HYDROGEOLOGY AND WATER QUALITY OF GLACIAL-DRIFT AQUIFERS IN THE BEMIDJI-BAGLEY AREA, BELTRAMI, CLEARWATER, CASS, AND HUBBARD COUNTIES, MINNESOTA

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MINNESOTA DEPARTMENT OF NATURAL RESOURCES and the BEMIDJI-BAGLEY GROUND-WATER STUDY STEERING COMMITTEE

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U.S. DEPARTMENT OF THE INTERIOR

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CONTENTS

CONTENTS

Page

ILLUSTRATIONS

ILLUSTRATIONS

TABLES

TABLES

CONVERSION FACTORS, VERTICAL DATUM, AND ABBREVIATED WATER QUALITY UNITS

New format December 21, 1990

Multiply Inch-Pound Unit	By	To obtain Metric Unit
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
foot per day (ft/d)	0.3048	meter per day
	0.0003528	centimeter per second
foot per mile (ft/mi)	0.1894	meters per kilometer
cubic foot per second (ft^3/s)	28.32	liter per second
foot squared per day (ft^2/d)	0.09294	meter squared per day
gallon (gal)	0.003785	cubic meter
gallon per day (gal/d)	0.003785	cubic meter per day
gallon per minute (gal/min)	0.06308	liter per second
million gallons per day (Mgal/d)	0.04381	cubic meter per second
square mile (mi^2)	2.590	square kilometer

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. For concentrations less than 7,000 mg/L, the numerical value is the same as for concentrations in parts per million.

Sea level In this report "sea level" refers to the National Geodetic Vertical Datum 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.--a 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, consists mainly of ground-water discharge to a stream.

Confined aquifer.--an aquifer bounded above by confining units. An aquifer containing confined ground water. Synonymous with buried aquifer.

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

Dissolved.--Pertains to the constituents in a representative water sample that pass through a 0.45-μm (micrometer) membrane filter. The "dissolved" constituents are determined from subsamples of the filtrate. This convenient operational definition is used by Federal agencies that collect water data.

Drawdown.--the vertical distance between the static (nonpumping) hydraulic head and hydraulic head caused by pumping.

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

Evapotranspiration.--water discharge to the atmosphere by evaporation from water surfaces and moist soil and by plant transpiration.

Ground water.--that 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 atomic 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 ice.

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

Pixel.--an element of a grid associated with a single characteristic, for example, agricultural land use.

Potentiometric surface.--surface that represents the static head of water in an aquifer; assuming no appreciable variation of head with depth in the 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.--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.--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.

Surficial aquifer.--the saturated zone between the water table and the first underlying confining unit; synonymous with unconfined aquifer.

Suspended, recoverable.--Pertains to the constituents in a representative water sample that are retained on a 0.45-μm membrane filter and that are brought into solution by digestion (usually by using a dilute acid solution). Complete dissolution of all the particulate matter is often not achieved by the digestion treatment, and thus the determination may represent less than the "total" amount (that is, less than 95 percent) of the constituent in the sample.

Determinations of "suspended, recoverable" constituents are made either by analyzing portions of the material collected on the filter or, more commonly, by calculating the difference between the dissolved and the total recoverable concentrations of the constituent.

Suspended, total.--Pertains to the constituents in a representative water sample that are retained on a 0.45-μm membrane filter. This term is used only when that analytical procedure assures measurement of at least 95 percent of the constituent determined.

Determinations of "suspended, total" constituents are made either by analyzing portions of the material collected on the filter or, more commonly, by calculating the difference between the dissolved and the total concentrations of the constituent.

Till.--unsorted, unstratified drift deposited directly by glacial ice.

Total, recoverable.--Pertains to the constituents in solution after a representative water-suspended sediment sample is digested (usually by using a dilute acid solution). Complete dissolution of all particulate matter is often not achieved by the digestion treatment, and thus the determination may represent less than the "total" amount (that is, less than 95 percent) of the constituent in the dissolved and suspended phases of the sample.

Total.--Pertains to the constituents in a representative water-suspended sediment sample, regardless of the constituent's physical or chemical form. This term is used only when the analytical procedure assures measurement of at least 95 percent of the constituent in both the dissolved and the suspended phases of the sample. (Note that the word "total" indicates both that the sample consists of a water-suspended sediment mixture and that the analytical method determines all of the constituent in the sample).

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.--an aquifer that has a water table; the saturated zone between the water table and the first underlying confining unit; synonymous with surficial aquifer.

Water table.--that 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.

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ABSTRACT

Unconfined and the upper confined aquifers in glacial drift are the primary sources of water in a 1,600 square-mile area including parts of Beltrami, Cass, Clearwater, and Hubbard Counties, Minnesota. The unconfined-drift aquifer consists of coarse sand and gravel in the center of the study area. The total area underlain by the unconfined-drift aquifer is approximately 550 square miles. The unconfined aquifer ranges in thickness from 0 to 130 feet, and is greater than 20 feet thick over an area of 280 square miles. On the basis of scant data, the transmissivity of the unconfined aquifer ranges from less than 70 feet squared per day in the south and west to greater than 8,900 feet squared per day in an area west of Bemidji. Well yields from 10 to 300 gallons per minute are possible in some areas. The unconfined and upper confined-drift aquifers are separated by a fine-grained confining unit of till or lake deposits.

The thickness of the upper confined-drift aquifer ranges from 0 to 60 feet in the Bemidji area. On the basis of specific-capacity and aquifer-thickness data, and results of model simulations, the transmissivity of the upper confined-drift aquifer ranges from less than 100 feet squared per day in the south and west parts of the aquifer to about 12,800 feet squared per day in the area around Bemidji. Well yields of 10 to 2,100 gallons per minute are possible in some areas.

The direction of ground-water flow in both unconfined and upper confined-drift aquifers is toward the Mississippi and Clearwater Rivers. These rivers are the major discharge points for both aquifers. Ground-water divides, which separate the ground-water flow systems that discharge to these rivers, are approximately coincidental with surface-water divides between the rivers.

Water from both aquifers generally is of the calcium bicarbonate type and is very hard, averaging 309 and 267 milligrams per liter as $CaCO_3$ from confined and unconfined-drift aquifers, respectively. Water from both aquifers generally is suitable for drinking, crop irrigation, and most other uses. Concentrations of ammonia, boron, chromium, iron, manganese, and phenols, however, locally exceed recommended limits for drinking water (Minnesota Pollution Control Agency, 1988). Longer residence time and leakage through glacial till is believed to cause higher concentrations of common inorganic constituents in water from confined-drift aquifers than concentrations in water from the unconfined-drift aquifer. Elevated concentrations of nutrients, chloride, and phenols in the unconfined-drift aquifer may be related to land-use practices.

Statistical comparisons of common chemical constituents in water from wells completed in the unconfined-drift aquifer in several land-use areas suggest that concentrations of many constituents and physical properties are generally greater for wells in areas of commercial and residential land-use than for wells in areas of agriculture or forest land-use. These constituents include ammonia plus organic nitrogen, phosphorus, calcium, sodium, potassium, chloride, sulfate, silica, dissolved solids, and specific conductances. The mean values of ammonia nitrogen, magnesium, and fluoride are generally greater for wells in commercial land-use type areas than for wells in forested and agricultural land-use type areas. The mean concentration of nitrogen (NO_2 + NO_3, dissolved) is generally greater for wells in residential land-use type areas than for wells in forested and agricultural land-use type areas.

The Kruskil-Wallis test, a nonparametric statistical technique, indicated that for 12 of the 21 constituents sampled in common in all land-use type groups in the unconfined-drift aquifer, a relation between the concentration of these constituents and land use was found to be statistically significant.

INTRODUCTION

State and local governmental agencies in Minnesota are concerned about regional degradation of ground-water quality that might be caused by certain land uses and land-use practices. Of particular concern are pervasive land-use practices considered to be non-point sources of pollution. The use of chemicals in agriculture and in forestry, dense residential development with septic systems, urbanization, transportation, and waste disposal are practices and land uses that have potential for contaminating aquifers on a regional basis over a long period of time.

Recent studies in surficial, sand-plain aquifers in agricultural counties in Minnesota have indicated that specific conductance, chloride, and nitrate concentrations have increased significantly in the last decade. Nitrate levels in many shallow wells currently exceed recommended limits for domestic and livestock consumption established by the Minnesota Pollution Control Agency (1988). These studies also indicate that nitrate has gone undetected in previous studies because wells selected for sampling were screened too deeply in the aquifer. Also, low concentrations of pesticides have been detected in shallow ground water.

Increasing population, intensified agricultural and commercial activity, and localized ground-water contamination from waste-disposal sites within the 550-square-mile Bemidji-Bagley unconfined-drift aquifer have resulted in concerns about present and future ground-water quality in the Bemidji-Bagley area in north-central Minnesota (fig. 1). State and local officials identified the need for a program to establish background water quality in aquifers, to determine seasonal variations, to determine impacts of various land uses on water quality, and to provide a means to observe future trends in water quality.

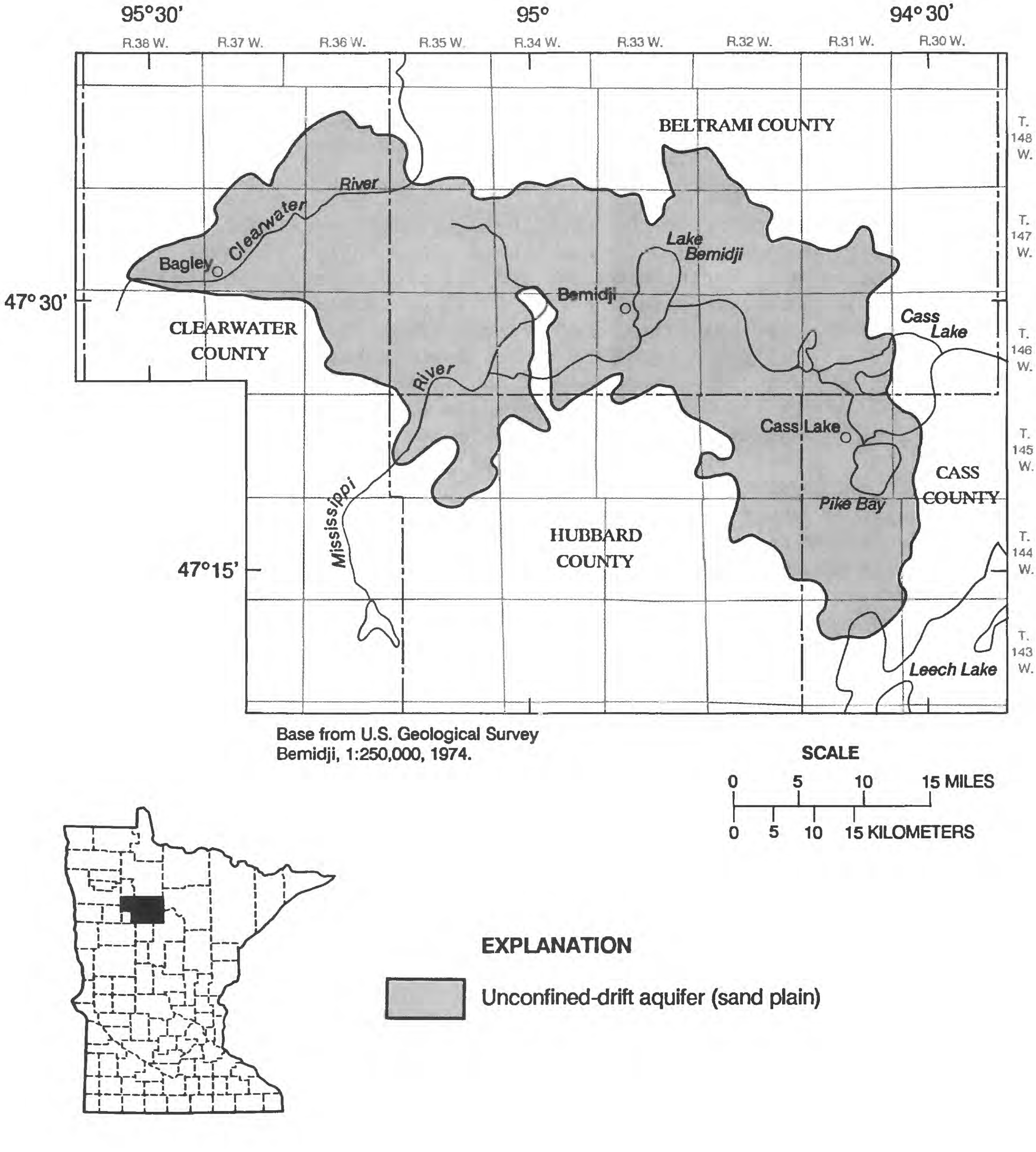


Figure 1.--Location of Bemidji-Bagley study area

Prior to this study, data in the Bemidji-Bagley area were not adequate to characterize ground-water quality at a scale comparable to that of the land uses that might affect water quality. Existing water-quality data generally were not adequate to assess long-term changes because too few wells were sampled or the samples were not analyzed for the appropriate constituents. Furthermore, previous sampling has been too infrequent to determine seasonal changes in water quality.

Agricultural interests in the Bemidji-Bagley area were considering increased use of ground water for irrigation of crops to (1) increase yields, (2) assure productivity during drought, and (3) produce crops on land that could not be cultivated economically with dry-land farming practices. Little was known about the geology, areal extent, thickness, hydraulic properties, or potential yields of drift aquifers in the Bemidji-Bagley area. There were concerns about the effects of increased withdrawals from aquifers because of uncertainty about (1) long-term yields of wells open to these aquifers, (2) effects of pumping and drought on water levels and streamflow, and (3) possible interference between nearby wells pumping from the same aquifer. The hydrogeologic framework of drift aquifers in the Bemidji-Bagley area and movement of ground water also needed to be defined before water-quality data could be adequately interpreted. The U.S. Geological Survey, in cooperation with the Minnesota Department of Natural Resources (MDNR) and the Soil and Water Conservation Districts of Beltrami, Cass, Clearwater, and Hubbard Counties conducted a 3-year study (1985-88) to appraise the ground-water resources in the area. This report presents the findings of that study.

Purpose and Scope

This report describes the occurrence, availability, and quality of ground-water in the Bemidji and Bagley area of north-central Minnesota. The report objectives are to (1) describe the hydrogeologic properties, water movement, and potential yield of the unconfined-drift and uppermost confined-drift aquifers, (2) define the quality of ground water in relation to hydrogeologic conditions and land use, (3) describe seasonal changes in water quality, and (4) provide baseline hydrologic and water-quality data for use in future assessments of long-term trends.

The unconfined-drift and uppermost confined-drift aquifers are the only aquifers considered in detail in this report. Other aquifers undoubtedly exist below these aquifers but data are insufficient to define their nature or extent.

This study was conducted in two phases. The first phase was to define ground-water resources of the unconfined-drift and uppermost confined-drift aquifers in the Bemidji-Bagley area. The second phase consisted of defining ground-water quality in these aquifers.

Location and Description of Study Area

The study area is about 220 mi (miles) northwest of Minneapolis and St. Paul, Minnesota. It covers approximately 1,600 mi^2 (square miles) and includes parts of Beltrami, Cass, Clearwater and Hubbard Counties (fig. 1). A 500 mi^2 area, locally referred to as the Bemidji-Bagley sand plain, is underlain by an extensive unconfined aquifer consisting of glacial outwash and glacial-lake deposits. The remainder of the study area, surrounding the area of the unconfined-drift aquifer, consists of glacial moraine with isolated and less extensive unconfined-drift aquifers. Confined-drift aquifers exist, at depth, in these areas. The area is drained by the Clearwater River (Hudson Bay drainage system) in the northwest and by the Mississippi River in the south. The topography is generally flat or gently rolling in sand-plain areas, and is rolling in areas of glacial moraine surrounding the sand plains. Annual precipitation ranges from 24-26 in. (inches) (Baker and Kuehnast, 1978), with most occurring as rain between May and September. Potential annual evapotranspiration is about 22 in. and annual runoff is about 2 in. (Baker and others, 1979).

Land use in the Bemidji-Bagley area is a mixture of several types. Land use has been mapped for the area (Minnesota State Planning Agency, written commun., 1987) based on data from U.S. Geological Survey topographic maps. These data, resolved to 40-acre pixels, are available from that agency. Based on their data, land uses for the study area are as follows:

Land use	Percent
Forested	68.4
Water	12.3
Cultivated	8.9
Marsh	2.4
Urban residential	1.5
Pasture and open	6.2
Other urban	0.3

Forested areas consist of second or third-growth stands of trees that are harvested primarily for paper pulp and wood products. Agricultural lands consist primarily of pasture, hay, small-grain crops, corn, and potatoes. Several large lakes, including Cass and Leech Lakes and Lake Bemidji, and numerous smaller lakes are in the area. Residential and urban areas are concentrated primarily around Bemidji (population 10,949), Bagley (1,321) and Cass Lake (1,001). Commercial areas are not extensive and exist primarily as localized areas of light industry, transportation, and commerce.

Ground-water pumpage is not presently a significant portion (about 2 percent) of the total water usage in the study area. Confined aquifers provide the majority of the ground water pumped. The primary consumptive use of ground water pumped from these aquifers is for domestic and municipal supply. Large volumes of surface water are used for industrial and commercial purposes, hydroelectric-power generation, irrigation, rural domestic and livestock use, recreation, and sewage treatment. A detailed description of water use for the study is given in Appendix A.

Previous Investigations

The first extensive work related to the glacial geology of the Bemidji-Bagley area was a map of Minnesota's Quaternary geology published by Leverett (1932). Wright and Ruhe (1965) and Wright (1972) also have published works summarizing the general glacial history of Minnesota. Wright and others (1973) and Wright (1973) describe the glacial history and glacial geology of the Superior and Des Moines lobes of the Wisconsin glaciation in the area. Harris and others (1974), Harris (1975) and Sackreiter (1975) discuss glacial history and stratigraphic nomenclature in the Bemidji-Bagley area. Melchior (Bemidji State University, written commun., 1987) has described glacial units in the area in stratigraphic terms based on the work of Harris (1975) and Harris and others (1974).

Oakes and Bidwell (1968) described the regional hydrology of the Mississippi Headwaters Area. Siegel and Winter (1980) describe a study of lake/ground-water interactions at Williams Lake in Hubbard County. Schubbe (1988) describes the glacial geology and ground-water hydrology of Spearhead Lake in Beltrami County.

Methods of Investigation

Field work for this study was conducted during the period from 1985-87. Hydrogeologic maps were prepared using reported data from 494 wells and test holes obtained from files of the Minnesota Geological Survey and the U.S. Geological Survey, and geologic logs from 273 test holes drilled for this study (figs. 2 and 3). The locations of wells having driller's logs were confirmed by locating the wells in the field or by confirming the location of wells from county plat books. Location, geologic, and hydrologic information from the logs were entered into a computer data base. Data points were assigned a Minnesota Geological Survey unique well number, latitude, and longitude. The data base was used to prepare maps showing the thickness, extent, and hydrologic properties of the unconfined-drift and uppermost confined-drift aquifers and of the uppermost confining unit. The uppermost confined-drift aquifer is considered as a single hydrogeologic unit in this report. The aquifer may be discontinuous and may consist of several aquifers separated by units of low hydraulic conductivity. However, data are not sufficient to map those discontinuities at the scale of this project. Data density, scale, variability in data reported from a variety of sources (logs from several drillers, test holes, data collected for this study), and actual variability in hydrogeologic properties over short distances prohibited exact contouring of some hydrogeologic maps in this report. Some of the maps in this report, therefore, were prepared using a computer program (Preusser, 1984) and "smoothed" or averaged using a method developed by Cleveland (1979) to show average values of hydrogeologic properties of aquifers and confining units. These "smoothed" or averaged contour maps are identified as generalized contour maps in this report. The maps were produced by applying a method of robust locally-weighted regression, and the contours represent approximate statistical trends in hydrogeologic data. Figure 4 compares interpreted contours and generalized contours of the top of the uppermost confined-drift aquifer for a small part of the study area. These maps should not be used to predict the exact value or hydrologic property at a point; rather they show approximate values and changes in values over space. Well logs and test-hole logs used to prepare all maps are available from the U.S. Geological Survey, Minnesota District.

