of pumping, the slope of each drawdown plot becomes relatively flat (fig. 21). This response is indicative of leakage.

3) After about 2,000 minutes of pumping, the slopes of the individual drawdown plots increase. This could be caused by a decline in head in the overlying aquifer (aquifer 1) or by the drawdown cone intersecting a barrier boundary, or both. Available data in the test area suggests that a decline in head in the overlying aquifer is more likely.

4) A Theis type curve was not superimposed on the composite t/r^2 versus drawdown plot to calculate aquifer coefficients. The selection of a match point would have been arbitrary because of violations of the Theis assumptions.

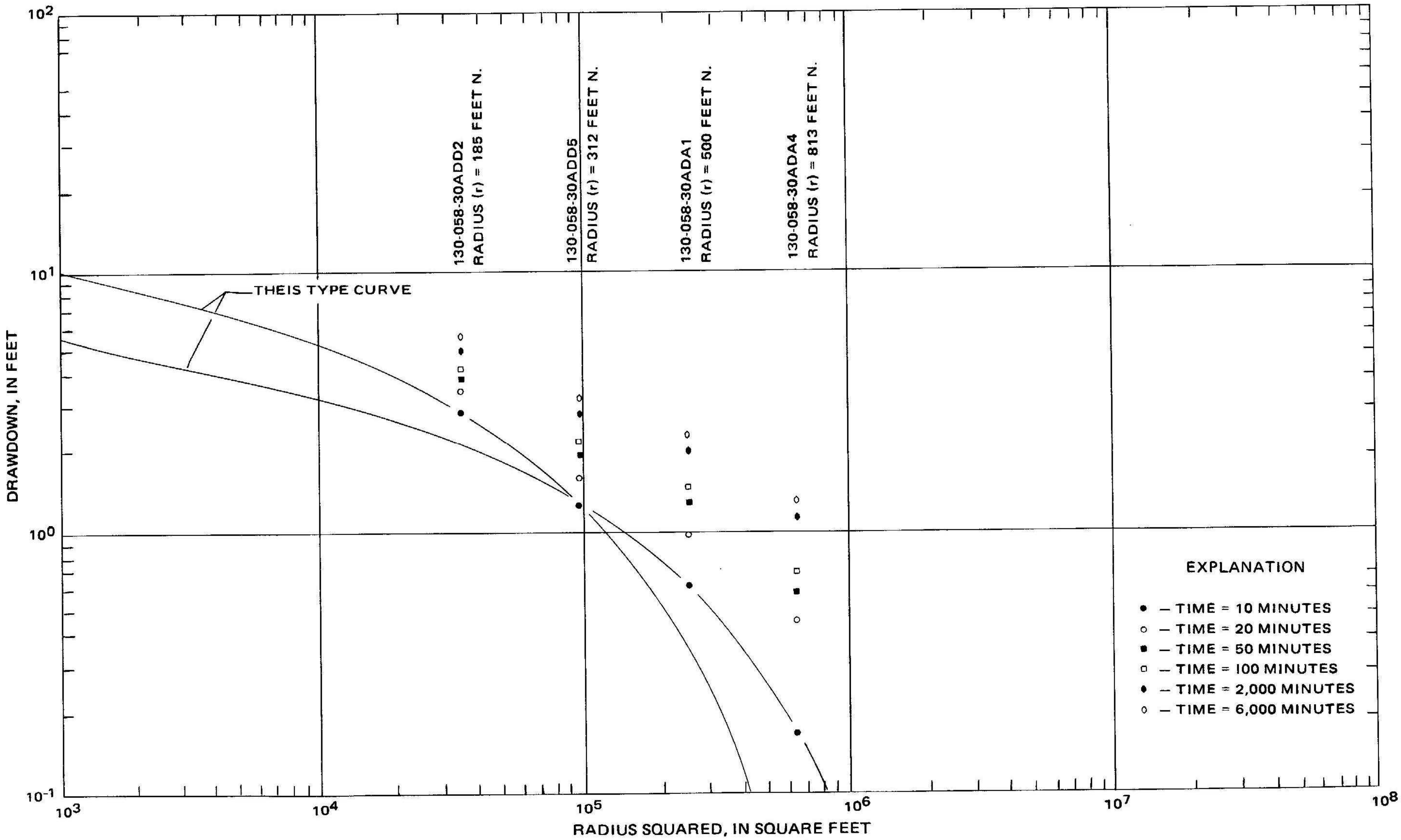


Figure 22.—Logarithmic distance squared versus drawdown plots for selected times at aquifer-test site AT-4.

The principal source of leakage is from aquifer 1 and not aquifer 3 (fig. 20). The total drawdown in aquifer 1 is about 60 percent of the total drawdown in aquifer 2 (table 1). The total drawdown in aquifer 3 ranged from about 10 to 25 percent of the total drawdown in aquifer 2. Reverse water-level fluctuations (Noordbergum effect) occurred in the piezometers completed in aquifer 3. The Noordbergum effect consists of a reverse water-level response in confining beds or in aquifers separated from the pumped aquifer by confining beds during early times of pumping and recovery tests (Rodrigues, 1983). Pumping from aquifer 2 caused confining bed 2 and aquifer 3 to compress thereby increasing pore water pressure. This response indicates that confining bed 2 is moderately compressible and contains a significant amount of clay.

Leakage from aquifers 1 and 3 coupled with a decrease in transmissivity between piezometers 130-058-30ADD2 and 130-058-30ADD5 preclude analysis of the aquifer-test data using available analytical methods.

Data from aquifer-test site AT-4 indicate individual well yields of about 1,000 gallons per minute are attainable if properly completed production wells are screened in both aquifer 2 and 3. Artificial recharge by surface infiltration methods (pits, ponds) may be severely restricted by the two confining beds. If surface recharge facilities (pits, ponds) are considered in this area of the aquifer, a three-dimensional finite-difference model needs to be developed to simulate aquifer-test AT-4 and, if possible, determine the hydraulic properties of the aquifers and confining beds. The model also could be utilized to simulate aquifer-system response to surface recharge facilities (pits, ponds).

Aquifer-test site AT-5

During April 1986, the North Dakota State Water Commission conducted an aquifer test using an irrigation well located at 129-058-06BAD5 (fig. 23). The production well was constructed using 12-inch diameter steel casing from land surface to a depth of 126 feet. A 10.75-inch outside diameter, stainless steel screen was installed from 126 to 158 feet below land surface. Slot size was 0.100 inch from 126 to 138 feet below land surface, 0.120 inch from 138 to 152 feet below land surface, and 0.140 inch from 152 to 158 feet below land surface. The driller's log of the production well indicates sand from 0 to 15 feet below land surface, sand and clay from 15 to 41 feet, sand from 41 to 52 feet, silt from 52 to 98 feet, silt containing pebbles from 98 to 118 feet, and sand and gravel from 118 to 160 feet. A geohydrologic section of

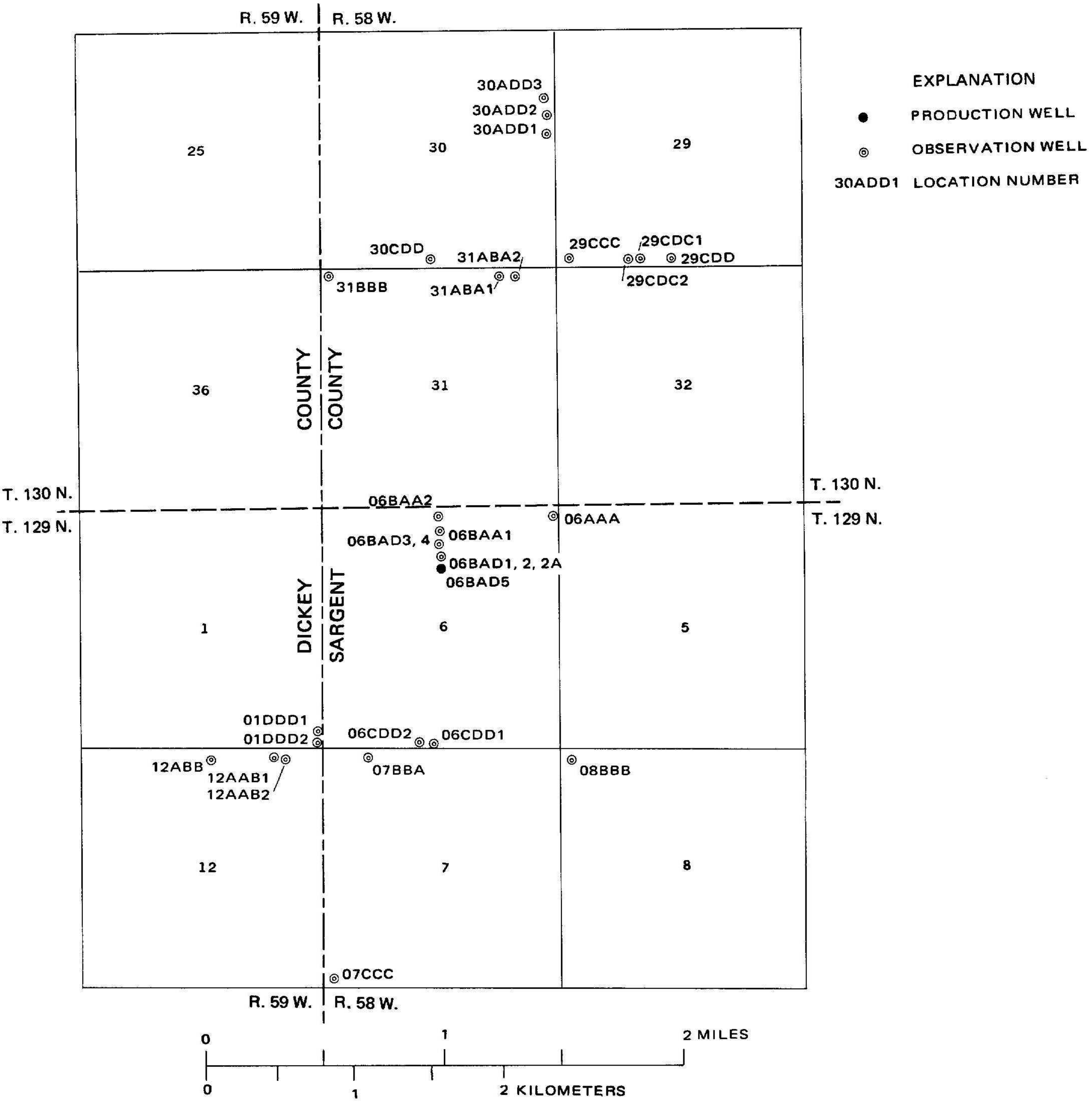


Figure 23.—Location of production well and observation wells for which water levels were measured at aquifer-test site AT-5.

the test area is shown in figure 24.

Water levels were measured in the production well and in 29 observation wells (fig. 23). Continuous water-level recorders were installed on seven observation wells completed within 803 feet of the production well. Water levels in the remaining 22 observation wells were measured twice daily using a chalked steel tape. The static water level in the production well was 3.5 feet below land surface. The production well was pumped continuously for 6,000 minutes at a constant rate of 1,683 gallons per minute. The specific capacity of the production well after 6,000 minutes of pumping was 102 gallons per minute per foot of drawdown. Water was discharged about 1.5 miles to the west through two center-pivot irrigation systems located in the SE1/4 of sec. 35, T. 130 N., R. 59 W., and the NE1/4 of sec. 2, T. 129 N., R. 59 W. The drawdown measured in the production well after 6,000 minutes of pumping and in the seven observation wells equipped with continuous recorders is shown in table 2. The drawdown measured in the remaining observation wells at the end of the test is shown in figure 25.

A log-log composite t/r^2 versus drawdown plot was analyzed using the Theis method (fig. 26). Semilog time versus drawdown plots (fig. 27) and semilog distance versus drawdown plots (fig. 28) were analyzed by using the Jacob method. Analysis of all three data plots indicates the following:

1) For about the first 40 minutes of pumping, individual drawdown plots are separated and, for the most part displaced downward (fig. 26). After about 40 minutes, the plots intersect. This drawdown response is similar to the early-time drawdown response for aquifer test At-4. The early-time separation and intersection of the drawdown plots is probably the result of leakage and a local decrease in transmissivity between observation wells 129-058-06BAD3 and 129-058-06BAA1 (fig. 24). Leakage is indicated by the immediate response to pumping observation wells 129-058-06BAD2 and 129-058-06BAD4. Leakage is further indicated by early time (less than about 50 minutes) calculation of apparent transmissivities that increase as radial distance from the production well to the observation well increases (fig. 27). A decrease in transmissivity between observation wells 129-058-06BAD3 and 129-058-06BAA1 is indicated by comparing the measured hydraulic gradient between observation wells 129-058-

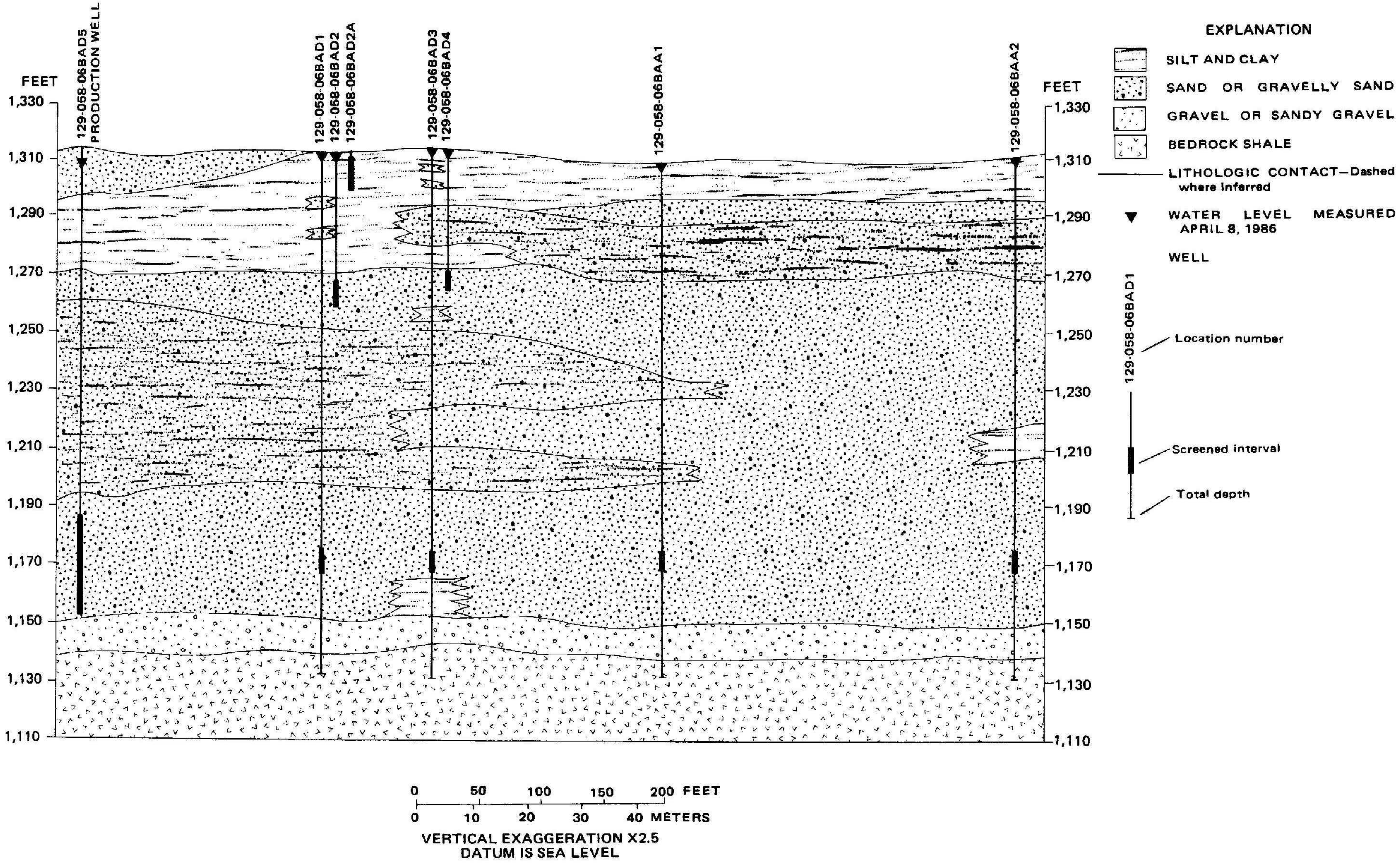


Figure 24.—Geohydrologic section showing the Oakes aquifer at aquifer-test site AT-5.

Table 2. -- Drawdown in production well and in selected observation wells after 6,000 minutes of pumping at a rate of 1683 gallons per minute at aquifer-test site AT-5

Type of well	Location	Radial distance and direction from production well to observation well, in feet	Screened interval, in feet below land surface	Drawdown after 6.000 minutes of pumping, in feet
Production	129-058-06BAD5	--	126 to 158	16.53
Observation	129-058-06BAD1	210 N.	138 to 143	5.61
Observation	129-058-06BAD2	207 N.	48 to 53	4.08
Observation	129-058-06BAD2A	206 N.	2 to 10	.78
Observation	129-058-06BAD3	304 N.	138 to 143	5.18
Observation	129-058-06BAD4	302 N.	43 to 48	4.01
Observation	129-058-06BAA1	500 N.	138 to 143	4.36
Observation	129-058-06BAA2	803 N.	138 to 143	3.81

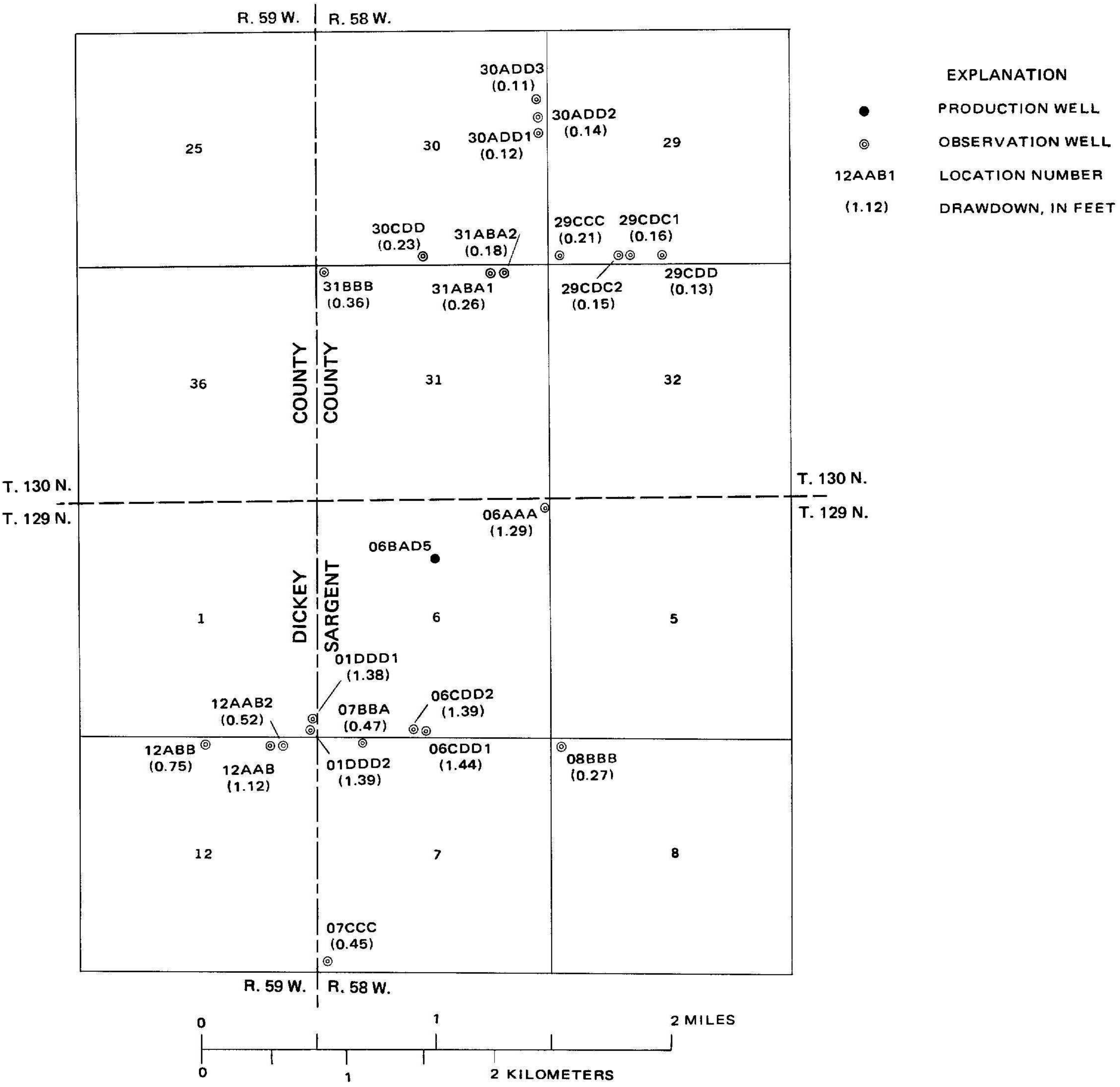


Figure 25.—Drawdown in selected observation wells after 6,000 minutes of pumping at aquifer-test site AT-5.

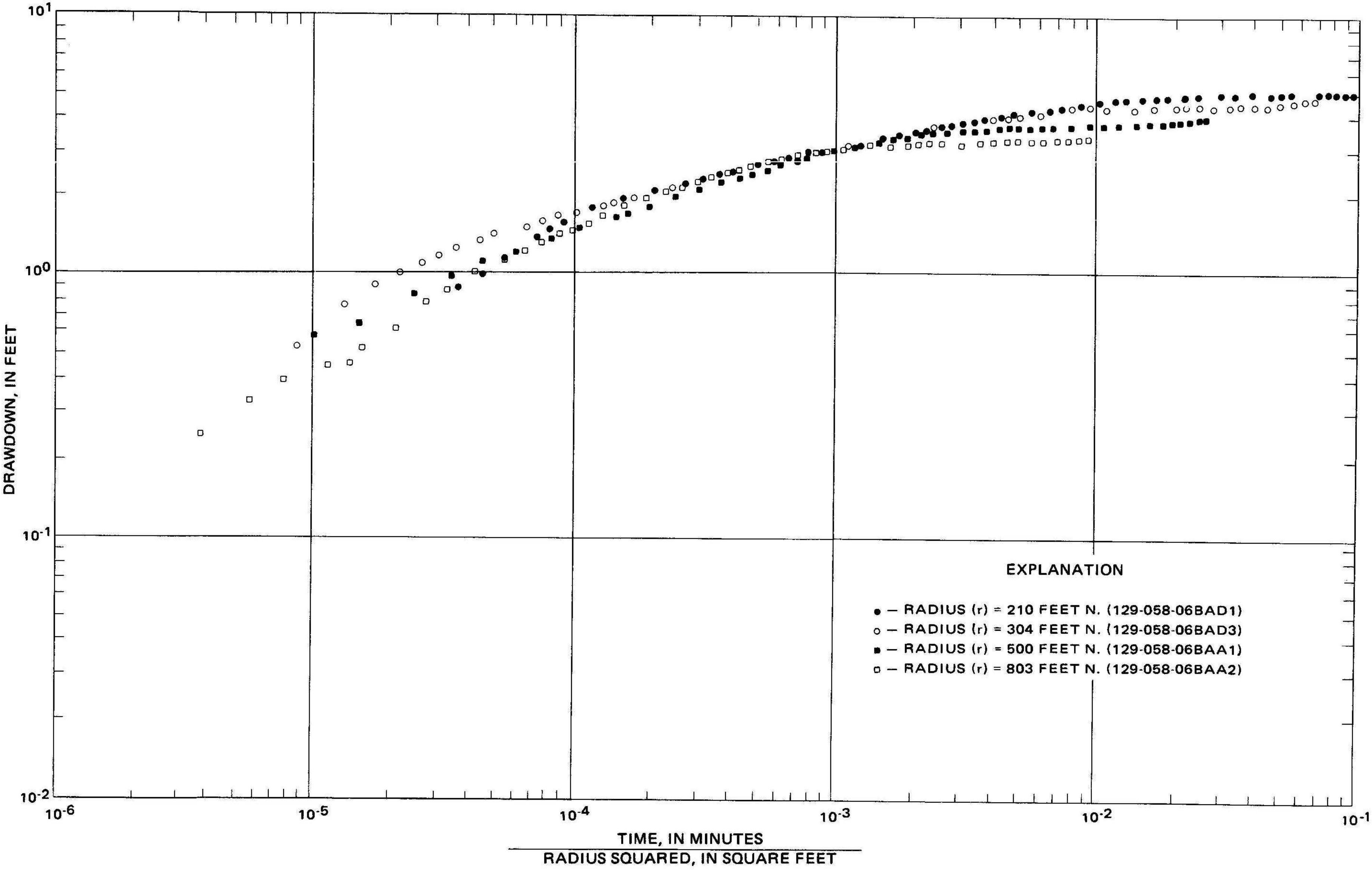


Figure 26.—Logarithmic composite t/r^2 versus drawdown plot at aquifer-test site AT-5.

