The Hydrogeology of

Major Glacial-Drift Aquifers

in Burleigh, Emmons, and Kidder Counties, North Dakota

By

David R. Larson

North Dakota Ground-Water Studies
Number 93 - Part II
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David R. Larson, Hydrogeologist
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ABSTRACT

Glacial-drift aquifers comprise an important ground-water resource in Burleigh, Kidder, and Emmons Counties. Ground-water studies for these counties identified and described these aquifers. Data gathered during this study further defined the hydrological character of the aquifers and the suitability of ground water for irrigation.

The study area includes about 1,461 square miles in portions of Burleigh, Kidder, and Emmons Counties, North Dakota. Glaciofluvial sand and gravel deposits of the Coleharbor Group constitute the aquifer complex. Thickness of individual layers of sand and gravel ranges from less than 10 feet to 165 feet.

Test holes drilled at 14 sites in Emmons County defined the hydrogeology of the Strasburg aquifer in areas not drilled in for the county study. Ten observation wells installed at 7 of the 14 sites included one 2-well and one 3-well site. These new data points verified the hydrology of the three-zone Strasburg aquifer; that of ground-water flow downward to the lower zone.

Additional test-hole and water-level data resulted in some adjustments to aquifer boundaries and the pattern of ground-water flow in the Burleigh County part of the study area.

In Kidder County, new data supported extending the boundaries of the Marstonmoor Plain aquifer from northwestern Stutsman County into the Pettibone area in northeast Kidder County. Additional data in east-central Kidder County defined an unconfined aquifer herein named the Tappen aquifer. In northwestern Kidder County, additional data identified an unconfined aquifer herein named

the "Robinson" aquifer. The additional subsurface and water-level data further defined the hydrogeology of the Kidder County aquifer complex. The complex includes as many as five separate sand and gravel intervals the total thickness of which ranges from about 10 feet to over 200 feet. The intervals are hydraulically interconnected to various degrees along the main trend of the aquifer complex.

Further investigation can be done in the study area on surface-water/ground-water interaction, the flow relationship between the drift aquifers and the adjacent bedrock, the role of the moraines in recharging the glacial-drift aquifers, and the ground-water flow system within the Kidder County aquifer complex.

INTRODUCTION

Purpose

Aquifers comprising an important ground-water resource occur in the glacial-drift deposits of Burleigh, Kidder, and Emmons Counties. Published ground-water studies for these counties identified and first described on a county-wide basis the nature and extent of the glacial-drift aquifers and the quality of water available from them.

The purpose of this study is twofold: to gain a better perception of the hydrogeology of the principal glacial-drift aquifer system in Kidder and Burleigh Counties, and to verify the conclusions of the Emmons County study regarding the Strasburg aquifer. Three study objectives were established to meet the study purpose and to utilize the data obtained during the study:

1. further define the areal extent, characteristics, hydrology, potential yields, and water quality of the glacial-drift aquifers
2. evaluate the suitability of the ground water for irrigation use
3. present the data gathered during this study as the basis for more detailed comprehensive studies of less extensive areas within the boundaries of the aquifers.

Further study is needed so that the ground-water resource can be developed and managed to achieve optimum beneficial use. This is particularly relevant to Kidder County where the effects on the ground-water resource of a possible U. S. Bureau of Reclamation project need to be analyzed at the appropriate time.

Study Area Location

The study area encompasses about 1,461 square miles in portions of Burleigh, Kidder, and Emmons Counties (figure 1). This area includes the broad valleys and some of the surrounding uplands in north-central, central, and southwest

Kidder County and southern Burleigh County, extending northward along Apple Creek to the Wing-Arena area in northeast Burleigh County. In Emmons County the study area includes the valley that extends southwest from Long Lake in Burleigh County to Dutton Slough, Badger Creek, and Lake Oahe. The study area also includes the extreme northwest corner of Emmons County adjacent to Lake Oahe, and the valley extending from Horsehead Flats to Strasburg and into Campbell County, South Dakota.

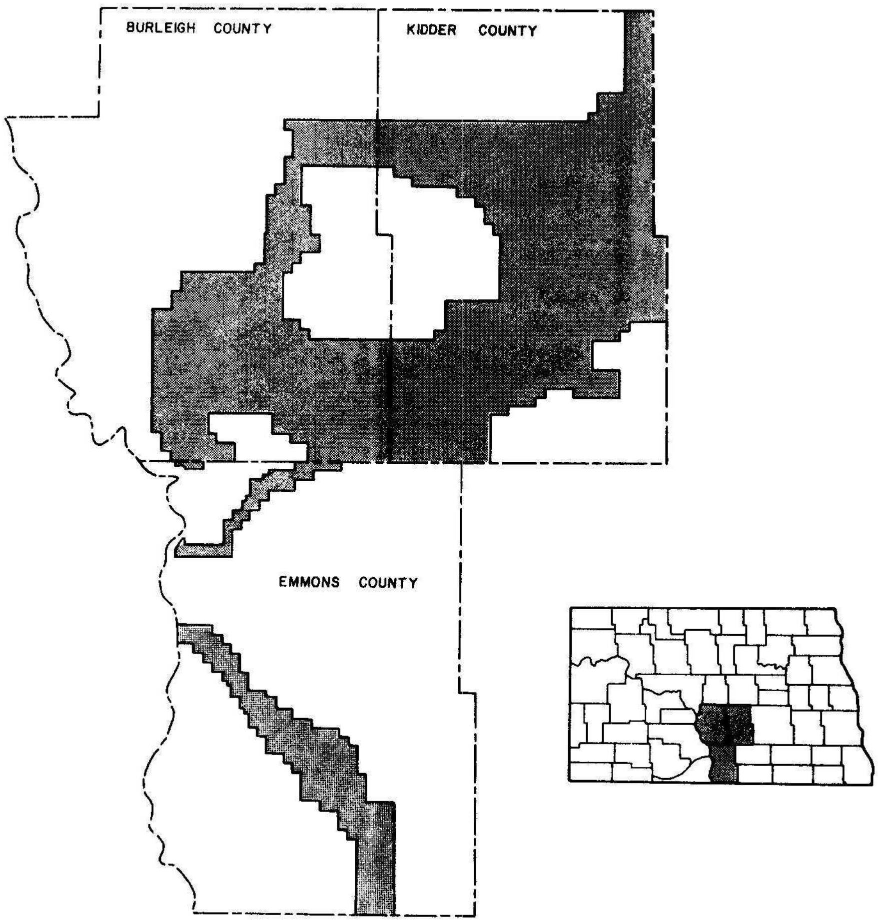


FIGURE 1. LOCATION MAP AND OUTLINE OF STUDY AREA

Previous Investigations

The ground-water resources of the study area have been mentioned or reported on to varying degrees since the late 1800's. Darton (1896) discussed the occurrence of artesian water found east of Bismarck. Simpson (1929) included information on the ground-water resources of Burleigh, Kidder, and Emmons Counties in his statewide summary. A report on municipal water supplies in North Dakota (Abbott and Voedisch, 1938) includes records and water quality analyses for 509 wells across the state, one of which is in Burleigh County and eight each in Kidder and Emmons Counties. Fischer (1952) reported on the geology of Emmons County, emphasizing the Fox Hills Formation. Robinove, Langford, and Brookhart (1958) discussed the occurrence of saline water in some aquifers and streams in the study area. Paulson (1962) summarized information on the occurrence and availability of ground water in glacial drift and bedrock formations. He mentions the buried valley that extends southeastward in Burleigh County from McKenzie to Long Lake and then to the northeast into Kidder County. Randich (1963) reported the results of a localized study of the geology and ground-water resources in the Linton-Strasburg area.

A county ground-water study presents the results of an extensive investigation into the occurrence and availability of ground water in the county, the nature of the aquifers present, the geology of the county, and total water use in the county categorized by type of use. The Kidder County study (Bradley et al., 1963; Randich et al., 1962, and Rau et al., 1962) and supplements (Brown, 1968; and Naplin, 1971) and the Burleigh County study (Kume and Hansen, 1965; Randich, 1965; and Randich and Hatchett, 1966) are first and third in a series that includes each county in North Dakota. The Emmons County study (Bluemle, 1984; and Armstrong, 1975 and 1978) occurs later in the series.

Methods of Investigation

Three principal sources of data support this study: published ground-water studies for Burleigh, Emmons, and Kidder Counties; unpublished test-hole logs, well driller's reports, and water-quality analyses on file; and field work done from 1976 to 1983 for this study. The field work included drilling test holes, constructing observation wells, collecting water samples for chemical analysis, and periodically measuring water levels in an observation-well network. Supplementing the results of this field work are test holes and observation wells used in some aquifer tests conducted in the study area in 1976, 1982, and 1983.

Test holes were drilled from 1977 to 1980 at 282 locations using forward rotary drill rigs. The driller and site geologist each prepared lithologic logs for the test holes. Spontaneous potential and resistivity logs were run in each test hole. Gamma and neutron logs were run in ten test holes. The lithologic and geophysical logs provide subsurface control on the thickness and stratigraphy of the glacial drift.

Single observation wells were constructed at most sites where a significant thickness of aquifer material was found. In many cases where multiple layers of such material were encountered, wells were constructed in each layer in separate bore holes. Both lithologic and geophysical logs helped to determine which sites were completed with multiple wells and at what depths the screens were set. A total of 142 wells were constructed at 113 of the 282 test-hole sites. Multiple wells were installed at 24 of the 113 sites, and 11 existing single-well installations had one or more additional wells constructed.

Most of the observation wells were constructed with 1¼" diameter ABS (Acrylonitrile-Butadiene-Styrene) or PVC (PolyVinyl Chloride) pipe; 2" diameter steel pipe was used in two wells. A 3-, 5-, or 6-foot long 1¼" diameter galvanized steel screen and attached check valve were joined to the bottom of the pipe. The screens were most commonly 0.018 or 0.012 inch slot size. The components of an observation well were assembled on the ground and then lowered into the drill hole. The screen was set at the desired depth, the well back-flushed with clear water to clean the aquifer material and bore hole of drilling fluid, and compressed air pumped into the well to collapse the formation around the screen. The annulus was filled to ground level with drill cuttings. Each new observation well was pumped for several hours to assure a good hydrologic connection between the well and the aquifer. Pumping was accomplished with an airline connected to a small, trailer-mounted air compressor driven by a gasoline engine.

Water samples were collected from 17 existing observation wells, the 142 wells constructed for this study, and 18 other observation wells constructed at aquifer test sites in the study area; also from the roadside spring at Crystal Springs. Both specific conductance and water temperature were measured in the field for each sample collected. Three-part water samples were collected in plastic bottles at each site:

1) 250 milliliter - raw
2) 500 milliliter - filtered
3) 500 milliliter - filtered and acidified

Filtration with a nitrogen-drive system and 0.45 micron filter removed suspended sediment from the water sample. A two milliliter ampule of concentrated nitric acid was added to stabilize the metals to reduce the likelihood of forming precipitates or colloids. The samples were delivered to the State Water Commission Laboratory in Bismarck for analysis of the major anions and cations. Unpublished water-quality data on file supplement these anlyses.

Water levels in a network of observation wells were measured periodically over the course of the study. The network consisted of 205 wells at 151 sites. A hydrograph for each well was prepared to show water-level fluctuations. The elevation of the top of each observation well was established by a field survey. The elevation of test-hole sites was interpolated from 7½' topographic quadrangle maps. Reference datum for land-surface elevation is National Geodetic Vertical Datum (NGVD).

Annual water use as authorized by the various water permits in the study area was determined from the yearly reports submitted by the water-permit holders. Domestic and livestock water use was estimated from population figures. Climatic data were taken from the annual summary for North Dakota published by the National Oceanic and Atmospheric Administration.

Location-Numbering System

The system used for identifying the location of an observation well or test hole is based on the federal system of rectangular surveys of public lands (figure 2). The first and second series of numbers denote the township north of a baseline and range west of the Fifth Principal Meridian, respectively. The third series of numbers designates the section. The first, second, and third letters after the section number indicate, respectively, the quarter section, quarter-quarter section, and quarter-quarter-quarter section (10-acre tract) lettered consecutively A through D counterclockwise beginning with the northeast quarter.

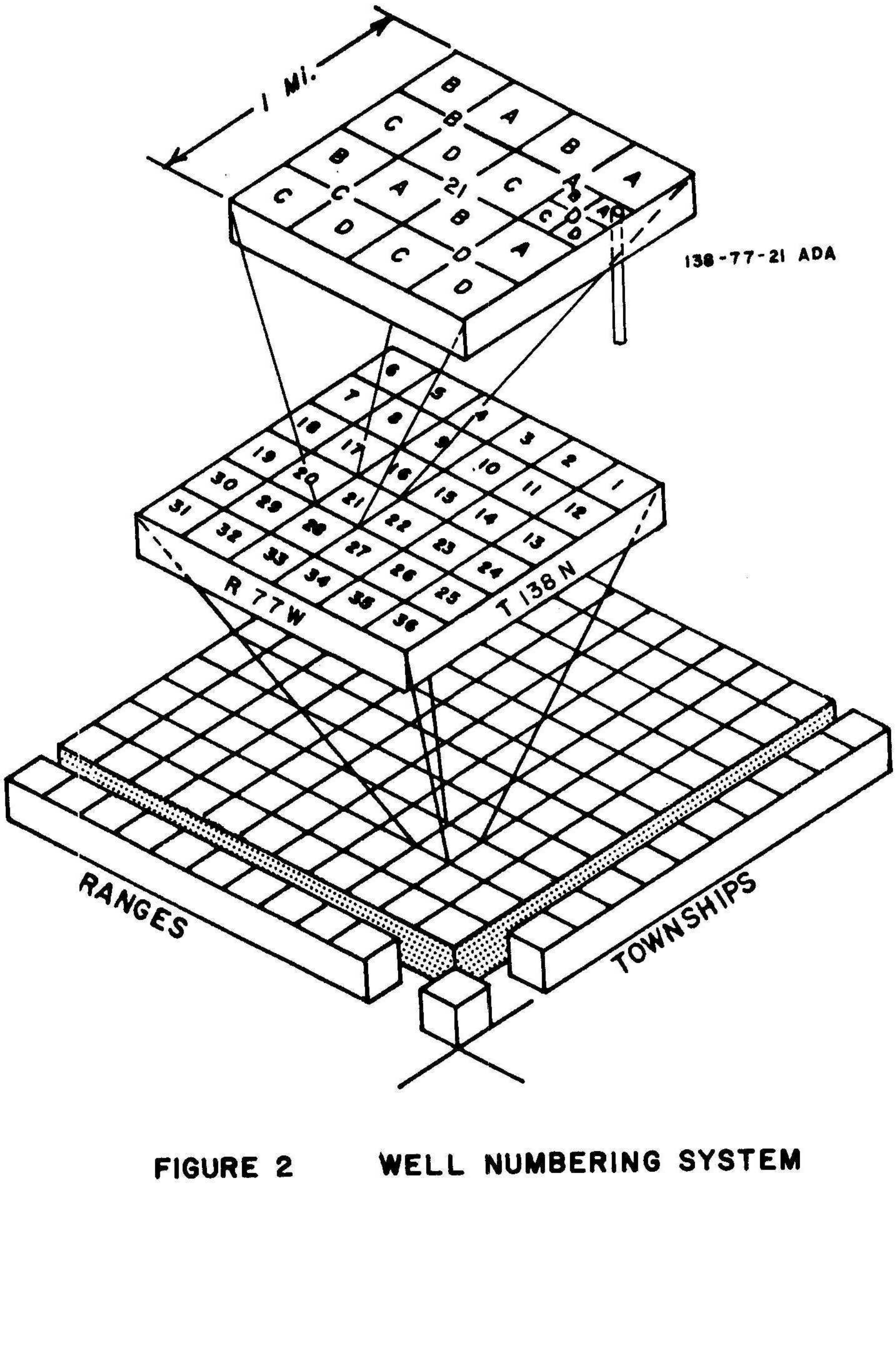


FIGURE 2 WELL NUMBERING SYSTEM

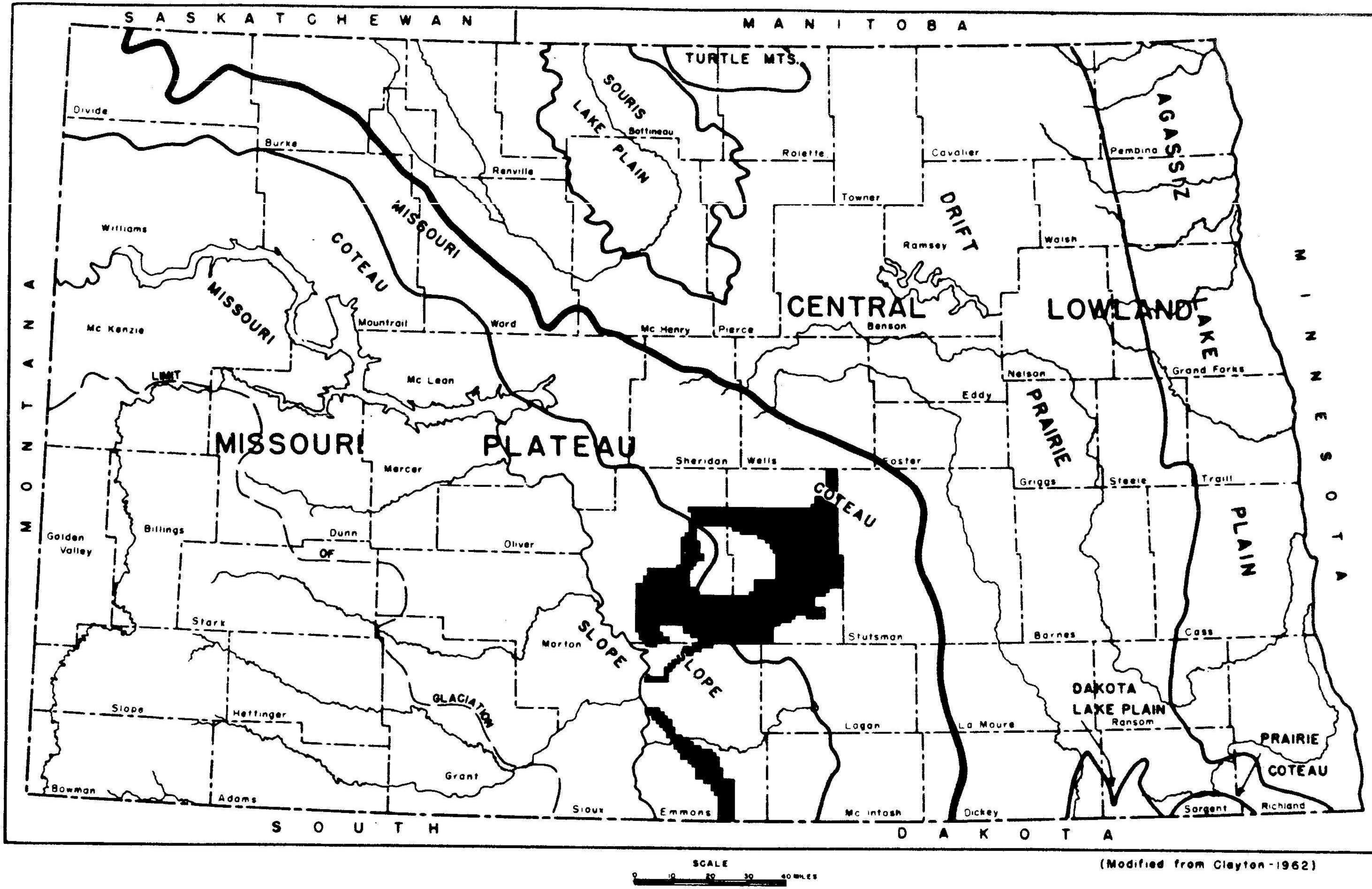
PHYSIOGRAPHY

The study area (figure 3) lies within the Glaciated Missouri Plateau section of the Great Plains Province (Fenneman, 1931) and in the Missouri Coteau and Coteau Slope Districts (Kume and Hansen, 1965). Much of the study area in all three counties is characterized by the gently rolling topography of outwash and lake plains. The hummocky features of collapsed glaciofluvial sediments occur locally. Rough morainal topography outlines the study area in Kidder County and much of Burleigh County. Stream eroded bedrock topography borders the study area in Emmons County and southwestern Burleigh County. The study area also includes the rugged morainal topography north of Pettibone where glacial deposits bury a deep bedrock valley.

Nonintegrated drainage characterizes the Missouri Coteau District. Relatively short ephemeral or intermittent streams drain into the numerous sloughs and potholes occupying limited drainage basins. There is no regional outlet. Drainage in the Coteau Slope District occurs in a mostly integrated system of intermittent and a few permanent streams with regional discharge westward to the Missouri River. However, some drainage in this District is internal with short ephemeral or intermittent streams discharging into undrained depressions.

CLIMATE

The climate of the study area is semiarid continental, characterized by short summers, long and cold winters, slight to moderate precipitation, and wide fluctuations of temperature. The inconstancy of weather patterns across the



(Modified from Clayton-1962)

FIGURE 3. MAP SHOWING LOCATION OF STUDY AREA AND THE PHYSIOGRAPHIC UNITS OF NORTH DAKOTA

study area arises from the interactions of three major air masses moving from the polar region, the northern Pacific, or the Gulf of Mexico.

The occurrence and pattern of precipitation varies considerably both during a year and from year to year. However, relatively widespread and prolonged rains typically occur in the spring. Summer rainfall is mostly from isolated thunderstorms or storm cells associated with frontal systems. Normal annual precipitation across the study area ranges from about 15" in the west to 16" in the east and 17" in the south (figure 4). Total annual precipitation between 1976

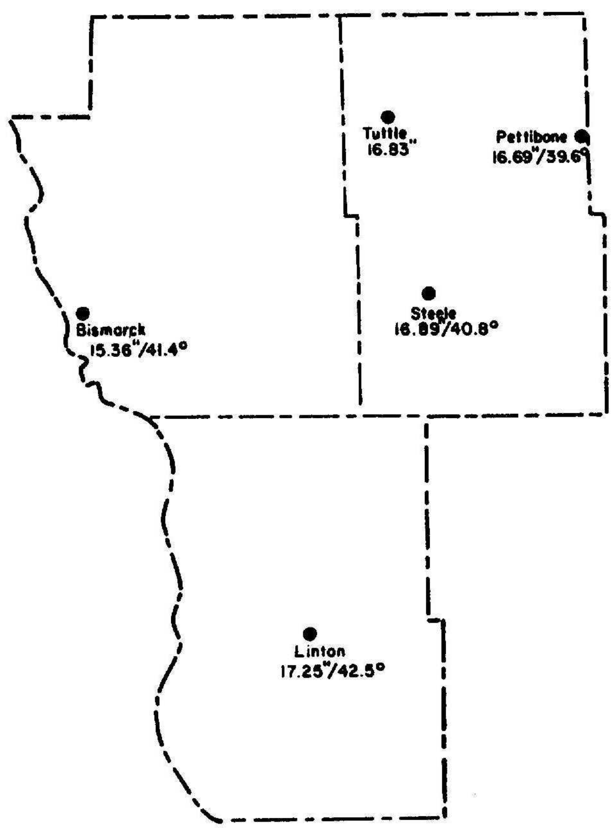


FIGURE 4. NORMAL ANNUAL PRECIPITATION (Inches) / NORMAL ANNUAL TEMPERATURE (°F)
(NOAA, 1976–1982)

and 1982 varied from more than 7" below normal to over 9" above normal (table 1).

Table 1. NORMAL AND TOTAL ANNUAL PRECIPITATION (Inches)
(Normal annual precipitation is the annual precipitation averaged over the 30-year period 1951-1980)

Station	1976	1977	1978	1979	1980	1981	1982	Normal
Bismarck	11.17	18.54	16.95	11.81	16.39	14.46	18.07	15.36
Bismarck 12ENE	12.89	20.79	16.65	13.68	17.63	14.91	(17.80)	-
Linton	9.69	26.87	19.46	12.12	-	-	-	17.25
Moffit 3SE	10.05	23.62	15.88	14.85	18.01	15.39	20.49	-
Pettibone	9.93	19.29	14.66	15.58	18.32	15.74	18.93	16.69
Steele	12.60	20.57	15.79	-	-	17.62	20.54	16.89
Tuttle	11.14	18.73	17.72	14.08	17.49	16.11	17.83	16.83

(NOAA, 1976-1982)

About 70% of the normal annual precipitation falls between April and August, the time of crop germination and growth. However, this precipitation varies markedly across the study area in total amount, intensity, and areal extent; typical of the pattern of summer rainfall.

Temperature also exhibits a pattern of variability with a wide range of daily, seasonal, and annual temperature extremes which contrast sharply with average annual temperatures. The average annual temperature for the study area (figure 4) decreases from the south (42.5°F) to the east (39.6°F), but the range between annual temperature extremes commonly exceeds 120°F and usually exceeds 130°F. Summer temperatures of 90°F or above and winter temperatures of -20°F and below are typical. The freeze-free period is the number of days between the last freeze of spring and the first one of fall. The length of the freeze-free period averages between 120 and 130 days, but ranges from less than

110 days to more than 160 days. The freeze-free period approximates the length of the growing season. Frost in the ground can remain beyond the last freeze of spring. Movement of water downward past the soil profile does not begin until the frozen ground has thawed.

Ground water in the glacial-drift aquifers in the study area is derived predominantly from precipitation and surface water infiltrating through the soil profile. The amount of precipitation entering the ground-water system is strongly influenced by evapotranspiration. Evapotranspiration is the process whereby water enters the atmosphere through plant transpiration and evaporation from the land surface and open bodies of water. The rate of evapotranspiration responds to a variety of factors relating to climate, vegetative cover, the degree of saturation of the soil profile, and the longevity of the water supply available for transpiration and evaporation. The amount of water moving into the atmosphere varies both seasonally, peaking during the summer, and from one year to the next. Annual evaporation as measured with evaporation pans at the Mandan Experiment Station (table 2) typically exceeds normal annual precipitation.

TABLE 2. TOTAL PAN EVAPORATION (Inches)
(Measured at the Mandan Experiment Station Using 48" Pan)

	1976	1977	1978	1979	1980	1981	1982
Total Inches	48.83	38.43	36.93	27.35	47.54	40.46	33.16
Months Included	April-Sept.	May-Sept.	May-Sept.	June-Sept.	April-Sept.	April-Sept.	May-Sept.

(NOAA, 1976-1982)

OCCURRENCE AND QUALITY OF GROUND WATER

General Concepts

All ground water in the glacial-drift aquifers of the study area essentially is derived from precipitation. Part of the precipitation returns directly to the atmosphere by evaporation, part runs off into streams, and the rest percolates into the soil profile. Some of the soil water evaporates or is transpired by plants. Water in excess of the maximum retention capacity of a soil infiltrates downward to the zone of saturation.

Ground water moves from recharge to discharge areas as a consequence of gravity and pressure. This movement is typically slow, traversing only a few feet per year. The rate of ground-water movement is governed by the hydraulic conductivity of the material through which the water moves and by the prevailing hydraulic gradient. Hydraulic conductivity is by definition the capacity of a rock or unconsolidated deposit to transmit water. The magnitude of hydraulic conductivity depends on the grain-size distribution of sediment particles for unlithified formations, and also on the nature and extent of secondary permeability features in consolidated formations. Deposits of materials with a large hydraulic conductivity constitute aquifers; deposits with a small hydraulic conductivity restrict ground-water movement.

Changes in the rate of recharge to or discharge from an aquifer cause water-level fluctuations in wells completed in the aquifer. The fluctuations generally indicate a change in the amount of water stored in the aquifer. In addition, changes in surface load or atmospheric pressure cause minor water-level changes in wells completed in a confined aquifer.

Shallow aquifers in the study area are usually recharged in the spring, early summer, and fall when soil moisture in excess of evapotranspiration requirements is present due to direct infiltration of precipitation, snowmelt, or runoff. Aquifers that are confined by deposits of fine-grained sediment are recharged more slowly by seepage from the confining beds or by water moving downgradient from recharge areas through overlying confining units or aquifers.