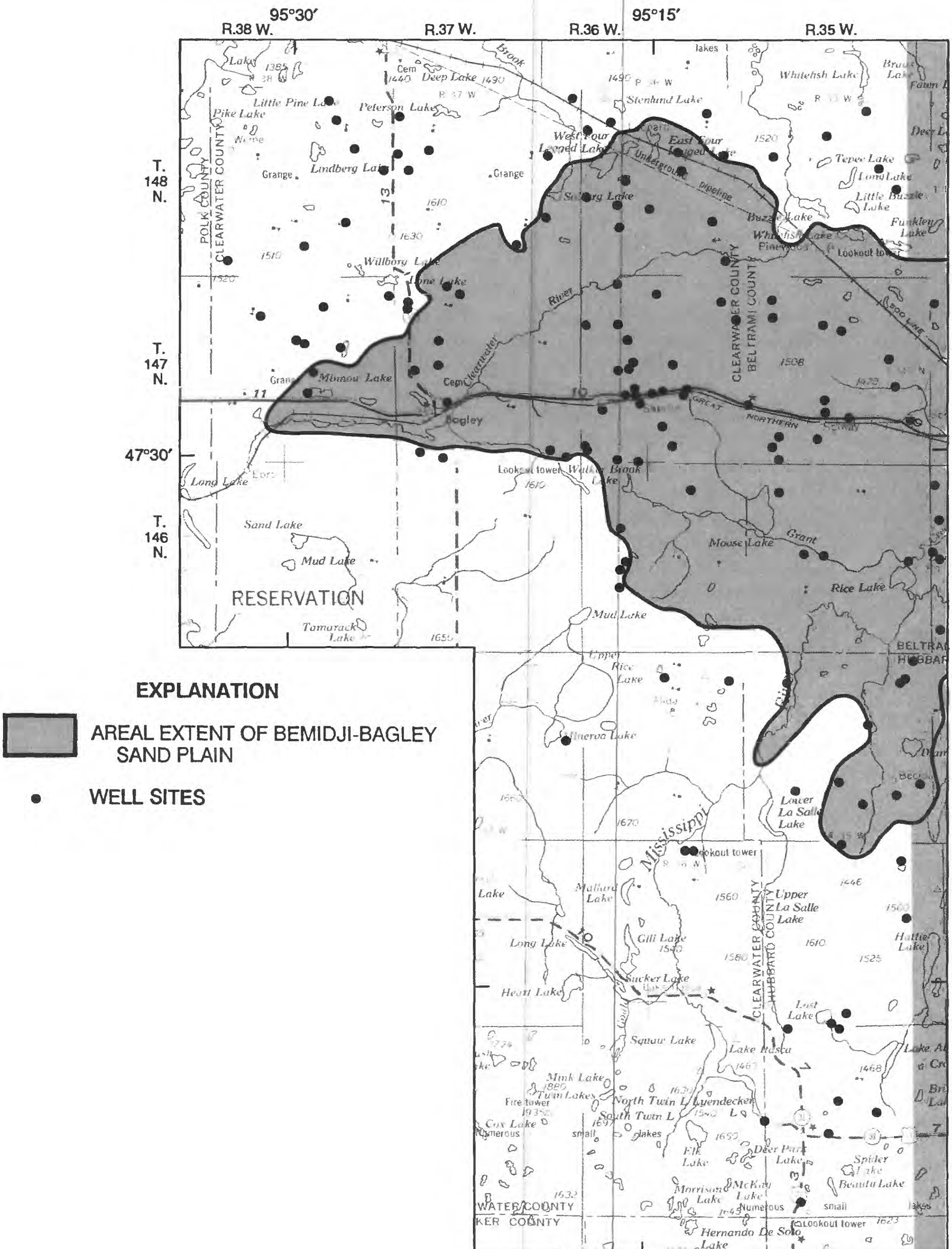
Eighty seven test holes (fig. 3) were completed as monitoring wells to determine spatial and temporal changes in water levels in the unconfined-drift aquifer and to collect water samples for chemical analysis. Data from these wells, coupled with water-level data from well logs, were used to produce potentiometric-surface maps of the unconfined and uppermost confined-drift aquifers.

A conceptually based, three-dimensional, finite-difference ground-water-flow model (McDonald and Harbaugh, 1984) was used to simulate ground-water flow to aid in understanding flow systems, hydrologic budgets, and the hydraulic properties of hydrogeologic units. The model was calibrated to steady-state conditions based on hydrologic data (potentiometric surfaces and stream-discharge rates) collected for this study. The model was used to estimate the hydraulic properties of hydrogeologic units and to examine the effects of hypothetical pumping and drought conditions on regional ground-water levels and streamflow. The objective of model development was to aid in understanding the hydrology of the hydrogeologic system. The model is not of sufficient detail to be used as a predictive tool. A detailed description of construction, use, and evaluation of the model is presented in Appendix B.

Horizontal hydraulic conductivity was estimated from specific-capacity information available from well logs for 129 locations in the uppermost confined-drift aquifer and for seven locations in the unconfined-drift aquifer. Transmissivity maps were produced by multiplying the mean hydraulic conductivity value of the aquifer at a given location by the aquifer thickness at that location. Transmissivity contours reflect local variations in horizontal hydraulic conductivity and aquifer thickness. Vertical hydraulic conductivity of the uppermost confining unit was estimated during calibration of the finite-difference, ground-water-flow model by simulating vertical hydraulic-head differences across the confining units.

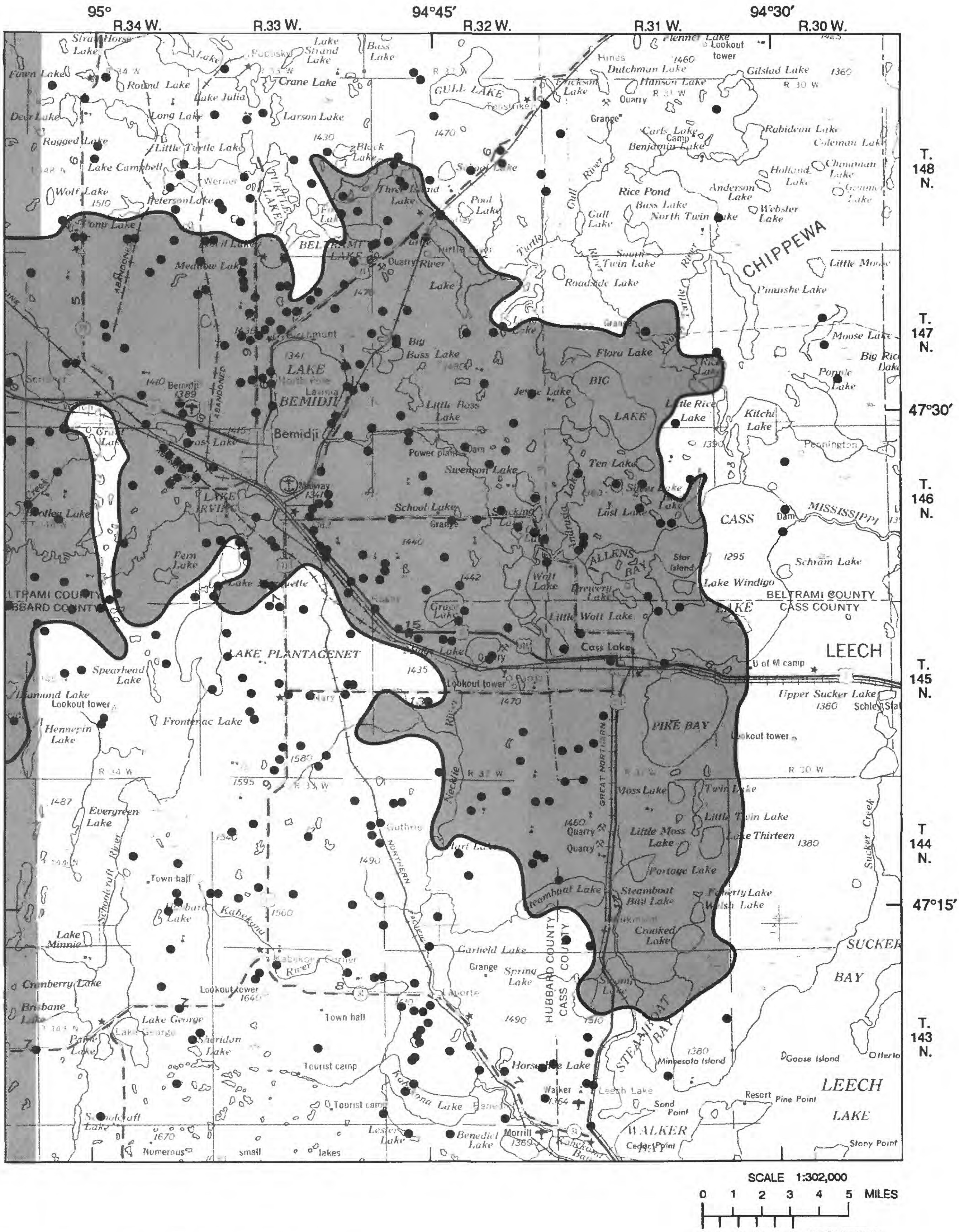
Water-use data were obtained from the Minnesota Water-Use Data System at the MDNR. Water-use data for 1985 were used to reflect current ground-water usage during model simulations. Land-use information was obtained from the Minnesota Planning Information Center (PIC). Land use data available from PIC consists of data resolved to 40-acre pixels obtained from U.S. Geological Survey topographic maps.

Data were collected to assess the quality of ground water in relation to hydrogeologic conditions and land use, to determine seasonal changes in water quality, and to provide baseline water-quality data for use in future assessments of trends caused by land-use practices. Forty-nine wells completed in the unconfined-drift aquifer were sampled. All available wells were assigned a land-use designation based on the PIC information. Land-use types comprised forested areas, agricultural areas (pasture and row crops), residential areas, and commercial or industrial areas. Wells for sampling were selected at random from each group. Also selected at random were 19 wells completed in the uppermost confined-drift aquifer. Samples were collected during July and August of 1987.

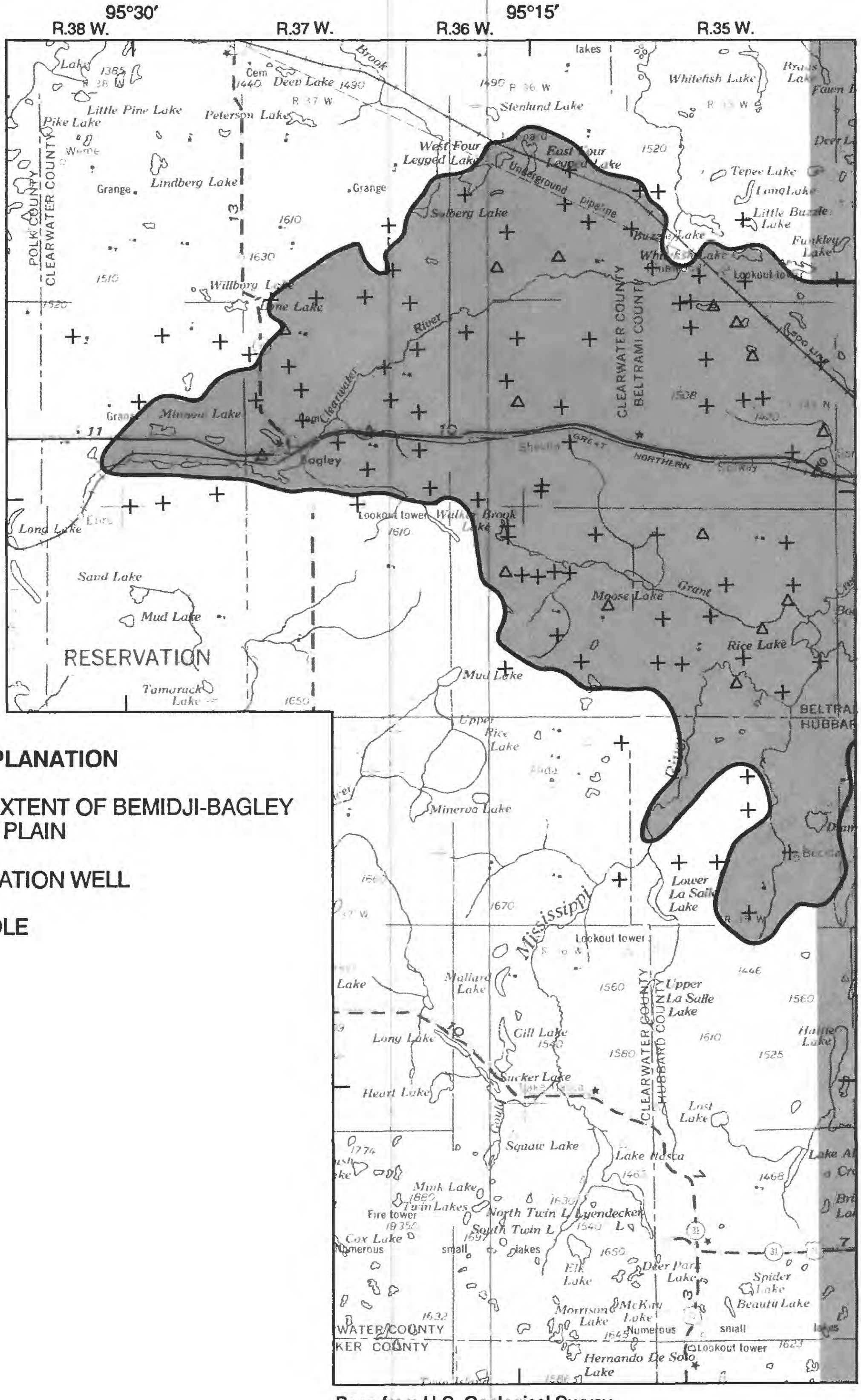


Base from U.S. Geological Survey
Bemidji 1:250,000, 1974

Figure 2.--Locations of non-U.S. Geological



Survey wells used as data for this report



EXPLANATION

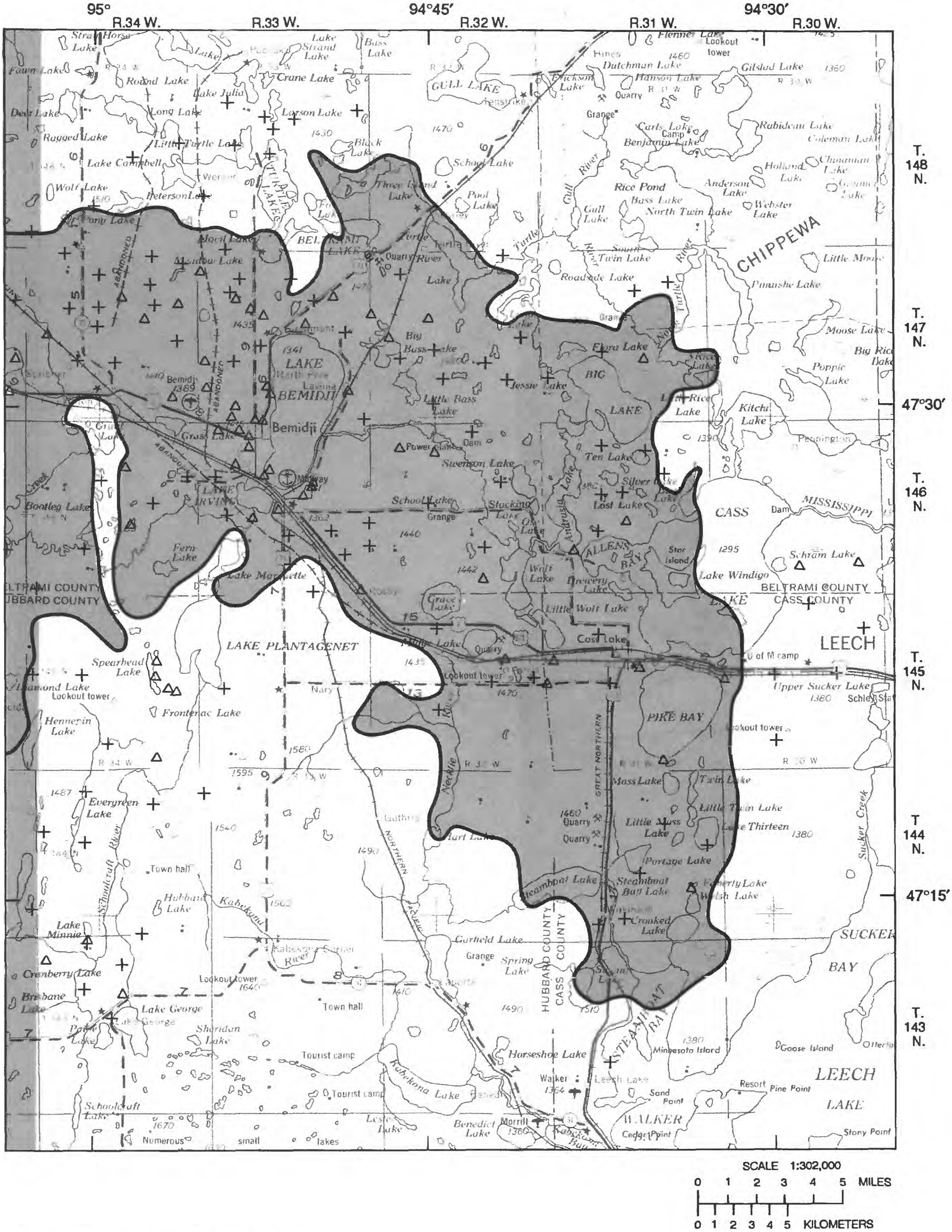
AREAL EXTENT OF BEMIDJI-BAGLEY SAND PLAIN