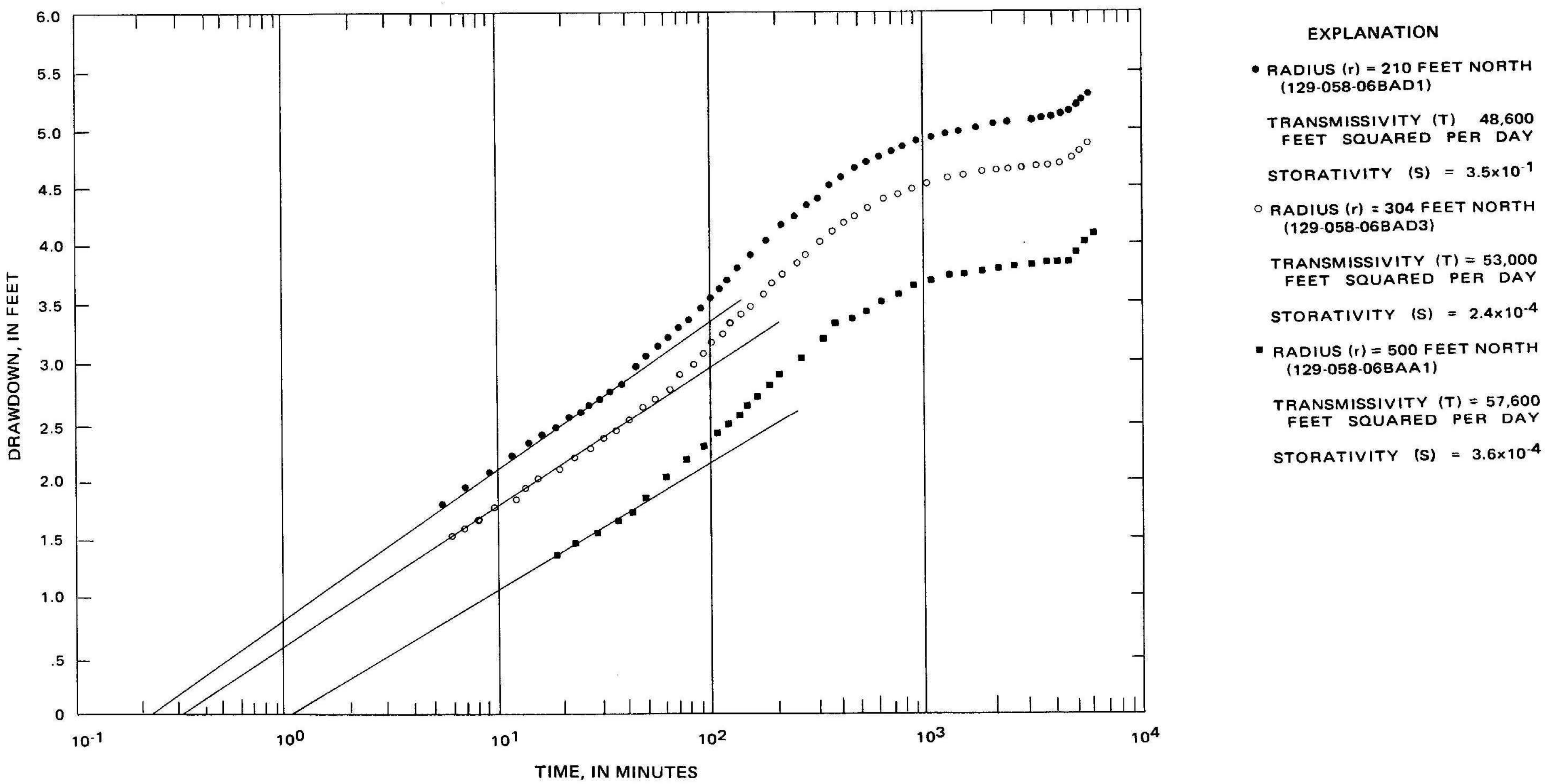


Figure 27.—Selected semilogarithmic time verses drawdown plots at aquifer-test site AT-5.

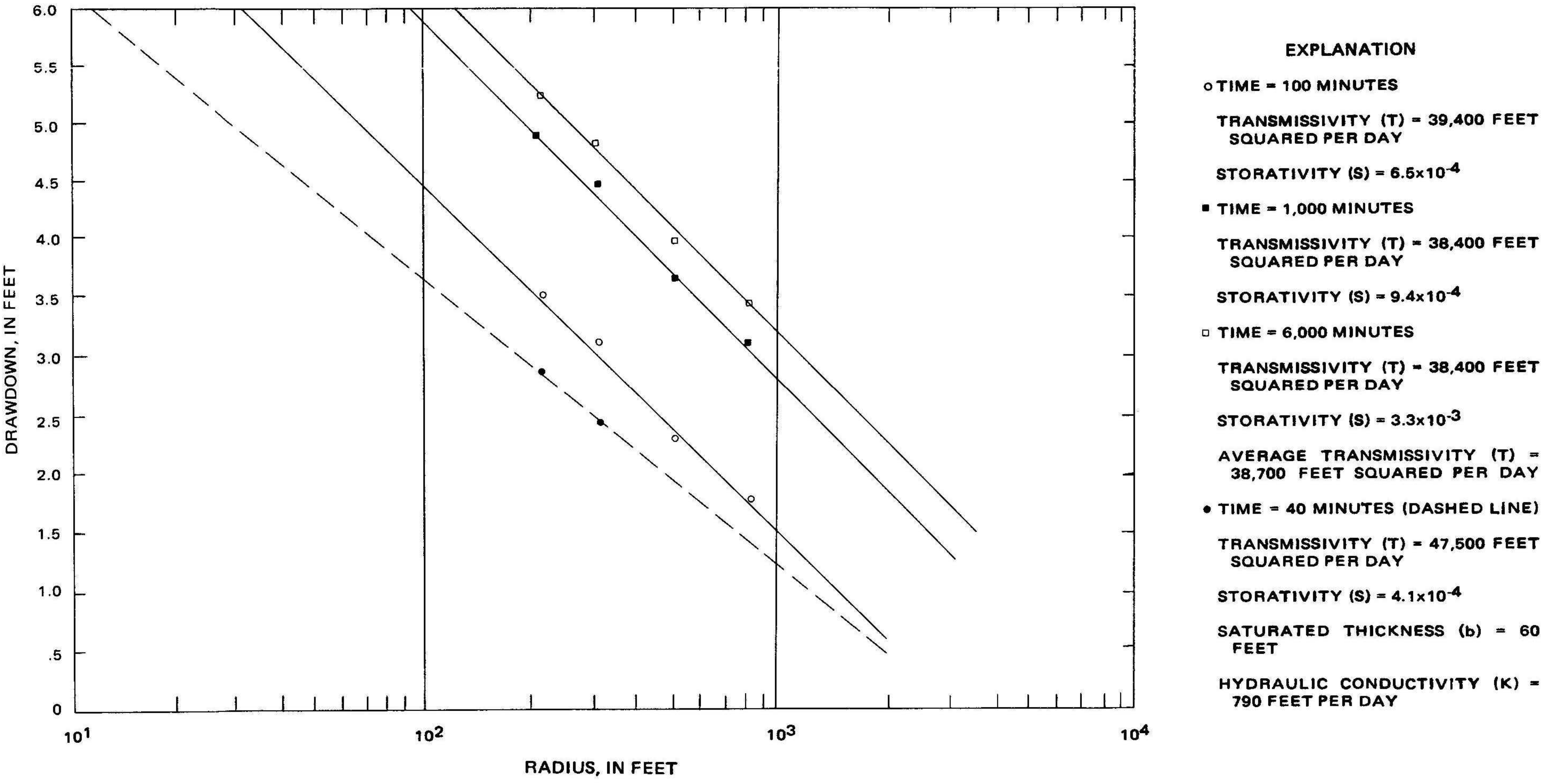


Figure 28.—Semilogarithmic distance versus drawdown plots for selected times at aquifer-test site AT-5.

06BAD3 and 129-058-06BAA1 and the hydraulic gradient determined by the straight-line fit using all four observation wells on the semilog distance versus drawdown plot (fig. 28).

2) After about 40 minutes of pumping, the individual drawdown plots on the composite t/r^2 graph converge and the slopes of the semilog time versus drawdown plots increase. This response is caused by the drawdown cone intersecting a barrier boundary. The production well is located about 2,000 feet east of the western flank of the outwash channel and about 2,500 feet west of the eastern flank of the outwash channel. A surficial fluvial silty-clay layer of variable thickness occurs in the test area. The fluvial silty-clay layer is a leaky confining layer.

3) After about 500 minutes of pumping, the slopes of the individual drawdown plots decrease on both the composite t/r^2 and time versus drawdown graphs. This response is caused by leakage. Although barrier boundary effects still occur during this time, leakage is dominant.

4) After about 4,500 minutes of pumping, slopes of the individual drawdown plots increase on both the composite t/r^2 and time versus drawdown graphs. This response indicates the effect of barrier boundaries or a decline in head in the aquifer overlying the producing interval or both.

5) A Theis type curve was not superimposed on the composite t/r^2 versus drawdown plot to calculate aquifer coefficients. The selection of a match point would have been arbitrary because of violations of the Theis assumptions.

Apparent transmissivity was calculated using the semilog distance versus drawdown plots (fig. 28). A Jacob analysis was applied to a straight line fitted through the four data points. An average apparent transmissivity of about 38,700 feet squared per day was computed from the apparent transmissivities calculated for the selected times shown. Calculated apparent storativities increased as time increased, thus indicating leakage. The points on the individual distance versus drawdown plots approximate a straight line. The slope of this straight line is relatively constant with time. This indicates that the drawdown cone as defined by the four observation wells in figure 28 is at quasi-steady state.

Therefore, the quantity of water derived from storage in the overlying confining layer in this area of the drawdown cone is negligible compared to the quantity of water moving laterally toward the production well. The observation wells are aligned approximately parallel to the flanking barrier boundaries. The distance between the production well and observation wells is small relative to the distance from the production well to the flanking boundaries of the outwash channel. The Jacob semilog distance versus drawdown analysis will provide a valid approximation of transmissivity based on quasi steady-state conditions and the well-boundary configuration.

The hydaulic gradient between observation wells 129-058-06BAD3 and 129-058-06BAA1 is larger than the hydraulic gradient established by the straight-line fit using the four data points (observation wells) on the distance versus drawdown plot (fig. 28). This is probably caused by the previously mentioned decrease in transmissivity between observation wells 129-058-06BAD3 and 129-058-06BAA1 (fig. 24). To calculate transmissivity near the production well, a Jacob analysis was applied to a straight line drawn through the first two points of the 40-minute distance-versus-drawdown plot (fig. 28). A transmissivity of 47,500 feet squared per day and an apparent storativity of 4.1×10^{-4} were calculated. Based on an average saturated thickness of 60 feet for the producting interval, hydraulic conductivity was about 790 feet per day.

Leakage is indicated during early time (first 50 minutes of pumping) because calculated apparent transmissivities using the semilog time versus drawdown plots increase as radial distance from the observation well to the production well increases. Therefore, the apparent storativity of 4.1×10^{-4} probably is slightly larger than actual. Based on an apparent storativity of 4.1×10^{-4} calculated from the semilog time versus drawdown plots, the storativity of the producting interval is estimated at 3.8×10^{-4}.

Observation well 129-058-06BAD2A is completed in the surficial fluvial silt and clay sequence. The screened interval is between 2 and 10 feet below land surface. The drawdown measured in observation well 129-058-06BAD2A after 6,000 minutes of pumping was 0.78 feet (table 2). The relatively small drawdown measured in this observation well as compared to the drawdown measured in observation wells 129-058-06BAD2 and 129-058-06BAD3 indicates the surficial silt and clay sequence has a small vertical hydraulic conductivity.

Data from aquifer-test site AT-5 indicate indicate individual well yields in excess of 2,000 gallons per minute are attainable from properly completed wells in this area of the Oakes aquifer. Surface recharge facilities (pits, ponds) will be precluded in this area because of the occurrence of a relatively thick, surficial, fluvial silt and clay sequence of small hydraulic conductivity.

Areal Hydraulic Conductivity of the Oakes Aquifer

An areal hydraulic conductivity map was prepared using values estimated from lithologic logs of drill holes or values determined from aquifer tests (pl. 7). Only lithologic logs prepared by the U.S. Bureau of Reclamation and the North Dakota State Water Commission were used to estimate hydraulic conductivity.

The U.S. Bureau of Reclamation Drainage Division, Bismarck, North Dakota, developed a table relating values of hydraulic conductivity to various U.S. Department of Agriculture textural classes (A. Mathison, personal commun., 1986). Values of hydraulic conductivity are average values for each textural class and are based on numerous field and laboratory hydraulic conductivity tests conducted on sediments in the Oakes area (table 3).

The Nebraska Geological Survey developed a table relating values of hydraulic conductivity to various grain-size classes based on the Wentworth scale (Nebraska Geological Survey, written commun., date unknown; table 4). Values of hydraulic conductivity were estimated at North Dakota State Water Commission drill-hole sites using this table in conjunction with lithologic logs prepared by the site geologist.

U.S. Bureau of Reclamation test holes are less than 35 feet deep. Where the Oakes aquifer is less than 35 feet deep, areas of equal hydraulic conductivity shown on plate 7 were determined primarily from U.S. Bureau of Reclamation lithologic logs used in conjunction with table 3. Where the Oakes aquifer occurs at depths greater than 35 feet, areas of equal hydraulic conductivity shown on plate 7 were determined primarily from North Dakota State Water Commission lithologic logs used in conjunction with table 4 and from aquifer-test data. Hydraulic conductivities estimated by the latter method range from about two to five times less than hydraulic conductivities determined from aquifer-test data. Sediment samples are severely disturbed and stratification is, for the most part, obscured by the forward mud rotary rig drilling process used to drill all North Dakota State Water Commission

Table 3.--Estimated hydraulic conductivities of selected sediment textural classes

Texture	Hydraulic conductivity, in feet per day
Coarse sand and gravel	100
Medium sand and gravel	70
Fine sand and gravel	40
Coarse sand	70
Medium sand	50
Fine sand	40
Very fine sand	20
Loamy sand	12
Loamy fine sand	12
Loamy very fine sand	10
Sandy loam	4
Fine sandy loam	4
Very fine sandy loam	3.6
Silt loam	1.0
Loam	1.0
Silty clay	<.4
Silty clay loam	<.4
Clay loam	<.4
Clay	<.4

Table 4. -- Estimated hydraulic conductivities of selected grain-size classes and description

Grain-size class or range and test-hole log description	Hydraulic conductivity, in gallons per day per square foot
Clay	0
Silt-clayey	10-30
Silt-slightly sandy	40
Silt-moderately sandy	50-60
Silt-very sandy	70-80
Sandy silt	80
Silty sand	100

	Degree of sorting			Silt content		
	Poor	Moderate	Well	Slight	Moderate	Very
Very fine sand	100	150	200	170	140	100
Very fine to fine sand	200	200		180	150	100
Very fine to medium sand	270-310-350			240	200	155
Very fine to coarse sand	360			300	230	180
Very fine to very coarse sand	440			380	300	220
Very fine sand to fine gravel	570			500	390	285
Very fine sand to medium gravel	740			600	490	370
Very fine sand to coarse gravel	960			800	640	480
Fine sand	200	300	400	250	200	150
Fine to medium sand	400	500		360	295	225
Fine to coarse sand	430-485-540			400	320	240
Fine to very coarse sand	525			450	355	260
Fine sand to fine gravel	660			550	440	330
Fine sand to medium gravel	850			700	560	425
Fine sand to coarse gravel	1,085			800	650	540
Medium sand	500	600	700	475	385	300
Medium to coarse sand	550	700		540	430	315
Medium to very coarse sand	630-730-830			550	455	365
Medium sand to fine gravel	775			625	510	390
Medium sand to medium gravel	980			850	610	490
Medium sand to coarse gravel	1,230			1,000	810	615
Coarse sand	600	800	1,000	700	550	400
Coarse to very coarse sand	700	1,000		700	560	425
Coarse sand to fine gravel	870-1,020-1,170			800	655	510
Coarse sand to medium gravel	1,100			850	700	550
Coarse sand to coarse gravel	1,380			1,000	745	690
Very coarse sand	800	1,100	1,400	850	700	550
Very coarse sand to fine gravel	1,000	1,600		900	775	650
Very coarse sand to medium gravel	1,270-1,485-1,700			1,100	920	740
Very coarse sand to coarse gravel	1,500			1,200	985	775
Fine gravel	1,200	1,600	2,000	1,200	1,050	800
Fine to medium gravel	1,500	2,500		1,500	1,250	1,000
Fine to coarse gravel	1,830-2,165-2,500			1,750	1,415	1,080
Medium gravel	1,800	2,400	3,000	1,800	1,500	1,200
Medium to coarse gravel	2,200	3,500		2,200	1,815	1,425
Coarse gravel	2,500	3,500	4,500	2,500	2,125	1,750

Reduce to 10 percent if grains are subangular
Divide by 7.48 to convert hydraulic conductivity into units of feet per day

test holes. As a result, sand and gravel intervals commonly are described by the site geologist as poorly sorted, and estimated hydraulic conductivities determined using table 4 generally are conservative. Zones of larger hydraulic conductivity shown on plate 7 were based mainly on aquifer-test data.

Zones of equal hydraulic conductivity were extended into South Dakota (pl. 7). In the central and western parts of South Dakota shown on plate 7, the areal distribution of hydraulic conductivity was inferred from land-surface topography. Channel-fill sand and gravel deposits predominate in the eastern part of the area of South Dakota shown on plate 7. Test-hole data were used to delineate the areal distribution of the channel-fill deposits in this area. Hydraulic conductivities were extrapolated from values determined for the channel-fill deposits in North Dakota.

Aquifer Transmissivity and Estimated Well Yields

Transmissivity is equal to the product of hydraulic conductivity and saturated thickness. Values of transmissivity can be used to estimate maximum individual well yields. In general, individual well yields are greatest in areas of large transmissivity.

There are two large-transmissivity areas of the Oakes aquifer that can accommodate individual well yields of greater than 500 gallons per minute (fig. 29). These areas are: (1) The northern part of the study area near Oakes (deltaic sand and gravel); and (2) the eastern flank of the lake plain (channel-fill sand and gravel).

Well yields in the Oakes aquifer were estimated using specific capacity values determined from: 1) aquifer tests conducted by the North Dakota State Water Commission; (2) pump efficiency tests conducted by the Agricultural Extension Service, North Dakota State University; and (3) pump tests conducted by well drillers. In addition, well yields were also estimated using a chart developed by Meyer (1963, p.338-340, fig. 100) relating well diameter, specific capacity, coefficient of storage, and transmissivity. Transmissivity was estimated as the product of saturated thickness and hydraulic conductivity. Specific yield was estimated as to be at 0.20. Wells were assumed to be 100 percent efficient and 12 inches in diameter. Specific capacity values determined from the chart and from the pumping tests were multiplied by four-ninths of the saturated thickness to estimate individual well yields. Specific capacity values calculated from aquifer, pump

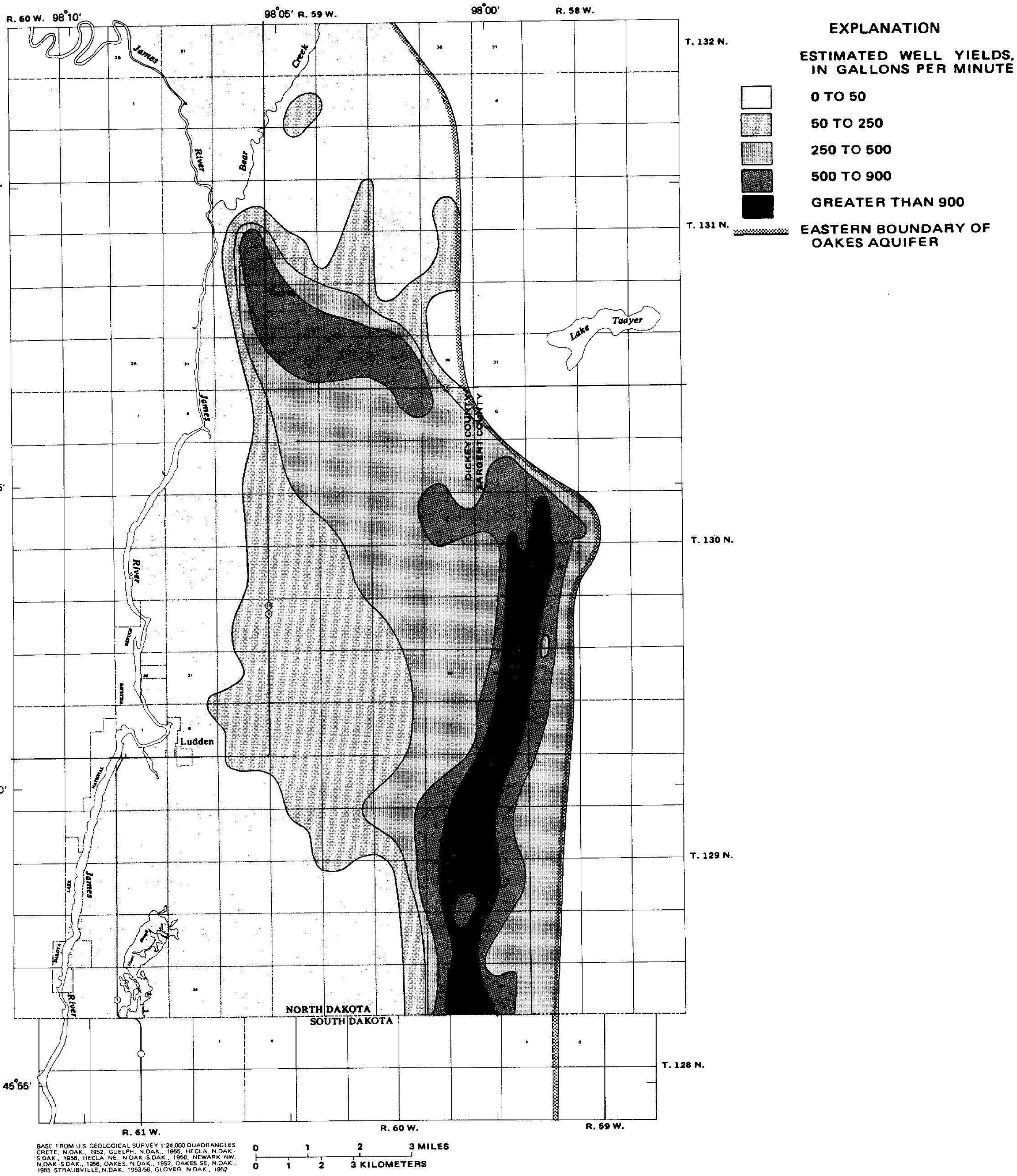


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Figure 29.—Estimated well yields in the Oakes aquifer.

efficiency, and pump tests were deemed more reliable and therefore were the basis for developing figure 29. In areas where aquifer, pump efficiency, and pump test data were not available, the method of Meyer (1963) was used to estimate individual well yields.

