#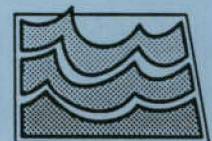 DISTRIBUTION OF OXYGEN-18 AND DEUTERIUM IN PRECIPITATION, PONDS, SLOUGHS, AND GROUND WATER IN THE OAKES AQUIFER STUDY AREA, SOUTHEASTERN NORTH DAKOTA

By
Robert B. Shaver

DISTRIBUTION OF OXYGEN-18 AND DEUTERIUM IN PRECIPITATION, PONDS, SLOUGHS, AND GROUND WATER IN THE OAKES AQUIFER STUDY AREA, SOUTHEASTERN NORTH DAKOTA

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Robert B. Shaver
North Dakota State Water Commission

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INTRODUCTION

Stable environmental isotopes oxygen (^{18}O) and hydrogen (^{2}H) are ideal ground-water flow system tracers because they are constituents of water and they are conservative (Payne, 1988). These isotopes have been used in ground-water investigations to evaluate: 1) the elevation of recharge, 2) ground water/surface water relationships, 3) leakage between aquifers, 4) aquifer recharge, and 5) mechanisms of salinization (Payne, 1988).

In modern ground waters the $^{2}H/^{1}H$ and $^{18}O/^{16}O$ ratios reflect the average values for precipitation in the recharge zone (Lyons, 1993). Shifts in these ratios can be attributed to annual temperature differences and, as a result, may serve as paleoclimate indicators.

Pleistocene buried-valley aquifers are important sources of ground water in the Western Glaciated Plains region of North America (Shaver and Pusc, 1992). In North Dakota, buried-valley aquifers consist mainly of sand and gravel deposits overlain by glacial drift comprised predominantly of till and underlain by bedrock shales, sandstones, and siltstones. The till aquitard controls recharge, discharge, response to pumping, water chemistry, and rates of contaminant movement to buried-valley aquifers (Keller and others, 1989).

The management of buried-valley aquifers requires quantitative evaluation of ground-water flow in till. Bradbury and others (1985), Simpkins and Bradbury (1992), Day (1977), and Hendry and others (1986) measured vertical profiles of $\delta^{18}O$ and δD in till at selected sites in Wisconsin, Manitoba, and Alberta to help evaluate ground-water flow. Most sites displayed shifts to more depleted $\delta^{18}O$ values with depth indicative of recharge water derived from a cooler climate. In addition,

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Simpkins and Bradbury (1992) estimated vertical ground-water velocities in till using $\delta^{18}O$ profiles. Based on these investigations, it is apparent that the spatial distribution of $\delta^{18}O$ and δD in till can be used to estimate ground-water velocity and recharge to underlying buried-valley aquifers.

Some areas of buried-valley aquifers are characterized by calcium-bicarbonate type waters with relatively low dissolved solids concentrations. Major ion chemistries are similar to meteoric waters in shallow, water-table aquifers. Meteoric water is defined as water that has been recently involved in atmospheric circulation (White, 1965). Based solely on major ion chemistries, it is inconclusive as to whether these deeper, ground- water bodies represent recharge areas or areas where older water (Pleistocene) has been trapped. Stable isotope signatures can be useful in differentiating ground-water ages.

Prior to evaluating the spatial distribution of $\delta^{18}O$ and δD in thick till profiles, fluvial inhomogeneities, and underlying buried-valley aquifers, the distribution of $\delta^{18}O$ and δD concentrations of modern precipitation in the study area should be evaluated. Next, the $\delta^{18}O$ and δD distribution in modern precipitation should be examined in relation to the $\delta^{18}O$ and δD distribution in a shallow, unconfined aquifer containing predominantly meteoric water.

The Oakes aquifer in southeastern North Dakota was selected to evaluate the distribution of $\delta^{18}O$ and δD in ground water. In addition, the $\delta^{18}O$ and δD of selected precipitation events were measured to establish a meteoric water signature. The hydrogeology of the Oakes aquifer is well defined (Shaver and Schuh, 1990). In addition, the Oakes aquifer was selected because it is located near the Spiritwood buried-

valley aquifer which, along with the overlying till, is targeted for future stable isotope analysis. Finally, local climate data is available from the Oakes U.S. Weather Service Station and the North Dakota State University agricultural experiment station four miles south of Oakes, North Dakota.

PURPOSE AND SCOPE

The purpose of this investigation is to evaluate the distribution of $\delta^{18}O$ and δD in precipitation at Oakes, North Dakota and a nearby shallow, unconfined aquifer (Oakes aquifer). Determinations of $\delta^{18}O$ and δD were made on precipitation samples from 19 precipitation events from April 1989 through April 1990. A local meteoric water line was developed using these data. The local meteoric water line was compared to global and regional meteoric water lines. In addition, the data were used to evaluate the relationship between 1) $\delta^{18}O$, δD, and moisture state (rain-snow), 2) $\delta^{18}O$ and ground temperature, and 3) deuterium excess in rain and snow.

Determinations of $\delta^{18}O$ and δD were made on samples taken from 32 monitoring wells and five ponds and sloughs located in the Oakes aquifer study area during the spring of 1989. These data were also compared with precipitation data on the local meteoric water line to provide a qualitative assessment of seasonal preference (if any) of the recharge process. In addition, the spatial distribution of ground-water $\delta^{18}O$ and δD was evaluated and the ground-water, pond/slough $\delta^{18}O$ and δD data were used to determine the method of salinization in areas of the Oakes aquifer characterized by relatively large dissolved-solids concentrations.

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 129-059-10AAA is located in the NE1/4 NE1/4 NE1/4 of Section 10, Township 129 North, Range 59 West. Consecutive terminal numerals are added if more than one well or test hole is located within a 10-acre tract.

SAMPLING AND ANALYTICAL METHODS

Samples for $\delta^{18}O$ and δD analysis were collected in 50-ml glass bottles with plastic caps fitted with expandable Teflon inserts to prevent the glass from cracking during transport and storage. Each bottle was top-filled to prevent air entrapment. Samples were sent unchilled to a lab operated by Global Geochemistry Corporation, Canoga Park, California. All $\delta^{18}O$ and δD values were calculated using Vienna Standard Mean Ocean Water (VSMOW) as the zero or reference point. Liquid samples were stored at 4° C in the lab prior to analysis. The $\delta^{18}O$ and δD determinations were made using a mass spectrometer. Sample duplicate precision is ±0.15 0/00 for $\delta^{18}O$ and ±1.5 0/00 for δD. The

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129-059-10AAA
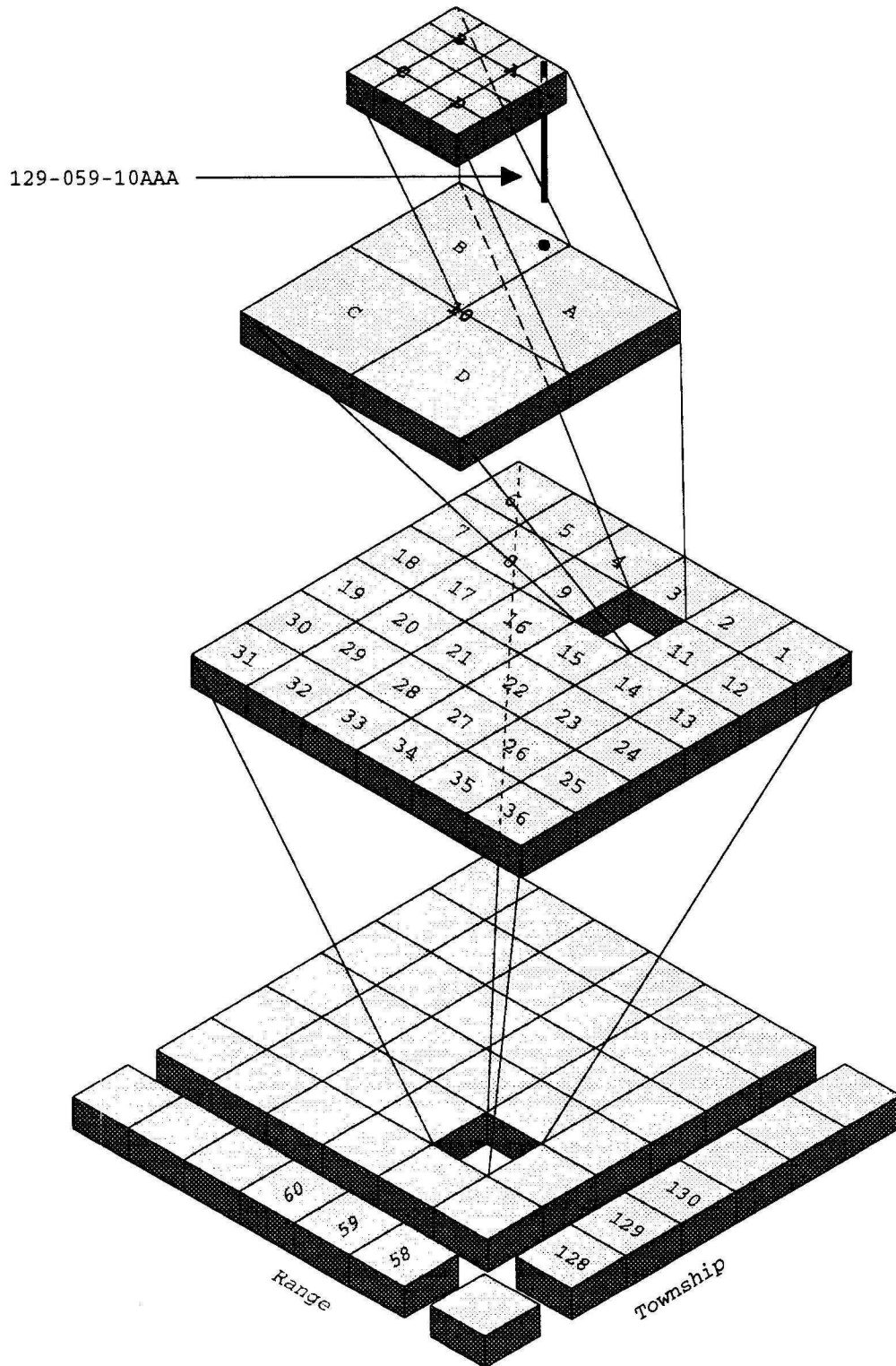
Figure 1. -- Location-numbering system

sampling protocol for major cation-anion analyses is described by Shaver (1991).

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 Larson 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) present 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 depression in the Oakes aquifer southeast of Oakes.

An artificial recharge feasibility study conducted by the North Dakota State Water Commission in cooperation with the U.S. Bureau of Reclamation was initiated in 1985. Shaver and Schuh (1990) described the hydrogeology of the Oakes aquifer, Shaver and Hove (1990 a, b, c) presented the ground-water data, which consists of lithologic logs of test

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holes and wells (volumes 1A and 1B), water-level measurements (volume 2), and water-quality analyses (volume 2). Schuh and Shaver (1988) described infiltration through recharge basins, physical processes that affected infiltration, and operational and maintenance techniques used to enhance infiltration rates. Shaver (1989) provided a preliminary design and cost-estimate analysis of a full project-scale and pilot-scale well field and artificial recharge system for the Oakes aquifer. Shaver and Schuh (1989) summarized the artificial recharge feasibility study.

Schuh, and others (1991) determined unsaturated soil hydraulic properties and parameters for the Oakes aquifer study area. Shaver (1991) evaluated sample bias in a hydrochemical investigation of the Oakes aquifer.

DESCRIPTION OF THE STUDY AREA
Physiography

The study area is located in the Central Lowland Physiographic Province in southeastern North Dakota (fig. 2) and 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. Runoff from the lake plain is minor as indicated by the lack of surface drainage.

Climate[*]

The Oakes aquifer study area is characterized by a semiarid to subhumid continental type climate. Annual, daily, and day-to-day temperature changes are relatively large. The mean annual temperature

[*] much of the following climate discussion is taken from Jensen (no date).

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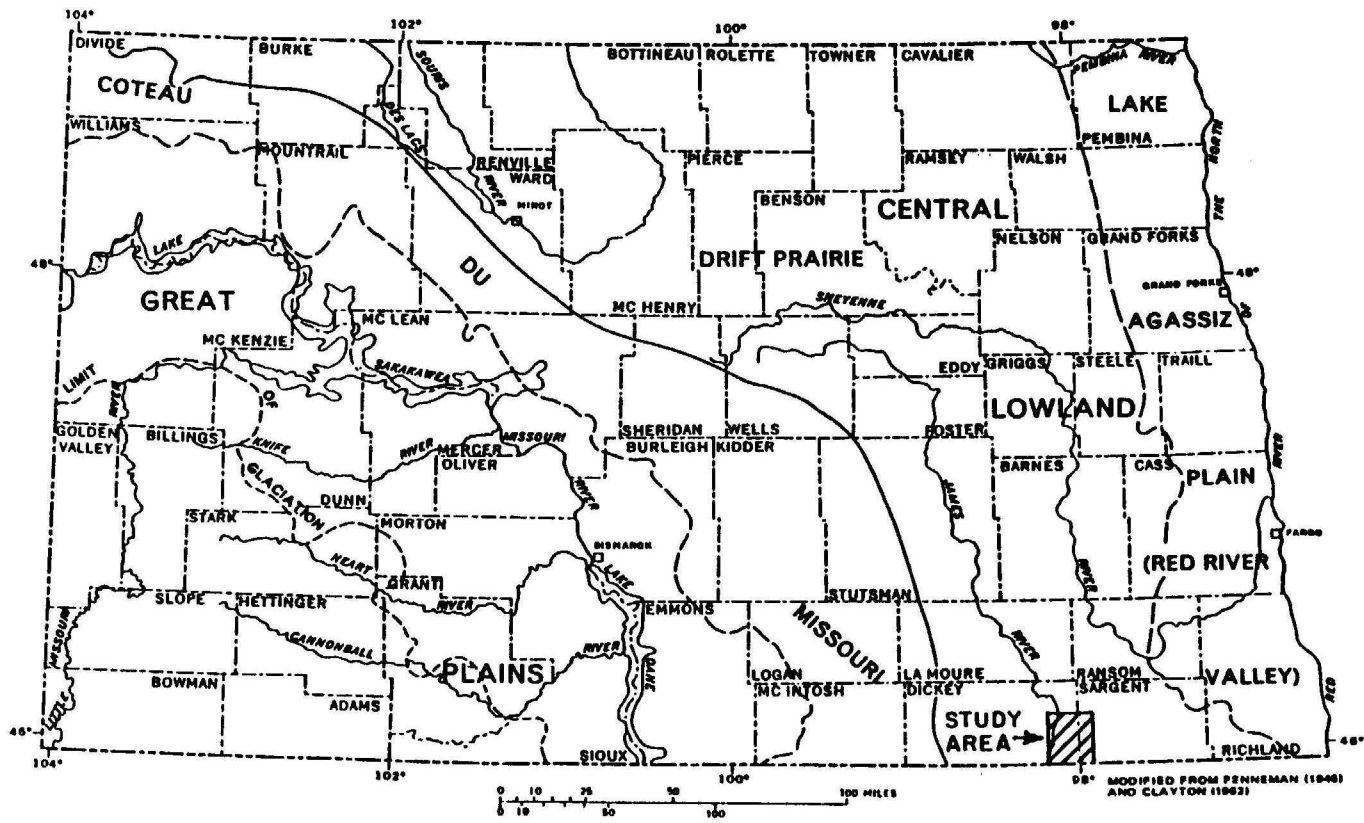
Figure 2. -- Location of Oakes aquifer study area

at Oakes from 1929 through 1989 is 42.4° F (5.8°C) (table 1). (U.S. Department of Commerce, 1960, 1962-1989, 1965, 1982.)

Precipitation tends to be irregular in time and space. Mean annual precipitation at Oakes from 1929 through 1989 is 18.95 inches (481.33 mm). The study area is characterized by low relative humidity, plentiful sunshine, and nearly continuous air movement.

Source of Air Masses

Weather patterns in North Dakota are primarily derived from the Pacific Ocean, Polar areas, and the Gulf of Mexico (fig. 3). The Rocky Mountains located west of North Dakota act as a barrier to the prevailing westerly flow of air in the atmosphere. This barrier modifies the temperature and moisture characteristics of air masses originating in the Pacific Ocean. No mountain barriers exist with respect to air mass source regions in the polar areas or the Gulf of Mexico. Air masses originating in these regions easily overflow North Dakota, sometimes with only minor changes in their basic characteristics. In every year and every season, North Dakota is overflown several times by cold and dry polar air masses, warm and moist Gulf of Mexico air masses, or mild and dry northern Pacific air masses. This is an important consideration with regard to temporal $\delta^{18}O$ and δD variations in precipitation.

Precipitation by Season

Winter

Precipitation is usually light in North Dakota during the winter because nearly all of the moisture-laden low pressure systems that result in large amounts of snow follow tracks well to the south of the state. Low pressure systems forming in the eastern slopes of the Rocky Mountains in Canada or originating in the northern Pacific Ocean frequently move

Table 1. -- Monthly temperature and precipitation data for the Oakes aquifer study area

MONTH	AVERAGE MONTHLY TEMPERATURE (DEGREES C)	RANGE IN MONTHLY TEMPERATURE (DEGREES C)	AVERAGE MONTHLY PRECIPITATION (INCHES)	AVERAGE MONTHLY PRECIPITATION (MILLIMETERS)	MONTHLY PERCENTAGE OF ANNUAL PRECIPITATION
JANUARY	-12.18	31.13	0.53	13.46	0.028
FEBRUARY	-9.53	39.45	0.59	14.99	0.031
MARCH	-2.09	21.48	1.00	25.40	0.053
APRIL	7.37	17.00	2.01	51.05	0.106
MAY	14.50	18.61	2.46	62.48	0.130
JUNE	18.95	17.56	3.42	86.87	0.181
JULY	22.89	15.95	2.44	61.98	0.129
AUGUST	20.91	11.37	2.25	57.15	0.119
SEPTEMBER	14.26	17.52	1.73	43.94	0.091
OCTOBER	7.03	16.89	1.28	32.51	0.068
NOVEMBER	-2.28	21.96	0.74	18.80	0.039
DECEMBER	-10.39	28.83	0.50	12.70	0.026

MEAN ANNUAL TEMPERATURE = 5.8 ^{0}C (42.6 ^{0}F)
MEAN ANNUAL PRECIPITATION = 18.95 INCHES (481.33 MILLIMETERS)

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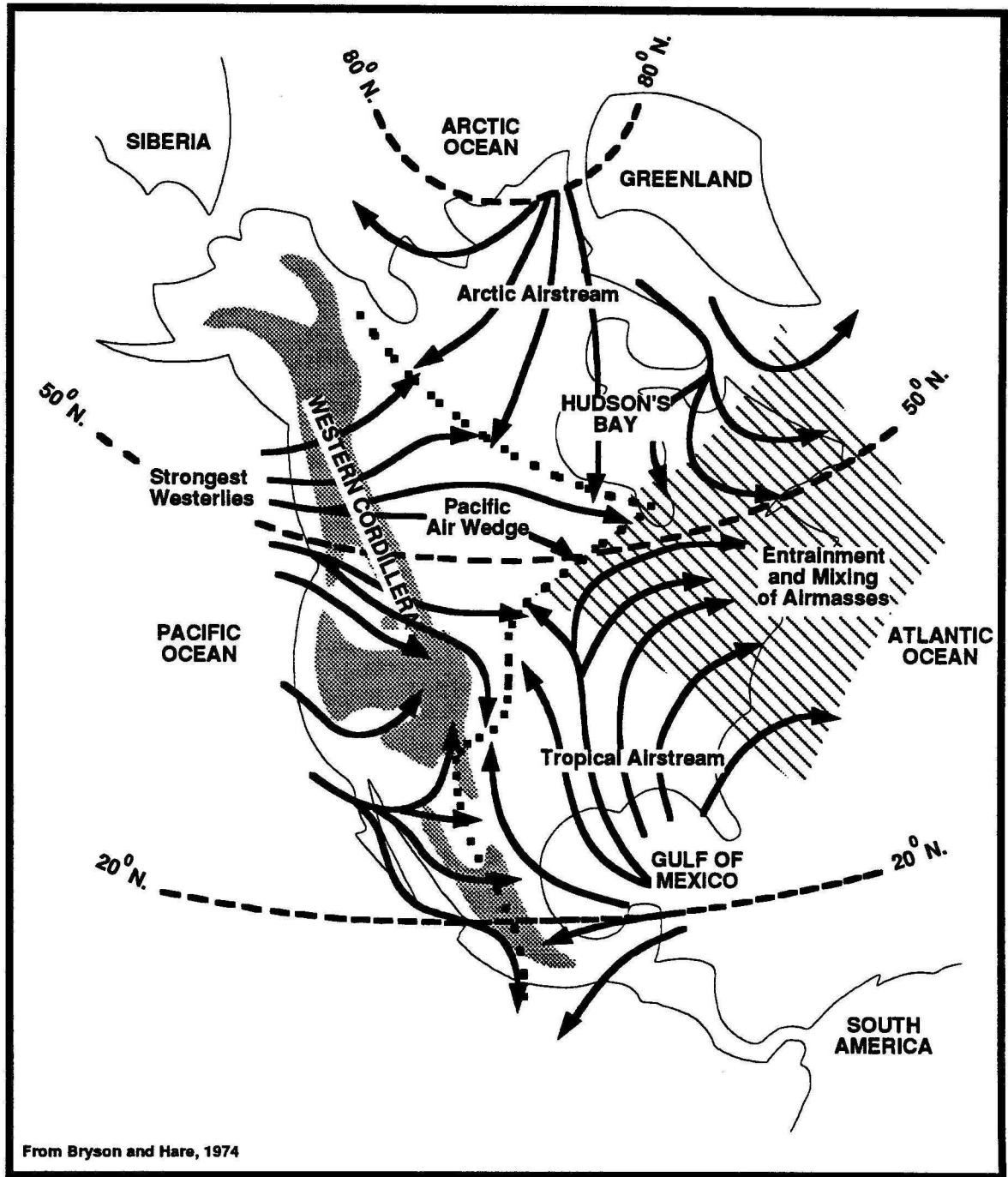
Figure 3. -- Schematic diagram of the surface flow across North America based on July resultant surface winds

SIBERIA

ARCTIC OCEAN

GREENLAND

80° N.

