Stream-Aquifer Interactions in the Straight River Area, Becker and Hubbard Counties, Minnesota

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

Readers who prefer to use metric (International System) units rather than inch-pound units can make conversions using the following factors:

Multiply Inch-Pound Unit	By	To obtain Metric Unit
inch (in.)	25.4	millimeter
foot (ft)	.3048	meter
mile (mi)	1.609	kilometer
foot per day (ft/d)	.3048	meter per day
foot per mile (ft/mi)	.1894	meters per kilometer
cubic foot (ft^3)	.02832	cubic meters
cubic foot per second (ft^3/s)	28.32	liter per second
foot squared per day (ft^2/d)	.09294	meter squared
gallon (gal)	.003785	cubic meter
gallon per minute (gal/min)	.06308	liter per second
acre	.4047	hectare
acre-foot (acre-ft)	1,233	cubic meter
square mile (mi^2)	2.590	square kilometer
degree Fahrenheit (°F)	(°F -32)/1.8	degree Celsius (°C)

Chemical concentrations are given in metric units. Chemical concentrations of substances in water are given in milligrams per liter (mg/L) or micrograms per liter (µg/L). Milligrams per liter is a unit expressing the concentration of chemical constituents in solution as weight (milligrams) of solute per unit volume (liter) of water. One thousand micrograms per liter is equivalent to one milligram per liter

Sea level In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)-- a geodetic datum derived from a general adjustment of the first-order level notes of both the United States and Canada, formerly called "Sea Level Datum of 1929".

Glossary

The geologic and hydrologic terms pertinent to this report are defined as follows:

Aquifer: Formation, group of formations, or part of a formation that contains sufficient saturated permeable material to yield significant quantities of water to wells or springs.

Base flow: Sustained streamflow, mainly consisting of ground-water discharge to a stream.

Confined aquifer: An aquifer bounded above and below by confining units. An aquifer containing confined ground water. Synonymous with a buried aquifer where hydraulic head rises above the top of the aquifer in a tightly cased well.

Confining unit: Body of material with low vertical permeability stratigraphically adjacent to one or more aquifers. Replaces the terms aquiclude, aquitard and aquifuge.

Drawdown: Vertical distance between the static (nonpumping) hydraulic head and hydraulic head caused by ground-water withdrawal.

Drift: General term applied to all material (clay, sand, gravel, and boulders) transported and deposited by glacial ice or melt water.

Evapotranspiration: Water discharged to the atmosphere by evaporation from water surfaces, moist soil, and by plant transpiration.

Ground water: The part of subsurface water that is in the saturated zone.

Head, hydraulic: The height above a standard datum of the surface of a column of water that can be supported by the static pressure at a given point.

Hydraulic conductivity: Capacity of porous material to transmit water under pressure. It is the rate of flow of water passing through a unit section of area under a unit hydraulic gradient.

Hydraulic gradient: The change in hydraulic head per unit distance of flow in a given direction. Synonymous with potentiometric gradient.

Isotope: Any of two or more species of atoms of a chemical element with the same number and position in the periodic table and nearly identical chemical behavior but with differing atomic mass or mass number and differing physical properties.

Outwash: Washed, sorted, and stratified drift deposited by water from melting glacial ice.

Permeability: Measure of the relative ease with which a porous medium can transmit a fluid under a potential gradient.

Potentiometric surface: A surface that represents the static head of water in an aquifer; it is defined by the levels to which water will rise in tightly cased wells from a given point in an aquifer.

Saturated zone: The zone in which all voids are ideally filled with water. The water table is the upper limit of this zone. Water in the saturated zone is under pressure equal to or greater than atmospheric.

Specific capacity: The rate of discharge of water from a well divided by the drawdown of water level within the well.

Specific yield: The ratio of the volume of water that an aquifer material will yield by gravity drainage to the volume of the aquifer material.

Storage coefficient: The volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head. In an unconfined aquifer, it is virtually equal to the specific yield.

Till: Unsorted, unstratified clay, silt, sand, gravel, or boulders of glacial origin.

Transmissivity: The rate at which water of the prevailing kinematic viscosity is transmitted through a unit width of an aquifer under a unit hydraulic gradient.

Unconfined aquifer: Saturated zone between the water table and the first underlying confining unit; an aquifer that has a water table. Surficial aquifers are unconfined aquifers.

Water table: The surface in an unconfined ground-water body at which the water pressure is atmospheric. Generally, this is the upper potentiometric surface of the zone of saturation.

Water year: The period from October 1 through September 30. Water year is designated by the calendar year in which it ends and which includes 9 of the 12 months. Thus, the year ending September 30, 1993 is called the 1993 water year.

Abstract

The Straight River, in north-central Minnesota, is a trout stream having cold, clear water. The 75-square-mile Straight River watershed contributes flow to the stream. The watershed is underlain by highly transmissive surficial and confined-drift aquifers. Ground-water discharge from these aquifers sustains flow in the Straight River, and the cold water supports a population of trout. Water withdrawals from these aquifers are increasing in response to changes in land use from dry-land to irrigated farming. Degradation of the stream's habitat for trout could result from the following: a decrease in ground-water discharge to the stream caused by ground-water withdrawals for irrigation, an increase in ground-water temperature resulting from percolation of irrigated water to the ground-water system, and introduction of agricultural chemicals to the stream through ground-water flow or runoff.

Physical data indicate a hydraulic connection between the stream and the surficial aquifer. Discharge of the Straight River increases from about 25 cubic feet per second at the outfall from a reservoir near the headwaters to about 51 cubic feet per second near the mouth. The rate of streamflow gain during summer decreases downstream, possibly as a result of ground-water withdrawal for irrigation. The water table and potentiometric surface of the uppermost confined-drift aquifer generally slope to the southeast and locally toward rivers and lakes; gradients decline to about 5 feet per mile from spring to summer.

Daily fluctuations of stream temperature are as great as 15 degrees Celsius during the summer, primarily in response to changes in air temperature. Ground-water discharge to the Straight River decreases stream temperature during the summer. Results of simulations from a stream-temperature model indicate that daily changes in stream temperature are strongly influenced by solar radiation, wind speed, stream depth, and ground-water inflow. Results of simulations from ground-water-flow and stream-temperature models developed for the investigation indicate a significant decrease in ground-water flow could result from ground-water withdrawal at rates similar to those measured during 1988. This reduction in discharge to the stream could result in an increase in stream temperature of 0.5 to 1.5 degrees Celsius. Nitrate concentrations in shallow wells screened at the water table, in some areas, are locally greater than the limit set by the Minnesota Pollution Control Agency. Nitrate concentrations in water from deeper wells and in the stream are low, generally less than 1.0 milligram per liter.

Introduction

The Straight River, in Becker and Hubbard Counties, Minnesota (fig. 1), is a trout stream having cold, clear water. According to State officials (Dennis Ernst, Minnesota Department of Natural Resources, written commun., 1990), the stream is one of the most productive trout-fishing streams in Minnesota. The stream is an important recreational resource partly because it is located in the north-central part of the State where trout streams are uncommon. Streams designated as trout streams in Minnesota are regulated by the Minnesota Department of Natural Resources (MDNR) to help protect the quantity and quality of the water. The Straight River is similar to many streams in the upper midwest that flow through and receive ground-water discharge from glacial outwash. Ground and surface water are closely related in the Straight River watershed. Infiltration through the permeable soils is rapid when the soils are free of frost, resulting in substantial recharge to highly-transmissive surficial aquifers that are hydraulically connected to the stream. The surface drainage to the Straight River, about 75 square miles in area, is underlain by highly transmissive confined and surficial sand and gravel (drift) aquifers. Flow of the Straight River is sustained by discharge from these aquifers, especially during periods of no rainfall.

Brook trout *(Salvelinus fontinalis* Mitchill*)* were common in the Straight River as late as the 1940's, but now are absent (Dennis Ernst, oral commun., 1990). In addition to adequate stream discharge, brook trout require cold, clear water with a silt-free, rocky substrate (Raleigh, 1982). The temperature of streams is critical because brook trout do not thrive in water where the temperature exceeds 20°C (degrees Celsius) for extended periods. The Straight River presently is too warm a habitat for brook trout.

Brown trout *(Salmo trutta)* were introduced into the Straight River in the 1940's and are abundant in the stream today (Dennis Ernst, oral commun., 1990). The stream produces some of the largest brown trout in Minnesota. Brown trout require stream conditions similar to brook trout. Like brook trout, the most important environmental factor that determines suitable habitat for brown trout is water temperature. Brown trout, however, can survive in warmer water than brook trout (Raleigh and others, 1986). The maximum, near-lethal water temperature for brown trout is 27°C, and optimum temperatures for growth and survival range from 12 to 19°C. During the summer of 1988, temperature and streamflow in the

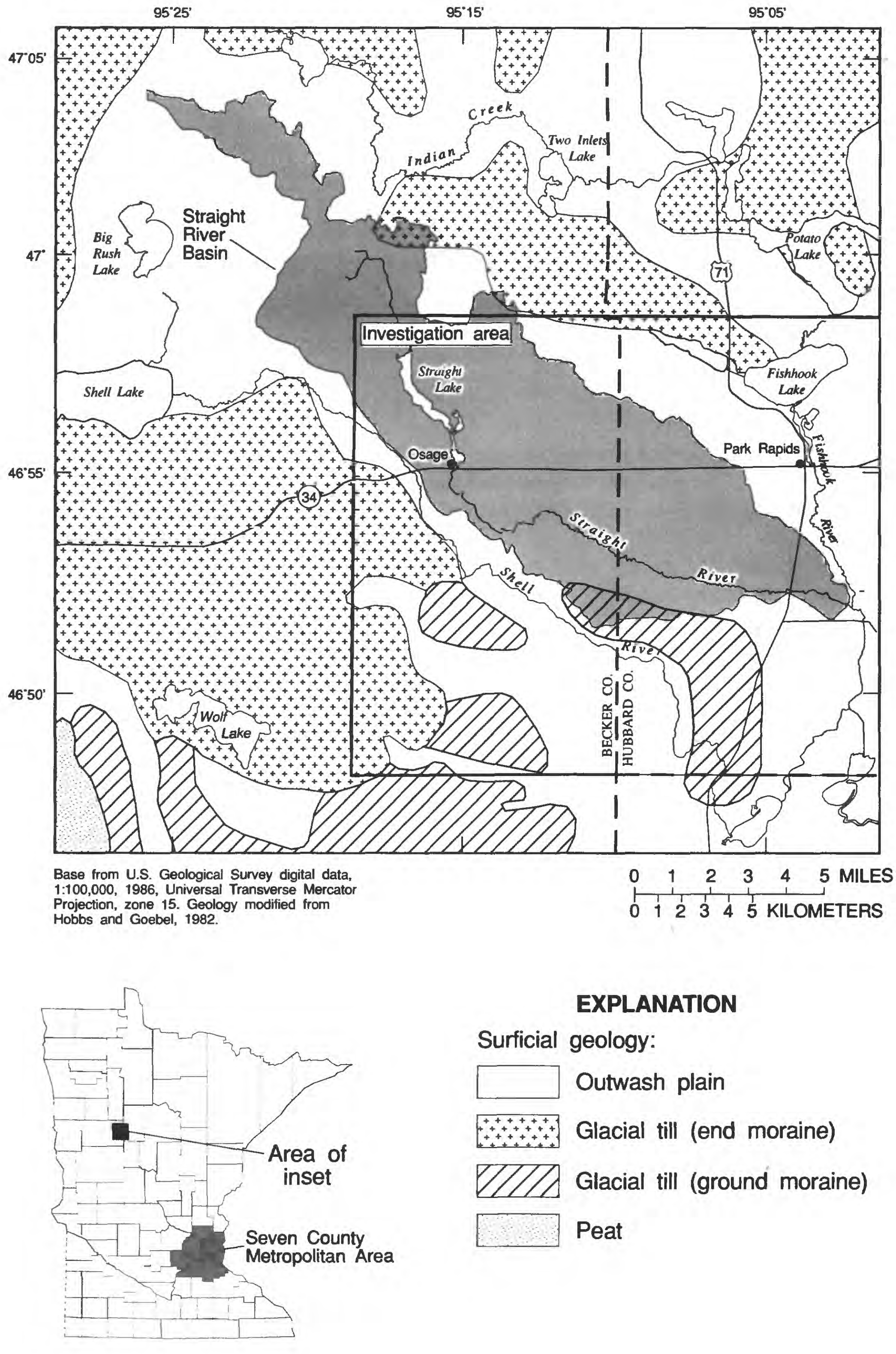


Figure 1.--Location of Straight River Basin, investigation area, and surficial geology in Becker and Hubbard Counties, Minnesota.

Straight River approached conditions that are lethal for brown trout.

Land use in the Straight River watershed is changing from dry-land to irrigated farming. Sandy soil and the availability of ground water have made the area a good location for large-scale cultivation of potatoes. In 1974, there were five irrigation wells in the area. By 1988 (a relatively dry year) there were 48 irrigation wells screened in drift aquifers. About 2.3 billion gallons of ground water were withdrawn from these wells for irrigation from May through August 1988. During the same period, total discharge near the mouth of the Straight River was about 4.0 billion gallons. Most irrigation is within 2 mi (miles) of the Straight River.

Withdrawal of water through irrigation wells could cause prolonged or permanent changes in the direction or magnitude of ground water flowing toward the stream. Such a reduction of streamflow resulting from ground-water withdrawal is called stream depletion (Jenkins, 1968).

The temperature of stream water would increase as the amount of cold ground-water flow discharging to the stream is reduced. Decreased stream discharge also results in a smaller thermal mass and thus the stream would be more susceptible to warming from solar radiation. Increased stream temperature also could result from a warming of ground water discharging to the stream because of warm irrigation return flow to the aquifer. Anecdotal information indicates that water temperature of Straight River has increased during the last several years. Data on stream temperature, however, were not well documented prior to this investigation, and few stream-discharge or water-quality measurements of the stream had been made.

Agricultural chemicals applied to the land may percolate to the shallow ground-water system. These chemicals could then migrate with ground-water flow as dissolved constituents and discharge to the stream. These water-quality factors could affect the ability of the stream to maintain a stable trout population.

Local officials are concerned that ground-water withdrawals for irrigation and intensive agriculture may adversely affect the quantity, quality, and temperature of ground water and water in the stream, and that these changes could degrade the stream's habitat for trout. This investigation was considered a priority by the MDNR and by the Legislative Commission on Minnesota Resources (LCMR) to examine the potential effect of irrigation on the quantity, quality, and temperature of ground and surface water in the area and was conducted by the U.S. Geological Survey (USGS) in cooperation with these agencies.

Purpose and Scope

This report describes hydrologic conditions in the Straight River watershed, including ground- and surface-water quantity and quality. The report also presents an estimate of the effects of ground-water withdrawal for irrigation on ground water and on surface water. Specifically, this report describes: (1) the variability in streamflow and ground-water levels, (2) stream and ground-water quality, (3) stream-aquifer interaction, and (4) the effect of irrigation on the quantity and quality of ground water and of the Straight River.

This report contains four parts. The first part of the report describes the quantity and quality of water in the Straight River. The second part describes the aquifers that discharge to the stream, defines quantity and quality of water in the aquifers, and describes seasonal changes in ground-water levels, flow, and quality. The third part describes interaction between the stream and the aquifers and the fourth part discusses the effects of irrigation.

Location and Physical Setting of Investigation Area

The investigation area is about 180 mi northwest of the Twin City Metropolitan Area, Minnesota, and covers approximately 240 mi^2 (square miles), including parts of Becker and Hubbard Counties (fig. 1). The investigation area does not include the entire Straight River Basin; parts of the investigation area are outside of the Straight River Basin. The investigation area is underlain by an extensive surficial aquifer consisting of glacial outwash. This aquifer is part of a large surficial aquifer system, called the Pinelands Sands (Helgesen, 1977), which underlies 770 mi^2 of Becker, Cass, Hubbard, and Wadena Counties. Confined drift aquifers also underlie most of the investigation area. A generalized section of the hydrologic system in the investigation area is shown in figure 2.

The topography of the Straight River area is generally either flat or gently rolling. The areas to the north and west of the investigation area consist of glacial moraine and have more relief than the outwash plain (shown as outwash in fig. 1). The Straight River flows approximately 19 mi from its source in Becker County to its mouth at the confluence with the Fishhook River in Hubbard County (fig. 1), and is part of the drainage basin of the Crow Wing River, in the Mississippi River drainage system. A dam at Osage stabilizes and raises the level of Straight Lake (fig. 1). This dam, constructed in the 1930's, also controls and stabilizes streamflow below Straight Lake. The river has no tributaries, and its flow is derived from ground-water discharge, discharge from Straight Lake, and a small amount of overland runoff.

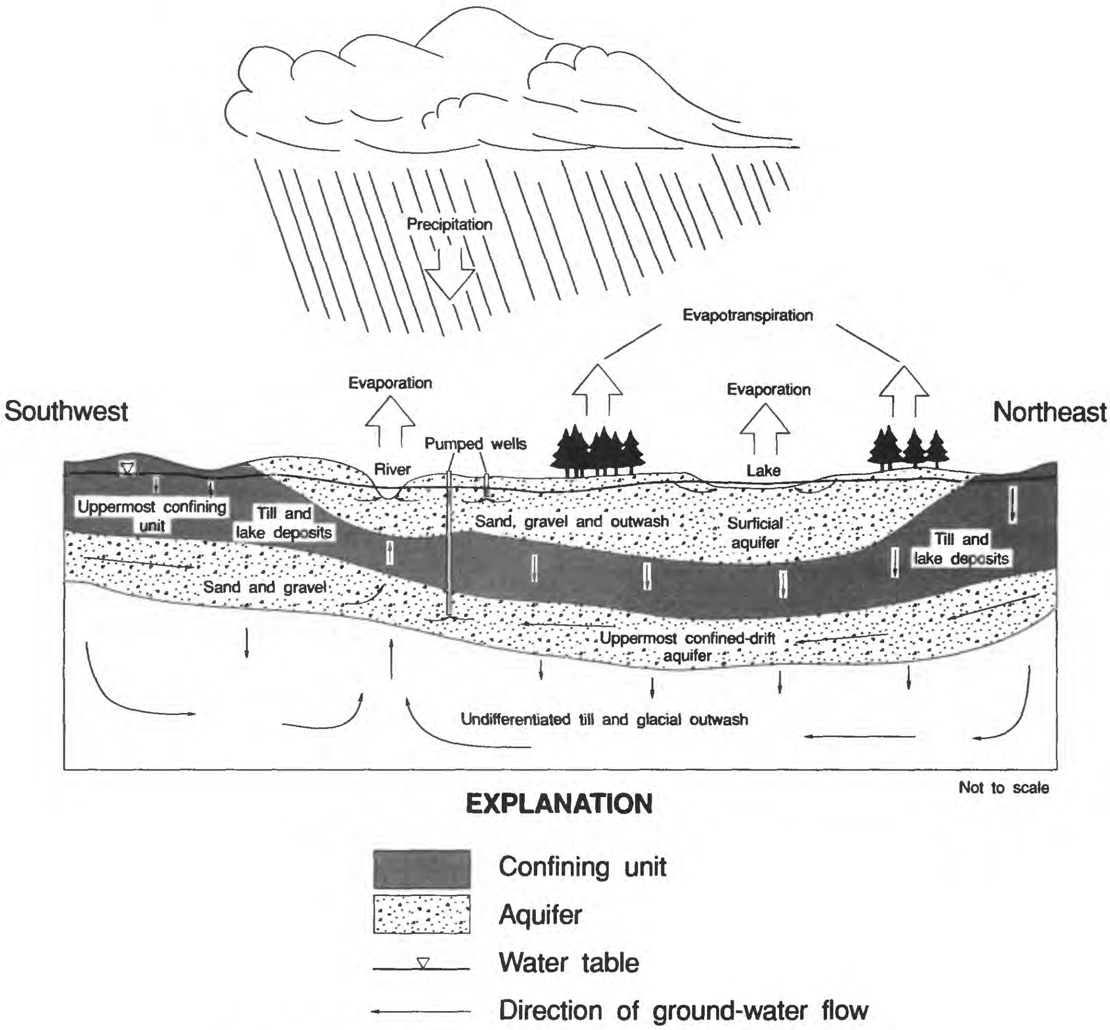


Figure 2.--Generalized hydrologic system of the Straight River investigation area.

Inflow to Straight Lake is primarily from streamflow in the upper Straight River and from ground-water discharge to the lake.

Basement rock, consisting of Proterozoic age (Precambrian igneous and metamorphic rocks includinggranite, gneiss, and schist) (Sims, 1970) and Cretaceous age (sandstone, siltstone, and shale) rocks directly underlie glacial drift throughout the investigation area. The Proterozoic rocks are dense, crystalline rocks with low porosity and permeability. Water is present in fractures and in weathered zones near the upper surface of the rocks. These rocks are not aquifers within the investigation area. The bedrock surface is irregular because of preglacial erosion by rivers and from glacial ice and meltwater during the Pleistocene Epoch.

Although few drill holes have reached the basement rock, a test hole (Minnesota unique-well no. 236103) penetrated Cretaceous shale at 435 ft (feet) below land surface and granitic rock at 544 ft below land surface.

The glacial drift is several hundred feet thick, and thickness increases from south to north (Lindholm and others, 1972). Glacial-drift deposits primarily are till, stratified (glacial) outwash deposits, and glacial-lake deposits. Till, deposited at the base of glaciers during glacial advances, is a poorly sorted mixture of clay, silt, sand, gravel, and boulders. Deposits of till are at the land surface along the edges of the outwash, in isolated locations within the outwash, and buried within the sequence of glacial deposits. Glacial-lake deposits formed as silt and clay were deposited in glacial lakes and ponds. These lake deposits were subsequently buried by outwash and till. Stratified sand and gravel (outwash) were deposited in glacial rivers and ponds during periods of glacial stagnation and retreat. Some sand and gravel deposits also were covered by till during subsequent glacial advances. The buried outwash deposits are referred to as confined-drift aquifers. Other sand and gravel units were deposited during the retreat of the last glaciers and are exposed at land surface. These surficial outwash deposits are referred to as surficial (unconfined) aquifers. Till and glacial-lake deposits form confining units within the glacial drift. Both confined and surficial aquifers are present throughout the investigation area, and are the major aquifers used in the area.

Hobbs and Goebel (1982) mapped the surficial geology of the Straight River area using Minnesota soils atlases, LANDSAT satellite imagery, and other published data. Figure 1 shows the distribution of the surficial glacial deposits in the investigation area. This map is based on the work of Hobbs and Goebel with modifications based on more recent test holes drilled for this investigation and well logs from the area.

Glacial deposits that resulted from the Wadena glacial lobe of late Wisconsin age underlie the Straight River watershed. This ice lobe advanced from and retreated to the north-northwest as ice was differentially directed by areas of less competent bedrock (Wright, 1972, and Wright and Ruhe, 1965). The Itasca highland, located north of the Straight River area, is an extensive complex of moraines resulting from this advance.

Discharge from the surficial and confined-drift aquifers mainly is to the Straight River and to irrigation-, domestic-, and municipal-supply wells. Discharge from ground-water by evapotranspiration occurs primarily during the growing season where the water table is within the root zone of vegetation.

Mean annual precipitation ranges from 24 to 26 in. (inches) over the investigation area (Baker and Kuehnast, 1978), with most occurring as rain during May to September. Figure 3 shows the range in annual precipitation at Park Rapids during 1894 through 1988. Potential annual evapotranspiration is about 22 in. (Baker and others, 1979).

Land use in the Straight River watershed primarily is agriculture, forestry, and recreation. Agricultural lands are mostly used to grow small-grain crops, corn, and potatoes. Agricultural land use is changing from dry-land to irrigated farming. Light-textured soils and productive aquifers in the area are conducive for large-scale cultivation of potatoes. There were 5 irrigation wells in the watershed in 1974, but by 1988 the number had increased to 48 wells. Ground-water withdrawals from these wells was about 2.3 billion gallons in 1988. Most irrigation withdrawals are within 2 mi of the Straight River (fig. 4). Forested areas consist of second- or third-growth stands of trees that are primarily harvested for paper pulp and wood products.

Residential and urban areas are located outside the Straight River watershed primarily around Park Rapids (1980 population of 2,772). Commercial areas are not extensive, and exist primarily as localized areas of light service industry, food processing, transportation, and commerce.

Previous Investigations

Early descriptions of the geology of the area were presented by Winchell and Upham (1888) and Winchell and others (1888). A general discussion of geology and ground water is included in the work of Allison (1932). Additional detail on the glacial geology of the area was presented by Leverett (1932), Wright (1962, 1972), and Wright and Ruhe (1965). Oakes and Bidwell (1968) described the regional hydrology of the Mississippi Headwaters area. Siegel and Winter (1980) described an investigation of lake/ground-water interactions at Williams Lake in Hubbard County.

Several previous investigations of the ground-water hydrology of the Straight River area have been conducted. Lindholm (1970) appraised the availability of water from glacial outwash immediately southwest of the investigation area. Lindholm and others (1972) made a reconnaissance of the water resources of the Crow Wing River watershed, which included the entire Pinelands Sands area. Helgesen (1977) investigated the ground-water geology of the Straight River watershed as part of a larger investigation of the Pinelands Sands surficial aquifer. This investigation focused on the surficial aquifer and did not include confined-drift aquifers, which are also present in the investigation area. Helgesen published hydraulic conductivity values for the aquifer, a water-table map, a map of theoretical well yields for the area, and maps of the extent, thickness, and hydraulic properties of the aquifer. He also included a map of the water table prior to significant development of ground-water supplies for irrigation. Helgesen developed a two-dimensional ground-water-flow model of the Pinelands Sands aquifer. Simulations of hypothetical ground-water withdrawal indicated that development of irrigation supplies from wells in the surficial aquifer would not significantly lower water levels in the aquifer.

Methods of Investigation

This investigation included the following work elements: (1) design and construction of a data-collection

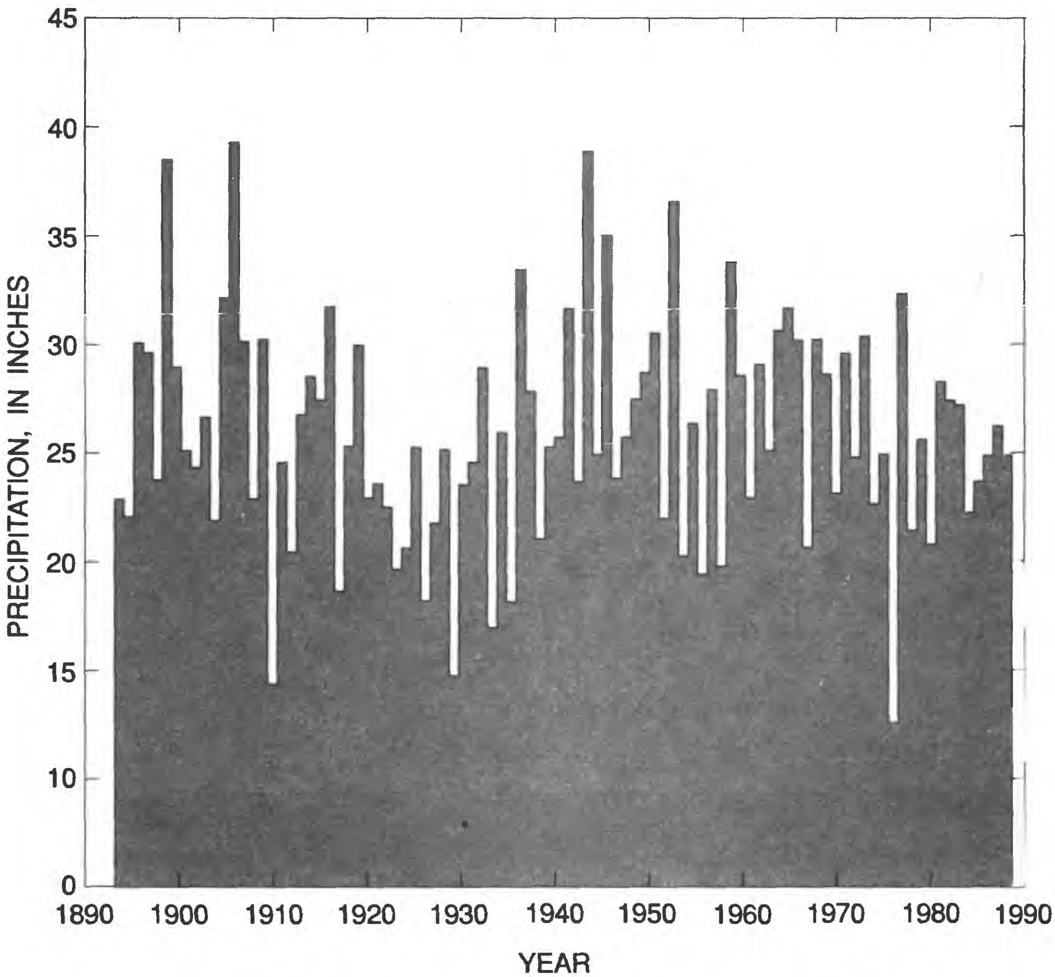


Figure 3.--Annual precipitation during 1894 through 1988 at Park Rapids, Minnesota.
(Data from Minnesota Department of Natural Resources)

network to define hydrology and water quality of the drift aquifers and the stream, (2) measurement of stream and ground-water temperatures to determine seasonal and daily fluctuations and temperature distribution, (3) analyses of hydraulic properties of drift aquifers, potentiometric surfaces, and directions of ground-water flow, (4) construction of ground-water-flow and stream-temperature models to represent the geohydrologic system and the interaction between the aquifers and the stream, and (5) application of model simulation results to test the hydrologic system over long periods of time.

Six sites along the Straight River were instrumented to measure stream stage and temperature, and ground-water level and temperature (fig. 5). These sites include three continuous-record stations (sites B, D, and F) and three partial-record stations where stream-stage data were measured periodically (sites A, C, and E). Electronic data loggers, potentiometers, and thermisters were installed at the three continuous-record stations and at one partial-record station to measure the following: stream stage; ground-water levels in observation wells near the stream; and air, ground-water, and stream-water temperature.

Hydrogeologic maps were constructed using well and test-hole data from the Minnesota Geological Survey (MGS), the MDNR, the USGS, and from geologic logs of test holes drilled for this investigation. The locations of wells having driller's logs were verified by locating wells in the field. Location, geologic and hydrologic information from the logs were entered into a computer data base. Wells and test holes were identified by local well number and by latitude and longitude. The data were used to prepare maps showing the thickness, extent, and

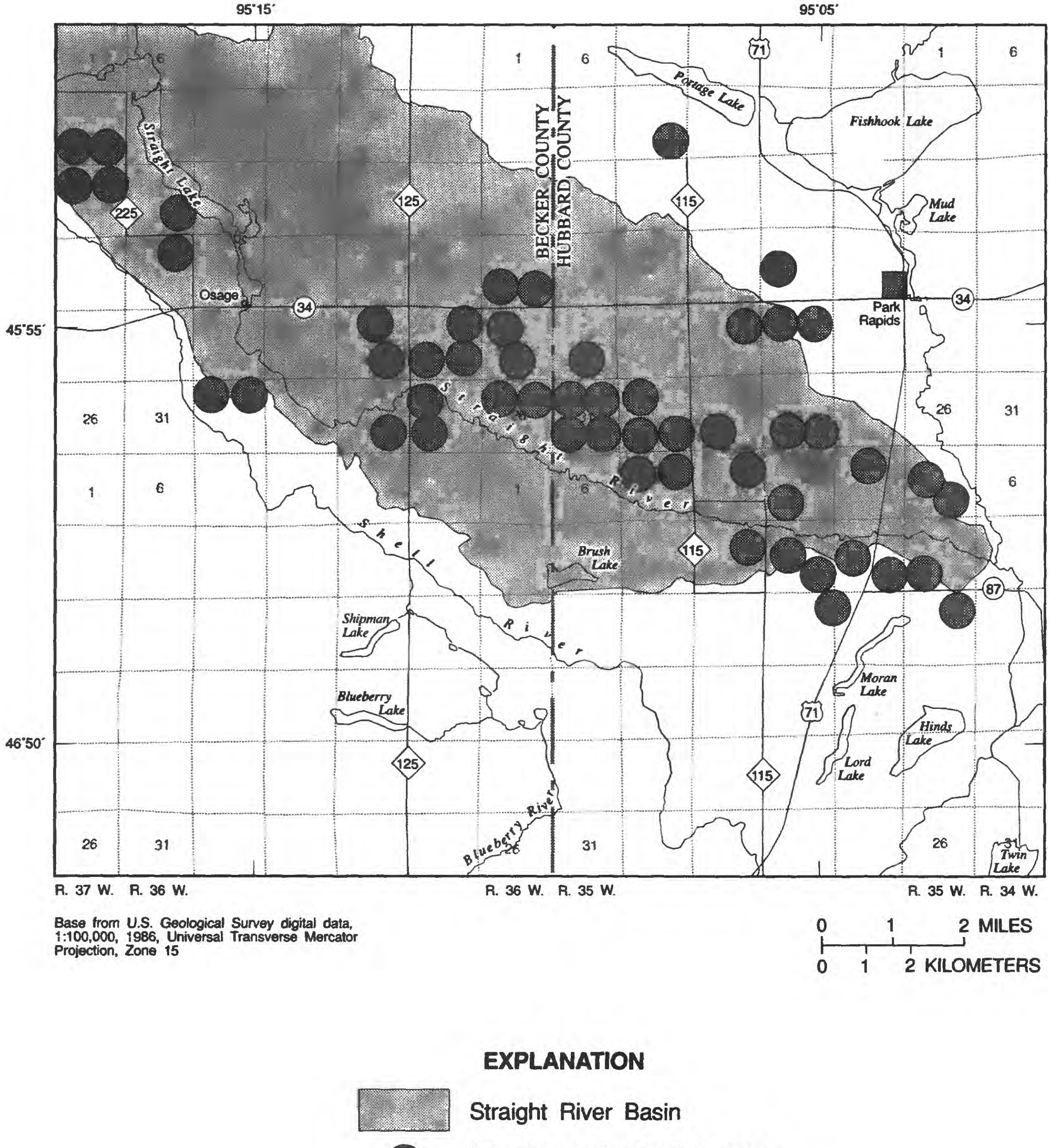
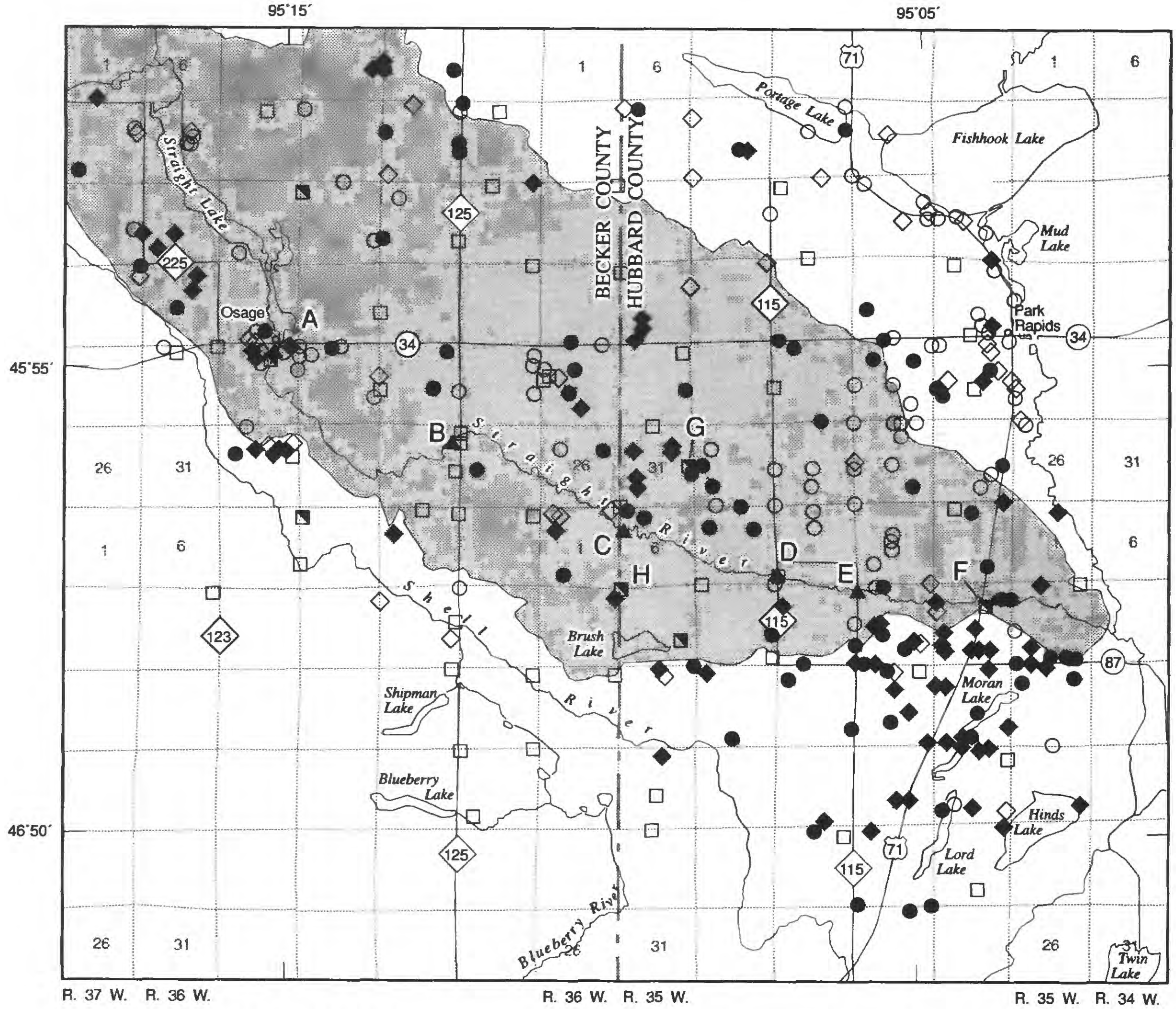


Figure 4.--Location of irrigation wells and municipal-well field in the investigation area.