Based on an average hydraulic conductivity of 200 feet per day and an average saturated thickness of 60 feet, average transmissivity of the deltaic deposits is 12,000 feet squared per day. Individual well yields of up to 900 gallons per minute are attainable from properly completed wells in the deltaic deposits that occupy the north-central part of the lake plain. Completion of 50 wells in the deltaic deposits would provide a total withdrawal rate of 45,000 gallons per minute.

Based on an average hydraulic conductivity of 780 feet per day and an average saturated thickness of 90 feet, average transmissivity of the channel-fill deposits is 70,750 feet squared per day. Individual well yields in excess of 2,000 gallons per minute are attainable from properly completed wells in the channel-fill deposits. Completion of 23 wells in the channel-fill deposits would provide a total withdrawal rate of more than 45,000 gallons per minute. In comparison to all other areas of the Oakes aquifer, the channel-fill deposits will provide the largest individual well yields. Therefore, the number of wells needed to meet peak irrigation demands will be minimized.

Infiltration Tests

During October 1985, three shallow-pit infiltration tests were conducted in the Oakes aquifer specifically for this study. The purpose of the tests was to determine if initial infiltration rates would preclude the use of surface artificial recharge facilities. Based on evaporation rates in the Oakes study area, an infiltration rate of at least 1 foot per day would accommodate surface recharge facilities. The objective of the tests was to determine steady-state infiltration rates for materials below the root zone. Infiltration-test site RM-1 was located at 130-058-20AAB, site RM-2 was located at 130-058-31AAB, and site RM-3 was located at 129-059-24AAB (fig. 30).

Additional infiltration tests have been conducted in the Oakes aquifer as part of a North Dakota State Water Commission study to assess spatial variation in recharge. Both surface and shallow-pit infiltration tests were conducted on a Hecla, a Ulen, and an Arveson soil series at area RM-4, located at

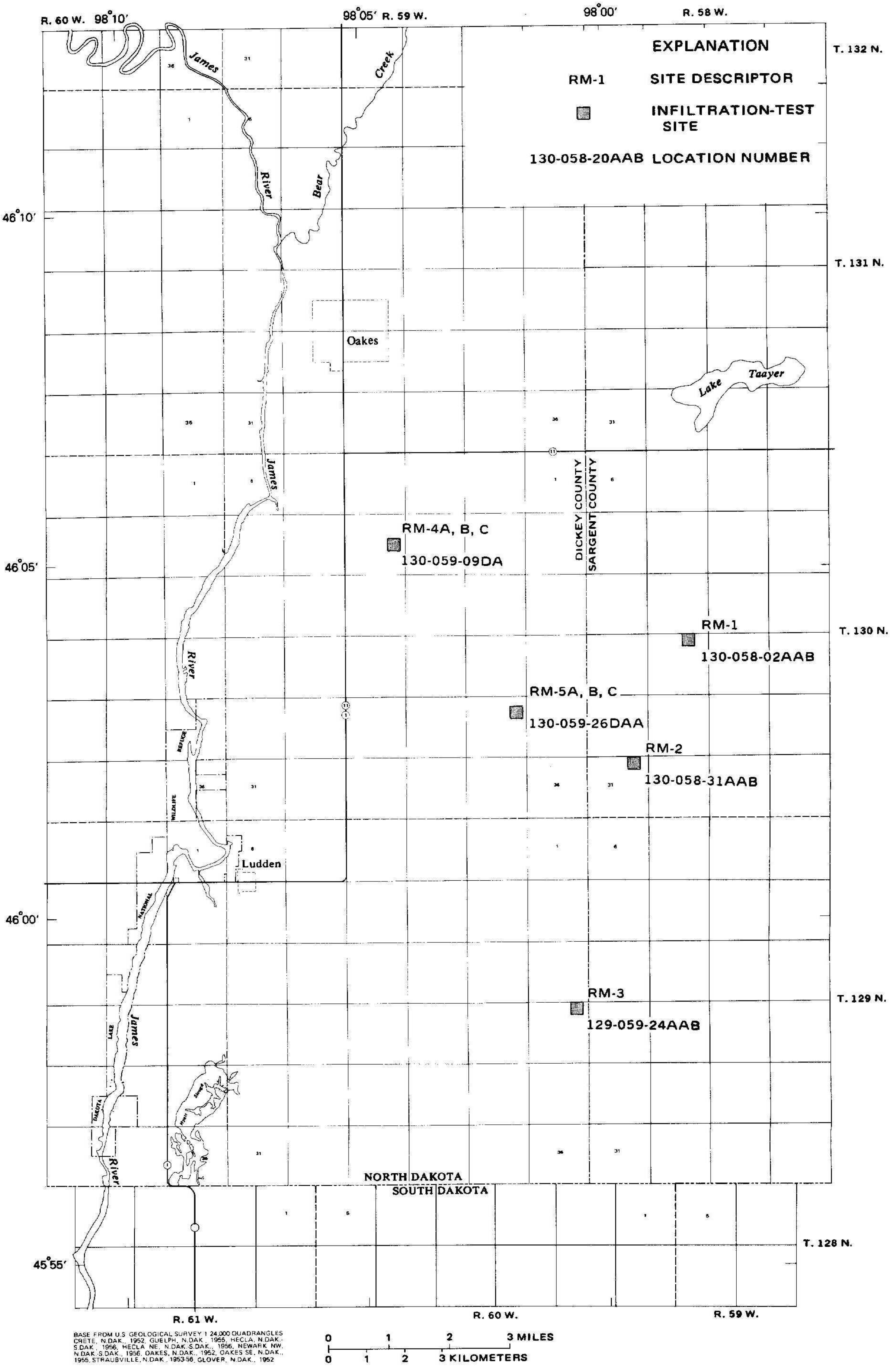

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Figure 30.—Location of infiltration-test sites.

130-059-09DA. Surface infiltration tests were conducted on one Hamar and two Hecla soil series at area RM-5, located at 130-059-26DAA.

A description of the soil profile at each of the five infiltration-test sites and areas is given in supplements 1-9. In addition, particle-size analyses for profiles at sites RM-1, RM-2, and RM-3 are given in supplements 10-12.

Methods of Construction and Operation

Pits were excavated to a depth of about 5 feet using a backhoe. Size was sufficient to allow for work room and the exposure of an undisturbed soil face for vertical infiltration measurement. The floor of the pit was cleaned carefully to keep the natural soil matrix intact as much as possible. Scaffold boards were used to avoid trafficking the measurement area.

A double-ring infiltrometer was constructed using a 24-inch diameter inner ring of 1/2-inch pvc pipe and a 48-inch diameter outer ring of 12-inch flashing. The inner ring was placed by digging a narrow trench around the outer trace of the ring and then shaving inward until the ring slid tightly into place to a depth of 4 inches. Material inside the border of the inner ring was compacted to one-fourth inch from the edge of the ring. The 1/4-inch space then was filled with plaster of paris to eliminate boundary flow. The outside border of the inner ring also was compacted and the space filled with plaster of paris. Both rings were fitted with float valves, and water levels inside each ring were maintained at 3 to 4 inches. After initiation of measurements, the outer ring float was adjusted to the water level of the inner ring. Water used to conduct the infiltration tests was obtained from a well completed in the Oakes aquifer at 130-059-26DAA.

The infiltration surface was roughed slightly to remove slicking effects from cleaning and was protected from washing during measurement by placing burlap under the inlet valve. At initiation (t=0), a premeasured quantity of water (6 to 8 gallons) known to be slightly greater than the capacity of the ring up to the float water line was added instantly. Water influx then was measured using calibrated barrels. At site RM-3, water accidentally began flowing through an open valve during preparation. As a result, the t=0 measurement is not true zero time (Schuh, 1985). Infiltration measurements were continued until the rate of influx remained constant for at least 3 hours.

Infiltration-test site RM-1

Infiltration-test site RM-1 was located on pastureland near 130-058-20AAB. The infiltration test was conducted on October 17, 1985. The pit was excavated to a depth of 5.7 feet. Prior to excavation, soil samples were collected using a Gidding probe. Depth to water table was 11.12 feet in observation well 130-058-20AAB located about 25 feet north of the pit.

Infiltration rate versus time is shown in figure 31. Steady-state infiltration calculated from these data is about 20 feet per day.

Infiltration-test site RM-2

Infiltration-test site RM-2 was located adjacent to a prairie trail near 130-058-31AAB. The infiltration test was conducted on October 17, 1985. The pit was excavated to a depth of 5 feet. Prior to excavation, soil samples were collected using a Gidding probe. Depth to water table was 9.3 feet in observation well 130-058-31ABA2 located about 50 feet west of the pit.

Infiltration rate versus time is shown in figure 31. Steady-state infiltration calculated from these data is about 7 feet per day.

Infiltration-test site RM-3

Infiltration-test site RM-3 was located adjacent to a prairie trail near 129-059-24AAB. The infiltration test was conducted on October 18, 1985. The pit was excavated to a depth of 5.25 feet. Prior to excavation, soil samples were collected using a Gidding probe. Depth to water table was 8.74 feet in observation well 129-059-13DDC located about 50 feet northeast of the pit.

Infiltration rate versus time is shown in figure 31. Steady-state infiltration calculated from these data is about 2.5 feet per day.

The smaller steady-state shallow-pit infiltration rates determined at sites RM-2 and RM-3 as compared to site RM-1 are caused by the occurrence of finer grained eolian sequences and associated buried A horizons.

Particle-size analyses indicate clay content of as much as 13.7 percent in the buried A horizons (supplements 10-12).

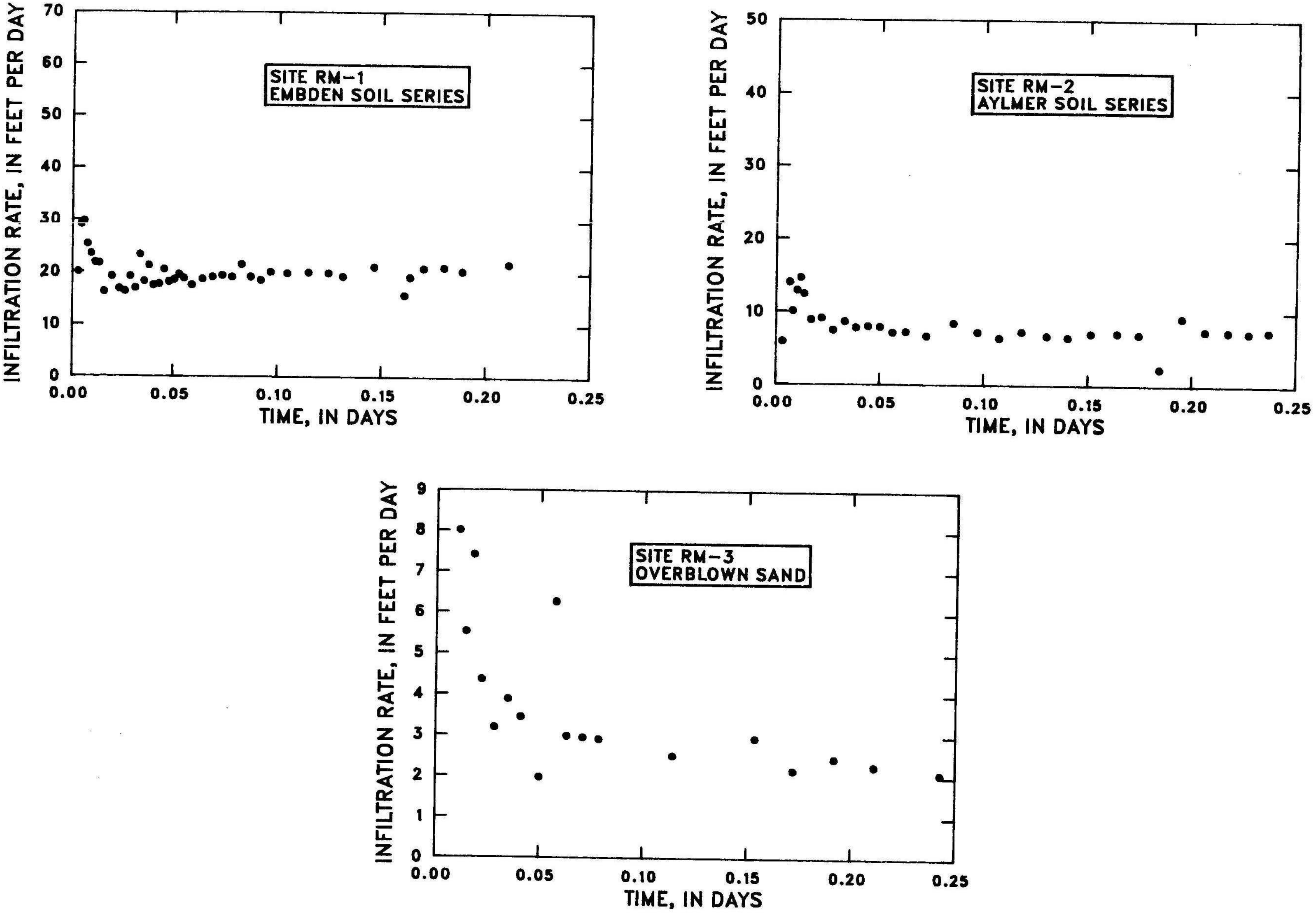


Figure 31.—Infiltration rate versus time within shallow pits at sites RM-1, RM-2. and RM-3.

In addition, a layer of clay about 1-inch thick was encountered at site RM-2. Larger infiltration rates probably can be achieved in the vicinity of sites RM-2 and RM-3. A more detailed sampling program will be needed to delineate areas where eolian sequences and buried A horizons are thin and clay layers are absent. The initial infiltration rates measured at all 3 sites exceed 1 foot per day and are adequate for large-scale surface recharge facilities (pits, ponds).

Infiltration-test area RM-4

Infiltration-test area RM-4 was located on pastureland near 130-059-09DA. A surface infiltration test was conducted on a Hecla soil series (site RM-4a) on June 18, 1985; a Ulen soil series (site RM-4b) on June 19, 1985; and an Arveson soil series (site RM-4c) on June 20, 1985. Soil samples were collected at each test site by using a Gidding probe.

Infiltration rate versus time at each site is shown in figure 32. Steady-state infiltration calculated from these data is about 10 feet per day for the Hecla soil series, 3.6 feet per day for the Ulen soil series, and 1.4 feet per day for the Arveson soil series.

Pits were excavated in each of the three soil series at area RM-4 to conduct shallow-pit infiltration tests. A shallow-pit infiltration test was conducted on a Hecla soil series (site RM-4a) on August 2, 1985; a Ulen soil series (site RM-4b) on August 6, 1985; and an Arveson soil series (site RM-4c) on August 6, 1985.

Infiltration rate versus time at each site is shown in figure 33. Steady-state infiltration calculated from these data is about 57 feet per day for the Hecla soil series, 67 feet per day for the Ulen soil series, and 26 feet per day for the Arveson soil series.

Infiltration-test area RM-5

Infiltration-test area RM-5 was located on an uncultivated corner of cropland at 130-059-26DAA. A surface infiltration test was conducted on a Hamar soil series (site RM-5a) on October 16, 1985; a Hecla soil series (site RM-5b) on October 21, 1985; and another Hecla soil series (site RM-5c) on October 22, 1985. Soil samples were collected at each test site by using a Gidding probe.

Infiltration rate versus time at each site is shown in

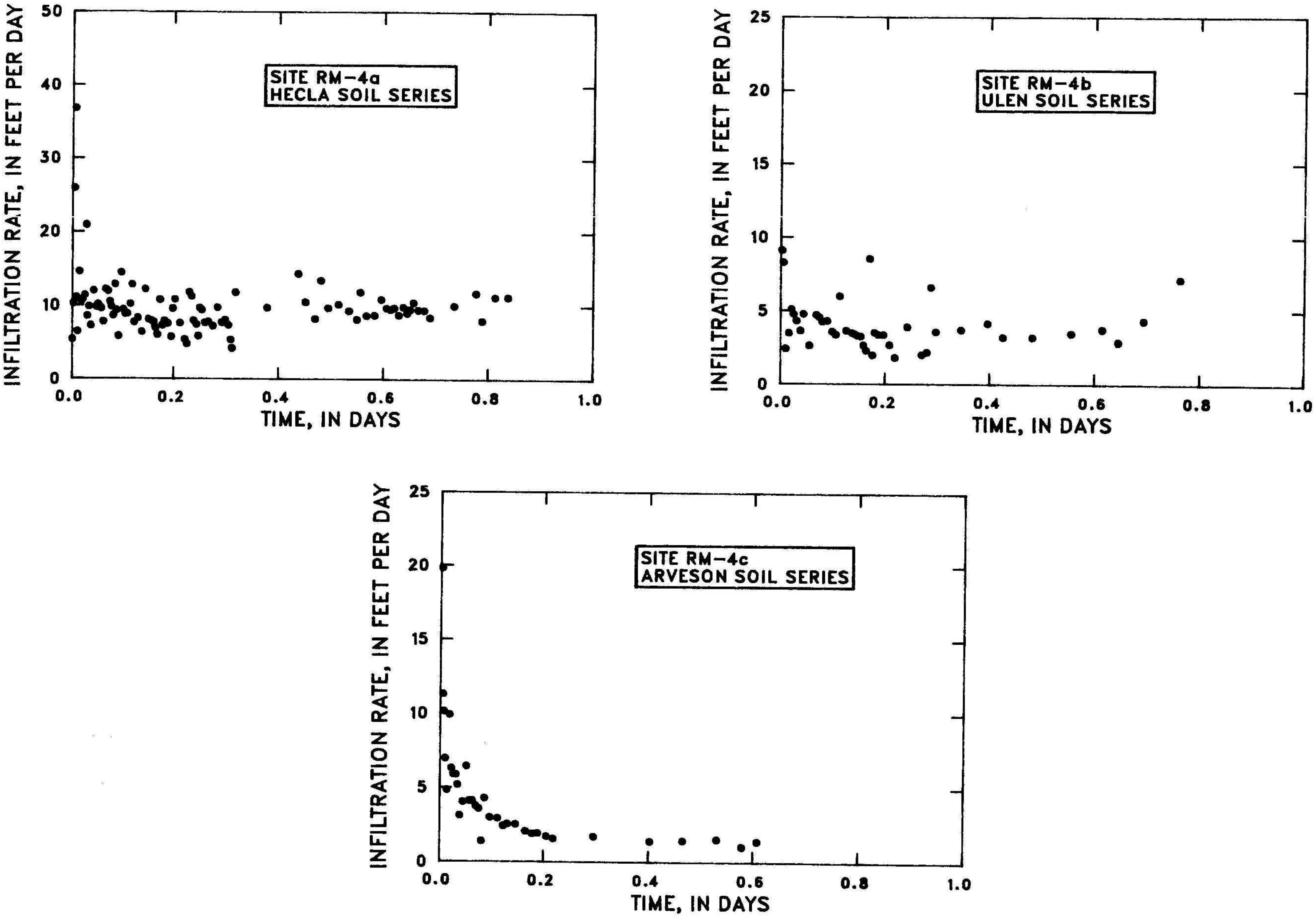


Figure 32.—Surface infiltration rate versus time for a Hecla, Ulen, and Arveson soil series at site Rm-4.

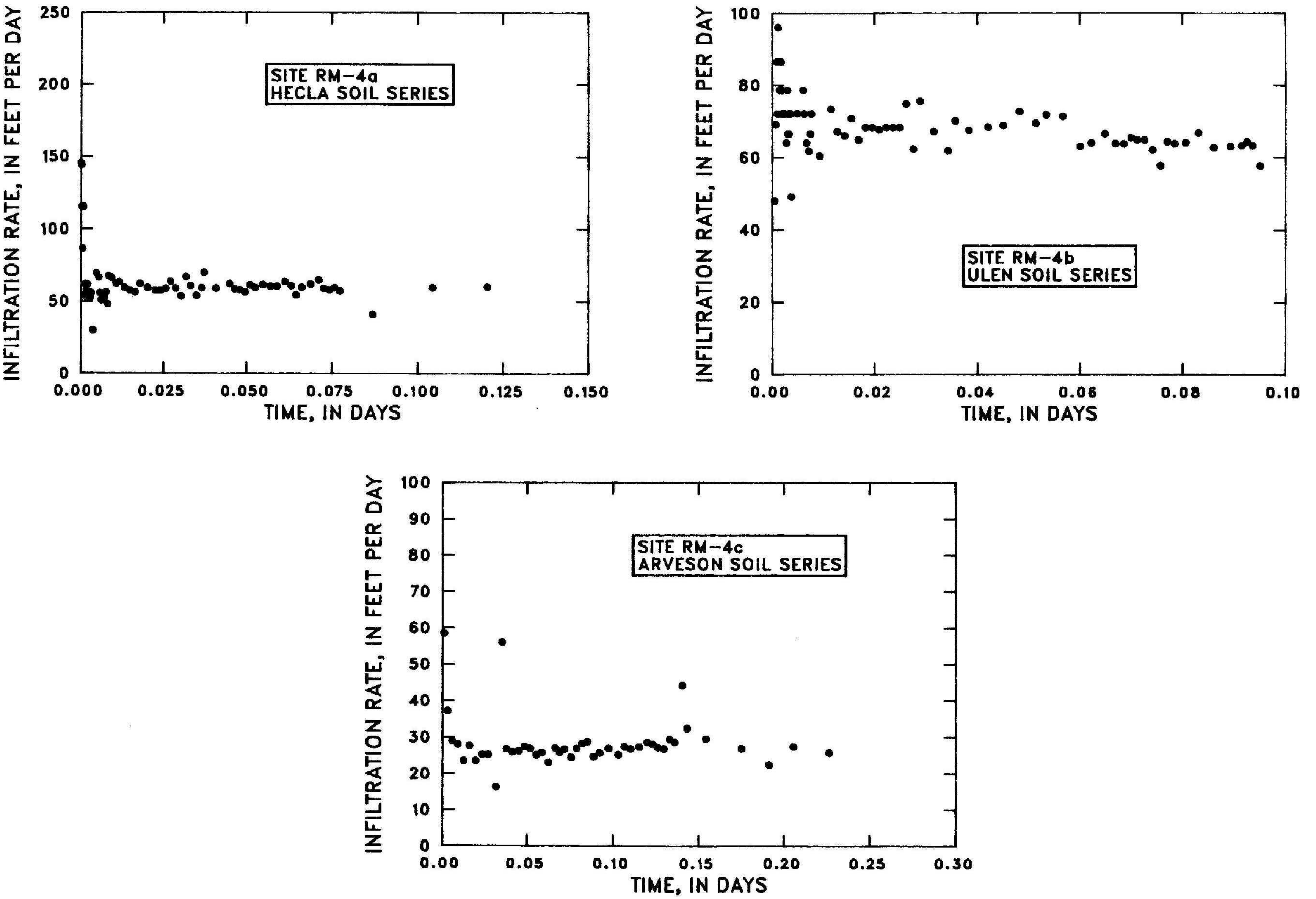


Figure 33.—Infiltration rate versus time within shallow pits for a Hecla, Ulen, and Arveson soil series at site Rm-4.

figure 34. Steady-state infiltration calculated from these data is about 12.9 feet per day for the Hamar soil series, 15.0 feet per day for the Hecla soil series at RM-5b, and 8.3 feet per day for the Hecla soil series at RM-5c.