80° N.

Arctic Airstream

HUDSON'S BAY

50° N.

50° N.

Strongest Westerlies

WESTERN CORDILLERA

Pacific Air Wedge

Entrainment and Mixing of Airmasses

PACIFIC OCEAN

ATLANTIC OCEAN

Tropical Airstream

20° N.

20° N.

GULF OF MEXICO

SOUTH AMERICA

From Bryson and Hare, 1974

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southeastward across the state during the winter. These low pressure systems are better characterized by the cold air invasions which follow their passage across the state rather than by moisture that falls. Winter (December, January, February) precipitation amounts to about 9 percent of the annual amount.

Spring

The first substantial rains of spring sometimes fall in late March, but usually in early April. Monthly precipitation amounts increase as spring moves on because the storms which traveled well south of the state in winter now follow more northerly tracks. During the spring months, the southeast corner of the state (Oakes aquifer study area) receives more precipitation than the rest of the state because it is closer to the main storm tracks and the Gulf of Mexico moisture source. Spring (March, April, May) precipitation amounts to about 29 percent of the annual amount.

Summer

Rainfall in North Dakota reaches its peak in June. In July and August, average rainfall amounts decrease from June levels. During July and August, most precipitation is caused by cold fronts, lifting the air and causing thunderstorms which generally cross the state from a northwest to southeast direction. Summer (June, July, August) precipitation amounts to about 43 percent of the annual amount.

Fall

Precipitation amounts decrease rapidly throughout the fall months. The chances of receiving measurable precipitation are lower in late October and early November than at any other time during the year. The first significant snowfall of the season usually occurs during the middle

or later part of November. Fall (September, October, November) precipitation amounts to about 20 percent of the total amount.

Geology

In descending order throughout most of the study area, the stratigraphic section consists of sand or sand and gravel, silt and clay, till, and bedrock shale (fig. 4). The Oakes aquifer consists predominantly of sand or sand and gravel deposits of the Pleistocene Coleharbor Group (Bluemle, 1979).

Near Oakes, stratified sand and gravel deposits form a deltaic complex up to about 80 feet thick (fig. 5). The deltaic 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. Average thickness of the lacustrine deposits is about 35 feet.

Channel-fill deposits consisting of stratified very fine sand to coarse, cobbly gravel up to 197 feet thick occur in an outwash channel along the eastern margin of the lake plain (fig. 5). A surface to near-surface fluvial silt and clay deposit overlies the northern and central parts of the outwash channel (fig. 6). The deltaic, lacustrine, and channel-fill deposits which comprise the Oakes aquifer are composed of quartz, shale, carbonates, Canadian Shield silicates and lignite fragments.
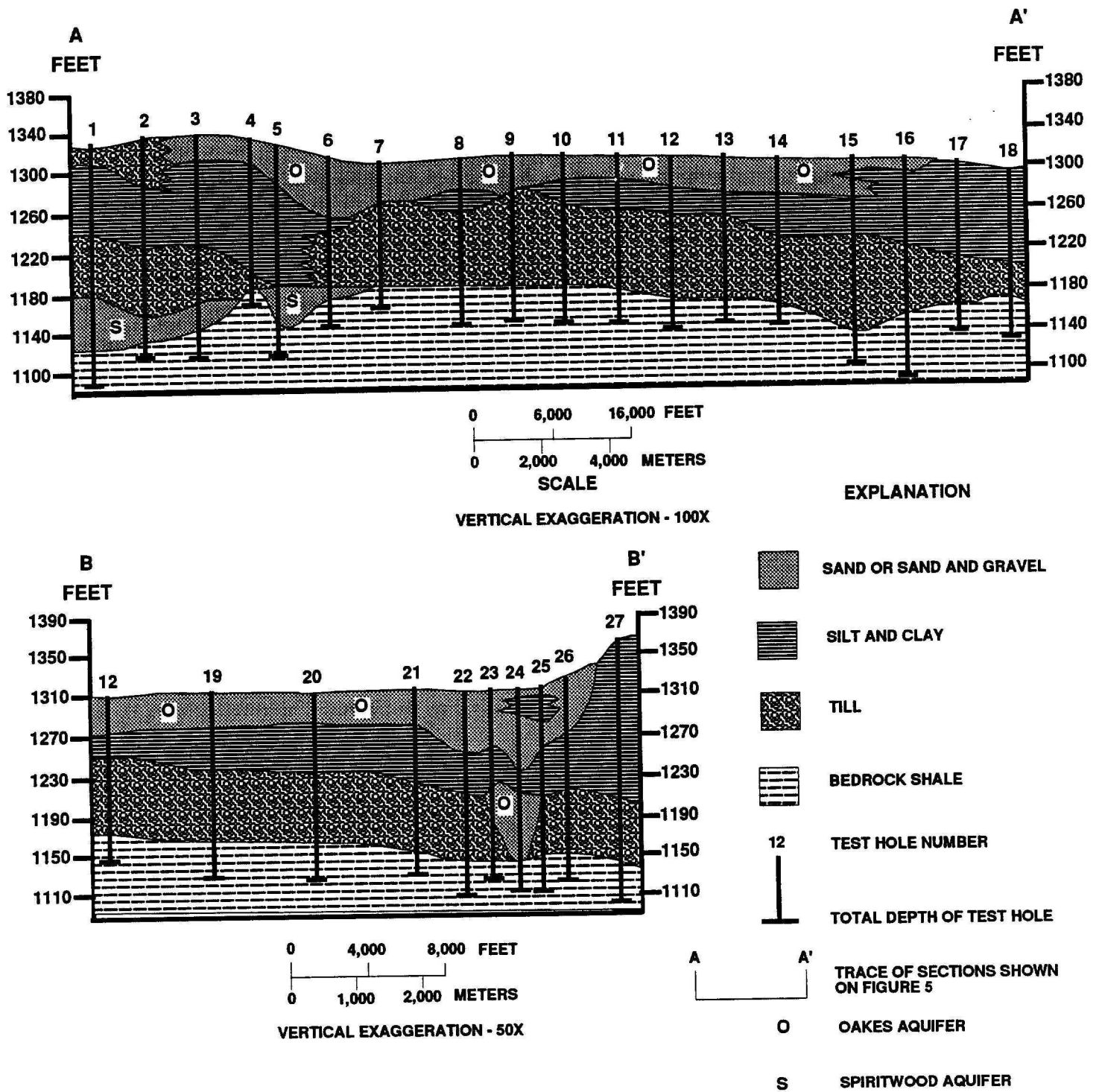
Figure 4. -- Geologic sections A-A' and B-B' showing the Oakes aquifer

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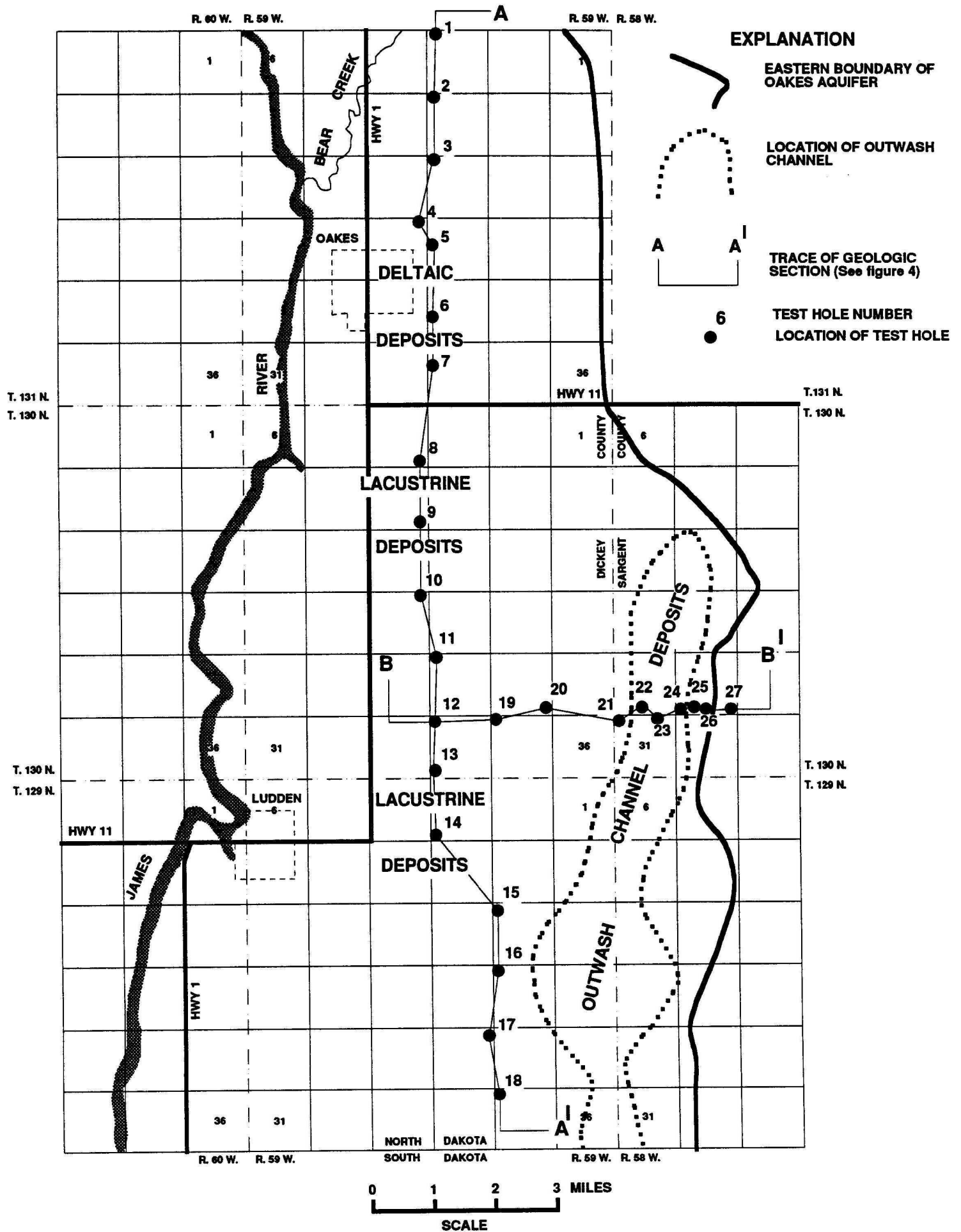
Figure 5. -- Distribution of depositional facies in the Oakes aquifer and location of geologic sections A-A' and B-B'

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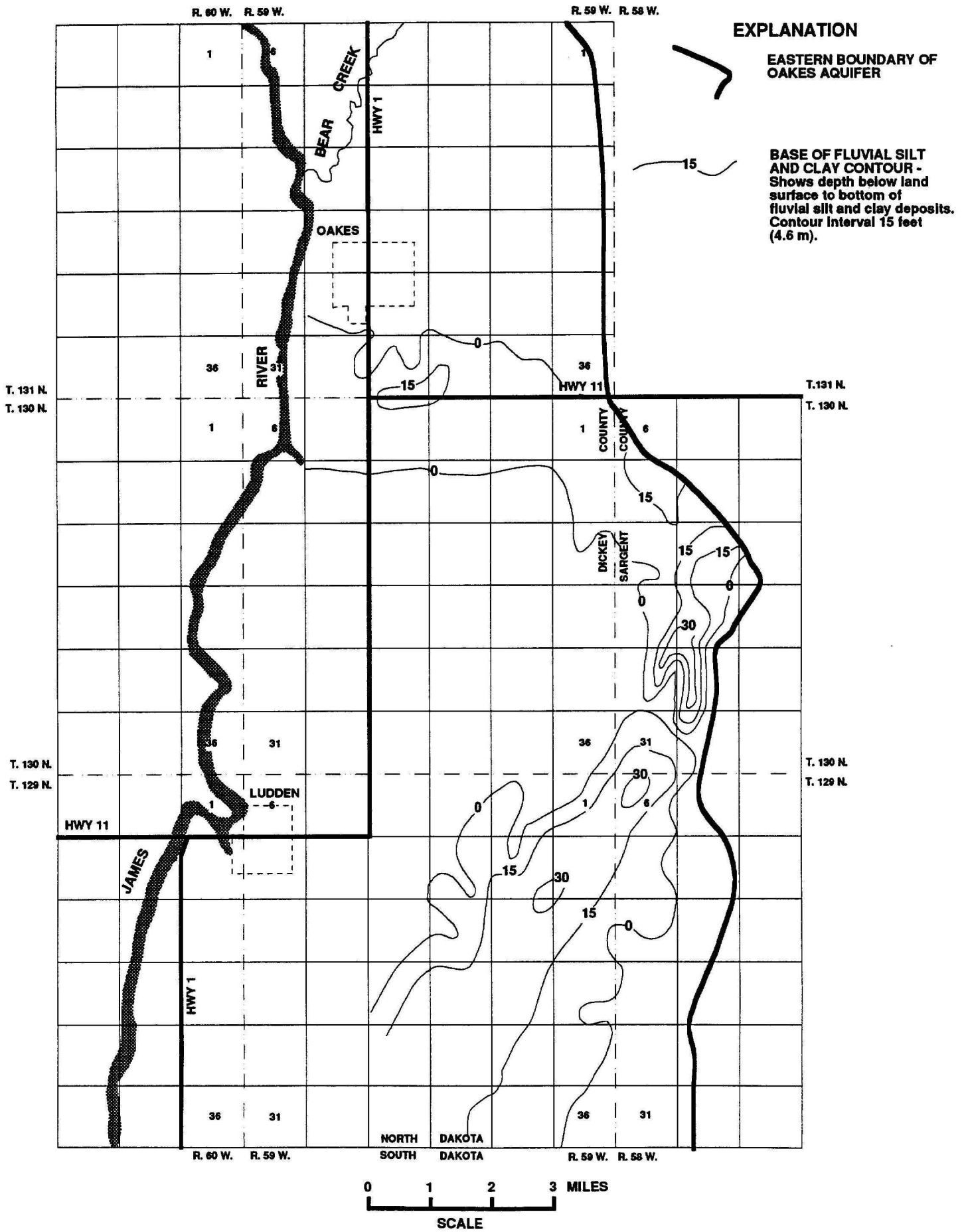
Figure 6. -- Depth below land surface to bottom of fluvial silt and clay deposits

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GROUND-WATER HYDROLOGY OF THE OAKES AQUIFER

Occurrence and Movement of Ground Water

For the most part, the Oakes aquifer is unconfined. Water occurs under leaky confined conditions where fluvial silt and clay sequences overlie the lacustrine and channel-fill deposits (fig. 6).

In general, regional ground-water flow in the Oakes aquifer is from east to west toward the James River valley (fig. 7). The water table configuration shown in figure 7 is a subdued replica of the land-surface topography shown in figure 8. Recent James River valley floodplain deposits that consist of sandy, silty clay truncate the western flank of the Oakes aquifer. As a result, ground-water flow from the Oakes aquifer westward to the James River is negligible.

Throughout much of the Oakes aquifer study area, depth to the water table is less than eight feet. Scattered sand dunes and blowouts cause a hummocky land-surface topography. Shallow water table aquifers in areas of hummocky topography are conducive to development of numerous localized flow systems in which underflow may be insignificant (fig. 9). 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.