Base from U.S. Geological Survey digital data, 1:100,000, 1986, Universal Transverse Mercator Projection, Zone 15

0 1 2 MILES

0 1 2 KILOMETERS

EXPLANATION

Straight River Basin

Wells completed in surficial aquifer indicated by open symbol
Wells completed in uppermost confined-drift aquifer indicated by solid symbol
Letter refers to local name of recording site

- □ U.S. Geological Survey well
- ◪ Nested U.S. Geological Survey wells
- ● ○ Domestic or irrigation well
- ◆ ◇ Test well
- ▲ Surface-water gage

Figure 5.--Hydrologic data-collection sites in the Straight River investigation area.

hydrologic properties of the surficial and uppermost confined-drift aquifers and of the uppermost confining unit. Several synoptic measurements of water levels in wells were made during the investigation. These data were used to prepare maps showing position of the water table in the surficial aquifer, and the potentiometric surface of the uppermost confined-drift aquifer.

Ground-water-level and temperature data were measured in nested wells with electronic data loggers, which were installed at different depths (fig. 5). The locations of these nested wells were selected to represent irrigated (site G) and nonirrigated (site H) parts of the watershed, and to monitor ground-water conditions near the stream (sites A, B, D, and F).

Average values of transmissivity of the surficial aquifer were determined by Helgesen (1977). Average values of transmissivity for the aquifer were estimated by multiplying the estimated-average value of horizontal hydraulic conductivity at a site by the thickness of the aquifer at that location. The method was assumed reasonable because the aquifer materials in the investigation were relatively homogeneous. Vertical hydraulic conductivity of the uppermost confining unit was estimated from a finite-difference ground-water-flow model by simulating vertical hydraulic-head differences across the confining units. Transmissivity of the uppermost confined-drift aquifer was estimated from ground-water-flow model analyses.

Ground-water withdrawal data were obtained from the Minnesota Water-Use-Data System at the MDNR. These data were verified by spot checks during the summer of 1988 at approximately 40 locations using a noninvasive flow meter. Water-use data for 1988 were used to represent ground-water withdrawals for model simulations.

A three-dimensional, finite-difference, ground-water-flow model (McDonald and Harbaugh, 1988) was used to better understand the ground-water flow system, hydrologic budgets, hydraulic properties of hydrogeologic units, and the interactions between the stream and aquifer systems. The model was calibrated to steady-state conditions based on hydrologic data (potentiometric surfaces and streamflow) collected during this investigation. The model also was used to examine the effect of irrigation on regional ground-water levels and stream discharge.

Water from the drift aquifers and from the Straight River was analyzed for major chemical constituents and nutrients to provide baseline water-quality data for use in future assessments and to identify trends caused by land-use practices. Water was collected from 17 wells screened in the surficial aquifer and from 5 wells screened in the uppermost confined-drift aquifer. Grab samples were collected from 4 sites along the Straight River during the summer of 1988.

A stream-temperature and transport model of the Straight River (Jobson, 1975, 1979, 1980a, 1980b, and Schoellhamer and Jobson, 1986) was used to simulate temperature conditions in the stream and the effect of changes in ground-water discharge to the stream on stream temperature. The model simulated steady-flow conditions of the stream similar to those during the summer of 1988.

Test-Hole and Well-Numbering System

Two systems of numbering wells and test holes were used for this investigation. The first system used was the MGS Minnesota unique-well number system that associates a well with Universal Transverse Mercator coordinates. The second system of numbering is based on the U.S. Bureau of Land Management's system of land subdivision (township, range, and section). Figure 6 illustrates this numbering system. The first numeral of a test-hole or well number indicates the township, the second the range, and the third the section in which the point is located. Uppercase letters after the section number indicate the location within the section; the first letter denotes the 160-acre tract, the second the 40-acre tract, and the third the 10-acre tract. The letters A, B, C, and D are assigned in a counterclockwise direction, beginning in the northeast corner of each tract. The number of uppercase letters indicates the accuracy of the location number. For example, the number 140N.36W.22ADC indicates a test hole or well located in the SW1/4, SE1/4, NE1/4, Sec. 22, T.140 N., R.36 W.

Acknowledgments

The authors are grateful to well owners, well drillers, and State and local agencies for data used in preparing this report. Thanks also go to land owners who permitted test holes to be drilled and observation wells to be installed, and to well owners who permitted their wells to be sampled and measured. Special thanks are extended to Bill Alden, Hubbard County Soil and Water Conservation District, and to Bob Merritt, MDNR, Detroit Lakes, for their coordination of the investigation at the local level, and to Jerry Johnson, MDNR, St. Paul, for his help in preparation of the report figures.

Surface Water

The Straight River flows approximately 19 mi from its source in Becker County to its mouth in Hubbard County where it discharges to the Fishhook River (fig. 1). The

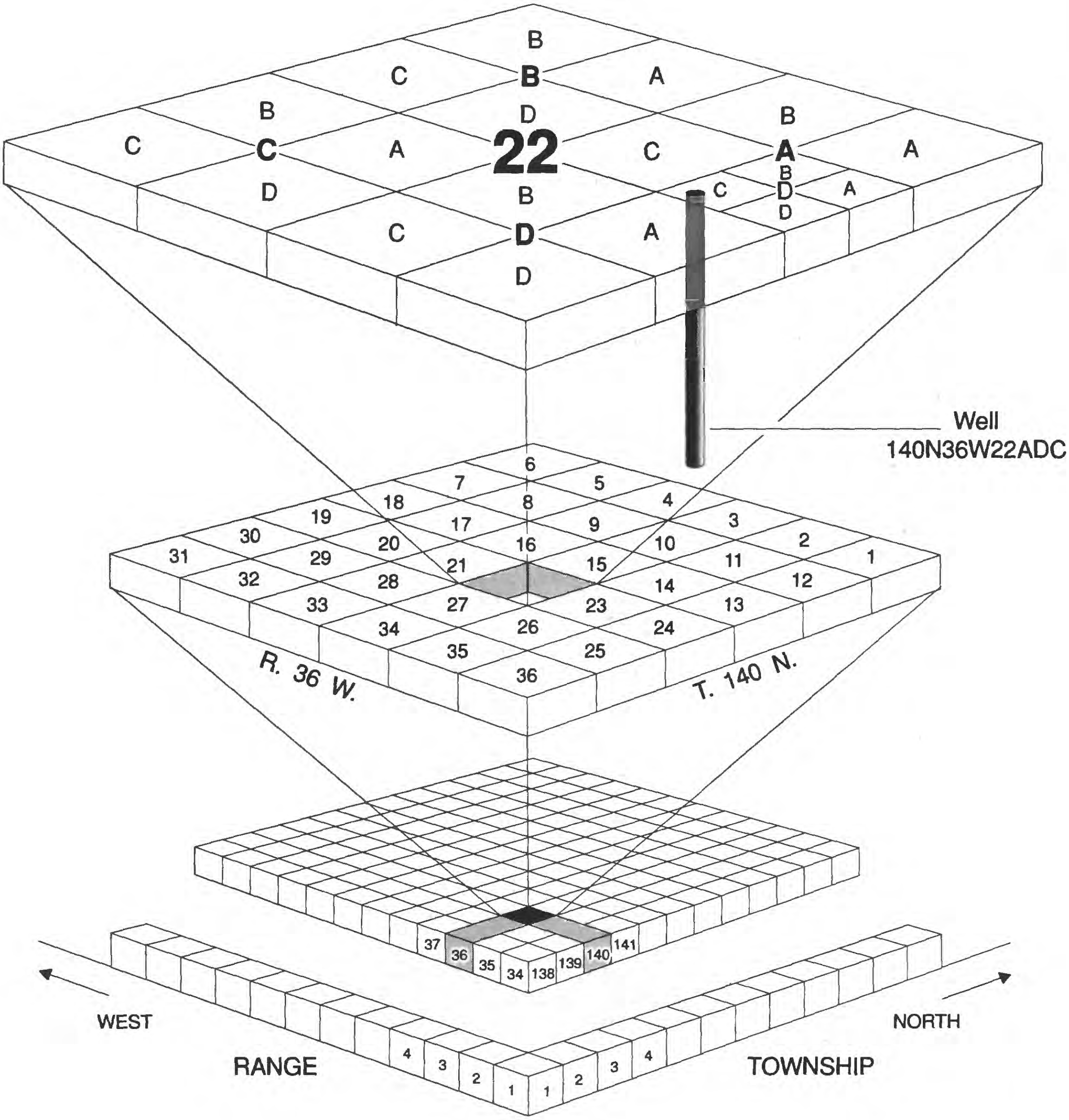


Figure 6.--Test hole and well-numbering system.

area of the watershed is about 75 mi^2. A dam at the outlet of Straight Lake, near Osage (fig. 1), controls the discharge of the stream. Average daily discharge increases from about 25 ft^3/s (cubic feet per second) at site A, near the outlet of Straight Lake, to about 51 ft^3/s at site F, at U.S. Highway 71, near the mouth. There are no perennial tributaries to the stream between Osage and the stream's mouth. Most gain in discharge is ground-water seepage from drift aquifers. Discharge is relatively uniform and does not significantly vary by season or in response to short-term dry or wet periods.

Flow Characteristics

Stream discharge is an indicator of climatic and human-caused variability because discharge is the residual of precipitation after the demands for evapotranspiration and water use are met. Because losses from evapotranspiration are fairly constant from year to year in a given area, variations in annual discharge are greater, as a percentage, than variations in annual precipitation (Searcy and Hardison, 1960).

Stage-discharge relations were established at the gaging stations on the stream for October 1987 through September 1988. During this period stream discharge was measured approximately monthly. Records of daily mean discharge were computed for the permanent-record gaging stations at sites B, D, and F (Gunard & others, 1990). Table 1 is a summary of monthly mean discharge at these stations.

Stream discharge hydrographs reflect three different types of contributions of water from a watershed to a stream. These are from (1) overland flow to the stream, (2) direct channel precipitation, and (3) subsurface flow. Peak discharges result from fast response due to overland flow and direct channel precipitation.

April through August discharge for the 1988 water year may have been below normal based on long-term precipitation data. Although annual precipitation for 1988 (26.32 in.), measured at the Park Rapids weather station, was near the mean of 26 in. (Baker and Kuehnast, 1978), precipitation during April, May, June, and July of 1988 was 4.21 in. less than average.

The total amount of water measured in the Straight River during the 1988 water year at U.S. Highway 71 (site F) was 1,615,000,000 ft^3 (cubic feet) (Gunard and others, 1990). Measured discharges at sites B and D were 1,157,000,000 and 1,460,000,000 ft^3, respectively. Monthly mean discharge ranged from 36.6 ft^3/s at site B to 51.1 ft^3/s at site F. These data indicate that stream discharge increased in a downstream direction during most of the year.

Discharge data from the three permanent-record stations indicate a general increase of 14.5 ft^3/s between sites B and F during the 1988 water year (table 1). The average increase in discharge between sites B and D is 9.6 ft^3/s; between sites D and F it is 4.9 ft^3/s (Gunard and others, 1990).

Monthly mean discharge data (Gunard and others, 1990) also indicate that stream discharge increased downstream throughout the water year. The gain between sites D and F was smaller than the gain between sites B and D. Daily-stream discharge data indicate that there were periods during 1988 when daily stream discharge at site D exceeded discharge at site F. This indicates that, during these periods the downstream reaches of Straight River were losing water to the aquifer system. The rate of gain in streamflow is less in June to August than in December to February, which may indicate an effect from irrigation withdrawals, evapotranspiration, or both.

Daily fluctuation in stream discharge

Daily fluctuation in stream discharge were measured during the summer. Similar fluctuations in streams in sand-plain areas in Wisconsin were attributed to evapotranspiration by phreatophytes growing in the stream (Weeks and others, 1965). The maximum discharge during the day in the Straight River generally occurs around noon and the minimum generally occurs around midnight. Daily fluctuation begins during May,

Table 1.--Monthly mean stream discharge of Straight River at continuous-record stations, Becker and Hubbard Counties, Minnesota, during 1988 water year (in cubic feet per second)

Station name and number	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Average monthly mean
05243721 (site B) Straight River at Becker County Road 125 near Osage	37.5	39.7	38.2	37.5	34.6	38.2	43.5	39.7	33.0	26.2	35.9	35.2	36.6
05243723 (site D) Straight River at Hubbard County Road 115 near Park Rapids	49.5	50.2	48.7	40.1	42.2	50.0	58.8	44.3	44.8	35.8	41.6	48.3	46.2
05243725 (site F) Straight River at State Highway 71 near Park Rapids	54.4	54.8	51.0	43.1	49.1	61.3	62.0	55.5	46.3	39.5	47.8	48.2	51.1

gradually increases to a maximum during July and August, and then decreases until it stops during October The fluctuation was most conspicuous when base-flow conditions prevail. At site F, the daily change in stage frequently was as great as 0.2 ft, corresponding to a change in stream discharge of about 10 ft^3/s. Daily fluctuation in discharge may be due to reduced ground-water inflow, evapotranspiration, or a combination of these processes.

Low flow

Low flow in the Straight River occurred in two distinct periods during water year 1988. The first period was during the winter, when most of the precipitation was stored as snow. The second period was during late summer, when evapotranspiration losses were high and there was little recharge to the ground-water reservoir.

Precipitation during April through July of 1988 was 4.21 in. below the average rate of precipitation for that period at Park Rapids, Minnesota. Stream discharge was significantly below normal in other streams in central Minnesota, according to long-term stream discharge records. From these data and the general widespread drought across Minnesota during 1988, it was assumed that flow in the Straight River approached record lows during 1988. The minimum daily mean discharges recorded at the three permanent-record stations on the Straight River were 23, 27, and 33 ft^3/s (Gunard and others, 1990), which occurred on July 23, 1988 (site B), July 29 and 30, 1988 (site D), and July 23 and 27, 1988 (site F), respectively. Recurrence intervals cannot be assigned to these low-flow stream discharges because of the short period of record available at the sites.

High flow

Flooding seldom is a problem along the Straight River because of the highly permeable soil. Maximum annual discharge peaks for streams in the area occur during the spring when the infiltration capacity of the soil is low because frost and surface runoff is greater than during summer. The maximum instantaneous flow recorded during the 1988 water year was 71 ft^3/s (site F) on March 24 (Gunard and others, 1990). Recurrence intervals cannot be assigned to high-flow stream discharges because of the short period of record for the stations. Peak stream discharge measured on the Straight River during the 1988 water year did not approach normal peaks because of the drought conditions.

Flow duration

Flow-duration curves (Searcy, 1959) are cumulative-frequency curves that show the percent of time during which specified stream discharges are equaled or exceeded in a specific period. The curves represent stream-discharge data across a range of stream discharge. Although flow-duration curves do not show the chronological sequence of stream discharge, they are useful in describing the stream discharge characteristics.

The shape of flow-duration curves is determined by hydrologic and geologic characteristics of a watershed. The curves may be used to characterize streamflow of a watershed and to compare the characteristics of different watersheds. A curve with a steep slope indicates a highly variable stream where flow is largely from direct runoff. A curve with a gentle slope indicates a stream that is less responsive to precipitation than a stream where flow is largely from runoff and indicates that the stream dominated by base flow from either ground-water discharge or surface storage. The slope of the lower end of the duration curve indicates the characteristics of the perennial storage (such as lakes or wetlands) in the watershed.

Flow-duration curves were prepared from stream-discharge for data at sites B,D, and F (fig. 7). These curves represent data for water year 1988 and are based on daily mean discharge. Flow duration curves computed from one year of stream-discharge records may not be representative of normal conditions, however, they are useful to show the general flow characteristics of the stream. For example, during the 1988 water year the daily mean discharge of the midstream station (site D) was at least 50 ft^3/s during nearly 50 percent of the year.

The curves from all stations have small slopes, which indicates that the stream was dominated by base flow. The stream did not respond quickly to drought. The stream also did not respond quickly to precipitation. The discharge gain between sites B and D was greater than the increase between sites D and F (fig. 7). The duration curves also indicate that stream discharge was relatively uniform throughout the year. For example, stream discharge at site F varied only from 45-60 ft^3/s for 60 percent of the time during water year 1988.

Flow-duration data also indicate that discharge at site B was influenced by surface runoff to a greater degree than at stations further downstream. The slope of the flow-duration curve decreases more abruptly for flows that were exceeded 13 percent of the time for this site.

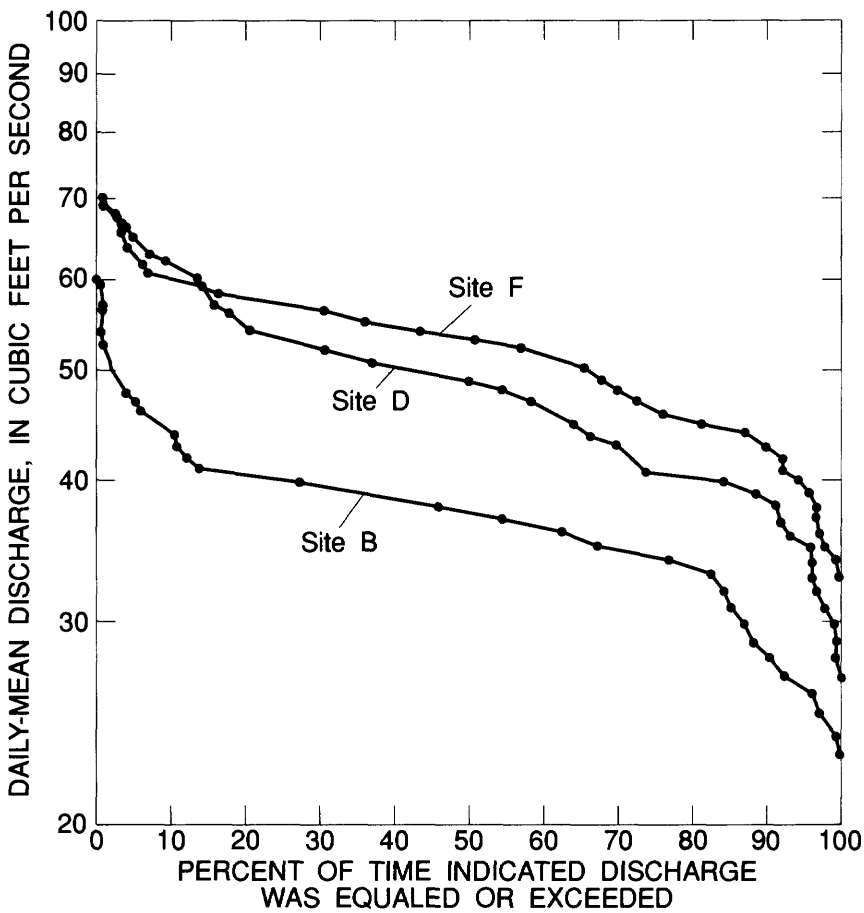


Figure 7.--Flow-duration curves for continuous-record stations on the Straight River during the 1988 water year.

The other stations were not influenced to the same extent by surface runoff, indicating a general lack of surface runoff from the watershed downstream from site B.

Cumulative stream discharge curves are another method to examine stream- discharge data (Searcy and Hardison, 1960). These curves, which plot cumulative-daily stream discharge and time, were prepared for the 1988 water year for the three permanent-record stations (fig. 8). The curves allow inspection of changes and trends in discharge for the 1988 water year. A cumulative stream-discharge curve, for discharge evenly divided throughout the year, will plot asa line with a constant slope. For the period May through September 1988, the curves depart from linearity with slopes decreasing with time; this indicates that stream discharge for the stations declined during this part of the 1988 water year.

Water Quality

General chemical quality

Chemical constituents in water from the Straight River were determined by analysis of four grab samples collected at four sites on the stream, data collected during a previous investigation that included a sampling site near the headwaters of the Straight River (Ruhl, 1989), and data from a previous investigation by the Minnesota Pollution Control Agency (MPCA) (Willard Mattson, Minnesota Pollution Control Agency, written commun., 1989). The results of these individual chemical analyses are shown in table 2.

The pH (a measure of relative acidity) of water in the Straight River is suitable for aquatic life. The Straight River is alkaline, with pH values generally greater that 8.0, probably relating to an abundance of carbonate-rich minerals in the glacial deposits within the watershed. A

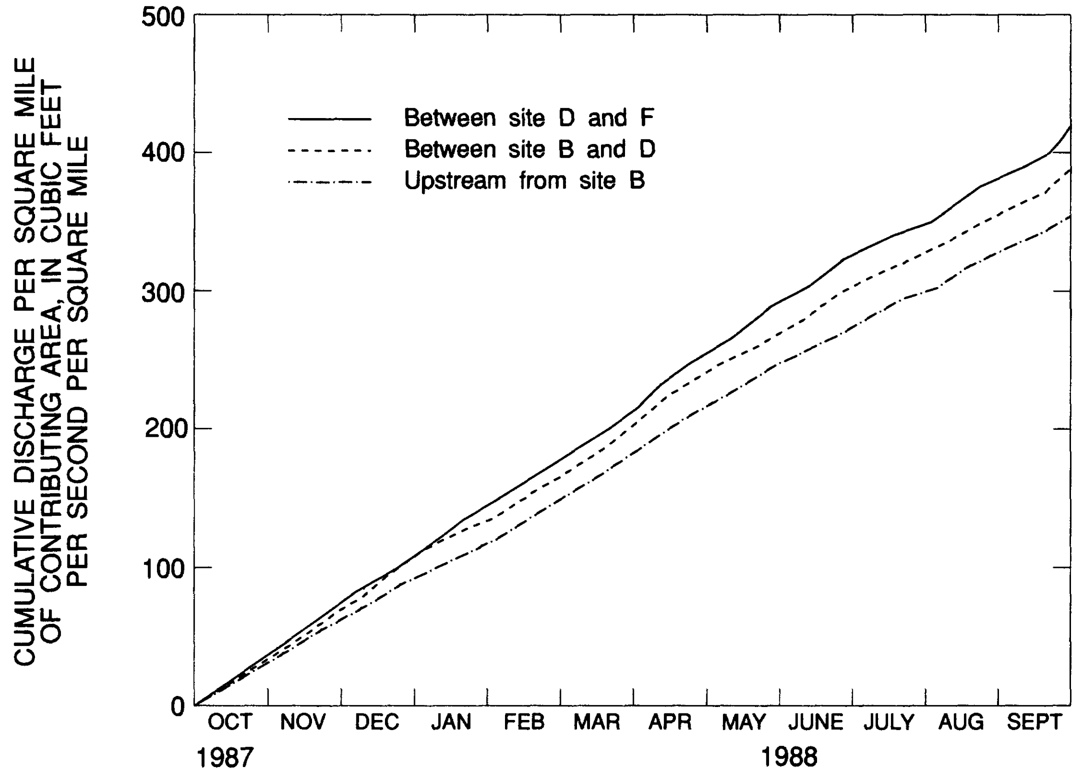


Figure 8.--Cumulative discharge of Straight River at continuous-record stations (sites B, D, and F) during the 1988 water year.

pH range from 6.5 to 9.0 generally is suitable for fish, although the toxicity of some compounds may be effected by the pH of water (U.S. Environmental Protection Agency, 1986). The pH of water in the stream tends to be within limits for aquatic life and wildlife, and generally is within the range of 7.7 to 8.6 (tab. 2). With certain pH conditions, some compounds may become more toxic and some environmentally harmful metals attached to or contained in bottom sediments of lakes and suspended materials in streams may become more soluble in water (U.S. Environmental Protection Agency, 1986).

Predominant chemical constituents in water from the stream are calcium and bicarbonate. The concentrations of major ions in the stream are similar at all sampling sites. The chemical concentrations and physical properties generally meet criteria established by the MPCA (1988) and the Minnesota Department of Health and Minnesota Department of Agriculture (1988) and are suitable for aquatic life, agriculture, wildlife, and domestic consumption. The concentrations of major ions and other properties also are within the recommended limits proposed by the U.S. Environmental Protection Agency (USEPA) for aquatic habitat (U.S. Environmental Protection Agency, 1986).

Nutrient loading can degrade the water quality of streams if high enough concentrations are present to support abundant growth of algae. Nutrient enrichment of streams can occur because of human activities, such as the use of fertilizer that contains nitrogen and phosphorus compounds, and direct discharge of sewage into streams. In general, the level of nitrate nitrogen (nitrite plus nitrate as N) in the Straight River is low.

Triazine-group herbicides were generally not detected in water from the Straight River (tab. 2). Water from one sample (05243720-site A) contained detectable levels of atrazine and cyanazine. This concentration was not confirmed in subsequent samplings.

Temperature

The temperature in a reach of a stream is affected by net solar radiation to and evapotranspiration from the open water surface, heat added to or lost from the stream by conduction and convection with the air, conduction to the earth, temperature and volume of surface water flowing into and out of the reach, and temperature and volume of ground water flowing into or out of the reach. Net radiation and evapotranspiration depend on the area and

Table 2.--Chemical and physical characteristics of water from Straight River

[mg/L, milligrams per liter; µg/L, micrograms per liter; µS/cm microsiemens per centimeter at 25 degrees Celsius; --, not determined; <, less than; IT, iterated titration; FET, fixed endpoint titration; field, value determined at sampling site; lab, value determined in a laboratory]

Station name	Station number	Date	Specific conductance Celsius (µS/cm)	Specific conductance lab (µS/cm)	pH (standard units)	pH, lab (standard units)	Water temperature (degrees Celsius)	Calcium, dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as Mg)
Straight River at Osage, Minnesota (site A)	05243720	05-23-88	353	389	8.4	8.2	19.5	50	20
		08-24-88	300	312	--	8.2	23.0	31	20
Straight River at Becker County Road 125, near Osage, Minnesota (site B)	05243721	05-23-88	393	427	8.0	8.1	22.0	57	21
		08-24-88	--	363	--	8.6	22.0	44	21
Straight River at Becker County Road 115, near Park Rapids, Minnesota (site D)	05243723	05-24-88	440	440	--	8.5	--	60	21
		08-24-88	--	--	--	8.3	23.0	50	21
Straight River at Minnesota Highway 71, near Park Rapids, Minnesota (site F)	05243725	05-24-88	452	452	8.2	8.4	15.0	62	21
		08-25-88	406	406	--	8.5	17.0	53	21
Straight River near Osage, Minnesota	465858-[1]095170801	05-22-84	398	387	--	--	17.0	54	13
Straight River at Becker County Highway [2]135		09-16-80	415	--	7.7	--	8.0	--	--
Straight River at Osage, Minnesota[2]		09-16-80	311	--	8.1	--	14.0	--	--
Straight River at Hubbard County Highway [2]117		09-16-80	317	--	8.0	--	11.0	--	--
Straight River at Minnesota Highway [2]71		09-16-80	372	--	8.3	--	11.0	--	--

Table 2.--Chemical and physical characteristics of water from Straight River--Continued

Station name	Station number	Date	Sodium dissolved (mg/L as Na)	Potassium, dissolved (mg/L as K)	Bicarbonate IT, field (mg/L)	Alkalinity, total field (mg/L as $CaCO_3$)	Alkalinity, lab (mg/L as $CaCO_3$)	Sulfate, dissolved (mg/L as SO_4)	Chloride, dissolved (mg/L as Cl)
Straight River at Osage, Minnesota	05243720	05-23-88	3.3	1.5	232	190	190	8.2	4.2
		08-24-88	3.2	1.3	--	--	--	7.2	4.7
Straight River at Becker County Road 125, near Osage, Minnesota	05243721	05-23-88	4.8	1.5	246	200	200	7.7	4.2
		08-24-88	4.2	1.4	--	--	--	6.4	4.6
Straight River at Becker County Road 115, near Park Rapids, Minnesota	05243723	05-24-88	4.4	1.3	--	--	--	9.5	7.1
		08-24-88	4.1	1.3	--	--	--	7.5	6.9
Straight River at Minnesota Highway 71, near Park Rapids, Minnesota	05243725	05-24-88	5.0	1.3	270	220	220	10	7.2
		08-25-88	3.9	1.3	--	--	--	8.5	7.2
Straight River near Osage, Minnesota	465858-[1]095170801	05-22-84	--	1.2	--	--	220	3.1	2.8
Straight River at Becker County Highway [2]135		09-16-80	--	--	--	240	--	--	--
Straight River at Osage		09-16-80	--	--	--	170	--	--	--
Straight River at Hubbard County Highway [2]117		09-16-80	320	8.0	--	220	--	--	--
Straight River at Minnesota Highway [2]71		09-16-80	--	--	--	200	--	--	--

Table 2.--Chemical and physical characteristics of water from Straight River--Continued

Station name	Station number	Date	Fluoride, dissolved (mg/L as F)	Silica, dissolved (mg/L as SiO_2)	Nitrite plus nitrate, dissolved (mg/L as N)	Iron, dissolved (µg/L as Fe)	Alachlor, total recoverable (µg/L)	Ametryne, total (µg/L)
Straight River at Osage, Minnesota	05243720	05-23-88	0.2	9.9	0.38	3	<0.10	<0.10
		08-24-88	.1	14	<.10	--	<.10	<.10
Straight River at Becker County Road 125, near Osage, Minnesota	05243721	05-23-88	.2	13	.45	<3	<.10	<.10
		08-24-88	.1	14	.25	--	<.10	<.10
Straight River at Becker County Road 115, near Park Rapids, Minnesota	05243723	05-24-88	.2	12	1.9	<3	<.10	<.10
		08-24-88	.1	14	1.1	--	<.10	<.10
Straight River at Minnesota Highway 71, near Park Rapids, Minnesota	05243725	05-24-88	.2	12	2.10	<3	<.10	<.10
		08-25-88	.1	14	1.60	--	<.10	<.10
Straight River near Osage, Minnesota	465858-[1]095170801	05-22-84	--	--	.53	30	--	--
Straight River at Becker County Highway [2]135		09-16-80	--	--	.25	--	--	--
Straight River at Osage, Minnesota		09-16-80	--	--	<.01	--	--	--
Straight River at Hubbard County Highway [2]117		09-16-80	--	--	.39	--	--	--
Straight River at Minnesota Highway [2]71		09-16-80	--	--	.69	--	--	--

Table 2.--Chemical and physical characteristics of water from Straight River--Continued

Station name	Station number	Date	Atrazine, total (µg/L)	Cyanzine total (µg/L)	Metolachlor, total recoverable (µg/L)	Metribuzin, total recoverable (µg/L)	Prometone, total (µg/L)	Prometyrne, recoverable (µg/L)
Straight River at Osage, Minnesota	05243720	05-23-88	0.10	0.10	<0.10	<0.10	<0.10	<0.10
		08-24-88	<.10	<.10	<.10	<.10	<.10	<.10
Straight River at Becker County Road 125, near Osage, Minnesota	05243721	05-23-88	<.10	<.10	<.10	<.10	<.10	<.10
		08-24-88	<.10	<.10	<.10	<.10	<.10	<.10
Straight River at Becker County Road 115, near Park Rapids, Minnesota	05243723	05-24-88	<.10	<.10	<.10	<.10	<.10	<.10
		08-24-88	<.10	<.10	<.10	<.10	<.10	<.10
Straight River at Minnesota Highway 71, near Park Rapids, Minnesota	05243725	05-24-88	<.10	<.10	<.10	<.10	<.10	<.10
		08-25-88	<.10	<.10	<.10	<.10	<.10	<.10
Straight River near Osage, Minnesota	465858-[1]095170801	05-22-84	--	--	--	--	--	--

Table 2.--Chemical and physical characteristics of water from Straight River--Continued

Station name	Station number	Date	Propazine (µg/L)	Simazine, total (µg/L)	Simetryne, total (µg/L)	Trifluralin, total (µg/L)
Straight River at Osage, Minnesota	05243720	05-23-88	<0.10	<0.10	<0.10	<0.10
		08-24-88	<.10	<.10	<.10	<.10
Straight River at Becker County Road 125, near Osage, Minnesota	05243721	05-23-88	<.10	<.10	<.10	<.10
		08-24-88	<.10	<.10	<.10	<.10
Straight River at Becker County Road 115, near Park Rapids, Minnesota	05243723	05-24-88	<.10	<.10	<.10	<.10
		08-24-88	--	--	--	--
Straight River at Minnesota Highway 71, near Park Rapids, Minnesota	05243725	05-24-88	<.10	<.10	<.10	<.10
		08-25-88	<.10	<.10	<.10	<.10
Straight River near Osage, Minnesota	465858-[1]095170801	05-22-84	--	--	--	--

[1] Data from Ruhl (1989)
[2] Data from Willis Mattson (MPCA, written commun., 1989)

residence time of open water, and on the type and extent of vegetation along the stream. Net incoming radiation also is significantly affected by cloud cover.

Stream temperatures were measured continuously during May 1988 through August 1989 at four sites (A, B, D, and F). Representative results are shown for site B on figure 9. This figure also summarizes air temperature, stream and ground-water temperature, and the relation between hydraulic head in the stream and in wells screened at different depths near the stream. These data generally are representative of conditions at other sites where data were collected.

Air temperature during the period ranged from a high of about 40°C to a low of about -35°C. Daily fluctuations in air temperature averaged about 25°C. The magnitude of daily and seasonal stream-temperature fluctuations were not as great as temperature fluctuations of air. Stream-water temperature ranged from a high of about 28°C in summer to a low of about 0°C in winter. Daily fluctuations in stream temperature were about 15°C in summer. In winter, while the stream is ice-covered, the water temperature remained at about 0°C. Figures 10 and 11 illustrate the variability in stream temperature at sites A and F during January 1989, and sites A and B during July 1988. Figure 12 illustrates the variability in stream temperature at sites A, B, D, and F during July 1988. The stabilizing effect of the release of water at Straight Lake is shown at site A in figure 12.

Daily variability in stream-water quality

On July 12 and 13, 1988 measurements of pH, air temperature, water temperature, and dissolved oxygen were made at about one-hour intervals at several locations on the stream. Figure 13 illustrates daily changes in these field measurements at sites A and F. The graph of site F is similar to data collected from sites B and D during this period. Data from site A is significantly different from the others because it is influenced by the reservoir at the outlet of Straight Lake.

The plot of temperature data from site F shows daily fluctuations caused by solar radiation, evaporation, and contact with warm air. The stream reaches its warmest temperature at about 1700 hours. After this maximum, the water becomes cooler as it loses heat to the atmosphere by radiation until about 0800 hours, when the daily cycle is repeated.

The graph of dissolved oxygen concentrations and pH also show daily fluctuations. These fluctuations are influenced by alternating photosynthesis and respiration of aquatic plants. Dissolved oxygen and pH reach their maximums shortly after solar radiation reaches its maximum and oxygen from photosynthesis has accumulated. Minimum values of dissolved oxygen and pH were measured at about sunrise, when respiration has utilized the maximum amount of accumulated oxygen.

Figure 14 illustrates data obtained at 2-hour intervals at sites A, B, D, and F. Little of the variation in stream temperature and dissolved oxygen exhibited at the other sites is evident at site A because of the moderating affect of the reservoir. Figure 14 also shows the downstream daily changes in stream temperature and dissolved oxygen at sites A, B, D, and F during July 12-13, 1988, and illustrates that temperature and dissolved oxygen of water at sites B, D, and F have similar trends, but vary in magnitude among sites.

Water Quality and Quantity for Trout Habitat

Trout generally need water of better quality than is needed for most fish. Brook trout *(Salvelinus fontinalis* Mitchill*)* are not found in the Straight River, but were common in the stream as late as the 1940's (Dennis Ernst, Minnesota Department of Natural Resources, written commun., 1990). Brook trout require clear, cold waters with a silt-free, rocky substrate (Raleigh, 1982), and do not thrive where the water temperatures exceed 20°C for extended periods. Brook trout are tolerant of stream pH conditions from 3.5 to 9.8 and to a wide range of alkalinity and specific conductance. Optimum oxygen levels for brook trout are greater than 7 mg/L at temperatures less than 15°C, and greater than 9 mg/L at temperatures greater than 15°C (Raleigh, 1982).

Stream temperature appears to be a limiting variable for trout in the Straight River. The stream probably is now too warm for the reproduction of brook trout, and may be near the upper limit for the maintenance of brown trout. Reduction in stream discharge also could degrade the habitat for trout in summer, further reducing the population of trout in the stream (Dennis Ernst, oral commun., 1990). Stream habitat for trout does not seem to be limited with respect to dissolved oxygen, even during summer.

Ground Water

Glacial deposits were divided into the following four hydrogeologic units for this investigation (fig. 2): (1) sand and gravel (outwash) deposits at or near land surface (surficial aquifer), (2) till and lake deposits (confining units) that separate the uppermost confined-drift aquifer and the overlying surficial aquifer, (3) buried sand and gravel deposits (uppermost confined-drift aquifer), and (4) glacial till or lake deposits exposed at land surface.