Water Quality

Ground water contains varying concentrations of dissolved mineral matter initially acquired as the water falls through the atmosphere and later as the water moves through the soil and sediments underlying the land surface. Dissolved minerals in the water vary in type and concentration due primarily to the composition and solubility of the various deposits encountered and the length of time the water is in contact with the different deposits. The temperature, pressure, and acidity of the water also affect dissolution rates and dissolved mineral concentrations. The concentration of dissolved minerals generally correlates directly to the residence time of the water in the ground.

The suitability of ground water for various uses is determined mostly by the kind and amount of the various chemical constituents present, and to a lesser extent by the water's physical properties. Different water-quality criteria may be emphasized depending on use. The most prevalent uses of ground water in the study area are domestic and farmstead supply and irrigation. The criteria of concern and the recommended limits are indicated in Table 3. The constituents used in this report to characertize the suitability of the ground water for drinking purposes are: hardness and the concentrations of iron, manganese, sulfate, and total dissolved solids.

The suitability of ground water for irrigation is evaluated in terms of its effect on the productivity and quality of crops and on the physicochemical properties of the irrigated soils. Four indices are used to evaluate the suitability:

TABIE 3. MAJOR CHEMICAL CONSTITUENTS IN WATER, THEIR EFFECTS UPON USABILITY FOR DOMESTIC SUPPLY, AND THE RECOMMENDED CONCENTRATION LIMTTS

Constituent	Effects upon Usability	U. S. Public Health Service (1962) Recommended Drinking-Water limits
Calcium (Ca) Magnesium (Mg)	Both retard the suds-forming action of soap and detergent; high concentrations of magnesium have a laxative effect.	- -
Sodium (Na)	High concentrations may affect people on sodium-restricted diets	-
Iron (Fe)	More than 0.1 mg/l will precipitate when exposed to air; stains plumbing fixtures, laundry, and cooking utensils, causes turbidity, and impacts tastes and colors to food and drink.	0.3 mg/l
Manganese (Mn)	More than 0.2 mg/l precipitates when exposed to air; causes undesirable taste and dark stains on fabric and porcelain fixtures.	0.05 mg/l
Sulfate (SO_4)	More than 500 mg/l tastes bitter and may be a laxative.	250 mg/l
Chloride (Cl)	More than 250 mg/l may impart a salty taste; greatly excessive concentrations may be physiologically harmful.	250 mg/l
Fluoride (F)	Optimum concentration helps prevent tooth decay; higher concentrations cause mottled teeth.	Recommended limits depend on annual average of maximum daily temperatures. Limits range from 0.6 mg/l at 32°C to 1.7 mg/l at 10°C.
Nitrate (NO_3)	More than 45 mg/l may cause methemoglobinemia in infants; more than 100 mg/l may cause a bitter taste and physiological distress.	45 mg/l
Total Dissolved Solids (TDS)	More than 500 mg/l is not desirable if better quality water is available; persons may become accustomed to water containing 2000 mg/l or more.	500 mg/l

1) salinity hazard determines the likelihood of an increase in salinity of the soil water; it is measured as total dissolved solids or specific conductance.

2) sodium hazard indicates the likelihood of sodium concentrations in the soil increasing to the level where it adversely affects the soil structure and causes high alkalinity in the soil water; it is calculated as the sodium adsorption ratio (SAR) from the milliequivalent concentrations of the sodium, calcium, and magnesium cations.

3) residual sodium carbonate (RSC) indicates the likelihood of cation-exchange with sodium occurring in the soil profile thereby decreasing soil permeability; it is calculated from the milliequivalent concentrations of the bicarbonate and carbonate anions and calcium and magnesium cations.

4) the potential toxicity of certain trace elements usually indicated by the concentration of boron.

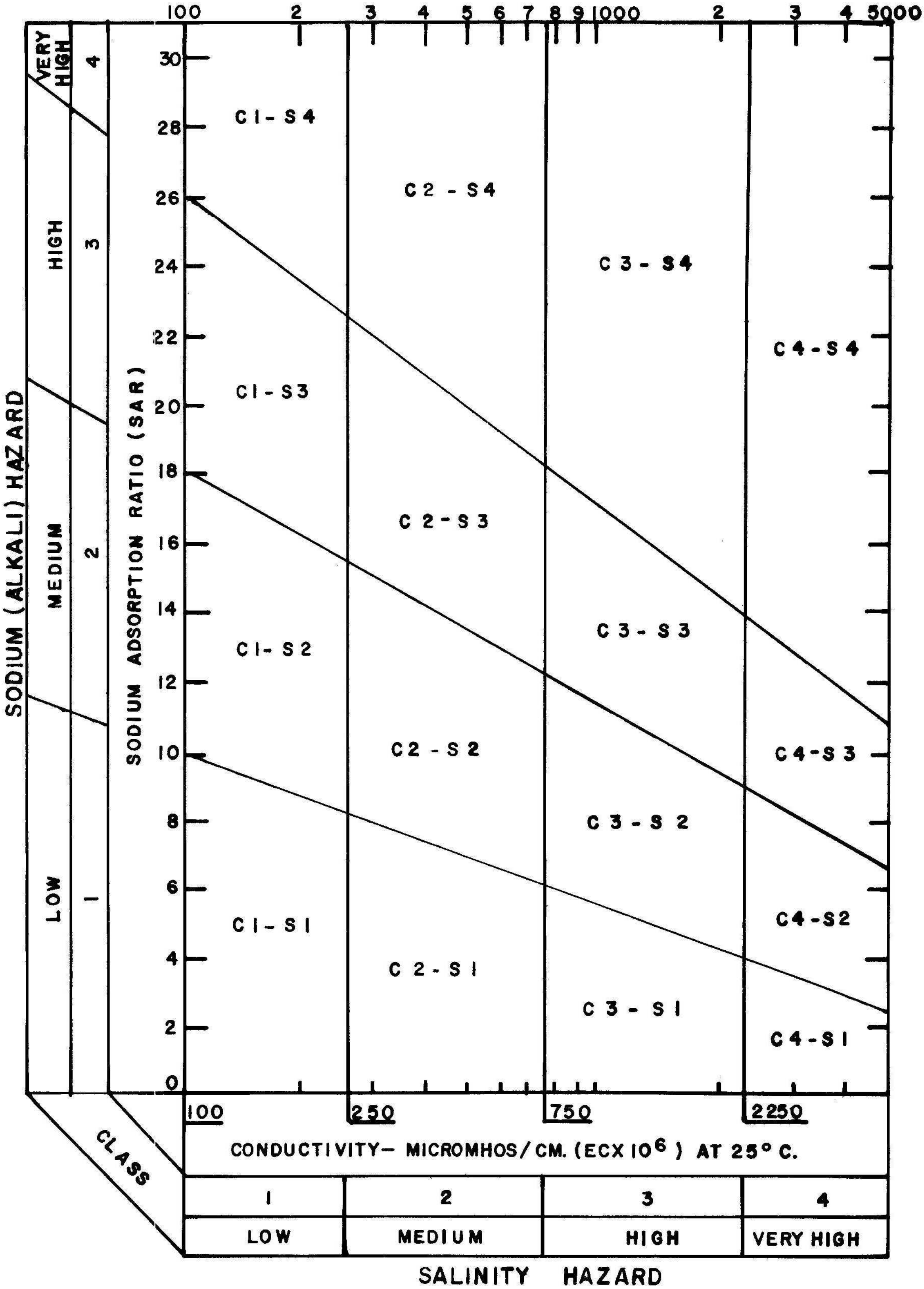
The first two indices are divided into four classes each - low, medium, high, and very high hazard - and combined into a system for classifying the quality of irrigation water (figure 5). The indices used in this report are percent sodium, SAR, RSC, and the irrigation classes for salinity and sodium hazards.

Aquifer Properties

The water-yielding capability of an aquifer is evaluated using the properties of the aquifer, especially hydraulic conductivity, transmissivity, and storage coefficient or specific yield. These aquifer properties together with the saturated volume of an aquifer as determined from interpretation of field data are used to quantify the volume of water stored in the aquifer. The amount of water available from an aquifer to wells is generally estimated as half the amount of water in storage. The yield to wells can be approximated using the aquifer properties, water level measurements, and certain assumptions concerning well construction.

FIGURE 5

DIAGRAM FOR CLASSIFYING THE QUALITY OF WATER FOR IRRIGATION



SOURCE:
USDA – HANDBOOK 60

The hydraulic conductivity, transmissivity, and storage coefficient or specific yield of an aquifer can be derived by two different approaches. These properties can be quantified through analysis and interpretation of aquifer-test data. However, the results of an aquifer test are valid only for a small area around the test site. The second approach for deriving these properties is as follows:

hydraulic conductivity - empirical values of hydraulic conductivity as determined for various associations of sediment grain sizes are applied to similar units described in a lithologic log.
transmissivity - the hydraulic conductivity of each lithologic unit is multiplied by the saturated thickness of that unit; total transmissivity is the sum of the transmissivities of the separate units.
storage coefficient or specific yield - several values are taken from a range of values characteristic for the type of aquifer being evaluated.

As is the case for the area of validity for aquifer-test results, the results obtained through the second approach are valid only for a small area surrounding a test-hole site. This is due to the characertistic heterogeneity of glacial-drift aquifers.

GEOLOGIC UNITS AND THEIR HYDROLOGIC PROPERTIES

Bedrock Formations

The Pierre, Fox Hills, and Hell Creek Formations of Late Cretaceous age and the Cannonball Formation of Tertiary (Paleocene) age directly underlie the glacial drift of the study area.

GENERALIZED STRATIGRAPHY OF GEOLOGIC UNITS

System	Formation	Dominant Lithology
Quaternary	Glacial drift	Clay, silt, sand, and gravel
Tertiary	Cannonball Fm.	Marine sandstone and shale
	Hell Creek Fm.	Claystone, sandstone, and siltstone
Late Cretaceous	Fox Hills Fm.	Sandstone, shale, and siltstone
	Pierre Fm.	Shale

Pierre Aquifer

The Pierre Formation is a consolidated, bluish-gray to dark gray shale. Thin sandy layers to sandstone lenses occur locally in the upper part as do fractures. The contact with the overlying Fox Hills Formation is gradational. The Pierre Formation directly underlies the glacial drift in eastern Kidder County and in the deep bedrock valleys of southwestern Kidder, southeastern Burleigh, and northwestern and central Emmons Counties.

The Pierre Formation is relatively impermeable. It acts as a barrier to flow for ground water in the overlying bedrock and glacial-drift aquifers and in the deeper aquifers of the Dakota and Madison Formations. The upper part of the Pierre can yield small quantities of relatively poor quality water from the sandy layers and sandstone lenses, and where fractures have increased the hydraulic conductivity of the formation. It is doubtful the Pierre aquifer is a source of supply in the study area except for Emmons County. Armstrong (1978) mentioned one well as probably completed in the Pierre aquifer. Little is known of the nature and occurrence of the Pierre aquifer in the study area and the hydrologic relationship between it and the overlying bedrock and glacial-drift aquifers.

Fox Hills, Hell Creek, and Cannonball Aquifers

The Fox Hills, Hell Creek, and Cannonball Formations consist mostly of interbedded sequences of semi-consolidated, fine-grained sandstone layers and shales and siltstones in various shades of brown and gray. These three formations underlie the glacial drift in the Burleigh County portion of the study area and near the flanks in the rest of the area. They also in part give expression to the topographic features used to delineate the study area.

The sandstone layers constitute aquifers that can yield a few tens of gallons per minute where adequate thicknesses occur. Small quantities of water may be available where shale or siltstone layers are fractured. These bedrock aquifers are a source for domestic and livestock water supplies where the glacial-drift aquifers are thin or absent. Recharge to the bedrock aquifers is principally by direct infiltration of precipitation where the aquifers crop out and by lateral flow eastward from the regional recharge area in western North Dakota and eastern Montana (Thorstenson, et al., 1979). The head difference between aquifers in the Fox Hills, Hell Creek, and Cannonball Formations and deeper aquifers in the Dakota and Madison Formations indicates slow upward leakage of water across the intervening confining formations (Thorstenson et al., 1979). In some locales in the study area, the Fox Hills, Hell Creek, and Cannonball aquifers may be recharged by water from adjacent glacial-drift aquifers. However, this hydrologic relationship is not well known. Discharge from the bedrock aquifers in the study area is generally by flow of water into the glacial deposits and by pumping of wells. Along the edges of the study area where the bedrock aquifers are at or near land surface, the water moves from higher elevations toward stream valleys.

The water in the bedrock aquifers is typically high in sodium with bicarbonate and sulfate the dominant anions, and concentrations of total dissolved solids ranging from about 500 mg/l to 2,500 mg/l. Water from the bedrock aquifers often influences the quality of water found in the glacial-drift aquifers.

Glacial-Drift Sediments and Aquifers

Unconsolidated sediments of the Coleharbor Group unconformably overlie the bedrock in the study area. Thickness of these sediments in the study area as determined by test drilling can be summarized as follows:

	Range	Average
Burleigh County	0' - 320'	107'
Emmons County	0' - 536'	195'
Kidder County	16' - 670'	210'
Entire Study Area	0' - 670'	169'

Three broad textural facies have been recognized for the Coleharbor Group (Bluemle, 1979) based on depositional environments. These are:

till facies - nonstratified, unsorted mixtures of clay particles through boulders deposited directly from glacial ice. The coarser grained fraction occurs in a clay-silt matrix and consists of angular to subrounded fragments of igneous, metamorphic, and carbonate rocks, shale, and lesser amounts of lignite.

sand and gravel facies - poorly sorted deposits of mostly sand and gravel characteristic of a glaciofluvial environment, and well sorted deposits of sand with some gravel associated with a lake shore environment.

silt and clay facies - deposits of silty clay, clayey silt, and fine sand laminae typical of a lacustrine environment.

The Coleharbor Group has been and continues to be reworked by erosion, particularly by wind, rain, and mass wasting. The sediments produced include alluvial and colluvial deposits on hillslopes and in valleys or other depressions, fluvial deposits along stream courses, and eolian deposits of dune fields and loess. Together these sediments comprise the Oahe Formation which is late Pleistocene to Holocene in age.

The sediments of the Coleharbor Group represent at least six major episodes of glaciation in the study area. The two oldest glaciations are thought to be late pre-Wisconsinan, possibly Illinoian in age, and each probably includes several advances of the ice margin (Bluemle, 1984). These two glaciations very likely covered the entire study area. Subsequent glacial advances are all Wisconsinan in age. The Napoleon advance is early Wisconsinan; the Long Lake and related Cat Tail Creek and Zeeland advances, the Burnstad, and the Streeter advances are all late Wisconsinan (Bluemle, 1984; Rau et al., 1962). Each advance covered less area than the previous one. The moraines associated with the last glaciation are found only in eastern Kidder County. Each advance deposited till and prolgacial glaciofluvial and lacustrine deposits and shaped the landforms associated with glaciation. The sediments and landforms of one advance were eroded, buried, or otherwise modified by the overriding ice sheet, proglacial processes, and periglacial environment of subsequent advances and the period of weathering between advances. The sediments and landforms of the more recent advances are better preserved and more evident than those of older advances which lie ahead of the younger ice margins.

The aquifer complex under investigation consists chiefly of outwash sand and gravel carried by meltwater flowing from the ice margins. These glaciofluvial sediments occupy former meltwater channels which aggraded and coalesced to form broader, sheetlike deposits. Advances of ice margins subsequent to sediment deposition eroded, buried, reworked, or otherwise modified the existing glaciofluvial deposits. The outwash sand and gravel of the last ice advance in the study area, the Streeter advance, remained unaltered by direct glacial action. It has been affected only by proglacial processes, periglacial climate, and post-glacial erosion.

Individual layers of sand and gravel range in thickness from about 5 to 165 feet with thicknesses of 20 to 60 feet common. Within the main aquifer complex the number of layers present varies from one to five or six. The number of layers varies almost randomly and the correlation of individual units over other than relatively short distances is tenuous because of the depositional environment. Individual sand and gravel layers can be hydraulically connected and respond as a hydrologic unit to changes in hydraulic head. Proper management of ground-water resources will be an important impetus for future study of the "Kidder County aquifer complex". The aquifer units proposed in this report are defined with an eye toward resource management and are based on hydraulic responses monitored in the existing observation-well network.

Strasburg Aquifer - Emmons County

The principal glacial-drift aquifer in Emmons County is the Strasburg aquifer (plate 1) described by Armstrong (1978). This aquifer underlies about 98 square miles of west-central to south-central Emmons County. It occupies a bedrock valley interpreted to be a diversion channel of the ancestral Missouri River (Kume and Hansen, 1965, p. 68 and Bluemle, 1984). Armstrong (1978) divided the aquifer into lower, middle, and upper sand and gravel zones separated by till, silt, and clay. Cumulative total thickness varies considerably, ranging from almost 0 feet near the aquifer edges to 275 feet in the thickest part.

The lower and middle zones are hydrologically confined; the upper zone is typically unconfined to leaky confined where buried by a relatively thin veneer of till, silt, or clay. The three zones are apparently three separate hydrologic units, but response of the aquifer system as a whole to high-capacity wells may reveal the lower and middle zones are hydraulically connected in at least parts of the aquifer (Armstrong, 1978). Recharge to the aquifer is mostly by infiltration of precipitation and runoff which moves downward and laterally in response to prevailing hydraulic gradients to the middle and lower zones. Discharge is mostly be evapotranspiration and wells. Some discharge in the southern part of the aquifer is by flow into South Dakota and Rice lake. In the northern part of the aquifer, discharge occurs into Beaver Creek and Lake Oahe or the sediments filling the Missouri River valley now flooded by Lake Oahe.

The sustained yield of a properly constructed well is determined by the thickness, lithology, hydraulic conductivity, and areal extent of the aquifer and the drawdown available in the well. Yield from the thicker part of the Strasburg aquifer is summarized as follows (Armstrong, 1978, p. 23)

Aquifer Zone	Range of Yield
Upper	generally <100 gpm
Middle	50 to >500 gpm
Lower	500-1000 gpm

Yield from the middle zone varies considerably due to abrupt changes in the thickness, lithology, and extent of the aquifer. Yield from the three zones together would probably be less than 1,000 gpm because the areas of each zone suitable for maximum yield do not coincide. An estimated 750,000 acre-feet of the water in the Strasburg aquifer is available to wells (Armstrong, 1978).

The quality of water varies both vertically and areally within the Strasburg aquifer system (Armstrong, 1978, p. 23). The water is generally very hard and a calcium bicarbonate type. However, in the northern part of the aquifer and where the Fox Hills aquifer adjoins the Strasburg aquifer the water is generally a sodium bicarbonate type. Total dissolved solids ranged from 362 to 1,720 mg/l for 56 samples. The salinity hazard of the water relative to irrigation use is typically high; sodium hazard typically low to medium. The sodium bicarbonate type water generally has a higher salinity hazard than the calcium bicarbonate type water (Armstrong, 1978, p. 25).

Some additional test drilling was done in the Strasburg aquifer as part of this study. Test holes were drilled at fourteen sites (plate 1). Ten observation wells were constructed at seven of the sites including one site with two wells and one site with three. The test-hole sites are in five areas along the Strasburg aquifer: between Rice Lake and Strasburg, just north of Strasburg, southwest of Linton, and across the Horsehead Valley at 133-78-24 and 26. The additional data further defined the geology of the Strasburg aquifer in areas not drilled in for the county study and allowed for better correlation of the three zones across these areas. Water levels measured in the observation wells constructed during this study verified the hydrology of the Strasburg aquifer as presented in the Emmons County ground-water report. The water levels indicate ground water moves downward from the upper to lower zones as well as laterally from a ground-water divide near Strasburg.

The total amount of water appropriated from the Strasburg aquifer by 1983 was 1330 acre-feet annually. Reported annual water use for the period 1973-1983 totaled about 1510 acre-feet. The recovery of water levels in observation wells 132-77-27DDD_1 and 27DDD_2 near current irrigation development indicates a minimal impact on the aquifer system (figure 6). However, the cone of depression generated by pumping for the city of Strasburg would fluctuate in response to any changes in the rate of withdrawal.

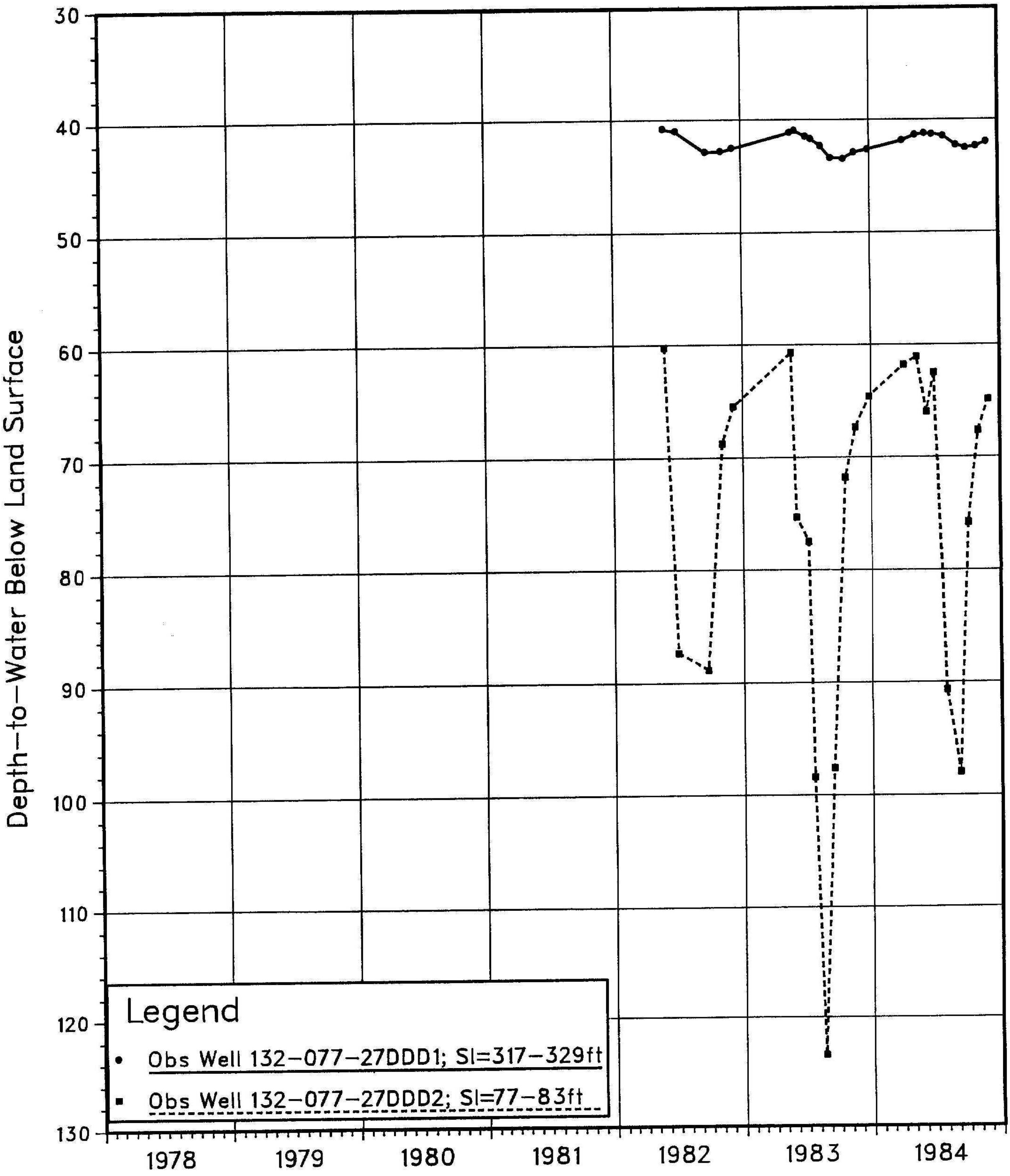
Glacial-Drift Aquifers - Burleigh County

The glacial-drift aquifers found in the Burleigh County portion of the study area were first delineated by Randich and Hatchett (1966) on the basis of geographic and hydrogeologic characteristics. This study includes the following

FIGURE 6

Hydrograph of Observation Wells – Strasburg Aquifer

Obs Well 132–077–27DDD1 Land–Surface Elev=1750ft NGVD
Obs Well 132–077–27DDD2 Land–Surface Elev=1750ft NGVD



of the aquifers found in the Burleigh County ground-water study:

Long Lake aquifer
Glencoe Channel aquifer
McKenzie aquifer
Random Creek aquifer
Lower and Upper Apple Creek aquifers
Wing Channel aquifer

These aquifers (plate 2) occur in surficial and buried-valley outwash deposits which occupy a system of valleys incised into bedrock (plate 3). Some of the valleys were the eastern pre-glacial courses of the ancestral Heart and Cannonball Rivers; others were modified by glaciation. Although the nomenclature of Randich and Hatchett (1966) for the glacial-drift aquifers established separate entities, the aquifers are more or less hydraulically connected because of the mode of deposition. The existing nomenclature is used in this report for consistency in aquifer identification, but the aquifer boundaries are somewhat modified.

Long Lake Aquifer

The Long Lake aquifer (plate 2) was originally defined as a glacial-drift aquifer underlying about 32 square miles in southeastern Burleigh County (Randich and Hatchett, 1966). Armstrong (1978) included as part of this aquifer the sand and gravel units found within a narrow, partially buried bedrock valley that trends south and west from Long Lake into Emmons County (plate 1). In Emmons County it follows Badger Creek to Lake Oahe. Armstrong (1978, p. 25) gives a full description of the Emmons County portion of Long Lake aquifer. The valleys incised into bedrock occupied by the Long Lake aquifer in Emmons and Burleigh Counties are interpreted to be part of the drainage system of the preglacial Heart and Cannonball Rivers (Kume and Hansen, 1965 and Bluemle, 1984).

Additional test drilling in the Long Lake aquifer done for this study indicates the aquifer occupies two bedrock valleys in Burleigh County (plate 3). The valleys separate about five miles west of the Kidder County line and rejoin about five miles NNW of Moffit. The northern valley is about five miles long, trends almost due west, and is relatively shallow. The southern valley follows the trend of Long Lake around a bedrock high. It is more deeply incised into bedrock than is the northern valley. The main part of the Long Lake aquifer occurs within the sediments in the southern bedrock valley.

Interpretation of the new data shows the Long Lake aquifer underlies about 46 square miles in southeastern Burleigh County (plate 2). The top of the aquifer lies 19 to 186 feet below land surface. Aquifer thickness encountered in test drilling varies from 3 to 97 feet and averages 36 feet. The aquifer material consists typically of medium sand to medium gravel, but can range from very fine sand to coarse gravel. The aquifer in the northern valley is predominantly very fine to medium sand, indicative of a lower energy depositional environment. However, at two locations beds 8 and 14 feet thick of the coarse sand to medium gravel of outwash were found. The Long Lake aquifer directly overlies the bedrock over most of its area (plate 9). However, in some localities intervening till or silty clay is present. At some other locations, till or lacustrine silts and clays separate the aquifer into more than one layer. The aquifer is predominantly overlain by silt and clay deposited from glacial Lake McKenzie. These sediments produce the confined conditions within Long Lake aquifer. The aquifer apparently is locally unconfined over a small area on the eastern flank near the Emmons County line where the aquifer lies within 20' of land surface. The results of an aquifer test in the Emmons County portion of the aquifer yielded transmissivity values ranging from 6,000 to 8,700 ft^2/day and a storage coefficient of 0.0002. Transmissivity values can be estimated over the areal extent of the aquifer from test-hole logs using the thickness and an estimated hydraulic conductivity for the various sand or gravel units encountered. The transmissivity values thus calculated range from about 300 to 7,200 ft^2/day, with an average value of 2,400 ft^2/day. An estimated 159,000 acre-feet of water are available from storage, based on a specific yield of 0.15, an average thickness of 36 feet, and an areal extent of 46 square miles.

The principal sources of recharge to the Long Lake aquifer are: direct infiltration of precipitation, underflow from the adjacent glacial-drift aquifer system in Kidder County and the Fox Hills aquifer, lateral flow from the surficial outwash and other drift deposits bordering the Long Lake aquifer, and Long Lake itself. Long Lake is divided by low earthen dams into three units. Spillways maintain slightly different water levels in each unit. Flow relationships between the three surface-water units in the Long Lake National Wildlife Refuge and the Long Lake aquifer can be established by comparing surface-water elevations and water-level elevations in nearby observation wells. Such comparison shows a downward gradient exists during the summer to early fall, indicating leakage from Long Lake into the aquifer.