△ OBSERVATION WELL

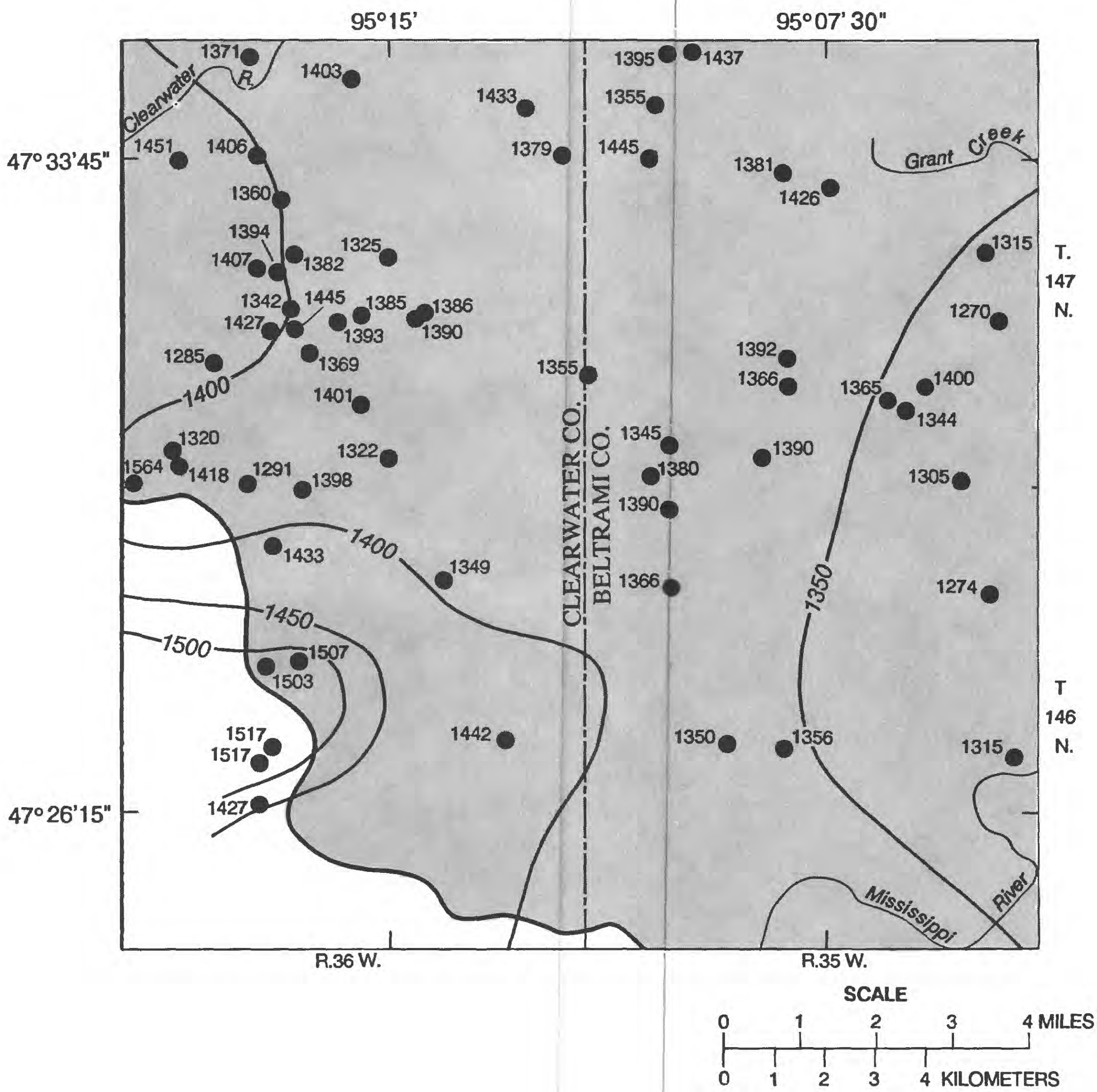
+ TEST HOLE

Base from U.S. Geological Survey
Bemidji 1:250,000, 1974

Figure 3.--U.S. Geological Survey



observation wells and test holes



EXPLANATION

BEMIDJI-BAGLEY SAND PLAIN

—*1350*— GENERALIZED STRUCTURE CONTOUR--Shows generalized altitude of top of uppermost confined-drift aquifer. Contour interval 50 feet. Datum is sea level.

1385● WELL LOG USED FOR CONTROL--Number is altitude of top of uppermost confined-drift aquifer, in feet above sea level.

Figure 4.--Comparison of generalized contours and point values in a small part of the study area (see figure 13 for location)

All wells were sampled for an identical group of "indicator constituents" (table 1). Data from these analyses were evaluated with graphical and non-parametric statistical techniques to test the assumption that concentrations of individual constituents vary significantly among land-use groups. Water from wells in individual land-use groups was also analyzed for potential contaminants in each land-use type group.

One well from each of the five land-use and aquifer-type groups was sampled in each of the four seasons during 1987-88 to quantify seasonal variability in water quality.

Test-Hole and Well-Numbering System

Two duplicate systems of numbering wells and test holes were used for this study. The first system used was the Minnesota Geological Survey unique well number system that associates a well with a latitude and longitude. The second system of numbering wells and test holes is based on the U.S. Bureau of Land Management's system of land subdivision (township, range, and section). Figure 5 illustrates the 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 146.35.15ADC indicates a test hole or well located in the SW1/4, SE1/4, NE1/4, Sec. 15, T.146 N., R.35 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 goes to land owners who permitted the drilling of test holes and the installation of observation wells, and to well owners who permitted sampling of their wells and measurement of water levels. Special thanks goes to Dale Krystosek, Beltrami County Soil and Water Conservation District, for coordination of the project at the local level.

HYDROGEOLOGY

Bedrock

Proterozoic (Precambrian) igneous and metamorphic rocks directly underlie drift throughout the study area. The rocks are primarily granite, gneiss, and schist for which areal distribution has been inferred from gravity and magnetic data (Sims, 1970). These crystalline rocks, which generally are dense with low porosity and permeability, only have water in fractures and in weathered zones near their upper surface; therefore they are not used for water supplies within the study area. The bedrock surface is irregular due to preglacial erosion by streams and erosion from glacial ice and meltwater during the Wisconsin glaciation.

Table 1.--*Constituents and properties determined for all sampled wells*

Reporting level is the lowest measured concentration of a constituent that may be reliably reported using a given analytical method. The reporting level is set somewhat higher than the detection unit.

[mg/L, milligrams per liter; μg/L, micrograms per liter; μS/cm, microsiemens per centimeter at 25 degrees Celsius; field, determined at the sampling site]

Property or constituent	Reporting level
Miscellaneous Constituents and Properties	
Temperature (degrees Celsius)	-
Specific conductance, field (μS/cm)	-
Dissolved solids, residue at 180 degrees Celsius, (mg/L)	1
pH, field (standard units)	-
Total organic carbon (mg/L as C)	0.1
Phenols, total (μg/L)	1
Nutrients	
Nitrogen, nitrite plus nitrate (mg/L as N)	.1
Organic nitrogen, ammonia plus organic (mg/L as N)	.2
Ammonia (mg/L as N)	.01
Dissolved phosphorus, (mg/L as P)	.005
Orthophosphate (mg/L as P)	.001
Major Inorganic Constituents	
Hardness (mg/L as $CaCO_3$)	-
Bicarbonate, field (mg/L as HCO_3)	-
Carbonate, field (mg/L as CO_3)	-
Hardness, non-carbonate (mg/L as $CaCO_3$)	-
Calcium, dissolved (mg/L as Ca)	.1
Magnesium, dissolved (mg/L as Mg)	.1
Sodium, dissolved (mg/L as Na)	.1
Potassium, dissolved (mg/L as K)	.1
Alkalinity, field, (mg/L as $CaCO_3$)	1
Sulfate, dissolved (mg/L as SO_2)	.2
Chloride, dissolved (mg/L as Cl)	.1
Fluoride, dissolved (mg/L as F)	.1
Silica, dissolved (mg/L as SiO_4)	.1

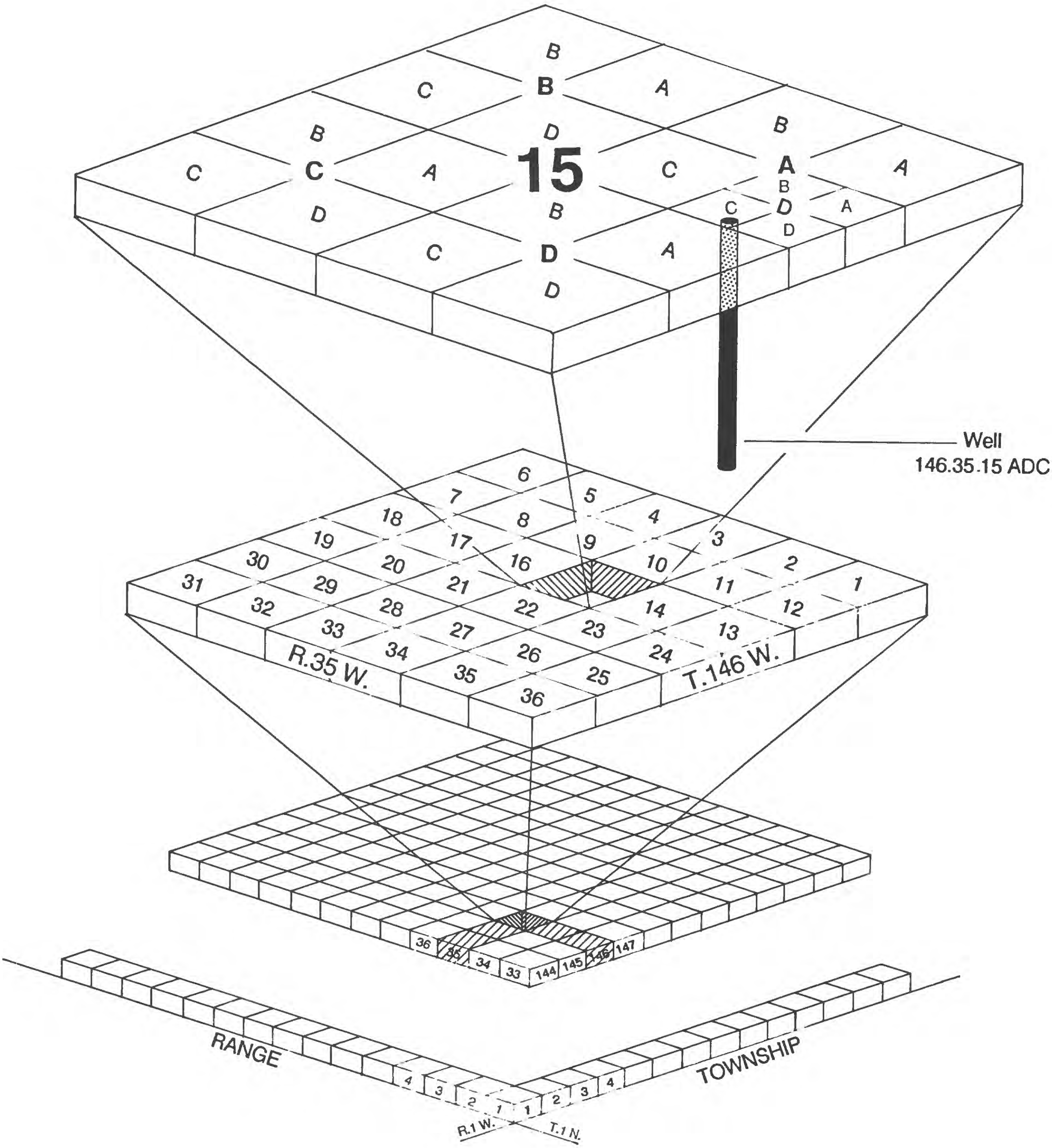


Figure 5.--Test-hole and well-numbering system

Drift

Origin and Extent

Glacial drift covers the entire study area. These deposits are primarily till, outwash sand, glacial-lake, and ice-contact deposits. The drift was deposited by various mechanisms during successive glacial advances and retreats during the Wisconsin glaciation, and reflects a complex glacial history. Till was deposited at the base of the glaciers during glacial advances. Sand, silt, and clay were deposited in glacial ponds and lakes during periods of glacial stagnation. Melt-water streams deposited sand and gravel in stream channels, outwash plains (commonly referred to as sand plains), kames, eskers, and beach ridges during glacial retreats. Some sand and gravel deposits were covered by till during subsequent glacial advances. These buried sand and gravel deposits are present throughout the study area.

At least three major ice lobes of late Wisconsin age advanced over the area. These lobes included: (1) the Des Moines lobe (including the St. Louis sublobe) that advanced from the northwest; (2) the Wadena lobe that advanced from the north-northwest; (3) and the Rainy lobe that advanced from the north-northeast. These ice lobes advanced and retreated separately as ice was directed differentially by areas of less competent bedrock (Wright, 1972 and Wright and Ruhe, 1965). The Itasca highland, located south of the sand-plain aquifer (unconfined-drift aquifer) (fig. 6), is a morainal complex that includes the Alexandria moraine, Wadena drumlin field, and Itasca moraine. These deposits are surrounded on three sides by deposits of the Des Moines lobe and the associated St. Louis sublobe. Several tunnel valleys, eskers, kames and associated ice-contact deposits transect the Itasca highland (Wright, 1972).

Hobbs and Goebel (1982) have mapped the surficial geology of the area using data from Minnesota soil atlases, interpretations of LANDSAT satellite imagery, and other published data. Figure 6 shows the distribution of the surficial glacial deposits in the study area. This map is based on the work of Hobbs and Goebel (1982) with modifications based on more recent test holes and well logs from the area.

Glacial deposits are divided into four hydrogeologic units for this study. They include: (1) sand and gravel (sand plain) deposits exposed at land surface (unconfined-drift aquifers); (2) fine-grained (till or lake) deposits that separate the uppermost confined-drift aquifer and unconfined-drift aquifer and serve as confining units; (3) buried sand and gravel deposits (uppermost confined-drift aquifers) and; (4) glacial till exposed at land surface.

Topography in areas where tills are exposed at the land surface (moraines) is generally rolling and irregular. The land surface is generally flat to gently rolling in areas of surficial outwash (sand plains). Tills exposed at the land surface south of the sand plain are generally attributed to deposition by the Wadena lobe and to the St. Louis sublobe of the Des Moines lobe north of the sand plain. Till associated with the St. Louis sublobe is generally yellowish-brown, calcareous, and silty to sandy in texture. Till deposited by the Wadena lobe is noncalcareous, brown, and silty-clay in texture. Tills of the Wadena lobe tend to contain abundant sand in the area of the Itasca moraine.

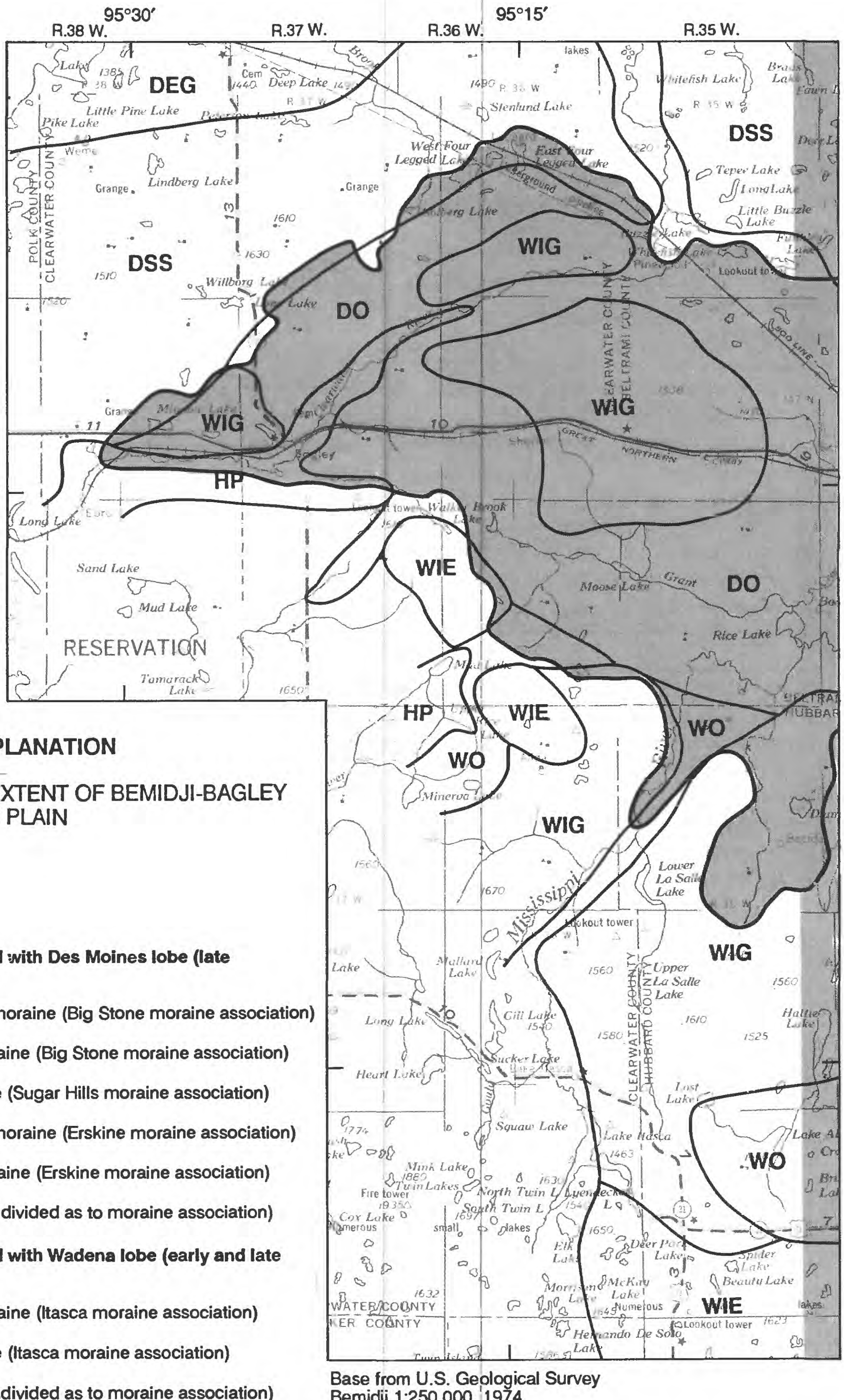
Aquifers and confining units occur throughout the entire thickness of the glacial drift in the area. Because detailed data related to deeper units (below the uppermost confined-drift aquifer) are not available, these units are not considered in this report. The uppermost confined-drift aquifer and confining unit identified from well logs were assumed to be continuous throughout the study area. However, data are scant, and these units may not be continuous.

The unconfined-drift aquifer (fig. 6) underlies an area between the Itasca Moraine to the south and west, and the terminal moraine along the south edge of the St. Louis sublobe of the Des Moines lobe. It is likely that the uppermost sand deposits occurring in the sand plain were deposited by meltwater from the St. Louis sublobe before it drained southward or eastward along the lowland that is now the Mississippi River valley. Confining units that separate the unconfined and confined-drift aquifers are probably tills or lake deposits associated with the Wadena lobe and the St. Louis sublobe of the Des Moines lobe. Glacial deposits in the Bemidji-Bagley area are as much as 550 ft deep (Oakes and Bidwell, 1968).

The hydraulic properties of these drift units are distinctly different. Unconfined and confined-drift aquifers have hydrologically distinct characteristics. Unconfined-drift aquifers have an unsaturated zone above the water table. They tend to be highly productive in yielding water to wells. This means that much water can be removed from a well per unit decline in available head. Unconfined-drift aquifers are rapidly recharged and tend to be susceptible to contamination from activities at land surface. Confined-drift aquifers are fully saturated and are isolated from land surface by one or more confining units. Confined-drift aquifers tend to have lower specific capacity than unconfined-drift aquifers. Confined aquifers are recharged by leakage from overlying or underlying aquifers through confining units, and tend to be relatively well protected from contamination by activities that occur at land surface.

Unconfined-Drift Aquifer

The unconfined-drift aquifer occurs near the Mississippi and Clearwater Rivers in the central portion of the study area (fig. 1). Several less extensive and isolated unconfined-drift aquifers occur to the south and east of the sand-plain area. The total area overlain by the unconfined-drift aquifers is approximately 550 mi^2. The sand plain aquifers (fig. 7) generally consist of coarse sand and gravel in the north and finer sand and gravel deposits to the south. The aquifers probably were formed by glacial outwash and lake sediment deposits at the end of Wisconsin glaciation.