The soil series at areas RM-4 and RM-5 predominate in the central part of the lake plain, and steady-state infiltration rates measured at areas RM-4 and RM-5 are considered representative for this area. Surficial silt and clay sequences generally are absent in the central part of the lake plain. As a result, initial infiltration rates in the central part of the lake plain are adequate for large-scale surface recharge facilities (pits, ponds).

The soil series at sites RM-2 and RM-3 are ubiquitous in the areas overlying the outwash channel along the eastern margin of the lake plain. Buried A horizons that contain significant amounts of clay are common in these soils. In addition, relatively thick surficial fluvial silt and clay sequences overlie parts of the outwash channel (129-058-06BAD). In other areas overlying the outwash channel, the surficial fluvial silt and clay sequences are thin or absent (129-059-13AAD). The selection of surface recharge sites overlying the outwash channel will need a detailed drilling and sampling program to delineate areas where buried A horizons and silt and clay sequences are thin or absent.

Aquifer Recharge and Discharge

Recharge to the Oakes aquifer occurs primarily by relatively direct infiltration of precipitation and snowmelt. Minor amounts of recharge occur as underflow from adjacent small-transmissivity units that include lacustrine silts and clays, till, and the Pierre and Niobrara Formations.

As previously described, land-surface topography of the study area is hummocky because of sand dunes and blowouts (fig. 3). The hummocky topography is an important control on both recharge and discharge processes.

To a great extent, recharge to the Oakes aquifer can be characterized as depression focused (Lissey, 1968). During the winter, a frost zone develops at or near the water table. Snow accumulates in depressions and on adjacent topographic-high areas. In the spring, snow melts before the frost zone dissipates. Snowmelt originating in the upland areas accumulates in depressions from surface runoff because of the inability to infiltrate through the frost zone. Ponded water in depressions infiltrates downward to the saturated zone

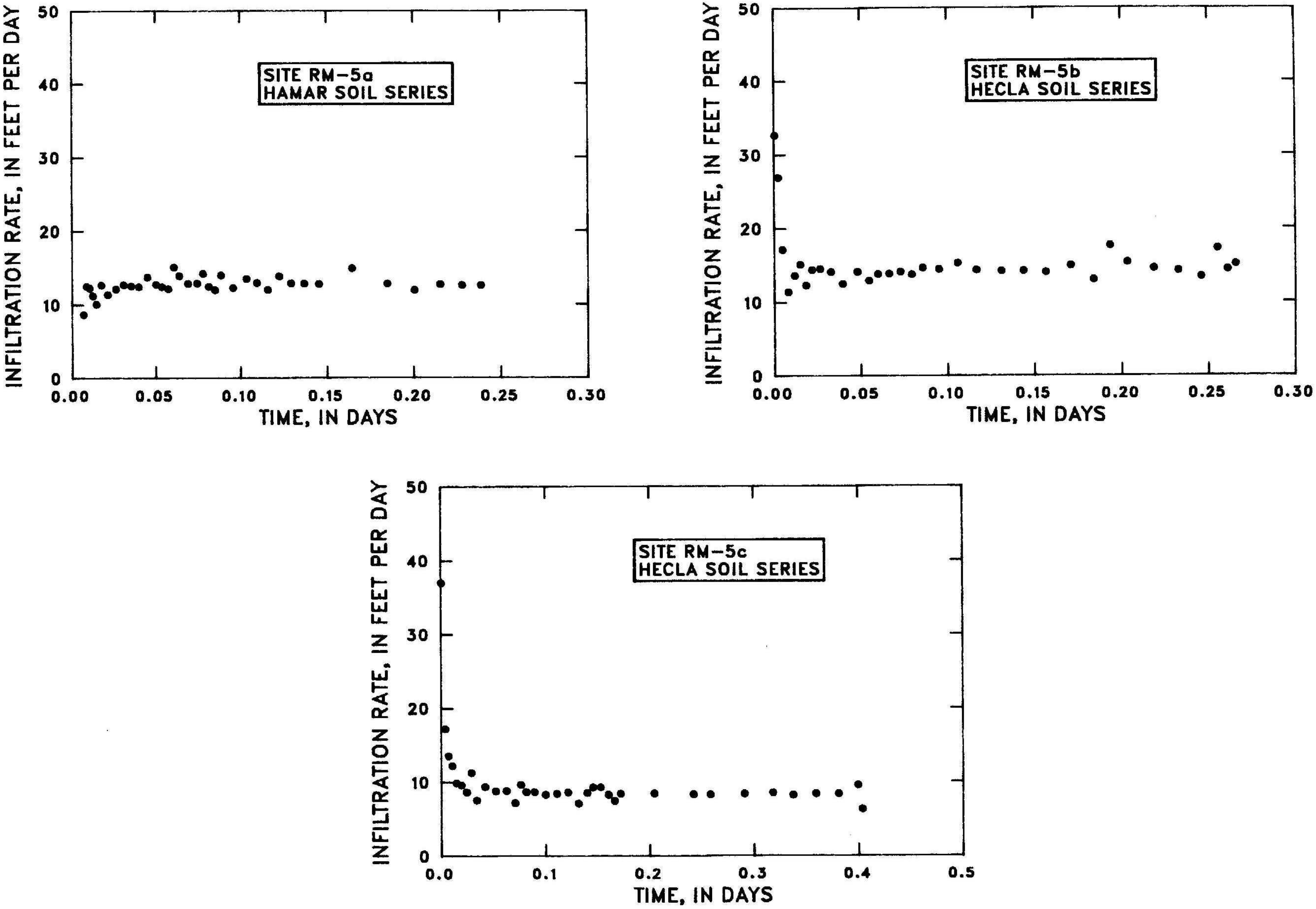


Figure 34.—Surface infiltration rate versus time for a Hamer and two Hecla soil series at site RM-5.

after the frost zone dissipates.

Recharge to the Oakes aquifer occurs primarily during the spring. Recharge probably is negligible during the summer months because, in most years, potential evapotranspiration exceeds precipitation (table 5). Summer precipitation events rarely are large enough to overcome soil-moisture deficits and generate recharge. Occasionally during the fall precipitation exceeds both evapotranspiration and soil-moisture deficits, and recharge occurs. Even when recharge does not occur during the fall, soil-moisture deficits generally are reduced, significantly affecting the magnitude of the following spring recharge event.

Depth to the water table over much of the study area is less than 8 feet. As a result, natural discharge from the Oakes aquifer is due primarily to evapotranspiration.

Discharge westward to the James River is negligible. Recent James River valley flood-plain deposits that consist of sandy silty clay truncate the western flank of the Oakes aquifer. The result is a small-transmissivity barrier that impedes ground-water flow westward from the Oakes aquifer toward the James River.

Hydrographs were prepared for selected observation wells completed in the Oakes aquifer (fig. 35). The hydrographs consistently show that recharge occurs primarily from March through May and discharge occurs primarily from June through August.

The North Dakota State Engineer has approved the appropriation of 18,274.8 acre-feet of water annually from the Oakes aquifer to irrigate 12,224 acres of land. Based on data from annual water-use forms, 6,697 acre-feet of ground water was diverted from the Oakes aquifer in 1985 to irrigate 6,835 acres of land. In addition, the city of Oakes has approval to divert 800 acre-feet of water annually from the Oakes aquifer for its municipal water supply. The city of Oakes reported the diversion of 479.9 acre-feet of water for municipal purposes in 1985.

In 1983, the U.S. Bureau of Reclamation began construction of a drain network in the central part of the study area. Construction was completed in 1985. A significant amount of discharge occurs from this drain network, particularly during the spring.

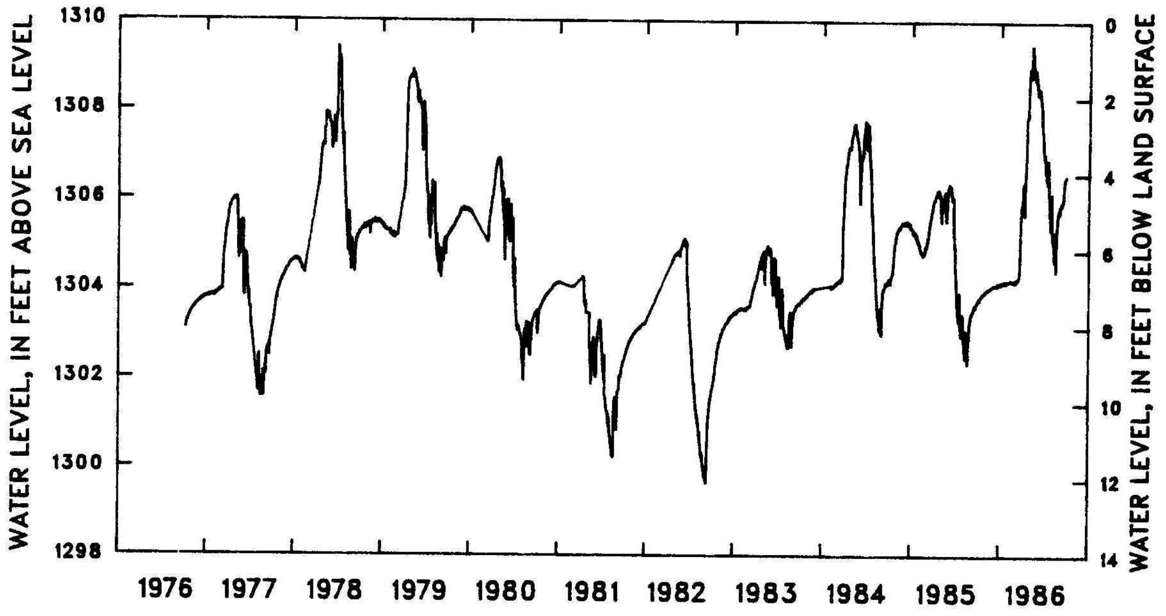
Quantification of recharge and natural discharge in the Oakes aquifer currently is virtually impossible because of the

Table 5. -- Summer precipitation and potential evapotranspiration at Oakes, 1972-79

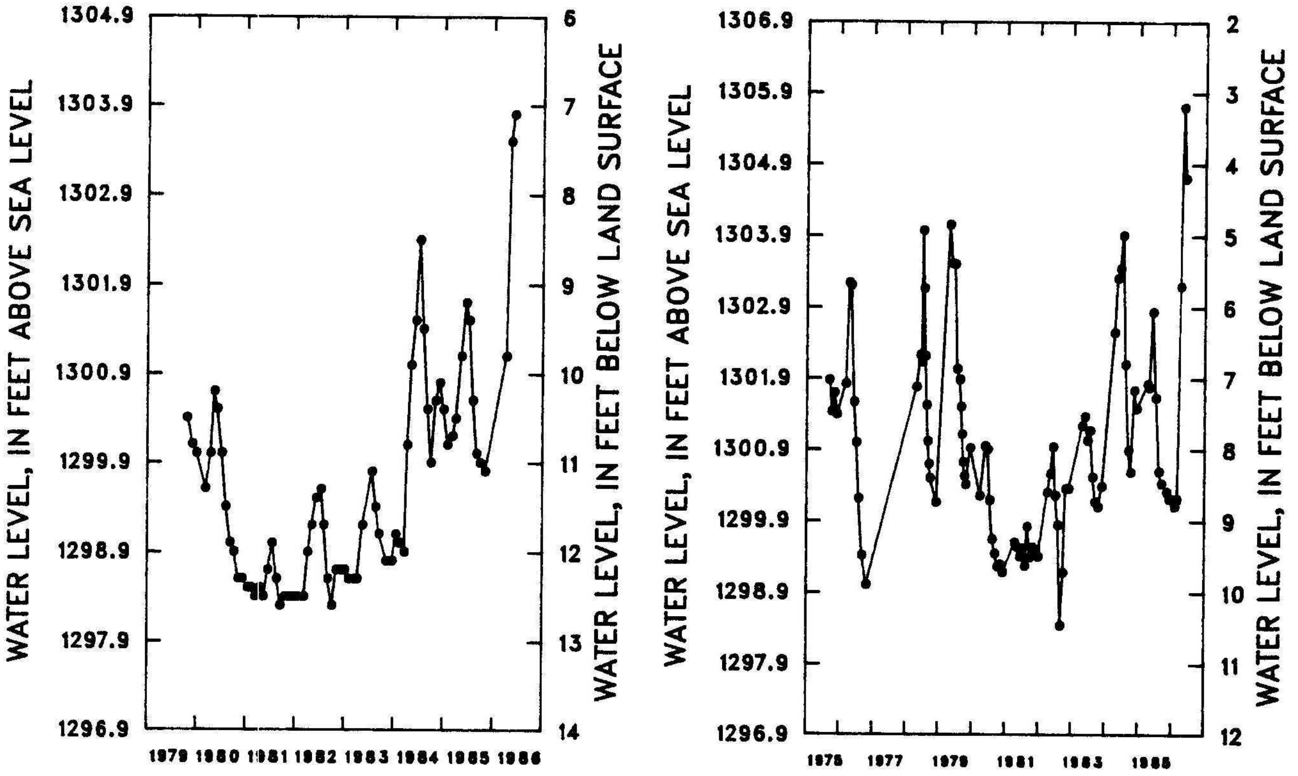
Year[1]	Precipitation, in inches	Potential evapotranspiration[2], in inches
1972	7.91	18.34
1973	5.21	19.82
1974	5.98	19.66
1975	20.25	19.42
1976	2.97	21.20
1977	7.88	15.42
1978	9.04	17.10
1979	9.41	14.37

[1] June 1 through August 31.

[2] Calculated using a modified Jensen-Haise method.



WELL 129–058–06AAA2
LAND SURFACE ALTITUDE 1,315.9 FEET
SCREENED INTERVAL FROM 51 TO 56 FEET



WELL 130–059–33DAA
LAND SURFACE ALTITUDE 1,310.9 FEET
SCREENED INTERVAL FROM 18 TO 21 FEET

WELL 129–059–10AAA2
LAND SURFACE ALTITUDE 1,308.9 FEET
SCREENED INTERVAL FROM 33 TO 36 FEET

Figure 35.—Selected hydrographs showing water levels in the Oakes aquifer.

inability to describe spatial variation in precipitation, land-surface topography, soil physical properties, and the evapotranspiration process. It is not within the scope of this study to determine areal recharge and evapotranspiration rates in the Oakes aquifer.

FINITE-DIFFERENCE MODEL OF GROUND-WATER FLOW

Model Objectives

A finite-difference model of ground-water flow in the Oakes aquifer was developed by the North Dakota State Water Commission in 1981 (R.B. Shaver, written commun., 1986). The model was developed for use as a management tool to allocate ground water primarily for irrigation. A U.S. Geological Survey two-dimensional finite-difference model (Trescott, Pinder, and Larson, 1976) was utilized. Various combinations of recharge and evapotranspiration rates produced very similar water-table configurations during steady-state calibration. Steady state simulations were insensitive to changes in hydraulic conductivity.

The model was calibrated against water levels measured by the U.S. Bureau of Reclamation from 1967 to 1981. Potential ground-water evapotranspiration was computed externally from the model by subtracting monthly precipitation from monthly potential evapotranspiration calculated by a modified Jensen-Haise method. An assumption of this approach is that most summer precipitation events do not contribute to ground-water recharge. Minor adjustments to the above monthly ground-water evapotranspiration calculations were made in the model during calibration to account for occasional summer recharge events. The average annual potential ground-water evapotranspiration calculated for the calibration period was 13 inches. Potential ground-water evapotranspiration was 100 percent of the maximum specified rate at land surface and was assumed to decrease linearly to zero at a depth of 8 feet below land surface.

Recharge was calculated within the model as the product of an assumed specific yield and the amount of water required to replicate observed change in storage. The average annual recharge rate calculated for the calibration period was 3 inches.

Various combinations of recharge, evapotranspiration, and specific yield produced equal water-level fluctuations. The model could not be utilized to calculate annual recharge and evapotranspiration rates because of this nonuniqueness. Both recharge and evapotranspiration must be determined externally from the model. As a result the model proved inadequate as a long-term predictive management tool.

A two-dimensional finite-difference model of the Oakes aquifer was found to be useful in approximating short-term response of the water table to selected intensive development scenarios. An important objective of this investigation was to estimate the effects on water levels in the aquifer of a continuous withdrawal of 100 cubic feet per second for 60 days. Available data indicate that the best potential for the above withdrawal scenario occurs within the channel-fill deposits that occupy the outwash channel along the eastern margin of the study area near sec. 13, T. 129 N., R. 59 W. This area of the Oakes aquifer was selected based on the following criteria:

(1) The channel-fill deposits have the largest transmissivity in comparison to other depositional facies of the Oakes aquifer. Individual well yields in excess of 2,000 gallons per minute are possible.

(2) The width of the outwash channel is at a maximum in this area. Therefore, the amount of water in storage is greater in this area as compared to other areas of the outwash channel.

(3) Thick overlying stream channel silt and clay confining beds are thin or absent, which is conducive to the development of surface recharge facilities (pits, ponds).

(4) Chemical analyses of water samples collected from the channel-fill deposits in this area pose no limitations for irrigation use.

Model Description

The finite-difference ground-water-flow model developed by the U.S. Geological Survey was utilized in this study (McDonald and Harbaugh, 1984). The model determines the approximate solution, in two dimensions, to the following partial differential equation for ground-water flow:

$$\frac{\partial}{\partial x}\left(kxx\,\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(kyy\,\frac{\partial h}{\partial y}\right)-W = Sy\,\frac{\partial h}{\partial t} \qquad (1)$$

where,

x and y are cartesian coordinates aligned along the major axes of hydraulic conductivity Txx, Tyy;

h is the potentiometric head (L);

W is a volumetric flux per unit volume and represents sources or sinks of water or both (t^{-1});

Sy is the specific yield of the porous material; and

t is time (t).

Ground-water flow within the aquifer is simulated using a block-centered finite-difference approach. The continuous system described by equation 1 is replaced by a finite set of discrete points in space and time, and the partial derivatives are approximated by differences between functional values at these points. The process leads to systems of simultaneous non-linear algebraic difference equations. The solutions to the systems of simultaneous equations yield values of head at specific points and time. The finite-difference equations can be solved using either the Strongly Implicit Procedure or Slice-Successive Overrelaxation (McDonald and Harbaugh, 1984). The Strongly Implicit Procedure was selected for this investigation.

Model Development

Boundary Conditions

The Oakes aquifer was discretized into 6,592 blocks (103 rows by 64 columns; pl. 8). The grid is variably spaced and the block dimensions range from 500 by 500 feet to 1,000 by 1,000 feet. Input for the steady-state simulation consisted of areally nonuniform and uniform parameters. For the areally nonuniform parameters, the average value within each block was assigned to that block. Nonuniform parameters were:

(1) Starting head,

(2) altitude of base of aquifer,

(3) hydraulic conductivity, and

(4) land-surface altitude.

The starting head array consists of water levels measured during May 1984 in 212 U.S. Bureau of Reclamation and North Dakota State Water Commission observation wells completed in the Oakes aquifer (pl. 9). The array for the altitude of the base of the aquifer was determined by subtracting aquifer thickness from land-surface altitude. The hydraulic conductivity array was developed from plate 7. The generalized land-surface altitude map (pl. 2) was used to develop the land-surface altitude array.

Areally uniform parameters were:

(1) recharge rate

(2) evapotranspiration rate, and

(3) evapotranspiration extinction depth.

Based on the finite-difference model of the Oakes aquifer developed by the North Dakota State Water Commission in 1987, an annual recharge rate of 3 inches and an annual ground-water evapotranspiration rate of 13 inches, with an extinction depth of 8 feet, were selected for the steady-state simulation.

The model simulates evapotranspiration by a simple linear decay function. The evapotranspiration rate is 100 percent of the maximum specified rate at land surface and decreases linearly to zero at a specified evapotranspiration extinction depth.

The eastern margin of the aquifer was treated as a no-flow boundary (pl. 8). The no-flow boundary appears to be a valid assumption because the moraine consists of small-transmissivity deposits. The northern and southern boundaries of the model also are treated as no-flow boundaries. The Oakes aquifer extends beyond the northern and southern boundaries of the model. Under steady-state conditions, ground-water flow is, for the most part, parallel to the northern and southern boundaries of the model and, as a result, the no-flow boundary assumption appears to be valid. The northern and southern no-flow boundaries are located far enough from projected stress areas to avoid image-well effects on the drawdown distribution. The James River comprises most of the western boundary of the model and was treated as a constant head boundary.

Steady-State Simulation

A volumetric water budget for the steady-state simulation is shown in table 6. Ground-water discharge is primarily from evapotranspiration and discharge to the James River is minor.

Table 6. -- Volumetric water budget for the Oakes aquifer steady-state computer simulation

Volumetric budget for entire model at end of time step 1 in stress period 1

Cumulative volumes	Cubic feet	Rates for this time step	Cubic feet per day
IN:		IN:	
Storage =	0.00000E+00	Storage =	0.00000E+00
Constant head =	4,380.7	Constant head =	4,380.7
Recharge =	.23528E+07	Recharge =	.23528E+07
Evapotranspiration =	.00000E+00	Evapotranspiration =	.00000E+00
Total IN =	.23572E+07	Total IN =	.23572E+07
OUT:		OUT:	
Storage =	0.00000E+00	Storage =	0.00000E+00
Constant head =	7,655.3	Constant head =	7,655.3
Recharge =	.00000E+00	Recharge =	.00000E+00
Evapotranspiration =	.23509E+07	Evapotranspiration =	.23509E+07
Total OUT =	.23586E+07	Total OUT =	.23586E+07
IN - OUT =	-1,346.0	IN - OUT =	-1,346.0
Percent discrepancy =	-.06	Percent discrepancy =	-.06

Water levels from the steady-state simulation (pl. 10) were compared to water levels measured during May 1984 (pl. 9) in 212 U.S. Bureau of Reclamation and North Dakota State Water Commission observation wells completed in the Oakes aquifer. The average absolute difference between simulated and measured water levels in the 212 wells is 2.2 feet. In the northern and north-central parts of the model area, simulated water levels are higher than measured water levels. The U.S. Bureau of Reclamation installed a pilot drain adjacent to the northern boundary of the model area in 1969. In 1983, the U.S. Bureau of Reclamation began construction of a drain network in the central part of the study area. Since the mid-1970's, ground-water withdrawals for irrigation in the north-central part of the model area have increased significantly. The area of influence of the drains and most irrigation development is in the north-central part of the model area. The best potential for large-scale ground-water withdrawals and artificial recharge is in the southeast part of the aquifer within the outwash channel. This area of the aquifer is outside the area of influence of the drains and irrigation development. As a result, ground-water discharge from the drains and irrigation development was ignored.

In the southeastern part of the model area, simulated water levels also were larger than actual measured water levels. Numerous topographic depressions occur in this part of the model area. The depressions are poorly approximated by the land-surface altitude array and grid size.