Discharge from the Long Lake aquifer is by evapotranspiration, seepage into Long Lake Creek, infiltration into Long Lake during the late fall to spring, underflow into the adjacent McKenzie aquifer, and wells. Domestic and stock wells discharge a relatively small amount of water. By 1983, appropriations for irrigation totaled 2141 acre-feet for 1414 acres. However, reported annual water use for the period 1973-1983 totaled about 1390 acre-feet. The hydrograph of observation well 137-76-05DCC (figure 7) indicates recovery of the aquifer system to the seasonal irrigation pumping, suggesting no adverse impacts on the aquifer with the current level of development.

The yield of a well is related in part to such aquifer properties as thickness, hydraulic conductivity, and areal extent. Well yields of the Long Lake aquifer, as estimated from test-hole and observation-well data, range from less than 50 gpm to more than 500 gpm (plate 4). Yields exceeding 1000 gpm may be obtained locally where the aquifer is thickest and has a high hydraulic conductivity. However, aquifer extent and barriers to ground-water flow preclude sustaining such yields for long periods of time. Sustained well yields in the northern valley of the aquifer probably will not exceed 200 gpm. This part of the aquifer is of limited thickness and areal extent and has a relatively low hydraulic conductivity.

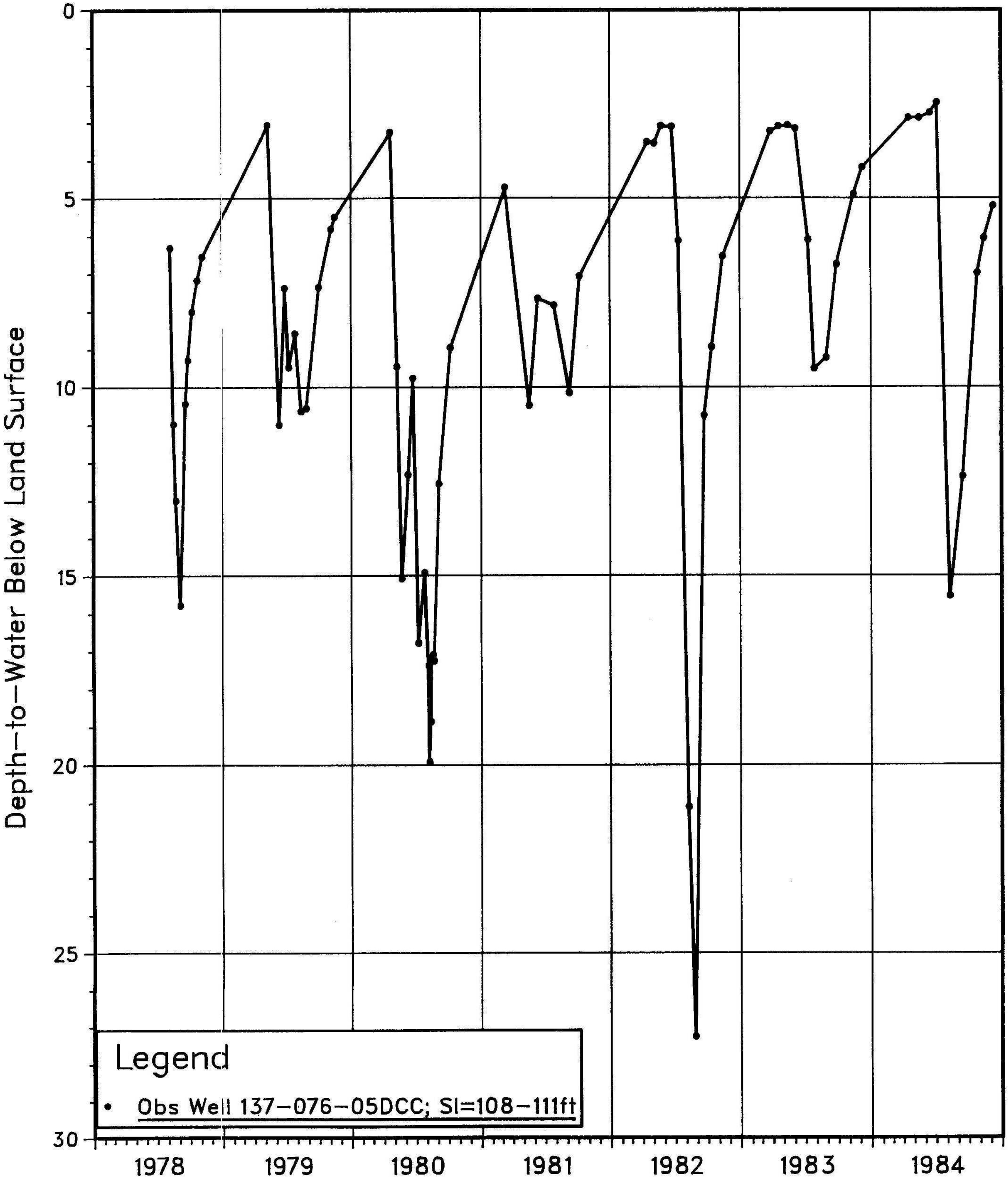
The slope of the potentiometric surface indicates ground-water movement year-round into the Long Lake aquifer from the equivalent glacial-drift aquifer in Kidder County and from the Long Lake aquifer in Emmons County. Water levels measured in observation wells near the northwest end of Long Lake suggest recharge to the Long Lake aquifer from the adjacent Fox Hills Formation. This flow relationship is somewhat masked by drawdowns in this part of the Long Lake aquifer during the summer. A ground-water divide occurs in the northern valley of the aquifer near 137-76-03ABB and also in the Emmons County part of the aquifer (Armstrong, 1978, p.26).

Water in the Long Lake aquifer is predominantly hard to very hard and of a sodium-bicarbonate type. The water quality can be summarized as follows:

FIGURE 7

Hydrograph of Observation Well – Long Lake Aquifer

Obs Well 137–076–05DCC; Land–Surface Elev=1721.9ft NGVD



	Range	Average
Fe(mg/l)	0.00 - 3.50	0.78
Mn (mg/l)	0.18 - 1.80	0.60
SO_4 (mg/l)	112 - 550	287
TDS (mg/l)	696 -1400	1028
%Na	47 - 96	73
SAR	3.2 - 27.9	10.4
RSC	0 - 11	6

Irrigation classifications range from C3-S1 to C3-S4 (figure 8). The salinity hazard is high; the sodium hazard is typically medium to high.

The water along the northern valley of the aquifer exhibits certain water-quality characteristics somewhat different from the general pattern. The sodium hazard ranges from low (S1) to medium (S2) although the salinity hazard remains high (C3). The water is of a sodium-sulfate type and very hard.

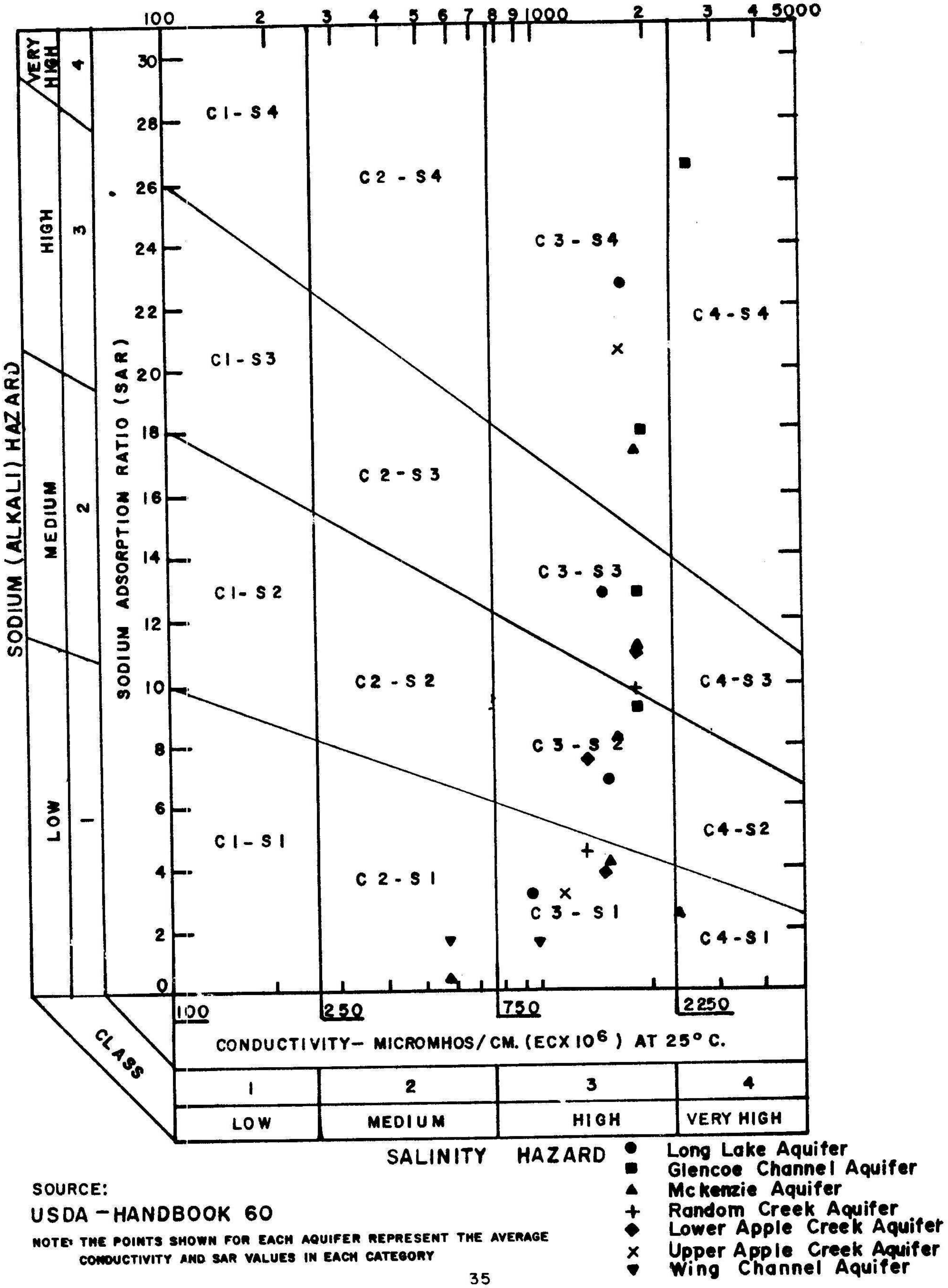
Glencoe Channel Aquifer

The Glencoe Channel aquifer as delineated by Randich and Hatchett (1966) and Armstrong (1978) encompasses about 27 square miles in south-central Burleigh County (plate 2) and the northwestern corner of Emmons County (plate 1). A broad bench to the northwest of the bend in the Glencoe valley and 30 to 80 feet higher than the valley floor was included within the aquifer boundaries of Randich and Hatchett (1966, p.52). Test drilling done for this study in this area encountered very little saturated material. The new data indicate the aquifer underlies about 22 square miles (plate 2) and occurs for the most part within the glaciofluvial sediments filling the bedrock valley. The bedrock valley (plate 3) is a proglacial melt-water channel incised into the Hell Creek and Fox Hills Formations by melt-water drainage from the Napoleon ice (Kume and Hansen, 1965). The width of this valley varies from one to three miles at its top and

FIGURE 8

DIAGRAM FOR CLASSIFYING THE QUALITY OF WATER FOR IRRIGATION

BURLEIGH COUNTY



SOURCE:
USDA – HANDBOOK 60

NOTE: THE POINTS SHOWN FOR EACH AQUIFER REPRESENT THE AVERAGE CONDUCTIVITY AND SAR VALUES IN EACH CATEGORY narrows rather abuptly to less than one-half mile at its base.

The Glencoe Channel aquifer occurs as units of sand and gravelly sand. Total thickness of the aquifer ranges from 5 to 147 feet and averages 60 feet. Due to the stratigraphy of the valley-fill sediments, the aquifer consists of two zones, an upper and a lower, which are hydraulically interrelated (plate 9).

The upper zone occurs in the central and south-central part of the Glencoe valley, beginning about three miles southwest of the McKenzie aquifer and ending within two miles of the Emmons County line. The zone pinches out at both ends by a rapid facies change to silty clay. The zone consists predominantly of very fine to fine and medium sand and may represent in part eolian deposition within the valley (Kume and Hansen, 1965, p. 65). The top of this zone lies 2 to 83 feet below land surface. Thickness of the zone ranges from 5 to 112 feet and averages about 42 feet. Test-hole data indicate that 10 to 40 feet of silt and clay commonly separate the upper zone into two layers. The data suggest the deeper layer is leaky confined for the most part and the surficial layer is unconfined. Transmissivity values estimated from test-hole logs range from about 100 to 6,900 ft^2/day and average approximately 1,500 ft^2/day. The range of values arises more from the variable thickness of the upper zone than from variations in hydraulic conductivity. Few water levels are available for the upper zone. Those that do exist indicate ground-water flow from the upper to the lower zone.

The lower zone directly overlies the Fox Hills Formation. It consists of coarse sediments, typically medium and coarse sand to medium gravel. This zone lies 97 to 163 feet below land surface. Thickness ranges from 22 to 85 feet and averages 47 feet. Beds of lacustrine silts and clays locally separate the lower zone into as many as five units, but these coalesce within a short distance.

The lower zone is overlain by 11 to 112 feet of silty clay and clayey silt which act as an aquitard and generate confined conditions in the lower zone (plate 9). Values of transmissivity estimated from test-hole logs range from 300 to 9,000 ft^2/day and average about 3,600 ft^2/day. Under natural conditions the water level in the lower zone is at an elevation of 1690 feet at the north end of the aquifer and 1637 feet at the south end indicating ground-water flow is to the west and south toward Lake Oahe (plate 2). The amount of water available from storage in the lower zone is estimated at 99,000 acre-feet, based on an average thickness of 47 feet, a specific yield of 0.15, and an areal extent of 22 square miles.

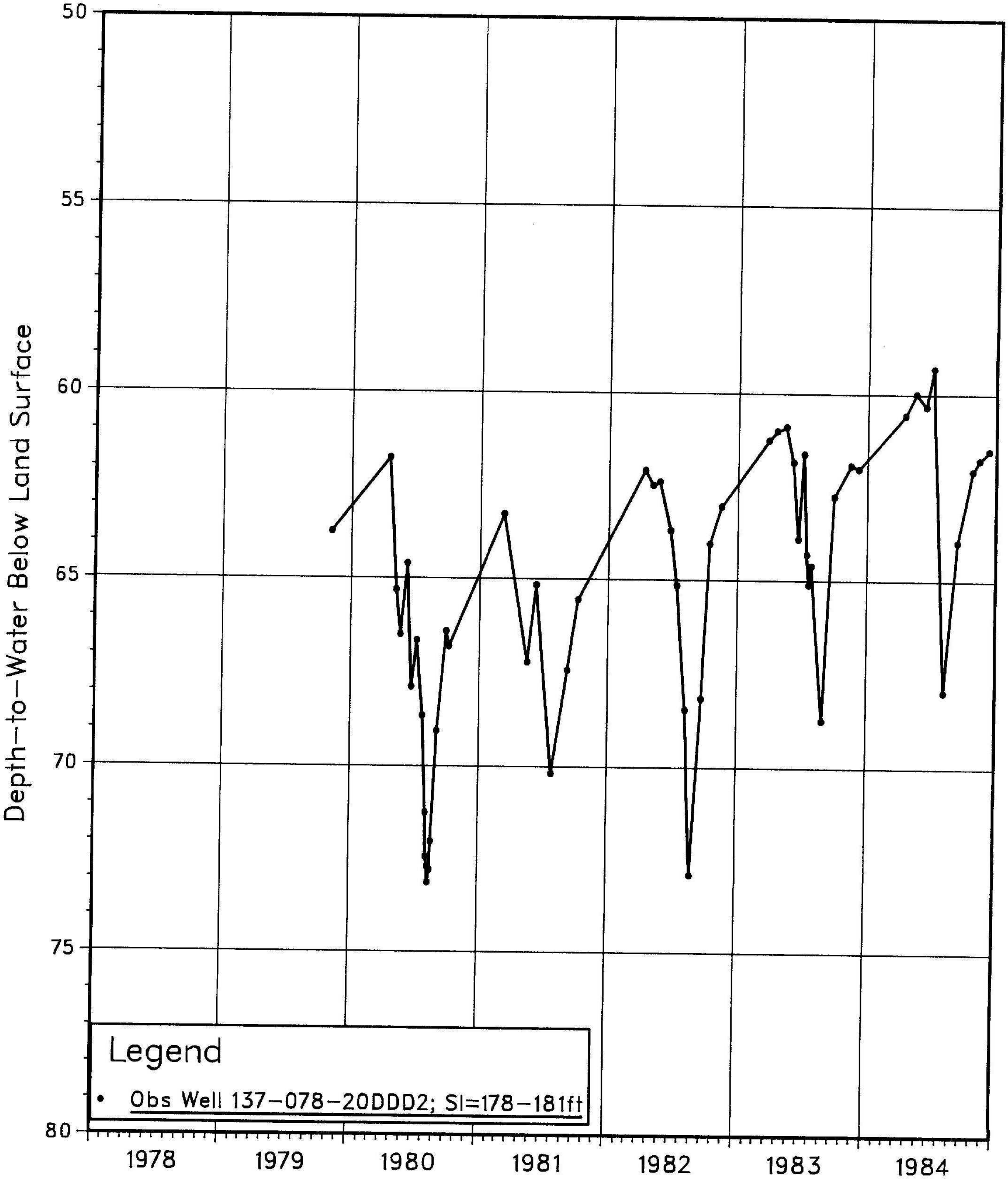
Recharge to the Glencoe Channel aquifer is derived from precipitation and runoff directly infiltrating the highly permeable surficial sand in the Glencoe valley and along the valley flanks in areas where unsaturated sand occurs. The water moves through these materials and downward to the lower zone of the aquifer. Underflow from the adjacent McKenzie and Fox Hills aquifers also recharge the Glencoe Channel aquifer.

Discharge from the Glencoe Channel aquifer is by ground-water movement into Lake Oahe, evapotranspiration, and water withdrawals for irrigation. Domestic and stock wells account for a relatively small proportion of the discharge. By 1983, appropriations for irrigation totaled 3837 acre-feet for 2410 acres. However, reported annual water use for period 1973-1983 totaled about 790 acre-feet. The hydrograph of observation well 137-78-20DDD$_2$ (figure 9) indicates recovery of the aquifer system from seasonal irrigation pumping, suggesting no adverse impacts on the aquifer with the present level of development.

FIGURE 9

Hydrograph of Observation Well – Glencoe Channel Aquifer

Obs Well 137–078–20DDD2; Land–Surface Elev=1721.5ft NGVD



Yields to wells in the Glencoe Channel aquifer, as estimated from test-hole and observation well data, range from less than 50 gpm near the edge of the aquifer to over 500 gpm along the aquifer's axis (plate 4). The level of development the aquifer will be able to support is limited by its narrow, elongate shape.

Water in the Glencoe Channel aquifer is mostly hard to very hard. All samples indicated a sodium-bicarbonate type water. The water quality can be summarized as follows:

	Range	Average
Fe(mg/l)	0.00 - 2.30	0.85
Mn(mg/l)	0.01 - 1.00	0.37
SO_4(mg/l)	0.8 - 607	318
TDS(mg/l)	1140 -1860	1338
%Na	72 - 97	85
SAR	9.2 - 40.7	17.5
RSC	7 - 19	12

Irrigation classifications range from C3-S2 to C4-S4 (figure 8). The salinity hazard is predominantly high (C3); the sodium hazard is high to very high (S3-S4).

McKenzie Aquifer

The McKenzie aquifer delineated by Randich and Hatchett (1966) included approximately 63 square miles. Additional test drilling redefined the margins of the aquifer and reduced its areal extent to about 49 square miles (plate 2). A bedrock high of about 1.5 square miles approximately two miles SSW of McKenzie elevates the land surface near the center of the aquifer (plate 3). The top of the aquifer lies 21 to 200 feet below land surface. The top of the aquifer is found at shallower depths along portions of the eastern flank. The aquifer consists predominantly of gravelly sand (plate 9). Total thickness ranges from less than 10 feet to 162 feet and averages about 54 feet. The aquifer directly overlies the Fox Hills Formation although an intervening silty clay unit can occur locally. Beds of silty clay locally separate the aquifer into several units, each of variable thickness, which coalesce within a relatively short distance. Water-level trends noted on hydrographs of dual-well monitoring sites indicate a similar hydrologic response in aquifer units separated by relatively thin beds of silty clay (figures 10 and 11). Where the silty clay interval is relatively thick, the aquifer is divided into two units which are hydraulically separate (figures 12 and 13). The silty clay confines the aquifer over most of its areal extent. Unconfined conditions do occur locally in very localized areas along the aquifer edges. The most pronounced of these is north of Random Creek valley where 73 feet of surficial outwash act as a conduit for recharging the central part of the McKenzie aquifer.

The results of two aquifer tests within one mile of each other yielded the following transmissivity values. The range of values from test 1 was 3,300 to 5,700 ft^2/day and from test 2 was 2,800 to 4,300 ft^2/day (Randich and Hatchett, 1966) with averages of 4,300 and 3,300 ft^2/day, respectively. Values of transmissivity extending over most of the McKenzie aquifer were estimated from test-hole data. These values vary from a low of around 300 ft^2/day where the aquifer is thin to about 13,200 ft^2/day, and average approximately 6,200 ft^2/day. Values for storage coefficient derived from the aquifer tests range from .00007 to .00040 for test 1 and .00017 to .00073 for test 2 (Randich and Hatchett, 1966) with averages of .00022 and .00042, respectively. An estimated 254,000 acre-feet of water are available from storage, assuming a specific yield of 0.15, an areal extent of 49 square miles, and an average thickness of 54 feet.

The McKenzie aquifer is recharged by precipitation and runoff infiltrating

FIGURE 10

Hydrograph of Observation Wells – McKenzie Aquifer

Obs Well 138–077–14DDD1; Land–Surface Elev=1720.4ft NGVD
Obs Well 138–077–14DDD2; Land–Surface Elev=1721.0ft NGVD

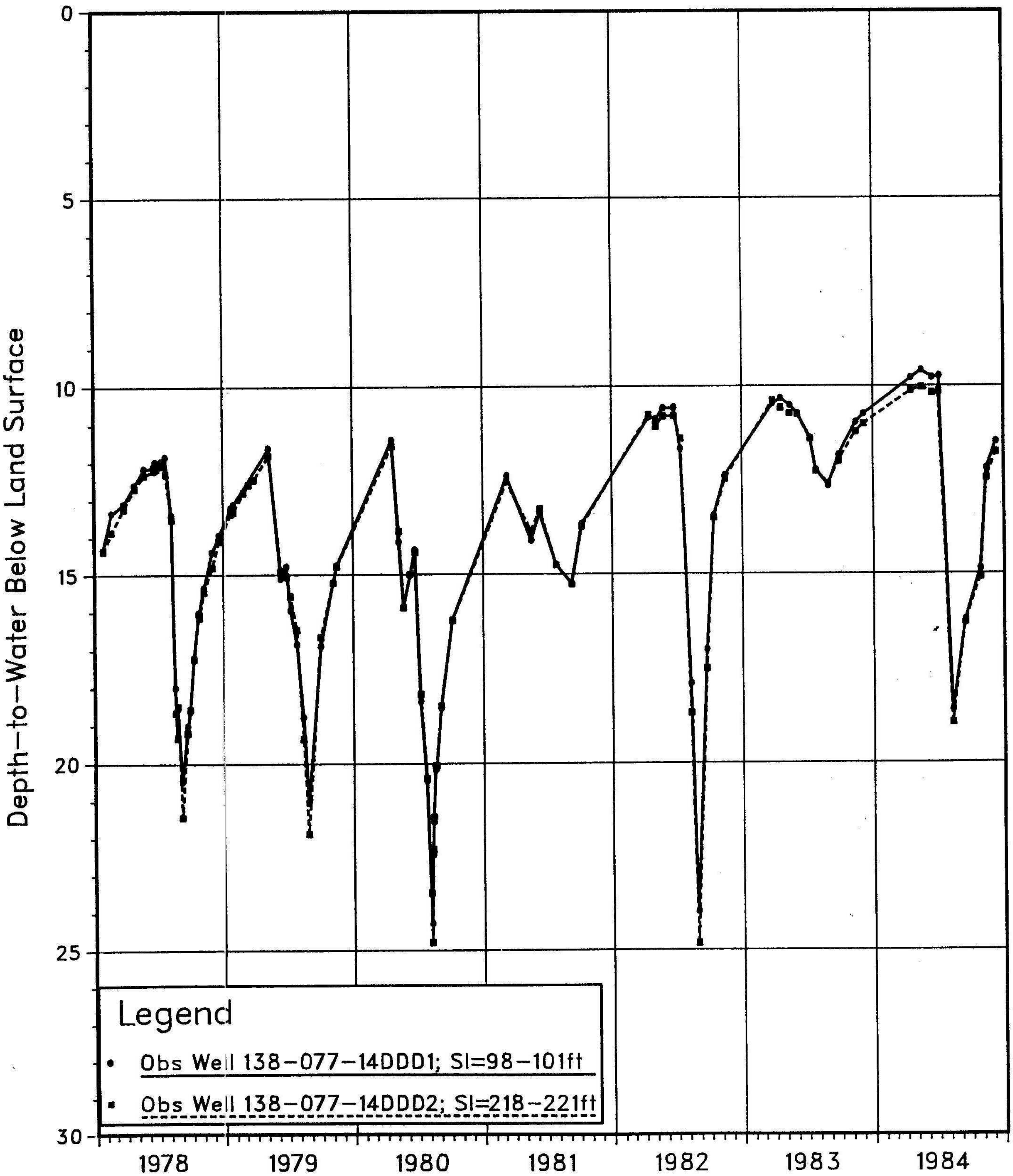


FIGURE 11

Hydrograph of Observation Wells – McKenzie Aquifer

Obs Well 138–077–24AAA1; Land–Surface Elev=1720.7ft NGVD
Obs Well 138–077–24AAA2; Land–Surface Elev=1720.4ft NGVD