Aquifer Hydraulic Properties and Surface Infiltration Rates

The hydraulic conductivity of the deltaic deposits, lacustrine deposits and channel-fill deposits range from about 50 to 250 feet per day, 5 to 100 feet per day, and 125 to 770 feet per day, respectively
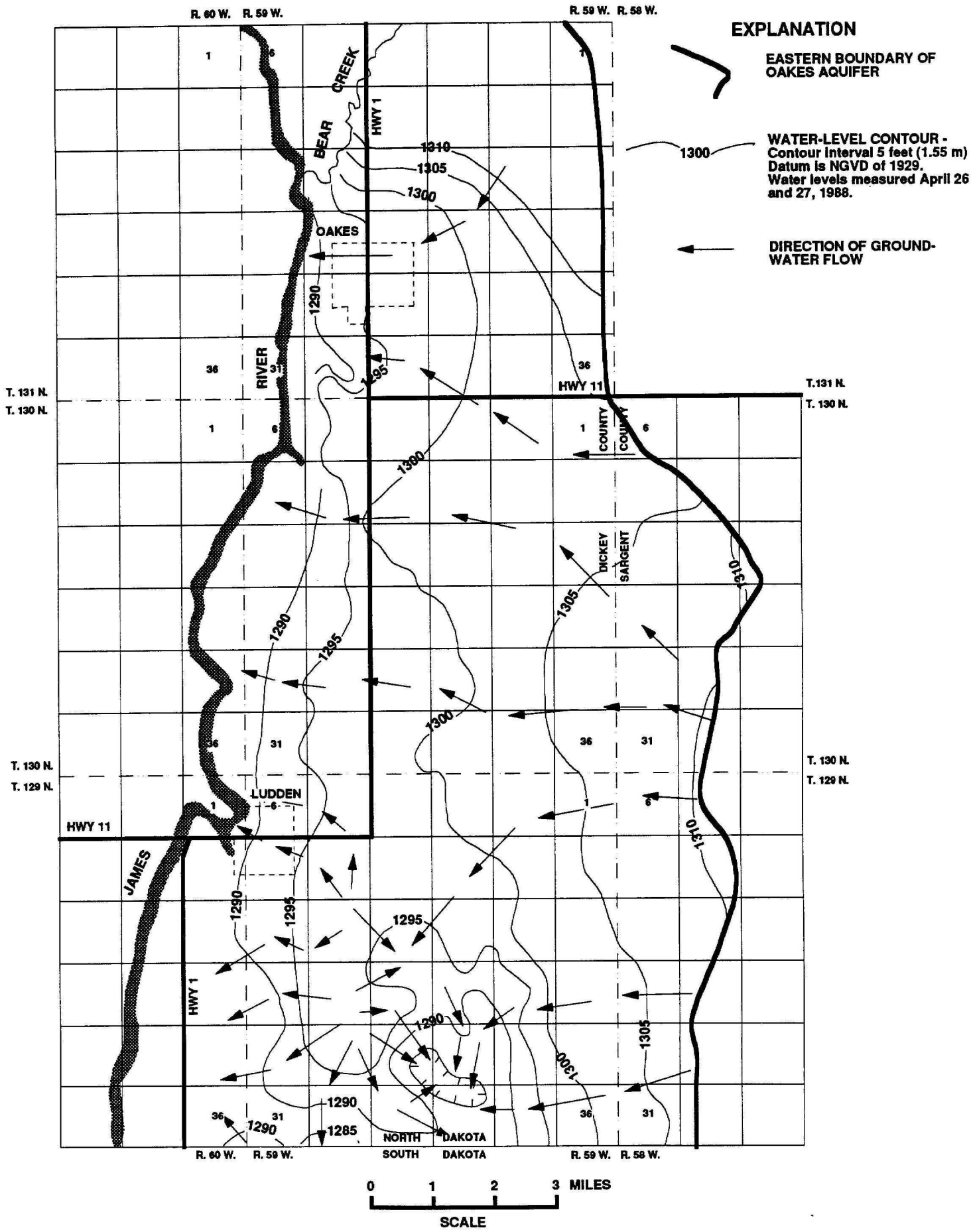
Figure 7. -- Altitude of water table in the Oakes aquifer on April 26 and 27, 1988, and direction of ground-water flow

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Figure 8. -- Land-surface topography in Oakes aquifer study area
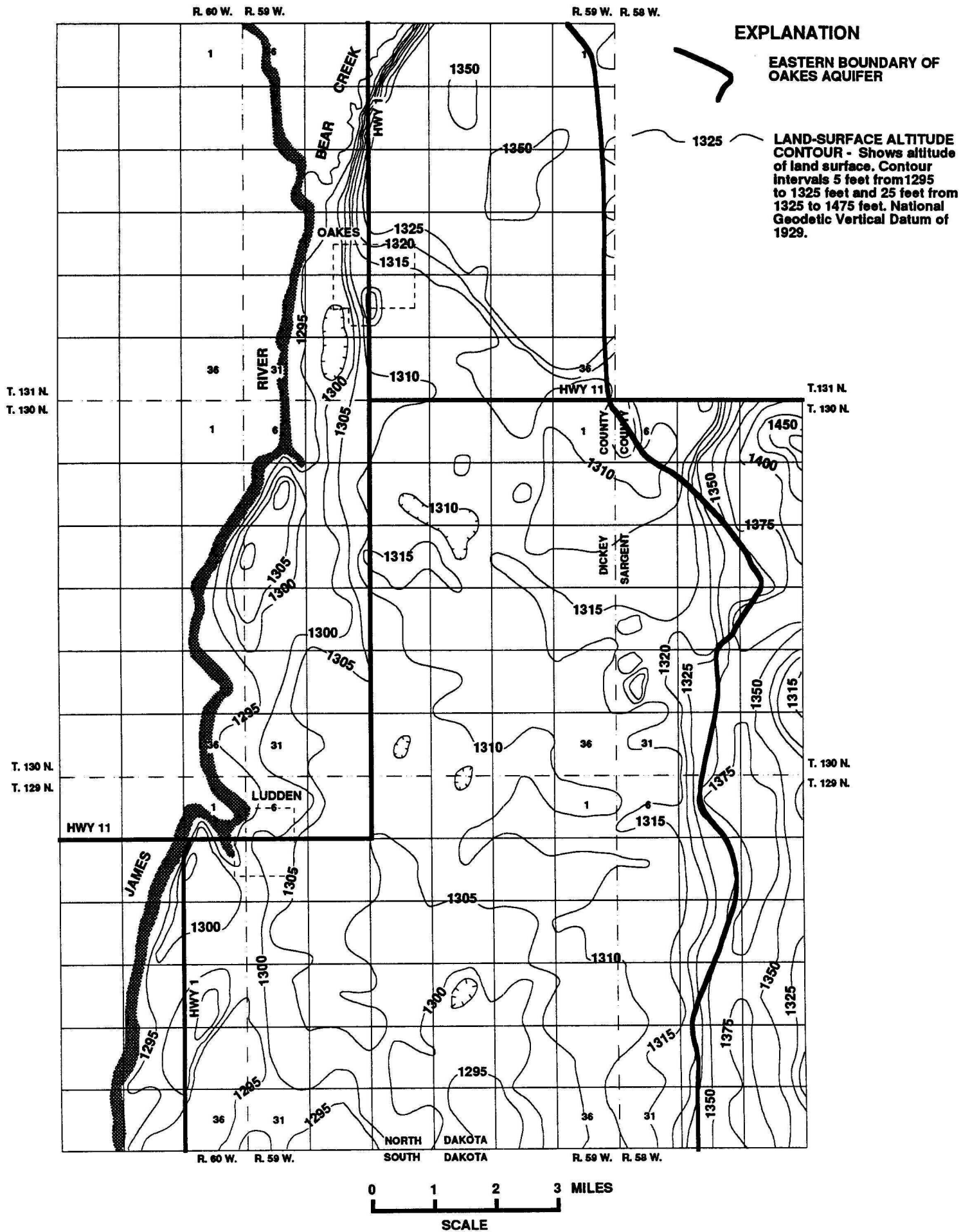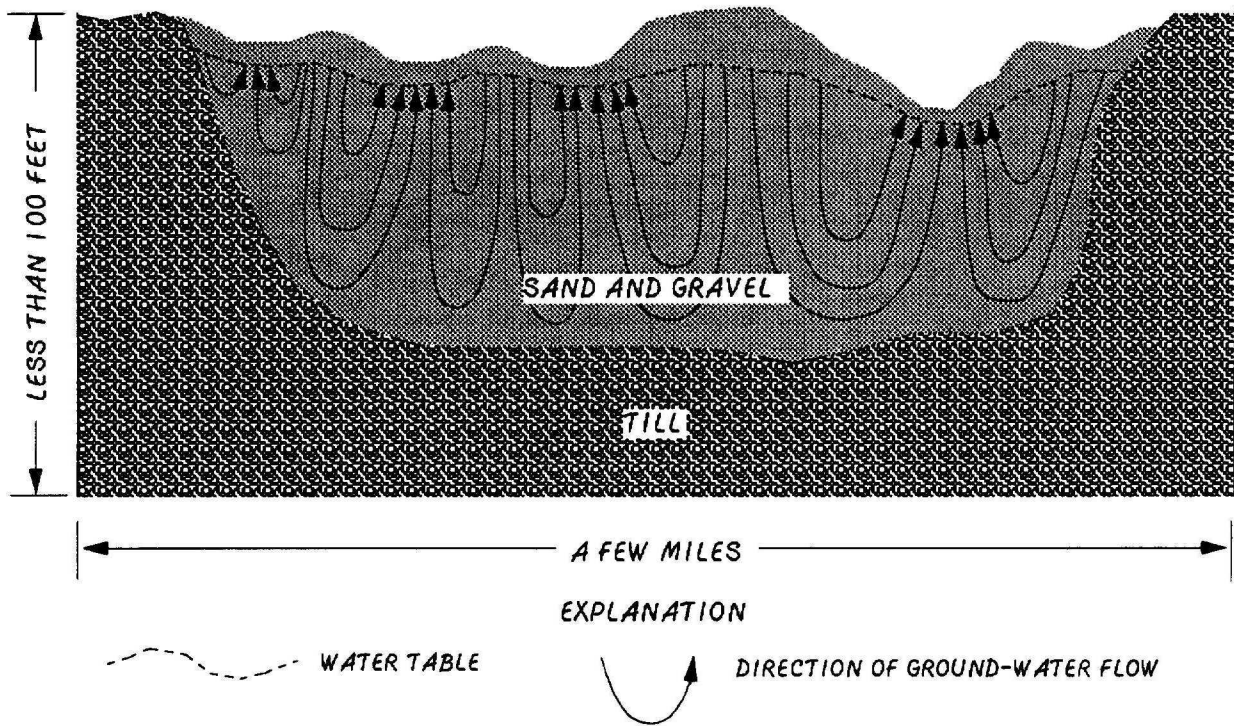
Figure 9. -- Schematic diagram showing a vertical profile of ground-water flow in the Oakes aquifer

(Shaver and Schuh, 1990). Apparent specific yield ranges from about 0.20 to 0.25.

Hecla-Ulen soil associations predominate in the Oakes aquifer study area (Thompson and Sweeney, 1971). Infiltration capacities for these soils are reported at 2.0 to 6.3+ inches per hour (4 to 12.6+ feet per day).

Surface and shallow pit infiltration tests conducted at five sites overlying the Oakes aquifer indicate initial infiltration rates ranging from 2.5 to 67 feet per day (Shaver and Schuh, 1990). Buried-soil horizons that contain up to about 14 percent clay and surficial fluvial silt and clay sequences overlie parts of the lacustrine and outwash channel deposits. In these areas, surface infiltration rates are estimated to be significantly less than one foot per day.

Ground-Water 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. 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 depressions 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

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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 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 (Shaver and Schuh, 1990). 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, thereby increasing the magnitude of the following spring recharge event.

Depth to the water table over much of the study area is less than eight feet. As a result, natural discharge from the Oakes aquifer is due primarily to evapotranspiration during the summer (fig. 10).

Discharge westward to the James River is negligible. Recent James River valley floodplain 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 in the Oakes aquifer toward the James River.

A hydrograph of observation well 129-059-10AAA2 is shown in figure 11. Water-level fluctuations indicate that recharge occurs primarily in the spring from March through May and discharge occurs primarily in the summer from June through August.

EVAPOTRANSPIRATION   PRECIPITATION

JAMES RIVER

OAKES AQUIFER

A FEW MILES

A FEW MILES

EXPLANATION

SAND AND GRAVEL

SILT AND CLAY

TILL
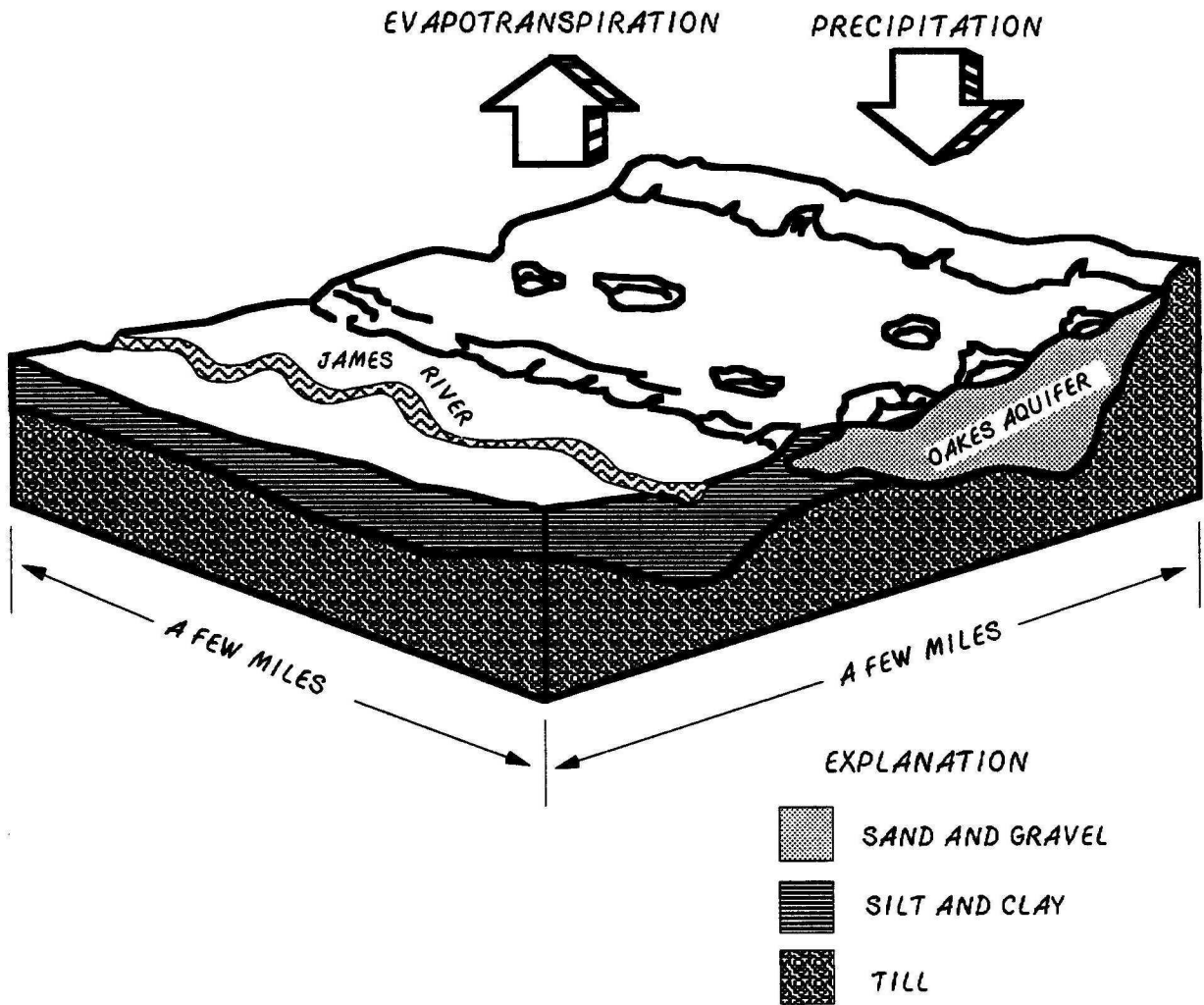
FIGURE 10. -- Schematic diagram showing primary recharge and discharge mechanisms in the Oakes aquifer

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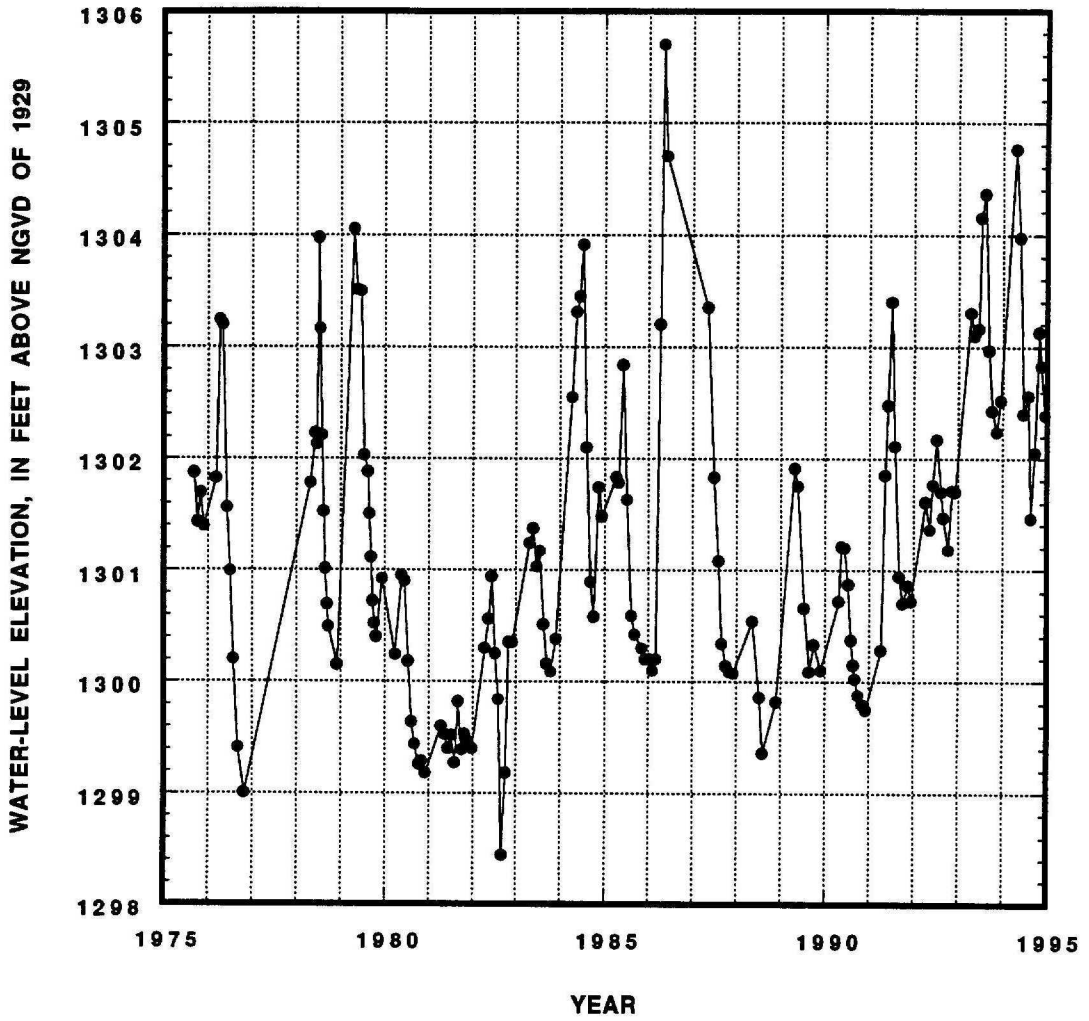
Figure 11. -- Hydrograph of observation well 129-059-10AAA2
completed in the Oakes aquifer

Water Chemistry

The areal distribution of dissolved solids in the Oakes aquifer is shown in figure 12. There are three 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 (fig. 8). In all three areas, depth to water table below land surface generally is greater than five 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 calcium-magnesium-bicarbonate type waters (fig. 13).

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 type water predominates (fig. 13).