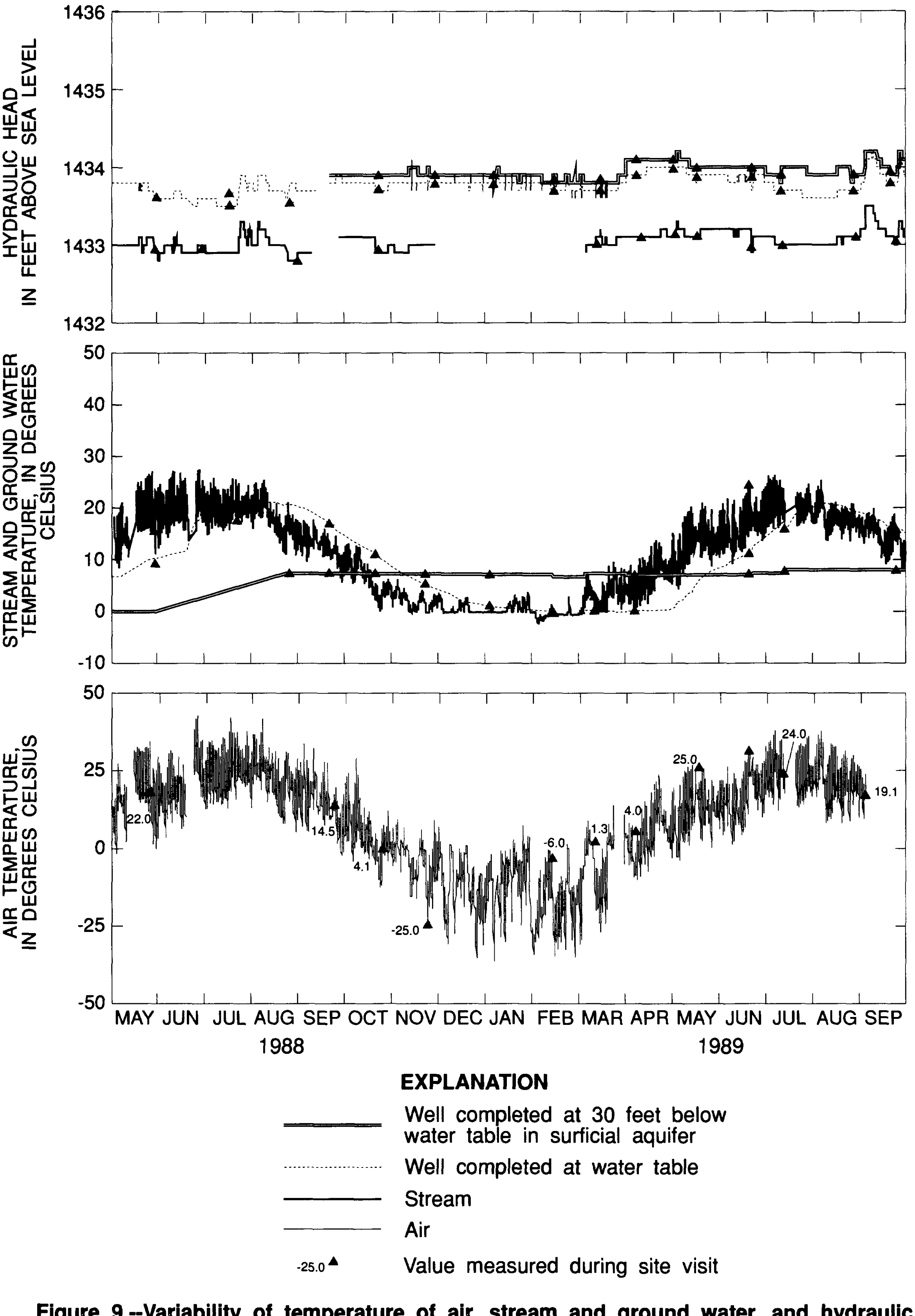


Figure 9.--Variability of temperature of air, stream and ground water, and hydraulic head of ground water and of the Straight River at Becker County Road 125 (site B), May 1988 through August 1989.

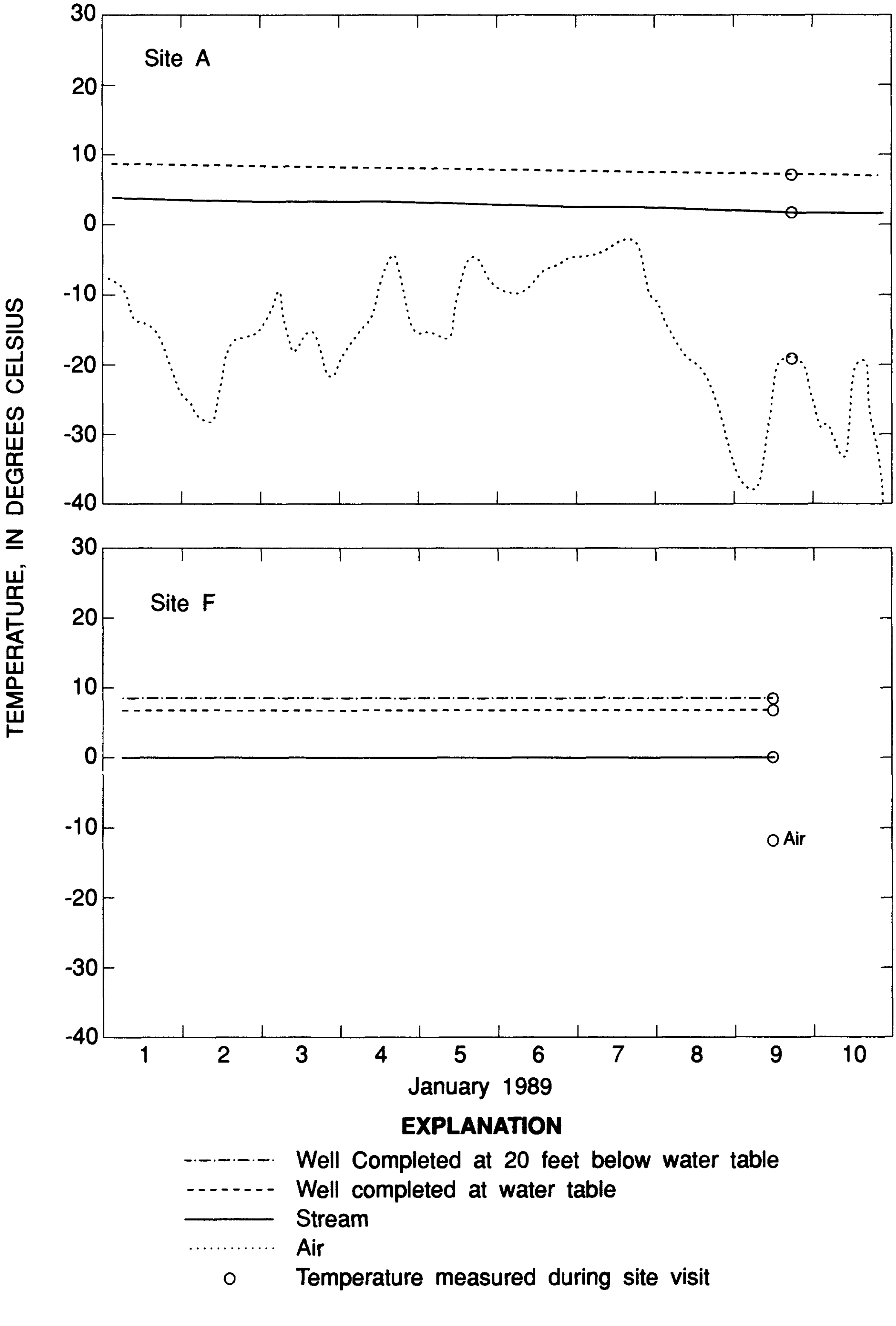


Figure 10.--Variability of air, stream, and ground-water temperature at Osage, Minnesota (site A) and at U.S. Highway 71 near Park Rapids, Minnesota (site F) during January 1989.

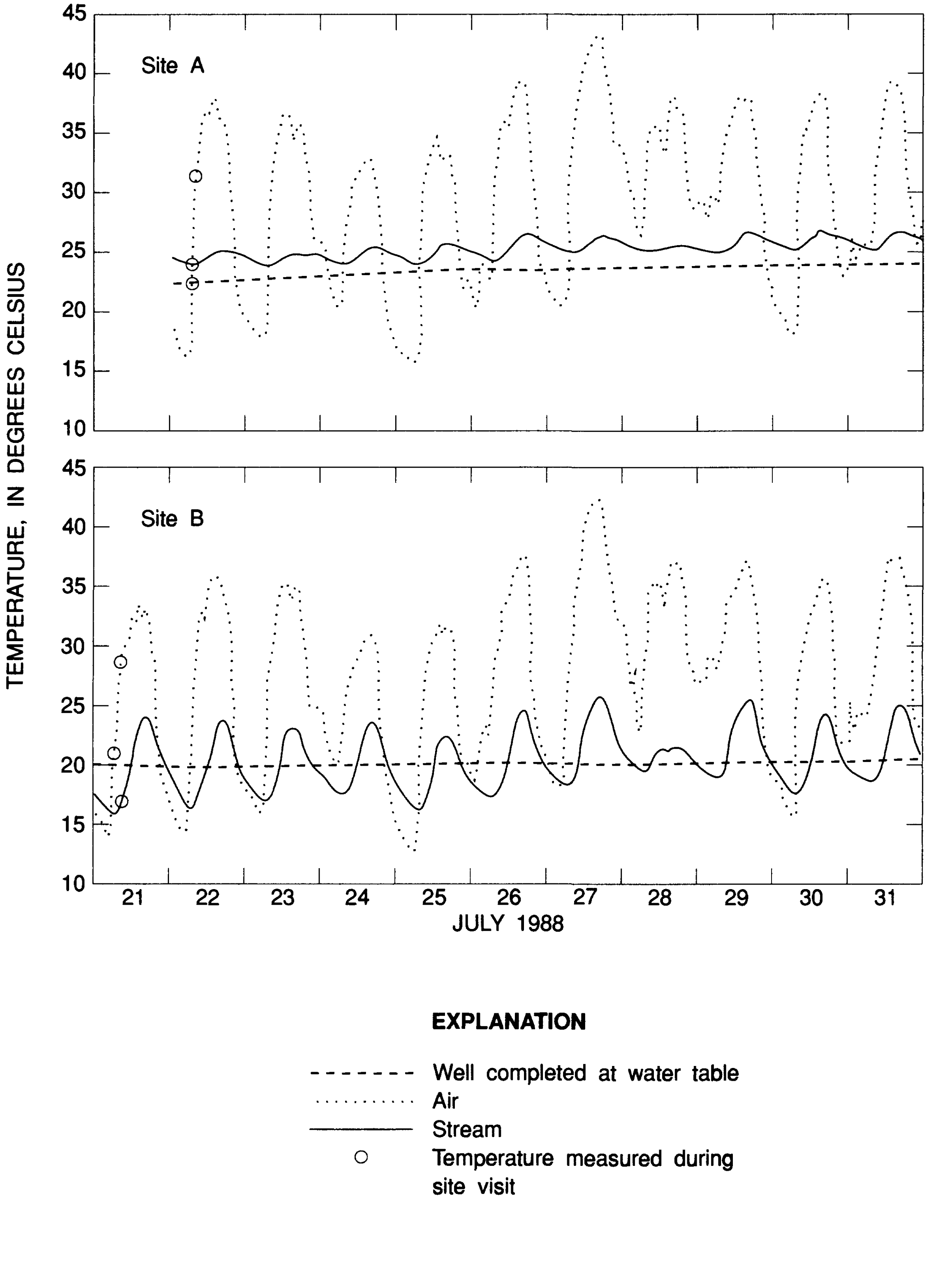
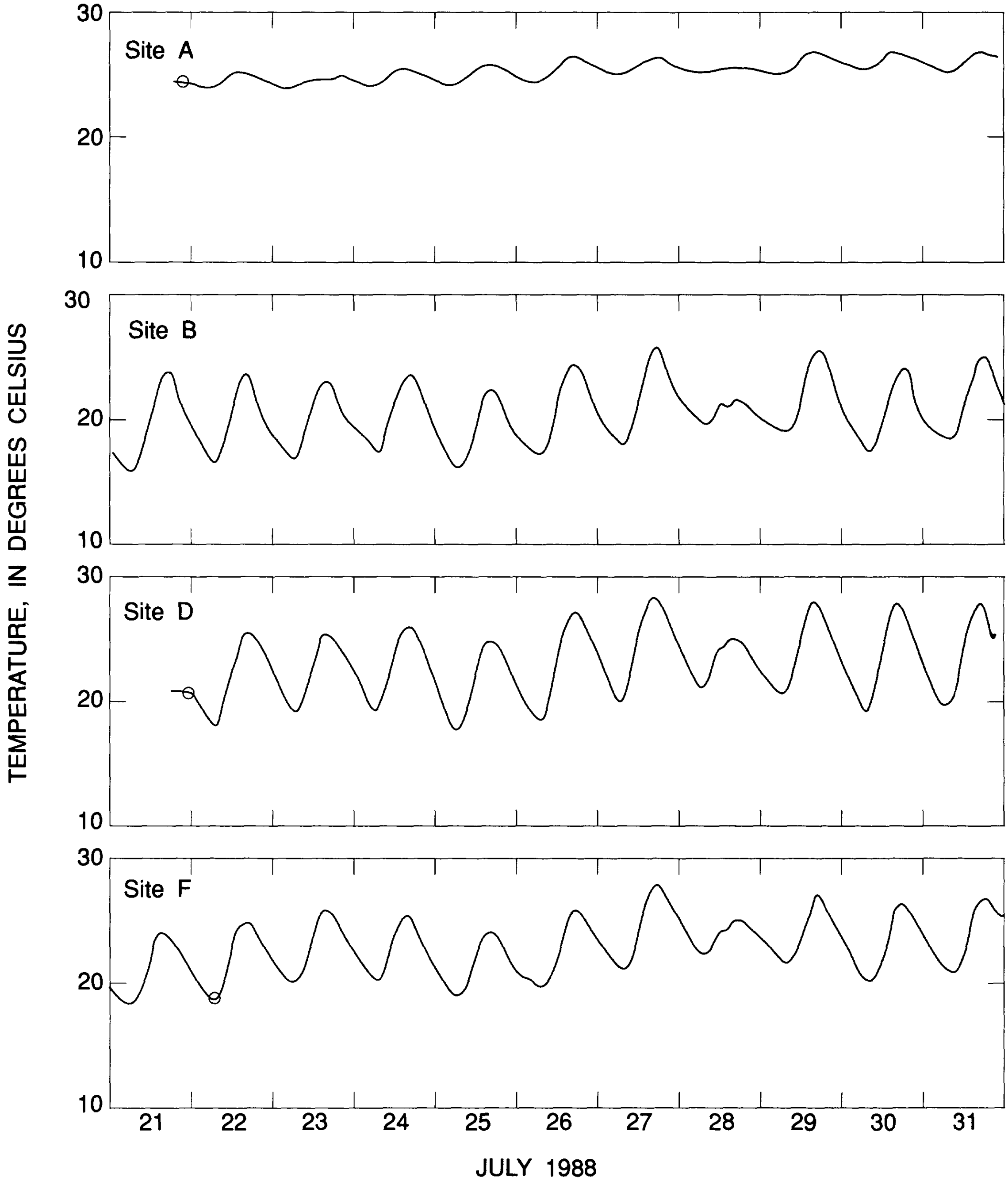


Figure 11.--Variability of air, stream, and ground-water temperature at Osage, Minnesota (site A), and at Becker County Road 125 near Osage, Minnesota (site B) during July 1988.



EXPLANATION

—o— Temperature measured during site visit

Figure 12.--Variability of stream temperature in Straight River (sites A, B, D, and F) during July 1988.

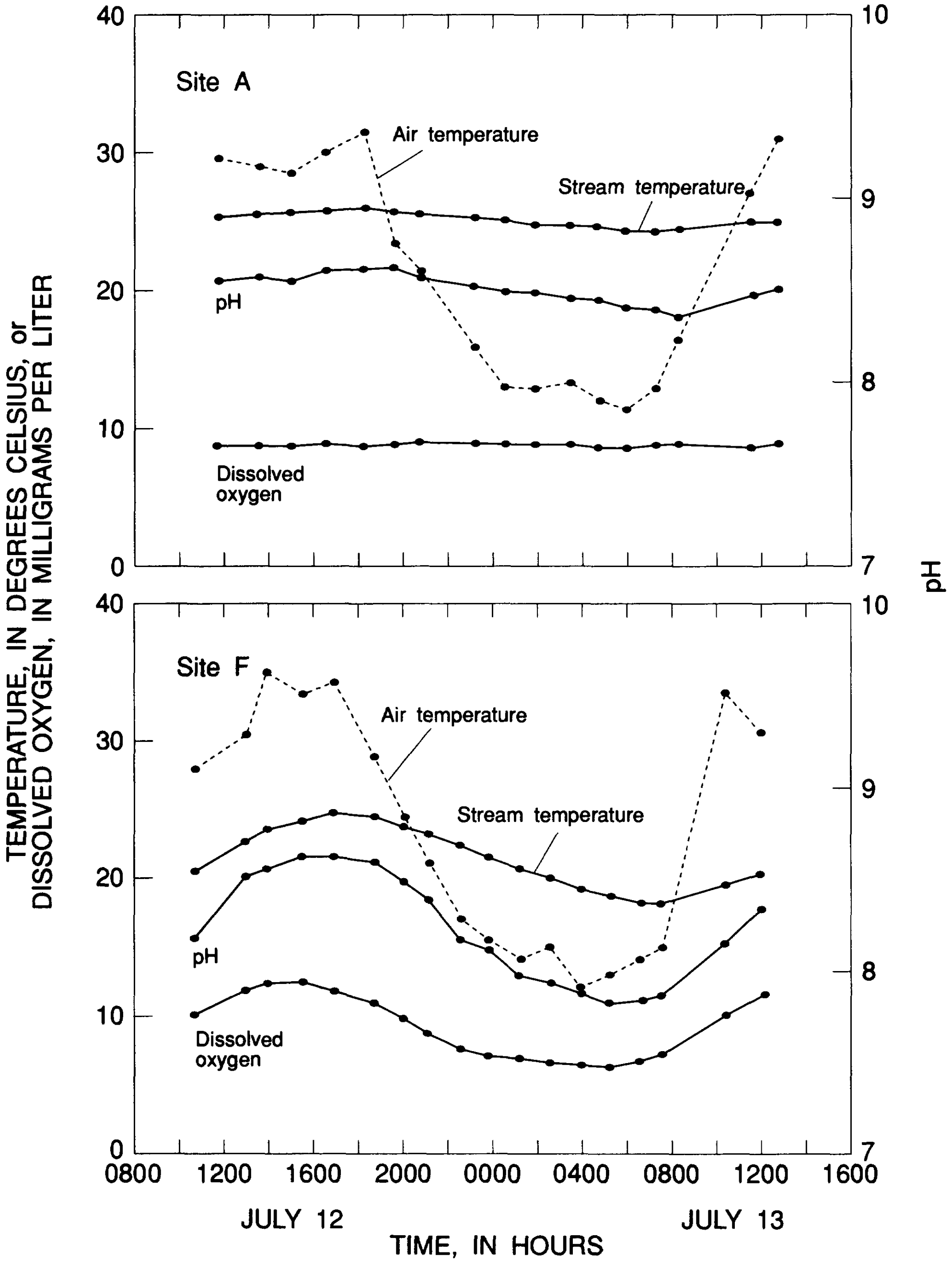


Figure 13.--Variability of pH, air and stream temperature, and dissolved oxygen of Straight River at Osage, Minnesota (site A), and at U.S. Highway 71 near Park Rapids, Minnesota (site F) July 12-13, 1988.

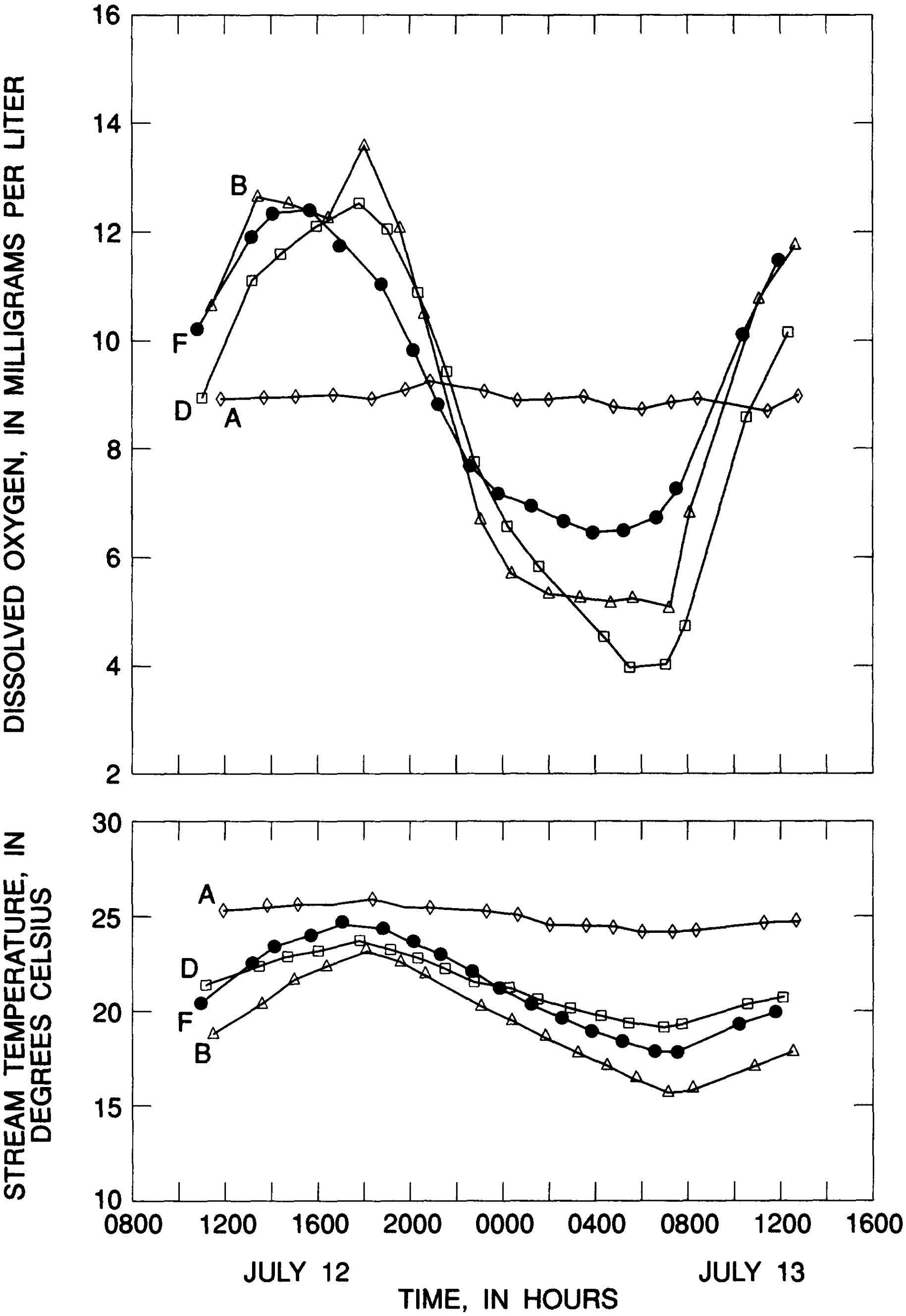


Figure 14.--Variability of stream temperature and dissolved oxygen of Straight River (sites A, B, D, and F), July 12-13, 1988.

Surficial and confined-drift aquifers have hydrologically distinct characteristics. Surficial aquifers have an unsaturated zone above the water table. They generally yield large quantities of water to wells and pumping causes small declines in available head. Surficial aquifers are recharged rapidly and thus are susceptible to contamination from the land surface. Confined-drift aquifers are fully saturated and are isolated from land surface by one or more confining units. Pumping from wells completed in confined-drift aquifers generally causes greater declines in available head than does pumping surficial aquifers. Confined aquifers are recharged by leakage from overlying or underlying aquifers through confining units, and tend to be better protected from contamination by activities at the land surface.

The surficial aquifer (outwash) consists of sand and gravel. Either till deposited at the base of glaciers during glacial advances or glacial-lake deposits act as confining units. Till comprises unsorted clay, silt, sand, gravel, and boulders. Lake deposits generally consist of silt or clay. Till and lake deposits transmit only small quantities of water to wells. The uppermost confined-drift aquifer (outwash) also consists of sand and gravel overlain by till or lake sediments. The surficial and uppermost confined-drift aquifers are the major aquifers in the investigation area.

Other aquifers and confining units are present at depth throughout the entire thickness of the glacial drift in the investigation area. A 550 ft-deep well, located near the Straight River (T. 140 N., R. 35 W., sec. 31, CCC, Minnesota unique well no. 236103) penetrated eight thin water-bearing sand units below the uppermost confined-drift aquifer before penetrating Cretaceous bedrock at 435 ft below land surface. Little data related to the units below the uppermost-confined aquifer are available because these units are not used extensively for water supply. The deeper units, therefore, are not considered in this report.

Discharge from the surficial aquifer is by outflow to the Straight River and to irrigation and domestic wells. Discharge from the surficial aquifer also occurs by evapotranspiration near lakes and rivers and near wetlands during the growing season where the water table is within the root zone of vegetation. Discharge from the uppermost confined-drift aquifer is by leakage through confining beds to the surficial aquifer. The average long-term potential evapotranspiration is 22 inches per year (Baker and others, 1979).

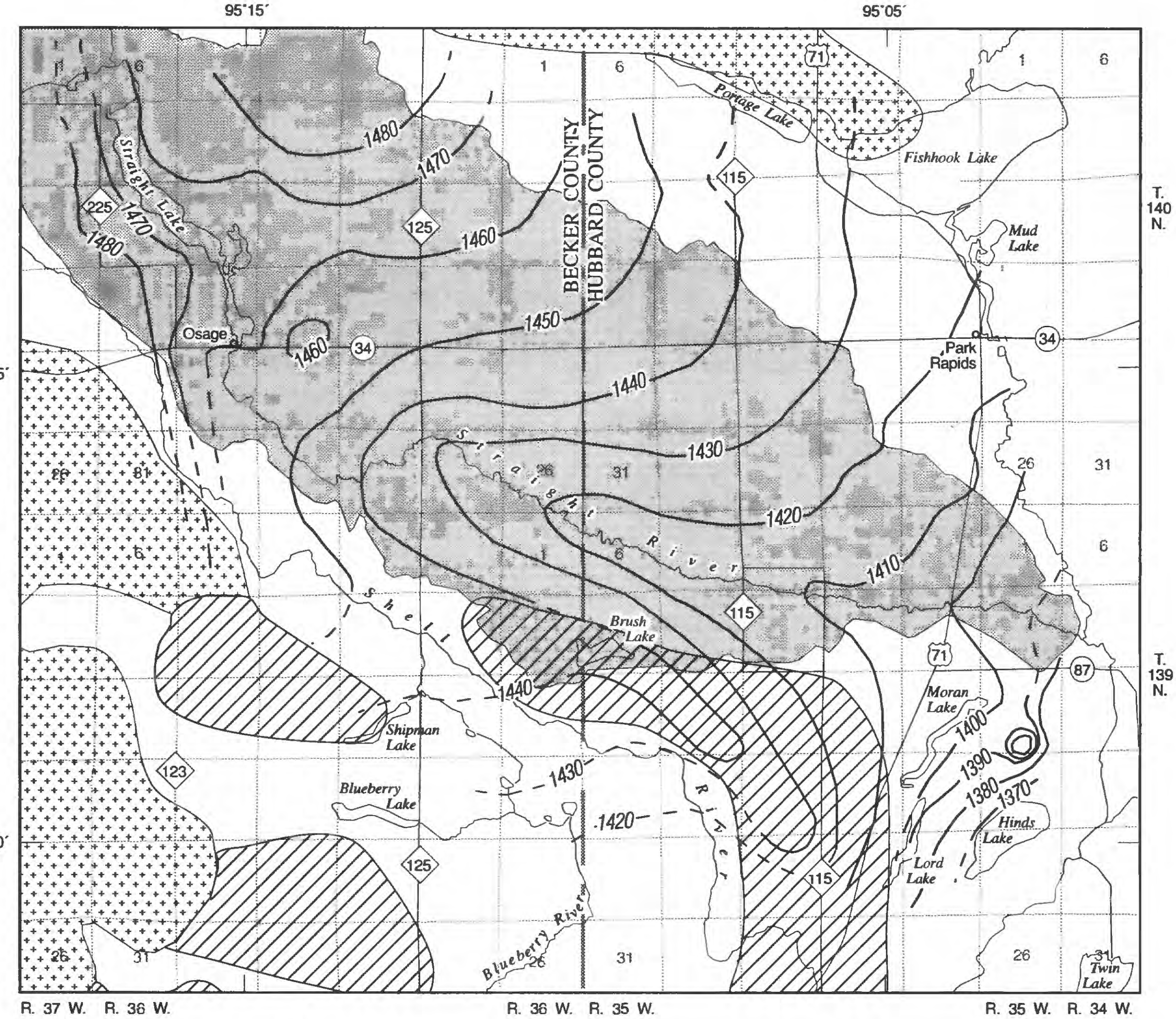
Ground-water discharge occurs as water flows from the surficial aquifer and discharges to the streams and lakes. Ground-water divides, which coincide roughly with topographic divides, separate ground-water-flow systems that discharge to the streams. The flow of ground water in the uppermost confined-drift aquifer is less affected by small streams, wetlands, and lakes than is the flow of water in the surficial aquifer.

Surficial Aquifer

The surficial aquifer is present in most of the investigation area (fig. 15). The aquifer consists of coarse sand and gravel in the north and finer sand and gravel to the south. Aquifer characteristics pertinent to evaluating ground-water flow include hydraulic conductivity, hydraulic gradient, transmissivity, areal extent, and storage. Data for wells completed in the surficial aquifer and used as data for this report are listed in table 11 in the Supplemental Information Section.

Horizontal hydraulic conductivity for the surficial aquifer was determined from a study of the Pineland Sands aquifer (Helgesen, 1977), and calibration of a ground-water-flow model developed as part of this investigation. Results of four aquifer tests in the Pineland Sands area (Helegesen, 1977) indicated that hydraulic conductivity of the surficial aquifer ranges from about 320 to 630 ft/d and storage coefficient ranges from 0.18 to 0.25. An average value of hydraulic conductivity of 215 ft/d was used in model simulations. This value provided the best match between computed and measured water levels for the aquifer. Hydraulic conductivity computed from aquifer tests may be increased as a result of production wells located in zones of higher-than-average hydraulic conductivity.

The top of the saturated part of the surficial aquifer is the water table (fig. 15), and the base of the aquifer is the top of the uppermost confining unit. The slope of the base of the surficial aquifer generally is complex, but slopes toward the east (fig. 16). The saturated thickness of the unconfined aquifer varies from 0 to greater than 80 ft, and exceeds 30 ft over most of the investigation area. Unconfined conditions prevail except where thin clay, silt or peat beds cause confined conditions in scattered locations. The water table was mapped from water levels in approximately 155 wells measured several times during a two-year period. The general direction of ground-water flow and the elevation of the water table for each of these periods are similar to that shown in figure 15. The altitude of the water table ranges from about 1,480 to about 1,370 ft above sea level and slopes regionally to the southeast at a gradient of about 10 ft/mi toward the Straight, Fishhook, and Shell Rivers, and locally to lakes, ponds, wetlands, and production wells. Depths to the water table below land surface range from 0 to about 30 ft. The ground-water basin roughly



Base from U.S. Geological Survey digital data, 1:100,000, 1986, Universal Transverse Mercator Projection, Zone 15

0 1 2 MILES

0 1 2 KILOMETERS

EXPLANATION

Straight River Basin

Surficial geology:

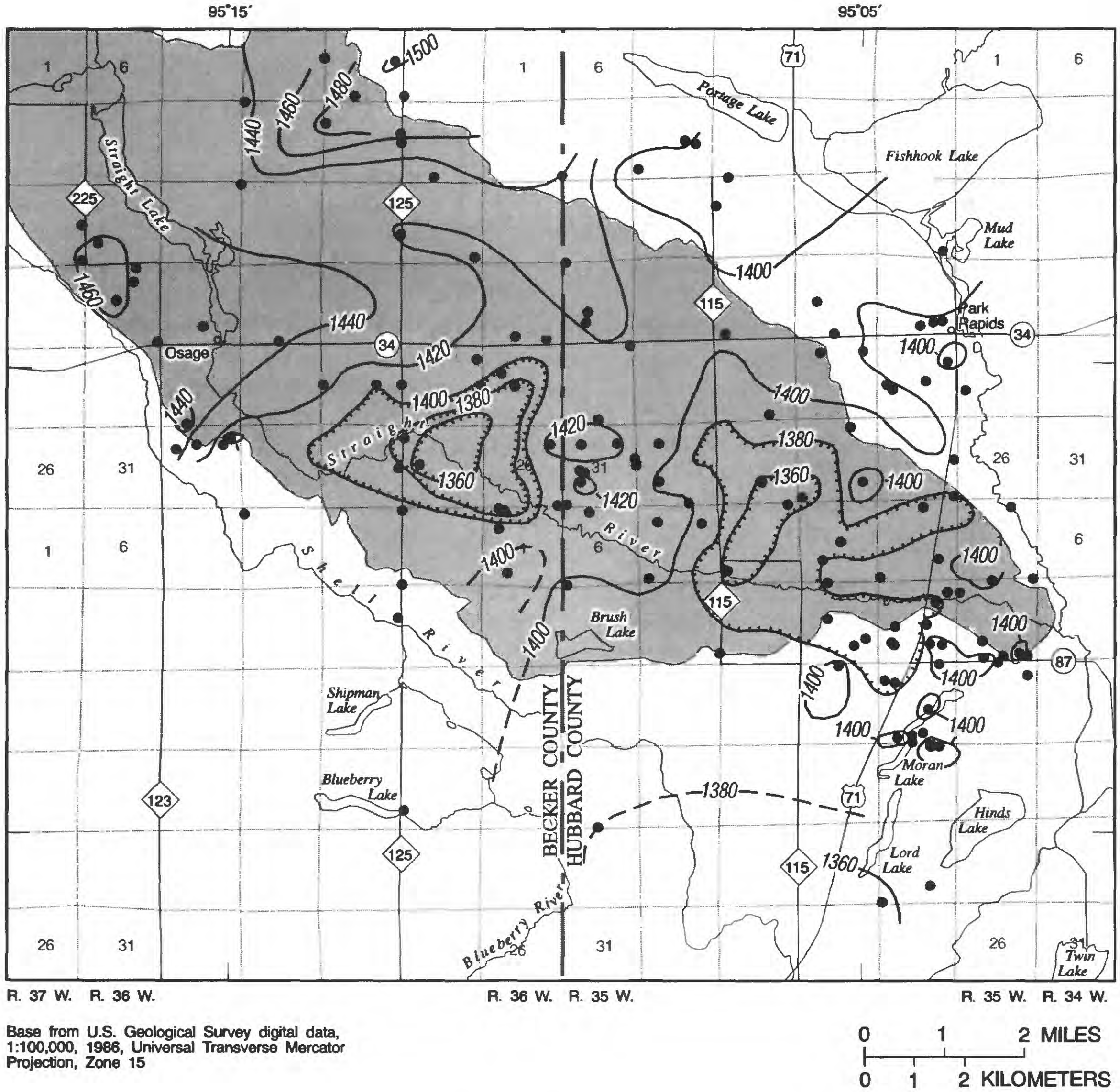
Outwash plain

Glacial till (end moraine)

Glacial till (ground moraine)

—*1440*— Potentiometric contour--Shows altitude at which water level would have stood in tightly cased wells open to the surficial aquifer. Dashed where approximately located. Contour interval 10 feet. Datum is sea level.

Figure 15.--Altitude of potentiometric surface (water table) of surficial aquifer during August 1988.



EXPLANATION

Straight River Basin

—1440— Structure contour--Shows altitude of top of uppermost confining unit. Dashed where approximately located. Contour interval 20 feet. Datum is sea level.

Structure contour enclosing lower altitude area of top of uppermost confining unit.

● Observation well

Figure 16.--Altitude of the top of the uppermost confining unit.

coincides with the surface-water basin, except in an area near the Shell River in the western part of the investigation area, where water levels from observation wells indicated that ground water flows beneath the Shell River and discharges into the Straight River.

With no withdrawals for irrigation, most ground-water discharge from the aquifer in the investigation area is to the streams and lakes. These areas of discharge are based on inferences made from potentiometric-surface maps and results of model simulations. Ground-water divides are inferred from data shown on figure 15. These divides separate ground-water-flow systems discharging to the streams.

Long-term water-level data are available from several observation wells screened in the surficial aquifer in the Straight River area. Data from these wells indicate that hydraulic head in the aquifer changed less than 2.0 ft during the summer irrigation periods (April to September) of 1987-89 (fig. 17). Available data also indicate that ground-water levels in the surficial aquifer declined by as much as 8 ft during 1985-88 (fig. 18), and that the seasonal change averaged about 1-2 feet during April through September 1987 (fig. 19). Each of these changes probably has occurred in response to a decrease in recharge from precipitation and an increase in ground-water withdrawals. Few long-term data, however, are available from wells to document the effects of ground-water withdrawals in the investigation area.

Uppermost Confining Unit

The surficial and uppermost confined-drift aquifers are hydraulically and physically separated by the uppermost confining unit, which consists of fine-grained glacial till or lake deposits. The top of the uppermost confining unit (also the bottom of the surficial aquifer) slopes generally to the southeast at a gradient of about 10 ft/mi (fig. 16). The thickness of the uppermost confining unit ranges from 10 ft to more than 140 ft; the unit is continuous throughout the investigation area.