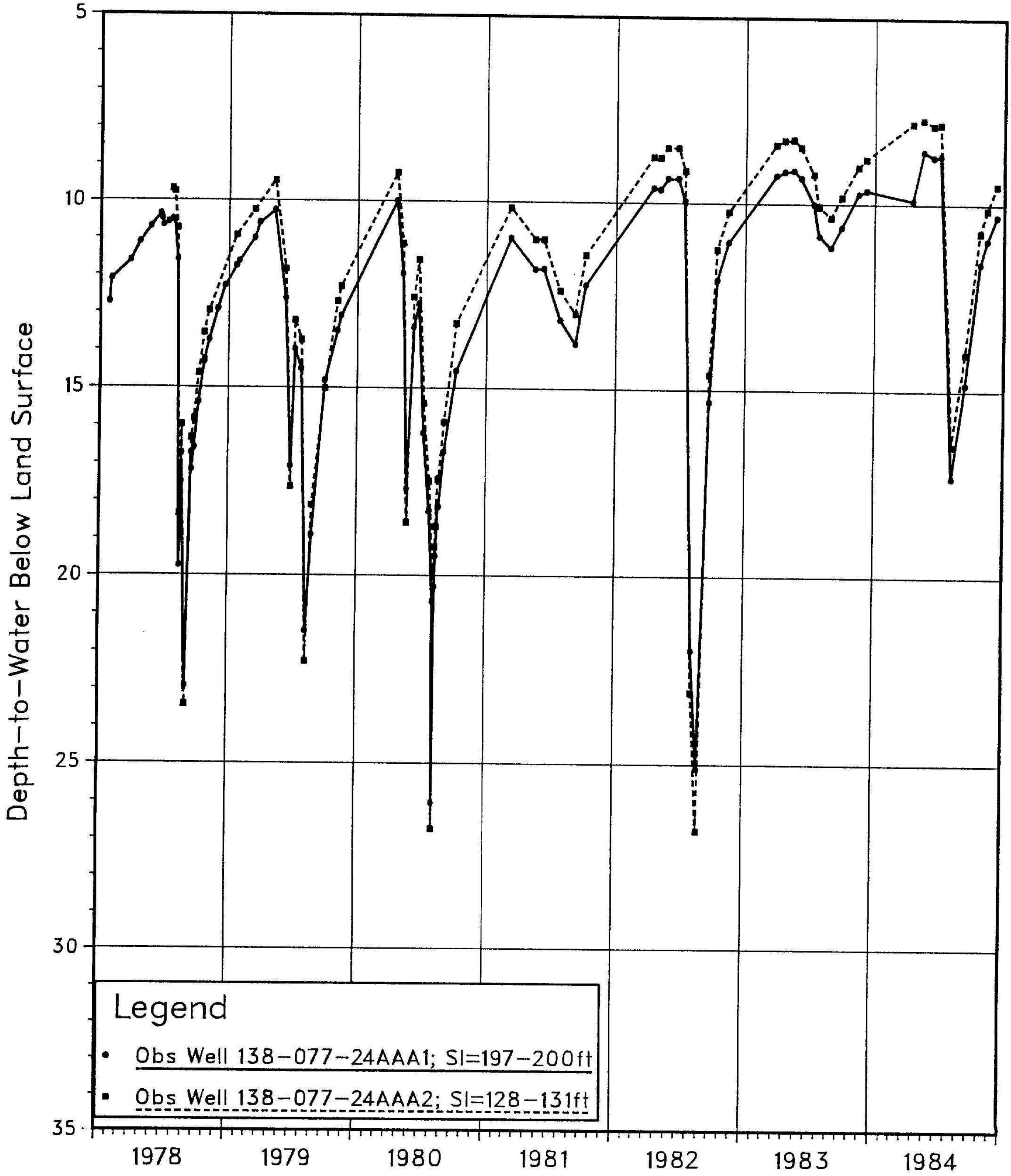


FIGURE 12

Hydrograph of Observation Wells – McKenzie Aquifer

Obs Well 138–077–13BBC1; Land–Surface Elev=1733.5ft NGVD
Obs Well 138–077–13BBC2; Land–Surface Elev=1732.6ft NGVD

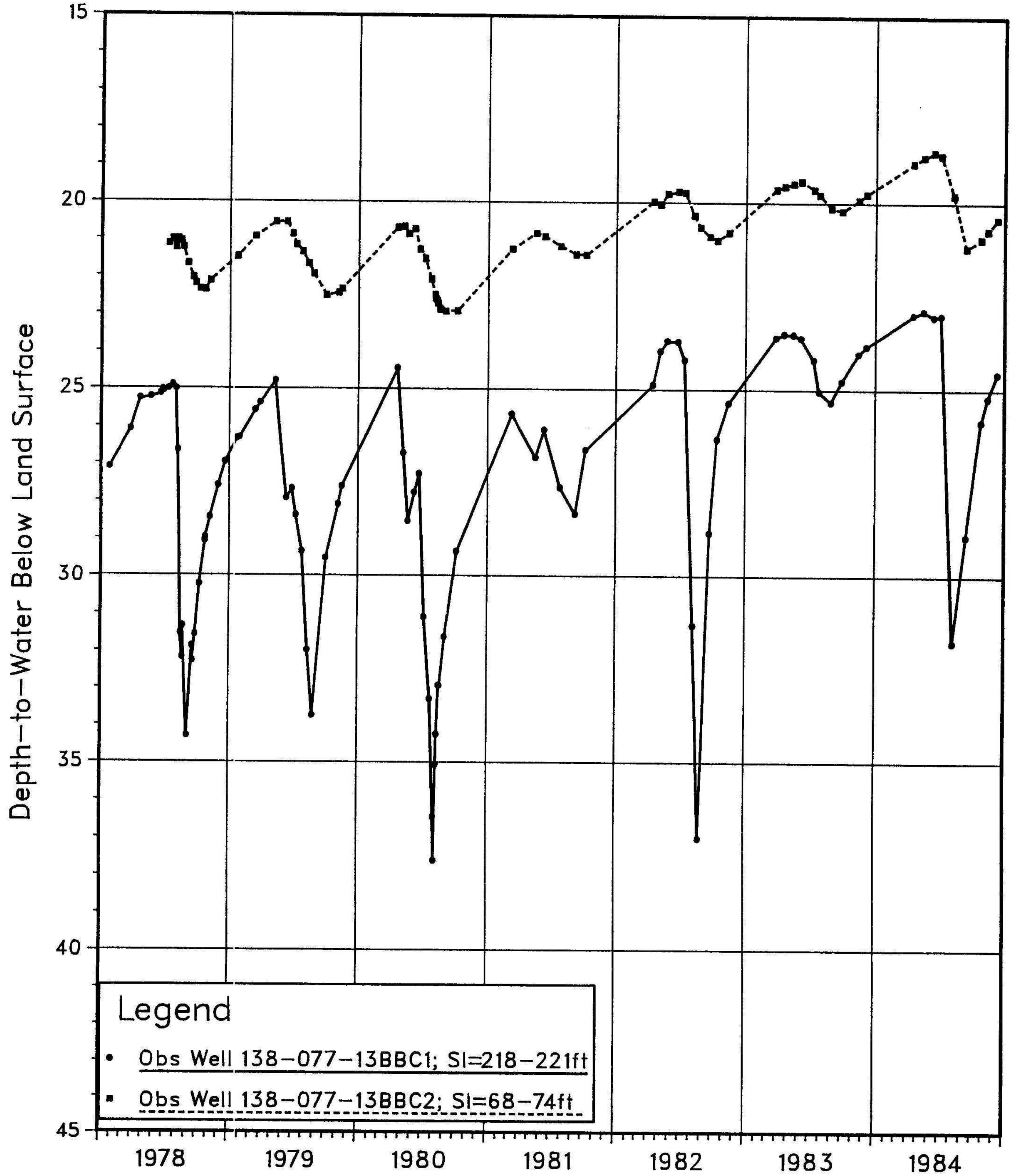
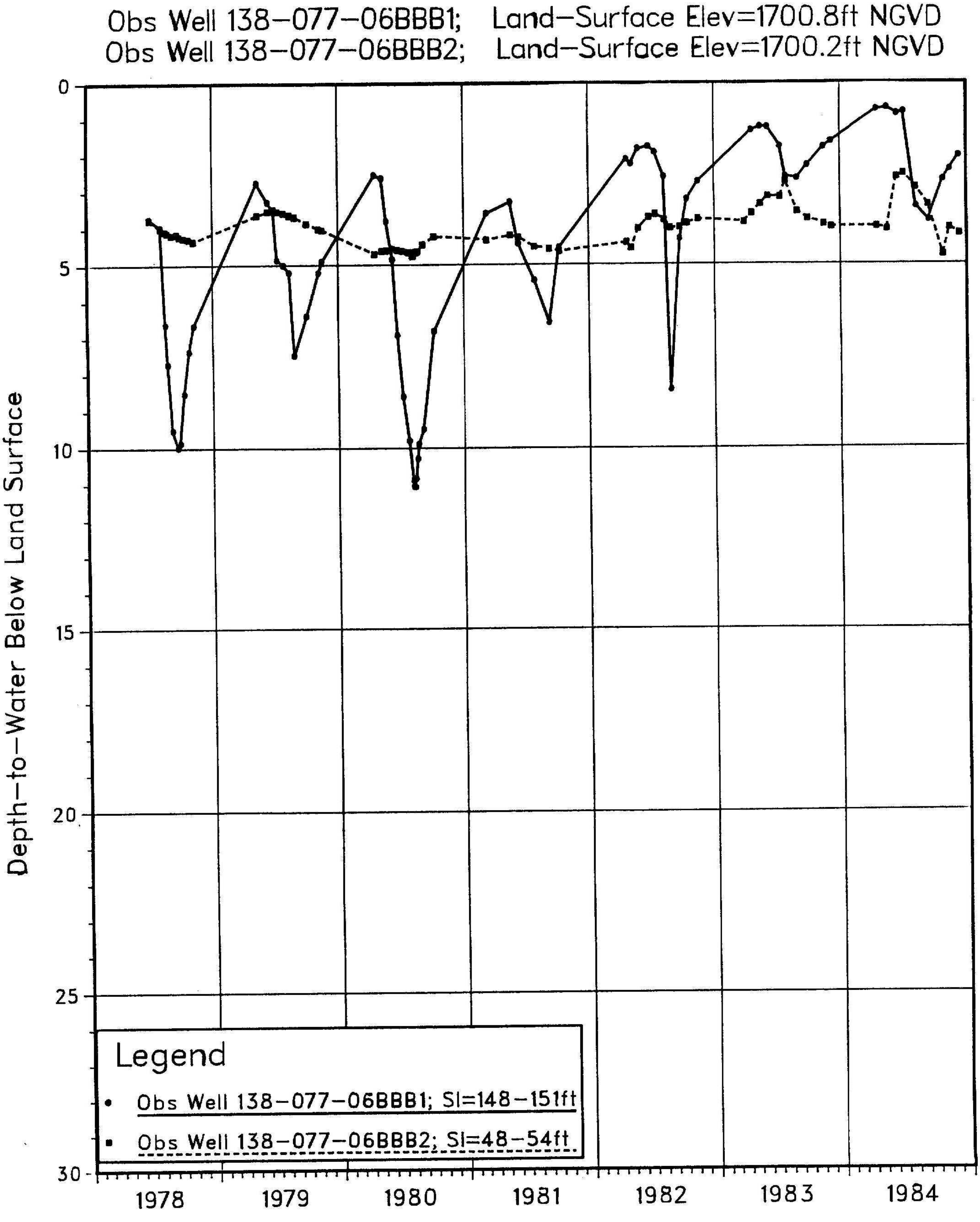


FIGURE 13

Hydrograph of Observation Wells – McKenzie Aquifer



through permeable material found along much of the edges of the aquifer and in the Random Creek valley. The recharge water moves through these materials and downward into the main body of the aquifer. At the height of the irrigation season, the downward gradient can be reversed locally for short periods of time. Another source of recharge is the lateral flow from the adjacent Long Lake and Fox Hills aquifers. Overall movement of water within the aquifer is to the northwest.

Discharge from the aquifer is by upward seepage into McKenzie Slough, evapotranspiration, lateral flow into the adjacent Glencoe Channel and Lower Apple Creek aquifers, and pumping of wells. Total appropriations for irrigation by 1983 were 6176 acre-feet for 4648 acres. Reported annual water use for the period 1973-1983 totaled about 4200 acre-feet. The hydrographs of observation wells in the McKenzie aquifer (figures 10, 11, 12, and 13) indicate overall recovery of the aquifer system from the effects of seasonal irrigation pumping. The trend suggests no adverse impacts on the system with the current level of development. However, the density of irrigation wells may be locally at an optimum level between seasonal recovery and long-term gradual decline of water levels.

Yields to wells as estimated from test-hole and observation-well data range from around 50 gpm near the flanks of the aquifer where it is thin to over 500 gpm in the center of the aquifer (plate 4). Yields greater than 1000 gpm may be available locally where the aquifer is thickest. Development of such wells will be limited by the variable thickness of the aquifer and the occurrence of interfingering beds of silt and clay.

Water in the McKenzie aquifer is predominantly very hard and of a sodium-bicarbonate type. The water quality can be summarized as follows:

	Range	Average
Fe(mg/l)	0.05 - 4.40	0.97
Mn(mg/l)	0.04 - 1.50	0.47
SO_4(mg/l)	100 - 780	340
TDS(mg/l)	571 -1560	1152
%Na	5 - 90	72
SAR	0.2 - 19.1	9.5
RSC	0 - 11	7

Irrigation indices range from C2-S1 to C4-S1 (figure 8). The salinity hazard is mostly high (C3); the sodium hazard medium to high (S2-S3).

Random Creek Aquifer

The Random Creek aquifer underlies about 4.5 square miles of the study area (plate 2) in southeastern Burleigh County south of Sterling. It generally follows the Random Creek valley and consists of gravelly sand. Based on the additional test drilling, the boundaries of the west end of the aquifer indicated by Randich and Hatchett (1966) were moved to the north about one-half mile. Subsurface data for the aquifer in this area show the top of the aquifer lies 20 to 32 feet below land surface and thickness to vary between 7 and 49 feet. The aquifer is confined by units of till or silty clay. The slope of the potentiometric surface to the southwest (plate 2) indicates ground-water flow along the trend of Random Creek valley. Very little flow is found in Random Creek because most of the water is moving within the aquifer (Randich and Hatchett, 1966, p. 72).

Recharge to the aquifer comes from infiltrating precipitation and runoff, and through leakage from adjacent bedrock or drift deposits on the surrounding uplands. Discharge is mostly by lateral flow into the McKenzie aquifer and by evapotranspiration, and to a lesser extent by low-yield domestic and stock wells.

The few water quality analyses available indicate a very hard, sodium sulfate type water with a high salinity hazard (C3) and low to medium sodium hazard (figure 8).

Lower Apple Creek Aquifer

The Lower Apple Creek aquifer includes the permeable sediments within the bedrock valley (plate 3) that follows Apple Creek (Randich and Hatchett, 1966). The aquifer underlies about 21 square miles of the study area (plate 2) in central Burleigh County. Top of the aquifer lies from about 10 feet to 89 feet below land surface. Total thickness ranges between less than 10 feet to 112 feet and averages 47 feet (plate 9). Sand comprises most of the aquifer with layers of gravelly sand common at most sites. The Fox Hills and Hell Creek Formations directly underlie the aquifer, although silty clay may locally separate the bedrock and aquifer. Silty clay and till divide the aquifer into two units which coalesce within a short distance. Silty clay also confines the aquifer. Values of transmissivity estimated from test-hole data range from 200 to 9,000 ft^2/day and average 2,600 ft^2/day. About 95,000 acre-feet of water are estimated to be available from storage, using an areal extent of 21 square miles, a specific yield of 0.15, and an average thickness of 47 feet.

Recharge to the Lower Apple Creek aquifer is derived from precipitation and runoff infiltrating permeable surficial materials on the adjacent uplands. Recharge is also derived from seepage of water moving down the Apple Creek drainage system and from the intermittent streams that end on the aquifer along the southeastern edge of the valley. Lateral flow from the McKenzie and Upper Apple Creek aquifers and adjacent and underlying bedrock aquifers also recharge the Lower Apple Creek aquifer. Ground-water flow is to the west (plate 2).

Discharge from the Lower Apple Creek aquifer consists of lateral flow along the aquifer out of the study area, seepage into Apple Creek, evapotranspiration, and wells. By 1983, appropriations for irrigation totaled 2480 acre-feet for 1654 acres. However, reported annual water use for the period 1973-1983 totaled about 2210 acre-feet. The hydrograph of observation well 139-78-21DDA (figure 14) suggests that the aquifer is not adversely affected by the current level of development.

Potential yields to wells as estimated from test-hole and observation-well data vary from less than 50 gpm along the aquifer flanks and in areas where the aquifer is thin to more than 500 gpm along the eastern edge near the McKenzie aquifer (plate 4). Well yields are anticipated to decrease toward the western end of the aquifer due to narrowing of the bedrock valley.

Water from the Lower Apple Creek aquifer in the study area is mainly a sodium-bicarbonate type and very hard. The water quality can be summarized as follows:

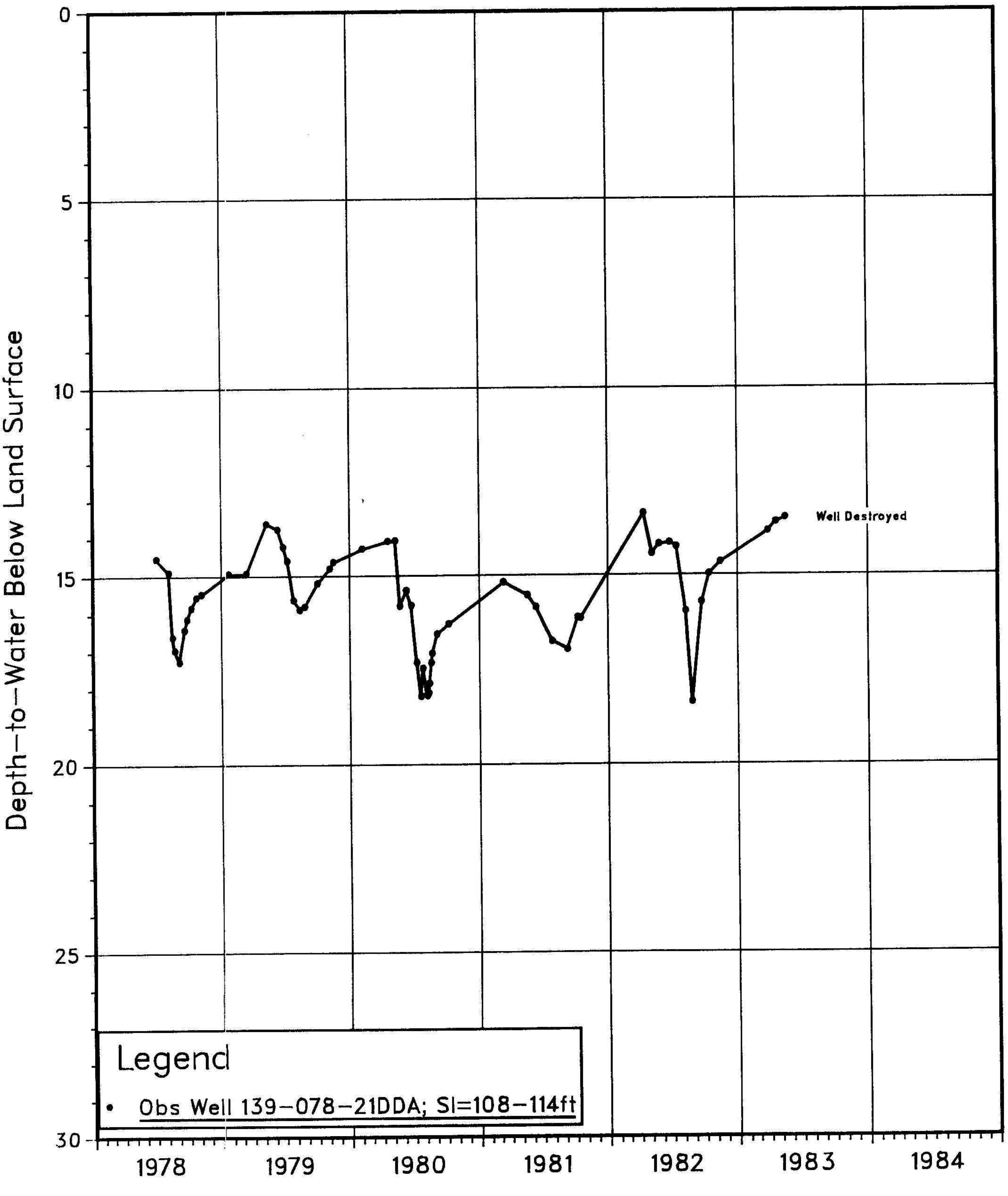
	Range	Average
Fe(mg/l)	0.08 - 4.30	1.90
Mn(mg/l)	0.01 - 0.80	0.31
SO_4(mg/l)	150 - 300	256
TDS(mg/l)	802 -1220	1050
%Na	47 - 79	70
SAR	3.8 - 11.1	8.6
RSC	2 - 9	6

Irrigation classifications range from C3-S1 to C3-S3 (figure 8). Salinity hazard is high (C3); sodium hazard low to high (S1-S3).

FIGURE 14

Hydrograph of Observation Well – Lower Apple Creek Aquifer

Obs Well 139–078–21DDA; Land–Surface Elev=1698.6ft NGVD



Upper Apple Creek Aquifer

The Upper Apple Creek aquifer underlies about 20 square miles of the study area (plate 2) in central Burleigh County. It for the most part occupies the valleys of the West and East Branch of Apple Creek (Randich and Hatchett, 1966) which are somewhat incised into the bedrock (plate 3). The aquifer also underlies Rice Lake and apparently trends to the southeast toward Clear Lake. The glacial-drift aquifers in the area centered around Clear Lake are not included in this study, but warrant further investigation to determine the hydrogeological relationships between the Random Creek and Upper Apple Creek aquifers.

The top of the Upper Creek aquifer lies at land surface in some parts of the Apple Creek valley to 48 feet below land surface. Average depth to the aquifer is 10 feet. Total thickness varies between 11 and 70 feet and averages 26 feet. Sand and gravelly sand comprise most of the aquifer. Till or silty clay units of variable thickness are common within the shallow bedrock valley of Apple Creek. These units generate confined conditions over much of the aquifer from Rice Lake southward to the juncture with the McKenzie and Lower Apple Creek aquifers. North of Rice Lake confined conditions exist along the center of the aquifer where several feet of silty clay or till overlie the sand and gravel. However, there is a transition to water-table conditions during the summer in some of the confined areas as water levels fall below the aquitard. Unconfined conditions are common along the flanks of the aquifer. The northern boundary of the aquifer is marked by an apparent ground-water divide with the Wing Channel aquifer and delineated by an intermittent stream about three miles SSW of Wing in 142-76-22. Values of transmissivity as estimated from test-hole data vary from 2,400 to 7,100 ft^2/day and average about 4,200 ft^2/day. The range of transmissivity values stems mostly from the varying thickness of the aquifer. Water-level elevations measured in observation wells in the Upper Apple Creek aquifer range from around 1870 feet toward the north end and 1788 feet toward the west end, indicating ground-water flow down the Apple Creek valley-fill sediments (plate 2). About 50,000 acre-feet are estimated to be available from storage. This is based on a specific yield of 0.15, an average thickness of 26 feet, and an areal extent of 20 square miles.

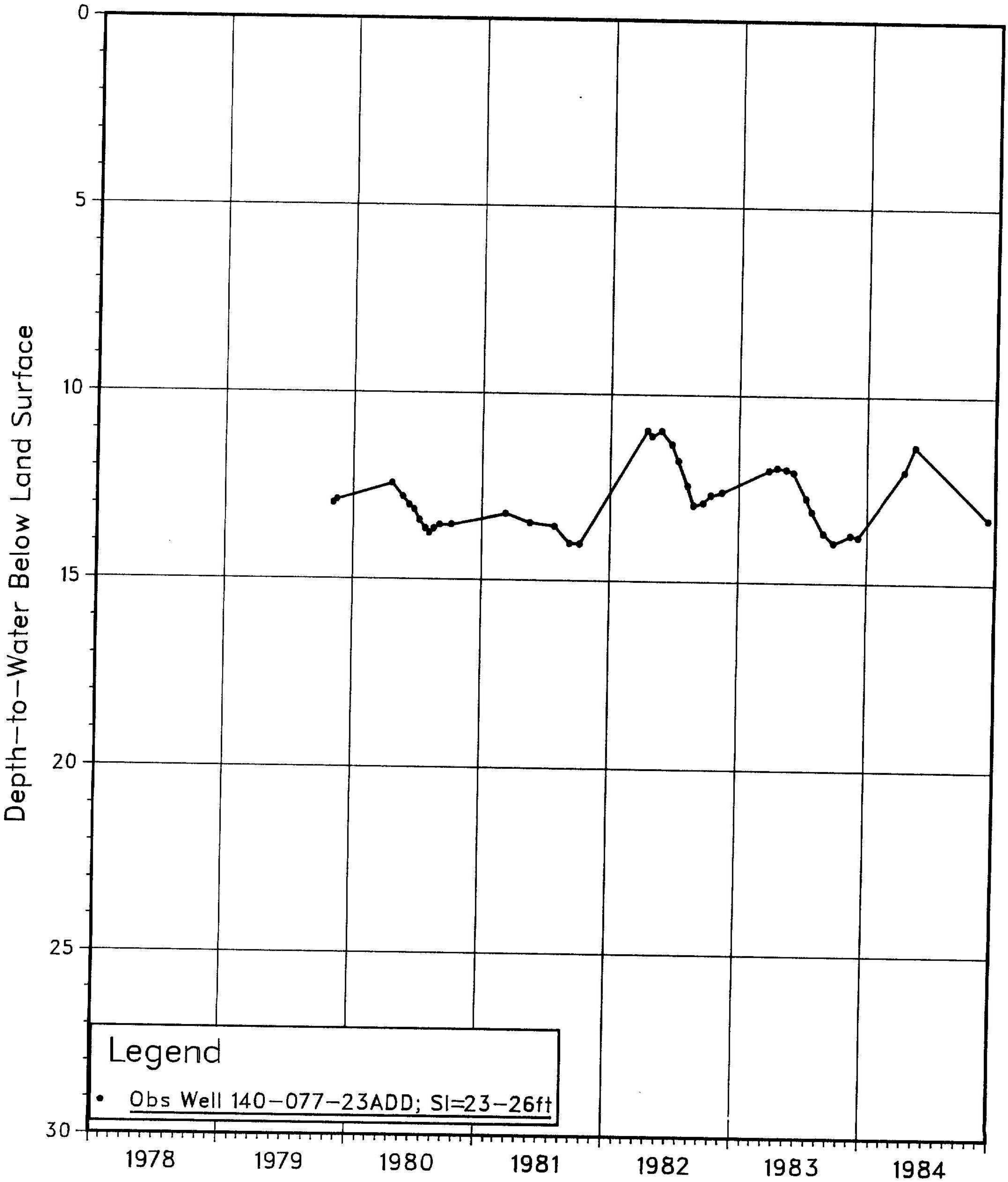
The Upper Apple Creek aquifer is recharged primarily by infiltrating precipitation and lateral flow from the outwash deposits on the surrounding uplands. Other sources of recharge are lateral flow from the adjacent bedrock aquifer and seepage from Apple Creek and Rice Lake.

Discharge from the aquifer is mostly by seepage into Apple Creek and Rice lake, subsurface flow into the Lower Apple Creek aquifer and possibly the northern end of the McKenzie aquifer, evapotranspiration, and low-capacity domestic and stock wells. Total appropriations for irrigation by 1983 were 833 acre-feet for 639 acres. Little development has occurred, however, due to the difficulty in developing a well of sufficient capacity for irrigation. Reported annual water use for the period 1973-1983 totaled about 86 acre-feet. The hydrograph of observation well 140-77-23ADD (figure 15), which is similar to hydrographs of the other observation wells in the aquifer, indicates slow response to changes in the amount of water in storage in the aquifer.

FIGURE 15

Hydrograph of Observation Well – Upper Apple Creek Aquifer

Obs Well 140–077–23ADD; Land–Surface Elev=1800.65ft NGVD



Potential yields to wells estimated from test-hole and observation-well data vary from less than 50 gpm over much of the aquifer to about 150-200 gpm at a few locales in the center of the aquifer where a maximum thickness is found (plate 4).

Water in the Upper Apple Creek aquifer is predominantly very hard and a sodium-bicarbonate type with concentrations of the calcium and magnesium cations increasing somewhat in the northern end of the aquifer. The water quality can be summarized as follows:

	Range	Average
Fe(mg/l)	0.39 - 1.10	0.73
Mn(mg/l)	0.55 - 1.20	0.95
SO_4(mg/l)	210 - 360	303
TDS(mg/l)	563 -1030	837
%Na	32 - 93	63
SAR	2.1 - 20.7	10.0
RSC	0 - 8	3

Irrigation indices range from C3-S1 to C3-S4 (figure 8). The salinity hazard is high (C3), sodium hazard low and very high (S1 and S4).

Wing Channel Aquifer

The Wing Channel aquifer underlies about 13 square miles of the study area in northeastern Burleigh County (plate 2). It occurs in the glacial drift filling the incised channel (plate 3) of the pre-glacial Wing River (Kume and Hansen, 1965, p. 67). The southwest end of the aquifer is topographically and geologically connected with the north end of the Upper Apple Creek aquifer, but is hydrologically separated by an apparent ground-water divide. The Wing Channel aquifer extends into Kidder County at least three miles based on test holes in the area. Its areal extent in Kidder County and relationships to the in Kidder County aquifer complex are undetermined.