EXPLANATION

AREAL EXTENT OF BEMIDJI-BAGLEY SAND PLAIN

Holocene

HP Peat

Pleistocene

Deposits associated with Des Moines lobe (late Wisconsinan)

DSS Stagnation moraine (Big Stone moraine association)

DSG Ground moraine (Big Stone moraine association)

DHE End moraine (Sugar Hills moraine association)

DES Stagnation moraine (Erskine moraine association)

DEG Ground moraine (Erskine moraine association)

DO Outwash (undivided as to moraine association)

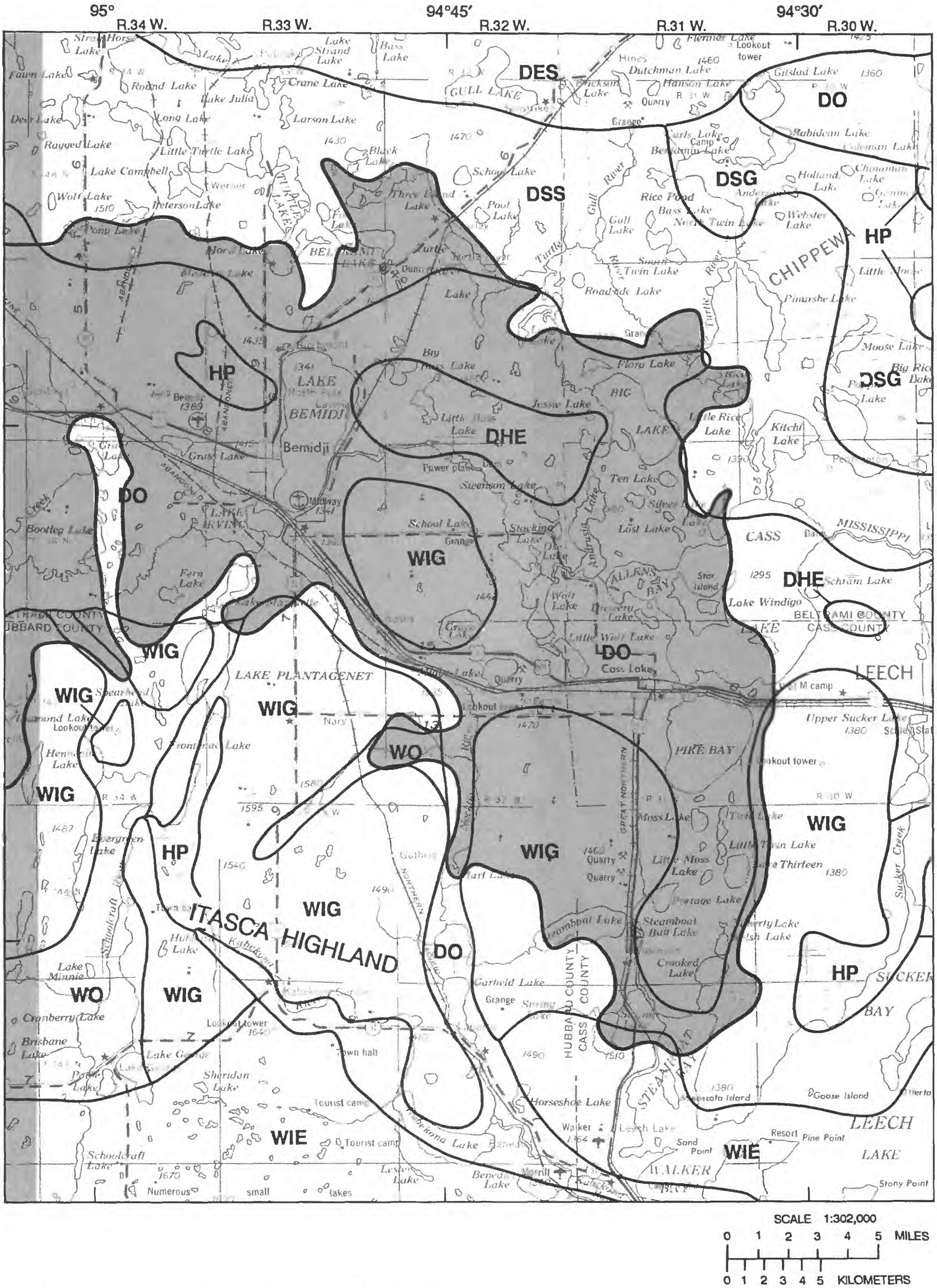
Deposits associated with Wadena lobe (early and late Wisconsinan)

WIG Ground moraine (Itasca moraine association)

WIE End moraine (Itasca moraine association)

WO Outwash (undivided as to moraine association)

Figure 6.--**Quaternary** geology of the Bemidji-Bagley



area (modified from Hobbes and Goebel, 1982)

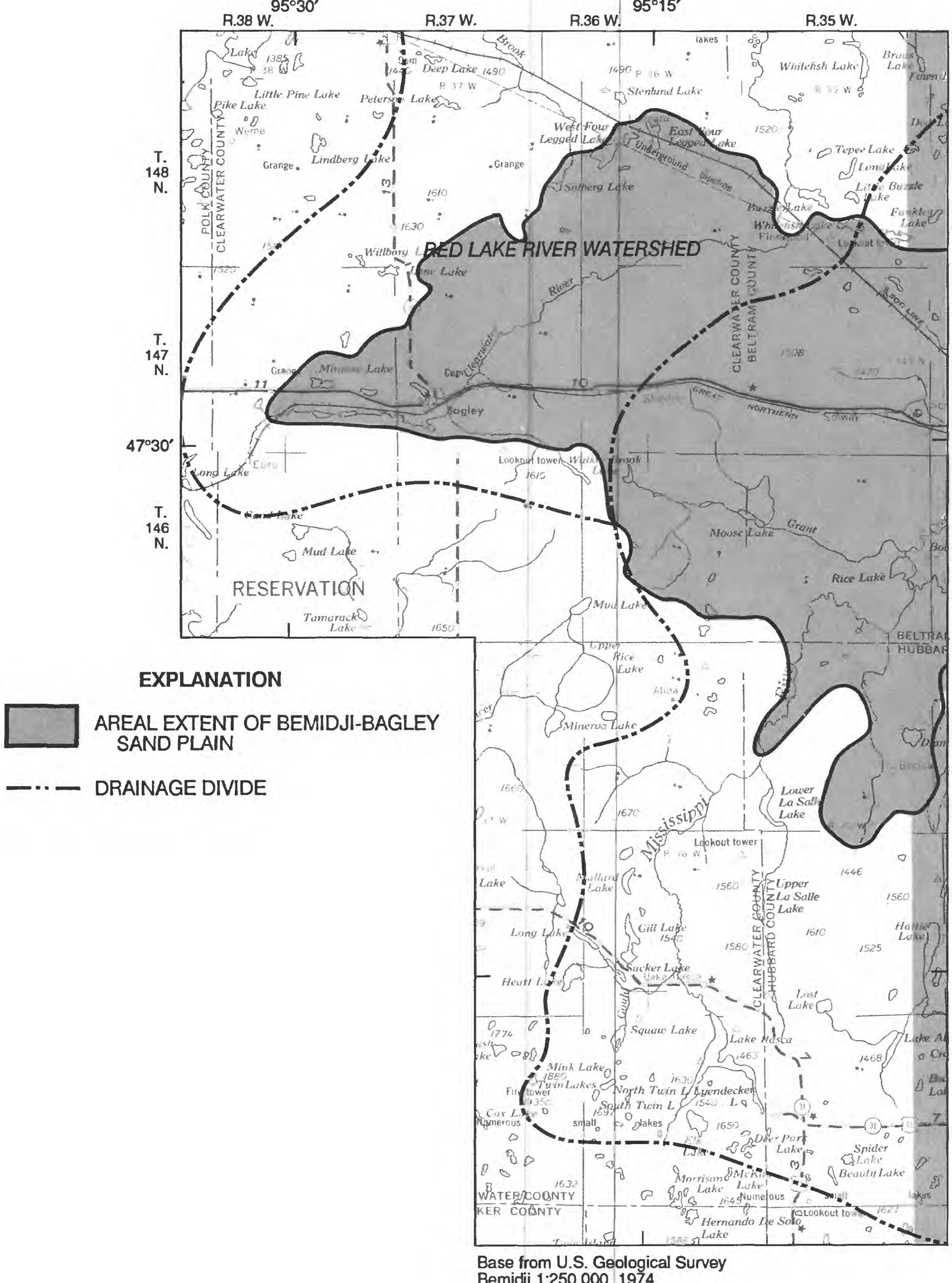
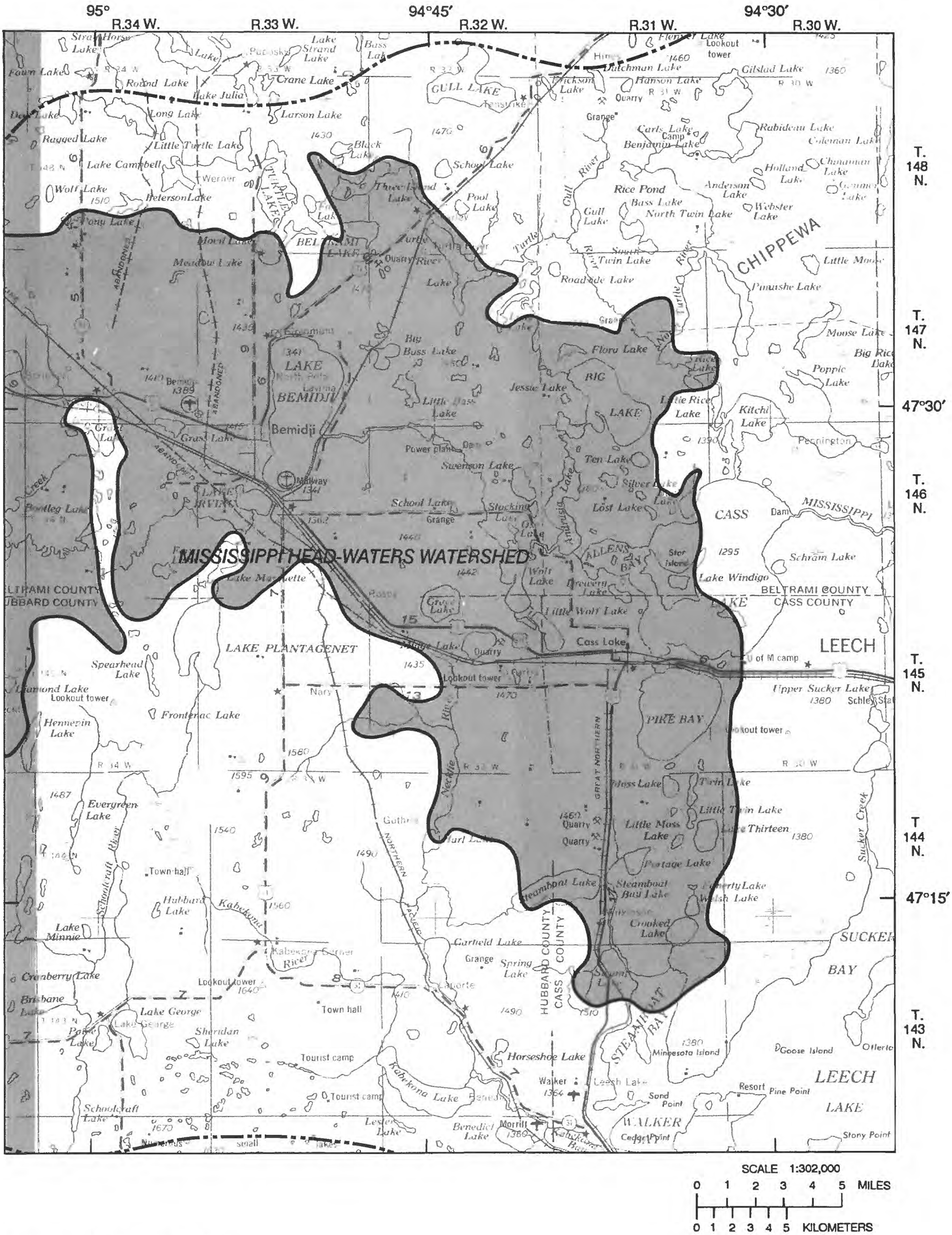


Figure 7.--Extent of sand



plain and drainage divides

The top of the saturated portion of the aquifers is the water table (fig. 8) and the base of the aquifer (sand plain) is the top of the uppermost confining unit. The base of the unconfined-drift aquifers slopes toward the east in the same general direction as the Mississippi River valley at about 10 ft/mi (feet per mile) (fig. 9). The saturated thickness of the unconfined aquifers varies from 0 to 126 ft (fig. 10). Much of the sand plain is unsaturated and not hydraulically interconnected. However, the saturated thickness of the aquifer exceeds 20 ft over an area of about 280 mi^2.

The maximum horizontal hydraulic gradient in the unconfined-drift aquifer, as inferred from the spacing of the water-table altitude contours, is 60 ft/mi near the southwest margin of the sand plain (fig. 8). Generally the horizontal hydraulic gradient is about 6 ft/mi. Hydraulic head in the unconfined-drift aquifer ranges from 1,290 to 1,560 ft and declines from west to east. Depth to the water table below land surface ranges from 0 to 150 ft.

Except in the Bemidji and Cass Lake areas, the unconfined-drift aquifer is not used extensively as a source of water to wells. Based on published values of horizontal hydraulic conductivity for similar deposits of sand and gravel underlying similar areas (Helgesen, 1977) and the results of the ground-water-flow model for this study, the horizontal hydraulic conductivity of the unconfined-drift aquifer varies from 250 to 750 ft/d (feet per day). On the basis of estimates of hydraulic conductivity derived from specific capacity information, the transmissivity of the aquifer ranges from less than 70 ft^2/d (feet squared per day) in the south and west parts of the aquifer to greater than 8,900 ft^2/d (horizontal hydraulic conductivities from 1 ft/d to 200 ft/d) in the area east of Bemidji (fig. 11). The differences between model-derived estimates of horizontal hydraulic conductivity and estimates based on specific capacity may result from the following: (1) Specific capacity information was obtained from data on drillers logs. These logs often report no drawdown in pumping wells during development. These data, therefore, probably reflect inadequate measurements, and were not used to prepare maps of transmissivity. Disregarding these specific capacity data may have resulted in transmissivity maps that do not include data from the most transmissive portions of the aquifer. (2) A second possible problem may be that the conceptual model, used to construct the digital model, is inadequate and additional, unmapped aquifers may exist at depth in the area included in the model. This would result in higher than actual values of horizontal hydraulic conductivity for aquifers included in the model. Additional drilling and aquifer tests would be required to better refine estimates of the hydraulic properties of the aquifers.

Well yields of several hundred gallons per minute may be possible in certain areas. The scant thickness of the aquifer over most of the area limits the potential productivity of the aquifer as a source of ground water to wells.

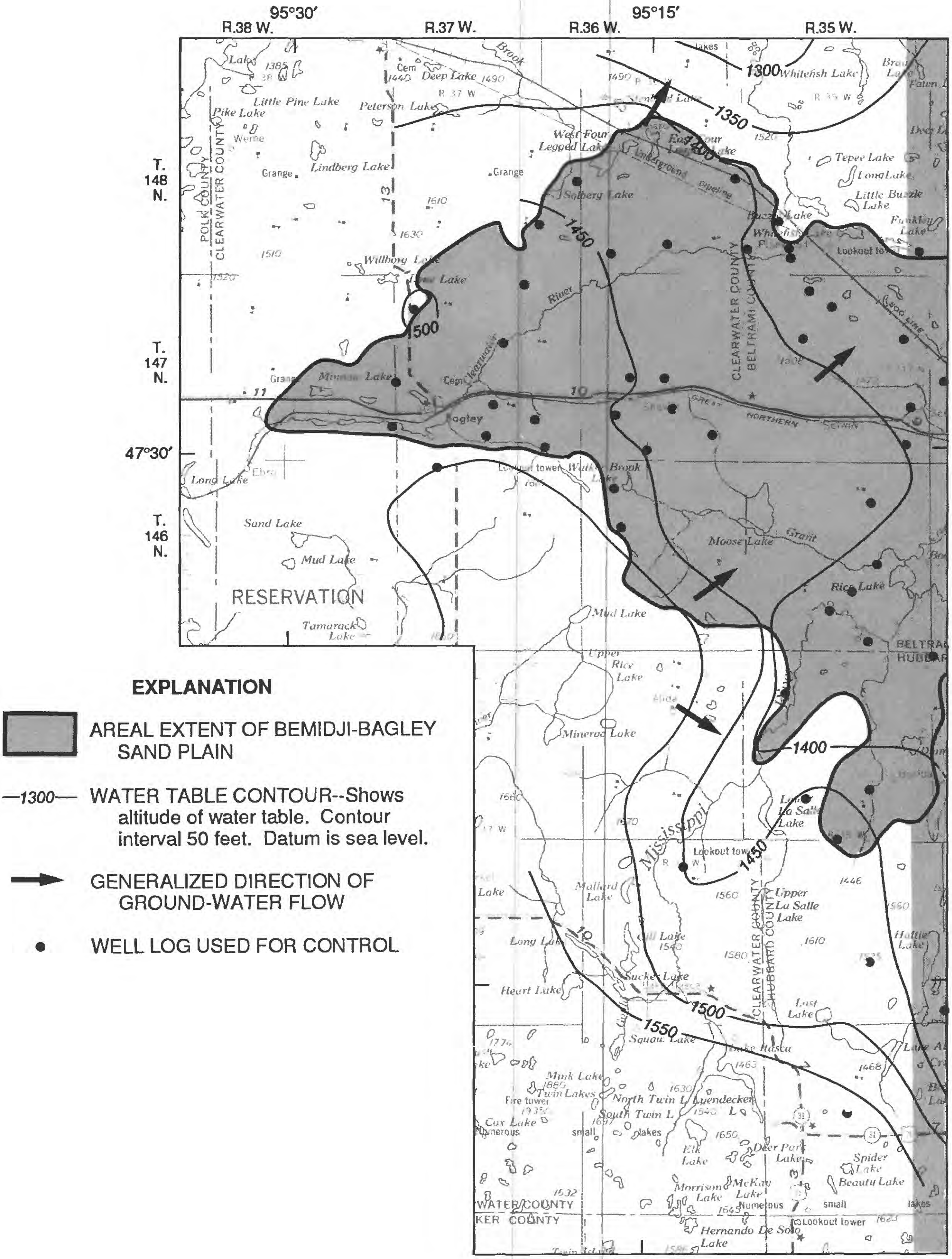
The direction of ground-water flow on a regional scale in the unconfined-drift aquifer is toward the Mississippi River, the Clearwater River, or Leech Lake (fig. 8). These rivers are the major discharge points for ground water from both the uppermost confined-drift and the unconfined-drift aquifers in the study area, based on inferences from water-level data in wells completed in both aquifers. Ground-water divides (fig. 8), which separate ground-water flow systems discharging to these rivers, are approximately coincidental with surface-water divides between the river systems. Locally, however, ground-water flow in the unconfined-drift aquifer is toward numerous small streams, wetlands, and lakes; and may vary significantly from the direction of regional ground-water flow shown on figure 8.