The steady-state model adequately approximates the geometry and hydraulic conductivity of the outwash channel near sec. 13, T. 129 N., R. 59 W. Therefore, the model can be used as a short-term (one year) predictive tool in this area of the Oakes aquifer. For these predictive simulations, long-term average recharge and evapotranspiration rates are not required.

Transient Simulation

The transient simulation was divided into two stress periods. The length of the first stress period was 60 days. Ground-water withdrawal from pumping was simulated using 22 wells located roughly parallel to the axis of the outwash channel near sec. 13, T. 129 N., R. 59 W. Each well was pumped continuously for 60 days at a rate of 2,040 gallons per minute. Recharge during the 60-day stress period was set at zero, and the evapotranspiration rate was set at 13 inches. Specific yield was set at 0.20. The location of the pumping wells and the drawdown distribution after 60 days of pumping are shown in figure 36. The maximum drawdown near the well field is about 37 feet. The cone of depression is asymmetrical, and the long axis roughly parallels the axis of the outwash channel.

The length of the second stress period was 245 days. The second stress period simulates aquifer response during the fall and winter. Recharge and evapotranspiration are negligible during the fall and winter and as a result, both parameters are set to zero. Ground-water withdrawal from the well field was also set to zero. The purpose of the second stress period was to estimate the maximum residual drawdown distribution from a single withdrawal period with no natural or artificial recharge. The residual drawdown at the end of the 245-day stress (recovery) period is shown in figure 37. The maximum residual drawdown near the well field is about 9 feet. The cone of depression remains asymmetrical, and the long axis roughly parallels the axis of the outwash channel.

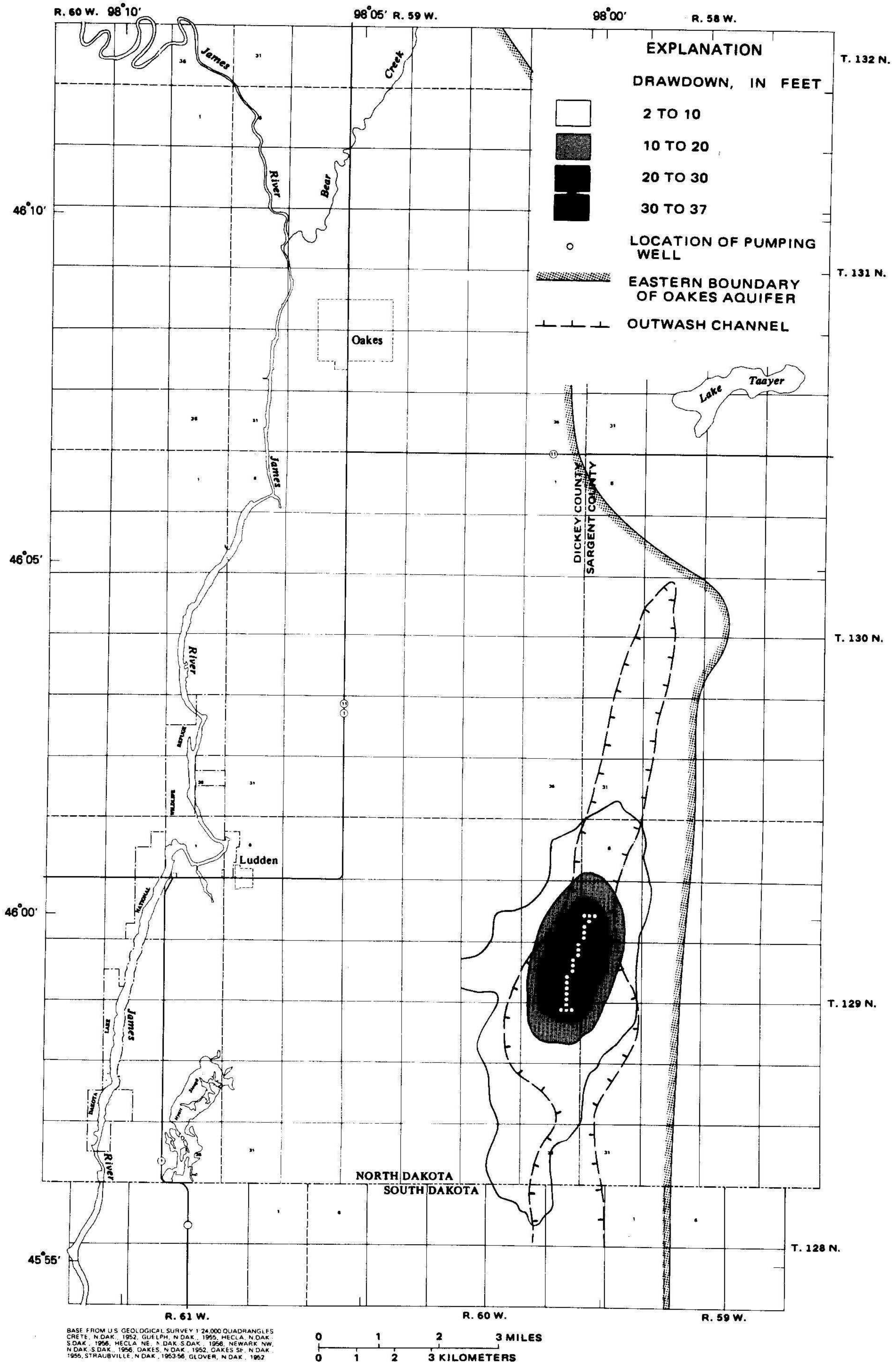
The channel-fill deposits are buried by a sequence of fluvial and lacustrine clayey silts and silty clays north and south of the well field. The clayey silt and silty clay sequence was omitted in the two-dimensional model, and the channel-fill deposits were modeled as a continuous section of sand and gravel with a specific yield of 0.20 over their entire length in the study area. Therefore, the drawdown distributions in figures 36 and 37 are approximate.

The saturated thickness of the channel fill near sec. 13, T. 129 N., R. 59 W. is about 120 feet. The maximum drawdown of 37 feet at the end of the 60-day pumping period is about 31 percent of the total available head in the stress area. Based on the results of the model study, the channel-fill deposits near sec. 13, T. 129 N., R. 59 W. can supply a continuous withdrawal rate of 100 cubic feet per second for 60 days.

WATER QUALITY IN THE OAKES AQUIFER

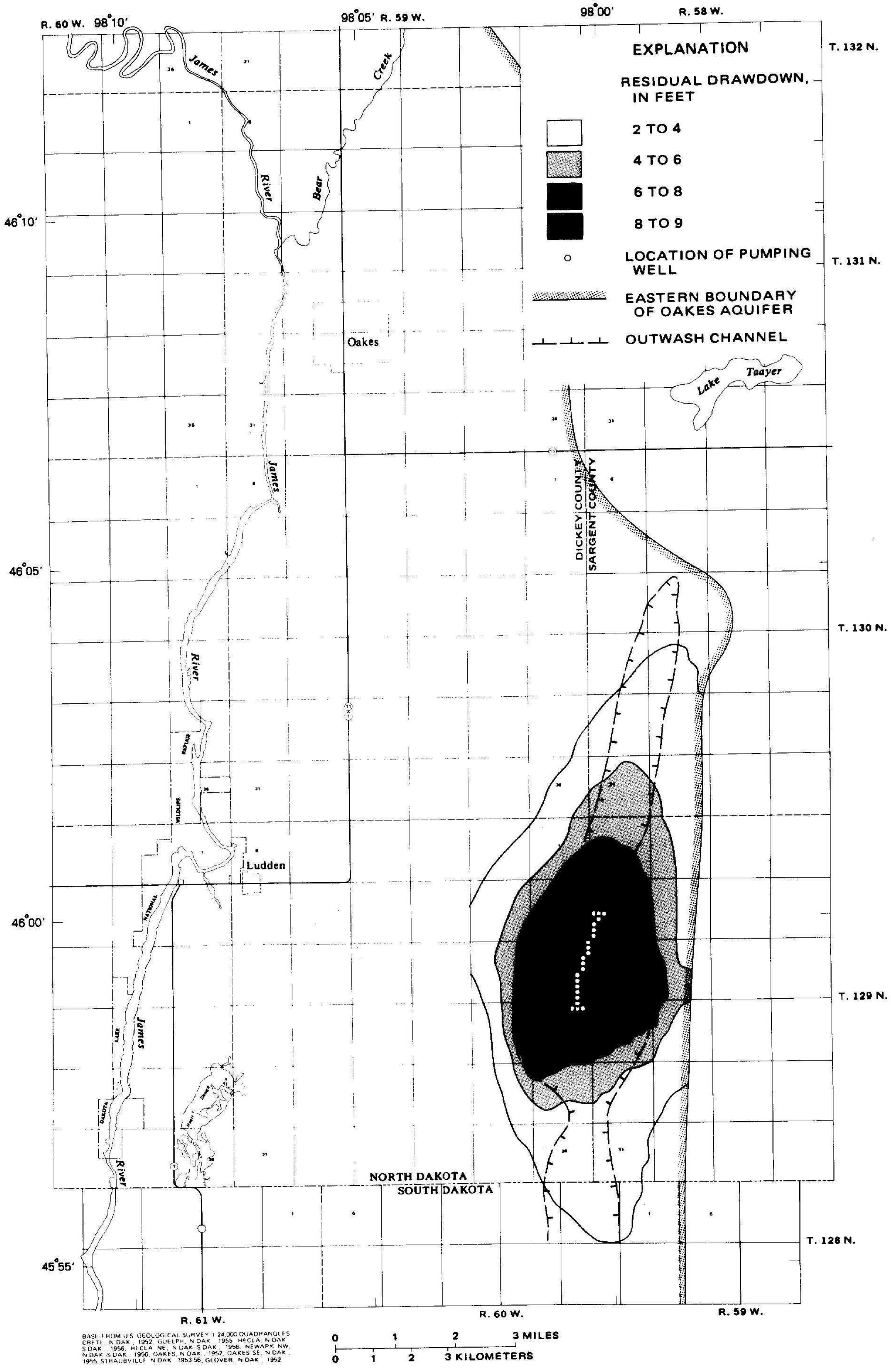
Conceptual Model

Rozkowski (1967), Freeze (1969), Charron (1969), Vandenberg and Lennox (1960), Cherry (1972), Grisak and others (1976) Davison and Vonhof (1978) Wallick (1981), Reardon and others (1980), and Hendry (1985) have investigated the origin and distribution of hydrochemical facies in glaciated terrains in the Interior Plains of North America. These investigatiors accounted for changes in the chemical composition of ground water with increasing depth or distance along a flow path by the following:



BASE FROM U.S. GEOLOGICAL SURVEY 1:24,000 QUADRANGLES CRETE, N.DAK., 1952, GUELPH, N.DAK., 1955, HECLA, N.DAK.-S.DAK., 1956, HECLA NE, N.DAK.-S.DAK., 1956, NEWARK NW, N.DAK.-S.DAK., 1956, OAKES, N.DAK., 1952, OAKES SE, N.DAK., 1955, STRAUBVILLE, N.DAK., 1953-56, GLOVER, N.DAK., 1952

Figure 36.—Computer-simulated drawdown distribution in the southeast part of the Oakes aquifer after pumping 60 days at a rate of 2,040 gallons per minute per well.



BASE FROM U.S. GEOLOGICAL SURVEY 1:24,000 QUADRANGLES CRETE, N.DAK., 1952, GUELPH, N.DAK., 1955, HECLA, N.DAK.-S.DAK., 1956, HECLA NE, N.DAK.-S.DAK., 1956, NEWARK NW, N.DAK.-S.DAK., 1956, OAKES, N.DAK., 1952, OAKES SE, N.DAK., 1955, STRAUBVILLE, N.DAK., 1953-56, GLOVER, N.DAK., 1952

Figure 37.—Computer-simulated residual drawdown in the southeast part of the Oakes aquifer after 245 days of recovery.

1. Dissolution and precipitation of calcite ($CaCO_3$) and dolomite ($Ca,Mg(CO_3)_2$) affecting concentrations of Ca^{2+}, Mg^{2+}, and HCO_3^- .

2. Dissolution and precipitation of gypsum ($CaSO_4 \cdot 2H_2O$) affecting concentrations of Ca^{2+} and SO_4^{2-}.

3. Cation exchange on montmorillonite clays effecting concentrations of Ca^{2+}, Mg^{2+}, and Na^+.

4. Oxidation of pyrite (FeS_2), increasing the concentration of SO_4^{2-}.

5. Oxidation of organic sulfur increasing the concentration of SO_4^{2-}.

6. Sulfate reduction decreasing the concentration of SO_4^{2-} and in the presence of carbonate minerals, increasing concentrations of Ca^{2+}, Mg^{2+}, and HCO_3^-.

7. Dissolution of halite (NaCl) increasing concentrations of Na^+ and Cl^-.

8. Chemical diffusion or mechanical dispersion of Cl^- upward from deeper bedrock aquifers.

Moran and others (1978), Groenwold and others (1983), investigated the chemical evolution of ground water at selected sites in western North Dakota. These studies demonstrated that the chemical composition of ground water in recharge areas is largely determined by geochemical processes that occur in the unsaturated zone during infiltration. These geochemical processes and the movement of major solutes are shown schematically in figure 38, and are considered applicable to local upland recharge areas in the Oakes aquifer.

Sampling and Analytical Methods

Information on the quality of ground water in the Oakes aquifer comes from a variety of sources. The U.S. Bureau of Reclamation has been collecting information on the major-element composition of ground water near Oakes since 1974. Prior to 1986, the U.S. Bureau of Reclamation used the following procedure to sample the Oakes wells:

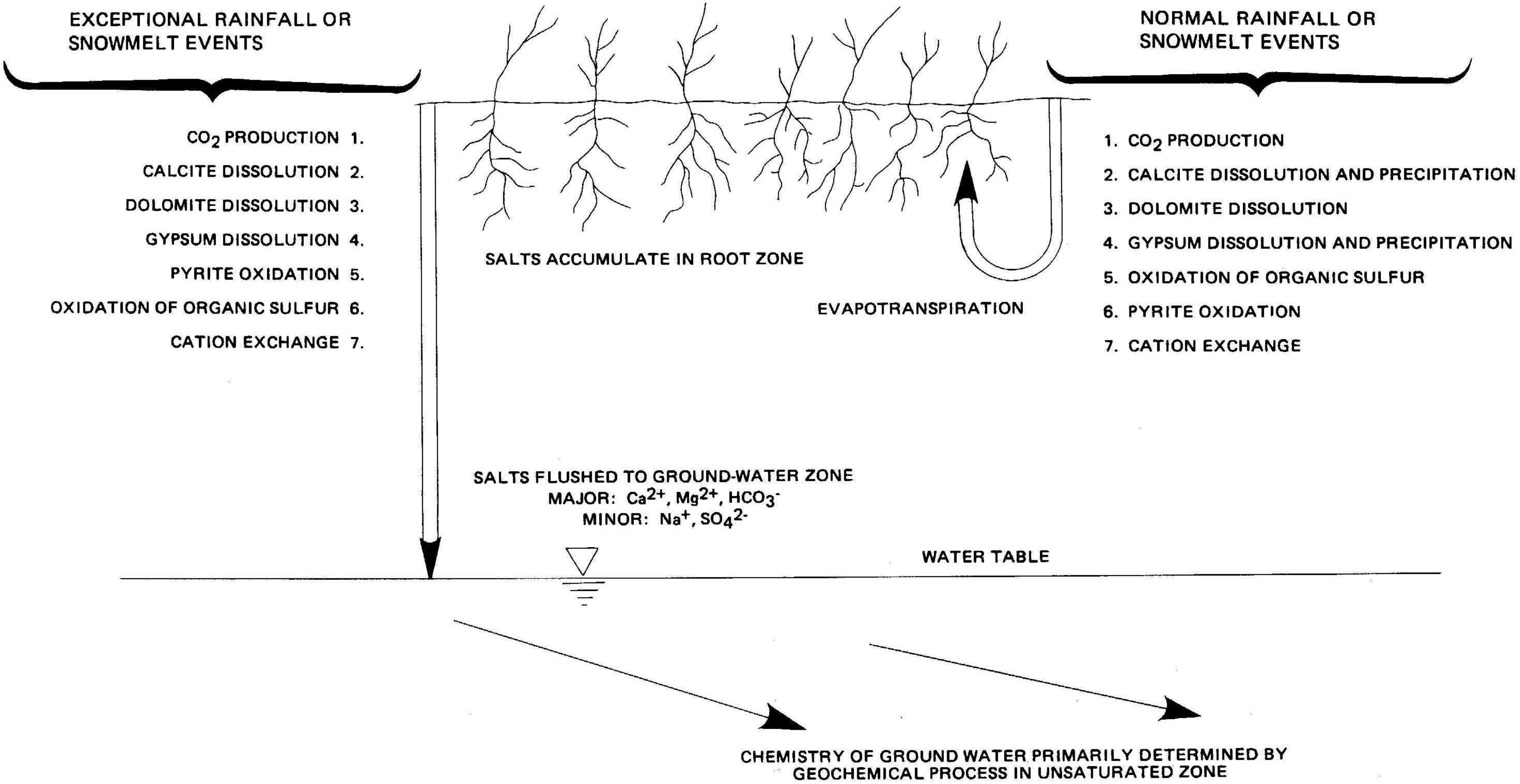


Figure 38.—Geochemical processes and movement of major solutes in the unsaturated zone. (Modifed from Moran and others, 1978).

1. The water level in the well was measured using a steel tape and recorded.

2. Standing water in the well casing was removed by bailing with a polyvinyl-chloride bailer until 2.5 times the volume of standing water had been removed.

3. The well then was allowed to recover for about 24 hours.

4. Prior to sampling, the water level in the well was remeasured. If the water level corresponded to the prebailing water level, sampling proceeded; if not, the well was allowed to recover another 24 hours prior to sampling. If sampling could not be completed within 4 days of original bailing, steps 2 through 4 were repeated.

5. Sampling was accomplished using a clean polyvinyl-chloride bailer. Bailer and sample containers were flushed with water from the first bailer volume. Subsequent bailer volumes were used to fill all requisite sample containers, usually a single 2-gallon container, as full as possible. Air temperature was measured and recorded after the final bailing, and water temperature of the final bailer volume also was recorded.

6. Samples were returned to the Oakes field office within 4 hours of sampling. In the field office, sample pH and specific conductance were measured. Then samples were filtered as necessary and split into appropriate sample bottles for subsequent analysis. Samples for cation analysis were preserved with 2 mL nitric acid per 250 mL of sample. Remaining samples were refrigerated until analysis.

7. Samples were analyzed by the U.S. Bureau of Reclamation laboratory in Bismarck using procedures approved by the U.S. Environmental Protection Agency. Laboratory quality assurance was provided through the North Dakota State Department of Health.

Since 1986, the U.S. Bureau of Reclamation has been sampling using procedures revised as follows:

1. The initial water level in the well is measured to the nearest 0.01 foot using a steel tape. If a second measurement differs from the first by more than 0.01

foot, the process is repeated until consistent measurements are achieved.

2. Standing water in the well casing is removed using a polyvinyl-chloride bailer. Initially, three casing volumes of water are removed from the well. If sample conductivity and pH have not stabilized, the process is repeated. No more than 10 casing volumes are removed from a well prior to sampling.
3. The well is allowed to recover overnight or longer, if necessary. If recovery time exceeds 4 days, the process is repeated from the beginning.
4. Downhole dissolved-oxygen concentrations and temperature measurements are determined using a Yellow Springs Instruments Model 57A[1/] dissolved-oxygen meter. Air temperature and barometric pressure also are recorded.
5. The reestablished water level in the well is measured as in step 1.
6. A clean polyvinyl-chloride bailer is used to sample the well. The bailer and all sample bottles are flushed with the first bailer volume. Bottles are filled as full as possible, and samples are stored in coolers until processing.
7. Samples are processed in the U.S. Bureau of Reclamation Oakes field office. Sample pH and specific conductance are determined for the raw sample. The sample then is filtered as necessary, split into appropriate sample bottles, and refrigerated until analysis.
8. Samples are analyzed by the U.S. Bureau of Reclamation laboratory in Bismarck using procedures approved by the U.S. Environmental Protection Agency. Quality assurance is provided through the U.S. Geological Survey and the North Dakota State Department of Health.

[1/] The use of trade names in this report is for identification purposes only and does not constitute endorsement by the North Dakota State Water Commission, the U.S. Geological Survey, or the U.S. Bureau of Reclamation.

The North Dakota State Water Commission has sampled some wells in the Oakes aquifer on an intermittent basis to evaluate management practices for conservation of the resource. Sampling prior to 1985 was according to the following procedures:

1. Water levels were measured according to the procedures of Garber and Koopman (1969).

2. Three well volumes of standing water in the well column were evacuated using an air-lift pump.

3. Samples subsequently were collected using the air-lift pump.

4. Temperatures and specific conductance of the air-lift sample were measured in the field.

5. Prior to 1977, two samples were collected from each well. A 250-mL sample was filtered and acidified with nitric acid immediately upon collection. Analysis of iron and manganese was made on this sample. All other cation and anion concentrations were determined on a raw 2,000-mL sample. Beginning in 1977, three samples were collected from each well: a 250-mL raw sample, a 500-mL filtered sample, and a 500-mL filtered sample that is acidified with 2 mL nitric acid. A 0.45-micron filter was used to remove suspended matter. Concentrations of bicarbonate, carbonate, and chloride and laboratory determinations of pH and specific conductance were measured on the 250-mL raw sample. Concentrations of sulfate, fluoride, boron, nitrate, silica, and total dissolved solids were determined on the 500-mL filtered sample. Concentrations of calcium, magnesium, sodium, potassium, iron, and manganese were determined on the filtered and acidified 500-mL sample. All samples were stored in plastic bottles and transported to the North Dakota State Water Commission laboratory in Bismarck for analysis.

6. Prior to 1981, concentrations of the major cations were determined using a Beckman Model DU-2 spectrophotometer. Beginning in 1981, concentrations of the major cations were determined using a Perkin-Elmer Model 4000 atomic absorption spectrophotometer. Concentrations of bicarbonate, carbonate, and chloride were determined using a Fisher Model 741 titralyzer; and the concentration of sulfate was determined by gravimetric methods. The North Dakota State Water Commission laboratory participates in quality-

assurance programs with the U.S. Geological Survey.

Since 1985, the North Dakota State Water Commission has developed wells using an air-lift pump, allowed at least 24 hours for the well to recover, and then sampled the well using a submersible pump or a polyvinyl-chloride point-source bailer. Specific conductance, pH, and temperature have been measured at land surface on water samples collected.

The U.S. Geological Survey also has sampled some wells in the Oakes aquifer on an intermittent basis. Procedures employed for sampling the ground water are detailed by Claassen (1982) and for processing and handling samples by Kister and Garrett (1982).

Preliminary analysis of available hydrogeologic data in the Oakes aquifer study area indicated that maximum individual well yields were associated with the outwash channel located along the eastern margin of the Oakes aquifer. Therefore, a test-drilling program was initiated to further define the outwash channel geometry and water quality. During the fall of 1985, 48 observation wells were completed in and near the outwash channel. Samples from each well were collected using a submersible pump. Field parameters (pH, dissolved oxygen, specific conductance, water temperature) were measured in an unsealed sampling chamber connected directly to the discharge line on the submersible pump. The potential for sampling bias was considered significant and unacceptable for mineral speciation analysis because a submersible pump was used, field parameters where measured in an unsealed sampling chamber, and field alkalinity was not measured. Therefore, in the spring of 1989, 43 of the 48 observation wells completed in and near the outwash channel were re-sampled using a gas-squeeze bladder pump. Field parameters (pH, dissolved oxygen, specific conductance, water temperature) were measured in a sealed sampling chamber connected directly to the discharge line of the gas-squeeze pump. In addition, field alkalinity was measured by sulfuric acid titration to an end point pH of 4.50. Results of the 43 water chemistry analyses are summarized in Table 7.