The top of the Wing Channel aquifer varies from 6 to 162 feet below land surface. The aquifer consists of fairly coarse material, medium-grained sand to coarse-grained gravel, except in the connecting valley with the Upper Apple Creek aquifer where silty sand commonly occurs. Total thickness of the aquifer ranges from 9 to 144 feet and averages 35 feet. Till and silty clay locally separate the aquifer material into as many as three units. The slightly permeable materials produce confined conditions over much of the aquifer. Water-table conditions are found where the till or clay are absent and the gravelly sand is exposed at land surface. Values of transmissivity estimated from test-hole logs vary from 300 to 9,300 ft^2/day with an average of 3,000 ft^2/day. Water levels measured within the aquifer at two sites suggest ground-water flow is to the east into Kidder County with an upward hydraulic gradient (plate 2). An estimated 44,000 acre-feet of water are available from storage, based on an areal extent of 13 aquare miles, a specific yield of 0.15, and an average thickness of 35 feet.

Recharge to the Wing Channel aquifer is mainly from infiltrating precipitation and runoff, seepage from the streams and lakes overlying the aquifer, and subsurface flow from the adjacent Cannonball and Hell Creek aquifers. Discharge is mostly by lateral flow into the adjacent drift aquifer in Kidder County, seepage into the streams and lakes overlying the aquifer, evapotranspiration, and to some extent by small-capacity wells. The most significant ground-water development in the aquifer is the municipal supply for the city of Wing. Reported annual use at Wing for the period 1973 to 1983 ranged from 10 to 28 acre-feet with an average of 19 acre-feet. Potential yield of the aquifer commonly is less than 100 gpm due to restricted width of the aquifer. However, several hundred gallons per minutes may be available from the thicker parts of the aquifer. The hydrograph of observation well 142-74-18BCC (figure 16) indicates only small changes in the amount of water in storage in the aquifer.

The water in the Wing Channel aquifer is very hard. The dominant anion is bicarbonate, but there is no predominant cation in the aquifer. The calcium, magnesium, and sodium ions combine in various ratios to form the dominant cations. The water quality can be summarized as follows:

	Range	Average
Fe (mg/l)	0.04 - 0.50	0.20
Mn (mg/l)	0.01 - 1.50	0.77
SO_4 (mg/l)	12 - 320	153
TDS (mg/l)	323 - 802	542
%Na	21 - 37	31
SAR	1.2 - 2.2	1.6
RSC	0 - 2	1

Irrigation indices range from C2-S1 to C3-S1 (figure 8). Salinity hazard is mediuim to high (C2-C3); sodium hazard is all low (S1).

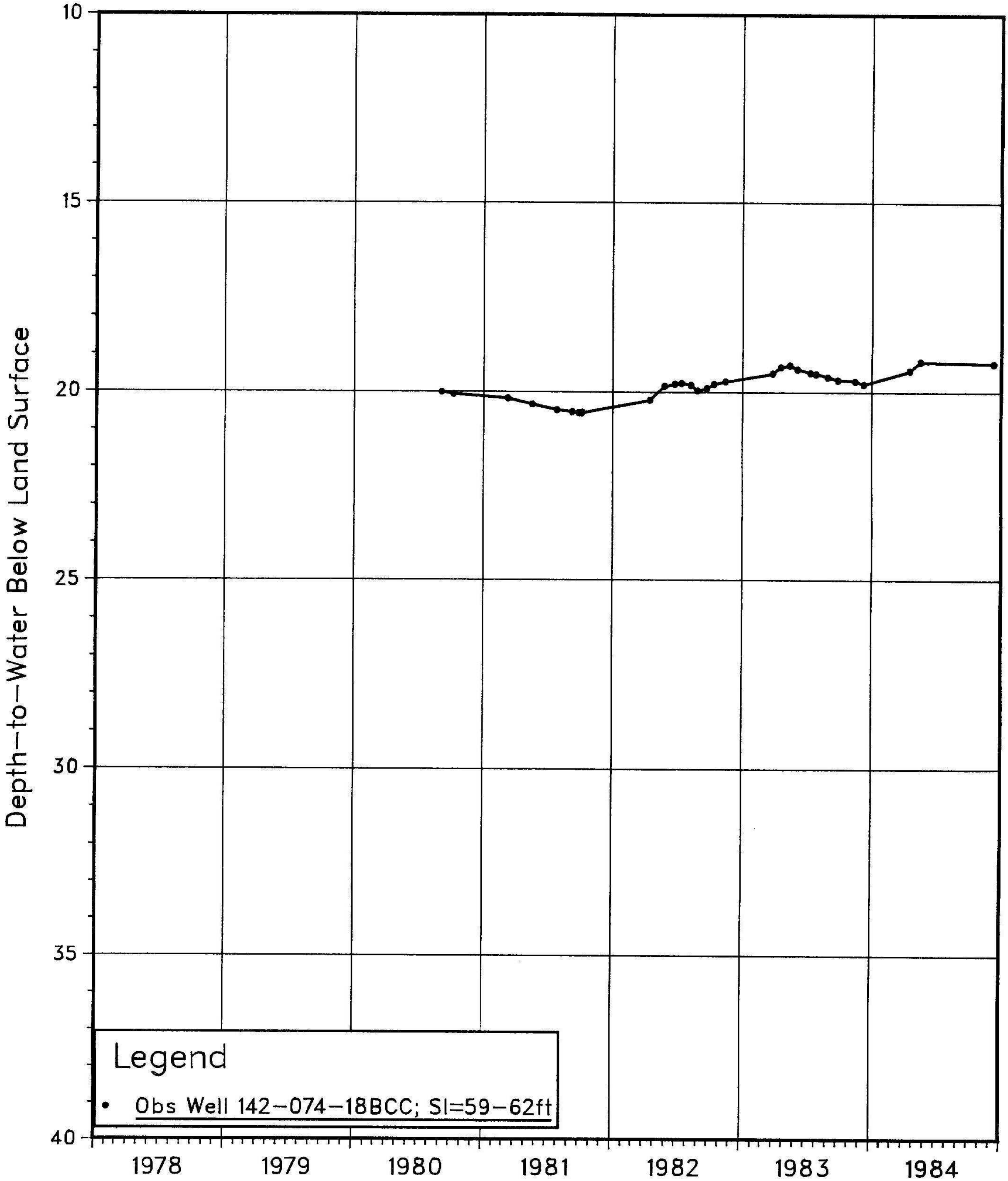
Glacial-Drift Aquifers - Kidder County

The Kidder County ground-water study (Bradley et al., 1963) considered the occurrence of ground water in the unconsolidated Quaternary deposits on the basis of type of deposit. The types of deposits distinguished included: surficial and buried-valley outwash deposits, ice-contact deposits, till with associated sand and gravel, and other unconsolidated deposits such as lacustrine and eolian

FIGURE 16

Hydrograph of Observation Well – Wing Channel Aquifer

Obs Well 142–074–18BCC; Land–Surface Elev=1861.74ft NGVD



sediments. The outwash deposits, in particular the buried outwash, comprise a system of glacial-drift aquifers in Kidder County. This aquifer system currently supplies high-capacity irrigation wells and offers considerable potential for additional irrigation development. The aquifer system is comprised of from one to five layers of sand and gravel more or less hydraulically connected. However, the geology of the aquifer system, the paths of ground-water flow, and the interaction between ground water and surface water are not well understood. This study further defines the geology and ground-water flow system of the glacial-drift aquifers based on the additional data gathered during the study.

The intervals of coarse sediment are subdivided into surficial and nonsurficial aquifers. These aquifers are hydraulically interrelated over most of the study area. The surficial aquifers occur where outwash or eolian deposits are sufficiently thick for saturated conditions to exist under the prevailing topography and hydrologic regime. The outline of the surficial aquifers as mapped (plate 5) generally shows where these conditions occur. The surficial aquifers are delineated on the presence or absence of unoxidized surficial sand and gravel. Included are some near-surface outwash deposits in which the water level is sufficiently low to create unconfined conditions. The role of the unsaturated deposits in the recharge and discharge of the surficial aquifers is not well understood and requires further study. The surficial aquifers identified in this study are the Tappen, Marstonmoor Plain, and "Robinson" aquifers.

The nonsurficial intervals of sand and gravel not included in the surficial aquifers form the Kidder County aquifer complex. The discussion of the aquifer complex follows that of the surficial aquifers.

Tappen Aquifer

The surficial aquifer located in east-central Kidder County is here named the Tappen aquifer (plate 5). It is delineated on the occurrence of unoxidized surficial sand and gravel. Included are some near-surface outwash deposits in which the water level is sufficiently low to produce unconfined conditions. The Tappen aquifer underlies an area of about 64 square miles. It extends from the Dawson area to about three miles east of Tappen and from the Lake Etta-Henry Lake area to Stony Lake. A narrow arm of the aquifer trends eastward toward Crystal Springs, but this segment is not well defined. The Tappen aquifer varies in width from about one-half to about five miles.

The Tappen aquifer consists primarily of sand and gravelly sand. Aquifer thickness varies from 5 to 120 feet and averages 26 feet (plate 10). Till and lacustrine silty clay directly underlie the aquifer. Depth to water below land surface is around six feet in the Tappen area and in general increases toward the edges of the aquifer. Maximum depth to water is 57 feet; average depth for the whole aquifer is 25 feet.

Two aquifer tests conducted at sites about one mile apart yielded the following transmissivity values: range of values from the first test is 5,100 to 5,900 ft^2/day; from the second test 3,000 to 4,200 ft^2/day. Average values are 5,500 and 3,600 ft^2/day, respectively. A third test near Henry Lake gave values of 16,000 to 24,100 ft^2/day which reflect the very coarse material comprising the aquifer at the location. Transmissivity values for the remaining area of the Tappen aquifer as estimated from test-hole logs vary from 300 to 6,700 ft^2/day and average 2,500 ft^2/day. Water levels measured in 19 observation wells in the aquifer show a general east-to-west movement of ground water (plate 5).

Recharge to the Tappen aquifer is primarily from infiltrating precipitation. Lateral flow of water from the surficial outwash on the uplands to the east and south of the aquifer is also a source of recharge. Seepage from ephemeral bodies of surface water adds to the total recharge during the spring. Head relationships with the underlying Kidder County aquifer complex, indicated at a dual-well site 139-71-17BBB (figure 17), show a net upward flow of water into the Tappen aquifer in the area from southeast of Harker Lake to just south of I-94 between Dawson and Tappen (plate 5). Another source of recharge may be the water withdrawn from the underlying Kidder County aquifer complex and applied to cropland. Water in excess of soil- and crop-moisture requirements percolates downward into the surficial aquifer. This process may play a part in causing the vertically decreasing head relationships between the Tappen aquifer and the deeper Kidder County aquifer complex evident north of I-94 (plate 5) at observation-well sites 140-71-19DDD (figure 18) and 140-71-28DAA (figure 19).

Discharge from the Tappen aquifer is mainly through evapotranspiration and by seepage and subsequent evaporation of water from depressions in the land surface. The degree of permanence of water bodies in such depressions is determined in part by the difference between the rate of water seepage and rate of evapotranspiration. Net downward flow discharges water from the Tappen aquifer into the underlying aquifer units in the area north of I-94 and a small area north of Henry Lake. Water-level elevations at multi-well sites in these two areas decrease with depth (plate 5). Small-capacity domestic and stock wells add a small proportion to the total discharge. Total appropriations for irrigation by 1983 were 2,511 acre-feet for 1,674 acres. Reported annual water use for the period 1973-1983 totaled about 5,210 acre-feet. Hydrographs of

FIGURE 17

Hydrograph of Observation Wells

Kidder County Aquifer Complex
Obs Well 139–071–17BBB1; Land–Surface Elev=1757.93ft NGVD
Tappen Aquifer
Obs Well 139–071–17BBB2; Land–Surface Elev=1758.68ft NGVD

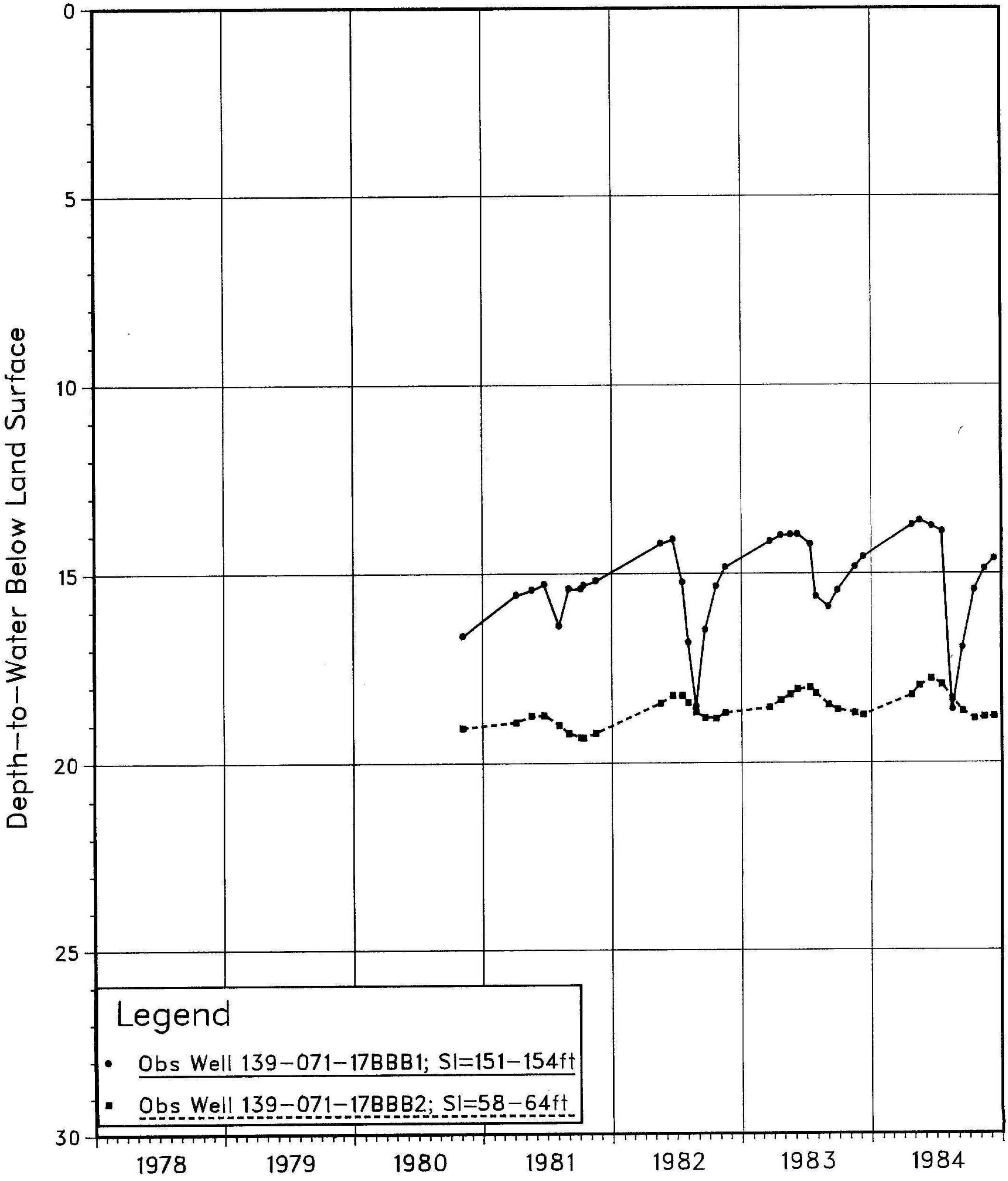


FIGURE 18

Hydrograph of Observation Wells

Kidder County Aquifer Complex
Obs Well 140–071–19DDD1; Land–Surface Elev=1757.02ft NGVD
Obs Well 140–071–19DDD2; Land–Surface Elev=1756.34ft NGVD
Tappen Aquifer
Obs Well 140–071–19DDD3; Land–Surface Elev=1756.10ft NGVD

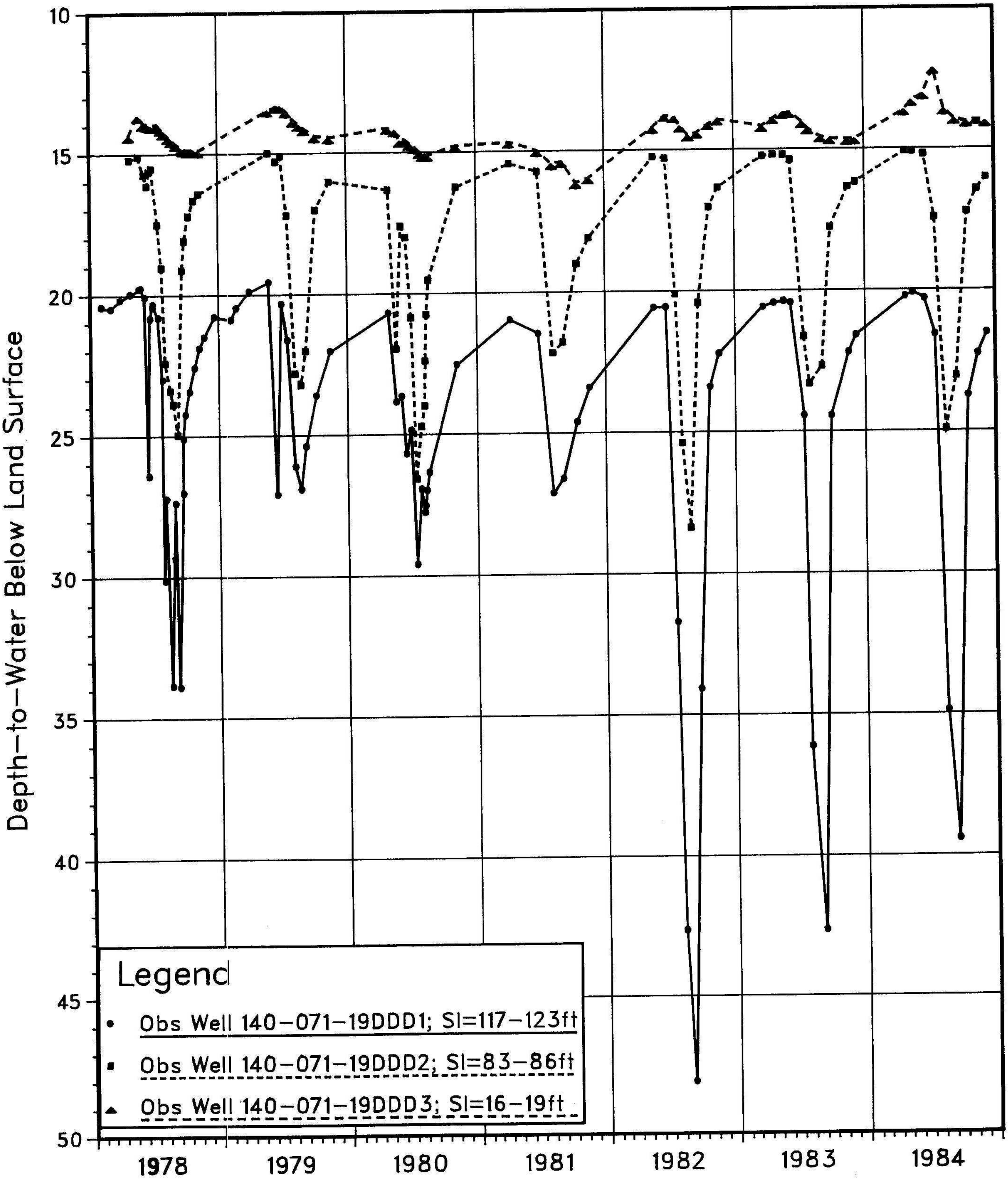
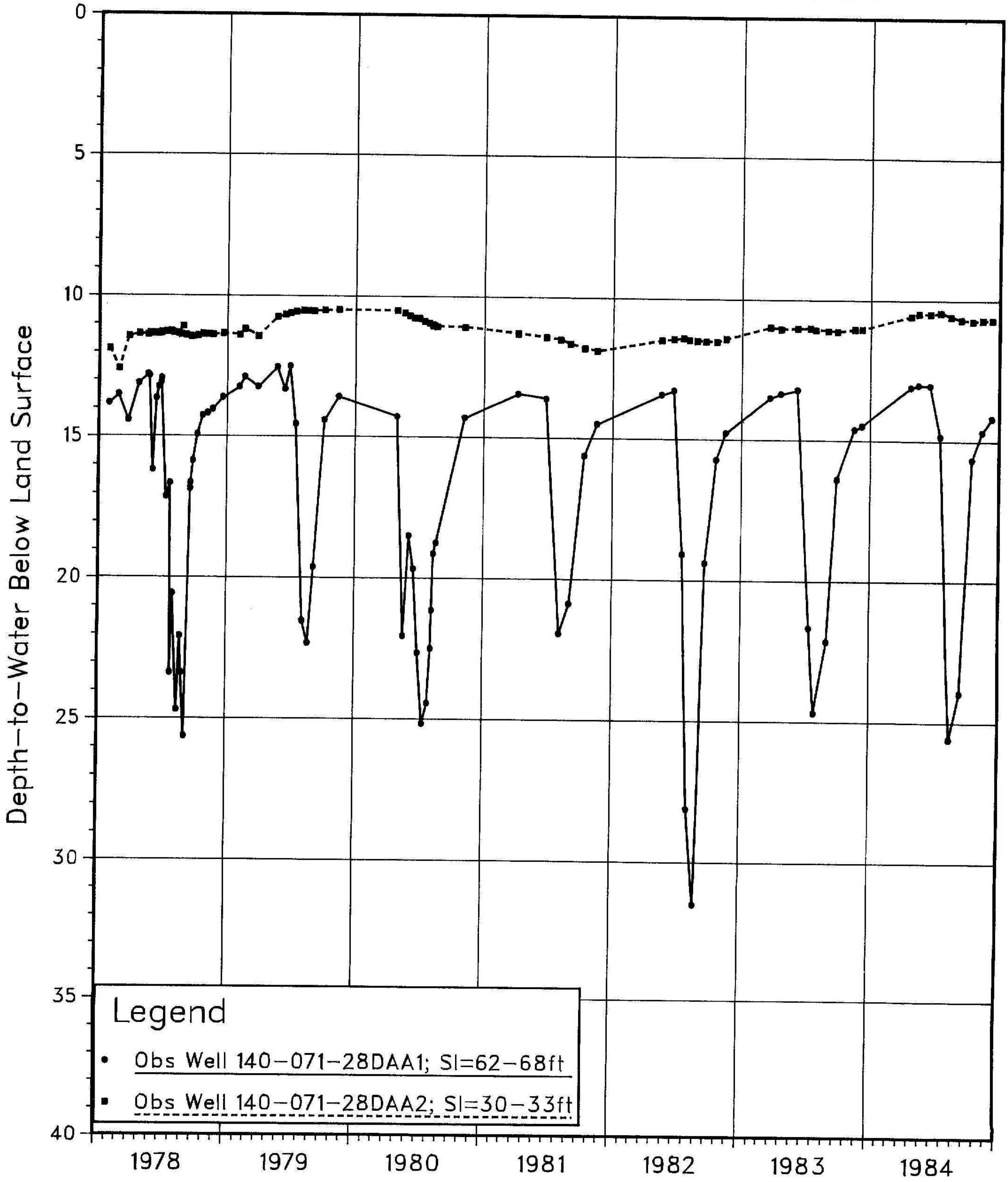


FIGURE 19

Hydrograph of Observation Wells

Kidder County Aquifer Complex
Obs Well 140–071–28DAA1; Land–Surface Elev=1766.92ft NGVD
Tappen Aquifer
Obs Well 140–071–28DAA2; Land–Surface Elev=1766.95ft NGVD



observation wells monitoring the Tappen aquifer (figures 17, 18, 19, and 20), show a water-level fluctuation of less than three feet from 1978 to 1984. The hydrographs indicate the minimum of an annual cycle occurs during the fall. Superimposed on the annual cycle is a general downward trend of water levels between 1978 and 1981 and a slight upward trend from 1981 to 1984. This trend reflects small changes in the amount of water in storage. The hydrographs suggest a minimum impact on the aquifer from the present level of development. Because of the unconfined nature of the aquifer, however, the density of the current observation-well network may not be adequate to assess the effects of development completely.

The potential yield of the Tappen aquifer was estimated from saturated thickness and hydraulic conductivity of the aquifer as derived from test-hole and observation-well data. The estimated potential yield varies from less than 50 gpm to over 500 gpm and is more a function of saturated thickness than variations in hydraulic conductivity. An estimated 160,000 acre-feet of water are available from storage based on an areal extent of 64 square miles, a specific yield of 0.15, and an average thickness of 26 feet.

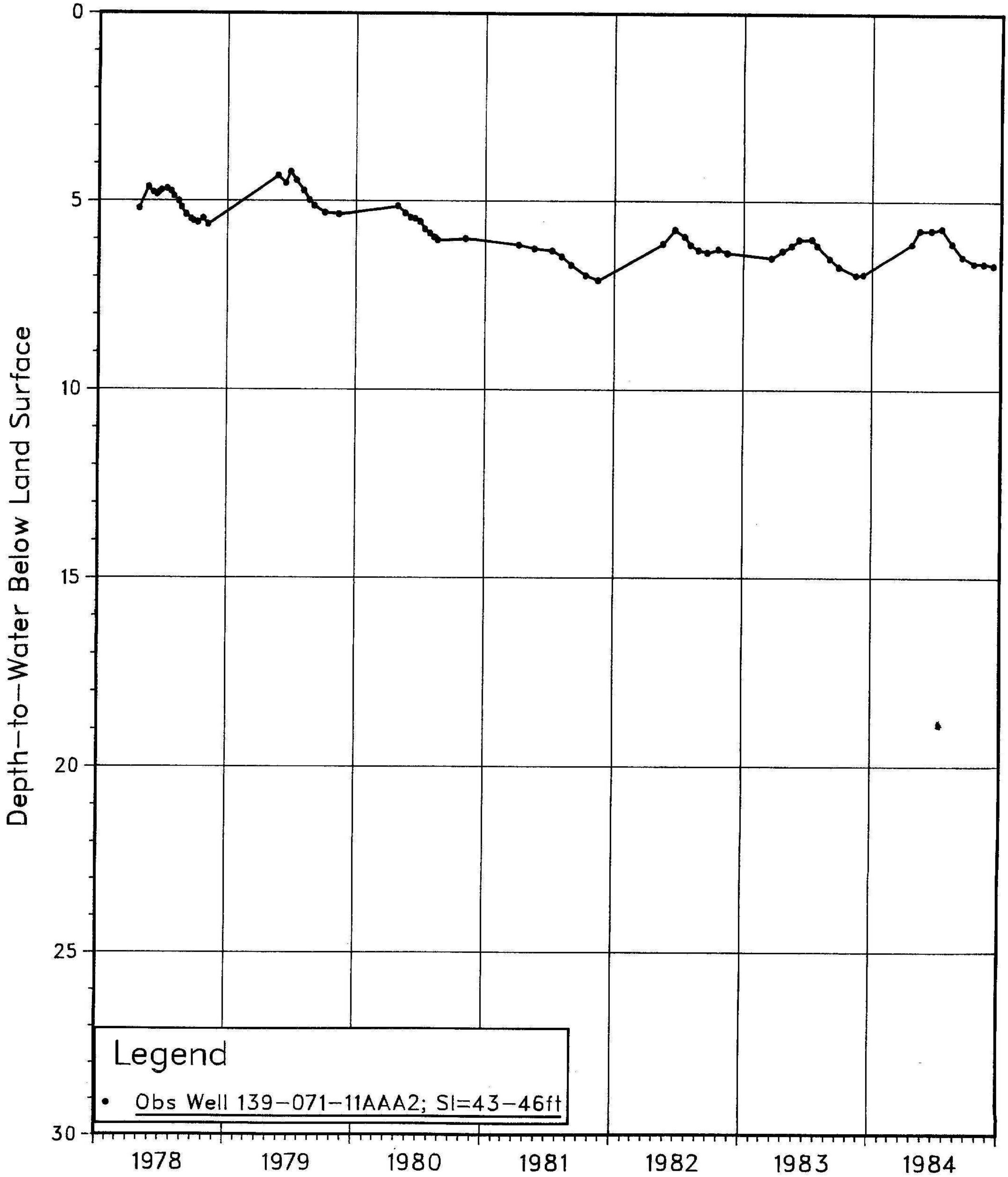
The Tappen aquifer contains a very hard, predominantly calcium-bicarbonate type water. The water quality can be summarized as follows:

	Range	Average
Fe(mg/l)	0.00 - 1.90	0.24
Mn(mg/l)	0.01 - 1.90	0.86
SO_4(mg/l)	27 -128	72
TDS(mg/l)	289 -541	401
%Na	5 - 45	16
SAR	0.2 - 2.7	0.7
RSC	0 - 1.7	0.2

FIGURE 20

Hydrograph of Observation Well – Tappen Aquifer

Obs Well 139–071–11AAA2; Land–Surface Elev=1782.55ft NGVD



Irrigation classifications are mostly C2-S1 with a few analyses of C3-S1 when the specific conductance exceeded 750 umhos (figure 21). Salinity hazard is predominantly medium (C2); sodium hazard is low (S1).