The thickness and vertical hydraulic conductivity of the uppermost confining unit and the differences in hydraulic head between the aquifers above and below the confining unit control the amount and direction of ground-water flow between the uppermost confined-drift aquifer and the surficial aquifer. The vertical hydraulic

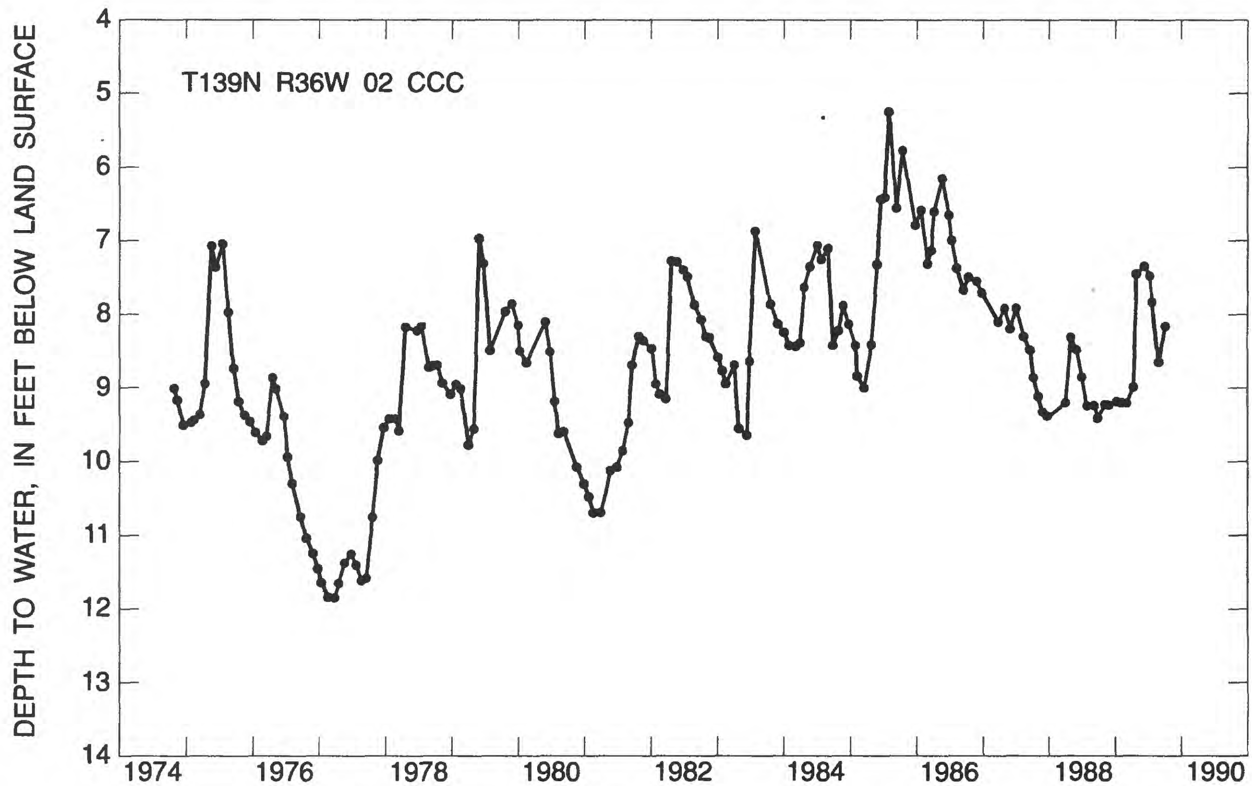
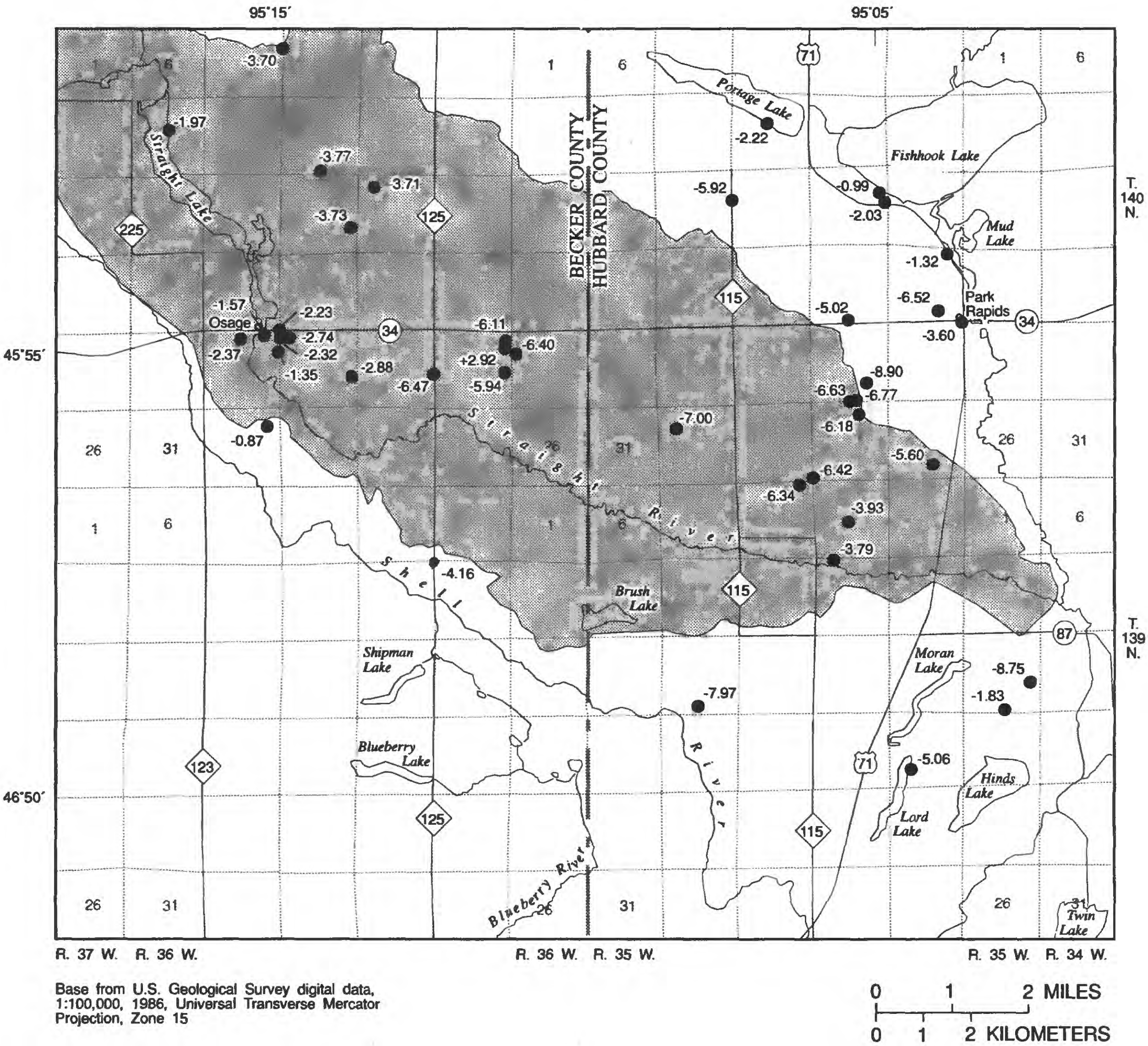


Figure 17.--Hydraulic head in Minnesota Department of Natural Resources well 3006 screened in the surficial aquifer, Becker County, during calendar years 1974 through 1989.

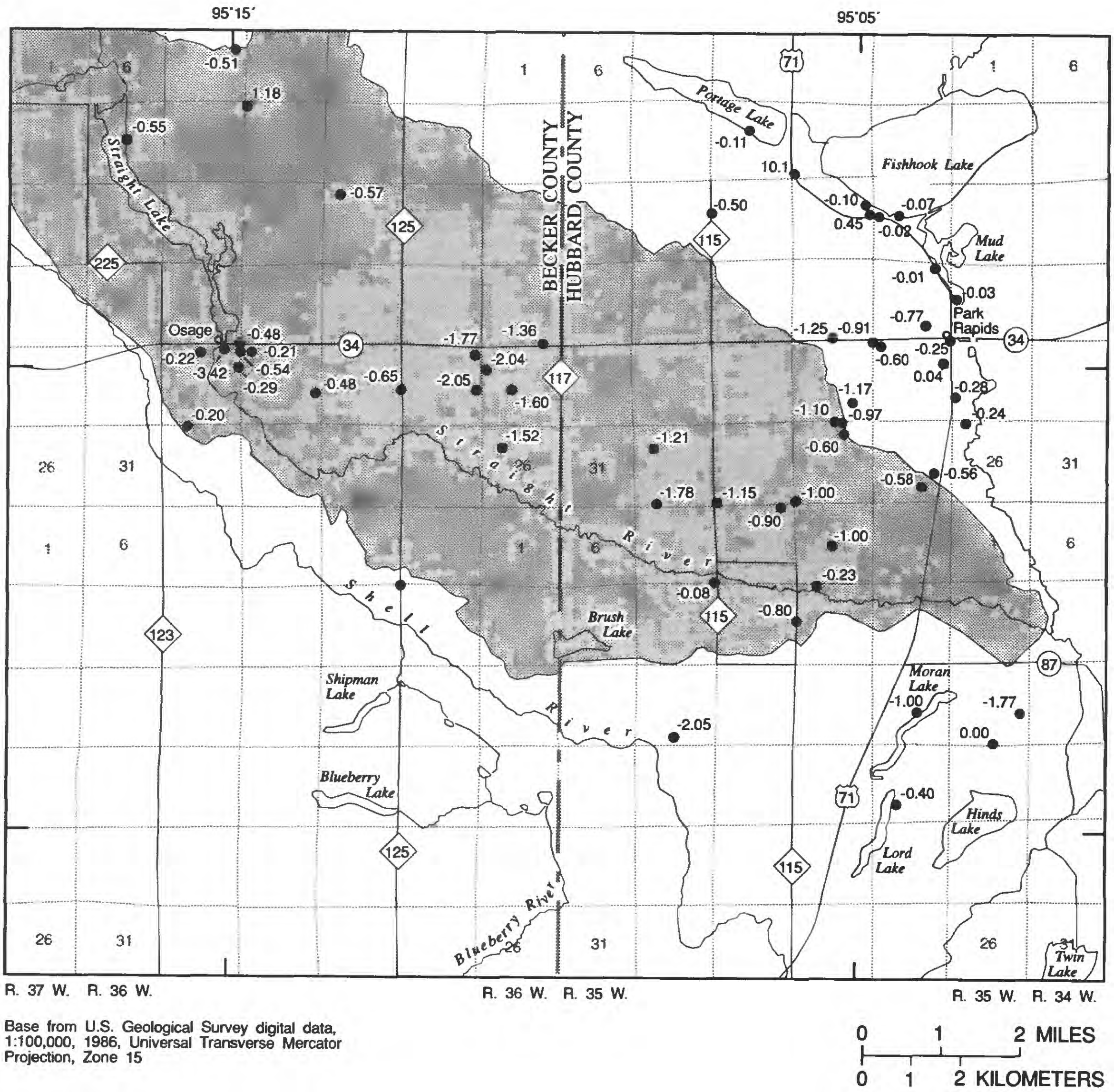


EXPLANATION

Straight River Basin

2.05 ● Observation well--Number shows water-level change.

Figure 18.--Change in hydraulic head in wells screened in the surficial aquifer, 1985-88.



EXPLANATION

Straight River Basin

3.93 ● Observation well--Number shows water-level change.

Figure 19.--Change in hydraulic head in wells screened in the surficial aquifer, April 1987 through September 1987.

conductivity of till and glacial-lake deposits generally is much lower than the vertical hydraulic conductivity of sand and gravel deposits. On the basis of analyses of 12 aquifer tests, Delin (1986) estimated the mean vertical hydraulic conductivity of till in the area of Morris, Minnesota, to be 2.5 x 10^{-2} ft/d. This is similar to the value of 1.8 x 10^{-2} ft/d for the Detroit Lakes area of Minnesota (Miller, 1982). These values of vertical hydraulic conductivity, which are higher than those reported for other parts of the glaciated northern United States, reflect the sandy nature of till in the investigation area.

Model analysis for this investigation indicated that a value of 0.2 ft/d is reasonable for vertical hydraulic conductivity for the uppermost confining unit in the investigation area. Although water flows between the surficial and confined-drift aquifers on a regional scale, the confining unit serves locally in the investigation area as a barrier to the rapid exchange of ground water between the aquifers.

Uppermost Confined-Drift Aquifer

The uppermost confined-drift aquifer is assumed to be continuous in the investigation area (fig. 20). Data for wells completed in the uppermost confined-drift aquifer and used as data for this report are listed in table 12, in the Supplemental Information Section. The thickness of the aquifer ranges from 10 to 75 ft (fig. 21). The uppermost confined-drift aquifer is the primary source of ground water to wells in the Straight River area.

Model calibration indicated that a reasonable average value of hydraulic conductivity for the aquifer would be about 300 ft/d. Use of this value in calculations yields a transmissivity of the aquifer from less that 300 ft^2/d (square feet per day) to greater than 22,500 ft^2/d.

Analysis of geologic, water-table, and potentiometric-surface data of the aquifers indicate that the surficial and uppermost confined-drift aquifers may be hydraulically connected in the Straight River area. The direction of ground-water flow in the uppermost confined-drift aquifer is toward the Straight, and Fishook Rivers (fig. 22).

Long-term water-level fluctuations in well T. 140 N., R. 35 W. Sec 28, DCC, (DNR Minnesota unique well no. 139200) screened in the uppermost confined-drift aquifer, shows a 7.63 ft water-level decline during 1987 through 1989 (fig. 23). The decline is probably caused by below average precipitation and above average ground-water withdrawals. Figure 24 shows the change in the water-level during November 1985 (a period of above-normal precipitation) through September 1988 (a period of below-normal precipitation). Water-level declines were as large as 16 ft near areas of irrigation. The water-level declines during 1985 to 1988 probably occurred in response to changes in recharge from precipitation and from ground-water withdrawal.

Water Quality

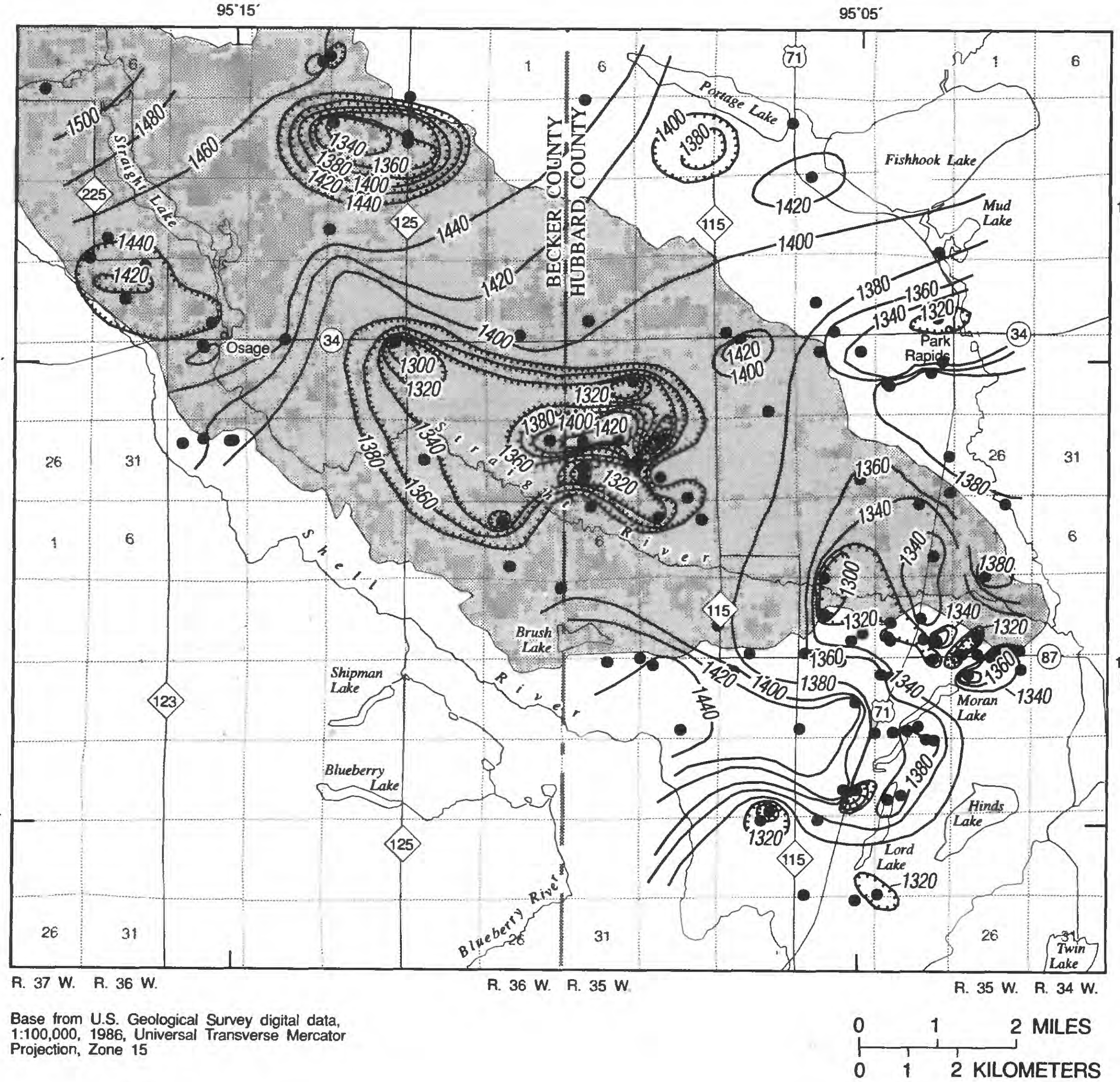
Chemical constituents dissolved in ground water are derived mainly from mineral-water interaction as the water flows through soil, glacial drift, and rock. Ground-water quality varies in response to changes in residence time, length of flow path, temperature, precipitation, and chemical reactions with soils, minerals, and aquifer materials. Ground-water quality also can be influenced by chemicals introduced to aquifers by human activities. Chemical constituents naturally present in ground water can, in some instances, be the same as those introduced by human activities. For example, chloride is derived naturally from chloride-bearing minerals, but also can be introduced to ground-water systems from human and animal wastes and by leaching from chemicals. Chemicals may be introduced directly into the ground-water system by accidental spills or by leaking storage tanks that discharge to the ground-water system, or from nonpoint sources related to land-use activities such as the application of pesticides and herbicides.

Water samples were collected from observation wells, domestic wells, and irrigation wells completed in the surficial and uppermost confined-drift aquifers. These samples were used to determine general ground-water quality, and to provide baseline hydrologic and water-quality data for use in future assessments of long-term trends.

General chemical quality

Calcium and bicarbonate are the predominant chemical constituents in water from surficial and the uppermost confined-drift aquifers (tab. 3). The percentage of total milliequivalents per liter of major constituents in water from the aquifers and from the Straight River are shown in figure 25. The points representing cation and anion data from the lower triangles are extended to the Piper diagram (Freeze and Cherry, 1979) to describe the general type of water indicated by concentrations of cations and anions. Calcium and bicarbonate are derived primarily from soil and rock weathering (Hem, 1985). Water from both aquifers generally is suitable quality for domestic and irrigation use (tab. 4).

Water from both surficial and uppermost confined-drift aquifers in the Straight River area is hard. Hardness generally is associated with the effects observed with the use of soap or with encrustations left by water that has



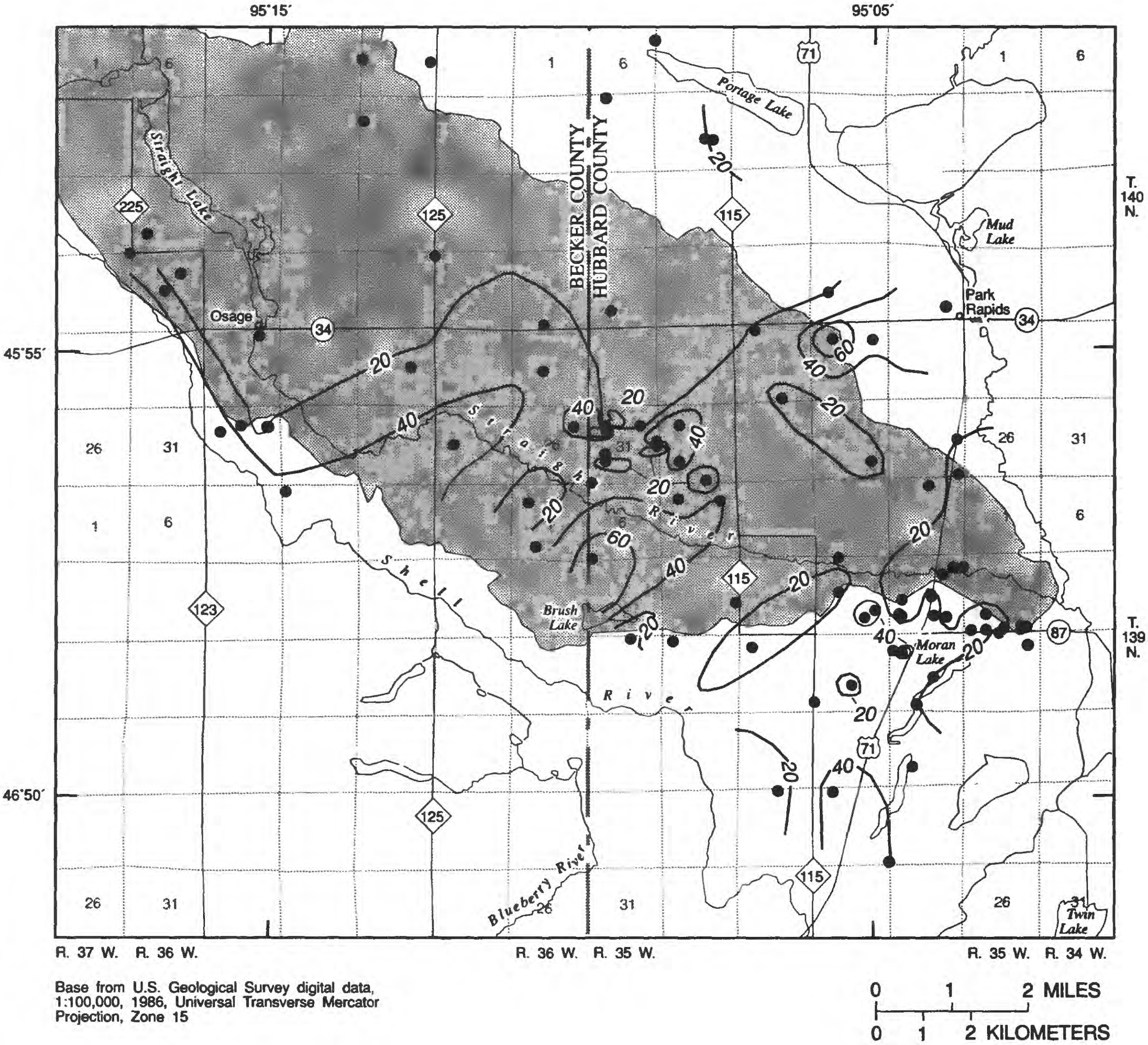
EXPLANATION

Straight River Basin

—1440— Structure contour--Shows altitude of top of uppermost confined-drift aquifer. Hachures indicate depression. Contour interval in feet. Datum is sea level.

• Observation well

Figure 20.--Altitude of the top of uppermost confined-drift aquifer.



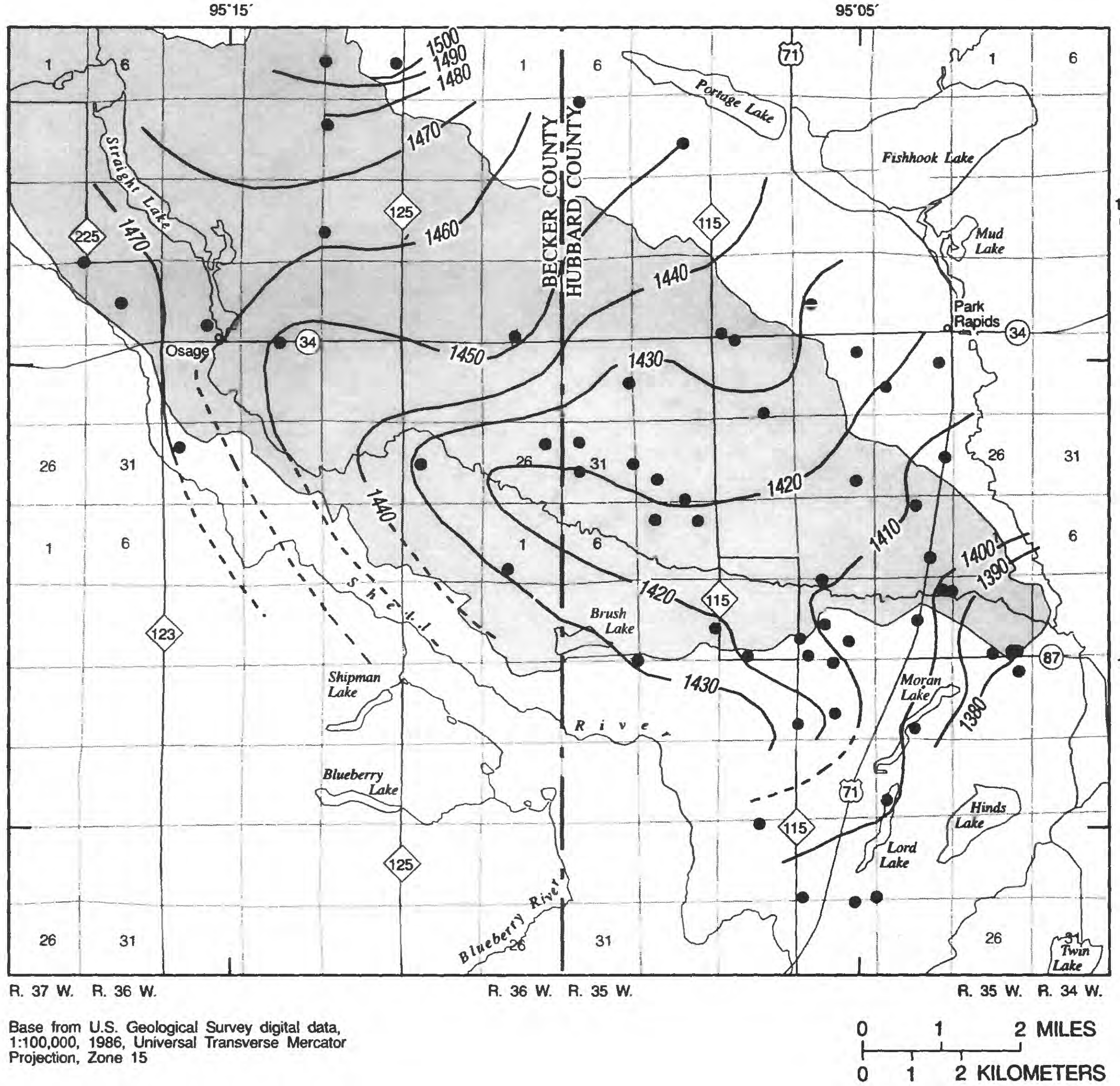
EXPLANATION

Straight River Basin

—40— Line of equal thickness of uppermost confined-drift aquifer. Interval 20 feet.

● Observation well

Figure 21.--Thickness of the uppermost confined-drift aquifer.



EXPLANATION

Straight River Basin

—1440— Potentiometric contour--Shows altitude at which water level would have stood in tightly cased wells open to the uppermost confined-drift aquifer. Contour interval 10 feet. Datum is sea level.

• Observation well

Figure 22.--Altitude of potentiometric surface of the uppermost confined-drift aquifer during August 1988.

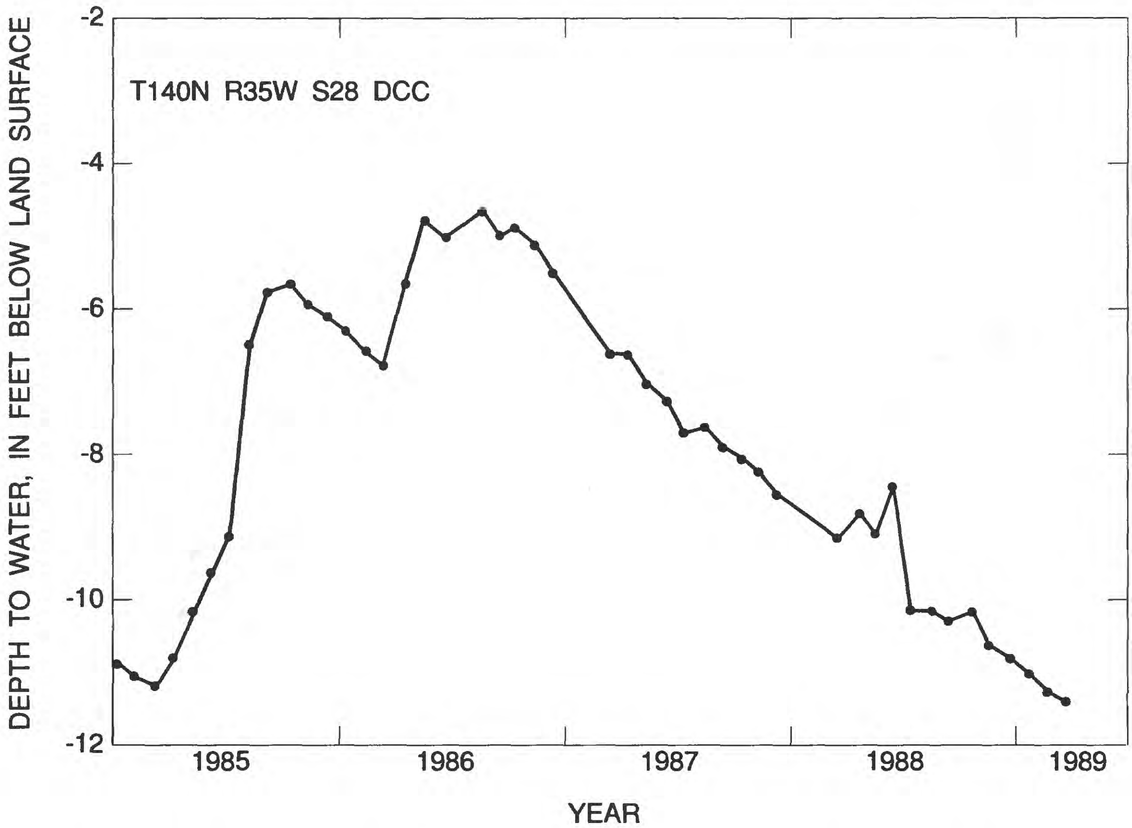


Figure 23.--Water level in Minnesota unique well number 139200 screened in the uppermost confined-drift aquifer, during calendar years 1985-89.

evaporated. The reactions with soap result from cations that form insoluble compounds with soap. Because hardness is a property attributed to more than one constituent (mainly calcium and magnesium), the convention of reporting hardness in terms of an equivalent concentration of calcium carbonate generally is used (Hem, 1985).

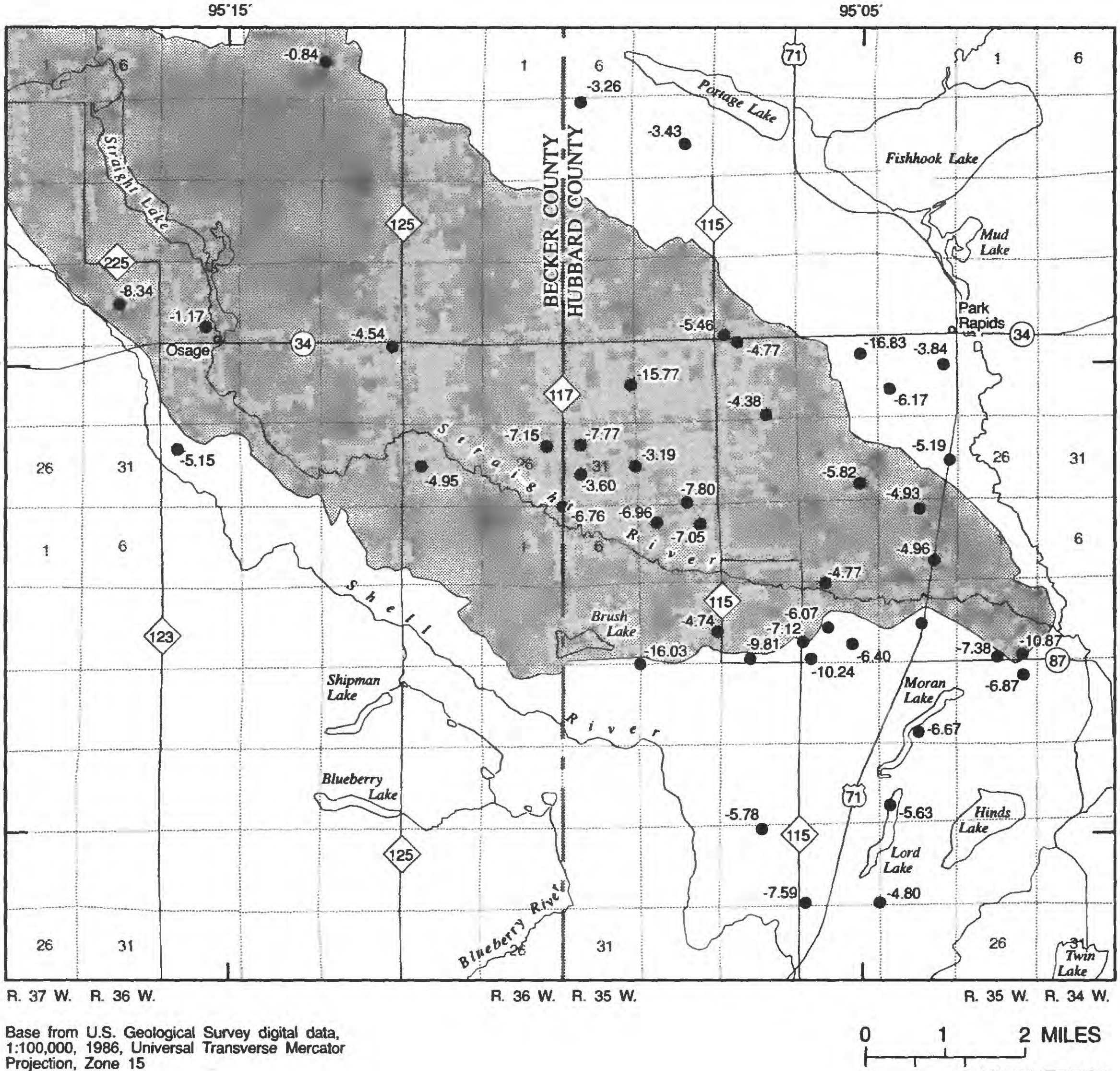
Nitrate (nitrite plus nitrate as N) concentrations in water from some shallow wells completed near the water table exceed the limit set by the MPCA (1988) drinking water standards (fig. 26). Concentrations of nitrate in water from wells with screens completed at the water table generally are greater than in wells with screens completed below the water table. Pesticides were only detected in samples of ground water from one well (tab. 3).

Nitrate contamination can result from infiltration of runoff from livestock feedlots, domestic septic systems, and fertilizers. Studies conducted by Myette (1984) near Staples, Minnesota, indicate that nitrate and chloride generally were largest in the surficial aquifer near the water table. Water containing increased levels of nitrate and chloride likely infiltrates to the water table, moves laterally along flow paths and discharges to streams and lakes. A minor amount of vertical mixing appears to occur within the saturated part of the surficial aquifer.

Temperature

Ground water in the surficial aquifer and in the uppermost confined-drift aquifer has a relatively constant temperature of about 7°C. Ground-water temperatures are more variable near the water table, where temperature is affected by percolation of recharge. Ground-water temperature varies from less than 6.5°C to about 9°C during the year, and increases slightly with depth due to the geothermal gradient.

Figure 27 shows ground-water temperature and water levels in wells at irrigated and nonirrigated sites. Data are from wells screened near the water table, near the bottom of the surficial aquifer, and in the uppermost confined-drift aquifer. Ground-water temperature in irrigated areas generally was less than one degree higher than in nonirrigated areas. The temperature differences also may be related to the depth to the water table, which is several



EXPLANATION

Straight River Basin

-7.15 ● Observation well--Number shows change in hydraulic head, in feet.

Figure 24.--Change in hydraulic head in wells screened in the uppermost confined-drift aquifer, November 1985 through September 1988.