Table 7. -- Water chemistry analyses from 43 observation wells completed primarily in and near the outwash channel of the Oakes aquifer

Location	Well Depth (ft)	Date Sampled	|<----(milligrams per liter)															---->|					
			SiO_2	Fe	Mn	Ca	Mg	Na	K	HCO_3	CO_3	SO_4	Cl	F	NO_3	B	TDS	Hardness as $CaCO_3$	NCH	% Na	SAR	Spec Cond (umho)	Temp (°C)	pH
130-058-21BBA	62	06-08-89	26	0.35	0.71	110	34	8	6	425	0	89	2	0.2	1	0.1	487	410	66	4	0.2	722	9.8	7.2
129-058-18AAA2	32	05-16-89	30	0.62	0.5	89	25	8	3	347	0	54	7	0.2	1	0.06	389	330	41	5	0.2	617	8.6	7.2
129-058-30CDD2	45	05-16-89	31	0.83	0.48	58	15	12	3	247	0	17	4	0.2	1	0.12	264	210	4	11	0.4	418	8.3	7.7
129-059-24DDD2	30	05-17-89	31	0.95	0.69	77	19	6	2	332	0	19	3	0.2	1	0.04	324	270	0	5	0.2	500	8.6	7.3
129-058-30CCD2	47	05-17-89	30	0.61	0.48	57	15	20	4	281	0	20	4	0.2	1	0.13	290	200	0	17	0.6	443	7.2	7.3
129-059-12AAB3	10	05-17-89	25	0.01	0.57	64	29	21	3	287	0	40	35	0.7	14	0.05	373	280	44	14	0.5	503	12.3	7.6
129-059-12AAB2	45	06-17-89	31	0.22	0.54	71	18	12	4	330	0	10	8	0.2	0.1	0.08	318	250	0	9	0.3	432	9.4	7.3
129-058-08BBB2	40	05-16-89	28	0.39	0.38	70	22	8	2	281	0	49	4	0.2	1	0.05	323	270	35	6	0.2	497	8.8	7.2
129-058-07BBA1	143	06-13-89	29	0.73	0.32	69	18	15	5	324	0	7	11	0.2	1	0.09	316	250	0	11	0.4	519	9.0	7.2
129-058-06CDD1	97	06-13-89	28	0.8	0.43	75	21	32	8	359	0	27	22	0.2	1	0.21	392	270	0	20	0.8	6	8.5	7.2
130-058-20BAA	92	06-07-89	29	0.95	1.5	200	53	50	10	380	0	270	180	0.1	0.3	0.18	982	720	410	13	0.8	1498	9.0	7.1
129-059-36ABA2	135	06-14-89	27	0.53	0.24	56	16	210	13	486	0	53	160	0.3	1	0.93	777	210	0	67	6.3	1162	7.5	7.4
129-058-06CDD2	40	06-13-89	29	1.7	0.45	73	19	14	6	340	0	19	4	0.2	1	0.14	334	260	0	10	0.4	544	8.5	7.2
129-059-13DDC1	110	06-13-89	28	1.3	0.42	94	26	28	8	440	0	31	13	0.2	1	0.14	448	340	0	15	0.7	698	9.0	7.1
129-059-13CDD1	97	06-13-89	28	0.63	0.3	75	22	20	6	366	0	16	10	0.2	1	0.12	360	280	0	13	0.5	568	8.5	7.2
129-059-14BBB3	39	06-13-89	27	0.4	0.59	71	21	58	9	379	0	81	16	0.2	1	0:16	472	260	0	31	1.6	706	8.7	7.2
129-059-12CCC2	55	06-13-89	28	0.21	0.72	76	19	28	6	355	0	33	8	0.2	1	0.12	375	270	0	18	0.7	589	8.5	7.2
129-058-07CCC1	110	06-14-89	29	0.64	0.33	71	21	15	5	337	0	11	9	0.2	1	0.09	329	260	0	11	0.4	426	8.5	7.4
129-058-18CCD1	87	06-14-89	29	0.44	0.45	63	16	32	8	357	0	14	4	0.3	1	0.17	344	220	0	23	0.9	464	8.2	7.4
129-058-19AAA2	65	06-14-89	30	0.3	0.51	54	13	10	6	241	0	14	3	0.2	0.2	0.06	250	190	0	10	0.3	366	8.0	7.6
129-058-20CCC2	38	06-14-89	27	0.01	0.23	51	15	3	1	221	0	16	2	0.2	1	0.02	225	190	8	3	0.1	333	8.2	7.5
130-058-31ABA2	131	06-09-89	27	0.21	0.42	49	13	85	9	324	0	28	52	0.2	1	0.2	425	180	0	50	2.8	595		7.4
130-058-30CDD1	62	06-09-89	28	0.05	0.68	63	18	6	3	273	0	16	4	0.2	0	0.04	273	230	8	5	0.2	361	9.0	7.4
130-058-18DCD1	78	06-08-89	29	0.28	0.66	74	19	20	6	383	0	10	7	0.2	3	0.1	359	260	0	14	0.5	525	9.4	7.3
130-058-29CDC2	55	06-08-89	28	0.06	0.44	71	21	4	3	267	0	49	8	0.1	1	0.01	317	260	45	3	0.1	463	8.7	7.3
130-058-29CDC3	13	06-08-89	21	0.01	0.01	63	16	3		195	0	29	11	0.2	11	0.02	250	220	63	2	0.1	363	8.0	7.5
130-058-31ABA3	50	06-09-89	29	1.6	0.27	58	18	4	3	195	0	49	13	0.6	0.2	0.03	273	220	59	4	0.1	359	9.7	7.4
130-058-29CDD2	58	06-08-89	28	0.11	0.43	83	24	5	4	331	0	60	13	0.2	1		381	310	34	3	0.1	541	8.9	7.3
130-058-31BBB1	25	06-09-89	29	0.95	0.76	62	13	5	2	257	0	8	3	0.2	1	0.02	252	210	0	5	0.1	393	8.1	7.3
130-059-15AAA2	43	06-07-89	29	2.8	0.49	120	29	54	8	594	0	9	22	0.2	1	0.14	569	420	0	21	1.1	944	9.4	7.4
130-058-20BBA2	40	06-07-89	30	0.29	0.65	82	22	20	6	391	0	39	6	0.1	1	0.09	400	300	0	13	0.5	635	9.4	7.3
130-058-29BAA	90	06-08-89	27	0.34	0.46	82	21	36	9	391	0	79	4	0.2	1	0.12	453	290	0	21	0.9	645	8.3	7.3
130-058-20AAB	50	06-08-89	28	0.22	0.4	69	22	36	6	368	0	72	8	0.3	2	0.1	424	260	0	23	1.0	604	9.0	7.4
130-058-20CCC2	30	06-08-89	28	0.12	0.56	75	29	3	2	357	0	26	6	0.3	1	0.02	347	310	14	2	0.1	526	8.3	7.2
130-058-08CDD2	45	06-15-89	28	1.1	0.58	120	33	4	7	405	0	110	10	0.2	1	0.07	515	440	100	2	0.1	638	9.0	7.1
130-058-08CDC2	53	06-15-89	29	1.7	0.83	170	48	13	8	530	0	210	6	0.2	1	0.08	749	620	190	4	0.2	834	8.0	7.0
129-059-36ABA3	30	06-14-89	28	0.2	0.72	68	17	6	3	302	0	32	5	0.2	1	0.05	310	240	0	5	0.2	423	7.4	7.5
130-058-31CCC2	50	06-14-89	28	0.38	0.56	70	18	21	6	330	0	14	9	0.2	1	0.06	332	250	0	15	0.6	502	8.0	7.5
129-059-01BBB2	48	06-14-89	28	2.6	0.8	98	31	21	6	460	0	13	13	0.2	1	0.07	442	370	0	11	0.5	702	8.0	7.3
129-059-23AAA1	38	06-13-89	28	0.95	0.29	78	22	17	6	390	0	17	9	0.2	1	0.12	372	290	0	11	0.4	583	8.0	7.1
130-058-28BBB1	150	06-15-89	28	0.45	0.43	80	20	35	10	388	0	43	3	0.2	1	0.23	412	280	0	21	0.9	523	9.0	7.3
130-058-08DDD2	110	06-15-89	29	0.94	0.88	130	35	10	7	434	0	140	3	0.2	1	0.07	571	470	110	4	0.2	664	8.5	7.0
130-058-08DDD1	212	06-15-89	28	1.0	0.74	140	39	53	10	479	0	230	8	0.2	1	0.2	747	510	120	18	1.0	810	9.2	7.1

Mineralogy of the Oakes Aquifer

Geologic logs of test holes completed by the North Dakota State Water Commission in the Oakes aquifer study area were prepared by a site geologist. The site geologist examined the mineralogy of the sample returns using a hand lens and recorded the results on a geologic log of the test hole. Based on these geologic logs, the Oakes aquifer consists primarily of quartz and lesser amounts of carbonates, Canadian shield silicates, detrital lignite and detrital shale. Gypsum nodules occasionally were reported from test holes completed in closed, land-surface depressions.

Williams (1984) provided x-ray diffraction mineralogy for surficial clays, sands of the Oakes aquifer, and underlying silt and till in a land-surface depression in the north-central part of the Oakes aquifer study area. The data are summarized in table 8.

Huff and Wald (1989) provided x-ray diffraction mineralogy in the unsaturated and saturated zones of the Oakes aquifer at 131-059-29DDC (table 9). Throughout the sampled profile, quartz and tridymite comprise 47 to 88 percent of the minerals and carbonates comprise 5 to 36 percent of the minerals.

Chemical Character of Water in the Oakes Aquifer

The spatial distribution of dissolved solids in the Oakes aquifer is shown on plate 11. There are three conspicuous areas of the Oakes aquifer where dissolved solids concentrations are less than 300 mg/L. The first area is located in the east and north central part of the aquifer, the second area is located in the southwest part of the aquifer, and the third area is located in the southeast part of the aquifer. All three areas coincide with local, land-surface topographic uplands (pl. 2). The two uplands in the eastern part of the Oakes aquifer study area are associated with sand dunes (fig. 5). In all three areas, depth to water table below land surface generally is greater than 5 feet. The uplands represent net recharge areas where discharge from the saturated zone by evapotranspiration is minor. The unsaturated and saturated zones are well flushed generally on an annual basis during fall and spring recharge events. Ground-water flow paths and residence times are relatively short. These areas are characterized by a calcium-magnesium-bicarbonate hydrochemical facies with calcite and to a lesser extent dolomite dissolution being the major geochemical processes.

Table 8. -- Mineralogy of sediment samples from the Oakes aquifer study area as determined by X-ray diffraction

Location	Depth	Lithology	Mo	Mu/I	Ch	K	Q	P	Gy	Ca	D	S	Go
130-58-7CCC	10-46 in.	Sur. Cl.	X	X	X		X	X		X	X		
130-58-18AAA	20-36 in.	*Sur. Cl.					X		X	X			
130-58-18AAA	75-85 in.	*Sur. Cl.					X		X				
130-58-18AAA	110-120 in.	Sur. Cl.	X	X	X	X	X	X					
130-58-18ADD	50-110 in.	*Sur. Cl.					X						
130-58-18BCC	8-8.5 ft.	Sh. S.	X	X	X		X	X		X	X		
130-58-19ADD	15.5-16.5 ft.	Sand					X	X		X	X		
130-59-1CCC	41-45 ft.	Silt					X	X	X	X	X		
130-59-1CCC	56-60 ft.	Till	X	X	X	X	X	X		X	X	X	
130-59-1DDD	42-44 ft.	Nodule					X		X				
130-59-2CDD	51-55 ft.	Till	X	X	X	X	X	X		X	X	X	
130-59-2DDD	25-32 in.	Sur. Cl.					X	X		X			
130-59-12DCC	13.5-14 ft.	Sand					X	X		X	X		
130-59-12DCC	33.5-34 ft.	Sand					X	X		X	X		

KEY:
Mo = Montmorillonite
Mu/I = Muscovite/Illite
Ch = Chlorite
K = Kaolinite
Q = Quartz
P = Plagioclase
Gy = Gypsum
Ca = Calcite
D = Dolomite
S = Siderite
Go = Goethite
Sh. S. = Shaly Sand
Sur. Cl. = Surficial clay/silt
* = Samples were prepared by pipette, all others were powdered

Table 9. -- Mineralogy of sediment samples at 131-059-29DCD as determined by X-ray diffraction

Depth below land surface, in feet	PERCENT MINERAL ABUNDANCE										
	Quartz	Plagioclase feldspar	Potassium feldspar	Calcite	Dolomite	Pyrite	Amphiobole	Tridymite	Chlorite	Illite/ mica	Smectite
4-5	45	4	2	11	35	--	-- --	2	trace	trace	1
6-7	51	4	1	trace	--	--	-- --	37	trace	trace	7
7-8	56	4	2	trace	--	--	-- --	28	trace	1	9
10-11	80	6	3	2	2	trace	2	trace	1	1	2
14-15	58	5	3	3	3	--	1	4	3	2	3
17-18	73	7	5	2	2	--	-- --	7	trace	1	1
18-19	54	7	5	10	10	--	-- --	10	1	4	2
21-22	60	7	4	3	3	--	-- --	15	--	1	3

Regional ground-water flow in the Oakes aquifer generally is from east to west. Overall, dissolved solids concentrations gradually increase from east to west as flow path length and residence time increase. Although water quality in the Oakes aquifer is variable, dissolved solids concentrations generally are less than 500 mg/L and the calcium-magnesium-bicarbonate hydrochemical facies predominates (fig. 39). These areas of the aquifer pose no limitations for irrigation use.

Some areas in the Oakes aquifer are characterized by abrupt increases in dissolved solids concentrations (pl. 11). These areas coincide with land-surface topographic depressions (pl. 2) where the depth to water table below land surface generally is less than 5 feet. The land-surface depressions represent net discharge areas where discharge primarily is by evapotranspiration. Evapotranspiration exceeds precipitation during the summer causing mineral precipitation in the unsaturated zone and at land surface. Efflorescent crusts commonly develop at land surface in these areas during the summer. Probable mineral precipitates include calcite, gypsum, and other sodium and magnesium efflorescent salts such as mirabilite and epsomite (Keller, and others, 1986). During fall and spring recharge events, the previously precipitated minerals are leached at land surface and from the unsaturated zone downward to the water table. Because evapotranspiration is the primary discharge mechanism, the ground-water flow system is poorly flushed and becomes enriched in dissolved solids. In these areas, dissolved solids concentrations of up to about 50,000 mg/L occur and a sodium-magnesium sulfate hydrochemical facies predominates. Ground water associated with net discharge areas poses salinity, sodium, and boron hazards for irrigation use.

Chemical Character of Ground Water in the Outwash Channel

Hydrochemical Facies

The 43 ground-water samples collected in the spring of 1989 are plotted on a Piper trilinear diagram (fig. 40). Ground water associated with the outwash channel generally is a calcium-magnesium-bicarbonate type with dissolved solids ranging from 200 to 500 mg/L.

The outwash channel is located one to three miles west of a regional upland area (Oakes moraine) that forms the eastern boundary of the Oakes aquifer. Regional ground-water flow generally is from east to west from the Oakes moraine toward the James River. The outwash channel is in close proximity to

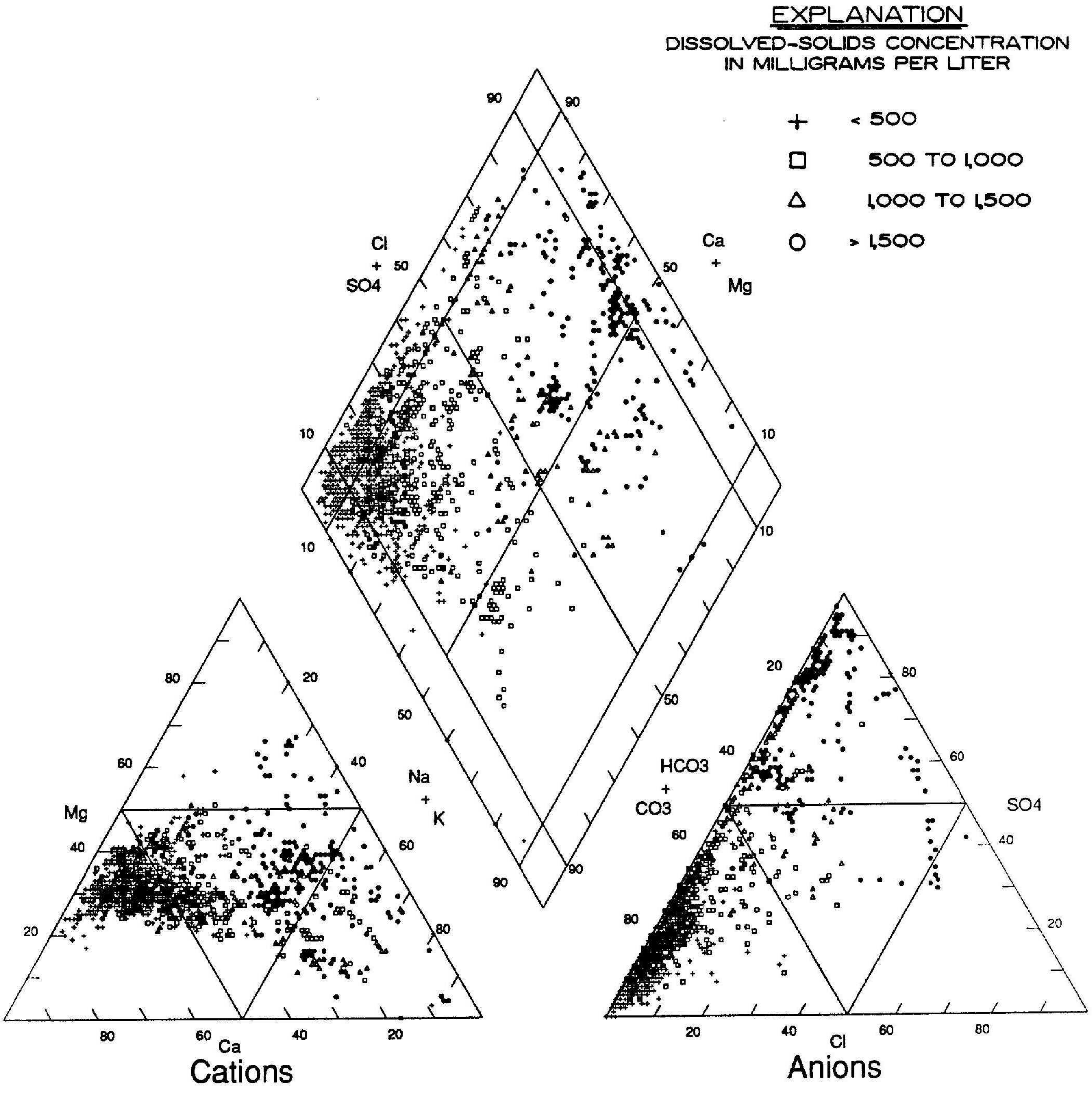


Figure 39.—Range in water quality in the Oakes aquifer.

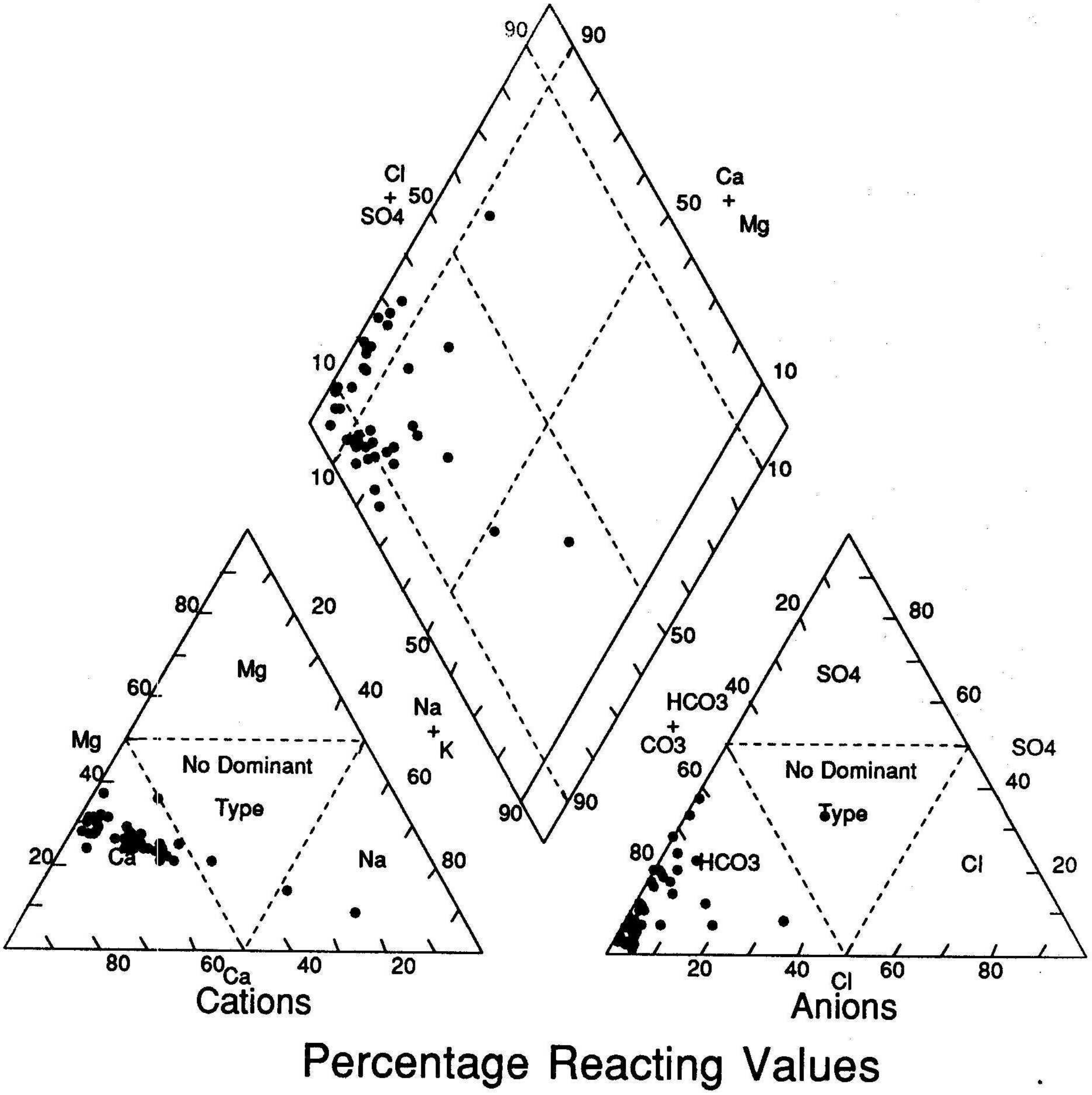


Figure 40.—Range in water quality in the outwash channel of the Oakes aquifer.

the Oakes moraine (short flow path length and residence time) and as a result a small dissolved solids, calcium-magnesium-bicarbonate hydrochemical facies predominates in this area of the aquifer.