Some areas in the Oakes aquifer are characterized by abrupt increases in dissolved-solids concentrations (fig. 12). These areas coincide with land-surface topographic depressions where the depth to water table below land surface generally is less than five feet. The land-surface depressions represent net discharge areas where discharge primarily is by evapotranspiration. Because evapotranspiration is the
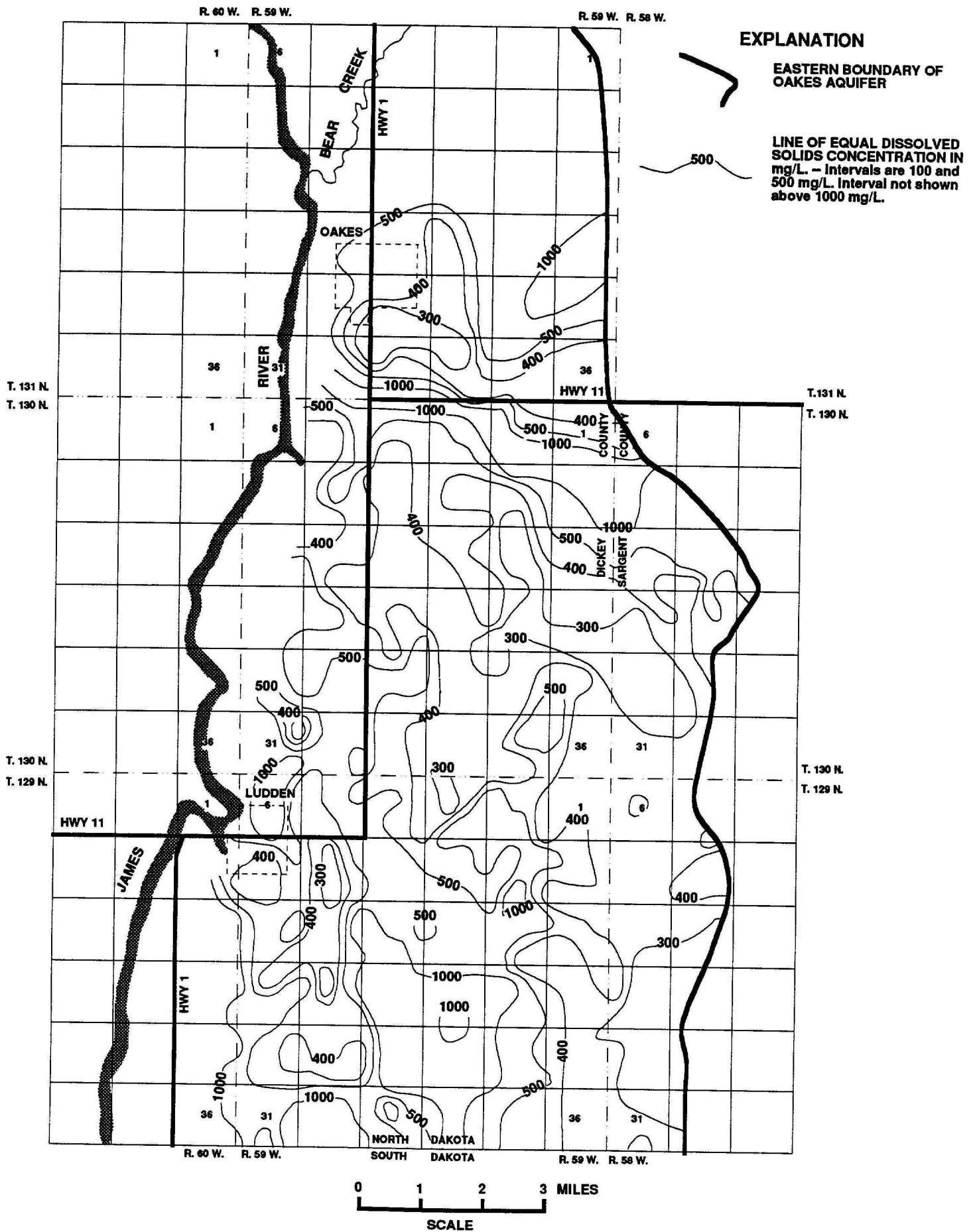
Figure 12. -- Areal distribution of dissolved solids concentrations in the Oakes aquifer

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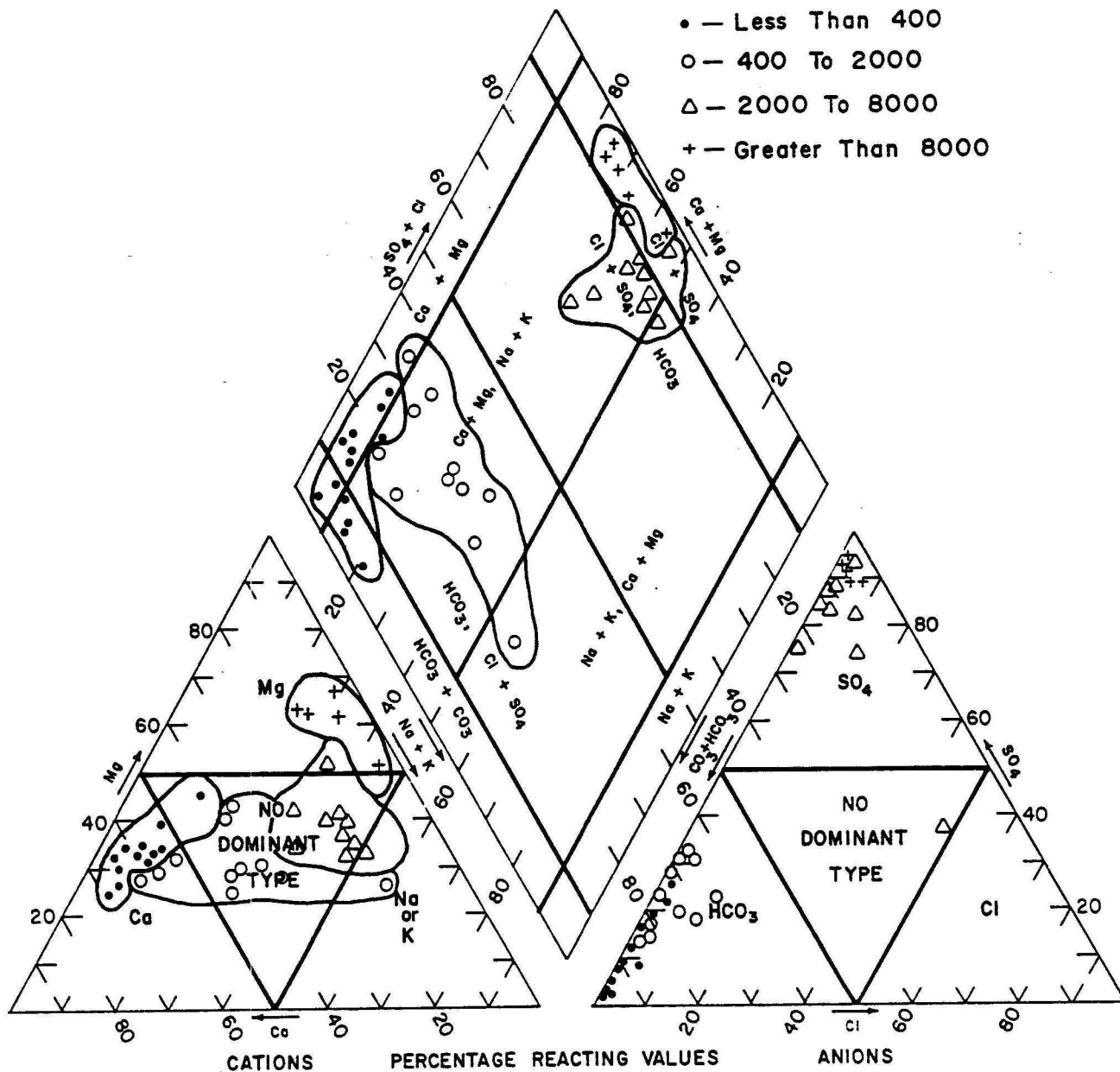
Figure 13. -- Range in ground-water chemistry in the Oakes aquifer

primary discharge mechanism, the local 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 water type predominates (fig. 13).

NOTATION FOR EXPRESSING STABLE ISOTOPE RATIO VARIATIONS

The absolute abundance ratio of isotopes is not usually measured in natural waters (Gonfiantini, 1981). Only the relative difference in the ratio of the heavy isotope to the more abundant light isotope of the sample with respect to a reference is determined. This difference is designated by the Greek letter δ and by definition is:

$$\delta = \frac{R \text{ sample } - R \text{ reference}}{R \text{ reference}} \qquad (1)$$

where the R's are, in the case of water, the $^{18}O/^{16}O$ and the $^2H/^1H$, isotope concentration ratios. Positive values indicate sample enrichment in the heavy-isotope species with respect to the reference and negative values indicate sample depletion with respect to the reference. Because the differences between samples and the reference are small, δ-values are expressed in per mil differences [$\delta(o/oo) = \delta \times 1000$].

STABLE ISOTOPE FRACTINATION

Stable isotope fractionation is due to slight variations in the physical and chemical properties and is proportional to differences in masses (Faure, 1977). The vapor pressures of the different isotopic molecules of water are inversely proportional to their masses. Therefore, $H_2^1O^{16}$ has a significantly higher vapor pressure than $H_2^2O^{18}$. For this

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reason, water vapor formed by evaporation of liquid water is enriched in ^{16}O and ^{1}H while the remaining water is enriched in O^{18} and H^2 (deuterium). The condensation process in the atmosphere is seemingly described by Rayleigh type equilibrium models (Gat, 1981). When water evaporates from the surface of the ocean, the water vapor is enriched in ^{16}O and ^{1}H because $H_2^1O^{16}$ has a higher vapor pressure than $H_2^2O^{18}$ or water molecules containing deuterium (D). Consequently, the $\delta^{18}O$ and δD values of water vapor in the atmosphere above the oceans are both negative.

The depletion of heavy isotopes in precipitation relative to the oceanic water source is the result of the removal of moisture from the atmosphere (Gat, 1981). Since the removal of vapor from the atmosphere by condensation is affected by cooling, a close relationship with temperature exists. Most features of isotopic data can be explained by the simplistic view that precipitation is formed through a continuous process of cooling of a marine air mass, with some local distortion due to the process of secondary evaporation or the addition of local vapor sources (Gat, 1981).

DISTRIBUTION OF $\delta^{18}O$ AND δD IN PRECIPITATION AT OAKES, NORTH DAKOTA

Craig (1961) demonstrated the systematic worldwide relationship between δD and $\delta^{18}O$ using equation 2.

$$\delta D = 8\,\delta^{18}O + 10 \qquad\qquad (2)$$

Equation 2 defines the global meteoric water line (GMWL). Equation 3, weighted mean global meteroic water line (WMGMWL), developed by Yurtsever and Gat (1981) refined equation 2 using a regression analysis of weighted mean δD and $\delta^{18}O$ values of precipitation from the International Atomic Energy Agency (IAEA) 144 station global network.

$$\delta D_W = (8.17 \pm 0.08)\ \delta^{18}O_W + (10.56 \pm 0.64) \tag{3}$$

The $\delta D - \delta^{18}O$ relationship for precipitation in a given region often differs from the global meteoric water line. Based on eight continental stations in North American, the $\delta D - \delta^{18}O$ relationship for long-term weighted mean values developed by Yurtsever and Gat (1981) is shown by equation 4.

$$\delta D_W = (7.95 \pm 0.22)\ \delta^{18}O_W + (6.02 \pm 3.08) \tag{4}$$

The distribution of $\delta^{18}O$ and δD in 19 Oakes study area precipitation samples from April 2, 1989, to April 16, 1990, is shown in table 2. In addition, the average daily temperature and deuterium excess parameter (d) based on equation 3 are also shown.

TABLE 2. -- Distribution of $\delta^{18}O$ and δD in precipitation at Oakes, North Dakota

SAMPLE DATE	MOISTURE STATE	DAILY TEMPERATURE (DEGREES C)*	δ OXYGEN-18 (o/oo)	δ DEUTERIUM (o/oo)	DEUTERIUM EXCESS** (d) (WMGMWL)
4/2/89	rain	5.0	-10.2	-67.0	16.3
4/25/89	rain	12.2	-10.4	-73.0	12.0
5/17/89	rain	19.4	-6.1	-50.0	-0.16
5/23/89	rain	17.8	-6.2	-38.0	12.7
6/11/89	rain	19.4	-5.9	-43.0	5.2
6/21/89	rain	23.3	-6.3	-41.0	10.5
7/11/89	rain	24.4	-3.5	-24.0	4.6
7/28/89	rain	23.3	-6.4	-43.0	9.3
8/19/89	rain	21.1	-7.2	-45.0	13.8
8/30/89	rain	17.2	-8.1	-64.0	2.2
9/20/89	rain	17.2	-8.7	-61.0	10.1
11/4/89	snow	-2.2	-21.5	-165.0	10.2
11/22/89	snow	-8.3	-18.6	-130.0	22.0
11/27/89	snow	-2.2	-21.7	-161.0	16.3
1/17/90	snow	-2.2	-19.9	-149.0	13.6
2/16/90	snow	-12.8	-25.0	-189.0	15.3
3/14/90	snow	2.2	-11.2	-70.0	21.5
3/16/90	snow	-1.7	-21.0	-159.0	12.6
4/16/90	snow	7.8	-22.4	-177.0	6.0

* Computed by: (maximum daily temperature + minimum daily temperature) /2

** Weighted mean global meteoric water line (Gat, 1981) $\delta D = 8.17\delta O^{18} + 10.56$

The relationship between $\delta^{18}O$ and δD in the 19 precipitation samples is shown by the linear regression analysis in figure 14. Equation 5 is the regression equation which describes the local meteoric water line.

$$\delta D = (7.83 \pm 0.38) \, \delta^{18}O + (6.99 \pm 5.53) \tag{5}$$

Table 3 summarizes the precipitation regression analysis. The slopes of equations 2, 3, and 4 are within the upper 95 percent confidence band for the slope of equation 5 indicating similarity with the global and North American meteoric water lines.
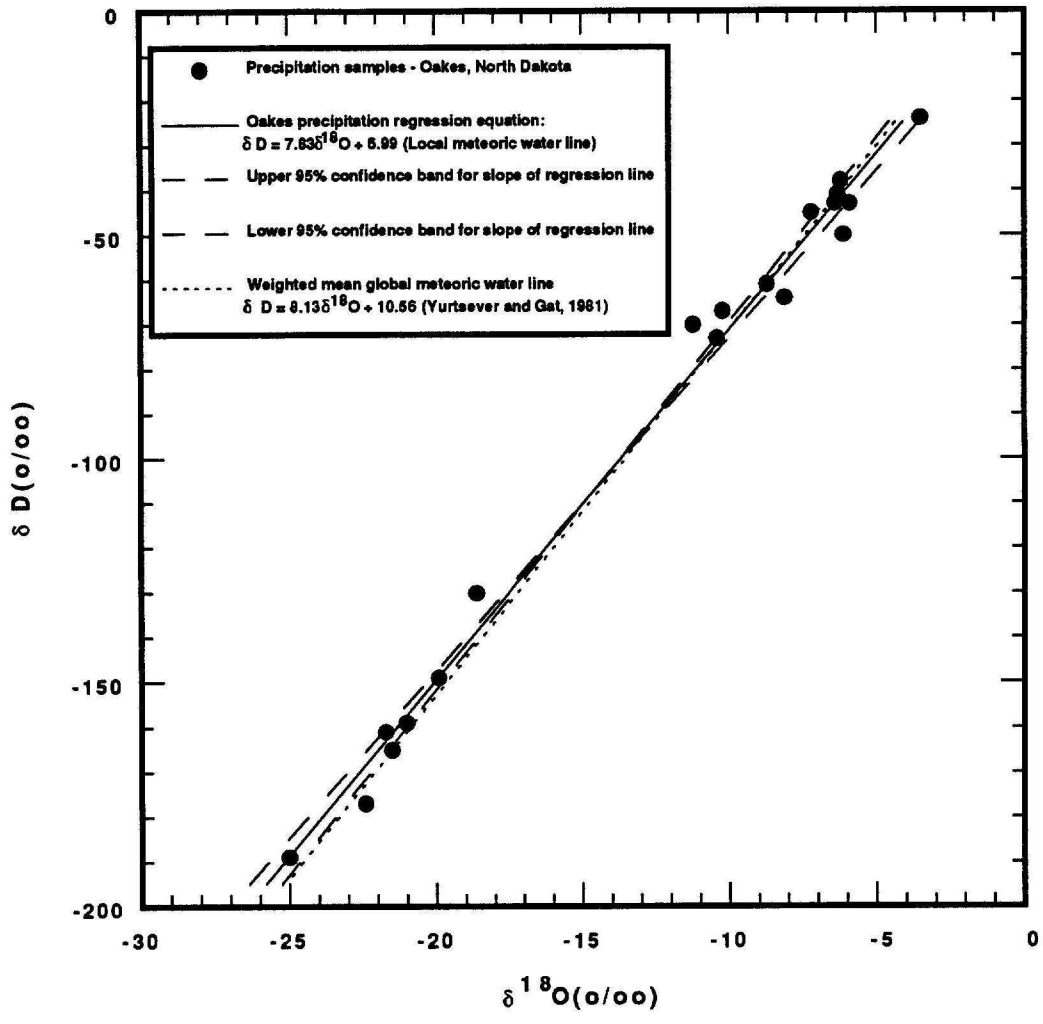
Figure 14. -- Oakes aquifer study area local meteoric water line and the weighted mean global meteoric water line (from Yurtsever and Gat, 1981)

Table 3. -- Summary of Oakes $\delta^{18}O$ and δD precipitation regression analysis

Number of Samples (N)	Slope of Regression Line	Upper 95% Confidence Band of Slope	Lower 95% Confidence Band of Slope	Y-Intercept	Upper 95% Confidence Band of Y-Intercept	Lower 95% Confidence Band of Y-Intercept	R	R^2
19	7.83	8.21	7.45	6.99	12.52	1.46	0.995	0.991

RELATIONSHIP BETWEEN $\delta^{18}O$ AND δD AND MOISTURE STATE

Precipitation δD values range from -24.0 to -189.0 and $\delta^{18}O$ values range from -3.5 to -22.4 (table 2). The large range in $\delta^{18}O$ and δD reflect both seasonal variations and the fact that the study area derives its moisture from three different sources: the Pacific Ocean, the Arctic Ocean, and the Gulf of Mexico.

A regression analysis of the 11 rain samples is shown in figure 15 and a regression analysis of the 8 snow samples is shown in figure 16. Summaries of both regression analyses are shown in table 4. The rain values display slightly more scatter as compared to snow. For the snow regression equation, the null hypothesis that the y-intercept is not different from zero is rejected at a 1.2 percent level of significance and it is concluded that the y-intercept of 30.98 is different from zero. For the rain regression equation, there is no basis to reject the null hypothesis that the y-intercept of -0.45 is different from zero. Based on the above, there is a statistical difference between the y-intercepts of the regression equations.
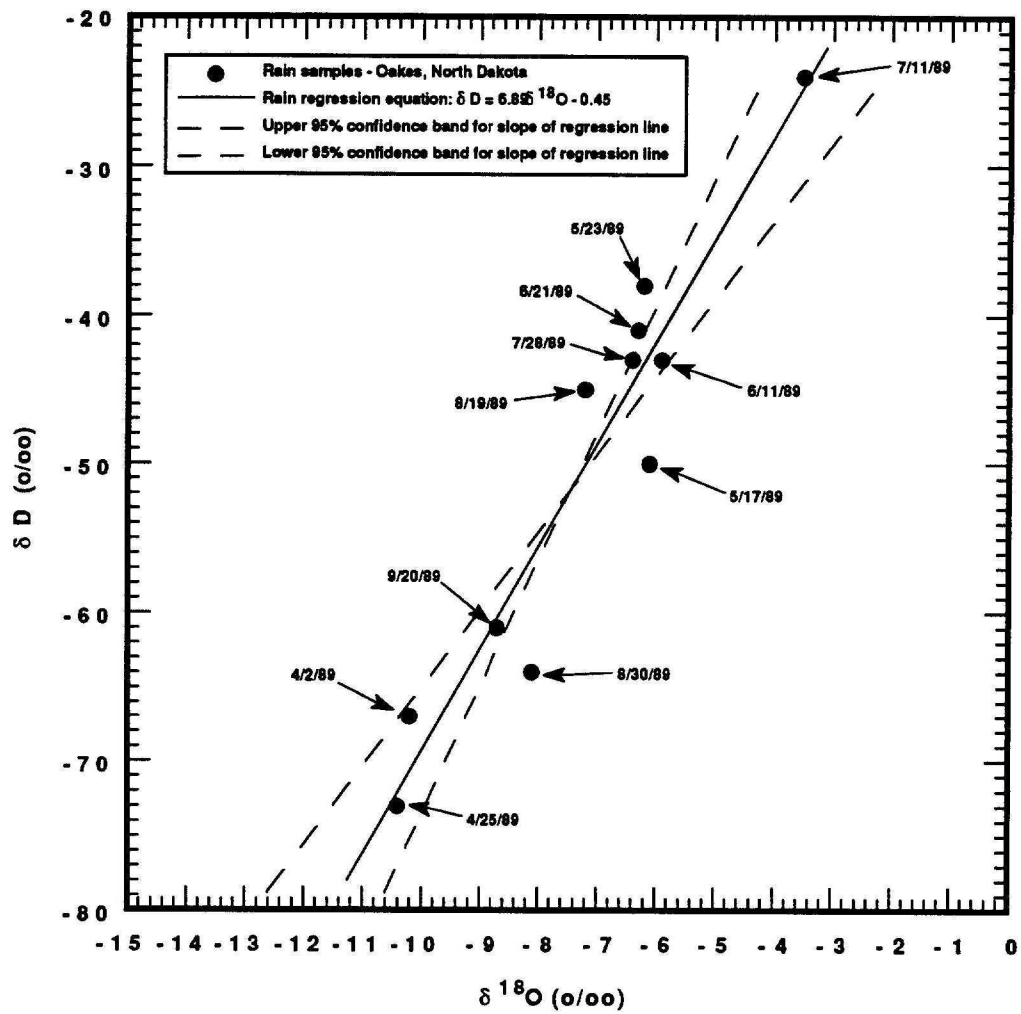
Figure 15. -- $\delta^{18}O$ **and** δD **composition of rain at Oakes, North Dakota and associated regression equation**
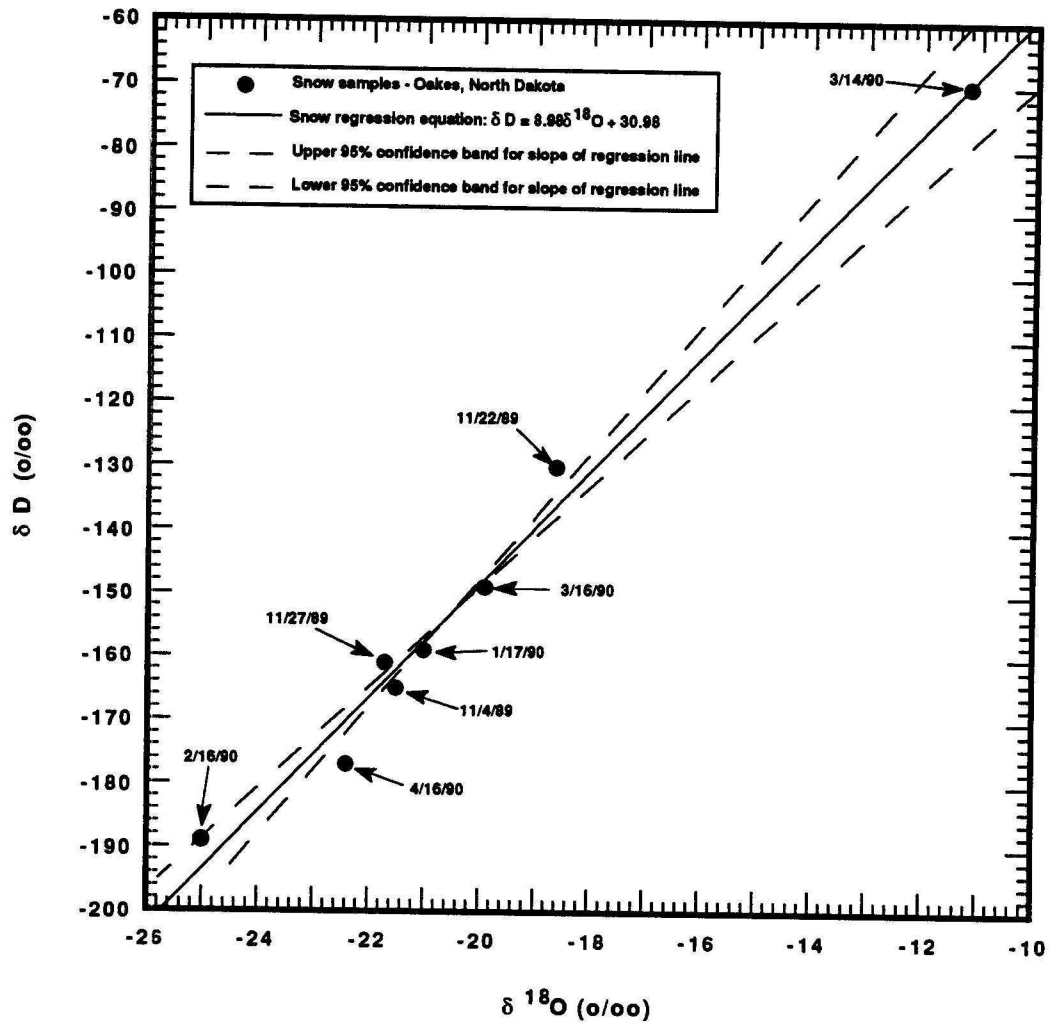
Figure 16. -- $\delta^{18}O$ and δD composition of snow at Oakes, North Dakota and associated regression equation