Table 3.--Chemical and physical characteristics of ground water in the investigation area

[µS/cm, microsiemens per centimeter at 25 degrees Celsius; °C, degrees Celsius; mg/L, milligrams per liter; µg/L, micrograms per liter; <, less than; --, not sampled; IT iterated titration; FET, fixed endpoint titration; field, value determined at sampling site; lab, value determined in a laboratory]

Well number	Local name	Date	Depth of water level below land surface (feet)	Depth of well, total (feet)	Elevation of land surface datum (feet above sea level)	Specific conductance (µS/cm)	Specific conductance lab (µS/cm)	pH, field (standard units)	pH, lab (standard units)	Temperature, water (°C)
4650039509090	139.36.19CDD-USGS17	05-25-88	15.00	22	1,436	342	337	8.0	8.0	--
		08-25-88	12.35	22	1,437	295	301	--	7.7	9.0
4651450950945	139.36.13AAA-USGS16	05-25-88	--	--	1,458	527	616	7.4	7.5	--
		08-25-88	--	--	1,461	--	596	--	7.6	--
4651470950332	139.35.14AAA-DOMESTIC5	05-27-88	--	--	1,431	560	--	7.8	--	--
		09-08-88	--	--	1,433	455	--	--	--	--
4651480950832	139.35.07DDD-STINAR	09-07-88	--	69	1,486	--	--	--	--	--
4652120951212	139.36.10CCC-USGS3	05-27-88	--	14	1,458	383	--	7.8	--	--
		09-08-88	--	14	1,453	273	--	--	--	12.5
4652120951212	139.36.10ADD02-USGS3D	05-27-88	--	--	1,453	--	--	--	--	--
		09-08-88	--	--	1,453	--	--	--	--	--
4652370950943	139.35.06CCC-USGS15	05-25-88	21.70	28	1,458	323	353	7.6	8.0	--
		08-25-88	22.30	28	1,459	312	286	--	8.1	8.5
4652390950533	139.35.10BAB01-29035	05-16-89	--	--	1,439	440	434	6.9	7.8	8.0
4652490950712	139.35.04DDD02-USGS2M	05-15-89	--	42	1,421	430	436	6.8	7.8	8.0
4653320950716	140.35.33CCC-LDW13	05-25-88	--	24	1,447	379	426	7.6	7.8	--
		08-25-89	--	23	1,450	336	410	--	7.9	9.5
4653560950832	140.35.32.CBB01-14D	05-15-89	485	145	1,454	490	--	6.9	7.6	8.5
4653560950834	140.35.31DAA-USGS14	05-24-89	--	29	1,456	503	583	7.4	7.8	--
		05-15-89	--	29	1,452	570	583	7.3	7.7	8.5
4653560951217	140.36.34ADD-USGS4	05-23-88	--	29	1,463	--	--	--	--	--
		09-08-88	--	29	1,463	--	--	--	--	--
4654260950716	140.35.27CCC-LDW9	05-26-88	20.10	25	1,447	352	--	7.6	--	--
4655000951047	140.36.25BCA-USGS11	05-24-88	--	24	1,470	--	797	--	7.6	--
		08-25-88	20.20	24	1,470	790	905	--	7.5	9.5
4655130950917	140.35.30BAA-DOMESTIC7	05-27-88	--	20	1,461	396	--	7.7	--	--
		09-08-88	--	20	1,461	--	--	--	--	--
4656080951113	140.36.14DDC-DOMESTIC4	05-27-88	--	--	1,485	559	--	7.5	--	--
		09-08-88	--	--	1,485	--	--	--	--	--
4656110950611	140.35.21DAB01-DOMESTIC2	05-27-88	--	--	1,451	353	--	7.6	--	--
		09-08-88	--	--	1,451	--	--	--	--	--
4656550950840	140.35.18AAA-DOMESTIC3	05-27-88	--	20	1,485	355	--	7.7	--	--
4656570951448	140.36.16BBB01-USGS23	05-16-89	43.42	49	1,508	460	467	7.0	7.7	7.0
4656570951448	140.36.16BBB02-23D	05-16-89	--	199	--	370	402	7.9	8.3	7.0
4657120951640	140.36.7DBD-DOMESTIC6	05-27-88	--	50	1,495	--	--	7.7	--	--
		09-07-88	--	50	1,495	--	--	--	--	--

Table 3.--Chemical and physical characteristics of ground water in the investigation area--Continued

Well number	Local name	Date	Calcium, dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as Mg)	Sodium, dissolved (mg/L as Na)	Potassium, dissolved (mg/L as K)	Bicarbonate, IT, field (mg/L as HCO_3)	Alkalinity, total, IT field (mg/L as $CaCO_3$)	Sulfate, dissolved (mg/L as SO_4)
4650039509090	139.36.19CDD-USGS17	05-25-88	49	12	2.4	1.2	200	160	4.6
		08-25-88	38	12	3.0	2.2	--	--	4.5
4651450950945	139.36.13AAA-USGS16	05-25-88	85	28	4.4	1.1	410	330	2.4
		08-25-88	81	27	4.5	1.1	--	--	2.9
4651470950332	139.35.14AAA-DOMESTIC5	05-27-88	--	--	--	--	--	--	--
		09-08-88	--	--	--	--	--	--	--
4651480950832	139.35.07DDD-STINAR	09-07-88	--	--	--	--	--	--	--
4652120951212	139.36.10CCC-USGS3	05-27-88	--	--	--	--	--	--	--
		09-08-88	--	--	--	--	--	--	--
4652120951212	139.36.10ADD02-USGS3D	05-27-88	--	--	--	--	--	--	--
		09-08-88	--	--	--	--	--	--	--
4652370950943	139.35.06CCC-USGS15	05-25-88	55	12	2.4	1.8	250	210	4.4
		08-25-88	41	10	2.3	1.2	--	--	3.5
4652390950533	139.35.10BAB01-29035	05-16-89	62	19	6.1	1.8	--	--	<1.0
4652490950712	139.35.04DDD02-USGS2M	05-15-89	66	18	2.6	1.2	--	--	25
4653320950716	140.35.33CCC-LDW13	05-25-88	65	15	2.2	.90	230	190	7.3
		08-25-89	62	15	1.6	.60	--	--	5.5
4653560950832	140.35.32.CBB01-14D	05-15-89	70	22	3.7	1.0	--	--	10
4653560950834	140.35.31DAA-USGS14	05-24-89	82	22	4.1	1.2	270	220	14
		05-15-89	80	21	3.7	1.0	--	--	13
4653560951217	140.36.34ADD-USGS4	05-23-88	--	--	--	--	--	--	--
		09-08-88	--	--	--	--	--	--	--
4654260950716	140.35.27CCC-LDW9	05-26-88	--	--	--	--	160	140	--
4655000951047	140.36.25BCA-USGS11	05-24-88	110	29	7.1	3.3	--	--	23
		08-25-88	120	34	7.3	4.0	--	--	34
4655130950917	140.35.30BAA-DOMESTIC7	05-27-88	--	--	--	--	--	--	--
		09-08-88	--	--	--	--	--	--	--
4656080951113	140.36.14DDC-DOMESTIC4	05-27-88	--	--	--	--	--	--	--
		09-08-88	--	--	--	--	--	--	--
4656110950611	140.35.21DAB01-DOMESTIC2	05-27-88	--	--	--	--	--	--	--
		09-08-88	--	--	--	--	--	--	--
4656550950840	140.35.18AAA-DOMESTIC3	05-27-88	--	--	--	--	--	--	--
4656570951448	140.36.16BBB01-23S	05-16-89	71	21	2.4	.70	--	--	10
4656570951448	140.36.16BBB02-23D	05-16-89	44	20	18	3.8	--	--	3.0
4657120951640	140.36.7DBD-DOMESTIC6	05-27-88	--	--	--	--	--	--	--
		09-07-88	--	--	--	--	--	--	--

Table 3.--Chemical and physical characteristics of ground water in the investigation area--Continued

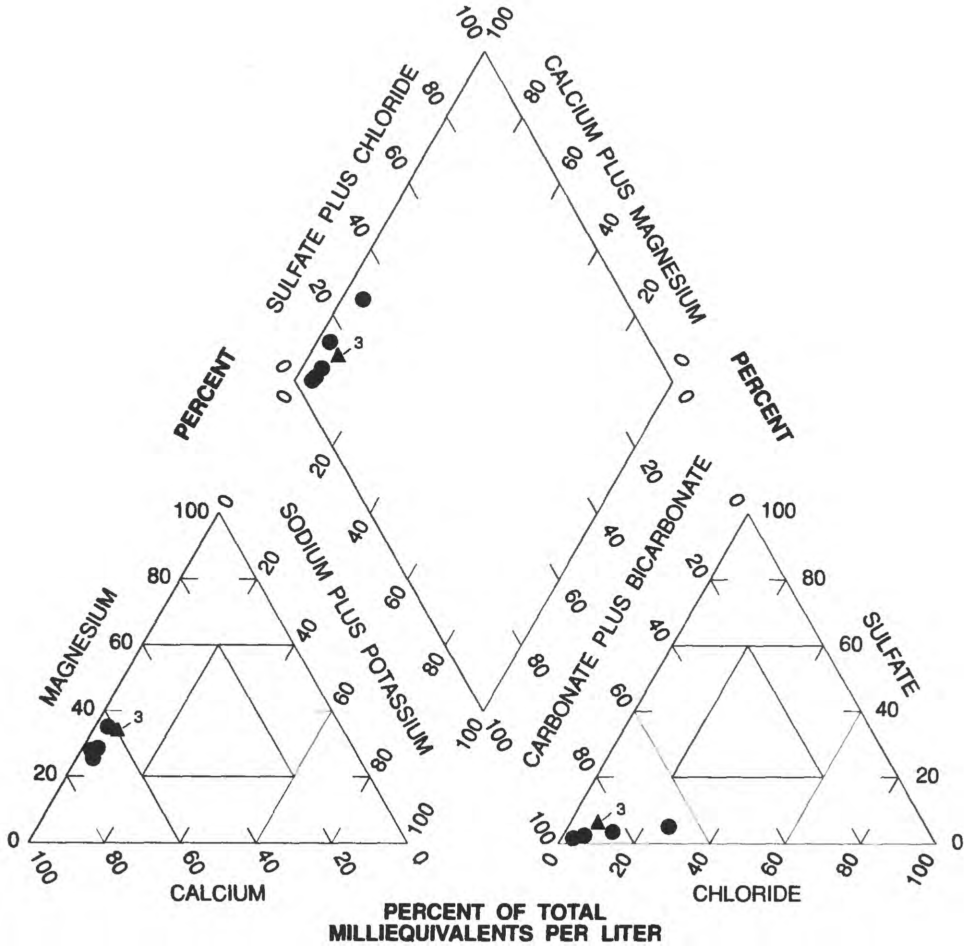
Well number	Local name	Date	Chloride, dissolved (mg/L as Cl)	Fluoride, dissolved (mg/L as F)	Silica, dissolved (mg/L as SiO_2)	Nitrite plus nitrate, dissolved (mg/L as N)	Solids, residue at 180°C dissolved (mg/L)	Alachlor, total recoverable (µg/L)	Ametryne, total
4650039509090	139.36.19CDD-USGS17	05-25-88	0.90	0.20	11	2.2	--	--	--
		08-25-88	1.5	.10	10	1.7	--	--	--
4651450950945	139.36.13AAA-USGS16	05-25-88	6.2	.30	21	<.10	--	--	--
		08-25-88	5.4	.20	21	.12	--	--	--
4651470950332	139.35.14AAA-DOMESTIC5	05-27-88	--	--	--	14	--	--	--
		09-08-88	--	--	--	18	--	--	--
4651480950832	139.35.07DDD-STINAR	09-07-88	--	--	--	4.2	--	--	--
4652120951212	139.36.10CCC-USGS3	05-27-88	--	--	--	8.3	--	--	--
		09-08-88	--	--	--	8.1	--	--	--
4652120951212	139.36.10ADD02-USGS3D	05-27-88	--	--	--	8.3	--	--	--
		09-08-88	--	--	--	8.3	--	--	--
4652370950943	139.35.06CCC-USGS15	05-25-88	1.1	.20	12	1.1	--	--	--
		08-25-88	1.1	.10	10	2.3	--	--	--
4652390950533	139.35.10BAB01-29035	05-16-89	.40	.20	23	<.10	242	--	--
4652490950712	139.35.04DDD02-USGS2M	05-15-89	8.0	.10	11	.84	252	--	--
4653320950716	140.35.33CCC-LDW13	05-25-88	4.8	.30	11	5.7	--	<0.1	<0.1
		08-25-89	4.4	.10	11	4.2	--	<.1	<.1
4653560950832	140.35.32.CBB01-14D	05-15-89	10	.10	19	<.10	267	--	--
4653560950834	140.35.31DAA-USGS14	05-24-89	15	.20	14	15	--	<.1	<.1
		05-15-89	14	.10	14	5.7	330	--	--
4653560951217	140.36.34ADD-USGS4	05-23-88	--	--	--	<.10	--	--	--
		09-08-88	--	--	--	<.10	--	--	--
4654260950716	140.35.27CCC-LDW9	05-26-88	--	--	--	11	--	--	--
4655000951047	140.36.25BCA-USGS11	05-24-88	41	.20	13	31	--	<.1	<.1
		08-25-88	57	.10	13	35	--	<.1	<.1
4655130950917	140.35.30BAA-DOMESTIC7	05-27-88	--	--	--	2.4	--	--	--
		09-08-88	--	--	--	2.0	--	--	--
4656080951113	140.36.14DDC-DOMESTIC4	05-27-88	--	--	--	<.10	--	--	--
		09-08-88	--	--	--	<.10	--	--	--
4656110950611	140.35.21DAB01-DOMESTIC2	05-27-88	--	--	--	1.9	--	--	--
		09-08-88	--	--	--	1.4	--	--	--
4656550950840	140.35.18AAA-DOMESTIC3	05-27-88	--	--	--	2.5	--	--	--
4656570951448	140.36.16BBB01-23S	05-16-89	.50	.10	15	.56	233	--	--
4656570951448	140.36.16BBB02-23D	05-16-89	2.5	<.10	11	<.10	--	--	--
4657120951640	140.36.7DBD-DOMESTIC6	05-27-88	--	--	--	1.0	--	--	--
		09-07-88	--	--	--	.99	--	--	--

Table 3.--Chemical and physical characteristics of ground water in the investigation area--Continued

Well number	Local name	Date	Atrazine, total (µg/L)	Cyanazine, total (µg/L)	Metribuzin, total recoverable (µg/L)	Metolachlor, total recoverable (µg/L)	Prometone, total (µg/ L)	Prometryne, total (µg/L)	Propazine, total (µg/L)	Simazine, total (µg/L
4650039509090	139.36.19CDD-USGS17	05-25-88	--	--	--	--	--	--	--	--
		08-25-88	--	--	--	--	--	--	--	--
4651450950945	139.36.13AAA-USGS16	05-25-88	--	--	--	--	--	--	--	--
		08-25-88	--	--	--	--	--	--	--	--
4651470950332	139.35.14AAA-DOMESTIC5	05-27-88	--	--	--	--	--	--	--	--
		09-08-88	--	--	--	--	--	--	--	--
4651480950832	139.35.07DDD-STINAR	09-07-88	--	--	--	--	--	--	--	--
4652120951212	139.36.10CCC-USGS3	05-27-88	--	--	--	--	--	--	--	--
		09-08-88	--	--	--	--	--	--	--	--
4652120951212	139.36.10ADD02-USGS3D	05-27-88	--	--	--	--	--	--	--	--
		09-08-88	--	--	--	--	--	--	--	--
4652370950943	139.35.06CCC-USGS15	05-25-88	--	--	--	--	--	--	--	--
		08-25-88	--	--	--	--	--	--	--	--
4652390950533	139.35.10BAB01-29035	05-16-89	--	--	--	--	--	--	--	--
4652490950712	139.35.04DDD02-USGS2M	05-15-89	--	--	--	--	--	--	--	--
4653320950716	140.35.33CCC-LDW13	05-25-88	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
		08-25-89	<.1	<.1	<.1	<.1	<.1	<.1	<.1	<.1
4653560950832	140.35.32.CBB01-14D	05-15-89	--	--	--	--	--	--	--	--
4653560950834	140.35.31DAA-USGS14	05-24-89	.3	<.1	<.1	<.1	<.1	<.1	<.1	<.1
		05-15-89	--	--	--	--	--	--	--	--
4653560951217	140.36.34ADD-USGS4	05-23-88	--	--	--	--	--	--	--	--
		09-08-88	--	--	--	--	--	--	--	--
4654260950716	140.35.27CCC-LDW9	05-26-88	--	--	--	--	--	--	--	--
4655000951047	140.36.25BCA-USGS11	05-24-88	<.1	<.1	<.1	<.1	<.1	<.1	<.1	<.1
		08-25-88	<.1	<.1	<.1	<.1	<.1	<.1	<.1	<.1
4655130950917	140.35.30BAA-DOMESTIC7	05-27-88	--	--	--	--	--	--	--	--
		09-08-88	--	--	--	--	--	--	--	--
4656080951113	140.36.14DDC-DOMESTIC4	05-27-88	--	--	--	--	--	--	--	--
		09-08-88	--	--	--	--	--	--	--	--
4656110950611	140.35.21DAB01-DOMESTIC2	05-27-88	--	--	--	--	--	--	--	--
		09-08-88	--	--	--	--	--	--	--	--
4656550950840	140.35.18AAA-DOMESTIC3	05-27-88	--	--	--	--	--	--	--	--
4656570951448	140.36.16BBB01-23S	05-16-89	--	--	--	--	--	--	--	--
4656570951448	140.36.16BBB02-23D	05-16-89	--	--	--	--	--	--	--	--
4657120951640	140.36.7DBD-DOMESTIC6	05-27-88	--	--	--	--	--	--	--	--
		09-07-88	--	--	--	--	--	--	--	--

Table 3.--Chemical and physical characteristics of ground water in the investigation area--Continued

Well number	Local name	Date	Simetryne, total (µg/L)	Trifluralin, total recoverable (µg/L)
4650039509090	139.36.19CDD-USGS17	05-25-88	--	--
		08-25-88	--	--
4651450950945	139.36.13AAA-USGS16	05-25-88	--	--
		08-25-88	--	--
4651470950332	139.35.14AAA-DOMESTIC5	05-27-88	--	--
		09-08-88	--	--
4651480950832	139.35.07DDD-STINAR	09-07-88	--	--
4652120951212	139.36.10CCC-USGS3	05-27-88	--	--
		09-08-88	--	--
4652120951212	139.36.10ADD02-USGS3D	05-27-88	--	--
		09-08-88	--	--
4652370950943	139.35.06CCC-USGS15	05-25-88	--	--
		08-25-88	--	--
4652390950533	139.35.10BAB01-29035	05-16-89	--	--
4652490950712	139.35.04DDD02-USGS2M	05-15-89	--	--
4653320950716	140.35.33CCC-LDW13	05-25-88	<0.1	<0.1
		08-25-89	<.1	<.1
4653560950832	140.35.32.CBB01-14D	05-15-89	--	--
4653560950834	140.35.31DAA-USGS14	05-24-89	<.1	<.1
		05-15-89	--	--
4653560951217	140.36.34ADD-USGS4	05-23-88	--	--
		09-08-88	--	--
4654260950716	140.35.27CCC-LDW9	05-26-88	--	--
4655000951047	140.36.25BCA-USGS11	05-24-88	<.1	<.1
		08-25-88	<.1	<.1
4655130950917	140.35.30BAA-DOMESTIC7	05-27-88	--	--
		09-08-88	--	--
4656080951113	140.36.14DDC-DOMESTIC4	05-27-88	--	--
		09-08-88	--	--
4656110950611	140.35.21DAB01-DOMESTIC2	05-27-88	--	--
		09-08-88	--	--
4656550950840	140.35.18AAA-DOMESTIC3	05-27-88	--	--
4656570951448	140.36.16BBB01-23S	05-16-89	--	--
4656570951448	140.36.16BBB02-23D	05-16-89	--	--
4657120951640	140.36.7DBD-DOMESTIC6	05-27-88	--	--
		09-07-88	--	--



EXPLANATION

● Ground-water sample

▲[3] Stream-water sample. Number represents samples with identical percentages of total milliequivalent per liter of major ion in samples.

Figure 25.--Percentage of total milliequivalents per liter of major ions in samples collected from surficial and uppermost confined-drift aquifers and from Straight River during 1988.

Table 4.--State-recommended limits for domestic consumption and agricultural and wildlife use for selected constituents in ground water, and percentages of wells sampled in the investigation area where water exceeds limits

[mg/L, milligrams per liter; µg/L, micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius] Recommended limits from Minnesota Pollution Control Agency and Minnesota Department of Health and Minnesota Department of Agriculture (1988).

Constituent	Concentration		Limit type	Number of wells sampled	Percent of wells exceeding limits
		Inorganic Constituents			
Sulfate	250.0	mg/L	domestic consumption	11	0
Chloride	250.0	mg/L	domestic consumption	11	0
Nitrate (nitrate plus nitrite as N)	10.0	mg/L	domestic consumption	22	18
		Other Constituent			
Specific conductance	1,000	µS/cm	Agriculture, wildlife	17	0
pH	6.0-8.5	standard units	Agriculture, wildlife	18	0
Dissolved solids	700	µg/L	Agriculture, wildlife	3	0
Alachlor	6.0	µg/L	domestic consumption	3	0
Atrazine	3.0	µg/L	domestic consumption	3	0
Cyanazine	9.0	µg/L	domestic consumption	3	0
Metolachlor	10.0	µg/L	domestic consumption	3	0
Metribuzin	175.0	µg/L	domestic consumption	3	0
Simazine	35.0	µg/L	domestic consumption	3	0
Trifluralin	2.0	µg/L	domestic consumption	3	0

feet deeper at the irrigated site than at the nonirrigated site.

Residence Time of Ground Water

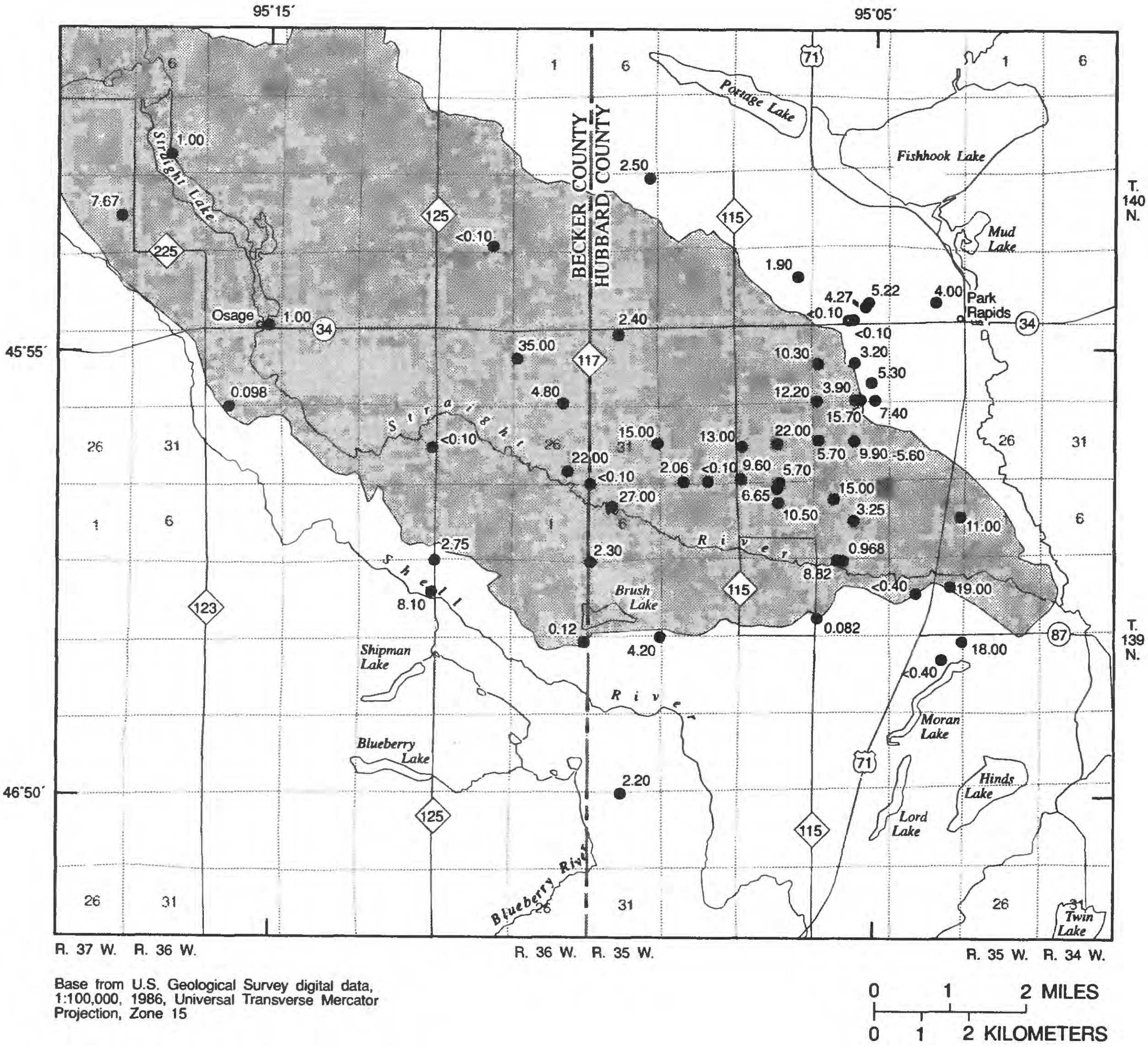
Residence time of ground water is the time that water has been in a ground-water-flow system since infiltration from precipitation. Residence times of ground water can range from a few days to thousands of years. Ground-water-flow systems developed in deep aquifers, and systems where water flows for long distances, generally have long residence times. Ground-water-flow systems developed in shallow aquifers with local-flow systems generally have short residence times. Ground-water flow can cause mixing of water from different sources, which can in turn result in inaccurate dating of water within the aquifer.

Knowledge of residence time of ground water is important to understand the effects of land use on water quality. Isotopic analysis using carbon 14 (^{14}C-- an isotope of carbon) and tritium (^{3}H-- an isotope of hydrogen) can be used to estimate ground-water residence time. Both ^{14}C and tritium are radioactive isotopes. Prior to and after above-ground thermonuclear testing, ^{14}C in the atmosphere was derived from natural atmospheric processes involving interactions between nitrogen and cosmic rays, and was in a steady state of dynamic equilibrium. Steady-state concentrations of ^{14}C in the atmosphere resulted in a constant source of ^{14}C to ground water from precipitation infiltrating into the ground.

The law of radioactive decay describes the rate at which the activity of ^{14}C and all other radioactive substances decrease with time. Thus, the ^{14}C content of ground water can be used as a guide for ground-water residence time. Because ^{14}C has a relatively long half life (5,730 years), it can be used to estimate the residence times for ground water that infiltrated as long as 30,000 to 40,000 years before the present.

The presence of tritium in ground water is the result of both human and natural causes. Tritium is produced in the earth's atmosphere by interactions of cosmic ray-produced neutrons and nitrogen. These naturally-produced sources of tritium result in low, but steady-state concentrations of tritium in ground water (generally less than 1 tritium unit). A tritium unit (TU) is the equivalent of one tritium atom in 10^{18} atoms of hydrogen. Large quantities of tritium were introduced into the atmosphere as the result of atmospheric testing of thermonuclear bombs during the 1950's and early 1960's (Freeze and Cherry, 1979). Because of the relatively short half-life of tritium (12.3 years), and the large amount of tritiated water that entered the hydrologic cycle during the 1950's and 1960's, trituim can be used as a sensitive indicator of water that has entered ground water since 1954.

A basic difference between tritium and ^{14}C is that tritium is part of water molecules, whereas ^{14}C is in dissolved constituents in water. The potential exchange between dissolved carbon and carbon contained in sediments in aquifers in the investigation area could influence residence time calculations.



EXPLANATION

Straight River Basin

3.93 ● Observation well--Number shows nitrate (nitrate plus nitrite as N) concentration (in milligrams per liter) in water from wells.

Figure 26.--Nitrate concentrations in ground water.

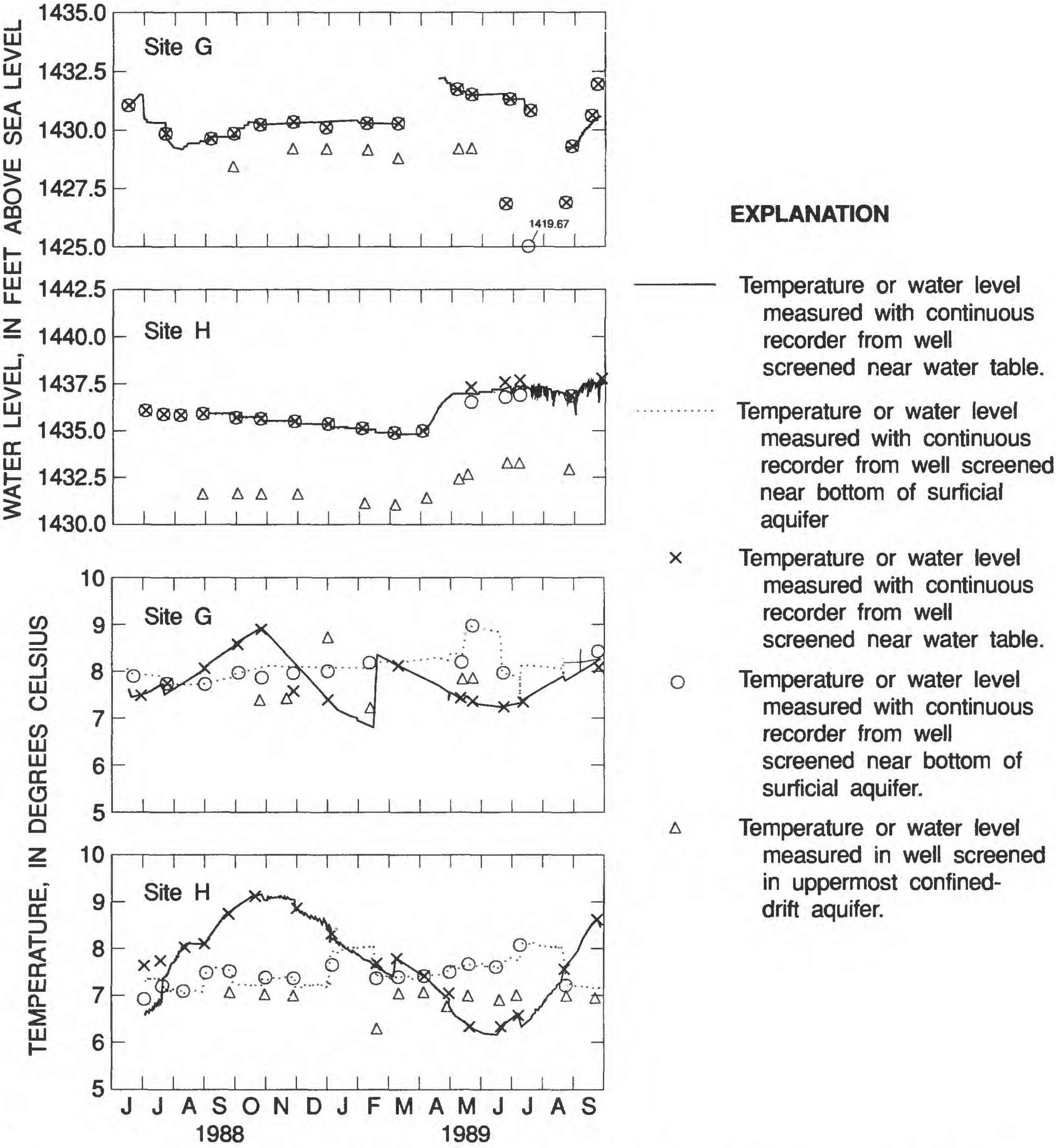


Figure 27.--Temperatures and water levels in surficial and uppermost confined-drift aquifers at irrigated (site G) and nonirrigated (site H) areas in investigation area.

A classification to describe the residence time of ground water based on the concentrations of ^{14}C and tritium in ground water has been developed by Calvin Alexander (University of Minnesota, written commun., 1990). Water with concentrations of ^{14}C of at least 50 percent of current precipitation and tritium concentrations greater than 10 TU are termed recent water. These waters are dominated by water that entered the ground since 1954. Vintage water is defined as that containing concentrations of ^{14}C less than 50 percent of the concentration of modern precipitation and tritium less than one TU. These waters are dominated by water that entered the ground before the advent of atmospheric testing of nuclear weapons in 1954. Mixed water contains water with ^{14}C greater than 50 percent of the concentration of modern precipitation and tritium between 1 and 10 TU. The average residence time of these mixed waters probably ranges from about 40 to a few-hundred years. Ancient waters contain concentrations of ^{14}C less than 50 percent of modern and no detectable tritium (less than 1 TU).

Water from 19 wells was collected and analyzed for ^{14}C and tritium. Results of the analyses of water from wells screened in the surficial aquifer showed that waters from that aquifer were isotopically recent, regardless of the depth of the well. Tritium concentrations generally were greater that 50 TU. The uppermost confined-drift aquifer contains waters that are recent, vintage, and mixed. Increased tritium in the uppermost confined-drift aquifer was in areas of significant irrigation ground-water withdrawal, indicating that ground-water withdrawal may be inducing downward leakage of isotopically younger waters from the surficial aquifers. Waters from the deeper confined-drift aquifers generally have tritium concentrations of less than one TU and, based on ^{14}C data, are about 12,000 years old. Residence-time data are significant because they indicate that waters in both the surficial and in the uppermost confined-drift aquifers are susceptible to contamination from local recharge.

Stream-Aquifer Interactions

A dynamic set of hydrologic conditions cause water to move through aquifers and confining units (fig. 2) in the Straight River watershed, resulting in discharge to the Straight River. The direction and rate of water movement from the aquifers to the Straight River is affected by (1) aquifer recharge, (2) hydraulic conductivity, (3) hydraulic gradient, (4) hydraulic conductivity of the streambed and, (5) the hydraulic head difference between the stream and aquifer. Recharge to the surficial aquifer occurs everywhere the aquifer is present. Ground-water discharges into the stream along most of the length of the stream because the hydraulic head in the surficial aquifer is greater than the hydraulic head of the stream. Part of the water flows through the surficial aquifer and part flows through surficial aquifer, confining units, and the uppermost confined-drift aquifer before being discharged to the stream.

Comparison of the potentiometric surfaces of the surficial and the uppermost confined-drift aquifers (figs. 15 and 22) shows that the two surfaces have similar configurations. The differences in hydraulic head between the aquifers also indicate that downward leakage occurs in highland areas where ground water flows vertically downward to the uppermost confined-drift aquifer. In areas of discharge (near streams), water moves vertically upward from the uppermost confined-drift aquifer to the surficial aquifer and then to the stream.

Ground water flows into the Straight River Basin in the southwestern part of the investigation area, near the Shell River, where the ground-water basin does not coincide with the surface-water basin. Ground-water flow in this area is from the southwest. Hydraulic gradients indicate that flow from areas outside the Straight River Basin is significant and contributes to the relatively high base flow of the stream compared to streams with similar surface-basin areas.

Results of the hydrograph analysis (tab. 5) indicate that at least 95 percent of streamflow in the Straight River during the 1988 water year was derived from base flow. Using a technique developed by Wahl and Wahl (1988), which is based on a method proposed by the Institute of Hydrology (1980a, 1980b), the data also show that incremental base-flow decreases slightly in a downstream direction.

Base-flow gain measured between gaging stations allows for analysis of the spatial variability of base flow within the watershed. Because the area upstream from site B is more than half of the watershed area, the change in base flow per square mile supplying the sites downstream from site B is masked by the magnitude of area and flow upstream of site B and by the effect of Straight Lake. Incremental base flow, which represents base flow contributing only to the areas between sites, is 0.835 ft/yr (feet per year) for the area between sites B and D, and 0.759 ft/yr for the area between sites D and F. These values are expressed as depth of water over the contributing area.

Recharge commonly occurs during the spring from snowmelt and rain. Recharge also may occur during autumn. Rates of ground-water recharge usually are low in the summer and winter because most precipitation is lost to evapotranspiration or is held as snowpack. Stream-base-flow data indicate that a recharge rate of greater that 12 in./yr (inches per year) is typical for the surficial aquifer in the Straight River watershed. This rate is significantly greater than most estimates of recharge to sand plain areas in Minnesota, and is twice as great as mean annual runoff for the general area (Jacques and Lorenz, 1988). The rate is also significantly greater than the average value of ground-water recharge (5.1 in./yr) reported by Helgesen (1977) for the Pineland Sands.

Recharge, estimated from base flow in the Straight River, may be larger than estimates of recharge to sand plain aquifers from other studies in Minnesota because of highly permeable surficial deposits, because of the contribution of underflow into the watershed, or because of a combination of these factors. This rate of recharge is one explanation for the sustained high base flow in the stream.

Table 5.--Stream base-flow data (1988 water year) computed at permanent-record stations in Straight River, Becker and Hubbard Counties, Minnesota

[acre-ft/yr, acre-foot per year; mi^2, square mile; $ft^3/mi^2/yr$, cubic foot per square mile per year; --, not determined]

Station name	Total runoff (acre-ft/yr)	Base flow [1](acre-ft/yr)	Base flow index	Drainage area (mi^2)	Base flow per square mile (acre-ft/mi^2/yr	Base flow per square mile (ft^3/mi^2/yr)	Base flow per square mile (in./yr)	Incremental base flow [2](ft/yr)
05243721 (site B) Straight River at Becker County Road 125, near Osage	26,560	25,230	0.95	32.3	781	34,020,000	14.64	--
05243723 (site D) Straight River at Hubbard County Road 115, near Park Rapids	33,520	32,180	.96	45.3	710	30,927,000	13.32	0.835
05243725 (site F) Straight River at U.S. Highway 71, near Park Rapids	37,080	35,970	.97	53.1	677	29,490,000	12.72	.759

[1] based on the method from Wahl and Wahl (1988).

[2] calculated as: $\frac{\text{change in base flow over the reach}}{\text{change in drainage area}}$

Ground water leaves the aquifer system by evapotranspiration, by withdrawals through wells, and as discharge to the Straight River, ponds, and wetlands. A significant portion of discharge from the ground-water system is to the Straight River and to production wells. The Straight River is the major discharge zone for the uppermost confined-drift and surficial aquifers; the aquifers are the primary source of water to the stream. Ground-water divides, which separate ground-water-flow systems discharging to the Straight River from systems that discharge to the other streams, are approximately coincidental with the surface-water divides between the streams. An exception is in the vicinity of the Shell River in the southwestern part of the investigation area where there is underflow into the Straight River watershed from the southwest. The direction of ground-water flow varies near many wetlands and ponds.

The amount of ground-water loss to evapotranspiration depends on water availability (particularly depth to the water table below land surface), solar energy supplied, air temperature, and humidity. The rate of evapotranspiration is assumed to be a maximum of 22 in./yr (Baker and others, 1979) where water levels are at land surface. This rate is assumed to decrease to zero where water levels are below the root-zone depth. The approximate root-zone depth for vegetation in the investigation area is assumed to be about 5 ft. Large quantities of water are discharged from the ground-water system through evapotranspiration during the summer. These losses decrease rapidly in the fall and are near zero in the winter.

Ground-water withdrawals to 53 high-capacity irrigation wells were a major use of ground water in the investigation area in 1988. Withdrawal from these wells was divided between the surficial aquifer (23 wells) and the uppermost confined-drift aquifer (25 wells) at that time. The average irrigated field received about 12 in. of irrigation water in 1988. During 1988 approximately 2.3 billion gallons of ground water were withdrawn from the aquifers beneath the drainage basin. This consisted of 0.9 billion gallons from the surficial aquifer, and 1.4 billion gallons from the uppermost confined-drift aquifer. The total compares with a total stream discharge of the Straight River at U. S. Highway 71 of 3.7 billion gallons during the four-month (May-August) summer period.

In general, ground-water discharge to the Straight River exceeds leakage from the river into the ground-water system. An exception may occur during periods of heavy ground-water withdrawal, when water from the river enters the aquifer along short reaches of the river. Measurements of ground-water discharge to lakes and to swamps were not made during this investigation.

Streamflow in the Straight River during September 1987-September 1988 ranged from about 25 ft^3/s near the outlet of Straight Lake near Osage to about 51 ft^3/s at U.S. Highway 71, near the mouth. Streamflow, which was relatively uniform throughout the year, increased in a downstream direction during most of the year. As described previously in the section on low flow characteristics, base flow increased by an average of 14.5 ft^3/s between sites B and F during the 1988 water year. Between sites B and D base flow increased by about 9.6 ft^3/s, between sites D and F, it increased by about 4.9 ft^3/s (tab. 5). During periods of low flow, the gain between sites D and F was a smaller percentage of the total base flow (Gunard and others, 1990). These data indicate that there were times, during periods of low flow, when the lower reaches of the Straight River lost water to the surficial aquifer. These losses may have been due to ground-water withdrawal or to increased evapotranspiration from wetlands near the stream in the lower reaches of the watershed. As a percentage of total flow in the stream, however, these losses were small. Analysis of discharge in the Straight River is complicated by backwater from ice in the winter and by aquatic vegetation in the channel during the summer. These conditions affect the collection of accurate stream-discharge data.