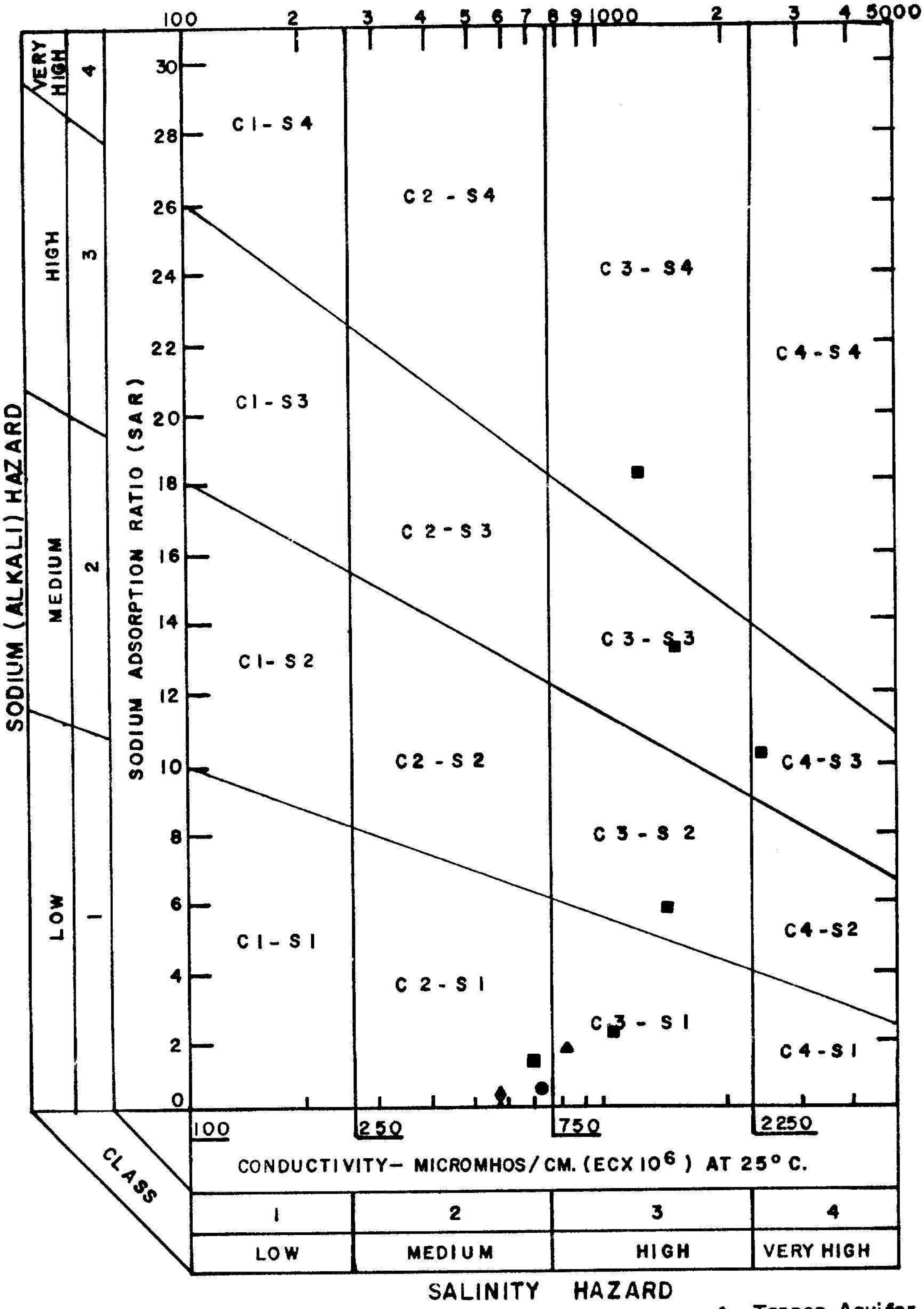
Marstonmoor Plain Aquifer

The outwash plain in northeastern Kidder County (Rau et al., 1962, p. 34) and northwestern Stutsman County (Winters, 1963, p. 43) comprises an unconfined aquifer defined by Huxel, Jr. and Petri (1965, p. 20) as the Marstonmoor Plain aquifer. The aquifer as defined does not include the deeper units of sand and gravel located in the area. Huxel, Jr. and Petri (1965) noted the Marstonmoor Plain aquifer extended into Kidder County. Thirteen test holes drilled for this study help define the Kidder County part of this aquifer (plate 5). In general the aquifer is delineated on the presence or absence of unoxidized surficial sand and gravel. In this study, near-surface outwash deposits are included in the aquifer where relatively thin layers of till or silty clay separate the surficial from the near-surface deposits. Water-level trends over an irrigation season suggest the Marstonmoor Plain aquifer is somewhat hydraulically connected with the underlying aquifer intervals of the Kidder County aquifer complex (figures 22 and 23). Also included in the Marstonmoor Plain aquifer in this study are the surficial sand and gravel deposits generally located between Kunkel Lake and Horsehead Lake. The part of the aquifer is here designated the Kunkel Lake segment. Water-level trends in the two observation wells at 141-71-20DDD (figure 24) show that this segment is somewhat hydraulically isolated from the deeper Kidder County aquifer. It may underlie part or all of Kunkel Lake. The Kunkel Lake segment may be

FIGURE 21

DIAGRAM FOR CLASSIFYING THE QUALITY OF WATER FOR IRRIGATION

KIDDER COUNTY



SOURCE:
USDA – HANDBOOK 60

NOTE: THE POINTS FOR EACH AQUIFER REPRESENT THE AVERAGE CONDUCTIVITY AND SAR VALUES IN EACH CATEGORY

▲ Tappen Aquifer
x Marstonmoor Plain Aquifer
● Robinson Aquifer
■ Kidder County Aquifer Complex

FIGURE 22

Hydrograph of Observation Wells

Kidder County Aquifer Complex
Obs Well 142–071–13DDD1; Land–Surface Elev=1766.80ft NGVD
Marstonmoor Plain Aquifer
Obs Well 142–071–13DDD2; Land–Surface Elev=1766.87ft NGVD

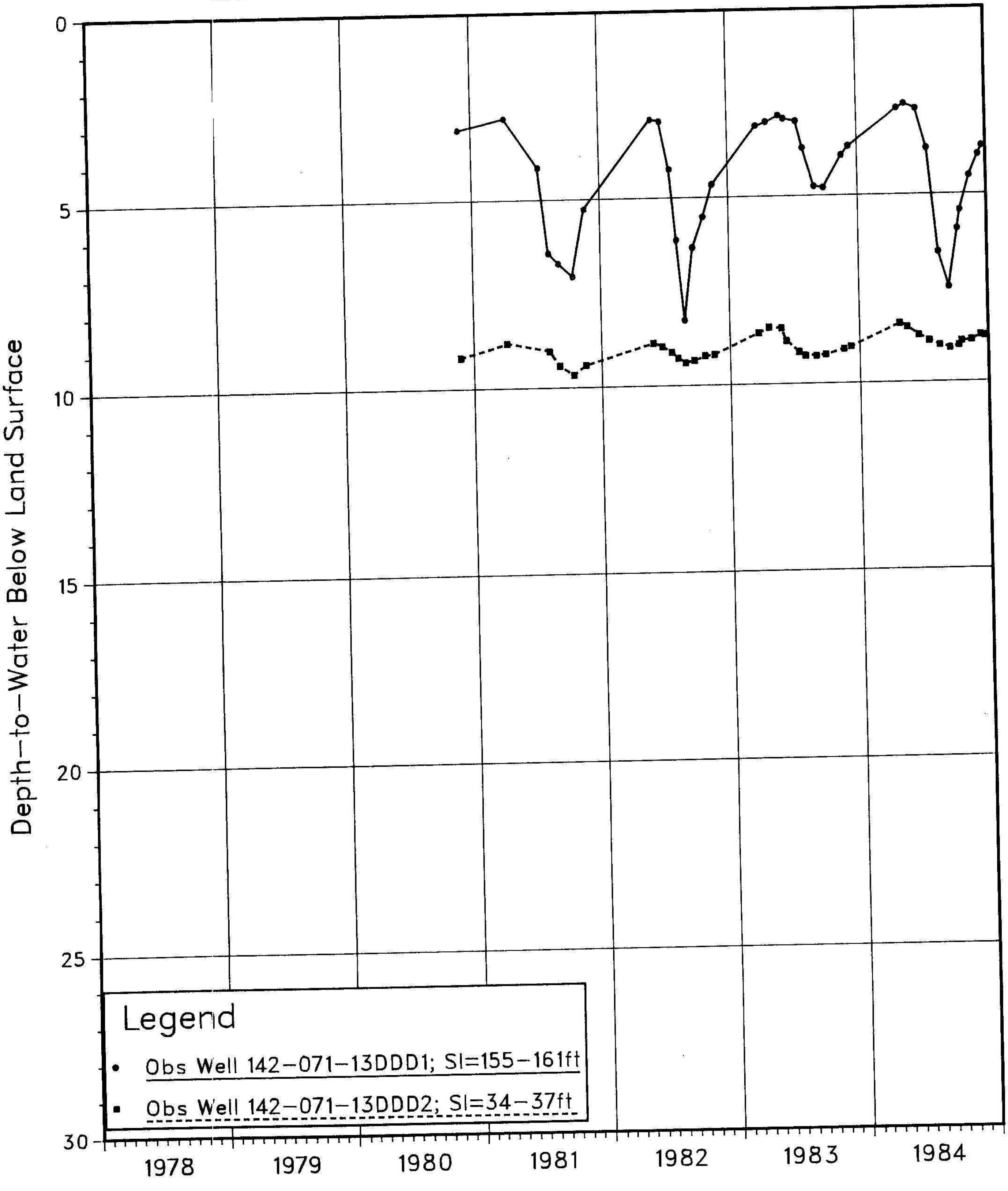


FIGURE 23

Hydrograph of Observation Wells

Kidder County Aquifer Complex
Obs Well 142-070-16BAD2; Land-Surface Elev=1806.96ft NGVD
Marstonmoor Plain Aquifer
Obs Well 142-070-16BAD3; Land-Surface Elev=1806.89ft NGVD

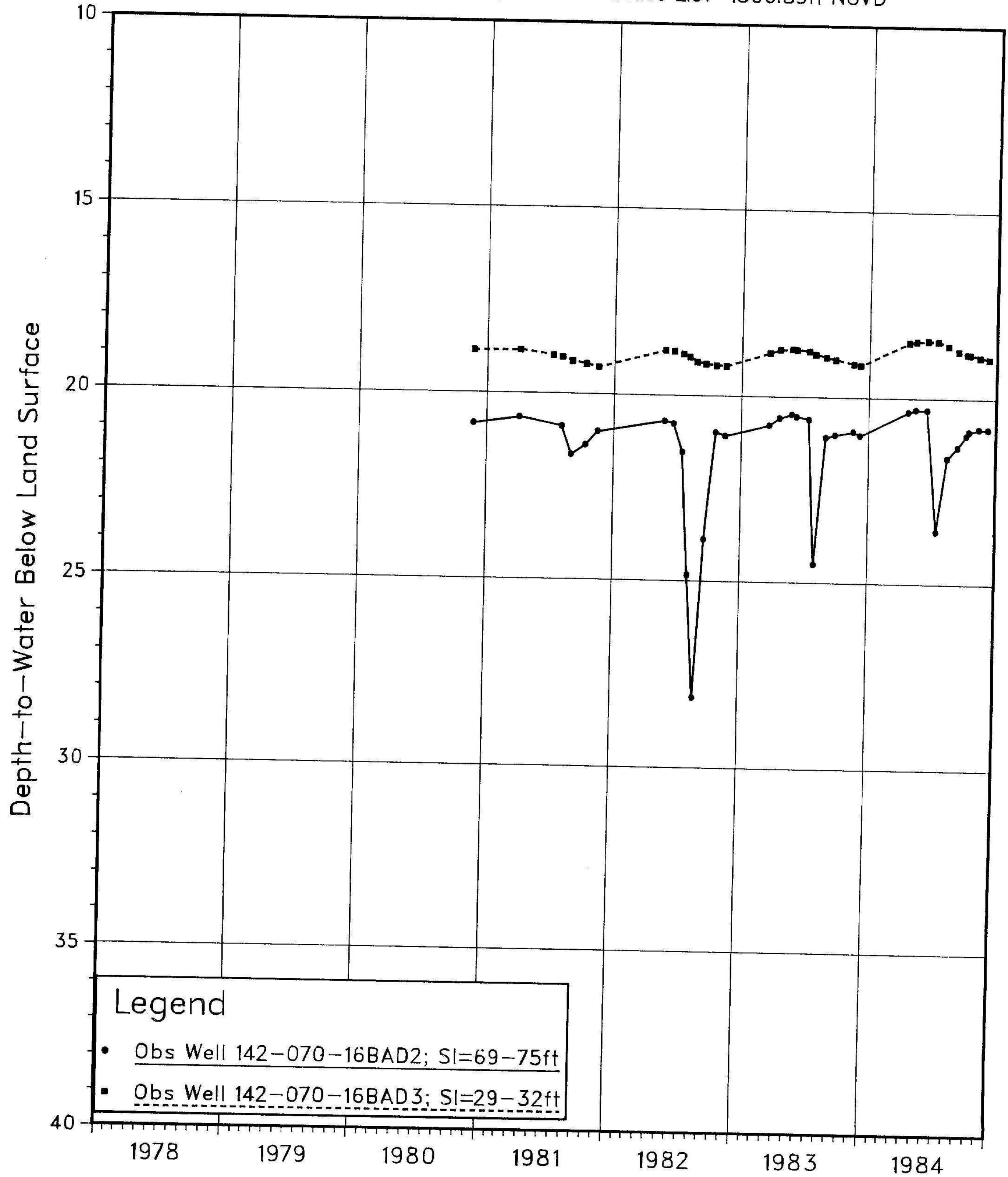
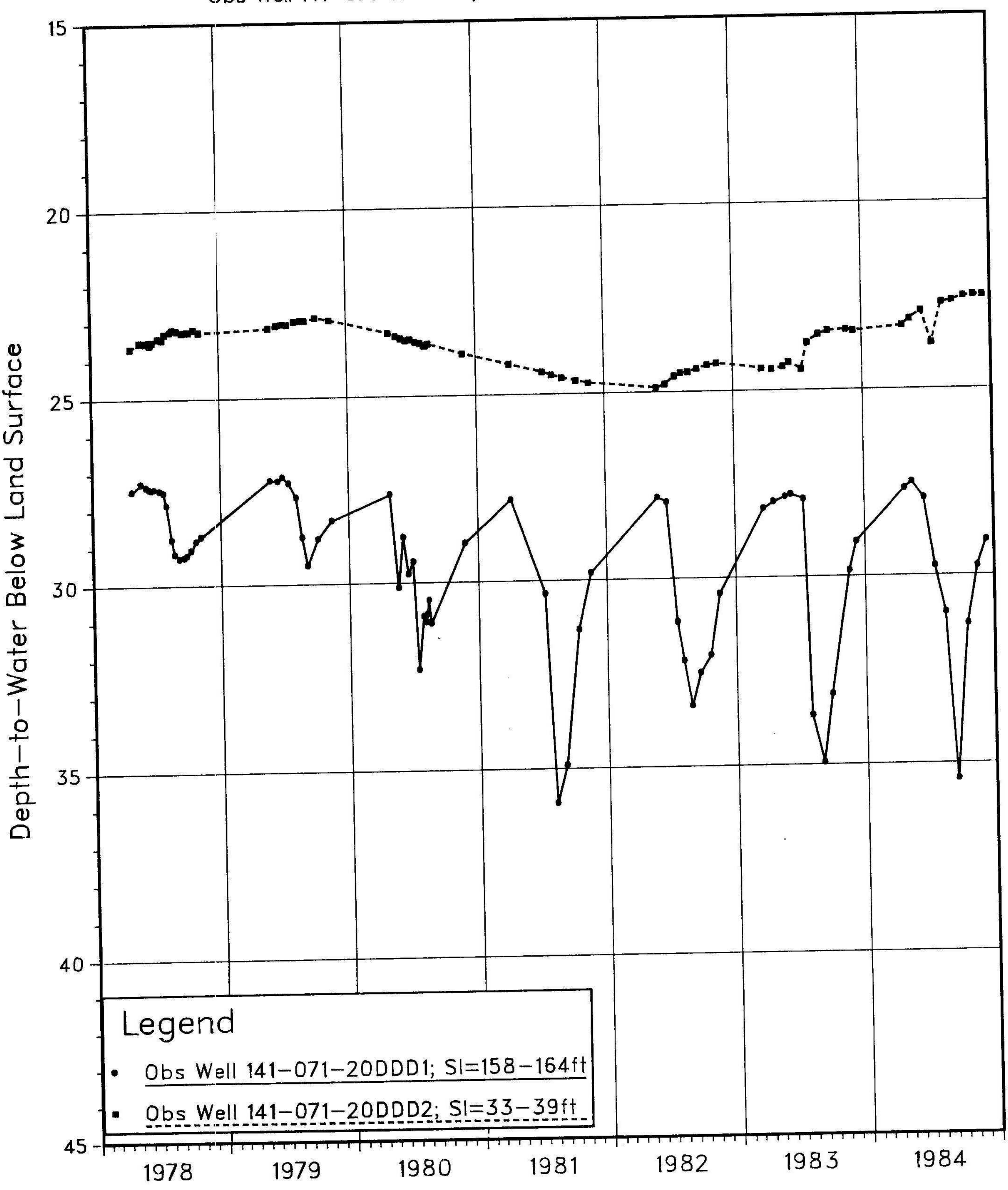


FIGURE 24

Hydrograph of Observation Wells

Kidder County Aquifer Complex
Obs Well 141–071–20DDD1; Land–Surface Elev=1769.71ft NGVD
Marstonmoor Plain Aquifer
Obs Well 141–071–20DDD2; Land–Surface Elev=1769.42ft NGVD



connected to the rest of the aquifer to the northeast along topographic lows north of Kunkel Lake where at least the lower part of the surficial outwash deposits may be saturated. The surficial sand and gravel on the topographic highs are typically oxidized, but provide a pathway to the surficial aquifer for infiltrating meltwater and precipitation. The Marstonmoor Plain aquifer underlies a total area of about 67 square miles in northeastern Kidder County.

Test-hole data indicate the Marstonmoor Plain aquifer consists mostly of gravelly sand to sandy gravel (plate 10). The aquifer overlies till except in some areas of the Kunkel Lake segment where lacustrine silt and clay occurs. Thickness of the aquifer varies from less than 5 feet to 80 feet, and averages about 26 feet. The thinnest part of the aquifer usually occurs near the base of oxidized sections of surficial outwash and directly overlying unoxidized till or silty clay. Depth to water ranges from 4 feet to 32 feet. Water-level elevations in observation wells and lakes indicate an overall east-to-west movement of ground water in the main part of the aquifer (plate 5). The flow pattern is less well defined in the Kunkel Lake segment of the aquifer because fewer data points are available. Here the apparent pattern of ground-water flow is from the southeast to the west and north. Values of transmissivity estimated from test-hole logs vary from 400 to 9,400 ft^2/day and average 3,200 ft^2/day. The range of transmissivity values is more the result of variations in saturated thickness rather than different hydraulic conductivities of the aquifer material. An estimated 167,000 acre-feet of water are available from storage, based on an average thickness of 26 feet, an areal extent of 67 square miles, and a specific yield of 0.15.

There are two primary sources of recharge to the Marstonmoor Plain aquifer: infiltration of precipitation and meltwater, and lateral flow of ground water from the uplands surrounding the aquifer. Seepage from bodies of surface water that are full in the spring may add to the total recharge. The western third of the main part of the aquifer is recharged by a net vertically upward component of ground-water flow as indicated at the double-well monitoring site 142-71-13DDD (figure 22). The recharge area may be delineated by the lakes around the town of Lake Williams. Another possible source of recharge may be the water withdrawn from deeper aquifers for irrigation. Water in excess of soil-moisture and crop requirements would move downward toward the saturated zone. This mechanism may play a part in the vertically decreasing heads evident between the Marstonmoor Plain aquifer and the deeper Kidder County aquifer complex in the Pettibone area of the main part of the aquifer and the Kunkel Lake segment of the aquifer.

The principal paths of discharge from the aquifer are evapotranspiration, withdrawals of ground water for irrigation and ground-water seepage into sloughs and lakes. Discharge also occurs as net vertical flow downward to the underlying Kidder County aquifer complex, both in the part of the aquifer around Pettibone (figure 23) and in the Kunkel Lake segment of the aquifer (figure 24). The permanent lakes around Pettibone suggest the presence of local flow systems which remain to be defined. Small-capacity domestic and stock wells add a small proportion to the total discharge. The Marstonmoor Plain aquifer as defined here is typically not thick enough to support irrigation wells. Most of the irrigation development within the Kidder County area of the aquifer is supplied by the underlying sand and gravel units of the Kidder County aquifer complex. However, near the Stutsman County line where the aquifer thickens towards the east, the aquifer does support some irrigation. By 1983, appropriations totaled 1,478 acre-feet for 1,030 acres. Reported annual water use for the period 1973 to 1983 totaled about 4,300 acre-feet. Head relationships between the surficial Marstonmoor Plain aquifer and the underlying Kidder County aquifer complex indicate downward leakage of water during the irrigation season. Hydrographs of observation wells screened in the Marstonmoor Plain aquifer (figures 22, 23, and 24) show a small total water-level fluctuation for the period of record. The low of an annual cycle occurs in late fall. Superimposed on the annual cycle is a general downward trend of water levels from 1978 to 1981 and an upward trend after 1981. The hydrographs suggest little impact on the aquifer from the current level of development of the underlying glacial-drift aquifers. No observation wells were constructed for this study within the area of irrigation development of the Marstonmoor Plain aquifer. There is a need for some observation wells to complement those in Stutsman County.

Water quality of the Marstonmoor Plain aquifer is characterized by six samples. All samples indicated a very hard, calcium-carbonate type water. The water quality can be summarized as follows:

	Range	Average
Fe(mg/l)	0.06 - 3.10	0.72
Mn(mg/l)	0.72 - 1.10	0.89
SO_4(mg/l)	21 - 65	44
TDS(mg/l)	294 -419	353
%Na	3 - 8	6
SAR	0.1 - 0.3	0.2
RSC	0	0

All six water samples show an irrigation classification of medium salinity hazard (C2) and low (S1) sodium hazard (figure 21).

Undifferentiated Surficial Aquifer

Surficial outwash deposits occur in the northwestern part of the study area from Robinson westward toward the county line (plate 5). Aquifers are present within these deposits where saturated conditions prevail. The surficial aquifers are poorly defined over much of this area. The only observation well in an unconfined aquifer in this part of the study area is about two miles southwest of Robinson at 142-72-16BBB (plate 5). This aquifer is tentatively named the "Robinson" aquifer. It most likely extends out of the study area northward to the Willow Lake area.

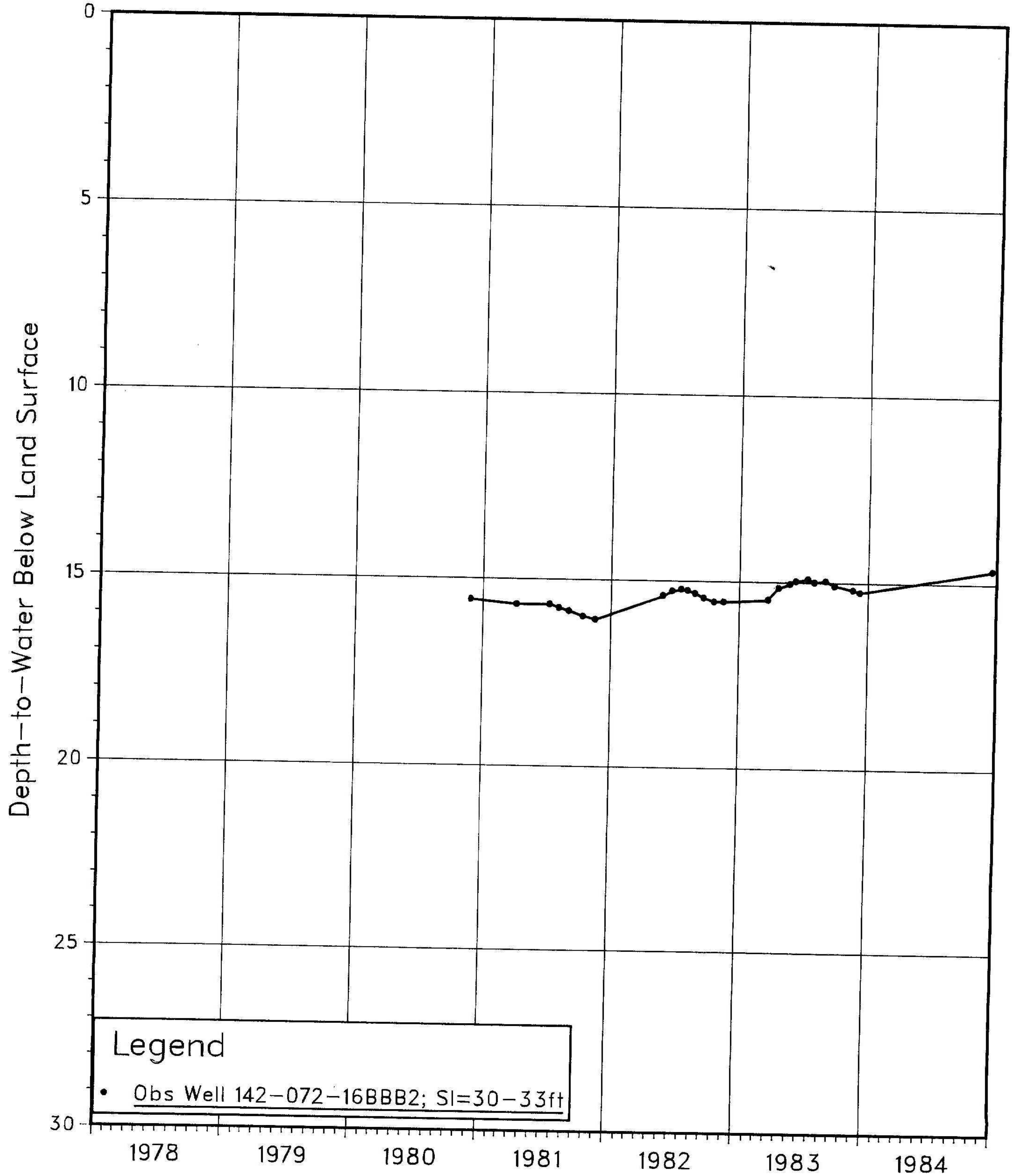
The "Robinson" aquifer underlies about six square miles of the study area along a northwest-southeast trend. The aquifer occurs as surficial outwash overlying till and consists of 15 to 20 feet of saturated gravelly sand. Transmissivity values are directly related to the saturated thickness of the aquifer. The transmissivity of the thicker parts of the aquifer is about 2,900 ft^2/day. Depth to water is about 15 to 16 feet below land surface (figure 25). An estimated 10,000 acre-feet of ground water are available from storage based on an areal extent of 6 square miles, a specific yield of 0.15, and an average saturated thickness of 17 feet.