Uppermost Confining Units

The unconfined and uppermost confined-drift aquifers are hydraulically separated by a fine-grained confining unit consisting of till or lake deposits. The top of the unit (also the bottom of the unconfined-drift aquifer) slopes gently to the east at about 10 ft/mi (fig. 9). The thickness and hydraulic properties of this confining unit vary from point to point in the area. The degree to which the confining unit isolates flow in the two systems is a function of the spatial variability of these properties. Figure 12 illustrates that the thickness of the uppermost confining unit ranges from 1 to more than 200 feet in the study area. The map indicates that the confining unit is continuous over the study area; however, the unit may be absent in some undetermined areas.

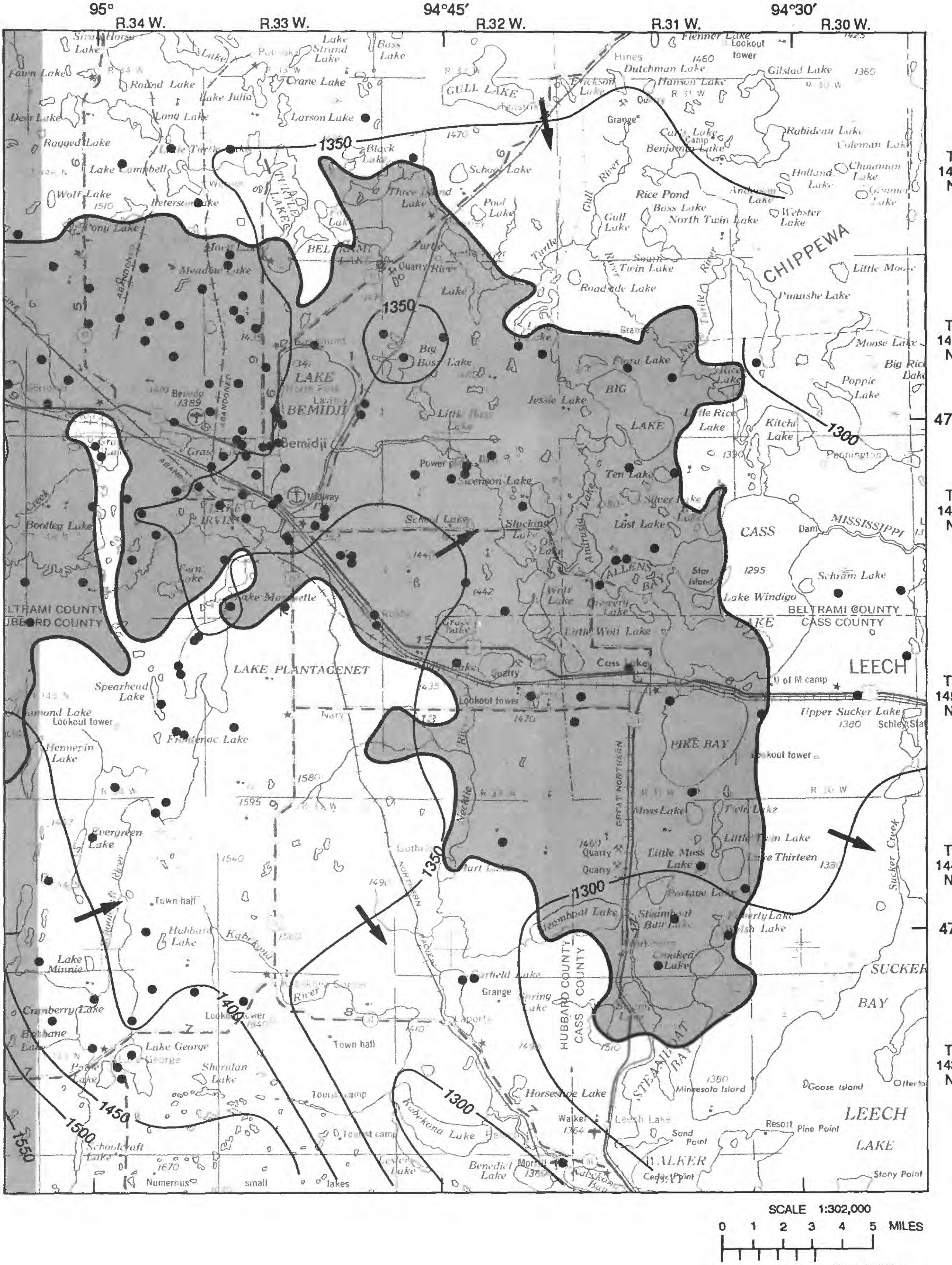
The thickness and vertical hydraulic conductivity of the confining unit and differences in hydraulic head of aquifers above and below the confining unit control vertical flow of ground water between the uppermost confined-drift aquifer and the unconfined-drift aquifers. The vertical hydraulic conductivity of till and glacial-lake deposits generally is much lower than the 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 2.5×10^{-2} ft/d. This compares favorably with the value of 1.8×10^{-2} ft/d for the Detroit Lakes area of Minnesota (Miller, 1982). These values of vertical hydraulic conductivity are higher than those reported for other parts of the glaciated northern United States and reflect the sandy nature of till in the study area. Perimeter tests conducted by Prudic (1982), for example, indicate that the vertical hydraulic conductivity of till in New York, ranges from 3.1×10^{-5} to 4.3×10^{-4} ft/d.

Although no field tests were made, the horizontal hydraulic conductivity of till in the study area probably is about one to two orders of magnitude higher than the vertical hydraulic conductivity. A value of 1 ft/d for the horizontal conductivity of alluvial clay was given by Lohman (1972). A value of 1 ft/d is also at the upper end of horizontal conductivity values for till given by Heath (1983). Model analysis for this study indicates that values from 0.1 to 1.0 ft/d are reasonable values of horizontal hydraulic conductivity for the uppermost confining unit in the study area. Although significant volumes of water flow between the unconfined and confined-drift aquifers on a regional scale, the confining unit serves as a significant barrier to the rapid exchange of ground-water between the aquifers.

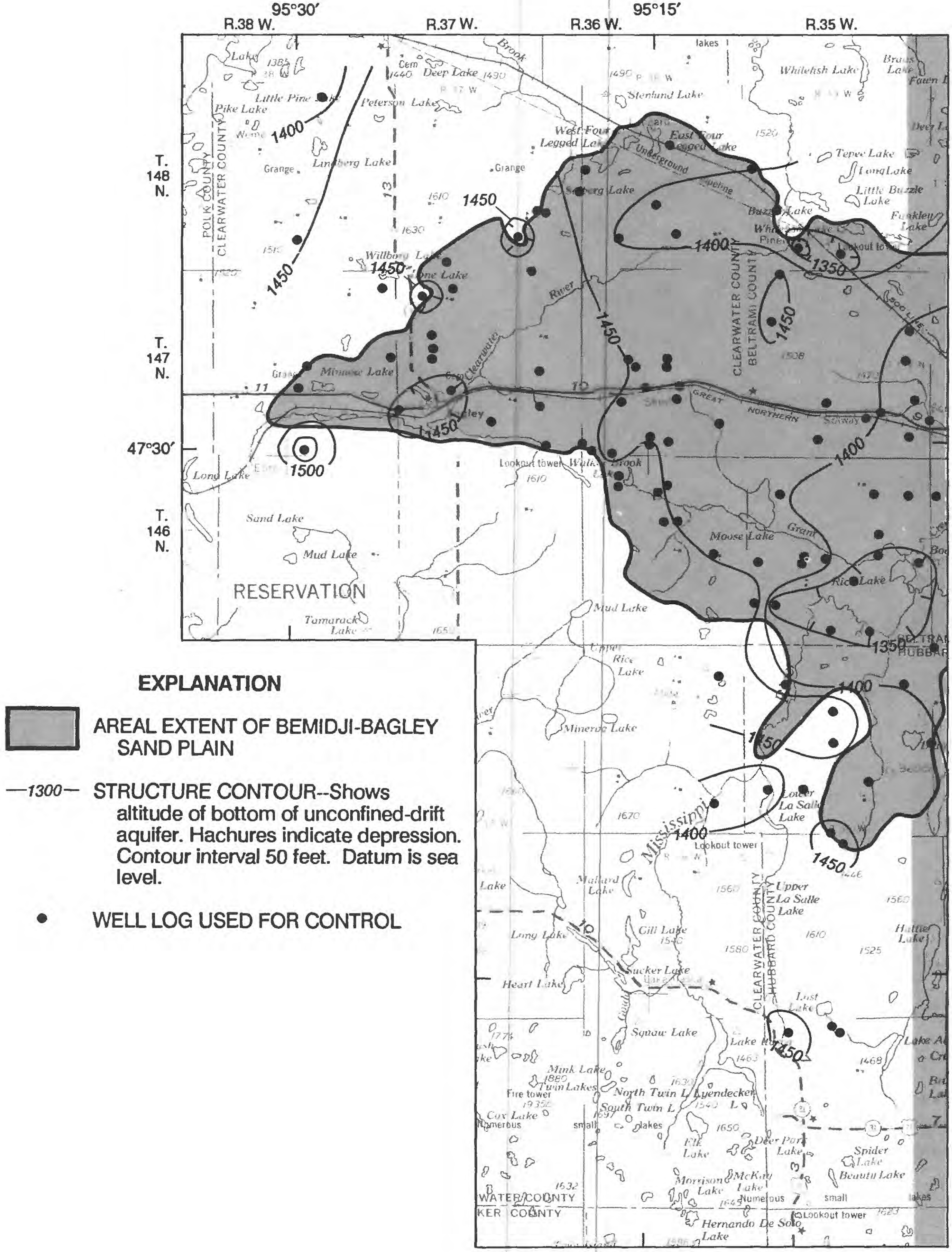


Base from U.S. Geological Survey
Bemidji 1:250,000, 1974

Figure 8.--Altitude of water table

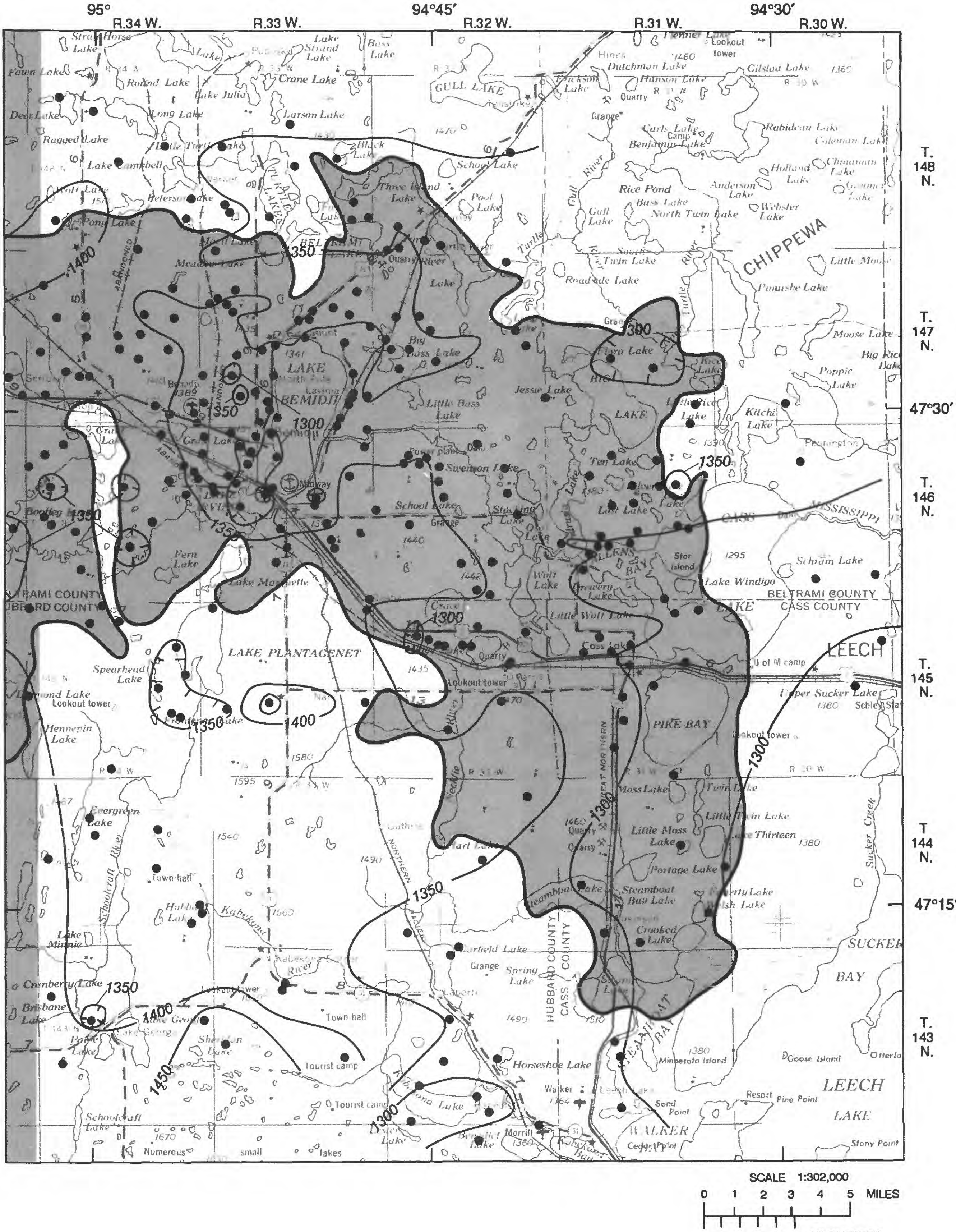


in unconfined-drift aquifer

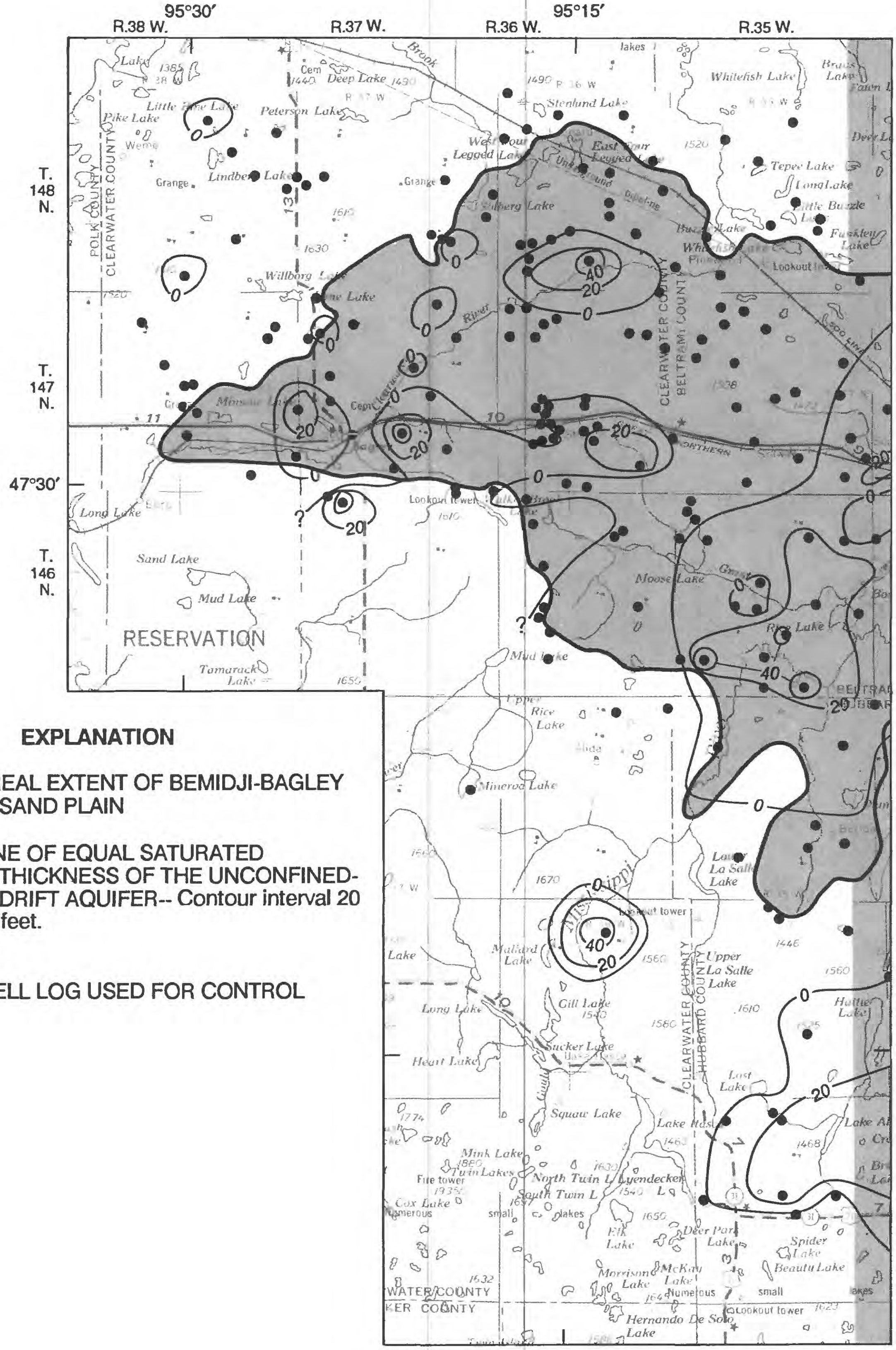


Base from U.S. Geological Survey
Bemidji 1:250,000, 1974

Figure 9.--Altitude of base of



unconfined-drift aquifer



EXPLANATION

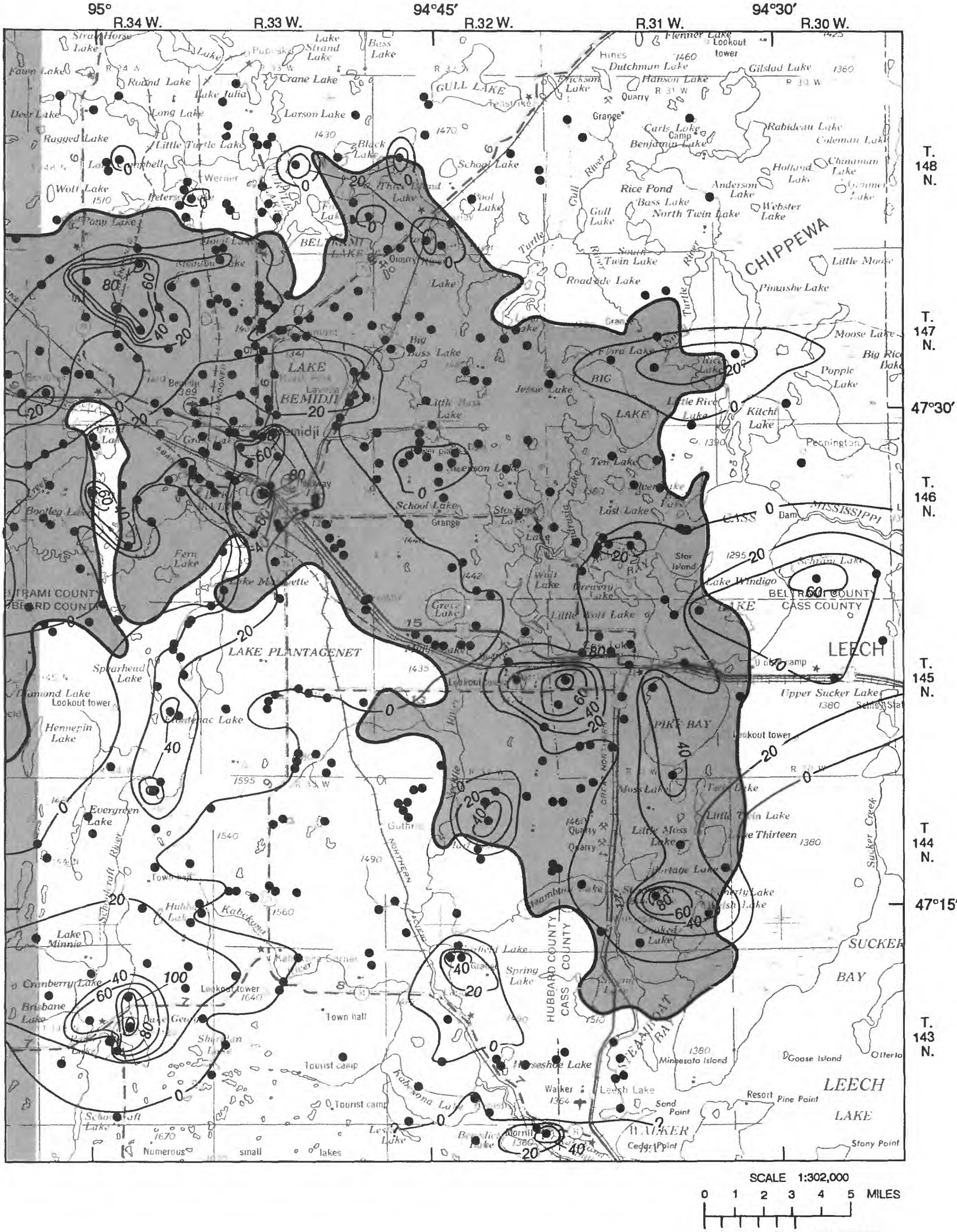
AREAL EXTENT OF BEMIDJI-BAGLEY SAND PLAIN

—20— LINE OF EQUAL SATURATED THICKNESS OF THE UNCONFINED-DRIFT AQUIFER-- Contour interval 20 feet.