The runoff and base-flow components upstream from each of the permanent-record stations on the Straight River were calculated for the 1988 water year using a technique developed by Wahl and Wahl (1988), which is based on a method proposed by the Institute of Hydrology (1980a, 1980b). It involves dividing the year into 5-day increments and identifying the minimum flow for each increment. When a value of 0.9 times this minimum is less than the preceding and following minima, the minimum is considered a turning point of the base-flow hydrograph. The area beneath a line drawn between turning points is used as an estimate of the volume of base flow for the period. The ratio of this volume to the actual volume of discharge for the period is defined as the base-flow index. Although the method does not exactly duplicate the values of base flow obtained from other methods, tests in Great Britain (Institute of Hydrology, 1980b; Swan and Condie, 1983) indicate results that are similar to that of other methods.

Stream discharge data (tab. 5) show that average base flow in the watershed (expressed as depth over the watershed) during the 1988 water year (a period of drought) was greater than one foot. This value is significantly greater than most estimates of ground-water

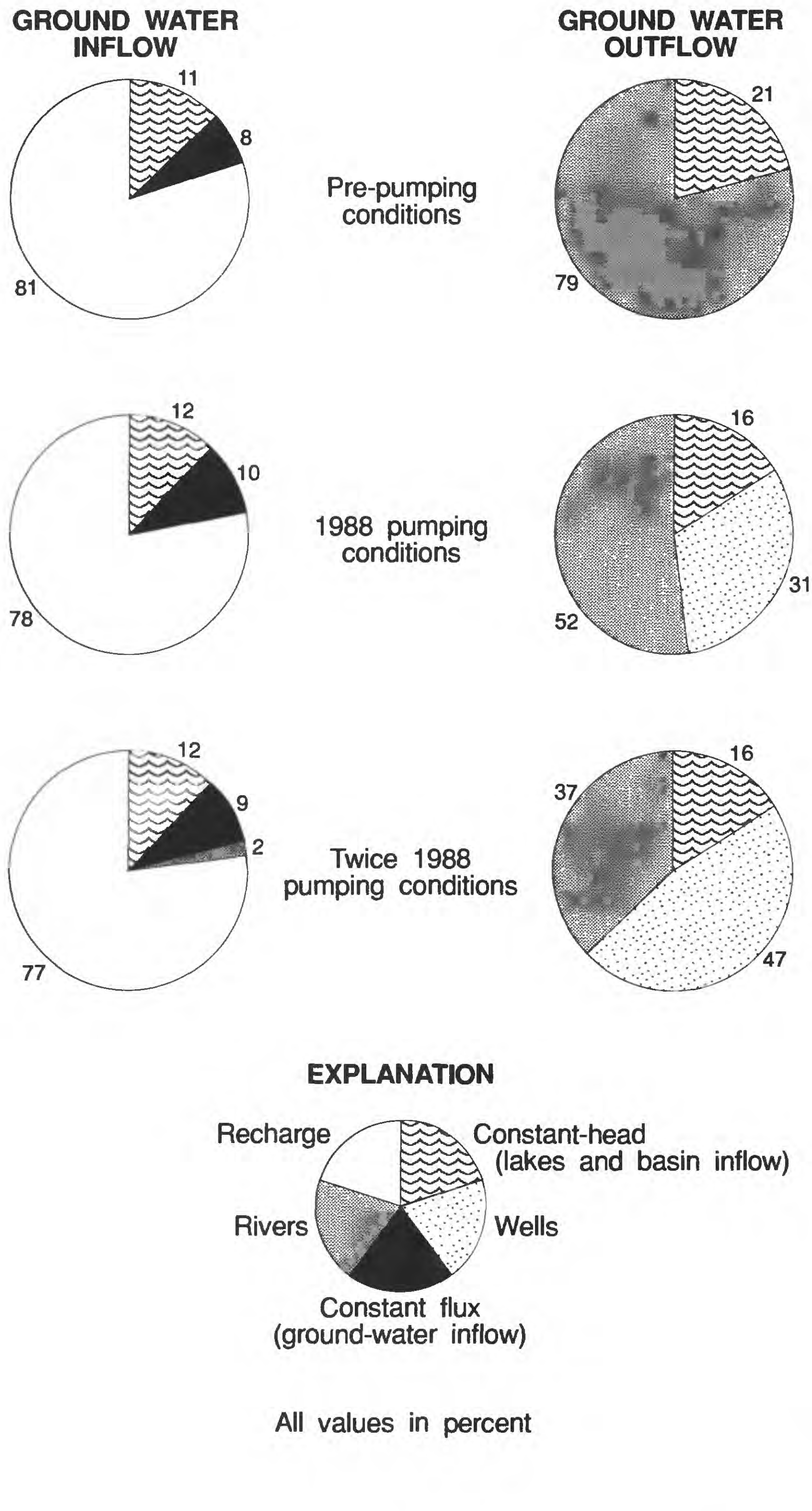


Figure 28.--Model-calculated, ground-water inflow and outflow for simulations representing pre-development, 1988, and hypothetical (doubling of 1988 ground-water withdrawal) rates of ground-water withdrawal from the investigation area.

recharge to sand plains in Minnesota. Helgesen (1977), estimated ground-water recharge in the Pineland Sands area at about 5.1 in./yr. Recharge to the ground-water system in this area may be increased because of highly-permeable surficial deposits.

Results of model simulations (fig. 28) conducted for this investigation indicate that ground-water withdrawal rates similar to those of 1988 have the potential to reduce streamflow gain by as much as 34 percent during the irrigation season.

Ground-water inflow temperature, which averages about 7°C throughout the year, helps to keep the Straight River cool during summer. Model simulations were conducted to evaluate the potential effect of reduced ground-water inflow on stream temperature. Reduced ground-water inflow was simulated to have resulted from ground-water withdrawal for irrigation. In these simulations, model-input conditions were identical to conditions for simulations used to calibrate the model to measured stream conditions except that ground-water inflow was reduced by 34 percent. Results of the simluations indicate that a potential reduction in streamflow due to irrigation has potential to cause an increase in stream temperature of 0.5 to 1.5°C. This potential increase may have an adverse effect on the habitat of the stream for trout. There currently is little evidence to indicate, however, that irrigation is having a significant effect on ground-water temperature, or on the temperature of the Straight River.

The construction of the dam at Osage also may have resulted in increased temperature of the Straight River. Measurements of water temperature in Straight Lake indicate that it ranges from about 22°C near the surface to about 10°C at depths of 45 feet below the lake surface during late summer. Relatively warm surface and near-surface lake water flows into the stream below the dam. Model simulations of the stream, in which the temperature of water discharging from the lake was reduced by 5°C, were conducted to represent possible bottom release of water from the dam. These simulations indicate that stream temperature could be reduced by as much as 1.3°C, about three miles downstream from the dam at site B, if the outlet structure of the dam were changed. The reduction in stream temperature was found to be less significant downstream from site B.

Ground water and stream water in the area generally are of the calcium bicarbonate type, and nearly identical in composition. The chemistries of water from the surficial and the uppermost confined-drift aquifers, and from the Straight River, generally are similar. Figure 25 illustrates that common cations and anions plot in the same general areas of the diagram for both aquifers and the stream. The similar grouping of data shows that major cations and anions in water samples from the surficial and uppermost confined-drift aquifers have concentrations which indicate that most stream water originates as ground water.

Figures 10 and 11 illustrate the temperature of the stream, air, and ground water in detail during July 1988 (sites A and B) and January 1989 (sites A nd F). At site A during July, (fig. 11) just downstream from the dam at the outlet of Straight Lake, stream temperature is relatively constant due to discharge of water from the lake, and averages about 25°C. The stream is not significantly influenced by fluctuations in air temperature at this site. At site B (downstream) stream temperature has significant daily fluctuations, and is primarily related to air temperature. Stream temperature at site B is colder than at site A because of an increase in ground-water inflow, and averages about 19°C during July.

Figure 10 illustrates the thermal characteristics of the stream at the sites A and F during January. Stream temperatures approach 0°C, but water generally does not freeze because of turbulence, the thermal heat of fusion, and the influence of warmer ground water flowing into the stream. Winter stream temperature is slightly warmer at site A than at site F because of continuous release of warmer water stored in Straight Lake and from ground water. Daily fluctuations of water temperature in the river are not significantly influenced by air temperature in the winter.

Water at site B generally is colder during the summer than at other sites because this is an area of ground-water inflow along the stream. Ground-water inflow temperature, which averages about 7°C throughout the year except in areas where the water table is near land surface, tends to reduce stream temperature during the summer and increase stream temperature during winter.

Effects of Irrigation

Stream discharge data indicate that the Straight River was affected by irrigation pumping during the summer of 1988. Model simulations, described in the Ground-Water Flow Model section of the Supplemental Information Section, were evaluated by matching model-calculated streamflow and ground-water-level information with measured data from the summer of 1988. A lack of long-term data on ground-water withdrawal for irrigation, ground-water recharge, and water level does not allow the time-dependent (transient) simulation of the ground-water system. During the summer, the water-table and potentiometric surface of the uppermost confined-drift aquifer approached low levels. These water levels are assumed to be near steady-state conditions where sources of water approximated sources of discharge, and little change in storage occurred. These simulations indicate that continuous irrigation at rates comparable to those of 1988, and given ground-water recharge similar to that of 1988, could result in water-level declines ranging from 0 to 10 ft in the surficial aquifer and 0 to 15 ft in the uppermost confined-drift aquifer. This lowering of the water table and the potentiometric surface could result in a reduction of stream base flow of about 34 percent compared to conditions of no ground-water withdrawal for irrigation (fig. 28).

Summary and Conclusions

The Straight River contains water that is cold and clear. The 75 mi^2 Straight River watershed is underlain by highly transmissive surficial and confined-drift aquifers. Ground-water withdrawals from these aquifers, which sustain flow of the Straight River, are increasing in response to changes in land use from dry-land farming to irrigated farming. A decrease in ground-water discharge to the stream caused by withdrawals for irrigation has potential to increase stream temperature, which would in turn affect the trout habitat in the stream.

Data indicate a hydraulic connection between the stream and the surficial aquifer. Discharge of the Straight River increased from about 25 ft^3/s near the outlet of Straight Lake to about 51 ft^3/s near the mouth. The rate of gain in discharge during summer decreased downstream, possibly as a result of ground-water withdrawal for irrigation. Hydraulic conductivity values for the surficial and uppermost confined-drift aquifers average about 255 and 300 ft/d, respectively, based on results of previous studies and model simulations. The water table in the surficial aquifer and potentiometric surface of the uppermost confined-drift aquifer slope toward the Straight River at a gradient of about 10 ft/mi.

Daily fluctuations of stream temperature are as great as 15°C during the summer. Ground-water discharge cools the stream during the summer and warms it in the winter. Results of stream-temperature model simulations indicate that daily changes in stream temperature are strongly influenced by solar radiation, wind speed, stream depth, and ground-water inflow. Nitrate concentrations in water from shallow wells completed at the water table are greater, at least locally, than the limit set by the MPCA. Nitrate concentrations in water from deeper wells and in the stream generally are less than 1.0 mg/L.

Results of simulations made using ground-water-flow and stream-temperature models developed for the study indicate that a significant decrease in ground-water flow may result from ground-water withdrawal at rates similar to those in 1988, and that this reduction in discharge to the stream may result in an increase in stream temperature of as much as 0.5 to 1.5°C.

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Supplemental Information

Stream Flow Velocity

Dye tracers were used in a time-of-travel study conducted on the Straight River to aid in calibration of stream-transport models and to better define the flow characteristics of the stream. Time-of-travel refers to the movement of water or conservative waterborne solutes in a stream during steady or gradually-varied flow conditions (Kilpatrick and Wilson, 1989).

The measurement of travel time using dye tracers involves the injection of dye along the stream and measurement of dye concentrations downstream. When a fluorescent dye is used as a tracer, the degree of fluorescence can be determined with a fluorometer. The concentration of dye in the sample is directly proportional to its fluorescence.

The dispersion and mixing of dye in the stream takes place in three dimensions in the channel. Vertical mixing normally takes place first, and lateral mixing later, depending on stream characteristics and velocity variations. Longitudinal dispersion continues throughout the length of the stream. A plot of concentration against time defines the dye-response curve at each sampling site. Time-of-travel is the time required for movement of the dye between sampling sites.

A time-of-travel study was conducted at the Straight River during August 23 through August 25, 1988. The results of the study summarized in table 6, indicate that the average velocity of the stream (about 0.5 ft/s) is relatively uniform but increases slightly downstream.

Ground-water-flow Model

A ground-water-flow model was developed for this investigation to help understand regional flow in the hydrogeologic system, hydraulic properties of hydrologic units, and the interaction between the aquifers and the stream. The model was calibrated using hydraulic, water-level, and water-use data compiled during the investigation and is intended as a tool to help understand the hydrologic system, and not as a predictive model. The U.S. Geological Survey's modular ground-water flow

Table 6.--Summary of data from time-of-travel study of the Straight River, August 1988
[mi, mile; ft^3/s, cubic feet per second; ft/s, feet per second; µg/L, micrograms per liter]

River Reach	Reach length (mi)	Discharge (ft^3/s)	Travel time (hours) leading	Travel time (hours) centroid	Trailing 5 percent	Velocity of centroid (ft/s)	Peak concentraion (µg/L)	Dye recovery (percent)
Minnesota Highway [1]34 to Becker County Highway 123 (center of stream)	1.36	25.5	2.78	4.33	6.97	0.46	7.53	94
Minnesota Highway [1]34 to Becker County Highway 123 (right bank)	1.36	25.5	2.78	4.20	5.27	.47	7.27	60
County Highway 123 to Station #05243721	3.30	32.4	10.25	12.80	19.03	.38	1.90	89
Station # [2]05243721 to Station #05343722	3.40	36.6	7.87	11.12	17.00	.45	2.90	64
Station # 05343722 to Station # 05243723	2.86	42.7	8.03	8.93	11.67	.47	1.40	63
Station # [3]05243723 to Station 05243724 (center of stream)	1.20	40.3	2.30	3.03	4.27	.58	5.42	70
Station # [3]05243723 to Station 05243724 (left bank)	1.20	40.3	2.30	3.03	4.27	.58	5.42	70
Station # 05243724 to Station # 05243725	2.12	47.2	4.33	5.41	7.05	.57	2.17	84

[1] Dye injected at 0600 hours on 08-25-88 (150 ml-20% Rhodamine W.T.)
[2] Dye injected at 1100 hours on 08-25-88 (150 ml-20% Rhodamine W.T.)
[3] Dye injected at 1600 hours on 08-25-88 (150 ml-20% Rhodamine W.T.)

model (McDonald and Harbaugh, 1988) was used. The model options used for simulations included the basic, block-centered flow, river, well, recharge, and strongly implicit model packages. The model uses natural hydrologic boundaries (streams and ground-water divides) to simulate the ground-water system (figs. 29-31). Model cells are small along the stream to more accurately simulate the exchange of water between the stream and the ground-water system. Model cells were expanded in size away from the stream. The model simulates horizontal and vertical ground-water flow in the surficial aquifer (layer 1), in the uppermost confining unit (layer 2), in the uppermost confined-drift aquifer (layer 3) and vertical flow through the streambed.

Once calibrated to the assumed steady-state hydrologic conditions of August 1988, the model was used to analyze ground-water discharge to the stream and to indicate the amount of decline in potentiometric head, changes in the direction and rate of movement of ground water, and decrease in streamflow that might result from increased ground-water withdrawal.

Model representation

The model solves a finite-difference approximation to the ground-water-flow equation in three dimensions, given in equation 1.

$$\frac{\partial}{\partial x}Kxx\frac{\partial h}{\partial x}+\frac{\partial}{\partial y}Kyy\frac{\partial h}{\partial y}+\frac{\partial}{\partial z}Kzz\frac{\partial h}{\partial z}-W = Ss\frac{\partial h}{\partial t} \quad (1)$$

where

x, y and z are Cartesian coordinates aligned along the major axes of hydraulic conductivity Kxx, Kyy, Kzz [L/t],

h is the hydraulic head [L],

W is a volumetric flux per unit volume and represents sources and/or sinks of water [t^{-1}],

Ss is the specific storage of the porous material (Ss is zero for steady-state simulations) [L^{-1}], and t is time [t].

The equation governs the simulated flow of water through aquifers and confining units in relation to aquifer characteristics and boundary conditions. A conceptually-based, physical model with simplifying assumptions about the ground-water system was formulated to aid in the development of the model. The conceptually based model consists of a qualitative description of the known characteristics and behavior of the hydrologic system. The major assumptions associated with the model are as follows:

1. The surficial aquifer, the uppermost confining unit, and the uppermost confined-drift aquifer (fig. 2) are represented as model layers 1, 2, and 3, respectively.

2. Drift (including aquifers and confining units) below the uppermost confined-drift aquifer are assumed to form an impermeable lower boundary and are not simulated.

3. Aquifers and the uppermost confining unit are simulated as homogeneous and isotropic.

4. Water levels in major surface-water bodies are relatively stable with time and are simulated as leaky cells or as constant-head cells.

5. Net recharge to the water table is from infiltration (less evapotranspiration) and can be varied depending upon the type of surficial material. Evapotranspiration is accounted for by using a net value of recharge (net recharge = recharge - evapotranspiration).

6. Leakage to and discharge from the uppermost confined-drift aquifer is through the uppermost confining unit. The leakage is dependent on vertical hydraulic conductivity and thickness of the confining unit, and on hydraulic head in adjacent aquifers.

7. Ground-water pumped from wells is not returned to the aquifer system. Although some applied irrigation water probably does percolate back to the water table, this amount was not estimated, and thus the effect of percolation of irrigated water on ground-water temperature was not determined.

Model design

The model represents steady-state ground-water flow by computing hydraulic head over the extent of the surficial aquifer or surrounding areas that extend to the watershed boundaries. These boundaries are represented by no-flow cells (figs. 29-31). The active area of the model is about 82.6 mi^2. The active model grid contains 44 rows and 64 columns. A uniform grid spacing of 1,320 ft on each side was used for most of the modeled area. This grid was not precise enough to accurately simulate the area of the Straight River and grid cells were reduced in size to 820 ft by 1,320 ft in these areas. The upper portion of the drift system was divided into three model layers: (1) layer 1 (the top layer) represents the surficial aquifer; (2) layer 2 represents the uppermost confining unit; and (3) layer 3 represents the uppermost confined-drift aquifer.

Boundary conditions for layer 1 were chosen to simulate hydrologic boundaries (fig. 29). In layer 1 ground-water divides were simulated as no-flow cells. The Straight River was simulated by head-dependent-flux cells. The Shell River was represented as a no-flow

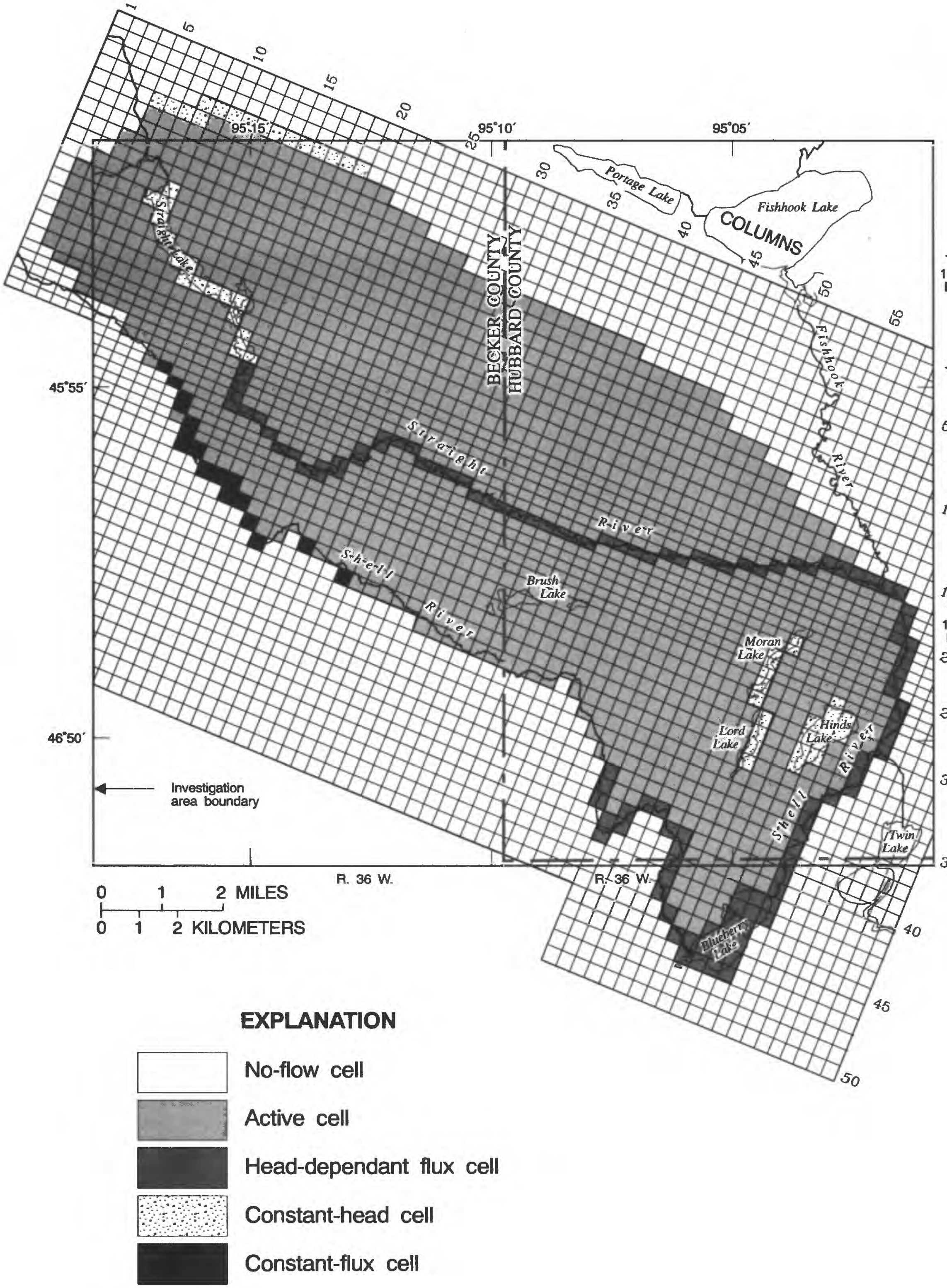

Figure 29.--Areal extent, finite-difference grid, and boundary conditions for layer 1 of ground-water-flow model.

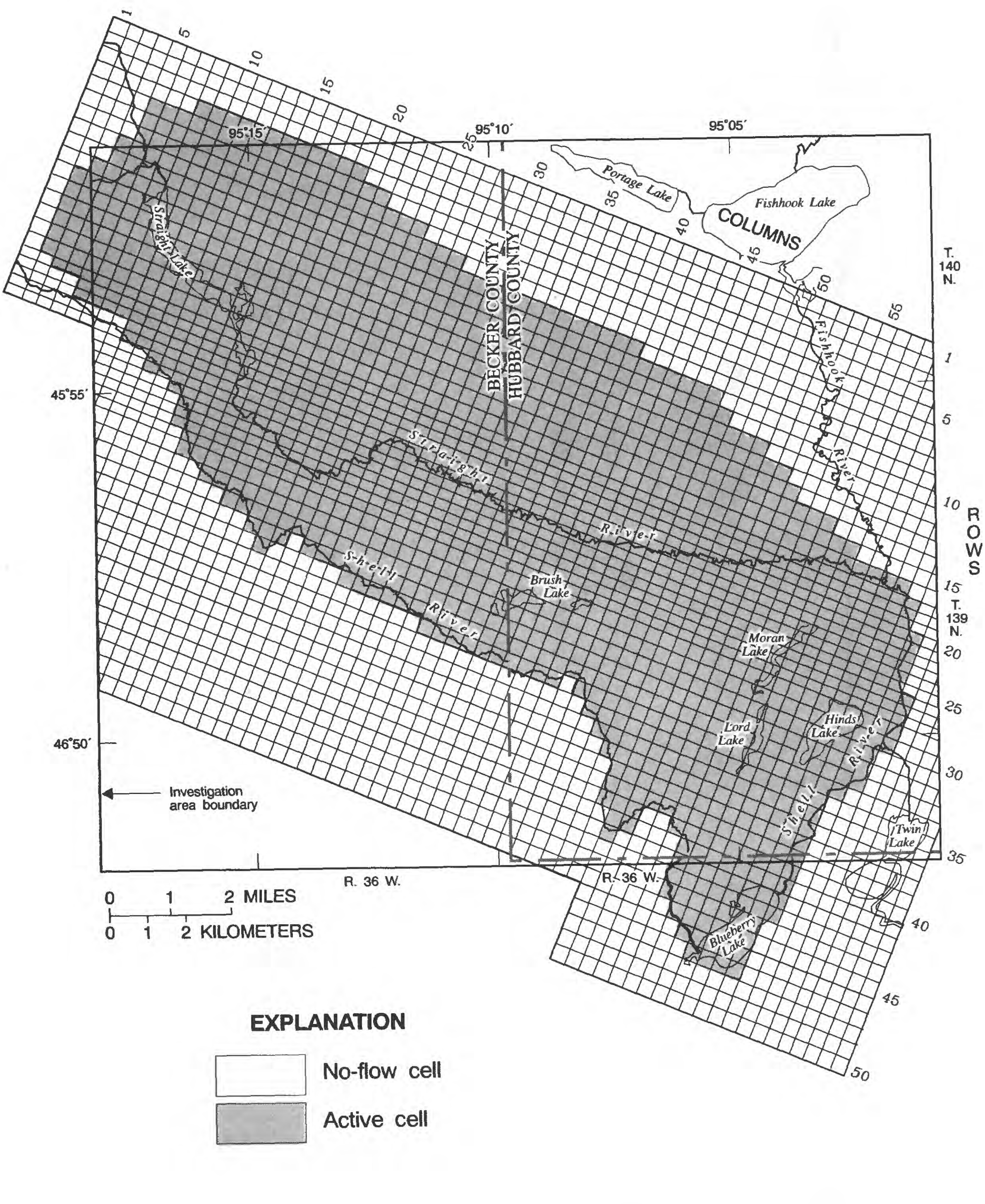

Figure 30.--Areal extent, finite-difference grid, and boundary conditions for layer 2 of ground-water-flow model.

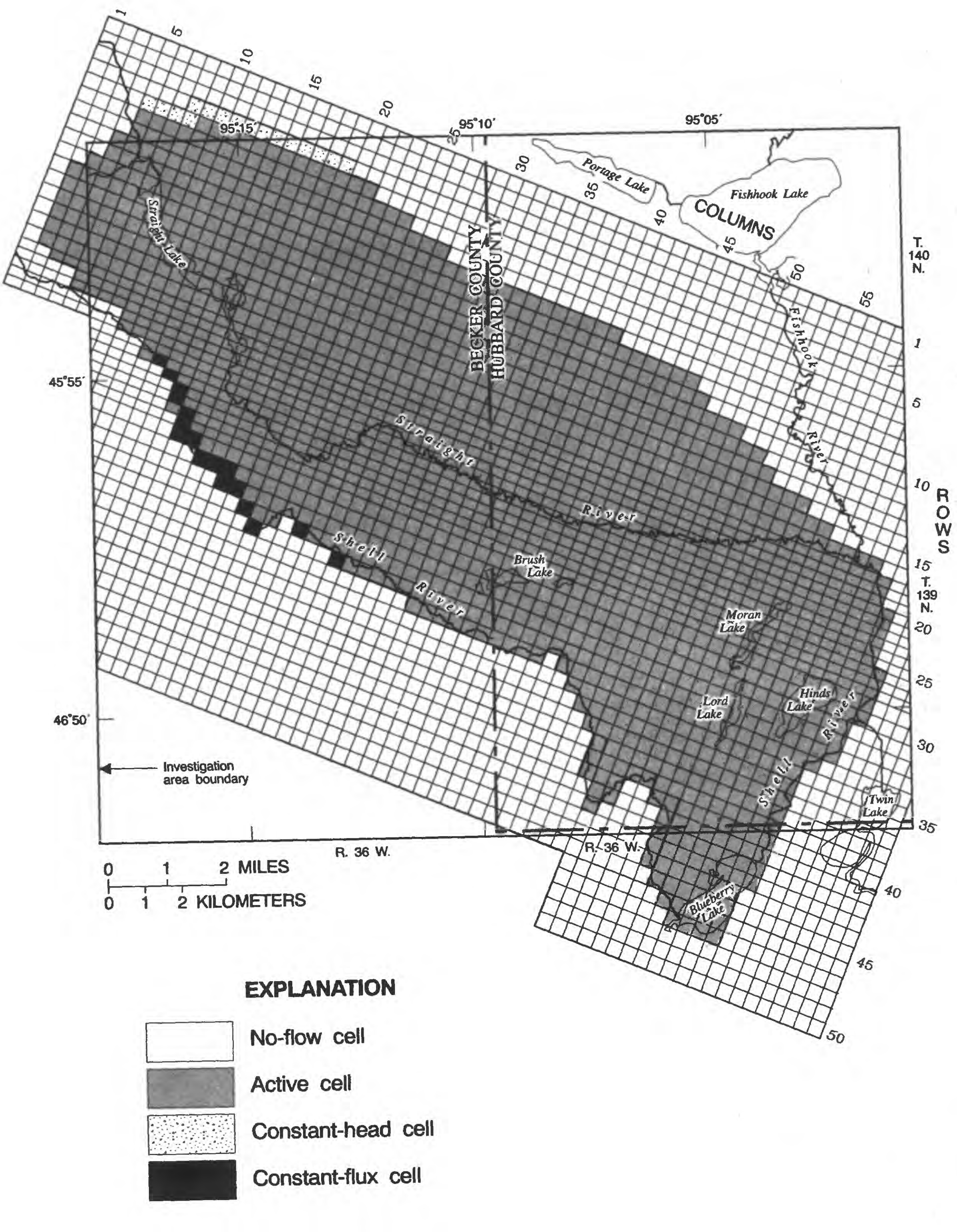

Figure 31.--Areal extent, finite-difference grid, and boundary conditions for layer 3 of ground-water-flow model.

boundary where the stream was hydraulically isolated from the aquifers because till was exposed at land surface and ground-water movement was parallel to the Shell River. The Shell River was represented by head-dependent flux cells in areas where the stream is a discharge boundary. Constant-flux cells were used to simulate underflow into the ground-water basin, from the southwest. This underflow was estimated to be about 5.5 ft^3/s based on calculations using Darcy's Law. Major lakes, including Straight Lake, were simulated as constant-head cells. Constant-head cells also were used to simulate inflow to the model in an area north of Straight Lake where the aquifer extends beyond the investigation area. It was assumed that assigned head values at boundaries represent an average potentiometric-surface condition over time.

Cell conditions for layer 2 consisted of active and no-flow cells (fig. 30). Boundary-cell conditions for layer 3 (fig. 31) consisted of active cells, no-flow cells (representing the limits of the uppermost confined-drift aquifer), constant-flux cells (simulating underflow into the ground-water basin from the southwest (2.4 ft^3/s) based on calculations using Darcy's law), and constant-head cells (representing inflow to the model in an area north of Straight Lake).

Geologic and hydrologic data compiled for this investigation were used to assign hydrogeologic characteristics to model cells. These data include the altitude of the top of the uppermost confining unit (fig. 16), potentiometric surfaces of the surficial and uppermost confined-drift aquifers (figs. 15 and 22), the altitude of the top of the uppermost confined-drift aquifer (fig. 20) and the thickness of the uppermost confined-drift aquifer (fig. 21). Initial values of hydraulic properties for the model hydrogeologic units were estimated from data prepared for this investigation or adopted from published reports. Initial recharge rates were estimated by combining the total amount of stream base flow (tab. 5) and water withdrawn for irrigation. Ground-water withdrawal rates were compiled from data provided by the MDNR and results of data collected for this investigation, and were simulated as 2.5×10^6 ft^3/d which represents the average irrigation-application rate during the four-month summer (1988) period (tab. 7).

Sensitivity analysis and model evaluation

Sensitivity analysis was conducted to identify model variables that have the greatest effect on simulated potentiometric heads and simulated discharge to streams. This analysis identified the variables to which the model

Table 7.--Withdrawal rates for model cells representing high-capacity production wells in the investigation area used during simulations of four-month 1988 summer period

[gal/min, gallons per minute]

Layer	Row	Column	Irrigation withdrawal (gal/min)
1	13	32	90.65
1	14	6	262.3
1	15	4	98.63
1	15	29	355.8
1	15	30	202.8
1	15	31	72.65
1	15	35	229.2
1	15	44	26.8
1	15	46	429.7
1	16	7	163.4
1	16	30	342.4
1	16	37	364.5
1	16	39	283.9
1	16	46	310.8
1	16	49	150.0
1	17	5	328.5
1	18	26	235.6
1	19	11	373.4
1	19	32	168.9
1	22	49	221.5
1	26	26	111.8
1	26	33	121.6
1	27	19	74.07
3	9	42	297.5
3	9	44	218.6
3	13	30	262.7
3	13	49	426.9
3	13	52	112.8
3	14	54	1235
3	17	35	327.4
3	17	38	223.1
3	18	9	271.9
3	18	34	192.8
3	18	40	245.6
3	18	41	386.8
3	19	25	607.3
3	19	36	511.7
3	19	42	264.1
3	20	12	542.0
3	20	58	394.2
3	20	60	210.1
3	21	40	233.2
3	21	56	238.0
3	22	50	184.5
3	22	51	190.6
3	23	28	324.7
3	24	53	127.9
3	29	17	79.89

was most sensitive, and therefore indicated types of additional data collection or model refinement that would most improve the model simulation of the hydrologic system.

Sensitivity analysis (based on comparisons between sensitivity-simulation results and a model-simulation using "best estimates" of hydrologic values, S1 in tab. 8) indicated that recharge, horizontal hydraulic conductivity of model layer 1, and horizontal hydraulic conductivity of model layer 3 were the variables that most affected model-simulated hydraulic heads and model-simulated discharge to streams and lakes (tab. 8). A total of 30 model cells were used to compare simulated hydraulic head in model layer 1 with measured hydraulic head in the surficial aquifer. A total of 9 cells were used for comparison of model layer 3 with measured hydraulic head in the uppermost confined-drift aquifer. Measured base-flow gain to the stream at three locations (sites B, D and F—fig. 5) also was used to compare to simulated streamflow gain.

The model also was tested to determine the range of values of hydrologic properties that provide simulated potentiometric heads and simulated stream discharge that best match those measured in the field. This process consisted of adjusting values of sensitive hydrologic properties (recharge and horizontal hydraulic conductivity of model layers 1 and 3) within realistic limits (based on ranges in published values) until simulated potentiometric heads and simulated ground-water discharge to the Straight River acceptably matched corresponding measured values. This combination of values, however, is not unique and other combinations of values could produce similar results.

Ground-water discharge to the Straight River and measured water-level elevations in selected wells were used to determine whether model-simulated output was acceptable. Base-flow discharge to the Straight River was measured at selected sites during the summer of 1988 and was compared to model-simulated ground-water discharge to the stream under steady-state conditions representing the summer of 1988. Measured streamflow in the Straight River at three locations (at Becker County Highway 125 (site B), at Hubbard County Highway 115 (site D), and at State Highway 71 (site F)) averaged 13, 24, and 29 ft^3/s, respectively during the summer of 1988. This compared with model-calculated streamflow at cells representing those locations (cells (21, 27), (22, 44), and (18, 54)) of 15, 27, and 30 ft^3/s, respectively. Other criteria used to evaluate model variables were the mean difference between model-simulated hydraulic heads in layers 1 and 3 of the model and measured hydraulic head in wells completed in the surficial and uppermost confined-drift aquifers. Because the model was used to improve the understanding of the regional flow system (as opposed to simulating local hydrologic conditions) model variables were not changed locally to produce a better match. A difference between simulated and measured head of 1 ft was arbitrarily chosen as an acceptable match. The distribution of model-simulated heads was in general agreement with the measured-head distribution (figs. 15 and 22). Model-computed hydraulic heads at 30 cells in model layer 1 averaged 0.10 ft less than hydraulic heads measured during the summer of 1988 in wells completed in the surficial aquifer in areas represented by those model cells. Maximum and minimum differences between model-simulated and measured hydraulic heads at individual cells were -20.74 and +12.63 ft in cells in model layer 1. Model-simulated hydraulic heads at 9 cells in model layer 3 averaged 0.67 ft less than hydraulic heads measured during the summer of 1988 in wells completed in areas represented by those model cells in the uppermost confined-drift aquifer. Maximum and minimum differences were -7.05 and +11.82 ft, respectively.

Values of horizontal hydraulic conductivity were estimated by varying the horizontal hydraulic conductivity in model cells representing the two aquifers (model layers 1 and 3) and in the uppermost confining unit (model layer 2). Values of horizontal hydraulic conductivity of 255 and 300 ft/d for the surficial and uppermost confined-drift aquifers, respectively, were found to provide acceptable results (tab. 9). The uppermost confining unit was simulated as having a horizontal hydraulic conductivity of 2.0 ft/d., and glacial till exposed at land surface (layer 1) was simulated as having a horizontal hydraulic conductivity of 12 ft/d. Vertical hydraulic conductivity values were changed in a similar manner. A value of 0.2 ft/d was considered an acceptable value of vertical hydraulic conductivity for the uppermost confining unit (layer 2) and values of 20 and 4 ft/d were considered to be acceptable for the surficial and uppermost confined-drift aquifers, respectively. Values of vertical streambed hydraulic conductivity were estimated by changing the model values for vertical hydraulic conductivity, assuming the streambed had a uniform thickness of 1 ft. The resulting value was found to be approximately 2.0 ft/d.