Mineral Speciation Analysis

The equilibrium state between ground water and mineral phases of the aquifer matrix can be examined by use of saturation indices (SI),expressed as: SI mineral = log IAP/Ksp where IAP is the ion-activity product calculated from analytical data and Ksp is the solubility product, an equilibrium constant for ions in a saturated solution in contact with excess solid phases. A saturation index of 0.0 indicates that IAP and Ksp are equal and that thermo-dynamic equilibrium of the solution exists with the solid phase in question. A negative or positive index indicates undersaturation and oversaturation respectively. Saturation indices for calcite, dolomite, gypsum and quartz computed using WATEQF (Plummer and others, 1976) are shown in table 10. About 50 percent of the analyses with dissolved solids concentrations less than 600 mg/L are undersaturated with respect to calcite and about 50 percent of the analyses are oversaturated with respect to calcite. Some of the negative calcite saturation indices are $\leq 10^{-2}$. Based on the accuracy of field pH, alkalinity measurements, and mineral thermo-dynamic data, these indices may reflect saturation conditions. Langmuir (1971) assumed saturation indices within ± 0.1 units of zero are saturated with respect to the carbonate in question. Using this criterea, only 12 percent of the analyses with dissolved solids concentrations less than 600 mg/L are undersaturated with respect to calcite. This indicates that for the most part ground water has reached thermo-dynamic equilibrium with calcite and dissolution of calcite is not plausible in this area of the aquifer.

Applying the above assumption of Langmuir, 90 percent of all analyses are undersaturated with respect to dolomite. This indicates that for the most part ground water has not reached thermo-dynamic equilibrium with dolomite and dissolution of dolomite is plausible in this area of the aquifer.

All of the analyses are undersaturated with respect to gypsum. Comparison of the saturation indices of gypsum with those of calcite and dolomite indicate that dissolution of calcite and dolomite is more significant than dissolution of gypsum in and near the outwash channel. This is consistent with the limited geochemical data for the Oakes aquifer that

Table 10. -- Saturation indices for aquifer waters with respect to naturally occurring minerals in the Oakes aquifer

Location	TDS	Calcite	Dolomite	Gypsum	Quartz
130-058-21BBA	487	+0.172	-0.041	-1.492	+0.887
129-058-18AAA2	389	+0.017	-0.418	-1.740	+0.970
129-058-30CDD2	264	+0.235	-0.026	-2.338	+0.988
129-059-24DDD2	324	+0.032	-0.449	-2.214	+0.984
129-058-30CCD2	290	-0.167	-0.845	-2.279	+0.993
129-059-12AAB3	373	+0.238	+0.299	-2.001	+0.827
129-059-12AAB2	318	+0.107	-0.182	-2.538	+0.886
129-058-08BBB2	323	-0.145	-0.690	-1.847	+0.936
129-058-07BBA1	316	-0.081	-0.645	-2.707	+0.948
129-058-06CDD1	392	-0.092	-0.642	-2.093	+0.942
130-058-20BAA	982	+0.158	-0.139	-0.903	+0.950
129-059-36ABA2	777	+0.072	-0.323	-1.990	+0.994
129-058-06CDD2	334	-0.093	-0.677	-2.235	+0.957
129-059-13DDC1	448	-0.007	-0.468	-1.976	+0.933
129-059-13CDD1	360	-0.086	-0.612	-2.311	+0.941
129-059-14BBB3	472	-0.085	-0.596	-1.668	+0.922
129-059-12CCC2	375	-0.049	-0.606	-1.996	+0.941
129-058-07CCC1	329	+0.122	-0.192	-2.483	+0.956
129-058-18CCD1	344	+0.112	-0.285	-2.419	+0.961
129-058-19AAA2	250	+0.028	-0.478	-2.438	+0.979
129-058-20CCC2	225	-0.046	-0.536	-2.398	+0.930
130-058-31ABA2	425	-0.193	-1.050	-2.192	+1.076
130-058-30CDD1	273	+0.022	-0.398	-2.346	+0.932
130-058-18DCD1	359	+0.095	-0.292	-2.540	+0.941
130-058-29CDC2	317	-0.111	-0.649	-1.838	+0.938
130-058-29CDC3	250	-0.074	-0.658	-2.073	+0.824
130-058-31ABA3	273	-0.203	-0.794	-1.897	+0.936
130-058-29CDD2	381	+0.053	-0.327	-1.718	+0.935
130-058-31BBB1	252	-0.172	-0.939	-2.620	+0.963
130-058-20BBA2	400	+0.119	-0.220	-1.911	+0.956
130-058-29BAA	453	+0.105	-0.286	-1.619	+0.929
130-058-20AAB	424	+0.083	-0.222	-1.718	+0.933
130-058-20CCC2	347	-0.055	-0.432	-2.108	+0.945
130-058-08CDD2	515	+0.050	-0.350	-1.372	+0.933
130-058-08CDC2	749	+0.145	-0.162	-1.030	+0.967
129-059-36ABA3	310	+0.090	-0.347	-2.023	+0.960
130-058-31CCC2	332	+0.149	-0.207	-2.379	+0.950
129-059-01BBB2	442	+0.194	-0.028	-2.336	+0.950
129-059-23AAA1	372	-0.103	-0.672	-2.272	+0.950
130-058-28BBB1	412	+0.087	-0.321	-1.878	+0.933
130-058-08DDD2	571	-0.009	-0.483	-1.254	+0.958
130-058-08DDD1	747	+0.128	-0.176	-1.060	+0.931

indicates gypsum primarily is associated with closed land-surface depressions (discharge areas).

All of the analyses are oversaturated with respect to quartz suggesting that dissolution of quartz is not plausible in this area of the aquifer. Both quartz and tridymite are abundant minerals in the Oakes aquifer. Tridymite thermodynamic data is not included in WATEQF. Tridymite is a mineral associated with volcanic rocks that forms at higher temperatures than quartz. Tridymite is less stable (more soluble) than quartz and, therefore, tridymite may be an important source of dissolved silica in the Oakes aquifer.

Other sources of dissolved silica may be from chalcedony or amorphous silica, both of which are more soluble than quartz. Available geochemical data does not indicate the occurance of either of these minerals in the Oakes aquifer.

Irrigation Classification

The 43 samples from observation wells completed in and near the outwash channel are plotted on a U.S. Department of Agriculture (1954) irrigation classification diagram (fig. 41). Ground water associated with the outwash channel has a low sodium hazard and a medium to high salinity hazard. With proper management, the medium to high salinity hazard should not pose a problem on the light textured, sandy loam soils in the West Oakes irrigation development tract of the Garrison Diversion Unit.

Trace-Element Analysis

Trace element analyses from the 43 observation wells completed in and near the outwash channel are shown in table 11. Except for arsenic, all trace elements are below the recommended limits for drinking water (U.S. Environmental Protection Agency, 1986). Seven of the 43 analyses exceed the recommended limit (50 mg/L) for arsenic.

The maximum limits for iron (300 mg/L) and manganese (50 mg/L) are exceeded for most analyses. The standards for iron and manganese are based principally on staining and objectionable taste and not on health and irrigation considerations.

Boron is an essential plant nutrient. A small excess over the required amount is toxic to some plants. Except for one analysis (129-059-36ABA2), all boron concentrations are

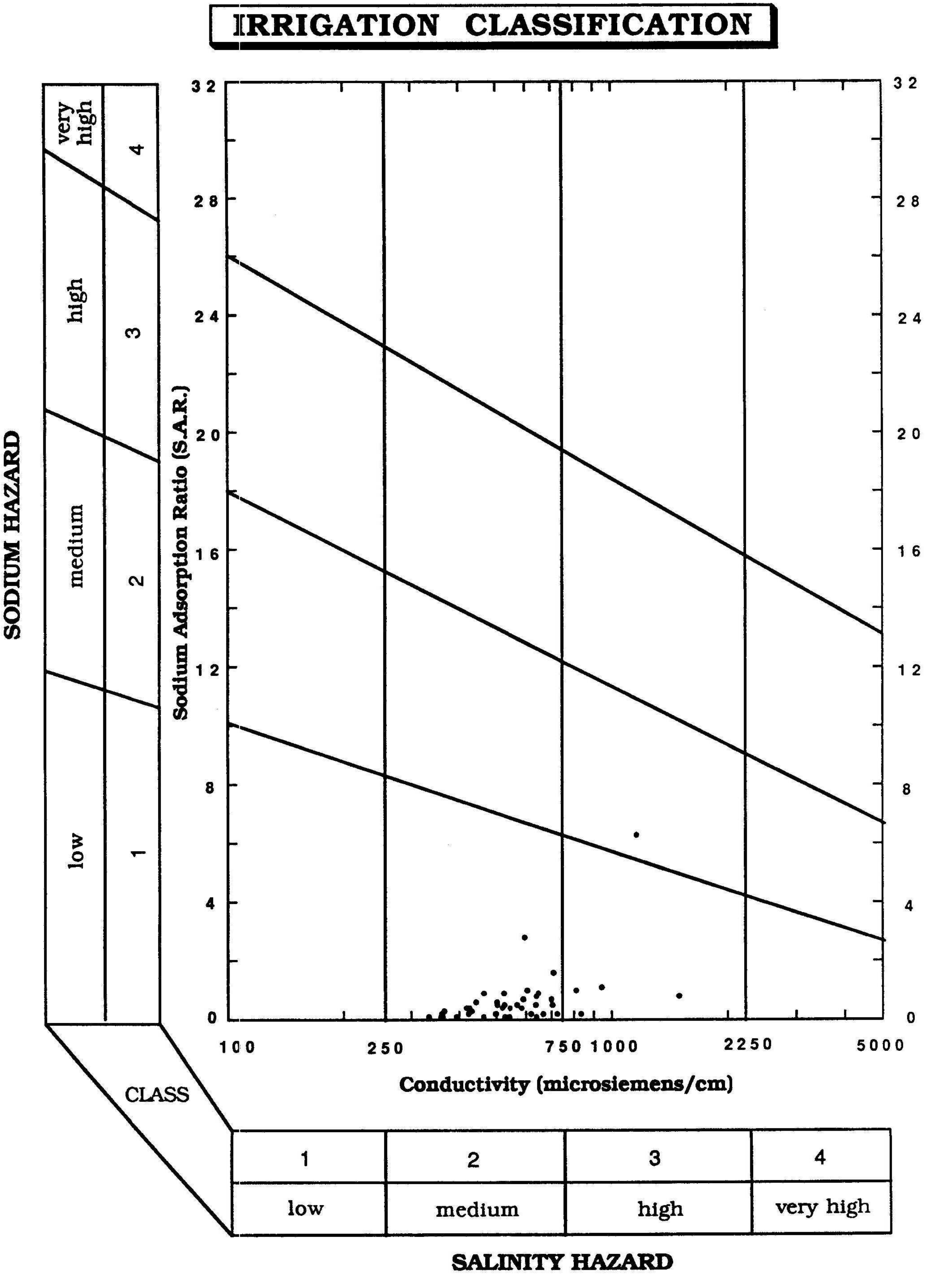


Figure 41.—Range of irrigation salinity hazard and sodium hazard of water in the outwash channel of the Oakes aquifer.

Table 11. -- Trace-element concentrations of ground water from 43 observation wells completed primarily in and near the outwash channel of the Oakes aquifer

(< indicates less than concentration shown)

Well Location	Date Sampled	Arsenic	Barium	Beryllium	Cadmium	Chromium	Cobalt	Copper	Iron	Lead	Manganese	Molybdenum	Nickel	Silver
		Micrograms per liter												
130-058-28BBB2	6/15/89	75	80	<0.5	<1	<5	<3	<10	540	<10	390	<10	<1	<1
129-058-07BBA	6/13/89	21	230	<0.5	<1	<5	<3	<10	880	<10	290	<10	<1	<1
130-058-08CDD2	6/15/89	27	58	<0.5	<1	<5	<3	<10	1200	<10	530	<10	<1	<1
129-059-36ABA3	6/14/89	20	230	<0.5	<1	<5	<3	<10	240	<10	650	<10	<1	<1
129-059-36ABA2	6/14/89	57	55	<0.5	<1	<5	<3	<10	630	<10	210	<10	<1	<1
129-058-06CDD2	6/13/89	38	150	<0.5	<1	<5	<3	<10	2100	<10	410	<10	<1	<1
129-058-07CCC	6/14/89	32	180	<0.5	<1	<5	<3	<10	790	<10	300	<10	<1	<1
129-058-18CCD1	6/14/89	48	160	<0.5	<1	<5	<3	<10	510	<10	400	<10	<1	<1
129-059-12CCC2	6/13/89	54	79	<0.5	<1	<5	<3	<10	240	<10	650	<10	<1	<1
130-058-31CCC2	6/14/89	37	190	<0.5	<1	<5	<3	<10	450	<10	510	<10	<1	<1
129-059-14BBB2	6/13/89	72	110	<0.5	<1	<5	<3	<10	570	<10	520	<10	<1	<1
130-058-08DDD2	6/15/89	44	28	<0.5	<1	<5	<3	<10	1200	<10	780	<10	<1	<1
129-058-20CCC2	6/14/89	6	140	<0.5	<1	<5	<3	<10	9	<10	200	<10	<1	<1
129-059-13DDC	6/13/89	43	100	<0.5	<1	<5	<3	<10	1700	<10	360	<10	<1	<1
129-058-19AAA2	6/14/89	24	290	<0.5	<1	<5	<3	<10	300	<10	440	<10	<1	<1
129-059-23AAA	6/13/89	37	140	<0.5	<1	<5	<3	<10	1100	<10	250	<10	<1	<1
129-059-01BBB2	6/14/89	15	250	<0.5	<1	<5	<3	<10	3400	<10	700	<10	<1	<1
129-059-13CDD	6/13/89	33	130	<0.5	<1	<5	<3	<10	790	<10	270	<10	<1	<1
130-058-08CDC2	6/15/89	39	44	<0.5	<1	<5	<3	<10	2100	<10	750	<10	<1	<1
130-058-08DDD1	6/15/89	63	36	<0.5	<1	<5	<3	<10	1300	<10	660	<10	<1	<1
130-058-18DCD1	6/8/89	20	140	<0.5	<1	<5	<3	<10	350	<10	640	<10	<1	<1
129-058-08BBB2	5/16/89	5	230	<0.5	<1	<5	<3	<10	510	<10	350	<10	<1	<1

(< indicates less than concentration shown)

Well Location	Date Sampled	Strontium	Vanadium	Zinc	Aluminum	Lithium	Selenium	Boron
		Micrograms per liter						
130-058-28BBB2	6-15-89	500	<6	5	<20	71	<1	230
129-058-07BBA	6/13/89	290	<6	9	<10	25	<1	90
130-058-08CDD2	6/15/89	450	<6	11	<10	38	<1	70
129-059-36ABA3	6/14/89	230	<6	4	<10	20	<1	50
129-059-36ABA2	6/14/89	380	<6	5	<10	110	<1	930
129-058-06CDD2	6/13/89	330	<6	5	<10	35	<1	140
129-058-07CCC	6/14/89	350	<6	5	<10	29	<1	90
129-058-18CCD1	6/14/89	350	<6	5	<10	53	<1	170
129-059-12CCC2	6/13/89	460	<6	3	<10	42	<1	120
130-058-31CCC2	6/14/89	410	<6	4	<10	34	<1	60
129-059-14BBB2	6/13/89	340	<6	10	<20	53	<1	160
130-058-08DDD2	6/15/89	450	<6	10	<10	54	<1	70
129-058-20CCC2	6/14/89	95	<6	3	<10	12	<1	20
129-059-13DDC	6/13/89	450	<6	7	<10	50	<1	140
129-058-19AAA2	6/14/89	210	<6	3	<10	25	<1	60
129-059-23AAA	6/13/89	420	<6	6	<10	38	<1	120
129-059-01BBB2	6/14/89	360	<6	6	<10	38	<1	70
129-059-13CDD	6/13/89	400	<6	12	<10	40	<1	120
130-058-08CDC2	6/15/89	690	<6	11	<10	55	<1	80
130-058-08DDD1	6/15/89	630	<6	19	<10	87	<1	200
130-058-18DCD1	6/8/89	370	<6	11	<10	39	<1	100
129-058-08BBB2	5/16/89	150	<6	24	<10	15	<1	50

below 750 mg/L, which is the maximum recommended limit for long-term irrigation on sensitive crops (U.S. Environmental Protection Agency, 1986).

FEASIBILITY OF ARTIFICIAL RECHARGE TO THE OAKES AQUIFER

Criteria used to select areas of the Oakes aquifer feasible for artificial recharge were:

(1) Transmissivity must be sufficiently large to support a continuous ground-water withdrawal of 100 cubic feet per second for 60 days over a relatively small area using a minimum number of wells.

(2) Initial infiltration rates must be at least 1 foot per day, and

(3) The ground water must not pose any water-quality limitations for irrigation.

There are two areas of the Oakes aquifer where individual well yields of greater than 500 gallons per minute are attainable. The first area is located in the north-central part of the Oakes aquifer near Oakes (fig. 29). Individual well yields between 500 and 900 gallons per minute are attainable in the deltaic complex that consists of sand and gravel deposits as much as 80 feet thick. The deltaic complex occupies an area of about 5 square miles. The city of Oakes overlies the northwest part of the deltaic complex and precludes land acquisition for large-scale surface recharge facilities. Based on test drilling data and soil types in this area, initial surface and near surface infiltration rates of greater than 1 foot per day are attainable. The ground water in this area is a calcium-magnesium-bicarbonate type with dissolved solids concentrations less than about 500 milligrams per liter (plate 11). The water quality does not pose any limitations for irrigation.

The second area where individual well yields greater than 500 gallons per minute are attainable is located along the eastern margin of the Oakes aquifer (fig. 29). Individual well yields between 500 and 2,000 gallons per minute are attainable in an area of about 14 square miles that overlies a glacial outwash channel consisting of sand and gravel deposits as much as 200 feet thick. The northern two-thirds of the outwash channel is buried by surficial fluvial deposits consisting of silty clay and clayey silt to a depth of about 50 feet (fig. 6). Initial surface and near surface infiltration rates in this area of the outwash channel are less than 1 foot per day.

Based on test drilling data, soil types, and infiltration tests, initial surface and near surface infiltration rates of greater than 1 foot per day are attainable in parts of sections 7 and 18, T. 129 N., R. 58 W. that overlie the southern part of the outwash channel. The width of the outwash channel is at a maximum in this area. Therefore the amount of water in storage is greater in this area as compared to other areas of the outwash channel. The ground water in this area is a calcium-magnesium-bicarbonate type with dissolved solids concentrations less than about 500 milligrams per liter (plate 11). The water quality does not pose any limitations for irrigation. Based on the above, the area in the Oakes aquifer, most feasible for surface or near surface artificial recharge and irrigation development is the southern part of the outwash channel in sections 12 and 13, T. 129 N., R. 59 W., and sections 7 and 18, T. 129 N., R.58 W.

SUMMARY AND CONCLUSIONS

The Oakes aquifer consists of four depositional facies that are grouped together into one hydrostratigraphic unit. The depositional facies include: (1) Deltaic sand and gravel; (2) lacustrine sand; (3) channel-fill sand and gravel; and (4) eolian sand. The deltaic facies occurs in the northern part of the study area near Oakes. The deltaic deposits consist of stratified sand and gravel as much as 80 feet thick.

The deltaic sand and gravel deposits grade into lacustrine sand south of Oakes. The lacustrine facies consists predominantly of medium sand as much as 60 feet thick in the central part of the lake plain. South of Ludden, the medium sand grades into fine to very fine silty sand, clayey silt, and silty clay.

Channel-fill deposits occupy a glacial-outwash channel that occurs along the eastern margin of the lake plain. The outwash channel trends north-south and varies in width from 0.5 to 2 miles. The channel-fill deposits consist of stratified very fine sand to coarse cobbly gravel as much as 197 feet thick. In some areas, the deposits are overlain by a fluvial silt and clay sequence. In other areas, the fluvial silt and clay sequence is absent.

The eolian facies consists of fine sand and silt that covers much of the lake plain in the study area. The eolian deposits range in thickness from less than 1 foot to about 50 feet near sec. 30, T. 130 N., R. 58 W.

Most of the Oakes aquifer is unconfined. Water occurs under leaky confined conditions where fluvial silt and clay sequences overlie the channel-fill deposits.

In general, regional ground-water flow in the Oakes aquifer is from east to west toward the James River valley. Recent James River valley flood-plain deposits that consist of sandy silty clay truncate the western flank of the Oakes aquifer. As a result, discharge from the Oakes aquifer westward to the James River is negligible.

Depth to the water table in the Oakes aquifer generally is less than 8 feet below land surface. Scattered sand dunes and blowouts cause a hummocky land-surface topography. Therefore, the Oakes aquifer consists of numerous localized flow systems. Within each local flow system, recharge is from direct infiltration of precipitation and local runoff that occurs primarily during the spring. Discharge primarily is from evapotranspiration that occurs during the summer. Estimating recharge and natural discharge in the Oakes aquifer is virtually impossible because of the inability to describe spatial variation in precipitation, land-surface topography, soil physical properties, and the evapotranspiration process.

There are two large-transmissivity areas of the Oakes aquifer that can accommodate individual well yields of greater than 500 gallons per minute. These areas are: (1) The northern part of the study area near Oakes (deltaic sand and gravel); and (2) the eastern flank of the lake plain (channel-fill sand and gravel). As compared to the deltaic deposits, the channel-fill deposits have the largest transmissivity (94,000 feet squared per day) and will provide the largest well yields (greater than 2,000 gallons per minute).

Initial infiltration rates are adequate for large-scale surface recharge facilities in sediments overlying the deltaic, lacustrine, and channel-fill deposits. Buried A soil horizons that contain up to 13.7 percent clay and surficial fluvial silt and clay sequences overlie parts of the outwash channel. In these areas, surface recharge facilities will be precluded. A more detailed test-drilling program will be needed along the axis of the outwash channel to delineate areas where buried A horizons and fluvial silt and clay sequences are thin or absent.

Water quality in the Oakes aquifer is variable. Dissolved-solids concentrations range from less than 300 to about 50,000 mg/L. Ground water with small (less than 500 mg/L) dissolved-solids concentrations is a calcium-magnesium-bicarbonate type. The small dissolved-solids calcium-magnesium-bicarbonate type predominates in the Oakes aquifer and poses no limitations for irrigation use. Ground water with large (greater than 2,000 mg/L) dissolved-solids concentrations occurs beneath closed land-surface depressions that represent net discharge areas. In these limited areas, ground water poses salinity, sodium, or boron hazards for irrigation use.

Results of the model study indicate that the channel-fill deposits near sec. 13, T. 129 N., R. 59 W. can supply a continuous withdrawal rate of 100 cubic feet per second for 60 days. This area of the Oakes aquifer is the most feasible for development of a well field and surface artificial recharge facilities to provide water during periods of peak irrigation demand for the west Oakes and west Oakes extension tracts of the Garrison Diversion Unit.

REFERENCES CITED

Armstrong, C.A., 1979, Ground-water basic data for Ransom and Sargent Counties, North Dakota: North Dakota Geological Survey Bulletin 69 part II, and North Dakota State Water Commission County Ground-Water Studies 31, 637 p.

.....1980, Ground-water resources of Dickey and LaMoure Counties, North Dakota: North Dakota Geological Survey Bulletin 70, part III, and North Dakota State Water Commission County Ground-Water Studies 28, 61 p.

.....1982, Ground-water resources of Ransom and Sargent Counties, North Dakota: North Dakota Geological Survey Bulletin 69, part III, and North Dakota State Water Commission County Ground-Water Studies 31, 51 p.

Armstrong, C.A., and Luttrell, S.P., 1978, Ground-water basic data for Dickey and LaMoure Counties, North Dakota: North Dakota Geological Survey Bulletin 70, part II, and North Dakota State Water Commission County Ground-Water Studies 28, 557 p.

Bluemle, J.P., 1979a, Geology of Dickey and LaMoure Counties: North Dakota Geological Survey Bulletin 70, part I, and North Dakota State Water Commission County Ground-Water Studies 28, 72 p.