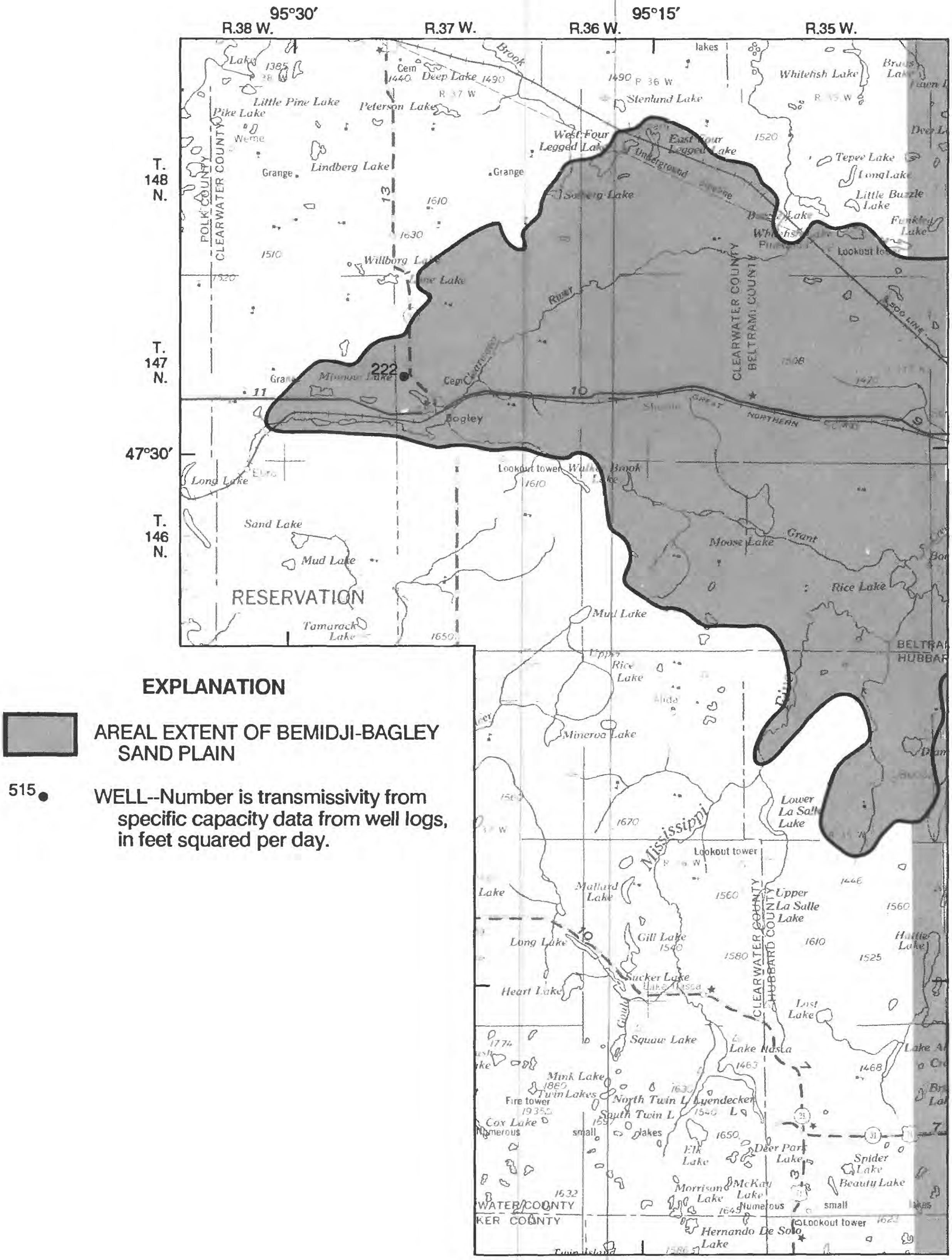
● WELL LOG USED FOR CONTROL

Base from U.S. Geological Survey
Bemidji 1:250,000, 1974

Figure 10.--Saturated thickness

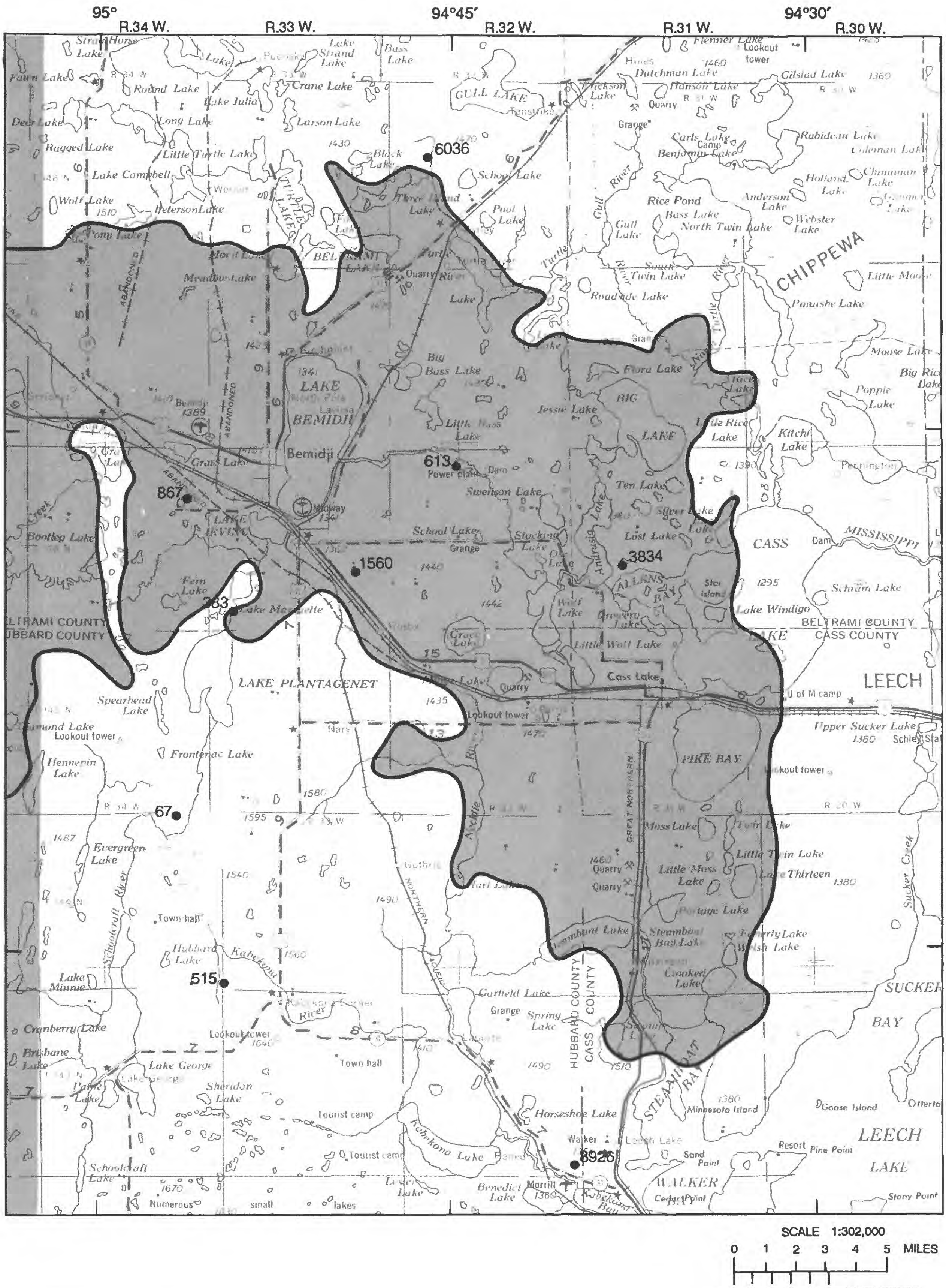


of unconfined-drift aquifer



Base from U.S. Geological Survey
Bemidji 1:250,000, 1974

Figure 11.--Transmissivity of



unconfined-drift aquifer

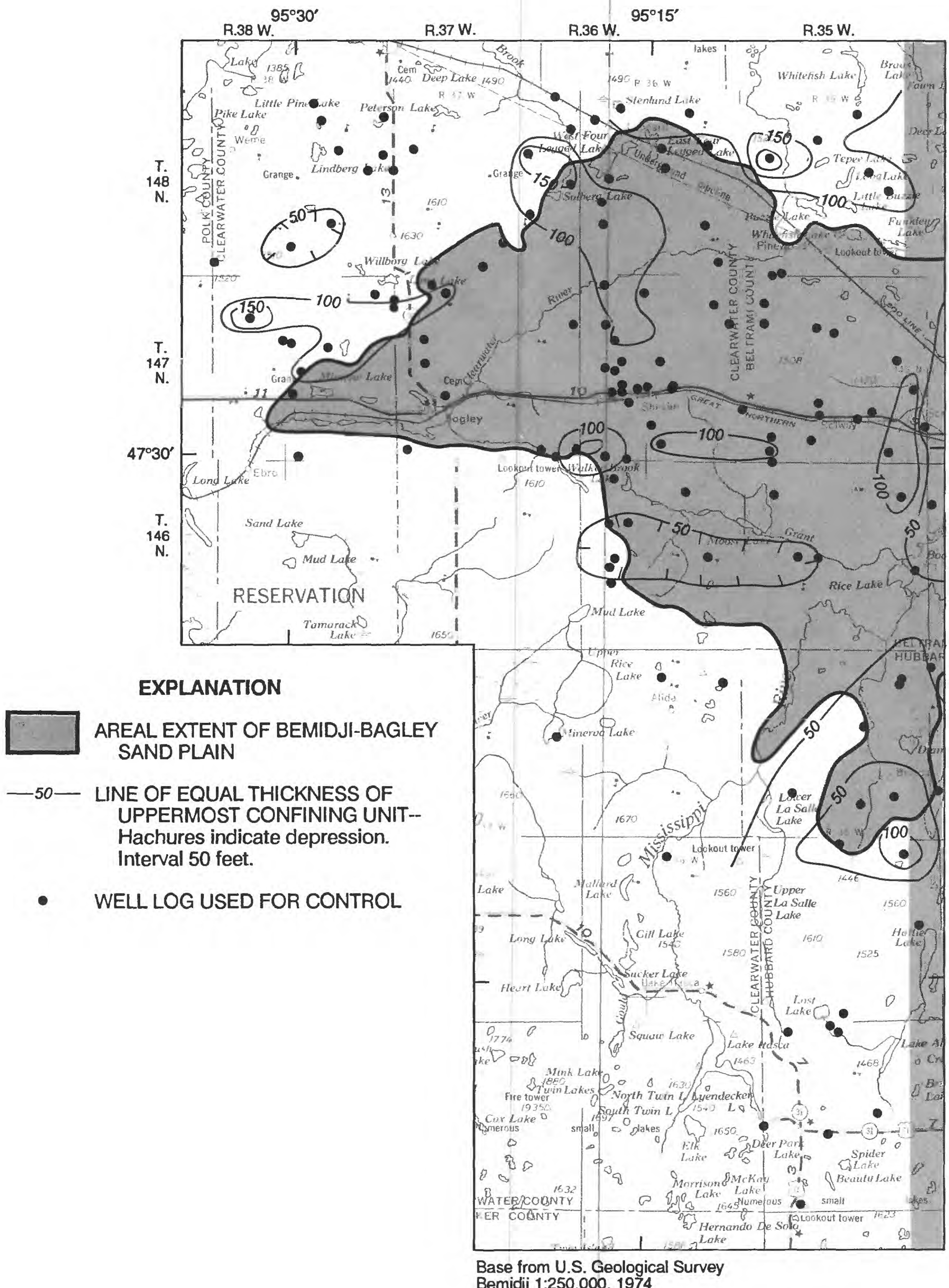
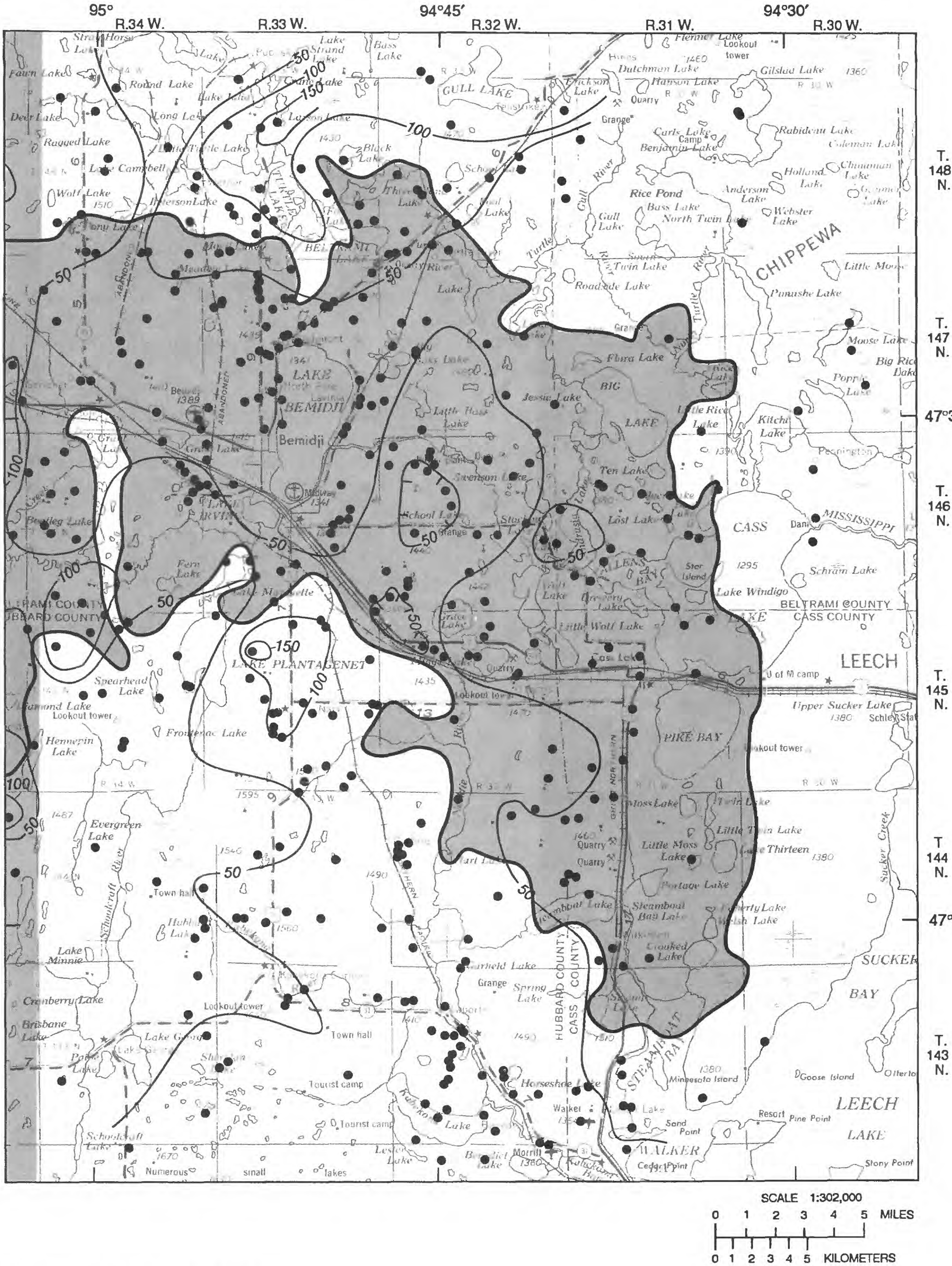


Figure 12.--Generalized thickness



of uppermost confining unit

Uppermost Confined-Drift Aquifers

Confined-drift aquifers consist of sand and gravel that are bounded above by confining units of till or lake deposits. Numerous confined-drift aquifers probably exist with depth in the Bemidji-Bagley area but little information is available about confined-drift aquifers below the uppermost unit. Therefore, only the uppermost confined-drift aquifer, the primary source of ground water to wells in the Bemidji-Bagley area, is discussed below.

The thickness and extent of the uppermost confined-drift aquifer was determined from logs of domestic wells that penetrated the entire thickness of the aquifer. The altitude of the top of the uppermost confined-drift aquifer ranges from about 1,500 feet south of Bagley to about 1,250 feet above sea level in the Bemidji and Cass Lake areas (fig. 13). The thickness of the aquifer varies from 0 to as much as 60 ft in the Bemidji area (fig. 14). The uppermost confined-drift aquifer is assumed to be continuous over the study area. The assumption of continuity is valid regionally but may be violated locally.

The horizontal hydraulic conductivity of the uppermost confined-drift aquifer ranges from 250 to 750 ft/d, on the basis of published values of horizontal hydraulic conductivity for sand and gravel deposits from similar studies (Helgesen, 1977), and from results of the ground-water-flow simulations conducted for this study. On the basis of specific-capacity data the transmissivity of the aquifer ranges from less than 100 ft^2/d in the southern and western parts of the aquifer to greater than 12,800 ft^2/d in the central part of the study area (horizontal hydraulic conductivities range from 1 to 250 ft/d) (fig. 15). The differences in estimates of hydraulic conductivity values between the two methods may result from factors described in the previous section of this report.

Well yields of 10 to 2,100 gal/min are possible in certain isolated locations. The scant thickness of the aquifer over parts of the area limits the potential of the aquifer as a source of ground water to wells.