The "Robinson" aquifer is recharged mostly by infiltrating precipitation and surface runoff moving downward to the zone of saturation. Lateral flow from the surrounding outwash deposits also recharge the aquifer. Discharge

FIGURE 25

Hydrograph of Observation Well –" Robinson" Aquifer

Obs Well 142–072–16BBB2; Land–Surface Elev=1778.79ft NGVD



is mostly through evapotranspiration and lateral outflow. Some irrigation development has occurred in the aquifer. By 1983, appropriations totaled 405 acre-feet for 270 acres. Reported annual water use for the period 1977, the initial year of irrigation, to 1983 totaled about 643 acre-feet. The hydrograph for observation well 142-72-16BBB$_2$ (figure 25) shows a slight annual fluctuation of less than a foot. The hydrograph shows little response to the irrigation development somewhat more than a half mile to the south. This is to be expected in an unconfined aquifer. A water sample from observation well 142-72-16BBB$_2$ suggests the water in the "Robinson" aquifer is a very hard, calcium/magnesium-bicarbonate type water. Analysis of the water sample gave the following results:

Fe(mg/l)	0.47
Mn(mg/l)	0.22
SO_4(mg/l)	61
TDS(mg/l)	430
%Na	15
SAR	0.6
RSC	0

The irrigation classification is C2-S1: medium salinity hazard (C2), and low (S1) sodium hazard (figure 21).

Kidder County Aquifer Complex

The near-surface and subsurface intervals of sand, gravelly sand, and sandy gravel distributed within the glacial drift of Kidder County are more or less hydraulically interconnected. The intervals comprise an aquifer system designated the Kidder County aquifer complex. The extent of this study's data base with respect to the hydrogeological complexity of the glacial-drift aquifer system is not sufficiently comprehensive to delineate separate hydrologic or aquifer units. Certain relationships are apparent, however, and are considered in the following discussion.

The Kidder County aquifer complex underlies about 470 square miles of the study area (plate 6). Test-hole data show that the top of the complex lies 10 to 508 feet below land surface and averages 67 feet below land surface. Thickness of the aquifer complex varies from 4 to 222 feet with an average of 52 feet. The test-hole data also indicate that the aquifer complex is typically made up of one, two, or three intervals of sand and gravel (table 4), although as many of five intervals may be present (plate 10). Till and/or lacustrine silty

TABLE 4. SUMMARY OF OCCURRENCE OF
SAND AND GRAVEL INTERVALS - KIDDER COUNTY AQUIFER COMPLEX

Number of Intervals	Number of Test-Hole Sites Where Found	% of Total Occurrence	Total Thickness of all Intervals Range	Average
1	82	45	4' - 166'	27'
2	62	34	9' - 159'	54'
3	25	14	30' - 222'	102'
4	6	3	71' - 109'	89'
5	7	4	49' - 222'	126'

clay deposits separate the sand and gravel units where more than one is present. Where one unit is present, till or silty clay occur between land surface and the aquifer and between bedrock and the aquifer. The slowly permeable till and lacustrine sediments act as aquitards and generate leaky confined conditions in most of the aquifer intervals. Water-level changes measured at sites with two or more observation wells show the separate intervals respond to water withdrawals from the complex. This indicates the intervals are more or less hydraulically connected throughout much of the aquifer complex.

The Pierre Formation directly underlies the aquifer complex along the trend of the buried valley in southwestern and central Kidder County and most of the study area in northeastern Kidder County. In the remaining part of the study area, the Fox Hills Formation lies adjacent to the aquifer complex. The hydrologic relationship between the bedrock, in particular the Fox Hills Formation, and the aquifer complex remains to be studied in Kidder County. However, the work of Thorstenson et al. (1979) and water-level elevations of about 1800 feet msl in wells at Steele suggest the Fox Hills is a regional discharge area with lateral flow of water from the bedrock into the drift aquifers.

The deepest interval of the aquifer complex consists of gravelly sand (plate 10) which occurs at or near the base of the buried bedrock valley trending southwest-northeast across Kidder County (plates 6 and 7). This valley is interpreted to be part of the preglacial Cannonball River system (Rau et al., 1962). Till and lacustrine silty clay deposits truncate the interval into two separate areas: south and north. Traces of western source material are found in the gravelly sand of both areas, implying that the two areas formed a continuous deposit at one time.

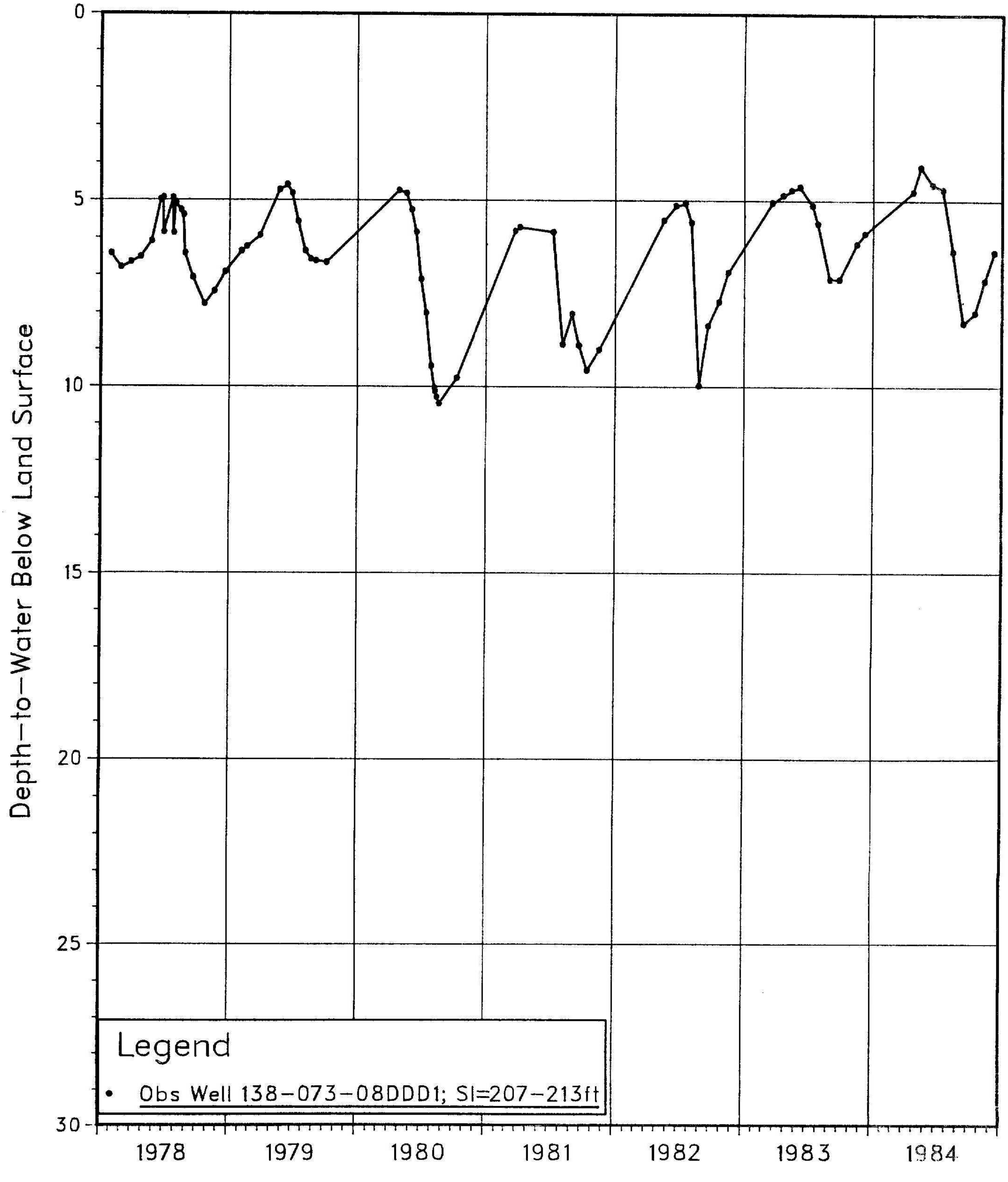
The south area extends about 20 miles from near Dawson to the Burleigh County line. The area averages 1.4 miles in width and has an areal extent of about 27 square miles. Ground water is not withdrawn from this interval for irrigation, but is from overlying intervals. The response of the deepest interval to irrigation withdrawals, as shown by the hydrograph of observation well $138\text{-}73\text{-}08DDD_1$ (figure 26), indicates a good hydraulic connection with shallower aquifer units in the complex.

The north area underlies about 12 square miles between Stony Lake and Kunkel Lake. It is located just southeast of some irrigation development. There

FIGURE 26

Hydrograph of Observation Well - Kidder County Aquifer Complex

Obs Well 138-073-08DDD1; Land-Surface Elev=1732.67ft NGVD



is no development within the boundaries of the area. Minor annual fluctuations in water levels are noted in observation wells monitoring this interval as represented by observation well 141-71-34DDD$_1$ (figure 27). The slight response may be due to intervening aquitards within the aquifer complex decreasing the response to stress on the aquifer system and also to the offset of irrigation development to the northwest.

A third area with a deep aquifer may occur north of Pettibone in a drift filled bedrock valley that is also buried by the Streeter Moraine. The beds of sand and gravel encountered in test drilling in this area are relatively thin and may be only discontinuous, isolated bodies of coarse sediment associated with till. The nature and extent of the bedrock valley, as well as the stratigraphy of the glacial material filling it, are poorly defined.

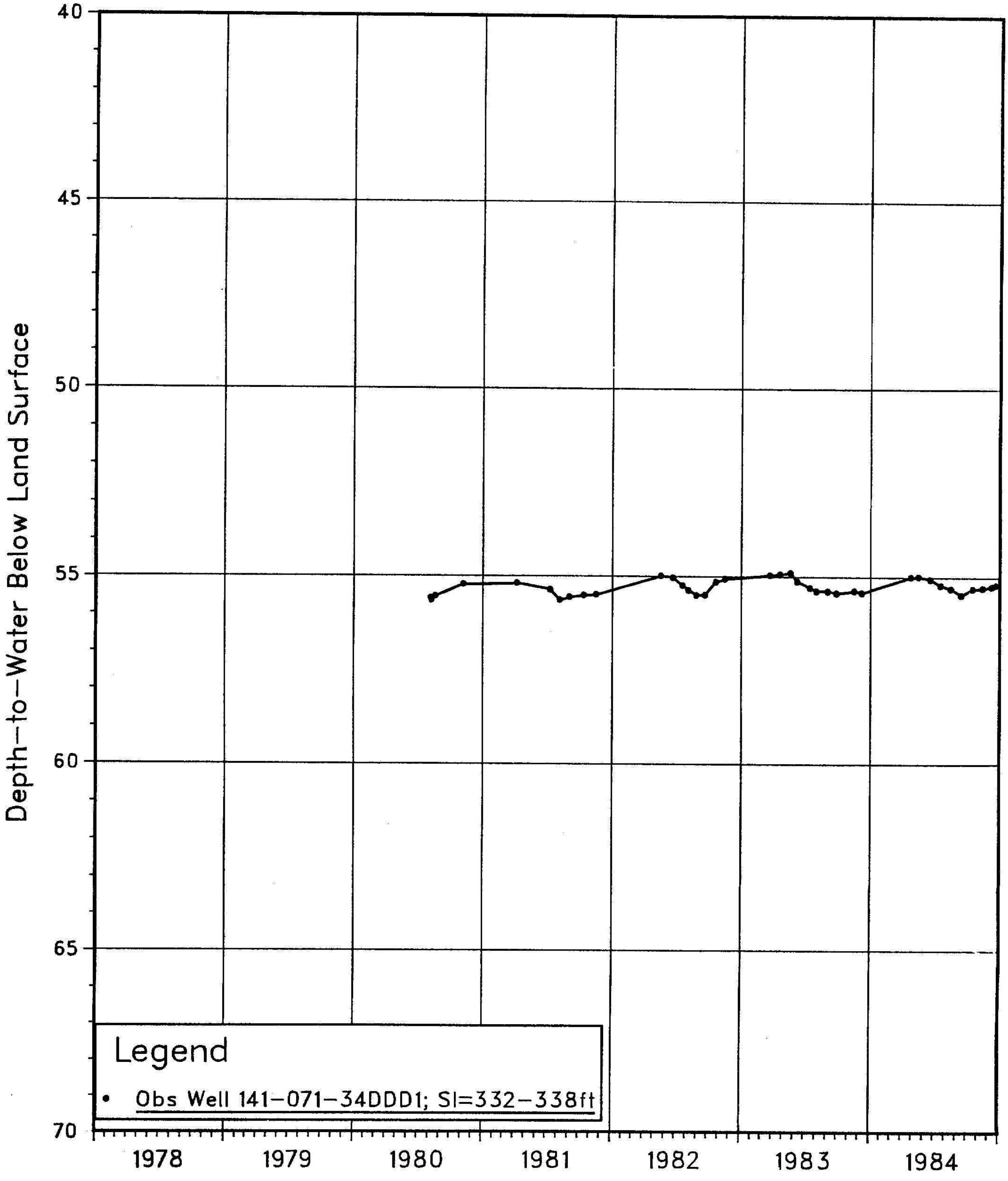
Several aquifer tests have been conducted at sites scattered along the main trend of the aquifer complex. The results of the tests characterize the aquifer properties at four sites and substantiate the hydraulic relationships within the aquifer complex suggested by different water levels measured in separate observation wells at multi-well sites. Both the aquifer tests and hydrographs indicate the leaky confined nature of the different aquifer intervals within the main part of the aquifer complex. The range of values for transmissivity calculated from the results of the aquifer tests are summarized as follows:

Location of Aquifer Test	Transmissivity (ft^2/day) Range	Average
138-72-3ABD	10,400 - 24,000	14,700
138-72-11ABB	5,500 - 10,700	7,800
141-71-09DDA	3,500 - 7,200	5,600
142-70-16DBD	4,300 - 14,300	8,600

FIGURE 27

Hydrograph of Observation Well — Kidder County Aquifer Complex

Obs Well 141–071–34DDD1; Land–Surface Elev=1800.44ft NGVD



Values of transmissivity estimated from test-hole data cover most of the Kidder County aquifer complex and were calculated using the entire thickness of all aquifer intervals. The range of these values is 100 to 30,200 ft^2/day with an average of 4,800 ft^2/day. Values for storage coefficient were calculated in the first two aquifer tests. The range of values was 7.9×10^{-6} to 8.2×10^{-4} for the first test and 3.2×10^{-3} to 8.3×10^{-3} for the second with average values of 2.1×10^{-4} and 4.9×10^{-3}, respectively.

Local, intermediate, and regional flow systems are very likely to occur within the Kidder County aquifer complex. The intermediate and regional flow systems originate in different areas of the Missouri Coteau which lies to the north and east of the study area. A comprehensive analysis of the origins, paths, and culminations of the three categories of flow systems is beyond the scope of this study. The impact of irrigation withdrawals on the overall flow systems is undetermined.

The principal source of recharge to the Kidder County aquifer system is the infiltration of precipitation. The water moves into the aquifer complex by downward flow from the overlying surficial aquifers and other glacial material, and by lateral flow from the surrounding uplands of diverse glacial deposits. Ground-water inflow from the Fox Hills Formation also recharges the aquifer complex. Water within the complex moves between aquifer intervals in response to prevailing hydraulic gradients and intrinsic geological properties of the glacial drift as a whole.

Water-level elevations of late June, 1982 (plate 6) were mapped in an effort to identify the flow patterns within the aquifer complex prior to irrigation pumping for the season. The elevations suggest recharge water moves into the buried outwash from the terminal and stagnation moraines surrounding the study area. The Tappen aquifer is a source of recharge over much of its area with a difference of 1 to 8 feet between water levels measured at multi-well sites. The Marstonmoor Plain has water-level elevations 2 to 3 feet higher than the underlying aquifer complex over much of the area of the surficial aquifer.

Ground water discharges through several avenues from the Kidder County aquifer complex. Net upward flow across the confining till and silty clay units into the surficial aquifers occurs in some areas. Two areas were identified in this study by dual-well sites two miles west of Tappen at 139-71-17BBB (figure 28) and just north of South Lake at 142-71-13DDD (figure 29, and plate 6). Differences in water-level elevations between the aquifer complex and the surficial aquifer at these sites are about 4 and 6 feet, respectively. Discharge from the aquifer complex most likely plays an important role in maintaining the sloughs and lakes within the study area. It is not known if these are discharge areas for local, intermediate, or regional flow systems. Lateral flow to the southwest discharges ground water from an apparent ground-water divide south of Dawson and from the Lake George-Henry Lake area into the Long Lake aquifer of southeastern Burleigh County. The Horsehead Lake basin apparently is a major discharge area for water flowing north from the ground-water divide at Dawson and water moving south and west from the Pettibone area. Small-capacity domestic and stock wells add a relatively small proportion to the total discharge of the aquifer complex. Total appropriations for irrigation supplies by 1983 were 18,231 acre-feet annually for 12,166 acres. Reported annual water use for irrigation during the period 1973-1983 totaled about 26,700 acre-feet.

FIGURE 28

Hydrograph of Observation Wells

Kidder County Aquifer Complex
Obs Well-139-071-17BBB1; Land-Surface Elev=1757.93ft NGVD
Tappen Aquifer
Obs Well 139-071-17BBB2; Land-Surface Elev=1758.68ft NGVD

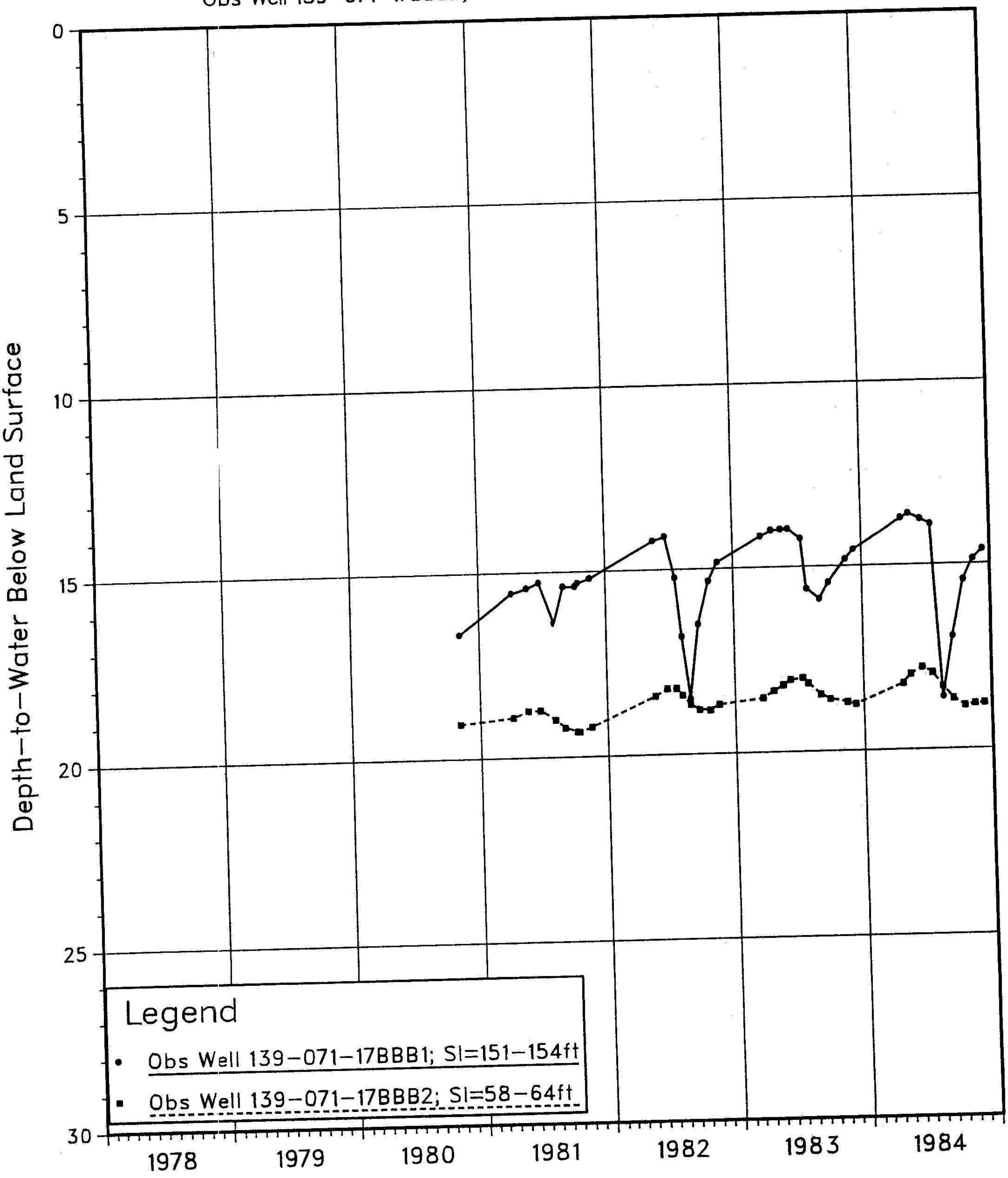
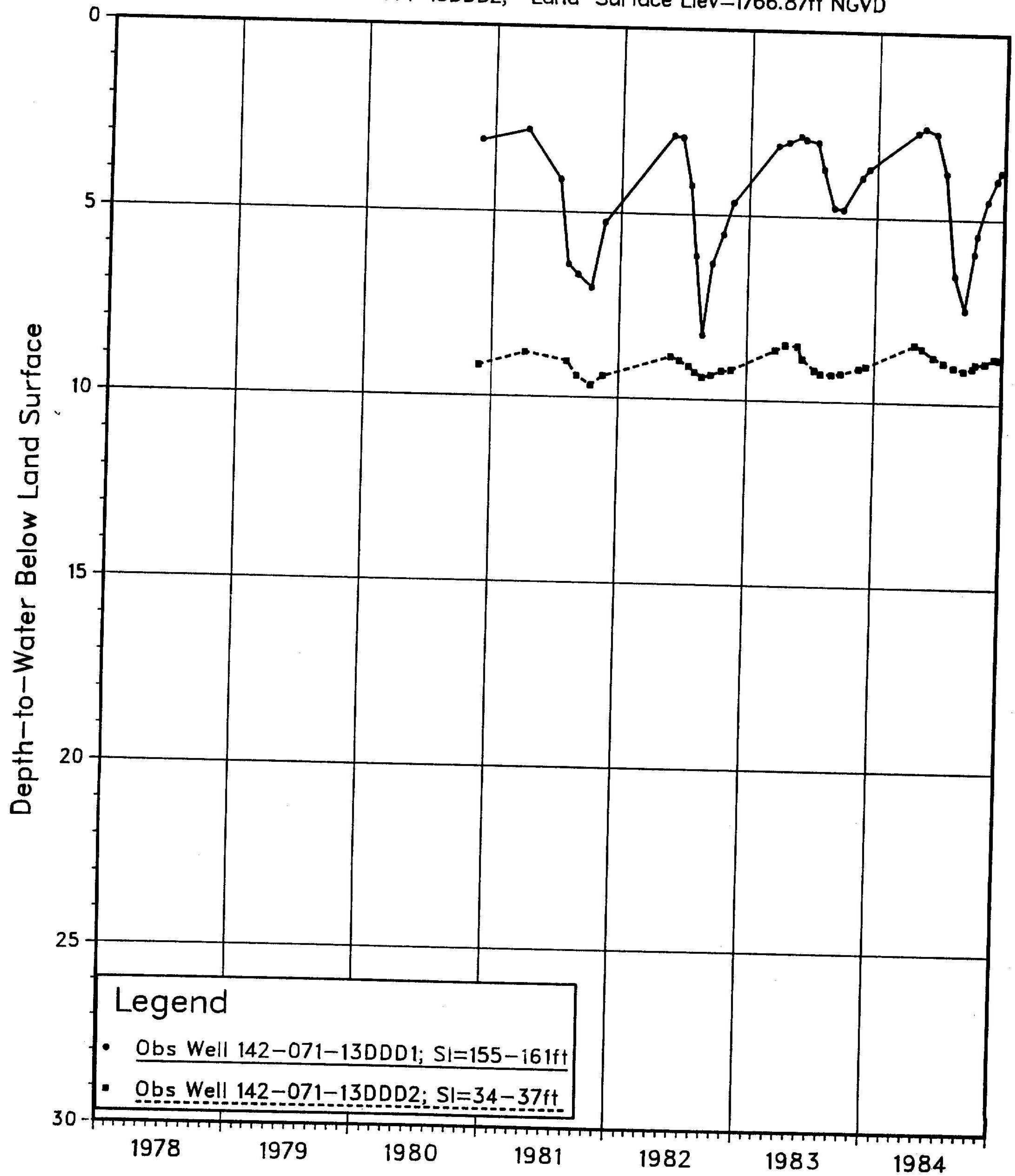


FIGURE 29

Hydrograph of Observation Wells

Kidder County Aquifer Complex
Obs Well 142-071-13DDD1; Land-Surface Elev=1766.80ft NGVD
Marstonmoor Plain Aquifer
Obs Well 142-071-13DDD2; Land-Surface Elev=1766.87ft NGVD



Observation wells monitor the impact of current irrigation development on the aquifer complex. The maximum measured water-level decline near irrigation wells is about 50 feet during the irrigation season. Water levels generally recover from the seasonal low to seasonal pre-pumping levels. Hydrographs typical for observation wells monitoring the aqufier complex are shown in figures 28 through 33 (see also figures 18, 19, 22, 23, and 24).

The yield of a well is partly related to properties of the aquifer in which it is completed such as saturated thickness, hydraulic conductivity, areal extent, and ground-water flow system. Test-hole and observation-well data can establish the order of magnitude for well yield of the Kidder County aquifer complex. The estimates range from less than 50 gpm to greater than 500 gpm (plate 8). Yields exceeding 1,000 gpm may be possible locally where a high hydraulic conductivity combines with a great saturated thickness to produce favorable hydrologic conditions. The capability of the aquifer complex to sustain such a high yield would require a detailed hydrogeological investigation of the site and surrounding area. Plate 8 shows the potential yield available from the glacial-drift aquifers as a whole, including the surficial aquifers.

The amount of water available from storage within the aquifer complex can be estimated from the areal extent and average thickness of the aquifer and an estimated specific yield. Using an areal extent of 470 square miles, an average thickness of 53 feet, and a specific yield of 0.15, an estimated 2,391,000 acre-feet of water are available from storage.

Water in the Kidder County aquifer complex is predominantly hard to very hard. The type of water varies both areally and with depth. The trend along the aquifer complex is calcium-bicarbonate and calcium/sodium-bicarbonate in the north to sodium/calcium-bicarbonate and sodium-bicarbonate in the south.