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Table 4. -- Summary of Oakes $\delta^{18}O$ and δD rain and snow regression analyses

Number of Samples (N)	Slope of Regression Line	Upper 95% Confidence Band of Slope	Lower 95% Confidence Band of Slope	Y-Intercept	Upper 95% Confidence Band of Y-Intercept	Lower 95% Confidence Band of Y-Intercept	R	R^2
Rain 11	6.89	8.54	5.24	-0.45	11.84	-12.74	0.95	0.91
Snow 8	8.98	10.01	7.94	30.98	52.17	9.78	0.99	0.99

Fritz and others (1987), demonstrated that the y-intercepts of the meteoric water lines show a clear break between Prairie stations in Canada and stations in Ontario and Eastern Canada. The Prairie stations are characterized by lower intercepts. In addition, y-intercepts of summer precipitation are smaller than those associated with winter precipitation. The difference in slopes and intercepts between summer and winter precipitation regression equations is attributed to different meteorological regimes and local processes which modify the isotopic composition of vapor and/or precipitation (Fritz and others, 1987). An example of a local process would be evaporation in falling raindrops, particularly during the summer, which would cause enrichment in both $\delta^{18}O$ and δD.

DEUTERIUM EXCESS

Deuterium excess, d, is defined as (Dansgaard, 1964)

$$d = \delta D - 8\, \delta^{18}O \tag{6}$$

If precipitation follows the global meteoric water line of Craig (1961) (equation 2), d should be close to 10. In this paper the weighted mean global meteoric water line of Yurtsever and Gat (1981) (equation 3) is used to calculate d. Equation 7 defines d as follows:

$$d = \delta D - 8.17\,\delta^{18}O \qquad\qquad (7)$$

If precipitation follows the weighted mean global meteoric water line of Yurtsever and Gat (1981), d should be close to 10.56.

Merlivat and Jouzel (1979) developed a theoretical model to account for the $\delta^{18}O$ and δD relationship measured in meteoric waters. Based on numerical examples the $\delta^{18}O$ and δD relationship measured for precipitation samples in nature depends mainly on the physical characteristics of the air masses at the origin of precipitation. The deuterium excess was found to be primarily dependent on the mean relative humidity of the air masses formed above the ocean surface.

A statistical summary of the d distributions of rain and snow is shown in table 5. The mean d for rain is 5.97 0/00 smaller than the mean d for snow.

Table 5. -- **Statistical summary of deuterium excess in rain and snow at Oakes, North Dakota**

	N	Mean	Variance	Standard Deviation	Standard Error
Rain	11	8.78	26.60	5.16	1.56
Snow	8	14.75	28.53	5.34	1.89

An analysis of variance (ANOVA) was used to calculate how much of the d variability in the 19 precipitation samples could be attributed to moisture state (rain-snow). Snow and rain d distributions are considered normal because probability plots of both distributions are approximately linear (figs. 17 and 18). Application of the Bonferroni/Dunn procedure to the ANOVA indicates that at a 2.5 percent level of significance, the mean
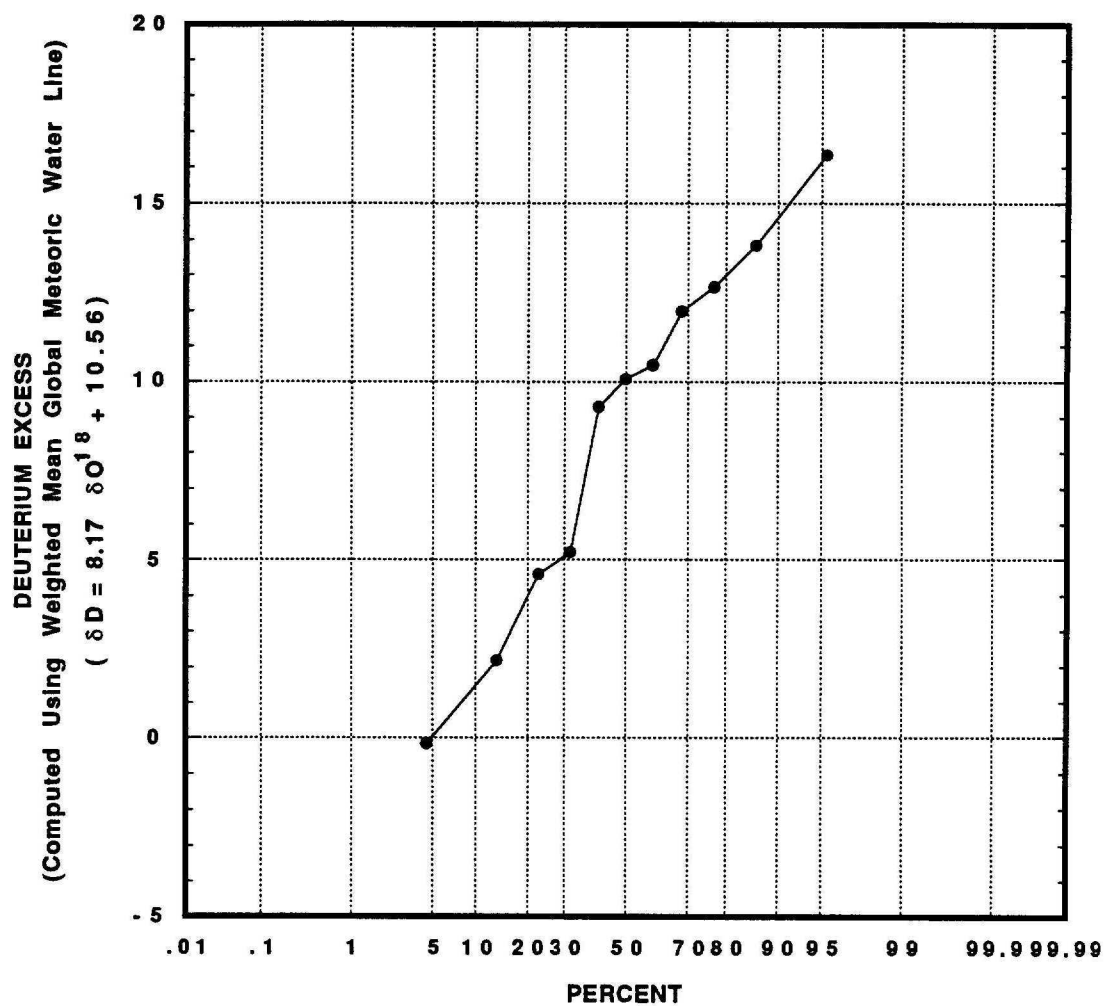
Figure 17. -- Probability plot of deuterium excess in rain at Oakes, North Dakota
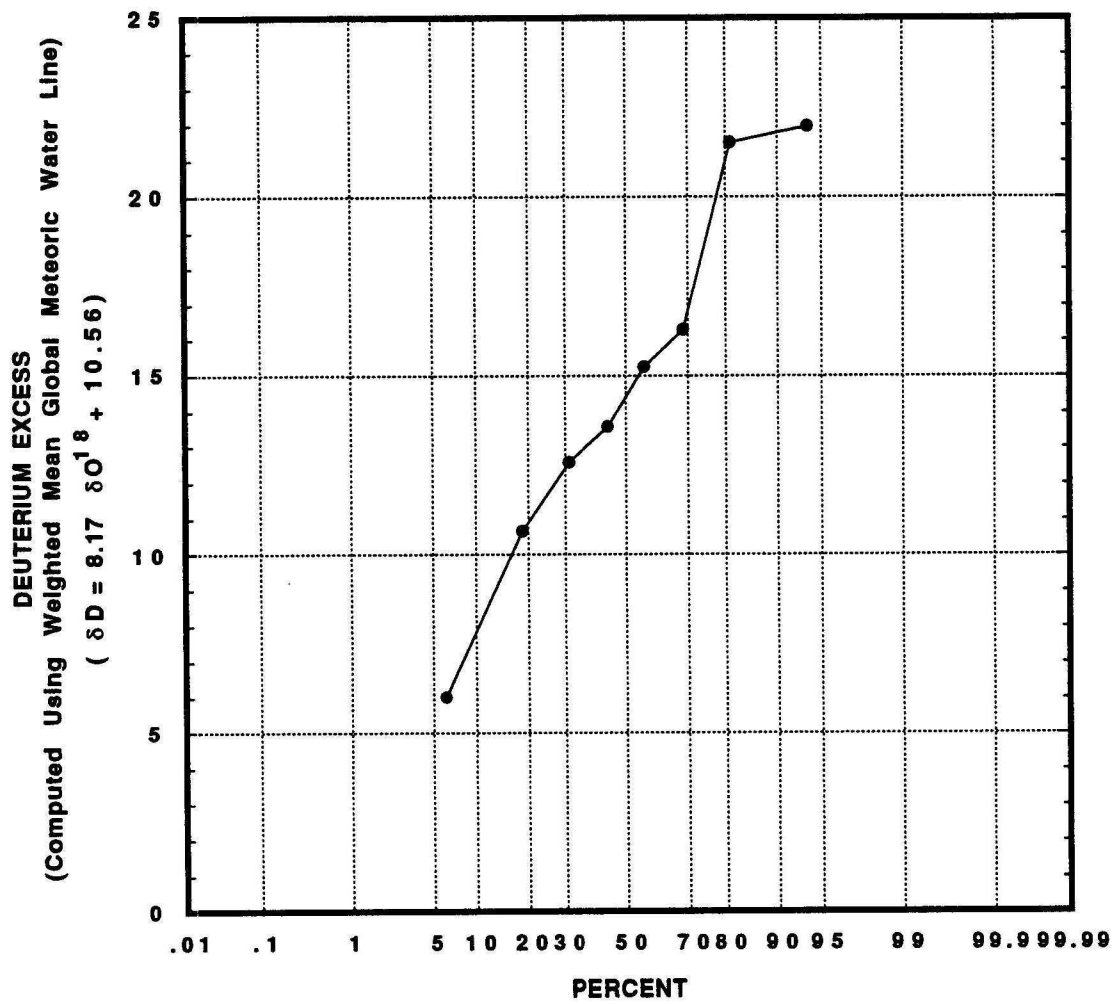
Figure 18. -- Probability plot of deuterium excess in snow at Oakes, North Dakota

d value for snow differs from the mean deuterium excess value for rain (table 6.)

Table 6. -- ANOVA for deuterium excess in rain and snow at Oakes, North Dakota

Moisture State (rain - snow)	Sum of Squares	Mean Square	F-Value	Mean Difference	P-Value
	165.28	165.28	6.03	-5.97	0.025

Fritz and others (1987) showed that western Canadian stations have distinctly lower d values than the eastern Canadian stations and that the differences are retained if seasonal precipitation is considered. Thus, they concluded the distribution of d is most likely, although not exclusively, the result of different meteorological regimes over Canada. The relatively large d values from winter precipitation shown by Fritz and others (1987) in the interior plains of Canada and those associated with snow in the Oakes study area suggest that winter precipitation is strongly influenced by relatively low-humidity, Arctic, air masses. The lower deuterium excess values for rain in the Oakes study area suggest that rainfall events, particularly those during the summer, are more strongly influenced by relatively high-humidity air masses that originate over the Gulf of Mexico.

RELATIONSHIP BETWEEN TEMPERATURE AND $\delta^{18}O$ CONTENT OF PRECIPITATION

Yurtsever and Gat (1981) demonstrated that the month-to-month variation of the $\delta^{18}O$ content is well correlated with temperature changes. The relationship between monthly values of $\delta^{18}O$ in

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precipitation and of temperature for four European stations (Thule, Groennedal, Nord, and Vienna) is defined by equation 8.

$$\delta^{18}O = (0.521 \pm 0.014)\ T - (14.959 \pm 0.208) \qquad (8)$$

The correlation coefficient (r) is 0.89 which means that 80 percent of the variations in the $\delta^{18}O$ composition of monthly precipitation can be explained by temperature variations.

Using western Canada climate stations (Edmonton, Wynyard, and Gimli) Fritz and others (1987) derived a relationship between average annual air temperature and weighted mean $\delta^{18}O$ values shown by equation 9.

$$\delta^{18}O = (0.49 \pm 0.12)\ T - (17.25 \pm 0.54) \qquad (9)$$

where T = mean annual air temperature in degrees centigrade

The relationship between average daily temperature during the 19 precipitation events at Oakes and $\delta^{18}O$ is shown in figure 19 and is described by equation 10.

$$\delta^{18}O = (0.55 \pm 0.14)\ T - (17.85 \pm 2.02) \qquad (10)$$

A summary of the regression analysis is provided in table 7. The correlation coefficient for equation 10 is 0.90 which means that 81 percent of the variations in the $\delta^{18}O$ composition of individual precipitation events can be explained by temperature variations. The slopes and y-intercepts of equations 9 and 10 are similar. The 95
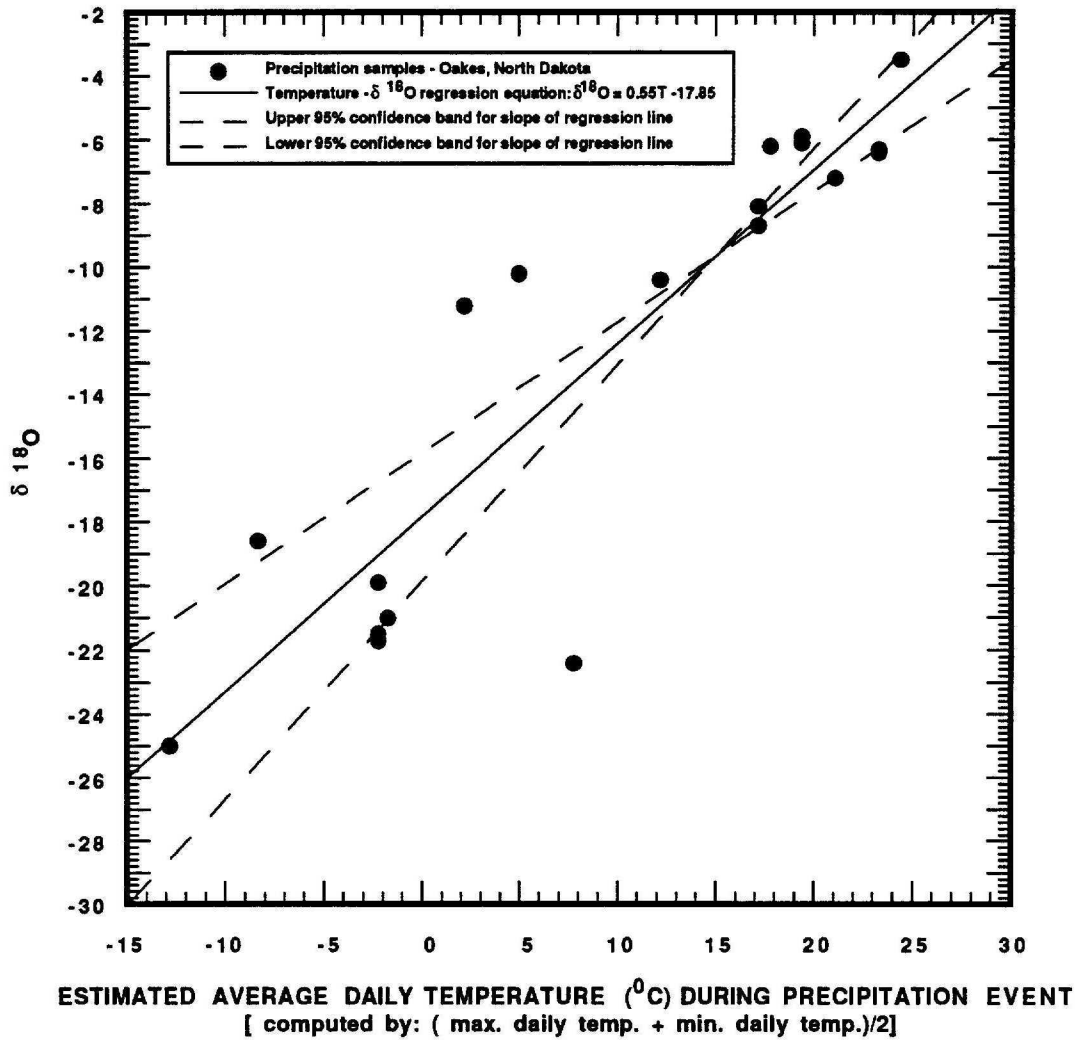
Figure 19. -- Relationship between average daily temperature during a precipitation event and $\delta^{18}O$

percent confidence band of the y-intercept is about twice as large for equation 10 as compared to that of equation 9. This probably reflects the difference in sample size between the Oakes data set and the data set for western Canada.