The ground-water-flow pattern in the uppermost confined-drift aquifer is similar to that in the unconfined-drift aquifer. The horizontal hydraulic gradient, however, is generally smaller, and averages about 4 ft/mi. Hydraulic head in the confined aquifer ranges from 1,290 to 1,600 ft. The direction of horizontal ground-water movement in the confined-drift aquifer and potentiometric contours are shown in figure 16. The maximum horizontal hydraulic gradient is about 50 ft/mi and occurs in the highlands (morainal) area north of the surficial outwash plain.

On a regional scale, the direction of ground-water flow in the uppermost confined-drift aquifer is toward the Mississippi and Clearwater Rivers and toward Leech Lake (fig. 16). These are the major discharge points for the aquifer in the study area. This discharge occurs as ground water flows from the aquifer through the confining unit and then discharges to the rivers and lakes. These areas of discharge are based on inferences made from potentiometric-surface maps and results of model simulations. Ground-water divides (inferred from data shown on figure 16), which separate ground-water flow systems discharging to the rivers, are approximately coincidental with surface-water divides between the river systems. The flow of ground water in the confined-drift aquifer is less affected by small streams, wetlands, and lakes than is the flow of water in the unconfined-drift aquifer.

Conceptual Model of Ground-Water Flow

A dynamic set of hydrologic conditions and hydraulic properties cause water to move through aquifers and confining units. The direction and rate of movement of ground water is affected by recharge, discharge, hydraulic conductivity, and hydraulic gradient. In general terms, water moves from highland (regional recharge) areas to discharge areas at lakes and streams (fig. 17). Along this path, part of the water flows through confining units and into or out of confined aquifers before being discharged.

The entire surface area of the unconfined-drift aquifer is recharged by that part of precipitation that percolates beyond the root zone in the soil. The confined-drift aquifers are recharged by leakage through confining units. Unconfined-drift and confined-drift aquifers generally discharge to lakes and streams near topographic lows. Because the hydraulic conductivity of an aquifer is much greater than that of a confining unit, aquifers offer less resistance to flow. Consequently, flow in aquifers is predominantly horizontal, whereas flow in confining units is predominantly vertical.

The general direction of ground-water flow in the unconfined-drift aquifer is similar to the general direction of surface-water drainage. Ground-water flow in the aquifer is toward the Mississippi and Clearwater Rivers. These rivers are major discharge points for uppermost confined-drift and unconfined-drift aquifers in the study area. Ground-water divides, which separate ground-water-flow systems discharging to these rivers, are approximately coincidental with surface-water divides between the river systems. As previously stated, local flow in the unconfined-drift aquifer is toward numerous small streams, wetlands, and lakes and may vary significantly from the regional direction of ground-water flow shown on figure 16.

Leakage to confined aquifers through confining units depends on (1) the head difference across the confining units, (2) the vertical hydraulic conductivity of the confining units, and (3) the thickness of the confining units.

Comparison of the potentiometric surfaces of the unconfined and confined-drift aquifers (figs. 8 and 16) show that the two surfaces are generally similar in areas underlain by the unconfined-drift aquifer. This suggests a tendency for horizontal flow within the aquifers and minimal vertical leakage between the two aquifers. In highland (morainal) areas surrounding the unconfined-drift aquifer, the water table in the till is as much as 11 feet higher than the potentiometric surface of the uppermost confined-drift aquifer. Near areas of discharge, such as lakes and rivers, the potentiometric surface of the uppermost confined-drift aquifer is as much as 13 feet higher than the potentiometric surface of the unconfined-drift aquifer. These relations suggest that downward leakage occurs in highland areas where ground water flows vertically downward from till to the uppermost confined-drift aquifer. In areas of regional discharge, water moves vertically upward from deeper to more shallow aquifers.

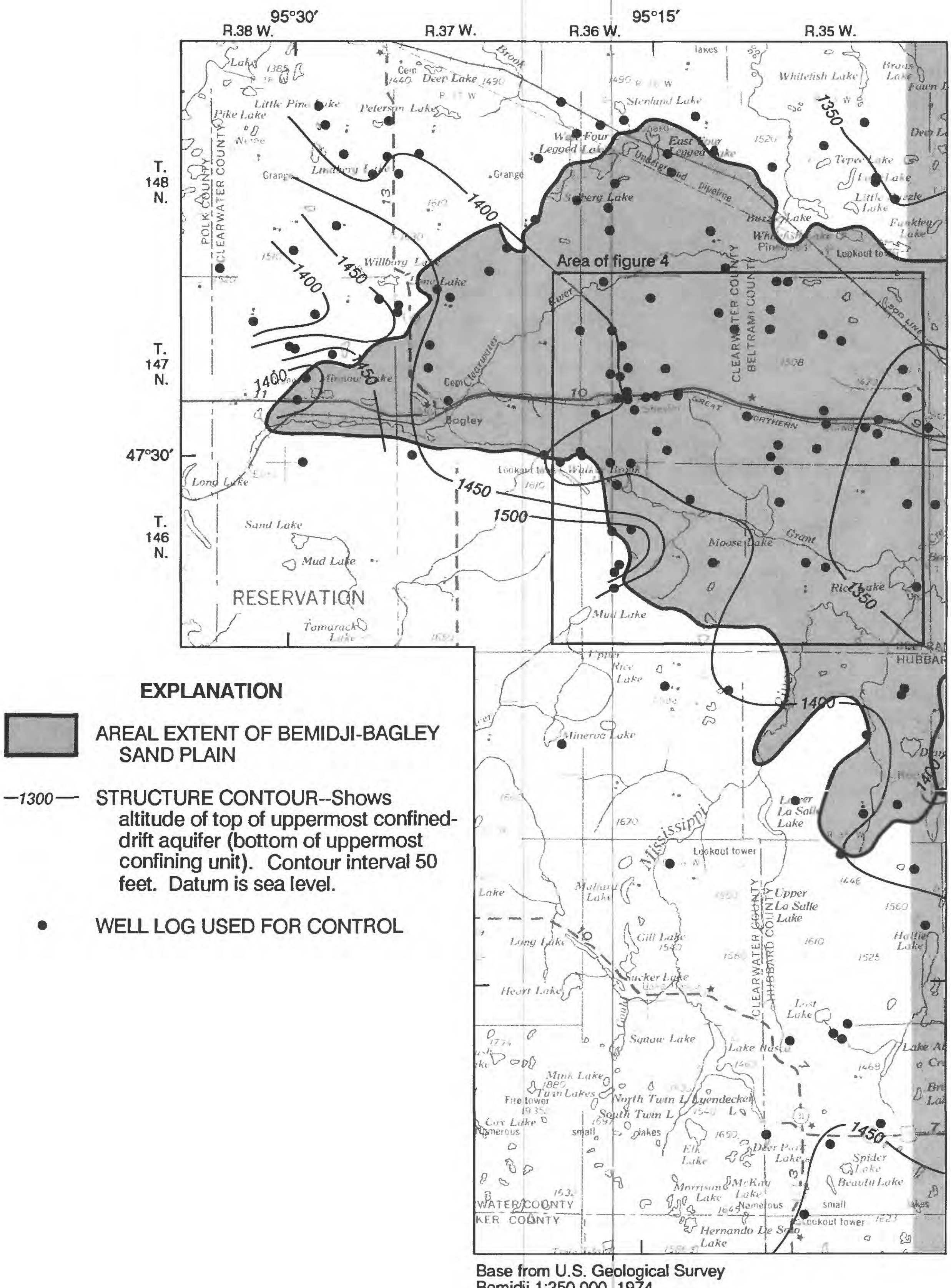
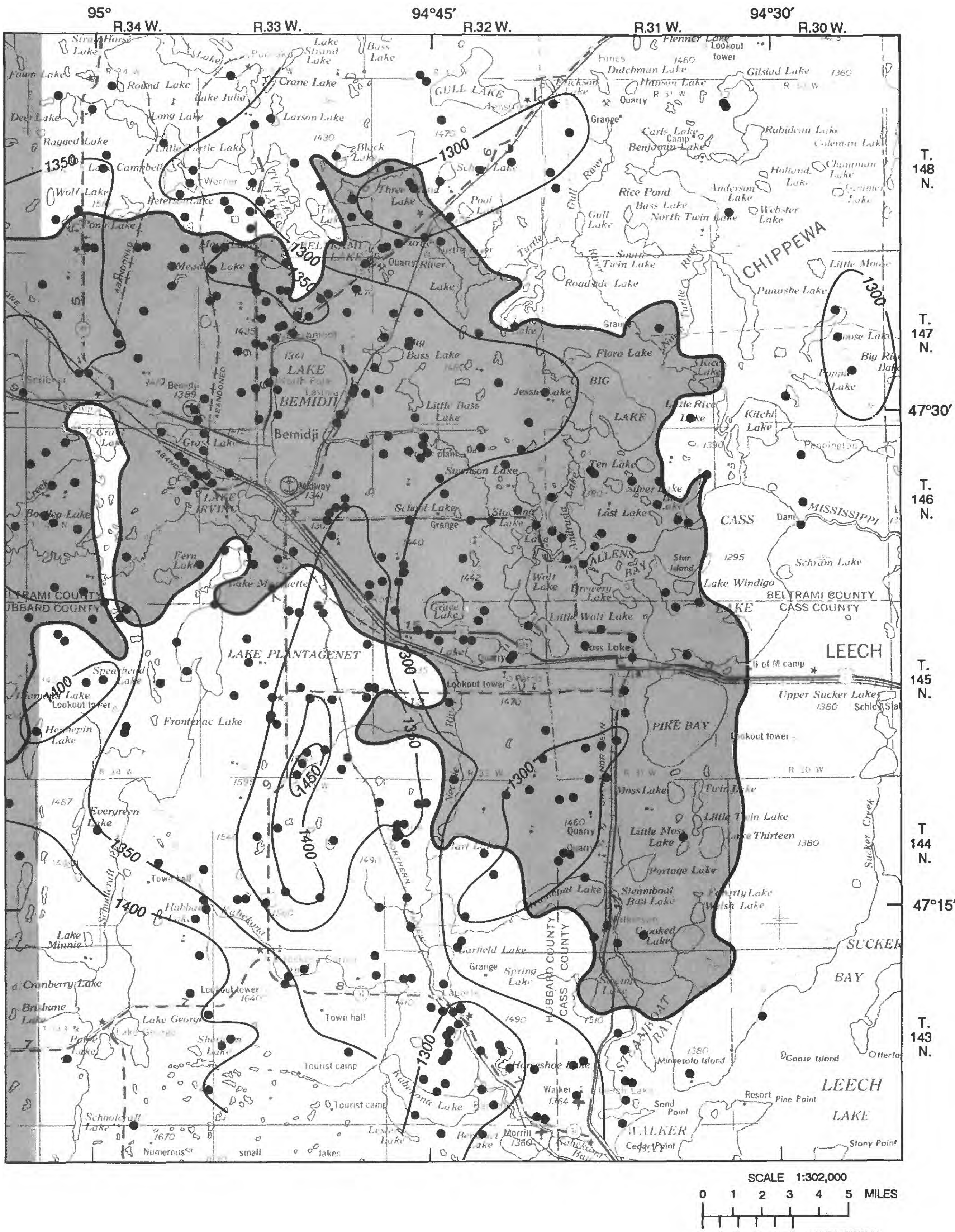
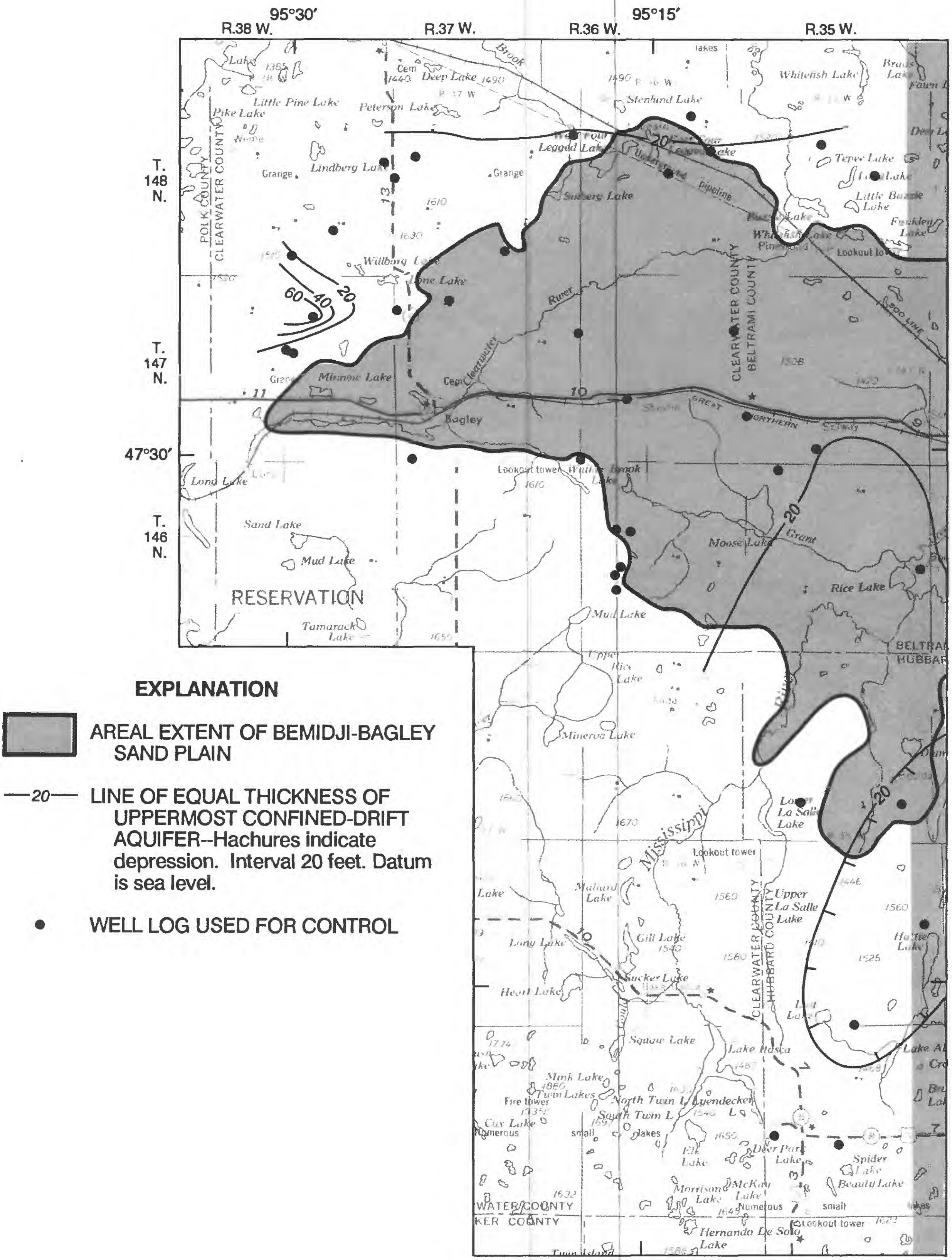