FIGURE 30

Hydrograph of Observation Wells – Kidder County Aquifer Complex

Obs Well 138–072–03BAA1; Land–Surface Elev=1756.54ft NGVD
Obs Well 138–072–03BAA2; Land–Surface Elev=1756.47ft NGVD
Obs Well 138–072–03BAA3; Land–Surface Elev=1757.29ft NGVD

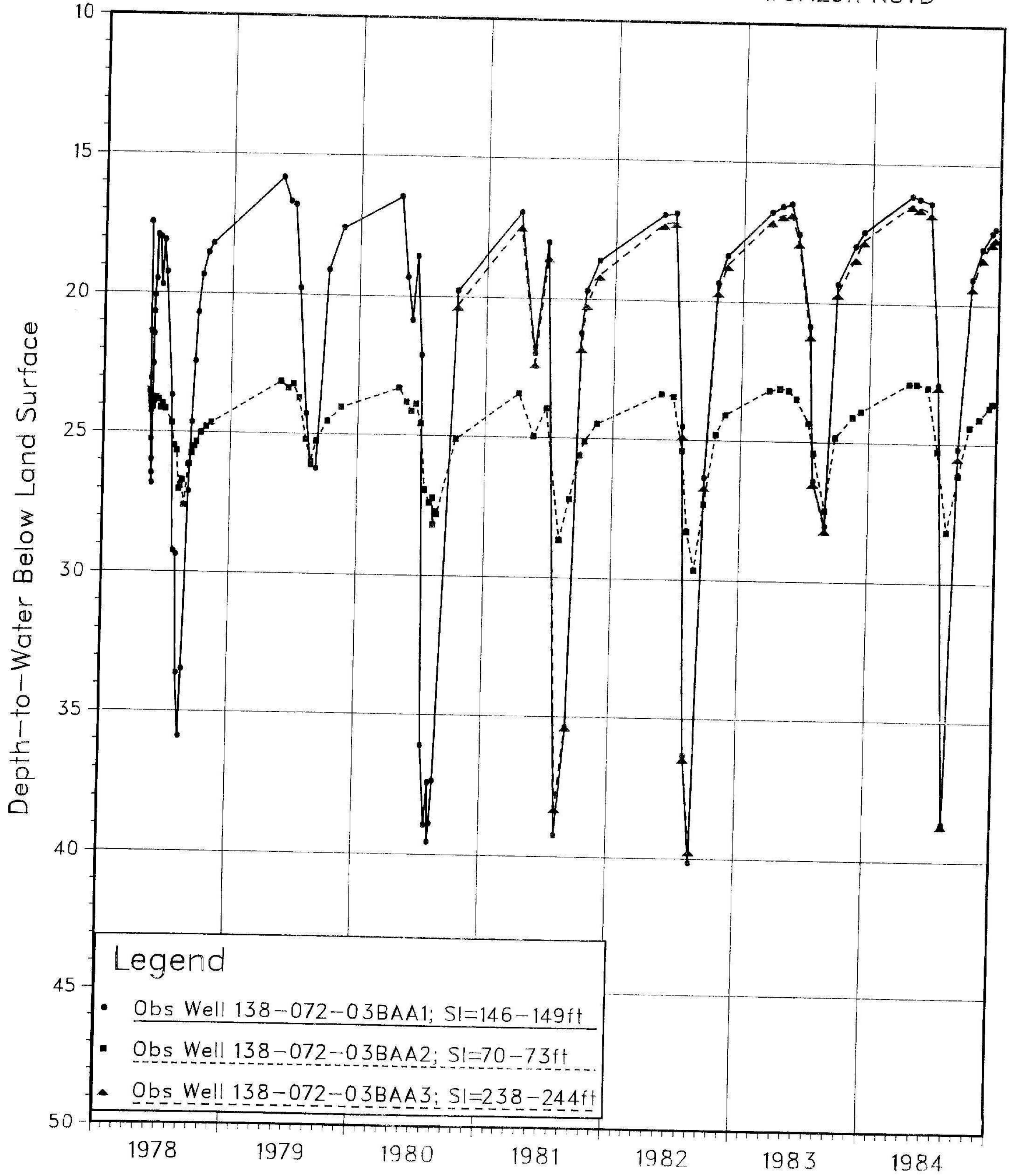


FIGURE 31

Hydrograph of Observation Wells – Kidder County Aquifer Complex

Obs Well 141–070–06BAA1; Land–Surface Elev=1802.03ft NGVD
Obs Well 141–070–06BAA3; Land–Surface Elev=1801.06ft NGVD

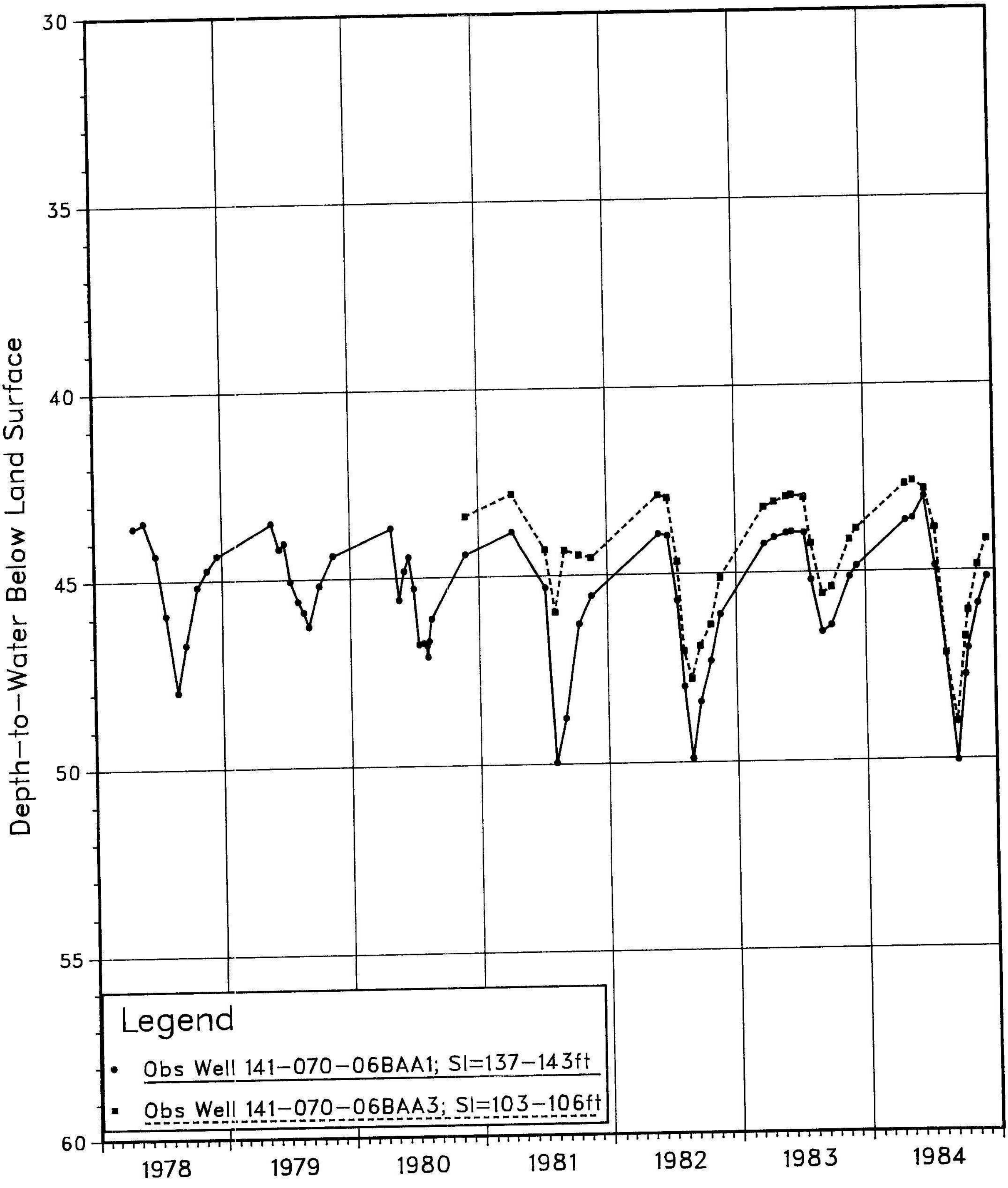


FIGURE 32

Hydrograph of Observation Wells – Kidder County Aquifer Complex

Obs Well 139–072–24BBB1; Land–Surface Elev=1767.99ft NGVD
Obs Well 139–072–24BBB2; Land–Surface Elev=1767.84ft NGVD

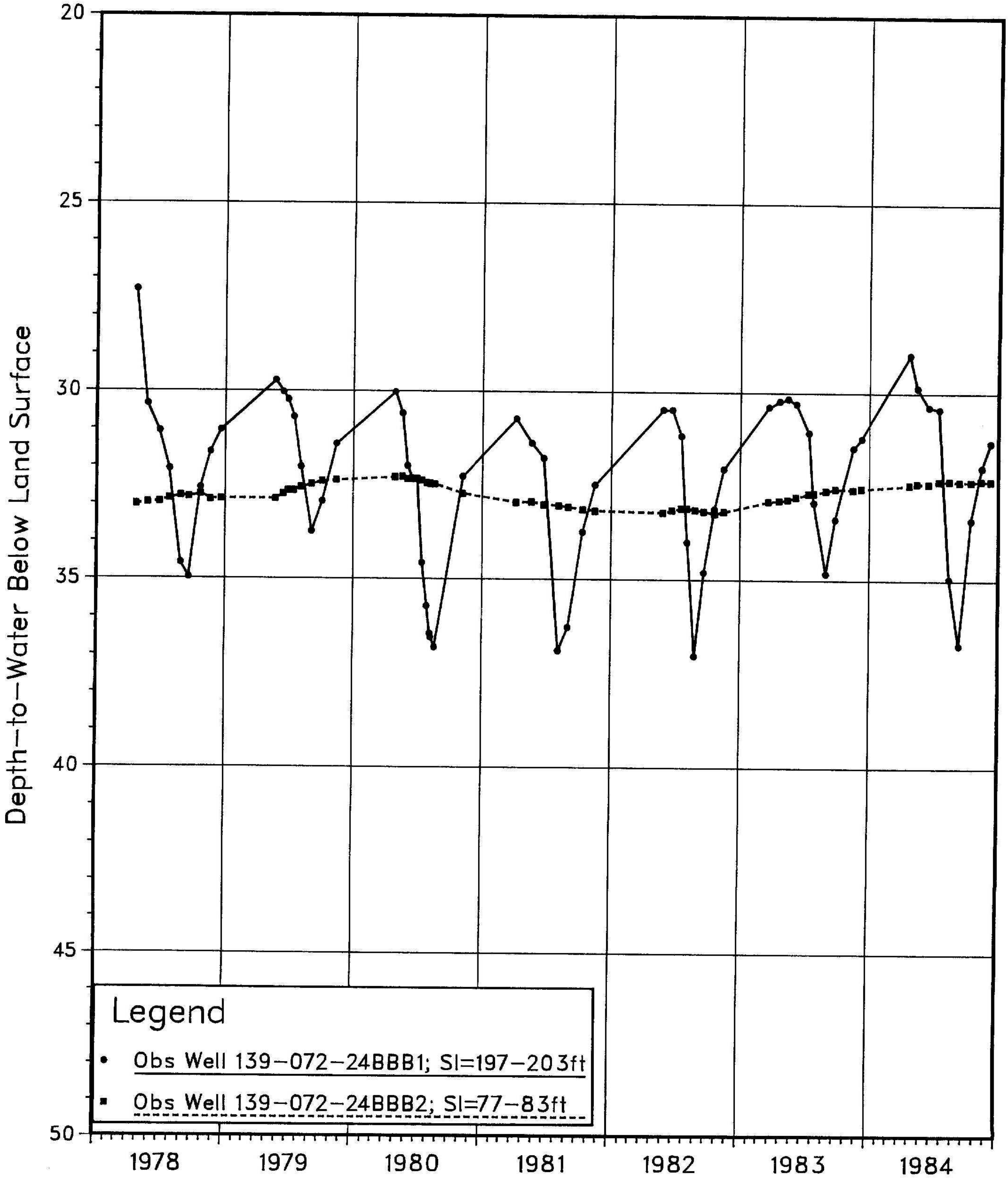
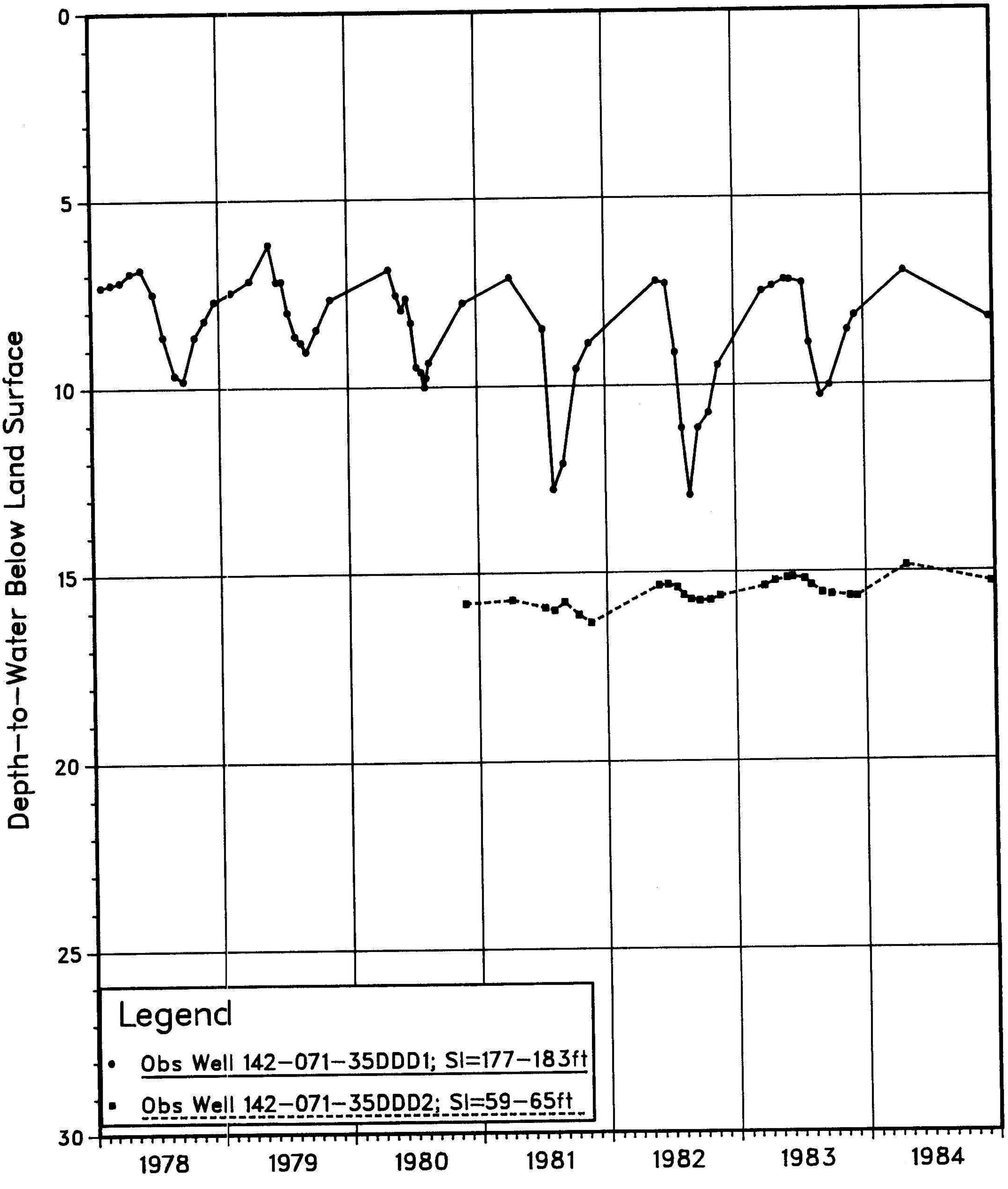


FIGURE 33

Hydrograph of Observation Wells – Kidder County Aquifer Complex

Obs Well 142–071–35DDD1; Land–Surface Elev=1763.65ft NGVD
Obs Well 142–071–35DDD2; Land–Surface Elev=1763.64ft NGVD



The trend with depth is toward the sodium-bicarbonate type water. The overall quality of the water can be summarized as follows:

	Range	Average
Fe(mg/L	0.00 - 6.30	0.58
Mn(mg/l)	0.06 - 2.30	0.95
SO_4(mg/l)	5.4 - 1020	128
TDS(mg/l)	323 - 1420	651
%Na	5 - 92	38
SAR	0.2- 18.5	3.0
RSC	0 - 11	2

Irrigation indices range from C2-S1 to C4-S3 (figure 21), but are predominantly C2-S1 to C3-S1.

At a few locations within the main part of the Kidder County aquifer complex, shallow relatively isolated sand and gravel units overlie the main part of the aquifer complex. Two such units are monitored by observation wells located at 139-72-24BBB$_2$ and 142-71-35DDD$_2$ (plate 6). Water levels in the two shallow wells at these sites show a slight seasonal fluctuation compared to the main part of the aquifer complex (see figures 32 and 33, respectively). Till and silty clay apparently isolate an area south and southwest of Tappen from the irrigation stresses imposed on the main part of the aquifer complex. Water levels in observation wells in this area on the flank of the aquifer exhibit a seasonal fluctuation of one-half foot or less.

Sand and gravel units within the stagnation moraine in the eastern part of the study area are also separate from the main aquifer complex. Water levels in observation wells in two such units at 140-70-27CCC$_2$ (figure 34) and 141-70-17DDD$_2$ (figure 35) fluctuate about two feet or less annually. The quality of the water is considerably different from that found within the aquifer complex.

FIGURE 34

Hydrograph of Observation Well – Kidder County Aquifer Complex

Obs Well 140–070–27CCC2; Land–Surface Elev=1784.43ft NGVD

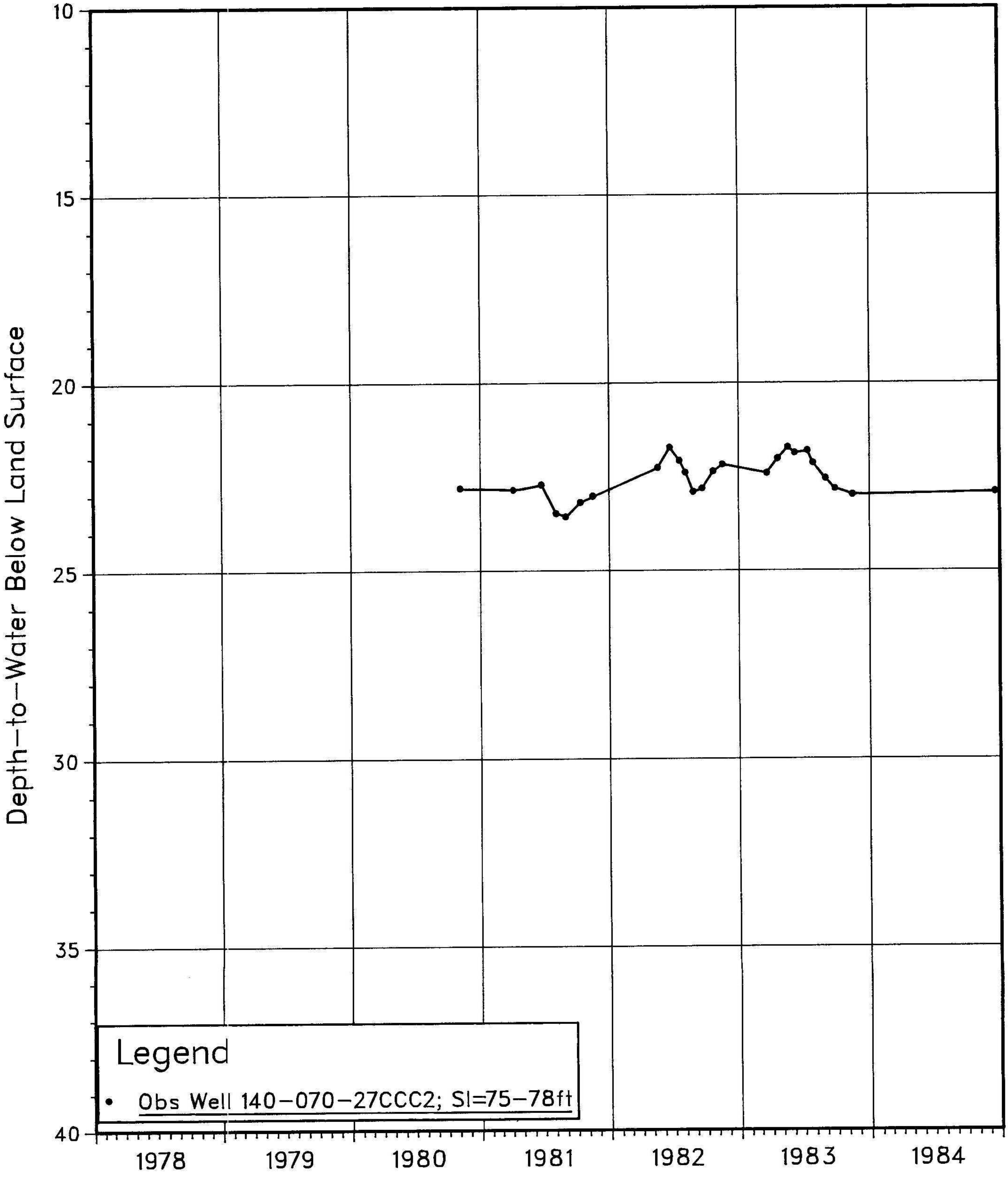
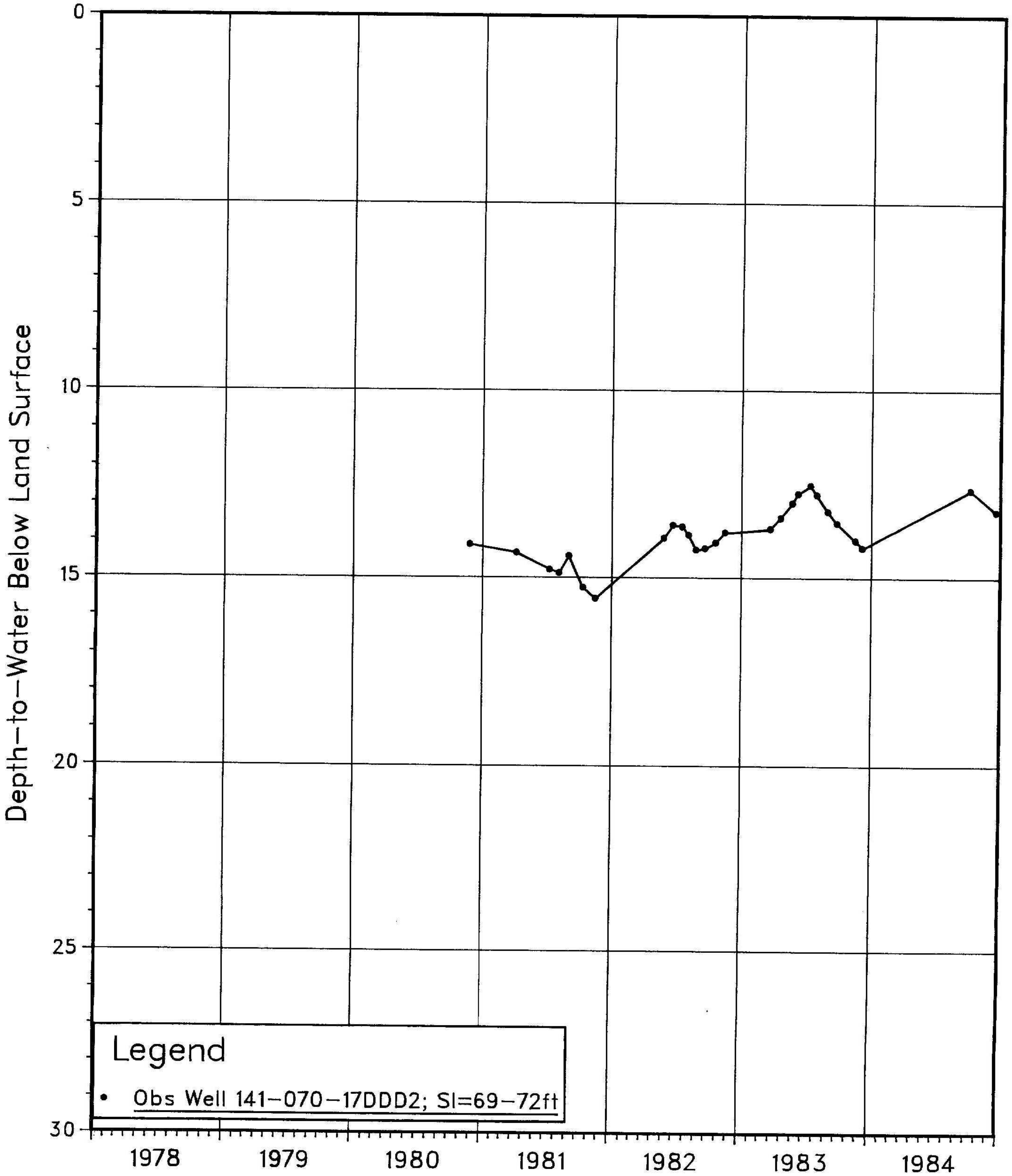


FIGURE 35

Hydrograph of Observation Well – Kidder County Aquifer Complex

Obs Well 141–070–17DDD2; Land–Surface Elev=1817.03ft NGVD



Water from observation well 140-70-27CCC2 is a sodium/magnesium-sulfate type with a total dissolved solids concentration of 7,330 mg/l and very high salinity and sodium hazards. Water from observation well 141-70-17DDD2 is a sodium-sulfate type. The sample had a total dissolved solids concentration of 1,150 mg/l, a high salinity hazard (C3), and a medium sodium hazard (S2). The extent of the sand and gravel units within the area of stagnation moraine and the ground-water flow systems associated with them are not well defined.

GROUND-WATER RESOURCE DEVELOPMENT

The major uses of ground water in the study area are: domestic and livestock supplies, municipal or public supplies, and irrigation. Irrigation constitutes the major use of ground water in the study area compared to all other uses.

Most farmsteads and rural residences in the study area have at least one well for domestic or livestock supplies. Very few records are available regarding the quantity of water used yearly for such supplies. The annual was use may be approximated from population figures (Table 5). The quantities thus approximated give magnitudes

Table 5. Domestic and Livestock Water Use

Use	Individual Requirements (gpd)	Population (rounded)	Estimated Quantity Used (rounded) (gpd)
Rural domestic1/	100	4,400	440,000
Cattle	15	67,4002/	1,011,000
Cows-dairy	35	3,2002/	112,000
Hogs	2	6,4002/	13,000
Sheep	1.5	7,1002/	11,000
Poultry	0.04	7,7003/	300

1/includes population of unincorporated towns and villages
2/based on a 1977-81 average prorated areally from county population figures to study area
3/based on average of 1978 and 1974 population figures prorated areally

of water use only. Actual daily ground-water use for domestic and livestock supplies will vary from the estimated quantities due to the approximation method employed, seasonal variations in farming operations, and an unknown proportion of the livestock water originating from surface water.

The cities in the study area depend on ground water for their source of supply. Four of these cities have distribution systems: Wing, Strasburg, Steele, and Tuttle. The residents of the other cities rely on private wells to supply water, and are included in the rural domestic category in Table 5. The wells for Wing and Strasburg are completed in the Wing Channel and Strasburg aquifers. Reported water use for 1973-1983 for these two municipalities is 215.9 and 1019.7 acre-feet, respectively. The wells for Steele and Tuttle are completed in the Fox Hills aquifer. Water use is not included in this report on the glacial-drift aquifers.

A total of 47,359 acre-feet of ground water was reported as used for irrigation in the study area during the period 1973-1983 (table 6). The annual

TABLE 6. Reported Annual Water Use - Irrigation
(in acre-feet)

Year	Burleigh	Emmons	Kidder	Annual Total
1973	417	137	2347	2901
1974	464	128	2178	2770
1975	329	80	2013	2422
1976	905	2	3342	4249
1977	1646	662	4158	6466
1978	250	80	3704	4034
1979	598	273	2467	3338
1980	1519	315	5225	7059
1981	302	422	4031	4755
1982	575	192	2473	3240
1983	897	272	4956	6125
Total	7902	2563	36,894	47,359

total use ranges from 2,422 acre-feet in 1975 to 7,059 acre-feet in 1980, and averages 4,305 acre-feet. Kidder County reported the greatest annual irrigation use, a trend that is expected to continue.

RECOMMENDATIONS FOR FURTHER STUDY

Three principal elements of the ground-water flow system in the study area remain for future investigation.

A) The areas and sources of recharge and areas of discharge should be further identified, particularly with regard to the moraines surrounding the study area and the bedrock aquifers underlying the drift aquifers.

B) The relationships between surface water and ground water are not well understood in the study area. Further study is needed to define the dynamic interactions between ground water and surface water.

C) This study indicates the complexities of the ground-water flow system within the Kidder County aquifer complex. Additional work is necessary to better delineate the aquifer entities within the glacial drift and define the effects of the heterogeneities within the drift on the flow of ground water within and between aquifer intervals. Aquifer simulation should be an integral part of such further study. A result of such study will be improved assessments of the impacts from proposed and current water-resource development on ground-water flow systems in the area of development.

The U. S. Bureau of Reclamation investigated the feasibility of a federally sponsored irrigation project in Kidder County. At least part of the total water requirements could be supplied by ground water. Projects with 50,000 and 120,000 acres were evaluated, which correspond to water demand of about 75,000 and 180,000 acre-feet. Further investigation as outlined in A, B, and C will be necessary in order to address the effects of such projects on the total water resource.

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