.....1979b, Geology of Ransom and Sargent Counties, North Dakota: North Dakota Geological Survey Bulletin 69, part I, and North Dakota State Water Commission County Ground-Water Studies 31, 83 p.

Charron, J.E., 1969, Hydrochemical interpretation of groundwater movement in the Red River valley, Manitoba: Inland Waters Branch, Department of Energy, Mines and Resources, Ottawa, Canada, Scientific Series no. 2, 31 p.

Cherry, J.A., 1972, Geochemical processes in shallow groundwater flow systems in five areas in southern Manitoba, Canada: 24th International Geological Congress Proceedings Section 11, p. 208-221.

Claassen, H.C., 1982, Guidelines and techniques for obtaining water samples that accurately represent the water chemistry of an aquifer: U.S. Geological Survey Open-File Report 82-1024, 49 p.

Davison, C.C., and Vonhof, J.A., 1978, Spatial and temporal hydrochemical variations in a semiconfined buried channel aquifer, Esterhazy, Saskatchewan, Canada: Ground Water, v. 16, no. 5, p. 341-351.

Fenneman, N.M., 1946, Physiographic divisions of the United States: U.S. Geological Survey map prepared in cooperation with Physiographic Committee, U.S. Geological Survey, scale 1:7,000,000 (reprinted 1964).

Follet, R.F., Doering, E.J., Reichman, G.A., and Benz, L.C., 1974, Effect of irrigation and water table depth on crop yield: Agronomy Journal, v. 77, p. 304-308.

Freeze, R.A., 1969, Regional groundwater flow - Old Wives Lake drainage basin, Saskatchewan: Inland Waters Branch, Department of Energy, Mines, and Resources, Ottawa, Canada, Scientific Series no. 5, 245 p.

Garber, M.S., and Koopman, F.C., 1969, Methods of measuring water levels in deep wells: U.S. Geological Survey Techniques of Water Resources Investigations, Book 8, Chap. A1, 23 p.

Garrison Diversion Unit Commission, 1984, Final report: 59 p.

Gillham, R.W., Robin, M.J.L., Barker, J.F., and Cherry, J.A., 1983, Groundwater monitoring and sample bias: American Petroleum Institute Publication 4367, 206 p.

Grisak, G.E., Cherry, J.A., Vonhof, J.A., and Bluemle, J.P., 1976, Hydrogeologic and hydrochemical properties of fractured till in the Interior Plains region: In Glacial Till, Royal Society of Canada Special Publications no. 12, p. 304-333.

Groenewold, G.H., Koob, R.D., McCarthy, G.J., Rehm, B.W., and Peterson, W.M., 1983, Geological and geochemical controls on the chemical evolution of subsurface water in undisturbed and surface-mined landscape in western North Dakota: North Dakota Geological Survey Report of Investigation, 79, 151 p.

Hard, H.A., 1929, Geology and water resources of the Edgeley and LaMoure quadrangles, North Dakota: U.S. Geological Survey Bulletin 801, 90 p.

Hendry, M.J., 1986, Origin of groundwater sulfate in a fractured till in an area of southern Alberta, Canada: Water Resources Research, v. 22, no. 1, p. 45-61.

Huff, G.F., and Wald, J.D., 1989, Geochemistry of artificial-recharge tests in the Oakes aquifer near Oakes, southeastern North Dakota: U.S. Geological Survey Water - Resources Investigations Report 89-41122, 74 p.

Jacob, C.E., 1963, Determining the permeability of water-table aquifers, in Bentall, Ray, Methods of determining permeability, transmissibility, and drawdown: U.S. Geological Survey Water-Supply Paper 1536-I, p. 245-271.

.....1963, Correction of drawdowns caused by a pumped well tapping less than the full thickness of an aquifer, in Bentall, Ray, Methods of determining permeability, transmissibility, and drawdown: U.S. Geological Survey Water-Supply Paper 1536-I, p. 272-282.

Keller, L.P., McCarthy, G.J., and Richardson, J.L., 1986, Mineralogy and stability of soil evaporites in North Dakota: Soil Science Society of America Journal, v. 50, no. 4, p. 1069-1071.

Kister, L.S., and Garrett, W.B., 1982, Field guidelines for collection and treatment and analysis of water samples, Arizona District: U.S. Geological Survey Miscellaneous Publication, 83 p.

Langmuir, D., 1971, The geochemistry of some carbonate ground waters in central Pennsylvania: Geochemical et Cosmochimica Acta, v. 35, p. 1023-1045.

Larsen, W.M., Omodt, Hollis, Evanson, Eldon, Kerle, Donald, and Dunnigan, Lorn, 1964, Soil survey of Sargent County, North Dakota: U.S. Department of Agriculture, Soil Conservation Service, and North Dakota Agricultural Experiment Station, 97 p.

Lissey, Allen, 1968, Surficial mapping of groundwater flow systems with application to the Oak River basin, Manitoba: University of Saskatchewan, Ph.D. thesis, 105 p.

McDonald, M.G., and Harbaugh, A.W., 1984, A modular three-dimensional finite-difference ground-water flow model: U.S. Geological Survey, Open-File Report 83-875, 528 p.

Meyer, R.R., 1963, A chart relating well diameter, specific capacity, and the coefficients of transmissibility and storage, in Bentall, Ray, Methods of determining permeability, transmissibility, and drawdown: U.S. Geological Survey Water-Supply Paper 1536-I, p. 338-340.

Moran, S.R., Groenewold, G.H., and Cherry, J.A., 1978, Geologic, hydrologic, and geochemical concepts and techniques in overburden characterization for mined-land reclamation: North Dakota Geological Survey Report of Investigation 63, 152 p.

Plummer, L.N., Jones, B.F., and Truesdell, A.H., 1976, WATEQF--A Fortran IV version of WATEQ, a computer program for calculating chemical equilibrium of natural waters: U.S. Geological Survey Water-Resources Investigations 76-13, 63 p.

Prickett, T.A., 1965, Type-curve solution to aquifer tests under water-table conditions: Ground Water, v. 3, no. 3, p. 5-14.

Rasmussen, W.C., 1947, Ground water in the deposits of ancient Lake Dakota, Dickey County, North Dakota: North Dakota Ground Water Studies no. 4, 80 p.

Reardon, E.J., Mozeto, A.A., and Fritz, p., 1980, Recharge in northern clime calcareous sandy soils - soil water chemical and carbon-14 evolution: Geochimica et Cosmochimica Acta, v. 44, p. 1723-1735.

Rodrigues, J.D., 1983, The Noordbergum effect and characterization of aquitards at the Rio Naior mining project: Ground Water, v. 21, no. 2, p. 200-207.

Rozkowski, A., 1967, The origin of hydrochemical patterns in hummocky moraine: Canadian Journal of Earth Sciences, v. 4, p. 1065-1092.

Schuh, W.M., 1985, Deep infiltration values for the Oakes aquifer: North Dakota State Water Commission office memo, 12 p.

Shaver, R.B., and Hove, M.H., 1990, Feasibility of artificial recharge to the Oakes aquifer southeastern North Dakota: Ground-water data, vol. 1A, Records and lithologic logs of wells and test holes (T. 128 N., R. 60 W. through T. 130 N., R. 58 W.). North Dakota State Water Commission Water-Resources Investigation No. 6, 420 p.

Shaver, R.B., and Hove, M.H., 1990, Feasibility of artificial recharge to the Oakes aquifer southeastern North Dakota: Ground-water data, vol. 1B, Records and lithologic logs of wells and test holes (T. 130 N., R. 59 W. through T. 131 N., R. 59 W.). North Dakota State Water Commission Water-Resources Investigation No. 6, 666 p.

Shaver, R.B., and Hove, M.H., 1990, Feasibility of artificial recharge to the Oakes aquifer, southeastern North Dakota: Ground-water data, vol 2, water levels and chemical analyses of ground water from selected wells. North Dakota State Water Commission Water-Resources Investigation No. 6, 332 p.

Sophocleous, Marios, and Perry, C.A., 1985, Experimental studies in natural groundwater - recharge dynamics: The analysis of observed recharge events: Journal of Hydrology, v. 81, p. 297-332.

Thompson, D.G., and Sweeney, M.D., 1971, Soil survey of LaMoure County and parts of James River valley, North Dakota: U.S. Department of Agriculture, Soil Conservation Service, and North Dakota Agricultural Experiment Station, 119 p.

Trescott, P.C., Pinder, G.F., and Larson, S.P., 1976, Finite-difference model for aquifer simulation in two dimensions with results of numerical experiments: U.S. Geological Survey Techniques of Water-Resources Investigations, Book 7, Chap. C1, 116 p.

U.S. Bureau of Reclamation, 1953a, Definite plan report, Oakes development tract, Garrison Diversion Unit, Missouri-Souris Division: 54 p.

.....1953b, Definite plan report, appendices, Oakes development tract, Garrison Diversion Unit, Missouri-Souris Division: 32 p.

U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Environmental Data Service, 1962-75, Climatological data, North Dakota, annual summaries 1961-73: Asheville, North Carolina, v. 70-83, no. 13.

.....1982, Monthly normals of temperature, precipitation, and heating and cooling degree days, 1951-80, North Dakota: Asheville, North Carolina, Climatography of the United States, No. 81, (by State).

U.S. Department of Commerce, Weather Bureau, reprinted 1960, Climatic summary of the United States, No. 11-28, North Dakota, 1931-52: 45 p.

.....1965, Climatic summary of the United States, No. 86-28, North Dakota, 1951-60: 76 p.

U.S. Environmental Protection Agency, 1986, Quality criteria for water 1986: U.S. Environmental Protection Agency EPA 440/5-86-001, unnumbered pages.

Vandenberg, A., and Lennox, D., 1969, Groundwater chemistry and hydrology of the Handhills Lake area, Alberta: Research Council of Alberta, Report 69-1, 49 p.

Wallick, E.I., 1981, Chemical evolution of groundwater in a drainage basin of holocene age, east-central Alberta, Canada: Journal of Hydrology, v. 54, p. 245-283.

Williams, D.L., 1984, The geochemical evolution of saline groundwater within a fresh water aquifer south of Oakes, North Dakota: Grand Forks, University of North Dakota, M.S. thesis, 328 p.

SUPPLEMENTAL DATA

Supplement 1.--Description of Embden soil profile at infiltration-test site RM-1

Lithologic description	Thickness, in inches	Depth, in inches
Dark-gray sandy loam.	9	9
Grayish-brown sandy loam.	8	17
Light-gray silty loam; violent effervescence because of lime accumulation.	11	28
Light-brownish-gray fine sandy loam; strong effervescence because of lime accumulation.	13	41
Light-brownish-gray fine sand; slight effervescence.	25	66
Light-brownish-gray fine sand; slight effervescence; few pebbles over 2 millimeters.	30	96
Slight-brownish-gray medium to coarse sand; slight effervescence; few pebbles over 2 millimeters.	12	108

Supplement 2.--Description of Aylmer soil profile at infiltration-test site RM-2

Lithologic description	Thickness, in inches	Depth, in inches
Dark-gray fine to medium sand.	10	10
Gray fine sand.	8	18
Gray fine sand; iron mottles.	8	26
Dark-gray fine to medium sand; buried A horizon.	2	28
Gray fine to medium sand; iron mottles.	17	45
Dark-gray loamy sand; buried A horizon.	4	49
Gray fine to medium sand; faint iron mottles.	7	56
Gray fine sand; slight effervescence; iron mottles.	24	80
Gray sandy loam; strong effervescence; iron mottles.	2	82
Gray fine to medium sand; slight effervescence; iron mottles.	62	144
Very dark gray silty clay; slight effervescence.	1	145
Gray fine to medium sand; slight effervescence; 1/4-inch thick silty clay strata.	13	158

Supplement 3.--Description of Overblown sand soil profile at infiltration-test site RM-3

Lithologic description	Thickness, in inches	Depth, in inches
Dark-gray fine sand.	14	14
Dark-grayish-brown fine sand.	16	30
Grayish-brown fine sand.	6	36
Light-brownish-gray fine sandy loam; violent effervescence because of lime accumulation.	16	52
Light-brownish-gray loamy fine sand; violent effervescence because of lime accumulation.	20	72
Light-brownish-gray sandy loam; violent effervescence because of lime accumulation.	8	80
Light-brownish-gray fine to medium sand; slight effervescence.	16	96
Light-brownish-gray fine to medium sand; slight effervescence.	9	105
Light-brownish-gray fine sand; iron mottles.	9	114
Dark-gray fine sand.	8	122

Supplement 4.--Description of Hecla soil profile at infiltration-test site RM-4a

Lithologic description	Thickness, in inches	Depth, in inches
Black loamy fine sand; soft; very friable; slightly sticky and nonplastic; weak medium and coarse granular structure; common very fine roots; abrupt smooth boundary.	5	5
Black loamy fine sand; soft; very friable; slightly sticky and nonplastic; weak medium prismatic parting to weak fine and very fine subangular blocky structure; common very fine roots; gradual wavy boundary.	10	15
Very dark grayish brown loamy fine sand; soft; very friable; slightly sticky and nonplastic; weak medium prismatic parting to weak medium and fine subangular blocky structure; common very fine roots; 5-inch krotovina; gradual wavy boundary.	10	25
Dark-grayish-brown to grayish-brown fine sand; loose; nonsticky and nonplastic; many medium distinct dark-brown mottles; single grain structure; few very fine roots; gradual wavy boundary.	9	34
Grayish-brown fine sand; loose; nonsticky and nonplastic; many fine prominent very dark brown mottles; single grain structure; gradual wavy boundary.	14	48
Grayish-brown medium sand; loose; nonsticky and nonplastic; many medium prominent very dark brown mottles; single grain structure; loose wavy boundary.	11	59
Light-brownish-gray medium sand; loose; nonsticky and nonplastic; common medium prominent very dark brown mottles; single grain structure; strong to violent effervescence.	11	70

Supplement 5.--Description of Ulen soil profile at infiltration-test site RM-4b

Lithologic description	Thickness, in inches	Depth, in inches
Black loamy fine sand; slightly hard; very friable; slightly sticky; slightly plastic; weak medium and coarse prismatic structure; common very fine roots; slight effervescence with depth; gradual wavy boundary.	7	7
Very dark grayish brown loamy fine sand; soft; very friable; slightly sticky and nonplastic; weak coarse prismatic structure; common very fine roots; slight to strong effervescence with depth; gradual wavy boundary.	9	16
Grayish-brown fine sand; soft; very friable; slightly sticky and nonplastic; weak very coarse prismatic structure; few very fine roots; strong to violent effervescence; gradual wavy boundary.	6	22
Light-brownish-gray loamy fine sand; soft; very friable; slightly sticky and nonplastic; weak very coarse prismatic structure; few very fine roots; strong to violent effervescence; gradual wavy boundary.	8	30
Grayish-brown loamy fine sand; soft; very friable; slightly sticky; common fine distinct very dark brown mottles; very weak very coarse prismatic structure; common very fine roots; strong effervescence; clear wavy boundary.	10	40
Brown to pale-brown medium sand; loose; nonsticky and nonplastic; many medium prominent yellowish-red very dark brown mottles; single grain structure; few very fine roots; slight effervescence.	20	60

Supplement 6.--Description of Arveson soil profile at infiltration-test site RM-4c

Lithologic description	Thickness, in inches	Depth, in inches
Black fine sandy loam; soft; very friable; slightly sticky and slightly plastic; moderate coarse sand; medium granular structure; many very fine roots; strong to violent effervescence; abrupt smooth boundary.	7	7
Black fine sandy loam; soft; very friable; slightly sticky and slightly plastic; moderate coarse prismatic parting to moderate medium and fine subangular blocky structure; many roots; violent effervescence; clear smooth boundary.	5	12
Gray fine sandy loam; soft; very friable; slightly sticky and slightly plastic; moderate coarse prismatic parting to moderate fine and medium subangular blocky structure; many roots; violent effervescence; clear smooth boundary.	11	23
Pale-olive fine sand; soft; very friable to loose; nonsticky and nonplastic; common manganese pellets at 34 inches and discontinuous organic staining on prism faces; very weak very coarse prismatic structure; few roots; very slight effervescence; clear wavy boundary.	17	40
Pale-olive fine sand; very friable to loose; nonsticky and nonplastic; common medium prominent very dark brown mottles and discontinuous organic staining on prism faces; clear smooth boundary.	15	55
Dark-gray fine sandy loam; massive; soft; very friable; slightly sticky and slightly plastic.	9	64

Supplement 7.--Description of Hamar soil profile at infiltration-test site RM-5a

Lithologic description	Thickness, in inches	Depth, in inches
Black loamy sand; soft; very friable; slightly sticky and nonplastic; weak fine and medium subangular blocky structure; common very fine roots; abrupt smooth boundary.	4	4
Black loamy sand; slightly hard; very friable; slightly sticky and nonplastic; moderate medium and coarse prismatic parting to moderate medium and coarse subangular blocky structure; common very fine roots; clear wavy boundary.	7.5	11.5
Very dark grayish brown sand; soft; very friable to loose; nonsticky and nonplastic; few very faint very dark brown mottles that increase to common with depth; very weak coarse prismatic parting to weak medium and coarse subangular blocky structure; few very fine roots; clear wavy boundary.	12	23.5
Light-yellowish-brown to light-olive-brown fine sand; soft; very friable to loose; nonsticky and nonplastic; common medium distinct dark-yellowish-brown mottles; very weak coarse prismatic structure; few very fine roots; clear wavy boundary.	16.5	40
Light-yellowish-brown to light-olive-brown sand; soft; very friable to loose; nonsticky and nonplastic; many medium distinct strong brown mottles; few very fine roots; abrupt smooth boundary.	23	63
Dark-gray loamy sand; soft; very friable to loose; nonsticky and nonplastic.	9	72

Supplement 8.--Description of Hecla soil profile at infiltration-test site RM-5b

Lithologic description	Thickness, in inches	Depth, in inches
Black loamy sand; soft; very friable; slightly sticky and nonplastic; weak fine and medium subangular blocky structure; common very fine roots; abrupt smooth boundary.	4	4
Black loamy sand; slightly hard; very friable; slightly sticky and nonplastic; moderate medium and coarse prismatic parting to moderate medium and coarse subangular blocky structure; common very fine roots; clear wavy boundary.	9.5	13.5
Very dark grayish brown sand; soft; very friable; nonsticky and nonplastic; weak medium and coarse prismatic parting to weak medium and coarse subangular blocky structure; common very fine roots; clear wavy boundary.	10.0	23.5
Light-olive-brown fine sand; soft; very friable to loose; nonsticky and nonplastic; few fine distinct dark-yellowish-brown mottles that increase to common with depth; weak medium and coarse prismatic structure; few very fine roots; gradual wavy boundary.	10.5	34
Light-yellowish-brown to light-olive-brown sand; soft; very friable to loose; nonsticky and nonplastic; common medium distinct dark-brown and common fine distinct very dark brown mottles; weak medium to coarse prismatic structure; few very fine roots.	26	60

Supplement 9.--Description of Hecla soil profile at infiltration-test site RM-5c

Lithologic description	Thickness, in inches	Depth, in inches
Black sandy loam; soft; very friable; slightly sticky and slightly plastic; moderate medium and coarse subangular blocky structure, common very fine roots; abrupt smooth boundary.	3.5	3.5
Black sandy loam; slightly hard; very friable; slightly sticky and slightly plastic; moderate medium and coarse prismatic parting to moderate medium and coarse subangular blocky structure; common very fine roots; clear wavy boundary.	6.5	10
Black loamy sand; slightly hard; very friable; slightly sticky and nonplastic; moderate medium and coarse prismatic parting to moderate medium and coarse subangular blocky structure; common very fine roots; clear wavy boundary.	12	22
Dark-brown loamy sand; soft; very friable; slightly sticky and nonplastic; weak medium and coarse prismatic parting to weak medium and coarse subangular blocky structure; common very fine roots; clear wavy boundary.	10	32
Light-olive-brown sand; soft; very friable to loose; nonsticky and nonplastic; few fine distinct dark-yellowish-brown mottles that increase to common with depth; weak medium and coarse prismatic structure; few very fine roots; clear wavy boundary.	7.5	39.5
Light-yellowish-brown to light-olive-brown sand; soft; very friable to loose; nonsticky and nonplastic; many medium distinct brown and few fine distinct dark-brown mottles; weak medium and coarse prismatic structure; few very fine roots.	15.5	55

Supplement 10.--Particle-size analysis of Embden soil profile at infiltration-test site RM-1

Soil horizon	Depth to top, in inches	Depth to bottom, in inches	Midpoint, in inches	U.S. Department of Agriculture textural class	Grain-size class and particle size, in microns		
					Sand (2,000 to 50)	Silt (50 to 2)	Clay (<2)
					Percent		
A	0	9	4.5	Fine sandy loam.	68.1	24.4	7.4
Bw1	9	17	13	Loam.	51.5	36.7	11.8
BCk	17	28	22.5	Silt loam.	27.7	52.9	19.4
C1	28	41	34.5	Very fine sandy loam.	53.3	32.2	14.5
C2	41	66	53.5	Sand.	90.1	7.5	2.4
C3	66	96	81	Sand.	91.5	7.5	.9
C4	96	108	102	Loamy sand.	86.9	9.6	3.5

Supplement 11.--Particle-size analysis of Aylmer soil profile at infiltration-test site RM-2

Soil horizon	Depth to top, in inches	Depth to bottom, in inches	Midpoint, in inches	U.S. Department of Agriculture textural class	Grain-size class and particle size, in microns		
					Sand (2,000 to 50)	Silt (50 to 2)	Clay (<2)
					Percent		
A	0	10	5	Fine sand.	97	2.4	0.6
C1	10	18	14	Fine sand.	97.4	2.4	.2
C2	18	26	22	Sand.	97.7	2.1	.2
2Ab	26	28	27	Sand.	94.4	4	1.7
2C1	28	45	36.5	Sand.	96.4	3.4	.2
3Ab	45	49	47	Fine sandy loam.	69.1	27.3	3.6
3C1	49	56	52.5	Fine sand.	91.6	6.7	1.7
3C2	56	80	68	Fine sand.	93.9	4.5	1.7
3C3	80	82	81	Fine sandy loam.	77	13.7	9.3
3C4	82	110	96	Sand.	91.4	5.1	3.5
3C5	110	144	127	Sand.	91.1	5.4	3.5
3C6	144	145	144.5	Fine sandy loam.	54.5	26.4	19.1
3C7	145	158	151.5	Loamy sand.	87.4	8	4.6

Supplement 12.--Particle-size analysis of Overblown soil profile at infiltration-test site RM-3

Soil horizon	Depth to top, in inches	Depth to bottom, in inches	Midpoint, in inches	U.S. Department of Agriculture textural class	Grain-size class and particle size, in microns Sand (2,000 to 50)	 Silt (50 to 2)	 Clay (<2)
					Percent		
A11	0	14	7	Fine sand.	91.8	5.8	2.4
A12	14	30	22	Fine sand.	95.9	3.2	.9
A13	30	36	33	Fine sand.	96.3	3.1	.6
Ak	36	52	4	Fine sandy loam.	74	12.2	13.7
ACk1	52	72	62	Loamy fine sand.	86.5	7.4	6.1
ACk2	72	80	76	Fine sandy loam.	71.6	15.4	12.9
C1	80	96	88	Loamy fine sand.	86.7	10.9	2.4
C2	96	105	100.5	Fine sandy loam.	78.7	12.3	9
C3	105	114	109.5	Fine sand.	92.5	5.1	2.4
C4	114	122	118	Fine sand.	95	2.3	2.7