Results of model simulation

A water budget is an accounting of inflow, outflow, and changes in storage in a ground-water system. For steady-state simulations inflow (sources) to and outflow (discharges) from the system are equal and there are no long-term changes in storage. For this investigation the ground-water system was assumed to approach steady-

Table 8.--Sensitivity of hydraulic heads in the surficial and uppermost confined-drift aquifers (model layers 1 and 3) to changes in values of model variables, Straight River Basin, Minnesota

[ft^3/s, cubic feet per second; -, computed head was less than head measured in the field; *, model simulation was numerically unstable; NA, not available]

Hydraulic property [Simulation number] (value of multiplication factor for hydraulic property)	Mean error in computed heads between simulated and measured values of potentiometric head (feet): Layer 1	Layer 3	Model-computed stream gain along stream reach above indicated site (ft^3/s): Cell (row 21, column 27) at County Highway 125 (site B)	Cell (row 22, column 44) at County Highway 115 (site D)	Cell (row 18, column 54) at State Highway 71 (site F)
Recharge to model layer (inches per year)					
[S1] 12.5	0.8	-3.0	16.5	49	55
[S6] 25.0	8.2	3.3	29	65	80
[S7] 6.2	*	*	*	*	*
Values of horizontal hydraulic conductivity of model layer 1(feet/day)					
[S1] 510	.8	-3.0	16.5	49	55
[S2] 255	4.6	.2	15	30	35
[S4] 1020	*	*	*	*	*
[S5] 765	*	*	*	*	*
Values of horizontal hydraulic conductivity of model layer 3 (feet/day)					
[S1] 215	.8	-3.0	16.5	49	55
[S8] 107	2.0	-5.4	NA	NA	NA
[S9] 430	-.5	2.0	17	34	38
Factor of change in vertical conductance between model layers					
Between model layers 1 and 2					
[S1] 1.0	.8	-3.0	16.5	49	55
[S17] .1	*	*	*	*	*
[S10] .5	*	*	*	*	*
[S11] 2.0	.6	-2.7	NA	NA	NA
[S18] 10.0	.5	-2.5	NA	NA	NA
Between model layers 2 and 3					
[S1] 1.0	.8	-3.0	16.5	49	55
[S14] .1	1.6	-5.5	NA	NA	NA
[S13] .5	.7	-3.8	NA	NA	NA
[S12] 2.0	.7	-2.6	NA	NA	NA
[S16] 10.0	*	*	*	*	*

Table 9.--Selected model-input parameters after calibration and used for hypothetical ground-water withdrawal and drought scenarios

[--, not calculated]

	Surficial aquifer	Uppermost confined-drift aquifer	Uppermost confining unit	Glacial till	Stream bed
Net recharge (inches/year)	12.5	--	--	12.5	--
Horizontal hydraulic conductivity (feet/day)	255	300	2.0	12	--
Vertical hydraulic conductivity (feet/day)	20	4.0	.2	.1	2.0

state conditions during the summer of 1988, and model results represented steady-state conditions for August 1988. A general equation of the steady-state water budget in the modeled area can be written as:

$$P - RO - ET + G_{rs} + G_i = G_{ds} + G_p + G_o$$

where:

P = precipitation[1];

RO = runoff[1];

ET = evapotranspiration[1];

G_{rs} = ground-water recharge from streams, lakes, and swamps;

G_i = ground-water inflow;

G_{ds} = ground-water discharge to streams, lakes, and swamps;

G_p = ground-water pumpage;

G_o = ground-water outflow.

[1] values are lumped in model recharge term

The steady-state water budget for the calibrated model (tab. 10) shows that net recharge from precipitation is the major source of water to the system. Leakage to streams and lakes accounts for most of the discharge from the ground-water system; however, withdrawal of ground water through wells is a major source of discharge from the modeled area for model simulations representing summer steady-state conditions.

Table 10.--Model-computed water budget for the Straight River basin
[ft^3/s, cubic feet per second]

Budget component	Inputs (ft^3/s)	Outputs (ft^3/s)
Net recharge[1]	71.5	0.0
Constant heads[2]	10.5	14.7
Stream and lake leakage	.90	47.6
Well discharge	0	28.4
Constant flux[3]	7.89	0
Storage	0	0
Total	90.8	90.7

[1] precipitation minus runoff and ground-water evaporation.
[2] inflow and outflow from the ground-water system to lakes and rivers in certain areas and inflow to the model area from within the surface-water basin.
[3] flow into the model area as underflow from outside the surface-water drainage basin.

Simulated effects of ground-water withdrawal

Simulations were made to estimate the general effect of ground-water withdrawal on the ground-water system and ground-water discharge to the Straight River. These simulations used model-input values that provided values of simulated head of within 1 ft of measured head and simulated stream discharge within 5 percent of stream discharge. The simulations indicate the following:

1. Simulations indicate that ground-water withdrawal for irrigation has potential to affect the quantity of flow in the stream. Results of model simulation further indicate that continued ground-water withdrawal from the aquifers at rates as great as those during 1988 might reduce stream discharge in the Straight River by as much as 34 percent of stream base flow compared to periods when there was no ground-water withdrawal for irrigation.

The effect of 1988 withdrawal by irrigation wells was simulated by comparing results of simulations of 1988 ground-water withdrawal with the simulation of a period with no ground-water withdrawal for irrigation. Results of the simulations indicate that with irrigation withdrawal the potentiometric surfaces in the surficial and uppermost confined-drift aquifers are reduced by an average of about 4 and 6 ft, respectively. The regional direction and rate of change in ground-water flow were minimal and net inflow of ground-water from constant-head cells changed by less than 2 percent when separate simulations were compared.

2. The effect of continued increase in the withdrawal of ground water for irrigation was simulated by doubling the withdrawal rate from all wells used in the summer 1988 simulation. Additional declines in the potentiometric surface averaged about 3 and 5 ft in the surficial and uppermost confined-drift aquifers, respectively, as a result of these increases in withdrawals. Simulated stream discharge decreased by 53 percent of stream base flow compared to periods when there was no ground-water withdrawal for irrigation for the Straight River. Stream discharge in much of the lower reaches of the stream was captured by leakage to the ground-water system.

Stream-Temperature Model

A streamflow and stream-temperature model of the Straight River was developed to help understand hydrologic and meteorologic relations that are significant for determining the temperature of the stream. The model was not intended as a predictive model. The U.S. Geological Survey's one-dimensional Lagrangian Transport Model (LTM) (Schoellhamer and Jobson,

1986) was used for these simulations. The model represents the Straight River from the outlet of Straight Lake downstream to U.S. Highway 71, near Park Rapids (fig. 1).

Several physical processes can be simulated with the LTM. These include: advection, dispersion, tributary or point-source mixing, and lateral-inflow mixing (ground-water inflow). Advection represents the movement of a constituent with the flow of water in a stream. Dispersion is the spreading out of a constituent in the longitudinal direction because of velocity variations within a stream. Tributary or point-source mixing and lateral-inflow mixing are used to simulate inputs of water and constituents from tributaries, point-sources and ground-water inflow. The change in constituent concentration due to dispersion is calculated with a basic mixing equation in the model.

The model was used to simulate steady-flow conditions and transient meteorological conditions. Simulation of these processes was accomplished by solving the advection-dispersion equation for a given set of boundary, initial, steady-flow, and transient meteorological conditions that were measured during this investigation. The advection-dispersion equation has been derived by considering the principle of conservation of mass and is solved by numeric approximation. The model uses a Lagrangian reference frame that moves the computational nodes, which simulate parcels of water moving down the stream. This technique eliminates the advection term from the advection-dispersion equation. As parcels pass both point and nonpoint sources, inflow is mixed and new parcel concentrations are computed.

Hydraulic inputs needed for simulation of steady-flow conditions are discharge at the upstream end of the stream reach, average cross-sectional properties (area, width), and ground-water inflow at each stream reach. In addition to hydraulic data, the model requires temperature data at the upstream end of each reach and heat flux at points of lateral inflow (ground water).

The temperature of the Straight River is a function of net solar radiation to and evaporation from the open-water surface, heat added to or lost from the stream by conduction and convection with the air, conduction to the earth, and the temperature and volume of ground water flowing in or out of the river. The net exchange of thermal energy between the atmosphere and water is the algebraic sum of the heat flux caused by incoming long-wave radiation, heat flux caused by evaporation, heat conducted from the water as sensible heat, and heat added or lost as rain falls directly on the surface.

Equilibrium temperature is defined as the temperature at which the net surface exchange of energy becomes zero because the heat gained from the sun and the sky plus conduction is balanced by the heat lost to back radiation and evaporation. It is easier to estimate the equilibrium temperature than to measure or estimate all of the meteorological parameters needed to compute the equilibrium temperature. When averaged over a day or more, the equilibrium temperature usually is found to be within about one or two degrees of the mean-daily temperature. The problem of temperature prediction in streams is thus reduced to the problem of estimation of the equilibrium temperature (H.E. Jobson, U.S. Geological Survey, written commun., 1989).

A stream-temperature algorithm (Jobson, 1980a) was used to simulate approximate stream temperature. Only equilibrium temperature and wind-speed data were required, and hourly-air temperature was used as an approximation of the equilibrium temperature (H.E. Jobson, U.S. Geological Survey, written commun., 1989).

The model was calibrated using hydraulic data (stream-discharge, stream-velocity, and channel cross-section data), meteorological data (air temperature), and ground-water temperature data collected during this investigation. Meteorological data collected for a U. S. Geological Survey study at Williams Lake, Minnesota, located about 20 miles east of the investigation area (Don Rosenberry, U. S. Geological Survey, written commun., 1990), and ground-water discharge information to the stream were from results of the ground-water-flow model.

The model is based on the discretization of the stream into several stream-reaches, separated by grid points. The stream was divided into 7 reaches for simulation. The reaches coincided with segments of the stream between major roads (fig. 5). These include stream reaches from one mile north of State Highway 34 to State Highway 34, from State Highway 34 to Becker County road 123, from Becker County road 123 to Becker County road 125, from Becker County road 125 to Hubbard County road 117, from Hubbard County road 117 to Hubbard County road 115, from Hubbard County road 115, to U.S. Highway 71, and from U.S. Highway 71 to the mouth of the Straight River. Available discharge and water temperature data for certain locations along several of these reaches were used to calibrate the model.

The model was calibrated in steps. The first step included evaluating the accuracy of the steady-state flow field. The cross-section areas of the stream were adjusted, within limits, until model-predicted stream velocity matched measured velocity (see Streamflow Velocity section of Supplemental Information). This was accomplished by adjusting the cross-section areas at the two upstream grid points and then by adjusting the next downstream cross-section area. After cross-section area and stream velocity combinations were determined, the width of the stream surface was adjusted. This was accomplished by dividing the width of the stream surface by the cross-section area to obtain average stream depths, and was completed by adjusting the width of the stream surface to represent either a measured or calculated average stream depth. The third step in the calibration process consisted of accounting for thermal dispersion. The final step was to adjust the decay rate. The calibration process (fig. 32) for the Straight River results in a simulated stream temperature that generally follows the same pattern as actual stream temperature during May through September 1988. Once calibrated to these conditions, the model was used to analyze the significance of a reduction in ground-water inflow to the stream on the temperature of the stream, and the significance of the temperature of outflow from Straight Lake Reservoir.

Ground-water inflow temperature, which averages about 7°C throughout the year, reduces the temperature of the Straight River during the summer. Model simulations were conducted to evaluate the potential effect of reduced ground-water inflow to the stream resulting from ground-water withdrawal for irrigation as determined from results of ground-water model simulations. In these simulations, model-input conditions were identical to conditions for simulations used to calibrate the model to measured stream conditions except that ground-water inflow was reduced by 34 percent. Results of the simluations indicate that a potential reduction in streamflow due to irrigation can increase stream temperature by 0.5 to 1.5°C (fig. 33). This potential increase can have an adverse effect on the habitat of the stream for trout. There currently is little evidence to

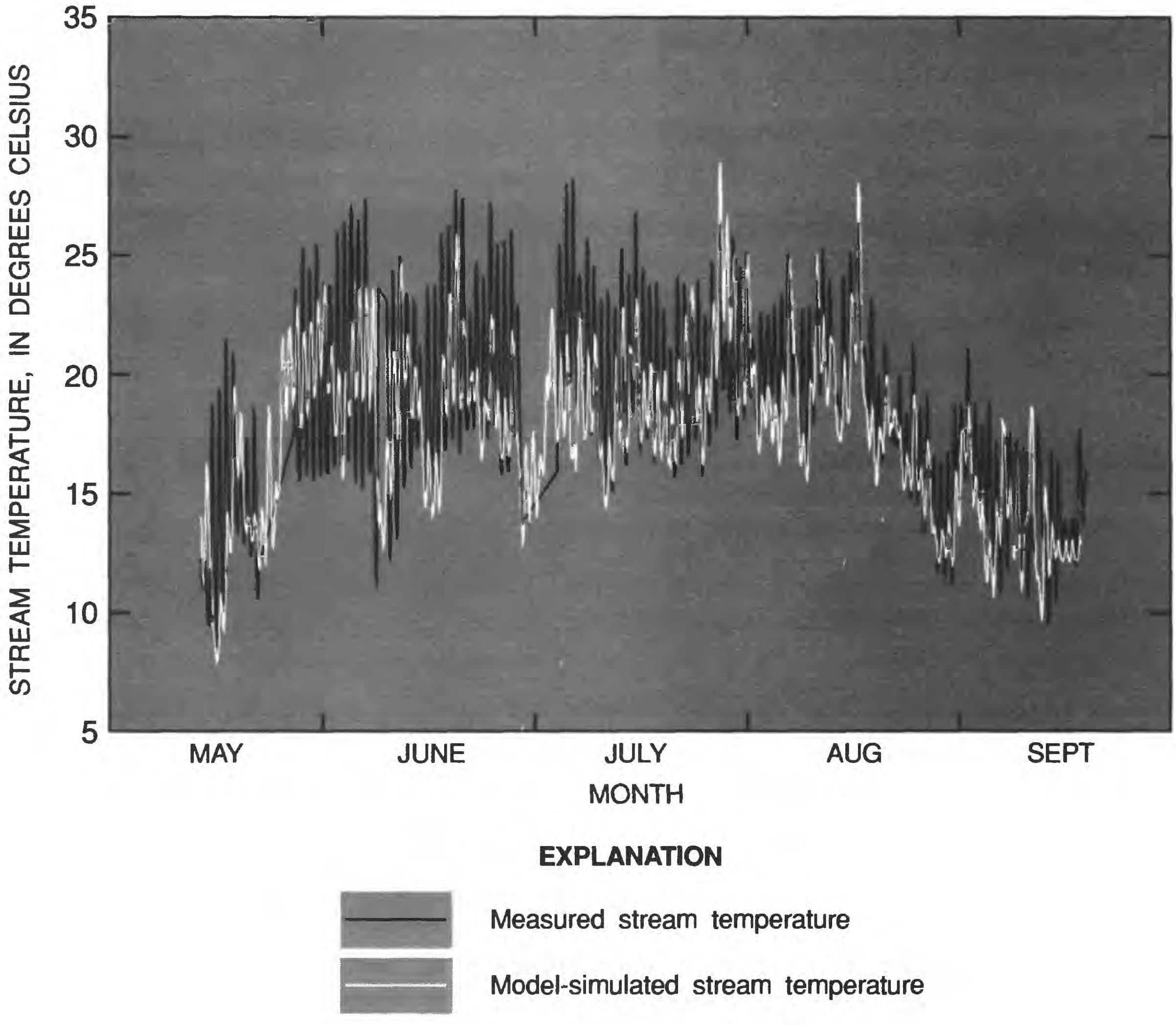

Figure 32.--Measured and model-simulated stream temperature of Straight River (site B) at Becker County Road 125 during May through September 1988.

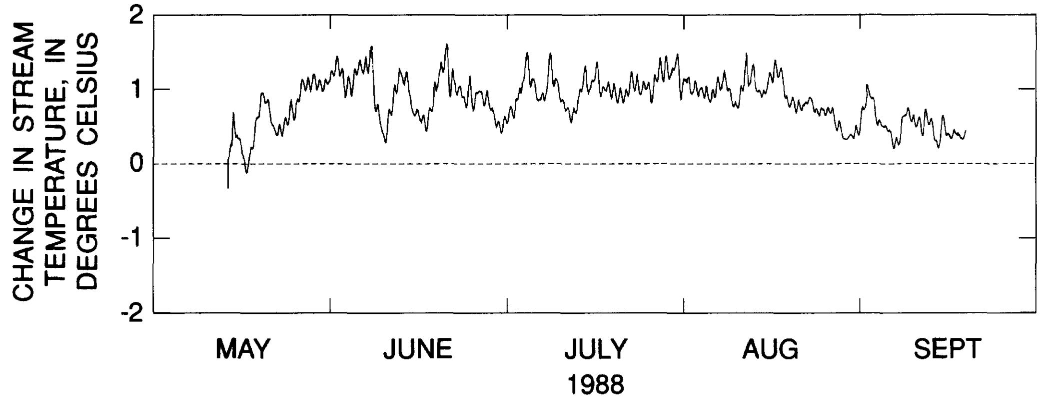

Figure 33.--Change in model-simulated temperature of Straight River at U.S. Highway 71 (site F) during May through September 1988, resulting from reduced base flow due to irrigation withdrawal of ground water, Straight River, Minnesota.

indicate, however, that irrigation is having a significant effect on ground-water temperature, or on the temperature of the Straight River.

The construction of the dam at Osage also may have resulted in increased temperature of the Straight River. Measurements of temperature in Straight Lake indicate that it ranges from about 22°C near the surface to about 10°C at depths of 45 feet below the lake surface during late summer. The effect of the dam, where outflow is from the surface, results in warm (lake-surface) water flowing into the stream below the dam. Model simulations of the stream, in which the temperature of water discharging from the lake was reduced by 5°C, were conducted to represent possible bottom release of water from the dam. These simulations indicate that stream temperature could be reduced by as much as 1.3°C, about three miles downstream from the dam, at site B, if the outlet structure of the dam were changed (fig. 34). The reduction in stream temperture was found to be less significant downstream from site B.

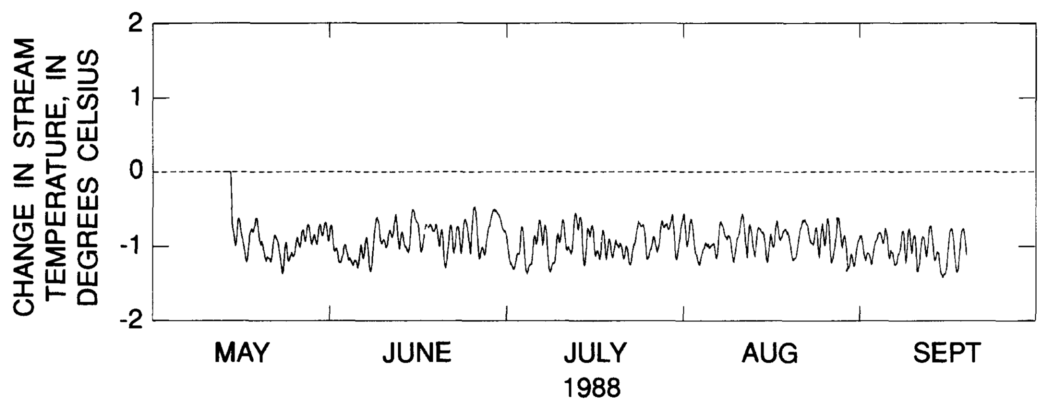

Figure 34.--Changes in model-simulated temperature of Straight River at Becker County Highway 125 (site B) during May through September 1988, resulting from a simulated 5-degree Celsius decrease in the temperature of discharge from Straight Lake.

Table 11.--Data for wells completed in surficial aquifer, Straight River area, Becker and Hubbard Counties, Minnesota

[ft, foot; na, not applicable; --, not determined; s.l., sea level; l.s.d., land surface datum; >, greater than]

Minnesota unique number	Local name	Township and range	Owner's name	Driller's name	Date drilled	Depth of well (ft)	Land surface datum (ft above s.l.)	Casing above land surface (ft)	Elevation of measuring point (ft above s.l.)	Water level elevation (ft above s.l.)	Date measured	Saturated thickness (ft)	Depth to top of confining layer (ft below l.s.d.)
Well logs used for geologic and hydrologic information													
167642	--	139.35.03.CAA	Monico	Traut Wells	3/04/81	45	1420.7	0.5	1421.2	1413.9	8/30/88	80.34	102
132612	--	139.35.03.CBD	Monico	Traut Wells	1/29/77	59	1439.9	1.45	1441.35	1413.15	8/30/88	30.8	65
--	UNK1	139.35.03.B	--	--	--	--	1435	--	--	1418.91	--	--	--
--	UNK2	139.35.03.B	--	--	--	--	1435	--	--	1399.87	--	--	--
163154	--	139.35.04.ABB	Monico	LTP	4/19/79	86	1445.6	1.3	1446.9	1420.26	8/30/88	--	--
--	LDW #10	139.35.04.ABB	Park Rapids	Hickok	1981	37	1446.15	2	1448.15	1421	8/30/88	46.22	65
--	LDW #11	139.35.04.ABB	Park Rapids	Hickok	1981	25	1445.96	2.05	1448.01	1420.8	8/30/88	18.98	45
--	LDW #12	139.35.04.ABC	Park Rapids	Hickok	1981	25	1444.62	2	1446.62	1419.36	8/30/88	27	53
138698	--	139.35.05.DDD	Str. R. Church	Traut Wells	9/29/78	43	1445.09	1	1446.09	1412.99	8/30/88	64.3	90
142259	--	139.35.09.ADD	Becker	Traut Wells	10/21/77	68	1442.1	.2	1442.3	1410.05	8/30/88	75.59	98
243850	29035	139.35.10.BAB	Guida	North Star	1986	31	1438.6	2.3	1440.9	1409.52	8/30/88	--	--
243827	29007	139.35.13.DAD	--	--	10/18/74	45	1422.3	2	1424.3	1377.58	8/30/88	47.04	62
226127	--	139.35.13.DCC	Carlson	Schultz	1974	44	1417	1.6	1418.6	1410.78	8/30/88	40.19	62
407693	--	139.35.14.DBB	Meacham	Westby	6/1/86	44	1427.88	--	--	1402.66	--	80.34	102
226276	--	139.35.17.CDD	Horgdahl	--	--	32	1462	--	--	1444.06	--	30.8	65
243486	3006	139.36.02.CCC	Obwell	--	09/18/74	16	1458.12	3	1461.12	1445.92	8/30/88	--	--
429735	--	140.35.09.AAC	Knoebel	Traut Wells	9/7/87	54	1456.84	1	1457.84	1431.2	8/30/88	60.93	70
173608	--	140.35.09.BDD	Tuller	North Star	6/24/80	49	1456.76	1.4	1458.16	1434.04	8/30/88	49.9	82
178788	--	140.35.10.CCC	Gulbranen	North Star	5/29/80	46	1463	1.7	1464.7	1447.3	8/30/88	28.75	61
405610	--	140.35.14.BDC	Williams	Traut Wells	9/20/84	46	1439.35	.6	1440.05	1425.45	8/30/88	59.29	65
410800	--	140.35.14.BCC	Devine	Johnson	5/30/86	54	1440	1	1441	1412.27	8/30/88	43.61	81
405631	--	140.35.14.DBA	Harold Jones	Traut Wells	6/2/86	54	1434.88	1	1435.88	1424.68	8/30/88	9.78	--
407689	--	140.35.15.BBA	Schmitt	Westby	5/16/86	38	1445	.8	1445.8	1424.62	8/30/88	34.51	60
199838	--	140.35.15.ABD	Hammers	Traut Wells	6/8/84	54	1439.21	1.1	1440.31	1424.32	8/30/88	40.89	56
142287	--	140.35.15.ADD	Ahrens	Traut Wells	11/23/77	50	1447.93	1.5	1449.43	1424.8	8/30/88	--	--
243831	29011	140.35.16.BCC	Obwell	--	1/3/74	26	1458	3	1461	1439.22	8/30/88	46.22	65

Table 11.--Data for wells completed in surficial aquifer, Straight River area, Becker and Hubbard Counties, Minnesota--(Continued)

Minnesota unique number	Local name	Township and range	Owner's name	Driller's name	Date drilled	Depth of well (ft)	Land surface datum (ft above s.l.)	Casing above land surface (ft)	Elevation of measuring point (ft above s.l.)	Water level elevation (ft above s.l.)	Date measured	Saturated thickness (ft)	Depth to top of confining layer (ft below l.s.d.)
226141	--	140.35.23.DCA	Park Rapids	Mueller Bros.	5/1/57	45	1444	3	1447	1417.98	8/30/88	18.98	45
226142	--	140.35.23.DCA	Park Rapids	Mueller Bros.	09/02/64	59	1444	2	1446	--	--	--	--
421676	--	140.35.23.AAB	United Methodist	Johnson	8/21/80	59	1450	1.5	1451.5	1422.35	8/30/88	--	--
438577	--	140.35.23.DBC	Pk Rapid School	Traut Wells	1/12/88	55	1448	1.5	1449.5	1423.98	8/30/88	--	--
190889	--	140.35.24.BCC	Vettels	Traut Wells	9/23/85	40	1435	1.1	1436.1	1415.8	8/30/88	--	--
190900	--	140.35.25.CBC	J&B Warehouse	Traut Wells	12/17/85	58	1442	1.3	1443.3	1413.61	8/30/88	--	--
407663	--	140.35.26.AAD	Stennes	Westby	03/15/85	40	1443	.9	1443.9	1413.08	8/30/88	--	--
189816	--	140.35.26.AAA	Lof	Westby	08/12/81	50	1441	1.1	1442.1	1415.3	8/30/88	--	--
190876	--	140.35.26BBB	Assembly	Traut Wells	07/19/85	53	1450	1	1451	1426.3	8/30/88	--	--
190875	--	140.35.26.BBB	Assembly	Traut Wells	07/19/85	40	1450	1	1451	1427.07	8/30/88	--	--
--	LDW #1	140.35.27.CBB	Park Rapids	Hickok	1981	25	1447.13	1.7	1448.83	1429.73	8/30/88	--	--
--	LDW #2	140.35.27.DCC	Park Rapids	Hickok	1981	34	1446.98	1.8	1448.78	1421.61	8/30/88	--	--
--	LDW #3	140.35.27.DCC	Park Rapids	Hickok	1981	40	1446.87	1.8	1448.67	1421.44	8/30/88	--	--
--	LDW #4	140.35.27.DCC	Park Rapids	Hickok	1981	35	1445.54	1.8	1447.34	1419.94	8/30/88	--	--
--	LDW #5	140.35.27.CAA	Park Rapids	Hickok	1981	35	1448.11	2	1450.11	1424.41	8/30/88	--	--
--	LDW #6	140.35.27.DCA	Park Rapids	Hickok	1981	35	1447.74	1.9	1449.64	1421.14	8/30/88	--	--
--	LDW #9	140.35.27.CCC	Park Rapids	Hickok	1981	25	1446.92	1.9	1448.82	1425.19	8/30/88	--	--
232423	--	140.35.32.BCA	Griffith	--	--	53	1457.4	.6	1458	1431.4	8/30/88	27	53
160255	--	140.35.32.CDC	Griffith	Traut Wells	5/3/79	58	1452.1	1.16	1453.26	1422.56	8/30/88	--	--
450066	--	140.35.33.CDA	Schroeder	Traut Wells	7/11/88	90	1448	1.3	1449.3	1422.3	8/30/88	64.3	90
--	LDW #13	140.35.33.CCC	Park Rapids	Hickok	1981	24	1447.27	1.9	1449.17	1421.69	8/30/88	--	--
--	LDW #14	140.35.33.CBB	Park Rapids	Hickok	1981	25	1450.62	1.8	1452.42	1427.64	8/30/88	--	--
--	LDW #15	140.35.33.CAA	Park Rapids	Hickok	1981	24	1445.61	1.9	1447.51	1424.96	8/30/88	--	--
--	LDW #7	140.35.34.BDD	Park Rapids	Hickok	1981	35	1442.41	2	1444.41	1419.28	8/30/88	--	--
--	LDW #8	140.35.34.BCC	Park Rapids	Hickok	1981	25	1442.47	2	1444.47	1422.48	8/30/88	--	--
163153	--	140.35.34.CCC	Monico	LTP	07/24/78	98	1442	1.4	1443.4	1419.59	8/30/88	75.59	98
226268	--	140.35.34.ABC	Pritchett	Sanford	4/74	40	1433.8	1.4	1435.2	1421.92	8/30/88	28.12	40
118423	--	140.35.35.DCB	Falk	Schmitz	4/11/76	41	1434.5	1	1435.5	1411.3	8/30/88	--	--
410768	--	140.35.35.DBA	Park Rapids	Johnson	11/21/85	67	1441.3	1.8	1443.1	1411.02	8/30/88	--	--

Table 11.--Data for wells completed in surficial aquifer, Straight River area, Becker and Hubbard Counties, Minnesota--(Continued)

Minnesota unique number	Local name	Township and range	Owner's name	Driller's name	Date drilled	Depth of well (ft)	Land surface datum (ft above s.l.)	Casing above land surface (ft)	Elevation of measuring point (ft above s.l.)	Water level elevation (ft above s.l.)	Date measured	Saturated thickness (ft)	Depth to top of confining layer (ft below l.s.d.)
425439	--	140.35.36.BBA	Street Dept.	Traut Wells	10/23/86	56	1430	0.8	1430.8	1402.75	8/30/88	--	--
193435	--	140.36.05.ADA	Hinckley	North Star	11/9/82	51	1508	1.4	1509.4	1485.9	8/30/88	--	--
425431	--	140.36.07.DCA	Dahl	Traut Wells	8/2/86	53	1505.48	.35	1505.83	1469.52	8/30/88	--	--
164312	--	140.36.07.ACA	Schluler	Traut Wells	9/14/79	70	1512.86	1.3	1514.16	1469.74	8/30/88	--	--
178383	--	140.36.07.ACC	Ullery	North Star	04/29/81	70	1505	1.03	1506.03	1450.46	04/86	--	--
189835	--	140.36.07.ACC	Kreisel	Westby	6/1/84	57	1512.86	.7	1513.56	1468.79	8/30/88	--	--
243487	3007	140.36.09.BBA	--	--	9/17/74	25	1500	3	1503	1485.04	8/30/88	47.04	62
178629	--	140.36.09.DCC	Sattler	North Star	4/17/80	75	1500	1	1501	1476.98	8/30/88	--	--
221178	--	140.36.11.BBB	Girtz	Traut Wells	1975	66	1550	.9	1550.9	1482.94	8/30/88	--	--
160222	--	140.36.15.BAC	Gustad	Traut Wells	11/15/78	74	1493	1	1494	1457.07	8/30/88	--	--
183629	--	140.36.16.DAD	Zwirtz	North Star	11/3/81	44	1490	.85	1490.85	1461.42	8/30/88	--	--
438650	--	140.36.17.CDB	Olson	Traut Wells	5/15/88	58	1503.54	1	1504.54	1469.78	8/30/88	--	--
222176	--	140.36.19.CDC	Henderson	--	1959	23	1496	.2	1496.2	1487.89	11/85	--	--
429745	--	140.36.20.DD	Osage Comm. Ctr.	Traut Wells	09/07/87	54	1498	1.2	1499.2	1463.52	8/30/88	--	--
429744	--	140.36.20.CD	Osage Elem. Sch.	Traut Wells	9/7/87	54	1499	.8	1499.8	1463.97	8/30/88	--	--
190877	--	140.36.20.CDA	Sloan	Traut Wells	9/23/85	54	1497.61	1	1498.61	1464.77	8/30/88	--	--
142204	--	140.36.21.CCC	Lydell	Traut Wells	4/20/78	44	1472.77	1.15	1473.92	1460.23	8/30/88	--	--
438635	--	140.36.21.DCC	Prichard	Traut Wells	5/21/88	55	1477.52	1.2	1478.72	1447.11	8/30/88	--	--
186572	--	140.36.24.DDC	Sjostrom	Cichig	05/14/85	62	1470.22	.8	1471.02	1448.41	8/30/88	40.19	62
411245	--	140.36.25.CAA	Monico	LTP	11/11/85	146	1465.26	--	--	1443.6	--	--	--
142296	--	140.36.25.BBD	Monico	Traut Wells	01/20/78	90	1468.88	.7	1469.58	1447.02	8/30/88	--	--
178383	--	140.36.25.BCD	Gomez	Traut Wells	12/17/76	80	1468.9	--	--	--	--	--	--
236081	--	140.36.26.CBB	Monico	Traut Wells	05/01/78	53	1477.79	.75	1478.54	1443.59	8/30/88	30.8	65
142216	--	140.36.26.AAA	Monico	--	1/28/78	57	1473.66	.33	1473.99	1449.26	8/30/88	--	--
--	PR-145	140.36.26.ADD	Obwell	--	9/18/74	58	1470.09	.8	1470.89	1454.57	8/30/88	42.48	58
243601	3124	140.36.26.DAA	Happle	--	1/24/78	66	1462.21	.33	1462.54	1446.24	8/30/88	47.03	66
199837	--	140.36.28.BBC	Bateman	Traut Wells	8/29/84	54	1482.41	.4	1482.81	1458.98	8/30/88	--	--
199802	--	140.36.28.BBA	Brolsman	Traut Wells	8/13/83	53	1486.69	1.25	1487.94	1458.68	8/30/88	--	--
132556	--	140.36.28.BBB	Blanchard	Traut Wells	5/12/77	54	1483.27	1.3	1484.57	1459.28	8/30/88	--	--
199848	--	140.36.28.DAA	Prichard	Traut Wells	7/21/84	54	1474.71	.65	1475.06	1453.33	8/30/88	--	--
421513	--	140.36.29.ABC	Nissen	Johnson	2/26/87	54	1490	1.8	1491.8	1456.68	8/30/88	--	--

Table 11.--Data for wells completed in surficial aquifer, Straight River area, Becker and Hubbard Counties, Minnesota--(Continued)

Minnesota unique number	Local name	Township and range	Owner's name	Driller's name	Date drilled	Depth of well (ft)	Land surface datum (ft above s.l.)	Casing above land surface (ft)	Elevation of measuring point (ft above s.l.)	Water level elevation (ft above s.l.)	Date measured	Saturated thickness (ft)	Depth to top of confining layer (ft below l.s.d.)
199820	--	140.36.29.AAA	Blanchard	Traut Wells	2/9/84	54	1482	1.4	1483.4	1458.08	8/30/88	--	--
423720	--	140.36.29.CDD	Holmer	Westby	10/16/86	44	1487.29	1.1	1488.39	1461.71	8/30/88	--	--
190896	--	140.36.29.ABB	Koskovich	Traut Wells	01/29/86	55	1491.6	1.61	1493.21	1457.18	8/30/88	--	--
107255	--	140.36.32.AAD	Monico	Frederic	12/06/75	95	1484.52	.5	1485.02	1454.42	8/30/88	64.9	95
429717	--	140.36.35.BBB	Soarinen	Traut Wells	06/09/87	47	1455	.75	1455.75	1432.55	8/30/88	--	--
403076	--	140.36.36.BDB	Pritchard	Johnson	04/26/85	100	1462.06	.65	1462.71	1428.78	8/30/88	--	--
438553	--	140.37.12.ADA	Nilson	Traut Wells	10/26/87	67	1523.5	1.5	1525	1474.64	8/30/88	--	--
147268	--	140.37.13.ADA	Offutt	LTP	06/09/78	122	1519	1.45	1520.45	1481.09	8/30/88	86.09	124
139244	--	140.37.11.BAD	Harris	North Star	03/14/78	95	1532	1.25	1533.25	1529	8/30/88	63.72	95
169077	--	140.37.11.BBC	Wilson	North Star	04/17/80	71	1533	1.2	1534.2	1530	8/30/88	--	--
107269	--	140.37.12.DAC	Monico	LTP	03/20/75	98	1521	1.5	1522.5	1518	8/30/88	--	--
147268	--	140.37.13.AAC	Greenberg	LTP	01/08/76	137	1512	1.45	1513.45	1509	8/30/88	--	--
--	SR-1	140.37.13.ADD	--	--	09/11/85	39	1512	3.4	1515.4	1509	8/30/88	--	--
170268	--	140.37.13.BAC	Greenberg	LTP	03/11/75	83	1522	1.3	1523.3	1519	8/30/88	85	88
167644	--	141.36.32.ADD	Wright	Traut Wells	05/21/81	40	1548	1.7	1549.7	1545	8/30/88	37	40
181134	--	141.36.32.ADD	Wright	Traut Wells	11/02/82	50	1527	1.3	1528.3	1524	8/30/88	47	50
243397	USGS #1	139.35.09.CCC	USGS	USGS	06/19/87	57	1481.1	1.7	1482.8	1422.51	8/30/88	36	85
243396	USGS #2S	139.35.04.DDD	USGS	USGS	06/18/87	16	--	2.5	--	--	--	64	70
243393	USGS #2M	139.35.04.DDD	USGS	USGS	--	42	1420.94	2.5	1423.44	1411.91	8/30/88	--	>59
244005	USGS #3S	139.36.10.ADD01	USGS	USGS	06/17/87	14	1458.31	2.2	1460.51	1446.33	8/30/88	>93	>101
244003	USGS #3M	139.36.10.ADD02	USGS	USGS	06/17/87	--	1458	2.2	--	--	--	--	--
--	USGS #4	140.36.34.DBB	USGS	USGS	--	--	1464.53	2.2	1466.73	1432.43	8/30/88	49.9	82
244006	USGS #5	139.36.02.BBB	USGS	USGS	--	--	1464.97	2.4	1467.37	1432.72	8/30/88	28.75	61
--	USGS #6	140.36.35.BBC	USGS	USGS	--	--	1436.75	2.6	1439.35	1431.04	8/30/88	59.29	65
244018	USGS #6D	140.36.35.BBC	USGS	USGS	06/14/89	55	1437	3.0	1440	--	--	--	55
244022	USGS #7	140.36.14.CBC	USGS	USGS	06/18/87	17	1500	2.4	1502.4	1462.61	8/30/88	43.61	81
243373	USGS #10	140.35.31.CCC	USGS	USGS	10/21/87	44	1460.75	3.5	1464.25	1416.91	8/30/88	>3	--
244016	USGS #11	140.36.25.BA	USGS	USGS	10/21/87	24	1470	0.2	--	1468	--	>10	>32
244015	USGS #12	140.36.25.BA	USGS	USGS	10/21/87	24	--	0.2	--	--	--	>13	>35
243875	USGS #14	140.35.31.DAA	USGS	USGS	10/21/87	--	1453.56	1.5	1455.06	1428.34	8/30/88	9.78	35
243395	USGS #15S	139.35.06.CCC	USGS	USGS	10/22/87	28	1458.2	3.2	1461.4	1432.71	8/30/88	34.51	60