Table 7. -- Summary of regression analysis of average daily temperature during precipitation event and $\delta^{18}O$ at Oakes, North Dakota

Number of Samples (N)	Slope of Regression Line	Upper 95% Confidence Band of Slope	Lower 95% Confidence Band of Slope	Y-intercept	Upper 95% Confidence Band of Y-intercept	Lower 95% Confidence Band of Y-intercept	R	R^2
11	0.545	0.680	0.411	-17.848	-15.828	-19.869	0.90	0.81

DISTRIBUTION OF $\delta^{18}O$ AND δD IN PONDS AND SLOUGHS IN THE OAKES AQUIFER STUDY AREA

Samples were collected for $\delta^{18}O$, δD, and major cation-anion analysis from three ponds and two intermittent sloughs in the Oakes aquifer study area on April 5, 1989 (fig. 20). The data are summarized in table 8. The ponds varied in area from about 3,000 to 20,000 square feet. The intermittent sloughs are about one square mile in area.

Table 8. -- $\delta^{18}O$ and δD, dissolved-solids , and sulfate concentrations in ponds and sloughs in the Oakes aquifer study area

Pond/Slough Location	$\delta^{18}O$ (o/oo)	δD (o/oo)	Dissolved-Solids Concentration (mg/L)	Sulfate Concentration (mg/L)
129-059-03DAD	-18.4	-141	No Sample	No Sample
129-059-08DCD	-18.1	-141	52	0.8
129-059-27BBB	-18.8	-141	179	60
130-059-03DAA	-18.1	-140	216	57
130-059-30DDA	-17.7	-137	135	1.6

The range in $\delta^{18}O$ and δD values is small and there is no correlation between these values and dissolved solids concentration or sulfate (table 8). In addition, the $\delta^{18}O$ and δD values of the pond and slough samples plot close to and just beneath the local meteoric water
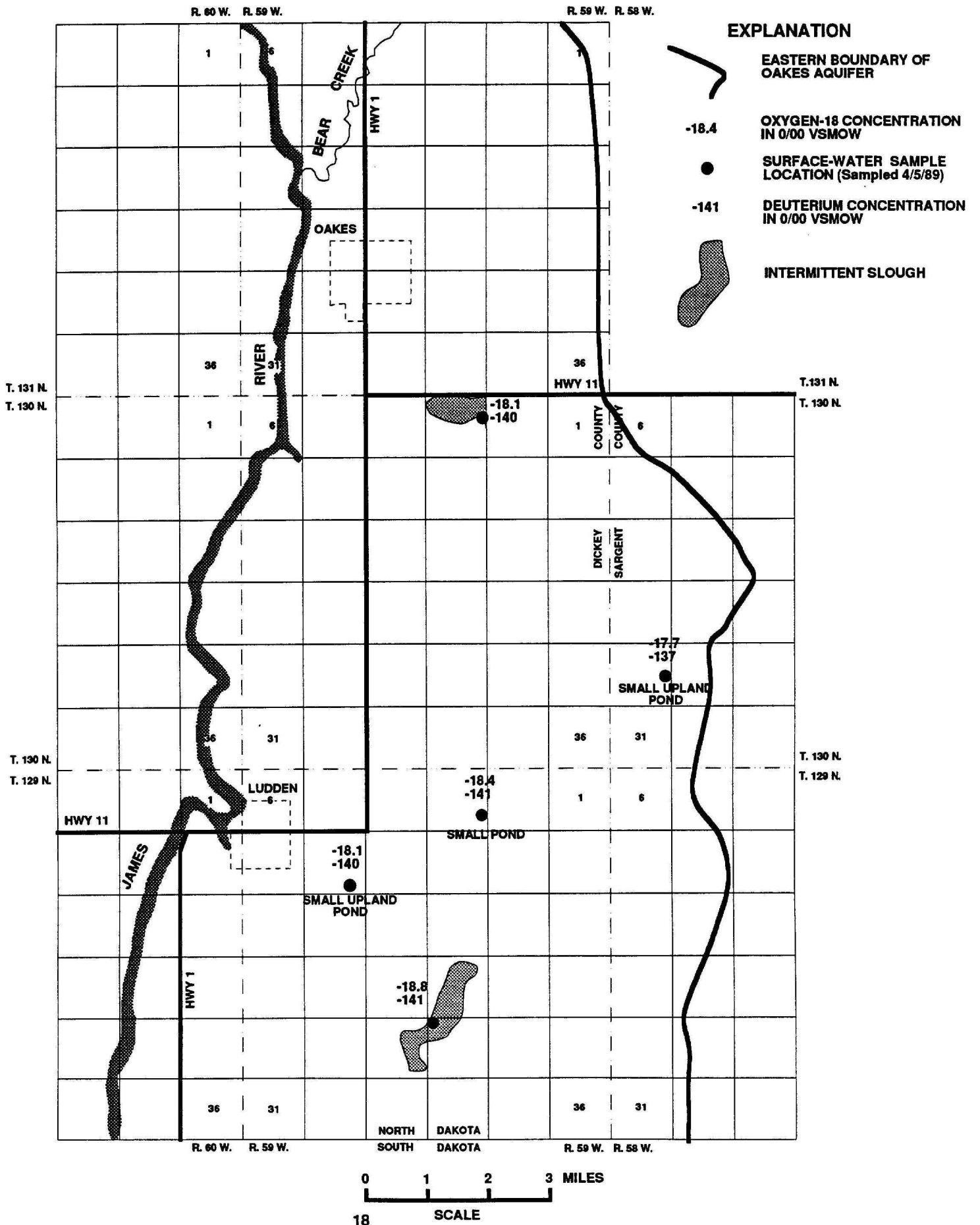
Figure 20. -- Concentration of δO and δD in ponds and intermittent sloughs

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line near more depleted values associated with winter precipitation (fig. 21). Based on the above, pond and slough water is derived primarily from spring snowmelt, and any evaporation from these surface-water bodies up until the time of sampling is minor. The higher salinity water within the two intermittent sloughs appears to be derived from leaching of mineral deposits formed at land surface and in the unsaturated zone during the previous summer when evapotranspiration exceeded precipitation. Williams (1984) identified calcite and gypsum in surficial clays associated with the intermittent slough at 130-059-03DAA. During late summer, white crusts form on soil surfaces in the intermittent slough areas (personal observations). These crusts probably consist in large part of highly soluble evaporite minerals such as gypsum ($CaSO_4 \cdot 2H_2O$), epsomite ($MgSO_4 \cdot 7H_2O$), hexahydrite ($MgSO_4 \cdot 7H_2O$), and konyaite ($Na_2 Mg(SO_4)_2 \cdot 5H_2O$) (Keller, and others, 1986). During the spring snow-melt period, these highly soluble minerals dissolve as the intermittent sloughs continue to fill up with local runoff.

DISTRIBUTION OF $\delta^{18}O$ AND δD IN GROUND WATER IN THE OAKES AQUIFER STUDY AREA

Ground Water $\delta^{18}O$ and δD in Relation to the Meteoric Water Line

Between May 16 and June 7, 1989, 32 ground-water samples were collected in the Oakes aquifer study area for major cation-anion, $\delta^{18}O$ and δD analysis (table 9). Twenty-nine samples were collected from monitoring wells completed in the Oakes aquifer. Two samples were collected from monitoring wells completed in till underlying the Oakes aquifer and one sample was collected from a monitoring well completed

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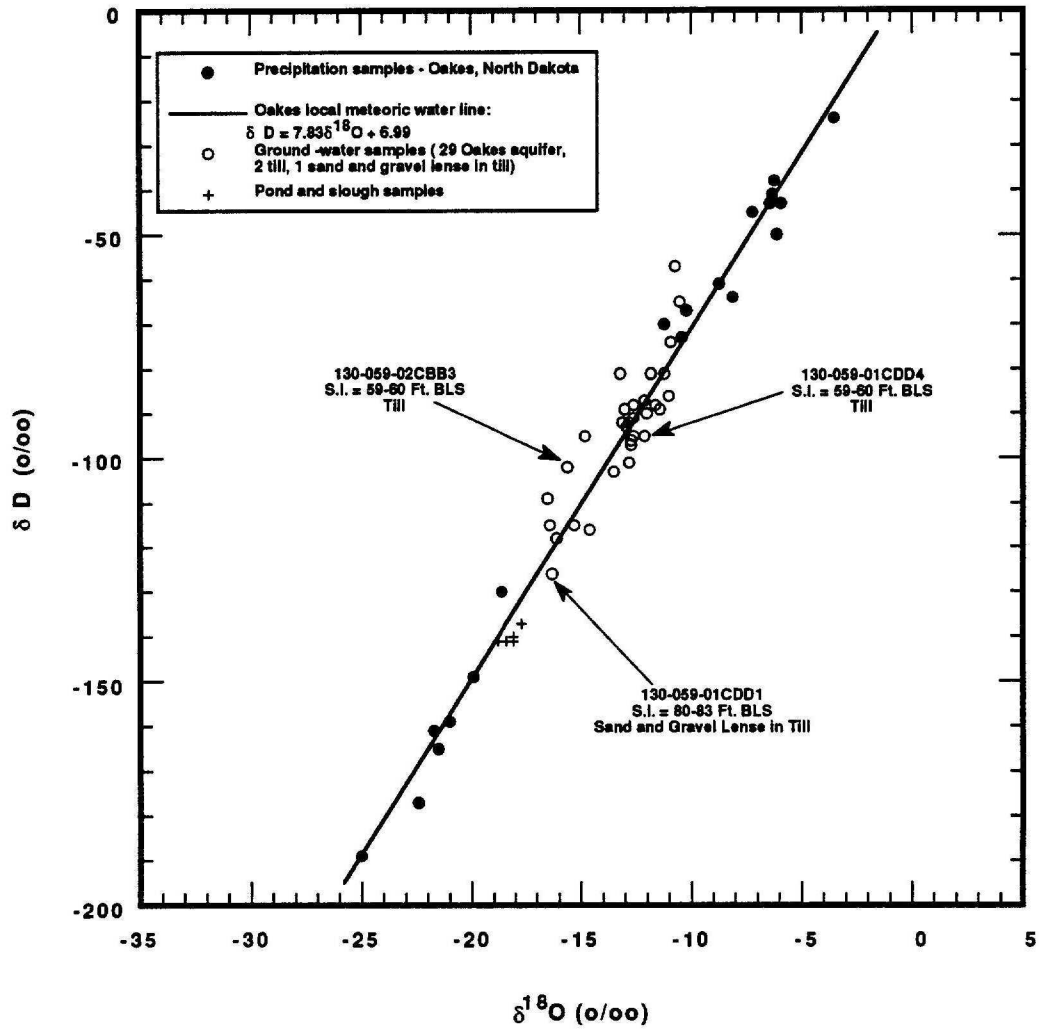
Figure 21. -- $\delta^{18}O$ **and** δD **composition of ground water, ponds, and sloughs in relation to the local meteoric water line**

Table 9. -- $\delta^{18}O$, δD and other selected data for ground-water sample sites in the Oakes aquifer study area

Location	Date Sampled (mo/d/yr)	Screened Interval (ft. bls)	Water Level (ft. bls)	Depth of Top of Screen Below Water Table (ft.)	$\delta^{18}O$ (o/oo)	δ Deuterium (o/oo)	Deuterium Excess (d=δD+8.17δ^{18}O)	Sulfate (mg/L)	Dissolved Solids Concentration (mg/L)
130-059-02CBB1	5/16/89	30-31	9.0	21	-12.7	-97	6.8	3000	4850
130-059-02CBB2	5/16/89	14-16	9.0	5	-16.1	-118	13.5	180	642
130-059-02CBB3	5/16/89	59-60	9.0	50	-15.6	-102	25.5	1300	2590
130-059-23CCC3	5/18/89	18-20	7.4	11	-16.5	-109	25.8	25	355
130-059-28CCC2	5/19/89	19.4-21.2	6.4	13	-12.7	-96	7.8	160	909
129-059-05DDD2	5/24/89	18.6-19.7	6.7	12	-12.6	-88	14.9	86	597
129-059-09DCC	5/24/89	19.9-21.9	3.9	16	-11.2	-81	10.5	310	1090
129-059-15ABB	5/24/89	18.9-21.1	5.4	14	-10.7	-57	30.4	290	1140
129-059-17ABB	5/25/89	19.3-21.2	6.7	13	-13.5	-103	7.3	34	274
129-059-17DCC	5/26/89	19.8-21.6	6.1	14	-14.6	-116	3.3	15	384
129-059-18DDD2	5/25/89	19.4-21.0	7.8	12	-12.8	-101	3.6	35	378
129-059-30ADD	5/26/89	19.2-21.4	3.3	16	-14.8	-95	25.9	19	384
130-058-30CBB2	5/31/89	19.0-20.7	7.8	11	-11.4	-89	4.1	14	228
130-059-01CDD2	5/30/89	20-25	6.1	14	-11.0	-86	3.9	6500	9970
130-059-01CDD1	5/30/89	80-83	6.0	74	-16.3	-126	7.2	1600	2850
130-059-01CDD3	5/30/89	5-11	5.9	0	-12.8	-92	12.6	4400	6870
130-059-01CDD4	5/30/89	59-60	11.0	48	-12.1	-95	3.9	4900	7390
130-059-11CDD	5/26/89	21.6-23.8	9.0	13	-10.9	-74	15.1	110	346
129-058-06CDD1	6/07/89	92-97	2.5	90	-13.1	-92	15.0	27	392
129-058-06CDD2	6/07/89	35-40	2.6	32	-13.2	-81	26.8	19	334
129-058-07BBA1	6/07/89	138-143	2.9	135	-12.9	-93	12.4	6.6	316
129-059-28AAA2	6/06/89	19.5-21.7	1.8	18	-11.6	-88	6.8	5800	11,300
129-059-28BAA	6/06/89	18.9-20.3	7.2	12	-16.4	-115	19.0	6500	9450
129-059-28BCC	6/06/89	19.3-21.4	8.0	11	-15.3	-115	10.0	28	416
129-059-13DDC	6/07/89	105-110	5.6	100	-12.6	-95	7.9	31	448
129-059-22AAA	6/06/89	16.5-18.5	5.5	11	-12.6	-91	11.9	160	601
129-059-33AAA2	6/06/89	18.8-20.6	1.4	17	-12.1	-87	11.9	1500	2240
129-059-35BBB2	6/06/89	12.1-14.0	1.2	11	-13.1	-92	15.0	16,000	24,000
130-058-19CDD	5/31/89	19.8-21.5	4.0	16	-11.8	-81	15.4	22	219
130-058-31ABA2	6/07/89	12.6-13.1	8.2	118	-13.0	-89	17.2	28	425
130-058-31ABA3	6/07/89	45-50	8. 0	37	-10.5	-65	20.8	49	273
130-059-25ABB	5/31/89	20.8-22.4	5.9	15	-12.0	-90	8.0	33	330

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in a sand and gravel lense in till also underlying the Oakes aquifer. The mean $\delta^{18}O$ and δD values for the 29 samples in the Oakes aquifer are -12.9 and -92, respectively (table 10).

Table 10. -- Summary statistics for ground-water $\delta^{18}O$ and δD in the Oakes aquifer

	$\delta^{18}O$ (o/oo)	δD (o/oo)
Minimum	-16.5	-118.0
Maximum	-10.5	-57.0
Sum	-374.5	-2676.0
Points	29	29
Mean	-12.9	-92.28
+ 95%	-12.29	-86.87
- 95%	-13.54	-97.66
Median	-12.7	-92.00
Standard Deviation	1.65	14.16
Variance	2.73	200.56
Skewness	-0.75	0.19

The relationship between the ground-water $\delta^{18}O$ and δD and precipitation $\delta^{18}O$ and δD is shown in figure 21. The range of ground-water $\delta^{18}O$ and δD values is smaller than the range of precipitation $\delta^{18}O$ and δD values indicating the homogenizing (mixing) effect of the aquifer and/or the effect of preferential seasonal recharge. Most ground-water samples plot closer to less depleted $\delta^{18}O$ and δD values associated with cooler rainfall events.

The relationship between $\delta^{18}O$ and δD in ground water is shown in figure 22. The slope of the regression equation (7.38) is close to the slope of the local meteoric water line (7.83-equation 5). If ground water is significantly affected by evaporation, then ground-water $\delta^{18}O$ and δD samples should plot below the local meteoric water line along "evaporative" lines with slopes ranging from about four to six (Craig and
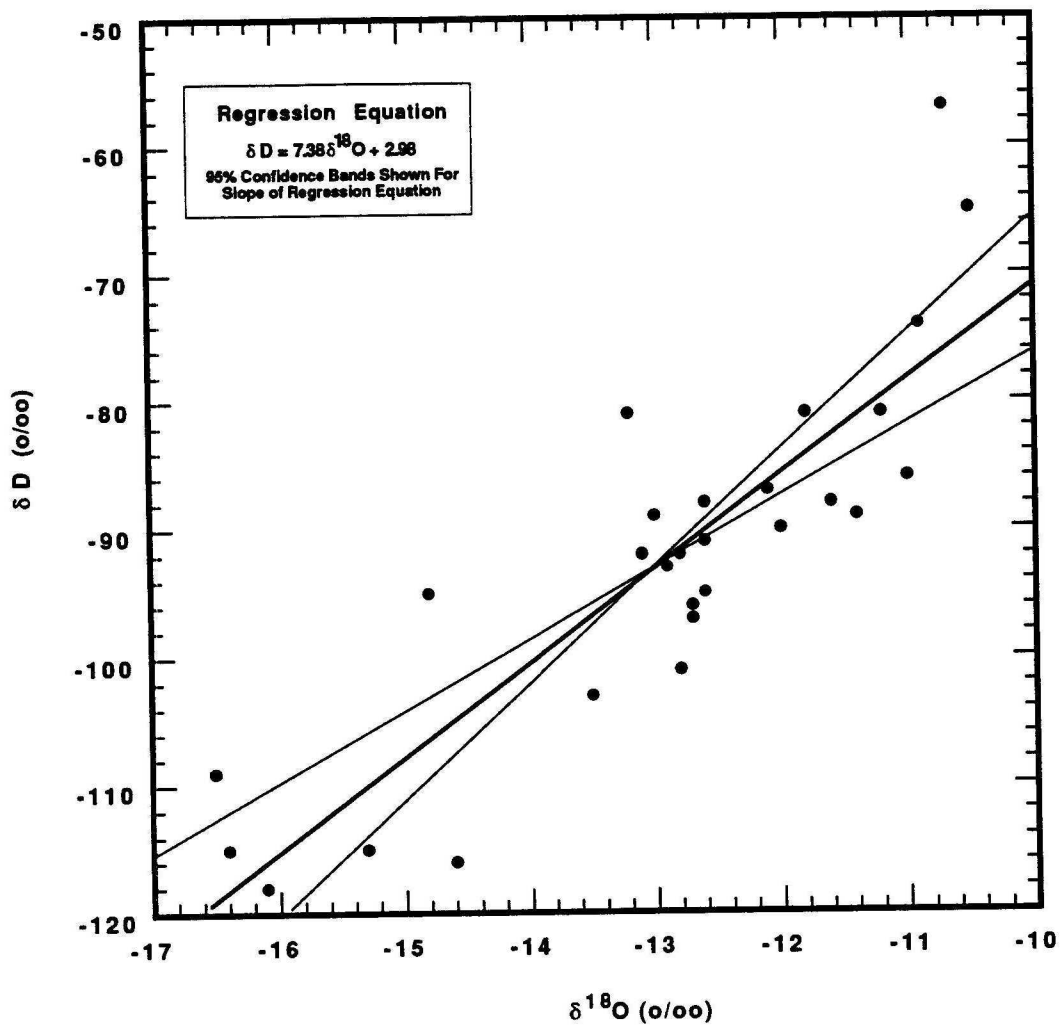
Figure 22. -- Linear regression analysis of $\delta^{18}O$ and δD in ground water in the Oakes aquifer

others, 1963; and Freeman, 1986). Based on the above, ground water in the Oakes aquifer is not significantly affected by evaporation, and the primary discharge mechanism is plant transpiration.

Komor and Emerson (1994) also observed that ground water was not significantly affected by evaporation at a test site in the Oakes aquifer study area. The study concluded that water unaffected by evaporation is most likely to reach the water table when the unsaturated zone is wetter than field capacity for comparatively long periods, such as during snowmelt and prolonged intense rain storms. In addition, it was concluded that water unaffected by evaporation can reach the water table through preferential flow paths that route water past near surface soils.

Assuming no seasonal preferential recharge or other fractionating process such as evaporation, $\delta^{18}O$ and δD values of modern (meteoric) ground water should reflect the average values for precipitation in the recharge zone. The mean annual temperature at Oakes ($5.8^\circ C$) was used in equations 9 and 10 to calculate the theoretical mean $\delta^{18}O$ for precipitation in the Oakes aquifer study area. Results are summarized in table 11.

Table 11. -- Theoretical mean $\delta^{18}O$ of recharge to the Oakes aquifer using equations 9 and 10

Equations 9	$\delta^{18}O$ (o/oo)
$\delta^{18}O = (0.49 \pm 0.12)T - (17.25 \pm 0.54)$	
(upper 95%) $\delta^{18}O = 0.61T - 16.71$	-13.17
(mean) $\delta^{18}O = 0.49T - 17.25$	-14.41
(lower 95%) $\delta^{18}O = 0.37T - 17.79$	-15.64
Equation 10	
$\delta^{18}O = (0.55 \pm 0.14) T - (17.85 \pm 2.02)$	
(upper 95%) $\delta^{18}O = 0.69T - 15.83$	-11.83
(mean) $\delta^{18}O = 0.55T - 17.85$	-14.66
(lower 95%) $\delta^{18}O = 0.41T - 19.87$	-17.49
Actual mean $\delta^{18}O$ Oakes aquifer ground water	-12.90
(upper 95%)	-12.29
(lower 95%)	-13.54

The theoretical mean $\delta^{18}O$ values of precipitation computed using equations 9 and 10 are more depleted in $\delta^{18}O$ as compared to the actual mean $\delta^{18}O$ of ground water in the Oakes aquifer. The actual range in mean $\delta^{18}O$ ($\pm$ 95% confidence band) for the Oakes aquifer, however, is within the theoretical $\delta^{18}O$ range ($\pm$ 95% confidence band) computed for precipitation using equations 9 and 10. The larger 95% confidence band using equation 10 probably reflects the smaller sample size.

Temporal variations in precipitation should be considered in the calculation of theoretical mean $\delta^{18}O$ precipitation values. The sum of products of mean monthly temperatures and monthly precipitation percentages in relation to total annual precipitation were used in equations 9 and 10 to calculate "weighted" mean theoretical $\delta^{18}O$ precipitation values. The results are summarized in table 12. The theoretical weighted mean $\delta^{18}O$ values of precipitation computed using equations 9 and 10 are less depleted in $\delta^{18}O$ as compared to the actual mean $\delta^{18}O$ of ground water in the Oakes aquifer. As with the

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unweighted case, the actual range in mean $\delta^{18}O$ (± 95% confidence

band) for ground water in the Oakes aquifer is within the theoretical

$\delta^{18}O$ range (± 95% confidence band) computed for precipitation using

equations 9 and 10.

Table 12. -- Theoretical weighted mean $\delta^{18}O$ of recharge to the Oakes aquifer using equations 9 and 10

Month	Mean Monthly Temperature (°C)	Monthly Percentage of Annual Precipitation	Equation 9 $\delta^{18}O=(0.49\pm0.12)T+(-17.25\pm0.54)$			Equation 10 $\delta^{18}O=(0.55\pm0.13)T+(-17.85\pm2.02)$		
			(0.37T-17.79)	(0.49T-17.25)	(0.61T-16.70)	(0.41T-19.87)	(0.55T-17.85)	(0.68T-15.83)
JAN.	-12.18	0.028	-0.62	-0.65	-0.68	-0.70	-0.69	-0.68
FEB.	-9.53	0.031	-0.66	-0.68	-0.70	-0.74	-0.71	-0.69
MAR.	-2.09	0.053	-0.98	-0.97	-0.95	-1.10	-1.01	-0.91
APR.	7.37	0.106	-1.60	-1.45	-1.29	-1.79	-1.47	-1.15
MAY	14.50	0.130	-1.62	-1.32	-1.02	-1.81	-1.29	-0.78
JUNE	18.95	0.181	-1.95	-1.44˙	-0.93	-2.19	-1.36	-0.54
JULY	22.89	0.129	-1.20	-0.78	-0.04	-1.35	-0.69	-0.04
AUG.	20.91	0.119	-1.20	-0.83	-0.47	-1.34	-0.77	-1.34
SEPT.	14.26	0.091	-1.14	-0.93	-0.73	-1.28	-0.92	-0.56
OCT.	7.03	0.068	-1.03	-0.94	-0.84	-1.16	-0.95	-0.75
NOV.	-2.28	0.039	-0.73	-0.72	-0.71	-0.81	-0.75	-0.68
DEC.	-10.39	0.026	-0.56	-0.58	-0.27	-0.63	-0.61	-0.23
			Σ=-13.29	Σ=-11.29	Σ=-8.63	Σ=-14.16	Σ=-11.22	Σ=-8.35

A more accurate approach to calculating theoretical $\delta^{18}O$ values of

ground water in the Oakes aquifer would be to develop a daily water

budget of the Oakes aquifer study area using available climate data. The

$\delta^{18}O$ signature of each recharge event can be determined using

equations 9 and/or 10 adjusted for a weighting factor corresponding to

the percentage amount of each recharge event as related to the total

amount of precipitation for the period of record under consideration.

Depression-focused, spring-snowmelt, recharge events pose

problems in the application of this approach. The $\delta^{18}O$ variation in

winter precipitation (snow) is large in relation to the $\delta^{18}O$ variation in

spring snowmelt ponds in the Oakes aquifer (fig. 21). This indicates the

$\delta^{18}O$ signature of snow changes after deposition, melting, and

redistribution prior to recharge. Freeman (1986) reported δD and $\delta^{18}O$ enrichment in snowbanks and ponded snowmelt.

Based on the above, individual winter snowfall events need not be accounted for in the water-budget/weighting approach used to calculate theoretical ground-water $\delta^{18}O$ in the Oakes aquifer. Assuming accurate determination of $\delta^{18}O$ and volume of other recharge events, the spring snowmelt/recharge events can be adjusted by using a "typical" spring snowmelt pond $\delta^{18}O$ signature and some volumetric weighting factor to arrive at a mean $\delta^{18}O$ of ground water in the Oakes aquifer that approximates the actual mean. The above approach may be useful as an external check on the validity of a water-budget method to calculate aquifer recharge. This is outside of the scope of this investigation.

Comparison of Deuterium Excess in Ground Water, Snow, and Rain

An analysis of variance (ANOVA) was used to compare the rain, snow, and ground-water, deuterium-excess distributions. Probability plots of deuterium excess in rain (fig. 17), snow (fig. 18) and ground water (fig. 23) are approximately linear indicating that the distributions are normal. The ground-water deuterium excess distribution has a skewness coefficient of 0.70 (table 13). Skewness analysis indicates at a five percent level of significance, that there is no basis to reject the null hypothesis that the ground-water, deuterium-excess distribution is normal (Snedecor and Cochran, 1989 - Table A-19).
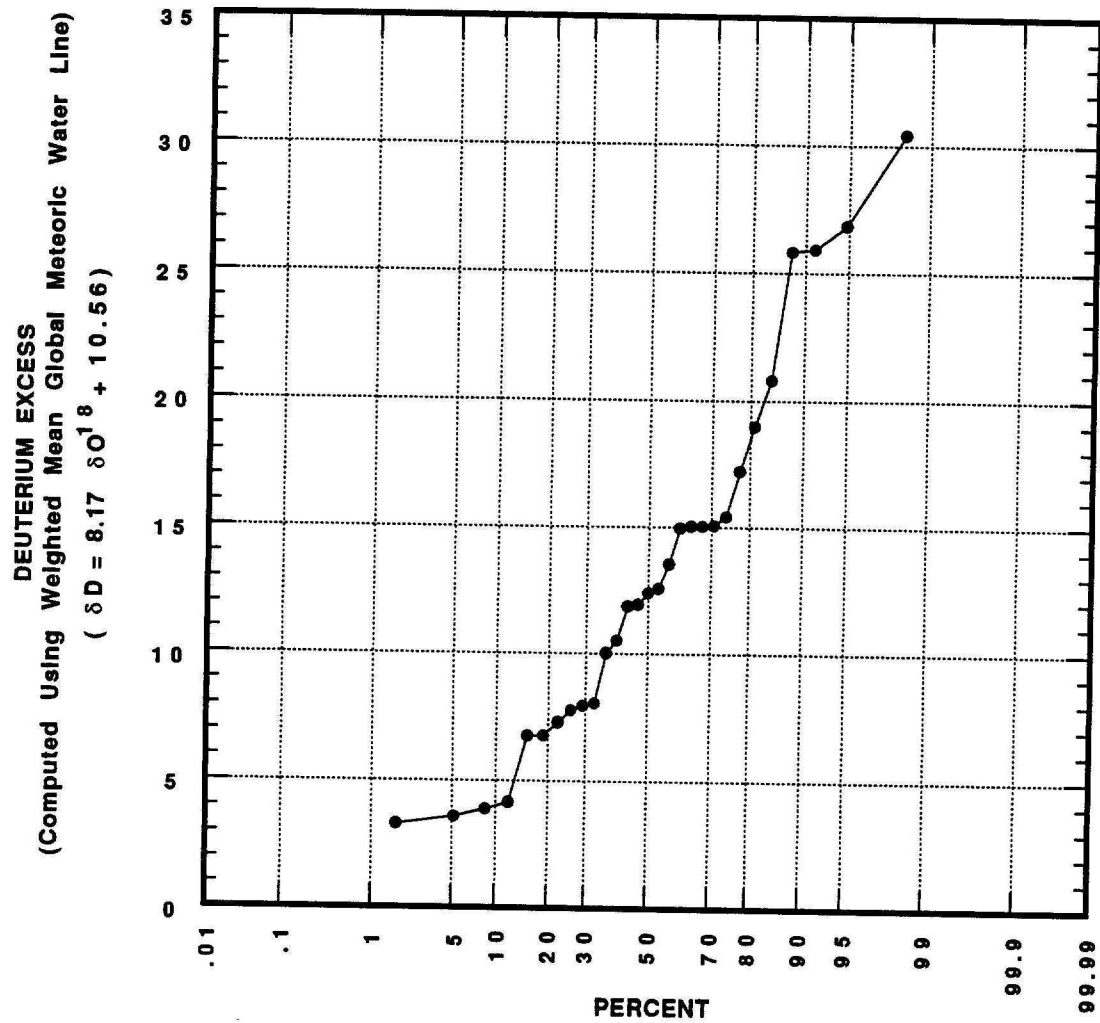
Figure 23. -- Probability plot of deuterium excess in ground water in the Oakes aquifer

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Table 13. -- Summary statistics for ground-water deuterium excess in the Oakes aquifer

Minimum	3.28
Maximum	30.42
Sum	383.67
Points	29
Mean	13.23
Median	12.39
Standard Deviation	7.35
Variance	54.00
Skewness	0.70

Results of ANOVA (table 14) indicate that at a 10.5 percent level of significance, deuterium excess varies according to moisture type (rain, snow, ground water). A Bonferroni-Dunn analysis indicates the mean difference between deuterium excess in ground water and rain is -4.45 and is significant at 6.4 percent. The mean difference between deuterium excess in ground water and snow is 1.52 and is significant at only 56.9 percent (table 14). Thus, there is no statistical difference between the ground water and snow deuterium-excess distributions. This supports the hypothesis that the Oakes aquifer receives significant recharge from spring snowmelt events.

Table 14. -- ANOVA for deuterium excess in rain, snow, and ground water in the Oakes aquifer study area

	Sum of Squares	Mean Square	F-value	P-value
MOISTURE STATE (rain-snow-ground-water)	208.40	104.20	2.37	0.105

MOISTURE STATE COMPARISON	Mean Difference	P-value
Rain vs. Snow	-5.97	0.059
Rain vs. Ground Water	-4.45	0.064
Snow vs. Ground Water	1.52	0.569

Areal distribution of $\delta^{18}O$ and δD in the Oakes aquifer

The areal distribution of δD is shown in figure 24 and the areal distribution of $\delta^{18}O$ is shown in figure 25. The more depleted $\delta^{18}O$ and δD values are associated with local, narrow, land-surface uplands and the upper part of the saturated zone in local, land-surface depressions.

The group of more highly depleted $\delta^{18}O$ and δD samples southeast of Ludden in figures 24 and 25 is associated with a relatively narrow north-south trending topographic upland area (fig. 8). The highly depleted sample at 130-059-23CCC is associated with a relatively narrow northwest-southeast trending land-surface upland area (fig. 8). Dissolved-solids concentrations in these areas of the Oakes aquifer are relatively small (less than 400 mg/L) (fig. 12). The uplands are net recharge areas where the homogenizing (mixing) effects of the aquifer are less significant. These areas probably are characterized by temporal variations in $\delta^{18}O$ and δD as related to temporal (seasonal) variations in recharge. The more highly depleted $\delta^{18}O$ and δD values in these areas probably reflect the most recent spring snow-melt recharge event.

More highly depleted $\delta^{18}O$ and δD values also occur at the top part of the water table at 130-059-02CBB2. Piezometer nest 130-059-02CBB is located along the axis of a local closed land-surface topographic depression. This area of the Oakes aquifer represents a net discharge area with dissolved-solids concentrations in excess of 1,000 mg/L (fig. 12). In early spring, during snow-melt events, this area commonly becomes ponded at the surface providing depression-focused type recharge to the underlying Oakes aquifer. During the spring, the upper part of the aquifer consists of cooler, spring-recharge-event water that
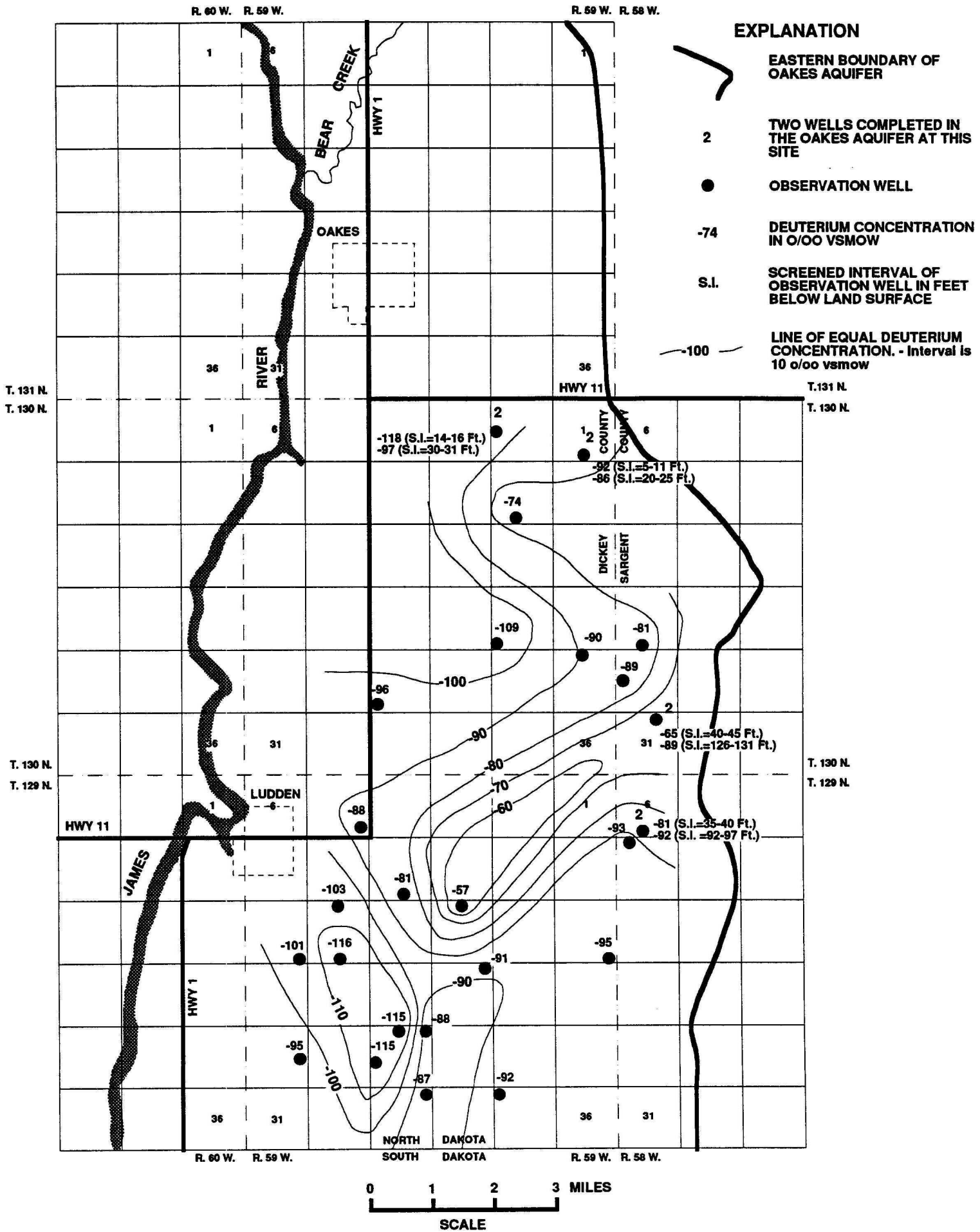
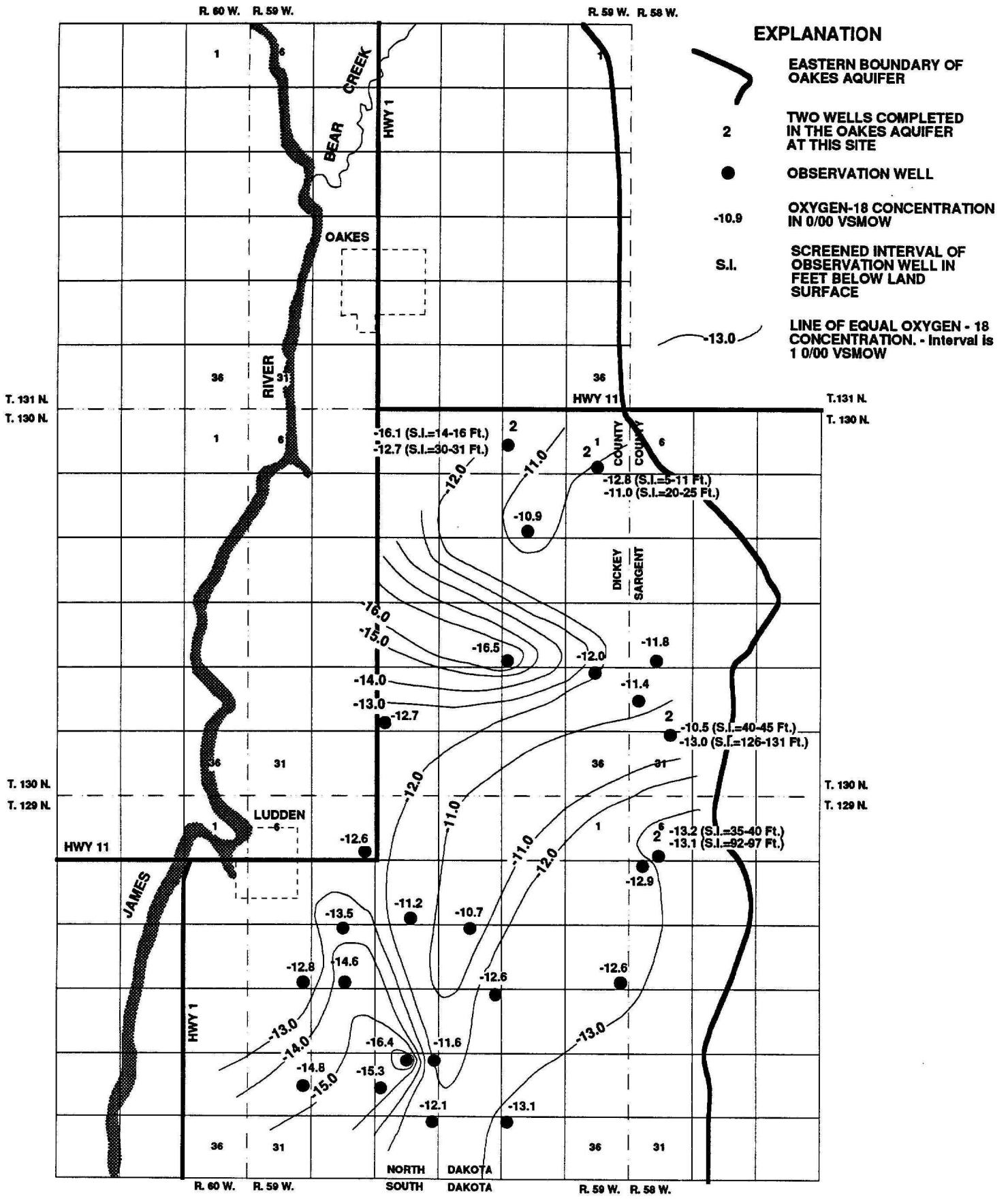**Figure 24. -- Areal distribution of δD in the Oakes aquifer**

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Figure 25 . -- Areal distribution of δO in the Oakes aquifer

has a more depleted $\delta^{18}O$ and δD signature. In the summer, this part of the aquifer becomes a discharge area with discharge occurring from evapotranspiration. Spring recharge to the upper part of the aquifer is lost by evapotranspiration during the summer, and probably little, if any, of this $\delta^{18}O$ and δD depleted spring recharge reaches the base of the aquifer. Salinity enrichment in the base of the aquifer may occur by miscible displacement (Williams, 1984).