Table 11.--Data for wells completed in surficial aquifer, Straight River area, Becker and Hubbard Counties, Minnesota--(Continued)

Minnesota unique number	Local name	Township and range	Owner's name	Driller's name	Date drilled	Depth of well (ft)	Land surface datum (ft above s.l.)	Casing above land surface (ft)	Elevation of measuring point (ft above s.l.)	Water level elevation (ft above s.l.)	Date measured	Saturated thickness (ft)	Depth to top of confining layer (ft below l.s.d.)
243389	USGS #15M	139.35.06.CCC	USGS	USGS	06/13/88	47	1458	3.8	1461.89	--	--	--	>48
244004	USGS #16	139.36.13.AAA	USGS	USGS	10/22/87	28	1457.59	1.5	1459.29	1437.7	8/30/88	738	60
243394	USGS #17	139.35.19.CDD	USGS	USGS	10/22/87	22	1436	2.6	1438.6	1420.89	8/30/88	40.89	56
244001	USGS #18	139.36.01.CCC	USGS	USGS	06/14/88	--	--	--	--	--	--	--	--
244002	USGS #19	139.36.14.AAA	USGS	USGS	06/14/88	23	1456.93	1	1457.93	1441.46	8/30/88	--	--
243391	USGS #20	139.35.05.CCC	USGS	USGS	--	35	1449.36	2.5	1451.86	1418.91	8/30/88	9.55	40
243392	USGS #21	139.35.11.ABD	USGS	USGS	--	19	1411.1	1	1412.1	1399.87	8/30/88	--	>31
243400	USGS #22	139.36.04.BBB	USGS	USGS	06/16/88	19	1476.9	2.8	1479.7	1455.63	8/30/88	15.73	37
244011	USGS #23	140.36.16.BBB	USGS	USGS	06/16/88	49	1508	1.6	1510	1465.28	8/30/88	33.88	77
244012	USGS #24	140.36.02.BAA	USGS	USGS	06/21/88	52	1522.9	2.1	1525	1472.64	8/30/88	14	64
244013	USGS #25	140.35.07.CCC	USGS	USGS	06/16/88	50	1502	2	1504	1456.21	8/30/88	>16.21	>62
243370	USGS #26	140.35.19.BBB	USGS	USGS	06/16/88	56	1476.7	1.3	1478	1455.17	8/30/88	31.47	53
244014	USGS #27	140.36.22.CBB	USGS	USGS	06/17/88	32	1483	1.9	1484.9	1457.17	8/30/88	6.17	32
243399	USGS #28	139.36.16.CDD	USGS	USGS	06/20/88	--	1460	1.2	1461.2	1436.27	8/30/88	13	38
243383	USGS #29	140.35.28.CBB	USGS	USGS	06/20/88	20	1453	2.4	1455.4	1435.8	8/30/88	46.8	64
244008	USGS #31	140.36.08.ABA	USGS	USGS	06/21/88	50	1523.6	2.4	1526	1477.22	8/30/88	--	--
244009	USGS #32	140.36.11.CDD	USGS	USGS	06/21/88	52	1517.5	2.5	1520	1466.24	8/30/88	>30.74	>82
244010	USGS #33	140.36.14.DDD	USGS	USGS	06/21/88	23	1475.5	2.5	1478	1456.01	8/30/88	37.51	57
243374	USGS #34	140.35.30.CDD	USGS	USGS	--	30	1465	2.5	1467.5	1438.05	8/30/88	23.05	50
243375	USGS #35	140.35.23.BBA	USGS	USGS	06/22/88	55	1447	.8	1447.8	1423.83	8/30/88	32	53
243376	USGS #36	140.35.16.DBA	USGS	USGS	06/22/88	--	1459	1	1460	--	8/30/88	>100	>126
243398	USGS #37	139.36.15.ABB	USGS	USGS	06/23/88	--	--	--	--	--	--	--	15
244073	USGS #38	139.36.23.CBC	USGS	USGS	06/23/88	34	1442.5	2.5	1445	1427.63	8/30/88	14.13	29
243377	USGS #39A	140.35.23.CDD	USGS	USGS	06/28/88	66	1450	3.2	1453.2	1429.2	8/30/88	39	60
243378	USGS #39B	140.35.23.CDD	USGS	USGS	06/28/88	45	1450	1.5	1451.5	--	--	--	>45
243379	USGS #40	140.35.30.AAA	USGS	USGS	06/28/88	49	1458	2.1	1460.1	1441.6	8/30/88	27.6	44
243380	USGS #41	140.35.26.DBB	USGS	USGS	06/28/88	68	1445	1.8	1446.8	1415.16	8/30/88	32.16	62
243384	USGS #42	139.35.12.AAA	USGS	USGS	--	47	1420	1.1	1421.1	1389.83	8/30/88	26.83	57
243385	USGS #43	139.35.23.ADD	USGS	USGS	--	35	1419	1.8	1420.8	1386.69	8/30/88	>37	>65
243386	USGS #44	139.35.26.DBC	USGS	USGS	--	--	1408	3.2	1411.2	1368.63	8/30/88	--	39
243387	USGS #45	139.35.28.AAA	USGS	USGS	--	26	1450	1.5	1451.5	1428.7	8/30/88	13	32

Table 11.--Data for wells completed in surficial aquifer, Straight River area, Becker and Hubbard Counties, Minnesota--(Continued)

Minnesota unique number	Local name	Township and range	Owner's name	Driller's name	Date drilled	Depth of well (ft)	Land surface datum (ft above s.l.)	Casing above land surface (ft)	Elevation of measuring point (ft above s.l.)	Water level elevation (ft above s.l.)	Date measured	Saturated thickness (ft)	Depth to top of confining layer (ft below l.s.d.)
244007	USGS #46	140.36.20.CCC	USGS	USGS	06/30/88	19	1489.24	2.3	1491.54	1469.33	8/30/88	13.09	33
244007	USGS #47	140.36.30.ABB	USGS	USGS	--	--	1493.7	1	1494.7	1483.16	8/30/88	--	--
243382	USGS #48	140.36.27.CCC	USGS	USGS	--	24	1475.73	2	1477.73	1454.01	8/30/88	30.28	52
244338	USGS #49	139.35.02.BAB	USGS	USGS	06/22/88	302	1438	1.8	1439.8	1410.4	8/30/88	40	65
244077	USGS #50	139.36.06DDD	USGS	USGS	07/11/89	29	1491	2.0	1493	1486.5	07/11/89	23	30
244078	USGS #51	140.36.32ADA	USGS	USGS	07/10/89	31	1478	1.8	1480	1460	07/10/89	44	64
244072	USGS #52	139.36.04.CBC	USGS	USGS	1989	13	1472	2.2	1474.07	1461.91	1989	5	15
244070	USGS #53	139.36.02.AAA	USGS	USGS	07/11/89	49	1465	3.1	1467.95	1425.0	07/11/89	12	55
243369	USGS #54	140.36.34.DCC	USGS	USGS	07/11/89	27	1467	2.3	1469.38	1446.08	07/11/89	37	59
244067	USGS #55	139.36.14.CCC	USGS	USGS	07/12/89	12	1450	1.9	--	--	--	15	27
244074	USGS #56	139.26.10.DDD	USGS	USGS	1989	--	1450	1.0	1455	1400	1989	95	100
244075	USGS #57	139.36.14.DDD	USGS	USGS	1989	18	1446	2.3	1448.2	1436.5	1989	77	95
243367	USGS #58	139.35.19.BBB	USGS	USGS	07/13/89	15	1437	2.0	--	--	--	38	45
243366	USGS #59	139.35.15.AAB	USGS	USGS	07/13/89	29	1433	2.0	1435	1410	07/13/89	12	37
243390	--	139.35.16.ADD	USGS	USGS	06/23/89	--	--	--	--	--	--	--	--
244071	--	139.36.01.BBC	USGS	USGS	08/23/90	43	--	--	--	--	--	--	>57
244001	--	139.36.01.CCC	USGS	USGS	06/14/90	--	--	--	--	--	--	--	--
244069	--	139.36.02.DDD	USGS	USGS	--	--	--	--	--	--	--	--	--
243372	--	140.35.31.DAA	USGS	USGS	10/22/87	30	--	1.5	--	--	10/22/87	>12	>37
243371	--	140.35.31.DAA	USGS	USGS	06/14/88	36	--	--	--	--	--	--	47
243368	--	140.35.36.CDC	USGS	USGS	06/22/90	31	--	1.8	--	--	--	--	65
244023	--	140.36.11.BBB	USGS	USGS	06/18/87	--	--	--	--	--	--	--	--
244017	--	140.36.25.BA	USGS	USGS	10/22/87	28	--	2.0	--	--	--	>17	>35
244021	--	140.36.27	USGS	USGS	06/18/87	--	--	--	--	--	--	--	--
244025	--	140.36.34	USGS	USGS	06/17/87	16	--	2.2	--	--	06/17/87	46	78
244024	--	140.36.35	USGS	USGS	06/17/87	13	--	2.6	--	--	06/17/87	61	65
244019	--	140.36.35.BDA	USGS	USGS	09/05/90	13	--	--	--	--	--	--	60
244020	--	140.36.35.BDA	USGS	USGS	09/05/90	56	--	--	--	--	--	--	>57
244086	--	140.36.35.BDC	USGS	USGS	08/24/90	68	--	--	--	--	08/24/90	>30	>67
--	--	140.36.29.ABA	USGS	USGS	09/13/88	--	--	--	--	--	--	--	--
244087	--	140.36.35.BDC	USGS	USGS	08/24/90	36	--	--	--	--	08/24/90	>1	>36

Table 11.--Data for wells completed in surficial aquifer, Straight River area, Becker and Hubbard Counties, Minnesota--(Continued)

Minnesota unique number	Local name	Township and range	Owner's name	Driller's name	Date drilled	Depth of well (ft)	Land surface datum (ft above s.l.)	Casing above land surface (ft)	Elevation of measuring point (ft above s.l.)	Water level elevation (ft above s.l.)	Date measured	Saturated thickness (ft)	Depth to top of confining layer (ft below l.s.d.)
244085	--	140.36.35.DCC	USGS	USGS	08/90	41	--	2.0	--	--	08/24/90	17	52
244079	--	140.36.36.CCD	USGS	USGS	08/90	64	--	--	--	--	--	--	62
244080	--	140.36.36.CCD	USGS	USGS	08/90	43	--	--	--	--	08/23/90	>2	>47
244083	--	140.36.36.CDA	USGS	USGS	08/90	46	--	--	--	--	08/22/90	>4	>42
244084	--	140.36.36.CDA	USGS	USGS	08/90	19	--	--	--	--	08/22/90	39	55
244082	--	140.36.36.CDC	USGS	USGS	08/90	57	--	2.0	--	--	--	--	64
244081	--	140.36.36.CDC	USGS	USGS	08/90	38	--	3.7	--	--	--	--	>47
243351	--	141.32.23.CCC	USGS	USGS	09/90	76	--	--	--	--	09/13/90	--	--
243352	--	141.32.25.BBA	USGS	USGS	10/90	45	--	--	--	--	--	--	>46
243353	--	141.32.25.BBA	USGS	USGS	09/90	--	--	--	--	--	--	--	>97
243354	--	141.32.25.CBB	USGS	USGS	09/90	--	--	--	--	--	--	--	75
243356	--	141.32.25.CBB	USGS	USGS	09/90	46	--	--	--	--	--	--	>47
243355	--	141.32.26.CA	USGS	USGS	09/90	19	--	--	--	--	--	--	>19
243358	--	141.32.26.CA	USGS	USGS	09/90	--	--	--	--	--	--	--	30
243359	--	141.32.26.DDA	USGS	USGS	09/90	29	--	--	--	--	--	9	35

Table 12.--Data for wells completed in uppermost confined-drift aquifer, Straight River area, Becker and Hubbard Counties, Minnesota

[ft, foot; --, not determined; s.l., sea level; l.s.d., land surface datum; >, greater than]

Minnesota unique number	Local name	Township and range	Owner's name	Driller's name	Date drilled	Depth of well (ft)	Land surface datum (ft above s.l.)	Casing above land surface (ft)	Elevation of measuring point (ft above s.l.)	Water level elevation (ft above s.l.)	Date measured	Saturated thickness (ft)	Depth to confining layer (ft below l.s.d.)
Well logs used for geologic and hydrologic information													
173610	--	139.35.02.DBD	Bush Brothers	North Star	07/10/80	80	1433.6	1.15	1434.75	1405.52	8/30/88	>4	35
214530	--	139.35.02.BAD	Monico	Traut Wells	--	200	1436.1	.55	1436.65	1410.8	8/30/88	45	66
123219	--	135.35.05.ACC	Griffith	Traut Wells	--	108	1452.1	1.45	1435.55	1418.35	8/30/88	>40	56
403072	--	139.35.05.BDA	Griffith	Johnson	04/03/85	169	1454.4	2.25	1456.65	1415.16	8/30/88	>35	43
243867	USGS15d	139.35.06.CCC	USGS	LTP	09/08/88	174	1454.4	1.37	1456.38	1431.75	9/08/88	32	57
423711	--	139.35.06.BAB	Vrieze	Westby	09/04/86	74	1453.3	1.3	1454.6	1420.6	8/30/88	>7	42
142203	Stinar	139.35.07.DDD	Stinard	Traut Wells	--	69	1485.47	1.55	1487.02	1429.42	8/30/88	>9	0
113105	--	139.35.08.DAA	Evink	CCW Const	07/25/75	94	1464.8	3.0	1461.8	1424.0	8/30/88	>25	0
123604	--	139.35.09.CDC	Henry	Johnson	10/12/76	115	1474.32	1.9	1476.22	1417.04	8/30/88	>8	0
116475	--	139.35.09.DAD	Hanson	Traut Wells	08/07/75	109	1460.2	1.0	1461.2	1413.54	8/30/88	>11	0
160266	--	139.35.10	--	--	--	238	1435	--	--	--	--	--	--
--	--	139.35.10	--	--	--	142	1436	--	--	--	--	--	--
--	--	139.35.10.CAB	Monico	--	--	75	1434.43	1.9	1436.33	1409.24	8/30/88	--	--
411243	--	139.35.10.DCB	Monico	LTP	--	156	1436.24	.85	1437.09	1407.89	8/30/88	48	71
226251	--	139.35.10.CCC	Cloutier	Wingard	--	135	1473.6	0.0	1437.6	1412.72	8/30/88	>10	0
149510	29033	139.35.10.BAB	Guida	Northstar	--	172	1438.2	1.35	1439.55	1410.51	8/30/88	22	51
226255	--	139.35.11	Monico	Traut Wells	--	180	1431	--	--	--	--	--	--
243870	USGS21d	139.35.11	USGS	LTP	--	75	1412	--	1415.07	--	--	--	45
226256	--	139.35.11.DCA	Monico	Traut Wells	--	280	1435	--	--	--	--	--	--
226257	--	139.35.11.CBA	Becker	Traut Wells	--	140	1435	--	--	--	--	--	--
113104	--	139.35.11.DBB	Deakins	CCW Const	04/02/75	142	1433.02	.8	1433.82	1405.46	8/30/88	17	50
425417	--	139.35.11.ADD	Clack	Traut Wells	09/11/81	86	1430	1.0	1431.0	1396.95	8/30/88	>6	34
425445	--	139.35.11.AAC	Thomas	Traut Wells	--	214	1433.3	1.6	1434.9	1397.62	8/30/88	3	40
419459	--	139.35.12.CDD	Monico	LTP	01/16/86	192	1426.5	1.0	1427.5	1381.8	8/30/88	39	44
--	--	139.35.12	--	LTP	01/09/86	120	1427	--	--	--	--	--	--

Table 12.--Data for wells completed in uppermost confined-drift aquifer, Straight River area, Becker and Hubbard Counties, Minnesota--(Continued)

Minnesota unique number	Local name	Township and range	Owner's name	Driller's name	Date drilled	Depth of well (ft)	Land surface datum (ft above s.l.)	Casing above land surface (ft)	Elevation of measuring point (ft above s.l.)	Water level elevation (ft above s.l.)	Date measured	Saturated thickness (ft)	Depth to top of confining layer (ft below l.s.d.)
--	--	139.35.12	--	LTP	01/14/86	123	1427	--	--	--	--	--	--
123605	--	139.35.12.DCC	Ernhart	Johnson	10/13/76	66	1423.9	1.2	1425.1	1379.98	8/30/88	>15	20
132579	--	139.34.12.DCD	Tho	Traut Wells	08/11/77	162	1427.1	.95	1428.05	1380.32	8/30/88	>7	60
106001	--	139.35.12.CCC	O'Dair	Traut Wells	09/29/75	88	1430.1	.95	1431.05	1404.72	--	>28	18
106252	--	139.35.13.BBC	Falk	Traut Wells	04/26/79	122	1429.7	.6	1430.62	1396.22	--	>7	18
214532	--	139.35.13.AAC	Monico	Traut Wells	--	173	1426.2	.25	1426.45	1379.74	8/30/88	>69	33
236601	--	139.35.13	Wright	Traut Wells	2/83	--	1428	--	--	--	--	--	--
226253	--	139.35.14.AAA	Monico	Traut Wells	--	140	1431	--	--	--	--	--	--
407693	--	139.35.14.DBB	Meacham	Westby	06/01/86	44	1427.88	1.0	1428.88	1402.66	8/30/88	>20	11
106409	--	139.35.14.DCB	Schmidtz	--	03/28/77	63	1425.74	--	--	--	8/30/88	8	39
178406	--	139.35.14	--	Traut Wells	02/04/81	90	1428.72	.3	1426.04	1393.4	--	--	--
423746	--	139.35.15.CAB	Heegard	Westby	08/22/87	45	1447	1.3	1448.3	1417.23	8/30/88	>17	0
423744	--	139.35.15.BAB	Nelson	Westby	07/25/87	74	1435	1.0	1436.0	1412.58	8/30/88	>8	26
199821	--	139.35.16.DDD	Belsham	Traut Wells	03/01/84	42	1455	.8	1455.8	1428.88	8/30/88	>16	2
191755	--	139.35.16.BBD	Armstrong	Northwest	09/21/82	179	1471.21	.5	1471.71	1444.24	8/30/88	>20	2
178376	--	139.35.16	--	North Star	04/23/81	130	1484.71	--	--	--	--	--	--
226276	--	139.35.17.CDD	Horgdahl	--	--	32	1462.0	.9	1462.9	1444.06	8/30/88	>14	0
176107	--	139.35.23.CCB	Underwood	Westby	08/24/82	50	1431.15	.7	1431.85	1404.82	8/30/88	>8	0
123623	--	139.35.23.CCA	Ackhoff	Johnson	11/21/76	84	1440	.85	1440.85	1388.85	8/30/88	36	0
118439	--	139.35.27.DDD	Suvanto	Schmitz	10/18/76	148	1422	.7	1422.7	1389.74	8/30/88	>8	66
154831	--	139.35.27.CCC	Hicks	North Star	10/04/78	135	1452	1.6	1453.6	1397.91	8/30/88	>5	35
180729	--	139.35.29.BAA	Henderson	North Star	06/30/81	140	1445	1.3	1446.3	1403.47	8/30/88	>14	0
193403	--	139.35.34.BCD	James	North Star	09/10/82	118	1412	1.5	1413.5	1388.8	8/30/88	>8	14
106411	--	139.35.34.ABA	Hilgendorf	Schmitz	03/28/77	96	1425	.25	1425.25	1395.16	8/30/88	>9	27
423777	--	139.35.36.CA	Burkel	--	--	108	1405	--	--	--	--	--	--
191756	--	139.36.01.CAC	Neumayer	Northwest	09/21/82	89	1461	1.6	1462.6	1429.03	8/30/88	>16	30
222190	--	139.36.01	--	--	--	164	1462	--	--	--	--	--	--
243605	USGS22d	139.36.04.BBB	USGS	LTP	9/12/88	97	1476.5	2.2	1478.7	--	--	39	--
189836	--	140.35.07.BAA	Morine	Westby	05/29/84	60	1495	1.0	1496.0	1457.34	8/30/88	>18	16
226135	--	140.35.07	--	Traut Wells	10/20/76	180	1467	--	--	--	--	--	--

Table 12.--Data for wells completed in uppermost confined-drift aquifer, Straight River area, Becker and Hubbard Counties, Minnesota--(Continued)

Minnesota unique number	Local name	Township and range	Owner's name	Driller's name	Date drilled	Depth of well (ft)	Land surface datum (ft above s.l.)	Casing above land surface (ft)	Elevation of measuring point (ft above s.l.)	Water level elevation (ft above s.l.)	Date measured	Saturated thickness (ft)	Depth to top of confining layer (ft below l.s.d.)
214536	--	140.35.08.DBA	McAdams	Traut Wells	10/20/76	157	1472	0.9	1472.9	1449.62	8/30/88	>61	50
190530	--	140.35.09.AAD	Holmquist	Laporte	05/13/83	43	1440	1.4	1441.4	1433.6	04/87	>10	16
160253	--	140.35.19	Erickson	Traut Wells	05/06/79	66	1465	--	--	--	--	--	--
405616	--	140.35.21.CCC	Mickelson	Traut Wells	11/07/84	64	1450	2.0	1452.0	1435.14	8/30/88	>11	46
154817	--	140.35.21.CDD	Hand Const	North Star	05/09/78	108	1451	2.1	1453.1	1432.2	04/86	>9	45
403060	--	140.35.22.CBD	Becker	Johnson	11/14/84	72	1450	.4	1450.4	1428.89	8/30/88	>20	45
226140	--	140.35.23	Keys	--		161	1444	--	--	--	--	--	--
193406	--	140.35.26.ADC	St. Jos. Hosp.	North Star	11/09/82	114	1444	1.1	1445.1	1417.36	8/30/88	>9	43
190822	--	140.35.26.CBB	Kriesel	Traut Wells	09/23/85	--	1443	1.8	1444.8	1425.05	04/87	>10	36
178764	--	140.35.26.CBC	Kriesel	North Star	09/16/80	60	1443	1.4	1444.4	1419.93	8/30/88	>12	36
455794	87-1143	140.35.27.BBD	Monico	LTP	12/16/86	156	1450	1.1	1451.1	1437.43	8/30/88	75	35
132626	--	140.35.27.AAC	Crookston	Traut Wells	03/28/77	151	1442	.8	1442.8	1424.73	8/30/88	>43	43
164354	--	140.35.28.BAB	Girtz	Traut Wells	07/02/81	42	1450	.2	1450.2	1436.23	8/30/88	22	0
139200	29031	140.35.28.DCC	--	Schroeder	12/06/84	91	1442.3	2.7	1445.1	1429.37	8/30/88	17	45
122070	--	140.35.30.DAA	Voalka	Johnson	02/18/83	191	1470.36	1.5	1471.86	1423.89	8/30/88	>10	0
150505	--	140.35.31.BDD	Griffith	North Star	10/10/80	107	1462.3	.9	1463.2	1429.63	8/30/88	34	35
--	77-1602	140.35.31.CAB	Monico	Traut Wells	02/16/78	197	1455.5	.8	1456.3	1419.5	8/30/88	32	45
--	TW 1TOD	140.35.30	--	--	--	189	1455	--	--	--	--	--	--
--	TW 2TOD	140.35.30	--	--	--	197	1455	--	--	--	--	--	--
149511	29034	140.35.31.CCC	--	--	--	108	1460.5	1.3	1461.8	1432.17	8/30/88	--	108
132623	--	140.35.31.DAA	Monico	Traut Wells	03/07/77	163	1451.4	.2	1451.6	1427.12	8/30/88	>43	38
214538	--	140.35.31.AAC	Becker	Traut Wells	10/01/76	180	1459.3	--	--	--	--	--	--
243874	USGS14d	140.35.32.CBB	USGS	LTP		145	1454	--	--	--	--	--	41
403089	--	140.35.32.CCA	Griffith	Johnson	05/09/85	139	1447.4	.9	1448.3	1424.9	8/30/88	>43	53
232423	--	140.35.32.BCA	Griffith	--		218	1457.4	.65	1449.05	1420.86	--	--	--
132611	--	140.35.32.DCC	Griffith	Traut Wells	01/18/77	158	1448.4	--	--	--	8/30/88	>40	48
132622	--	140.35.34.DDB	Monico	Traut Wells	03/08/77	195	1439.1	1.2	1440.3	1416.38	8/30/88	25	35
226271	--	140.35.34	--	--		220	1439	--	--	--	--	--	--
142299	--	140.35.35.DAA	Kostal Ford	Traut Wells	03/06/78	67	1439.6	1.8	1441.4	1408.21	8/30/88	>20	40
142218	--	140.35.35	Walsh Farm	Traut Wells	02/13/78	77	1435	--	--	--	--	--	--

Table 12.--Data for wells completed in uppermost confined-drift aquifer, Straight River area, Becker and Hubbard Counties, Minnesota--(Continued)

Minnesota unique number	Local name	Township and range	Owner's name	Driller's name	Date drilled	Depth of well (ft)	Land surface datum (ft above s.l.)	Casing above land surface (ft)	Elevation of measuring point (ft above s.l.)	Water level elevation (ft above s.l.)	Date measured	Saturated thickness (ft)	Depth to top of confining layer (ft below l.s.d.)
425447	--	140.36.02.CCC	Hensel	Traut Wells	12/29/86	103	1547	.7	1547.7	1489.07	04/87	>4	70
113124	--	140.36.03.BCC	Peterson	CCW Const	12/11/76	108	1526	1.25	1527.25	1494.81	8/30/88	6	44
438610	--	140.36.03	Lanquist	Traut Wells	07/26/88	137	1543	1.5	1544.5	1508.6	8/30/88	8	42
429727	--	140.36.10.BCA	Blanchard	Traut Wells	06/06/87	192	1520	.8	1520.8	1477.39	8/30/88	3	33
405603	--	140.36.11	Hensel	Traut Wells	08/29/84	189	1530	1.37	1531.37	1474.99	04/87	>6	87
116802	--	140.36.15	Dodge	Marino	04/30/77	47	1488	1.34	1489.34	1461.08	8/30/88	>7	30
243608	USGS23d	140.36.16.BBB	USGS	LTP	9/14/88	200	1510	--	--	--	--	15	79
411241	--	140.36.18.CCC	Monico	LTP	11/11/85	114	1509	1.6	1510.6	1478.8	8/30/88	32	48
--	TW 60SAG	140.36.18	--	--	--	--	1505	--	--	--	--	--	--
411242	85-1171	140.36.19.ACC	Monico	LTP	11/11/85	102	1503	1.8	1504.8	1478.39	8/30/88	33	40
--	TW 10SAG	140.36.19	--	--	--	--	1500	--	--	--	--	--	--
--	TW 40SAG	140.36.19	--	--	--	--	1510	--	--	--	--	--	--
192988	--	140.36.20.DAO	Miller	Traut Wells	09/02/82	52	1482.8	.9	1483.7	1464.82	8/30/88	>12	25
423703	--	140.36.21.DCC	Noeske	Westby	06/30/86	52	1478.64	1.5	1480.14	1449.27	8/30/88	>8	36
145686	--	140.36.24.CDD	Becker	Traut Wells	11/16/78	100	1467.49	.35	1467.84	1451.3	8/30/88	>34	58
411245	86-1050	140.36.25.CAA	Monico	LTP	11/11/85	147	1465.26	.13	1466.58	1443.6	8/30/88	35	.1
157968	--	140.36.27.AAA	Schultz	North Star	04/30/78	199	1479.81	1.0	1480.81	1464.09	8/30/88	>6	13
163155	77-1994	140.36.27.ACD	Monico	LTP	04/19/79	411	1478.44	1.3	1479.74	1431.05	8/30/88	21	78
148469	--	140.36.29.BAA	Osage Lndry	North Star	11/18/78	55	1495.0	1.0	1496.0	1465.76	04/86	>4	0
243603	USGS18d	140.36.29.ABA	USGS	LTP	09/13/88	161	1466.4	2.5	1468.9	--	--	3	95
214159	--	140.36.32.BDB	Monico	Fredrickson	04/14/76	106	1483.19	1.1	1484.29	1467.79	8/30/88	24	37
222195	--	140.36.32.ABC	Greenberg	LTP	04/19/76	102	1482	--	--	--	--	--	--
222193	--	140.36.32.AAD	Greenberg	LTP	04/20/76	112	1481	--	--	--	--	--	--
222197	--	140.36.32.AAC	Greenberg	LTP	04/15/76	102	1482	--	--	--	--	--	--
--	77-1995	140.36.35.BCD	Offutt	LTP	08/30/78	--	1457.66	1.05	1458.71	1429.38	8/30/88	22	58
132609	77-1326	140.36.36.AAC	Griffith	Traut Wells	07/11/77	110	1464.7	.05	1465.2	1428.74	8/30/88	43	48
132206	--	140.37.12.CCA	Stearns	Hydro Eng.	02/28/77	143	1526	1.1	1527.1	1490.5	04/86	41	95
147230	--	140.37.14.DAA	Greenburg Farms	LTP	12/04/78	89	1513	2.55	1515.55	1487.33	04/86	>9	46
226279	--	140.37.14.AAC	Greenburg Farms	Fredrickson	09/08/76	135	1521	.8	1521.8	1492.85	04/86	32	52

Table 12.--Data for wells completed in uppermost confined-drift aquifer, Straight River area, Becker and Hubbard Counties, Minnesota--(Continued)

Minnesota unique number	Local name	Township and range	Owner's name	Driller's name	Date drilled	Depth of well (ft)	Land surface datum (ft above s.l.)	Casing above land surface (ft)	Elevation of measuring point (ft above s.l.)	Water level elevation (ft above s.l.)	Date measured	Saturated thickness (ft)	Depth to top of confining layer (ft below l.s.d.)
142278	--	141.36.31.ACB	Boyce	Traut Wells	12/16/77	56	1510	1.0	1511.0	1495.6	04/86	>41	0
142280	--	141.36.31.DBD	Boyce	Traut Wells	12/14/77	56	1510	0.4	1510.4	1506.5	04/86	51.5	3
				Well logs used for geologic information									
164343	--	139.35.01.ABB	Monico	Traut Wells	11/06/79	59	1432	na	na	na	na	6	46
160266	--	139.35.10.BDC	Monico	Traut Wells	05/05/79	160	1435	na	na	na	na	10	56
226252	--	139.35.10.CCD	Gottzman	Wingard	--	124	1469.66	na	na	na	na	>10	0
116476	--	139.35.10.CCC	Daniels	Traut Wells	08/05/75	115	1436	na	na	na	na	>7	0
226255	--	139.35.11.DCB	Monico	Traut Wells	--	160	1431	na	na	na	na	30	30
226257	--	139.35.11.CBA	Becker	Traut Wells	--	125	1435	na	na	na	na	10	52
118407	--	139.35.12.BAA	Wagner	Schmitz	07/02/75	40	1423	na	na	na	na	8	19
106001	--	139.35.12.CCC	O'Dair	Traut Wells	09/31/75	88	1430.1	na	na	na	na	--	--
160252	--	139.35.13.BBC	Falk	Traut Wells	04/26/79	122	1429.72	na	na	na	na	--	--
118426	--	139.35.13.DDD	Lepping	Schmitz	01/10/76	79	1411	na	na	na	na	9	35
236601	--	139.35.13.BAA	Wright	Traut Wells	02/83	69	1428	na	na	na	na	15	30
407693	--	139.35.13.DBB	Meacham	Westby	06/01/86	44	1427.88	na	na	na	na	--	--
199830	--	139.35.14.CDC	Indrehus	Traut Wells	05/17/84	65	1424	na	na	na	na	--	--
199810	--	139.35.14.CDC	Hand	Traut Wells	10/28/83	60	1424	na	na	na	na	--	--
226253	--	139.35.14.BBD	Monico	Traut Wells	--	136	1431	na	na	na	na	61	55
101646	--	139.35.14.ABA	Massie	Nevis	07/30/81	138	1430	na	na	na	na	>10	28
178406	--	139.35.14.BBC	Becker	Traut Wells	12/18/80	90	1428.72	na	na	na	na	27	52
226259	--	139.35.14.CCD	Riedesel	Hanson	1969	79	1435	na	na	na	na	>9	30
226260	--	139.35.15.DDD	Hoefs	Peterson	1965	80	1455	na	na	na	na	>5	0
226261	--	139.35.15.DBA	Hoefs	--	1906	40	1447	na	na	na	na	>20	0
101603	--	139.35.15.BAA	Heegard	Hartlyns	04/25/75	75	1434.65	na	na	na	na	>5	25
178376	--	139.35.17.BBA	Morgan	North Star	04/23/81	130	1484.71	na	na	na	na	>7	70
226276	--	139.35.17.CDD	Horgdahl	--	--	32	1462	na	na	na	na	>14	0
160225	--	139.35.18.ABB	Paulson	Traut Wells	10/20/78	54	1463	na	na	na	na	>17	11
226264	--	139.35.21.DCC	Hoefs	--	1922	163	1456	na	na	na	na	>3	5
226262	--	139.35.22.DBD	Berthelot	Schmitz	--	43	1453	na	na	na	na	>7	0

Table 12.--Data for wells completed in uppermost confined-drift aquifer, Straight River area, Becker and Hubbard Counties, Minnesota--(Continued)

Minnesota unique number	Local name	Township and range	Owner's name	Driller's name	Date drilled	Depth of well (ft)	Land surface datum (ft above s.l.)	Casing above land surface (ft)	Elevation of measuring point (ft above s.l.)	Water level elevation (ft above s.l.)	Date measured	Saturated thickness (ft)	Depth to top of confining layer (ft below l.s.d.)
133583	--	139.35.22.DBD	Erickson	Johnson	06/28/77	141	1452	na	na	na	na	>11	39
116838	--	139.35.23.ABA	Saar	Nevis	10/23/79	48	1424	na	na	na	na	>8	20
116839	--	139.35.23.ABB	Hanson	Nevis	10/23/79	48	1424	na	na	na	na	>8	20
--	PR-25	139.35.23.CDA	--	--	08/08/74	66	1425	na	na	na	na	36	20
226263	--	139.35.27.BBA	Stepka	Schmitz	--	144	1453	na	na	na	na	>9	0
222190	TW	139.36.01.BBD	Monico	Traut Wells	--	164	1462	na	na	na	na	9	57
222189	--	139.36.12.AAA	Knobloch	Peterson	1952	76	1465.65	na	na	na	na	8	10
152050	--	140.35.06.ADA	Nielsen	North Star	6/15/78	140	1487	na	na	na	na	>12	0
226135	TW	140.35.07.DAB	McAdams	Traut Wells	10/20/76	175	1467	na	na	na	na	37	55
116477	--	140.35.14.DDC	Tichich	Traut Wells	08/05/75	58	1448	na	na	na	na	>9	40
407689	--	140.35.15.BBA	Schmitt	Westby	05/16/86	38	1445	na	na	na	na	>14	10
160253	TWB	140.35.19.CDD	Erickson	Traut Wells	05/04/79	198	1465	na	na	na	na	--	36
154817	--	140.35.22.CDD	Hand	North Star	05/09/78	108	1451	na	na	na	na	--	--
190900	--	140.35.23	--	--	--	58	--	na	na	na	na	--	--
226140	--	140.35.23.DCA	Park Rapids	Keys	1951	166	1444	na	na	na	na	59	45
101631	--	140.35.26	Thielen	Nevis	11/10/76	40	1445	na	na	na	na	>8	18
--	TW 1TOD	140.35.31.CBD	Monico	Traut Wells	01/31/78	189	1455	na	na	na	na	16	35
214538	--	140.35.31.AAC	Becker	Traut Wells	10/01/76	177	1459.3	na	na	na	na	22	38
232424	TW	140.35.31.BBD	Griffith	North Star	--	118	1462	na	na	na	na	28	40
226271	TW	140.35.34.DDB	Monico	Traut Wells	1976	200	1439	na	na	na	na	31	37
142218	--	140.35.35.DDD	Walsh Farm	Traut Wells	02/13/78	77	1435	na	na	na	na	14	56
116421	--	140.36.03.DAA	Burrell	Traut Wells	--	35	1517	na	na	na	na	>7	0
405617	--	140.36.11.BCC	Girtz	--	10/24/84	176	1530	na	na	na	na	>6	44
118438	--	140.36.11.DDD	Shepersky	Schmitz	10/05/76	66	1510	na	na	na	na	>15	23
411241	TW 70SAG	140.36.18.CBB	Monico	LTP	03/19/85	104	1511	na	na	na	na	18	67
411241	TW 80SAG	140.36.18.CAA	Monico	LTP	03/20/85	102	1505	na	na	na	na	37	35
160240	--	140.36.24.BCD	Gomez	Traut Wells	12/17/76	80	1468.9	na	na	na	na	--	--
411242	TW 10SAG	140.36.19.ABC	Monico	LTP	06/25/84	93	1500	na	na	na	na	5	47
411242	TW 40SAG	140.36.19.ABA	Monico	LTP	06/27/84	81	1510	na	na	na	na	8	61
--	TW 140SAG	140.36.25	--	--	--	--	1465	na	na	na	na	--	0

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148469	--	140.36.29	Osage Lau	North Star	11/18/78	55	1495	na	na	na	na	--	--
132601	--	140.36.29	Beck	Traut Wells	01/13/77	55	1495	na	na	na	na	>15	0
423720	--	140.36.29	Ho	Westby	10/16/86	44	1487.27	na	na	na	na	>17	22
222195	--	140.36.32.ABC	Greenberg	LTP	04/09/76	83	1482	na	na	na	na	33	64
222193	TW 13	140.36.32.AAD	Greenberg	LTP	04/20/76	76	1481	na	na	na	na	21	66
222197	TW 9	140.36.32.AAC	Greenberg	LTP	04/15/76	82	1482	na	na	na	na	5	58
101625	--	140.37.1.C	Harris	Nevis Well	05/19/76	64	1527	na	na	na	na	>14	0
142278	--	140.36.11.BCC	--	--	--	--	1510	na	na	na	na	--	--
147230	--	140.37.14	Greenberg	LTP	12/04/78	92	1513	na	na	na	na	--	--
226279	--	140.37.14.AAC	--	Fredrick	09/08/76	140	1521	na	na	na	na	--	--
192979	--	141.36.32.ADA	Wright	Traut Well	01/05/83	62	1527	na	na	na	na	14	42

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