Most of the $\delta^{18}O$ and δD values range between about -14 to -11 and -80 to -100, respectively. These samples correspond to either transitional areas between local land-surface uplands and lowlands or the bottom parts of the aquifer beneath land-surface depressions. Ground-water flow paths and residence times are longer in transitional areas, and lateral flow components are more significant. As a result, the flow system has a more pronounced homogenizing effect with regard to the distribution of $\delta^{18}O$ and δD.

Origin of Highly Saline Ground Water in the Oakes Aquifer

Stable isotope ($\delta^{18}O$ and δD) analysis is useful in evaluating the cause of ground-water salinity (Gat, 1971; Payne, 1988; and Sami, 1992). Where the cause of salinity in ground water is due to the concentration of dissolved salts by evaporation, then the regression of δD against $\delta^{18}O$ displays an evaporative trend with slopes between four and six. Also, the regression of $\delta^{18}O$ and δD against selected ionic species is positively correlated.

Where the cause of salinity is due to leaching of evaporitic minerals such as gypsum, then the leaching process produces no change in the

stable isotopic composition of the infiltrating water. Therefore, there is no correlation between $\delta^{18}O$ and δD and the ionic species (Payne, 1988).

The slope of the Oakes aquifer ground water $\delta^{18}O$ and δD regression equation (7.38 - fig. 22) is close to the slope of the local meteoric water line (7.83; see equation 5). The R-values indicate that there is no positive correlation between ground water sulfate and $\delta^{18}O$ and δD (figs. 26 and 27). Based on the above, the cause of highly saline ground water is due to leaching of evaporitic minerals in areas occupied by intermittent sloughs. The evaporitic minerals are deposited as surface/near-surface crusts as the sloughs dry up during the summer when evapotranspiration exceeds precipitation. During the following spring, these minerals are leached into the local ground-water flow system by isotopically depleted snow melt and early spring rainfall.

The above pattern of mineral accumulation from evapotranspiration during the summer and dissolution during the spring, is reflected by the relationship between the temporal fluctuation of the water table and selected chemical constituents at observation well 129-059-28AAA2 (fig. 28, Shaver, unpublished data). This well is located adjacent to an intermittent slough (fig 20). The higher-salinity, ground-water zone beneath the intermittent slough moves outward from the slough area as a water-table mound develops from the spring recharge pulse. During the summer, as the slough dries up, and evapotranspiration creates a ground-water discharge area, the higher-salinity ground-water zone moves back toward the area previously occupied by the slough and minerals are redeposited in the unsaturated zone, and at land surface.

Temporal variation in bicarbonate is minor in relation to temporal variations in sulfate and chloride (fig. 28). This indicates that more
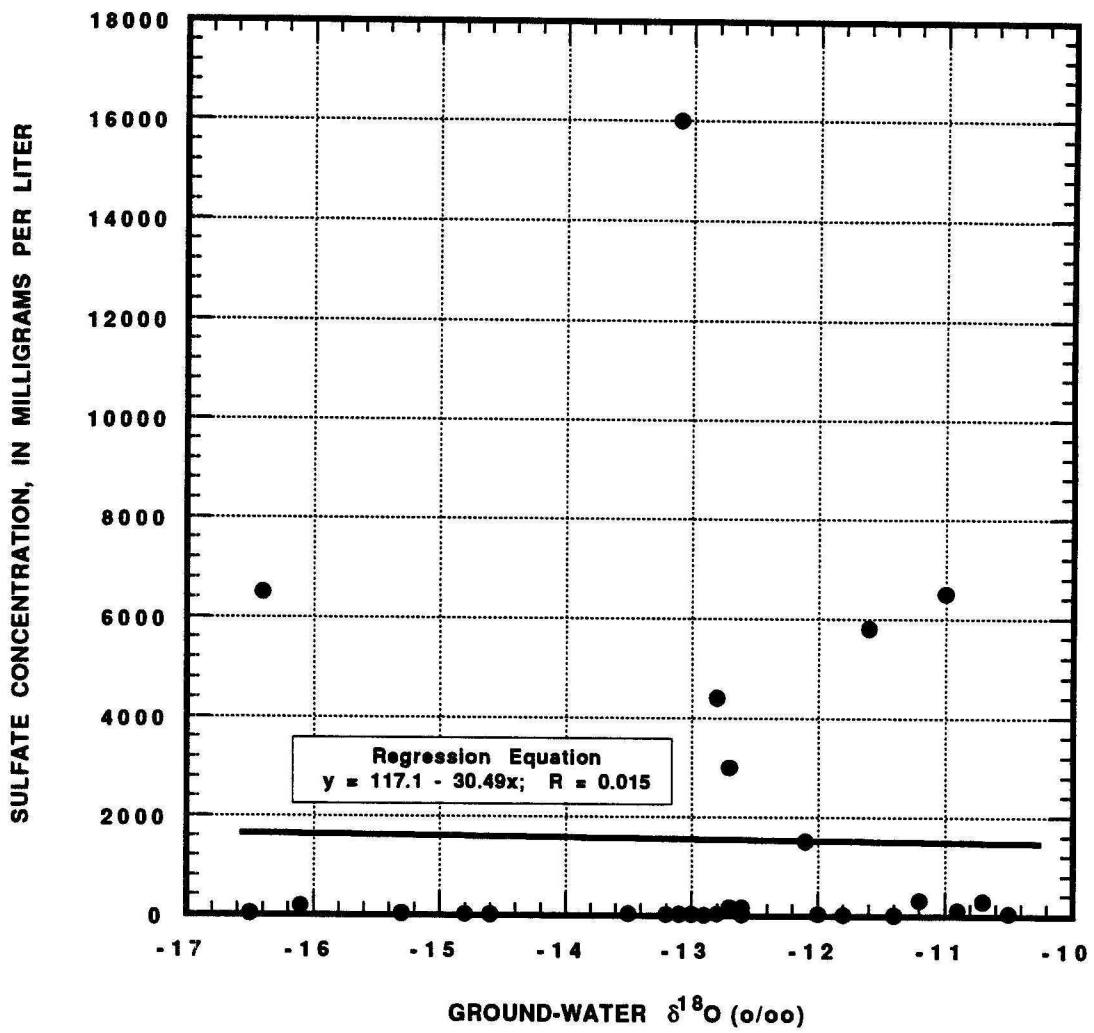
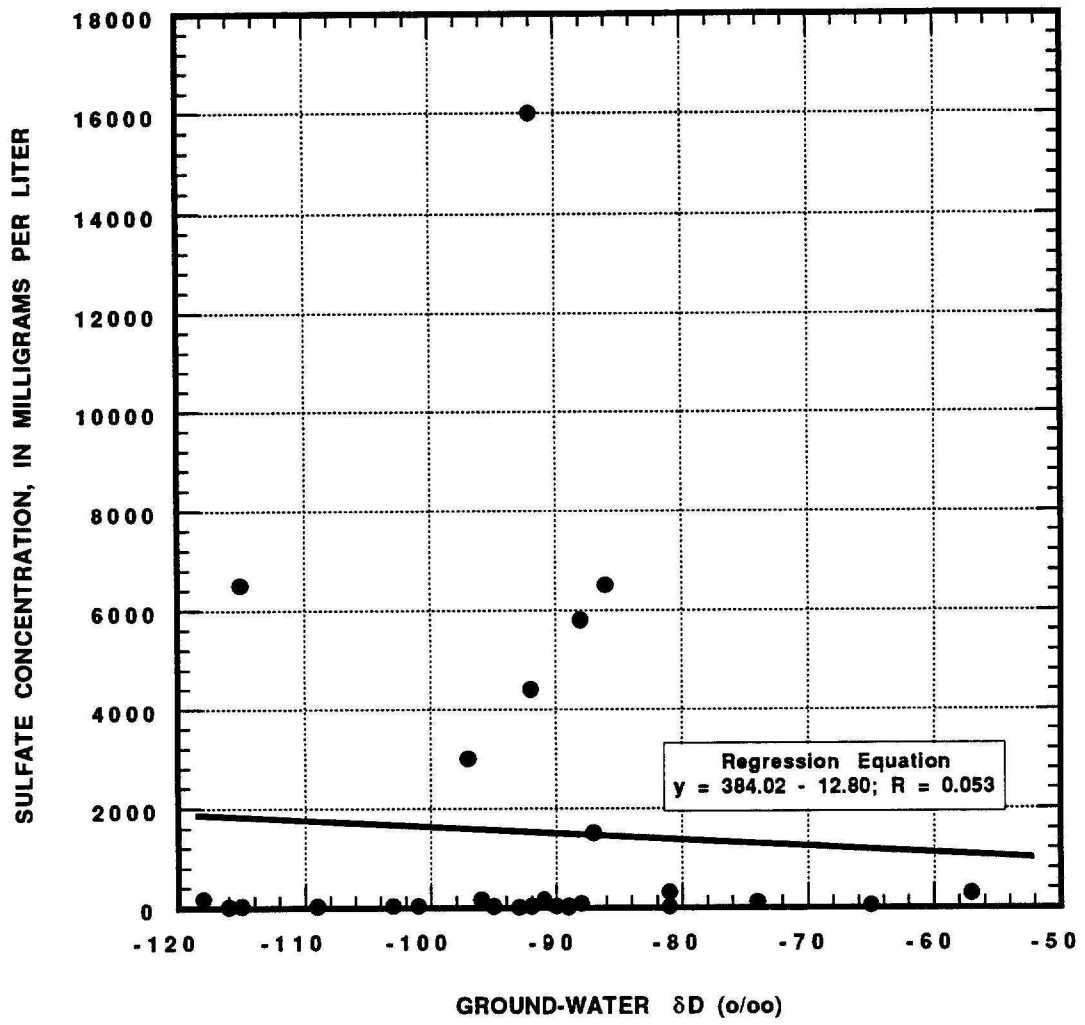Figure 26.-- Linear regression analysis of ground water $\delta^{18}O$ and sulfate

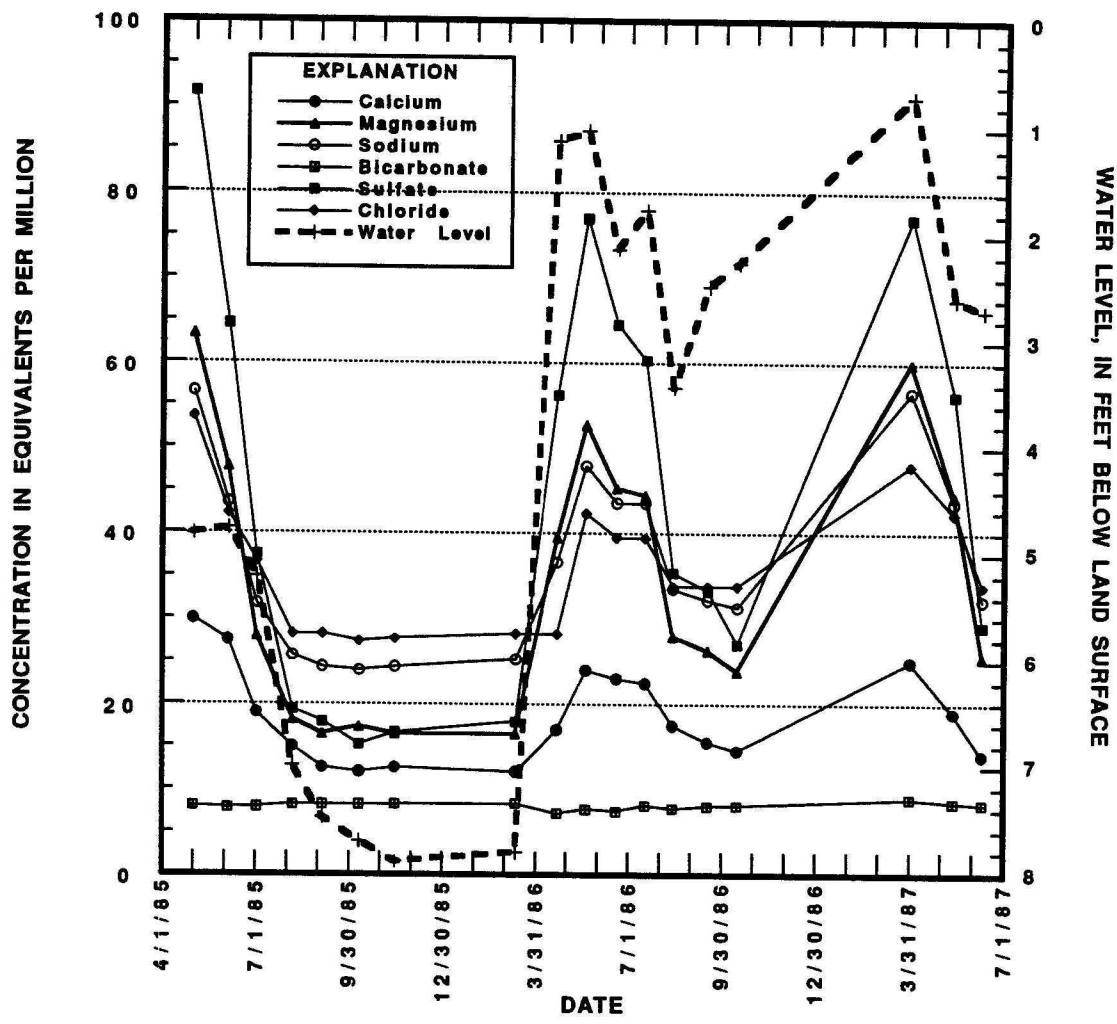Figure 27. -- Linear regression analysis of ground water δD and sulfate

Figure 28. -- Temporal fluctuation of water table and selected chemical constituents at observation well 129-059-28AAA2

highly soluble sulfate and chloride minerals are the primary sources of dissolved solids in ground water associated with net discharge areas in the Oakes aquifer study area.

SUMMARY AND CONCLUSIONS

The Oakes aquifer consists primarily of glacioaqueous sand and gravel deposits of Pleistocene age. For the most part, the Oakes aquifer is unconfined and the depth to the water table is less than eight feet. Recharge is from direct infiltration of precipitation and local runoff that occurs primarily during the spring. Much of this recharge can be characterized as depression focused. Discharge primarily is from evapotranspiration that occurs during the summer.

Although water quality in the Oakes aquifer is variable, dissolved-solids concentrations generally are less than 500 mg/L and the calcium-magnesium bicarbonate type water predominates. Sodium-magnesium sulfate type waters with dissolved-solids concentrations up to about 50,000 mg/L occur in net discharge areas (land-surface depressions). Evapotranspiration is the primary discharge mechanism in these areas.

The Oakes aquifer study area is characterized by a semi-arid to sub-humid continental type climate. Mean annual temperature and precipitation at Oakes from 1929 through 1989 are 42.6° F and 18.95 inches, respectively. Weather patterns in North Dakota are primarily derived from the Pacific Ocean, polar areas, and the Gulf of Mexico. Pacific Ocean air masses are mild and dry, Polar air masses are cold and dry, and Gulf of Mexico air masses are warm and moist. In every year and season, these three air masses overfly North Dakota.

The equation of the local meteoric water line (LMWL) is $\delta D = (7.83 \pm 0.38) \, \delta^{18}O + (6.99 \pm 5.53)$ and was developed from a regression analysis of 11 rain and 8 snow samples collected at Oakes from April 1989 through April 1990. The slopes of the global and North American meteoric water lines are within the upper 95 percent confidence band for the slope of the local meteoric water line.

The regression equation for rain is $\delta D = 6.89 \, \delta^{18}O - 0.45$ and the regression equation for snow is $\delta D = 8.98 \, \delta^{18}O + 30.98$. The y-intercept of the rain equation is not statistically different from zero. At a 1.2 percent level of significance, the y-intercept for the snow equation is statistically different from zero. Y-intercepts of summer precipitation are smaller than those associated with winter precipitation. The difference in slopes and intercepts between rain and snow regression equations is attributed to different meteorological regimes from which the water is derived and local processes which modify the composition of vapor and/or precipitation.

At a 2.5 percent level of significance, the mean deuterium excess (d) for snow differs from the mean d for rain. Larger d values from winter precipitation suggest that winter precipitation is strongly influenced by relatively low humidity, arctic air masses. Smaller d values for rain suggest that rainfall events, particularly those during the summer, are more strongly influenced by relatively high humidity air masses that originate over the Gulf of Mexico.

The range in $\delta^{18}O$ and δD values is small (-1.1 $\delta^{18}O$, -4 δD) for five pond and slough samples collected on April 5, 1989. The $\delta^{18}O$ and δD values plot close to and just below the local meteoric water line near more depleted values associated with winter precipitation. This suggests

that pond and slough water is derived primarily from spring snowmelt and that evaporation from these surface-water bodies is minor. The lack of a correlation between $\delta^{18}O$ and δD with dissolved-solids concentrations and sulfate and the fact that pond and slough samples plot close to the local meteoric water line indicate that salinity is derived by dissolution of soluble minerals previously deposited by evapotranspiration at or near land surface.

The mean $\delta^{18}O$ and δD values for 29 ground-water samples in the Oakes aquifer are -12.9 and -92, respectively. More depleted $\delta^{18}O$ and δD values are associated with local, narrow, land-surface upland areas and the upper part of the saturated zone in and adjacent to local land-surface depressions. The range of ground-water $\delta^{18}O$ and δD values is smaller than the range of precipitation $\delta^{18}O$ and δD values indicating the homogenizing (mixing) effect of the aquifer and/or the effect of preferential seasonal recharge. Most ground-water samples plot closer to less depleted $\delta^{18}O$ and δD values associated with cooler rainfall events.

The slope of the ground water $\delta^{18}O$ and δD regression equation is 7.38 and is close to the slope of the LMWL (7.83). This indicates that ground water is not significantly affected by evaporation and, therefore, the major discharge mechanism in the Oakes aquifer is from plant transpiration. In addition, because the ground water does not display an evaporative trend and there is no correlation between $\delta^{18}O$ and δD and selected ionic species, the source of highly saline ground water in the Oakes aquifer is due to leaching of evaporitic minerals.

Results of ANOVA indicate that at a 10.5 percent level of significance, deuterium excess varies according to moisture type (rain,

snow, or ground water). The mean difference between deuterium excess in ground water and rain is -4.45 and is significant at 6.4 percent. The mean difference between deuterium excess in ground water and snow is 1.52 and is significant at only 56.9 percent. There is no statistical difference between ground-water and snow deuterium-excess distribution. This suggests the Oakes aquifer receives significant recharge from spring snowmelt events.

Integrating the temperature/$\delta^{18}O$ relationship into a daily water-budget model of the Oakes aquifer study area may provide an external check on the validity of a water-budget method to calculate recharge. This application should be evaluated in the future.

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