Figure 13.--Generalized altitude of top

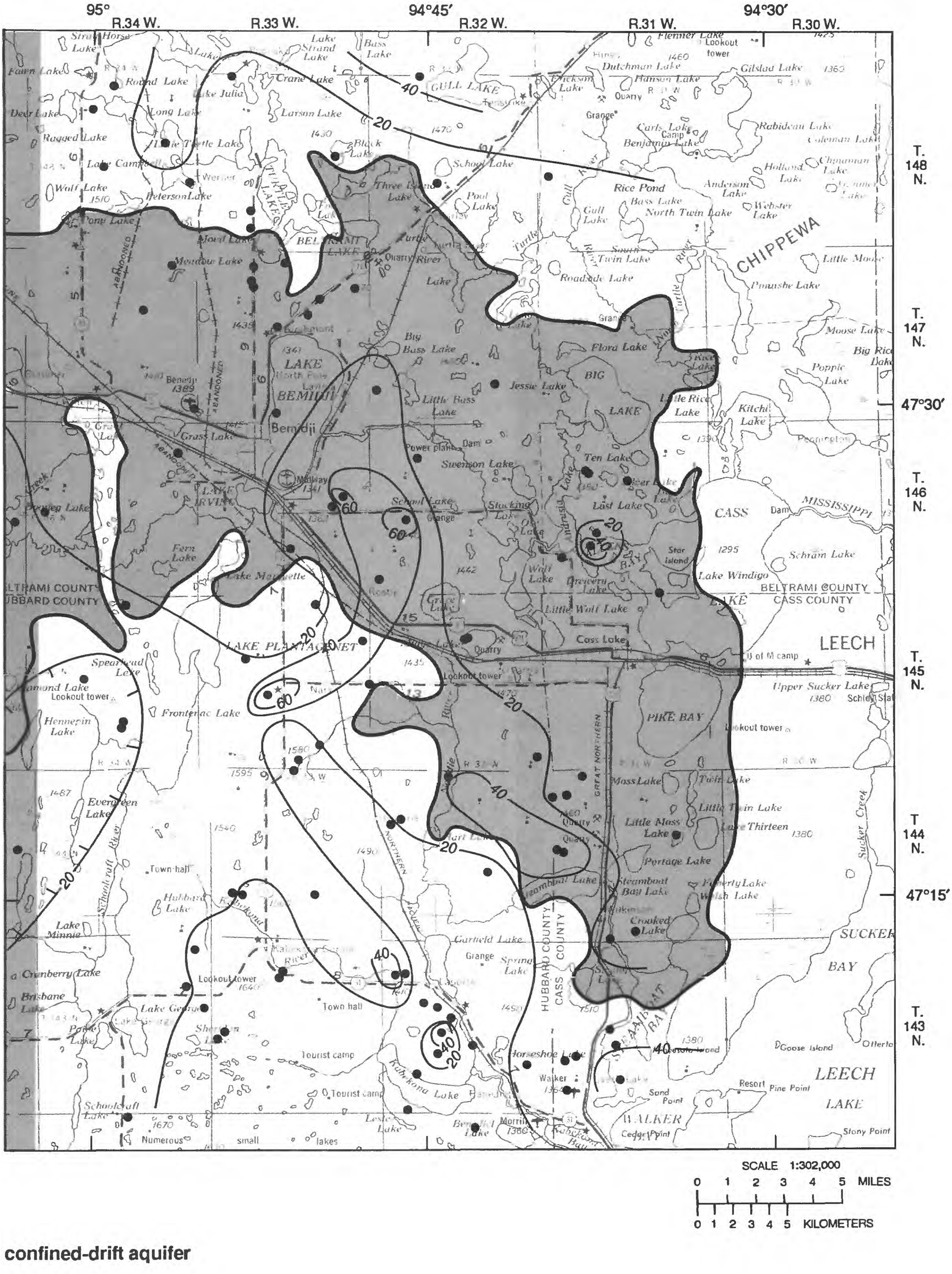


of uppermost confined-drift aquifer

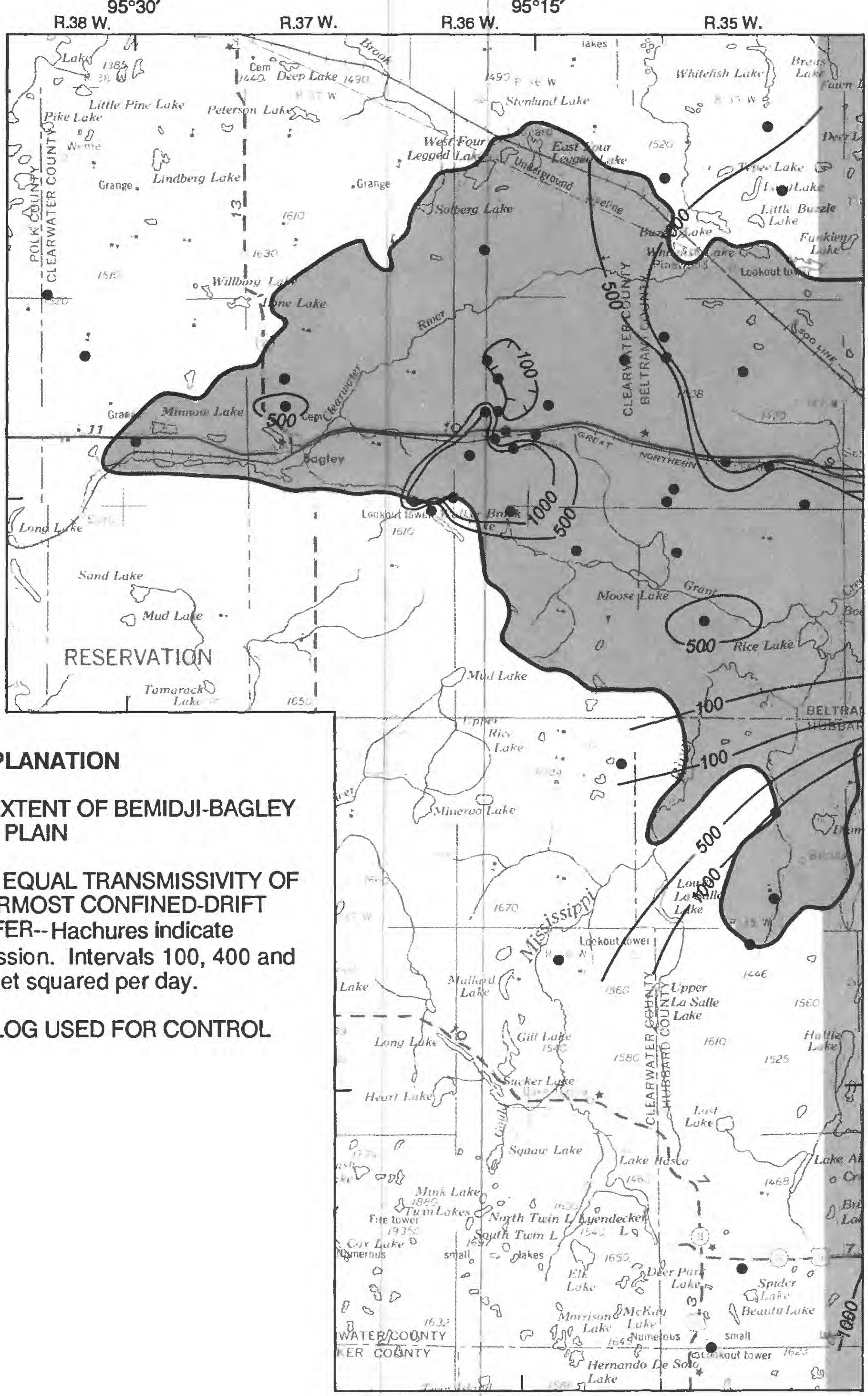


Base from U.S. Geological Survey
Bemidji 1:250,000, 1974

Figure 14.--Thickness of uppermost



confined-drift aquifer



EXPLANATION

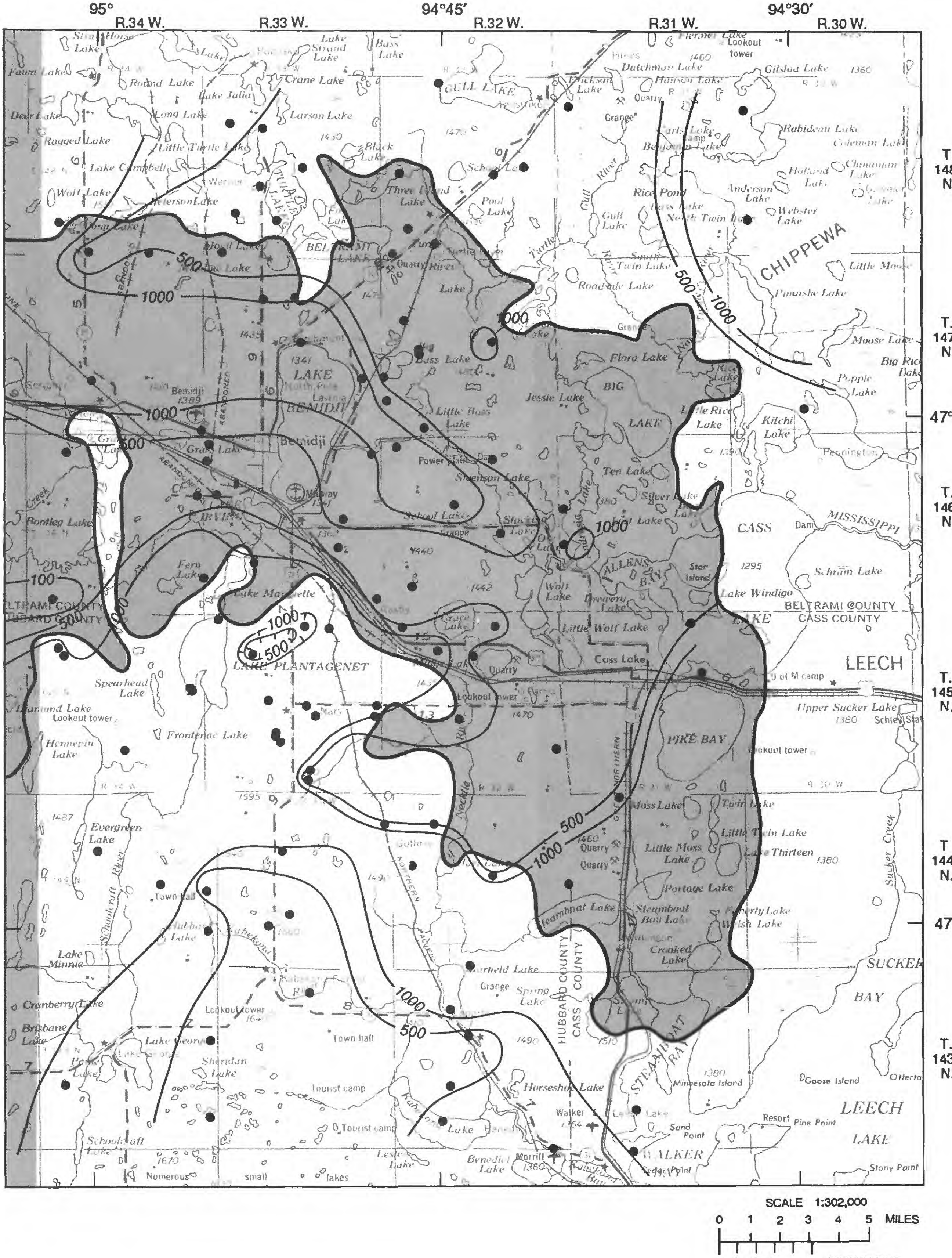
AREAL EXTENT OF BEMIDJI-BAGLEY SAND PLAIN

—500— LINE OF EQUAL TRANSMISSIVITY OF UPPERMOST CONFINED-DRIFT AQUIFER--Hachures indicate depression. Intervals 100, 400 and 500 feet squared per day.

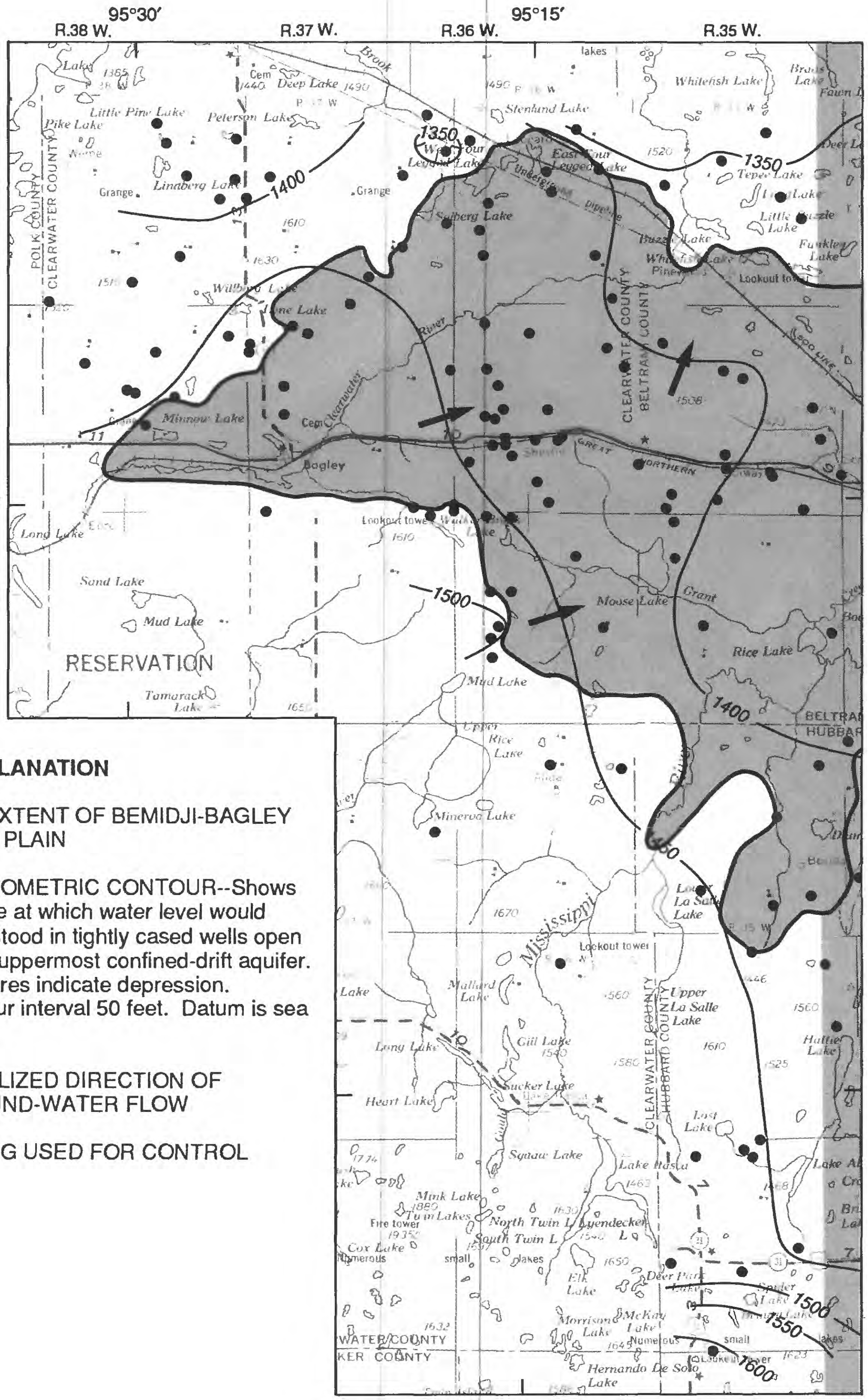
● WELL LOG USED FOR CONTROL

Base from U.S. Geological Survey
Bemidji 1:250,000, 1974

Figure 15.--Transmissivity of



uppermost confined-drift aquifer



EXPLANATION

AREAL EXTENT OF BEMIDJI-BAGLEY SAND PLAIN

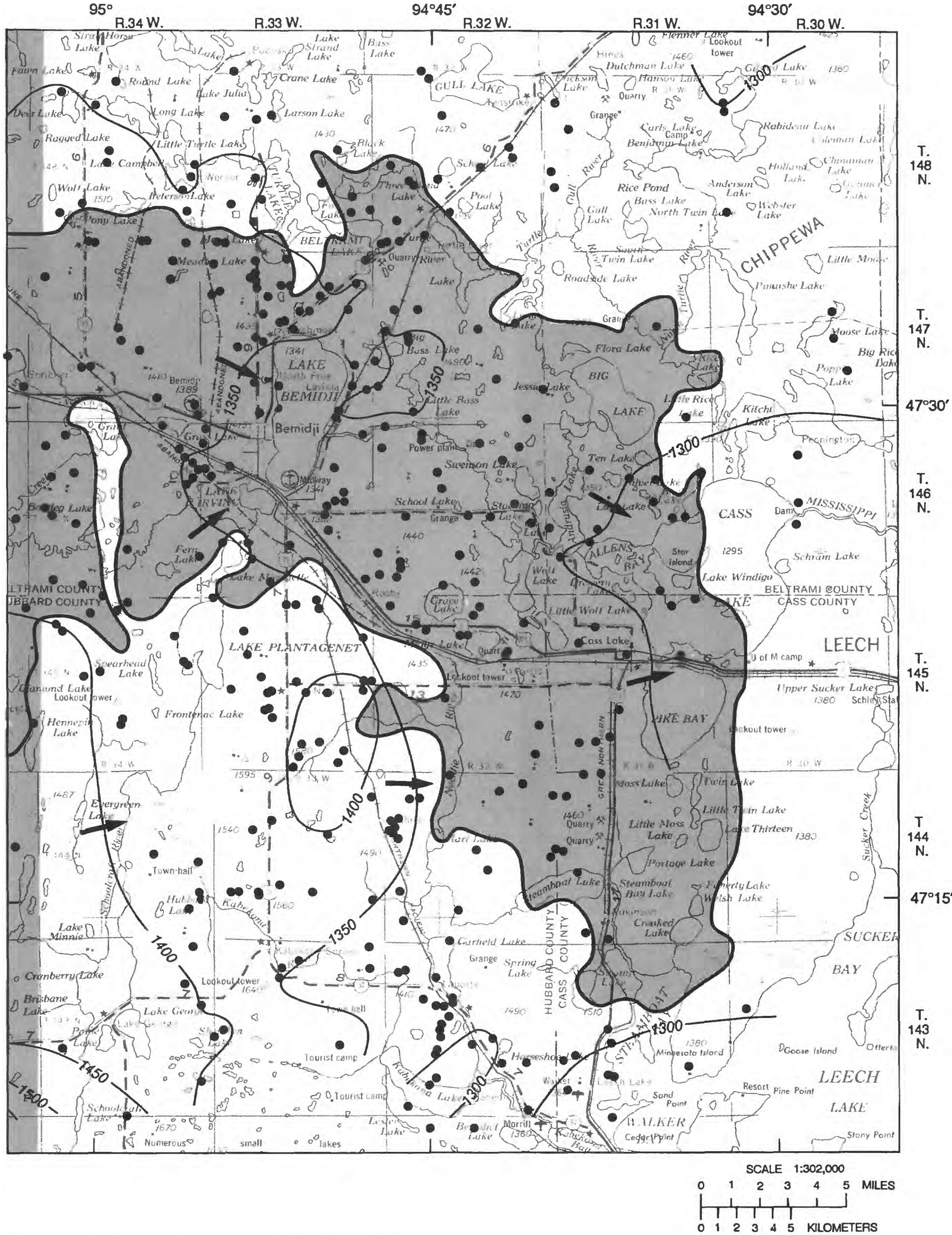
—1500— POTENTIOMETRIC CONTOUR--Shows altitude at which water level would have stood in tightly cased wells open to the uppermost confined-drift aquifer. Hachures indicate depression. Contour interval 50 feet. Datum is sea level.

GENERALIZED DIRECTION OF GROUND-WATER FLOW

• WELL LOG USED FOR CONTROL

Base from U.S. Geological Survey
Bemidji 1:250,000, 1974

Figure 16.--Generalized potentiometric



surface of uppermost confined-drift aquifer

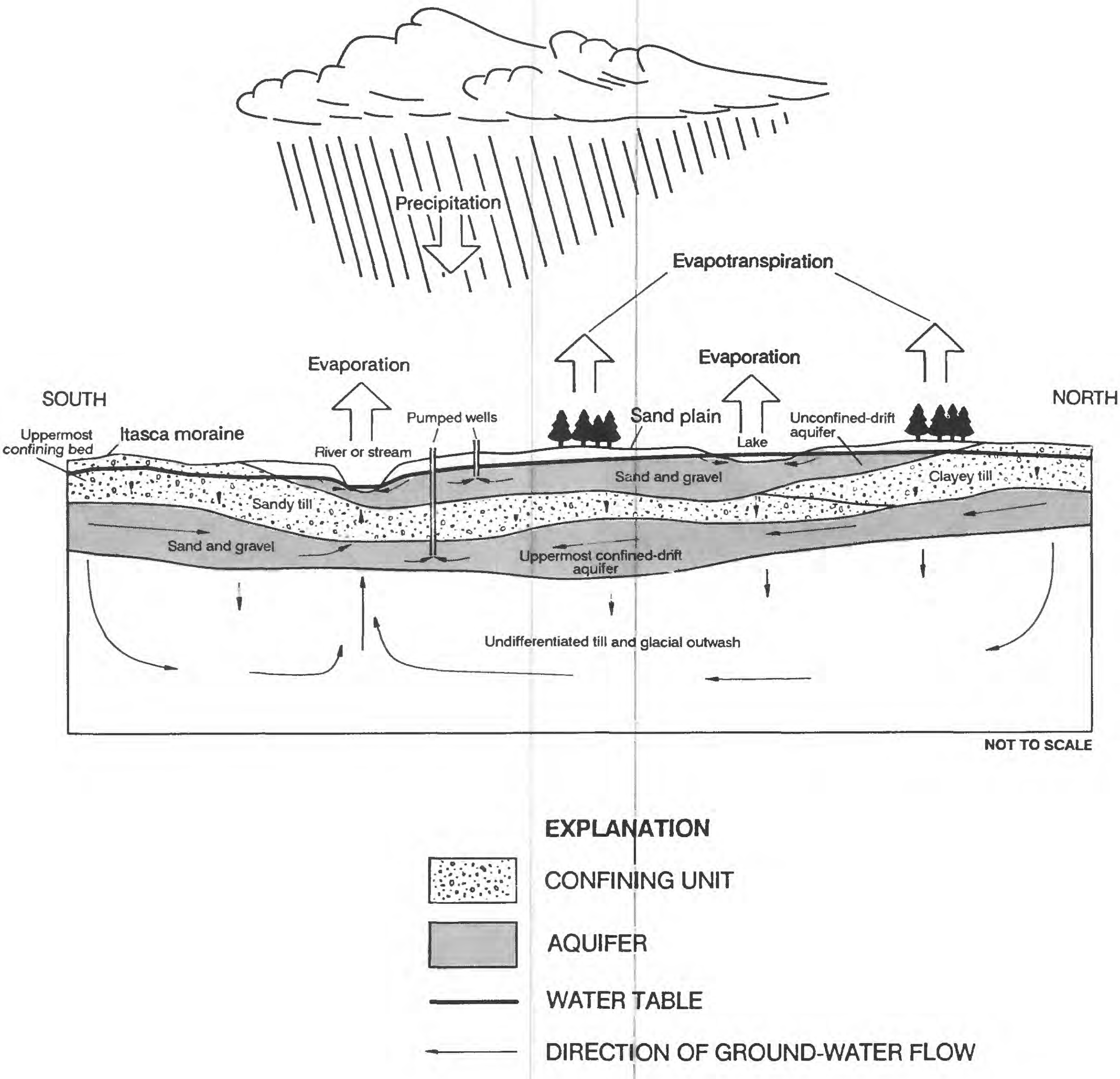


Figure 17.--Generalized ground-water-flow system and source and discharge areas for ground water

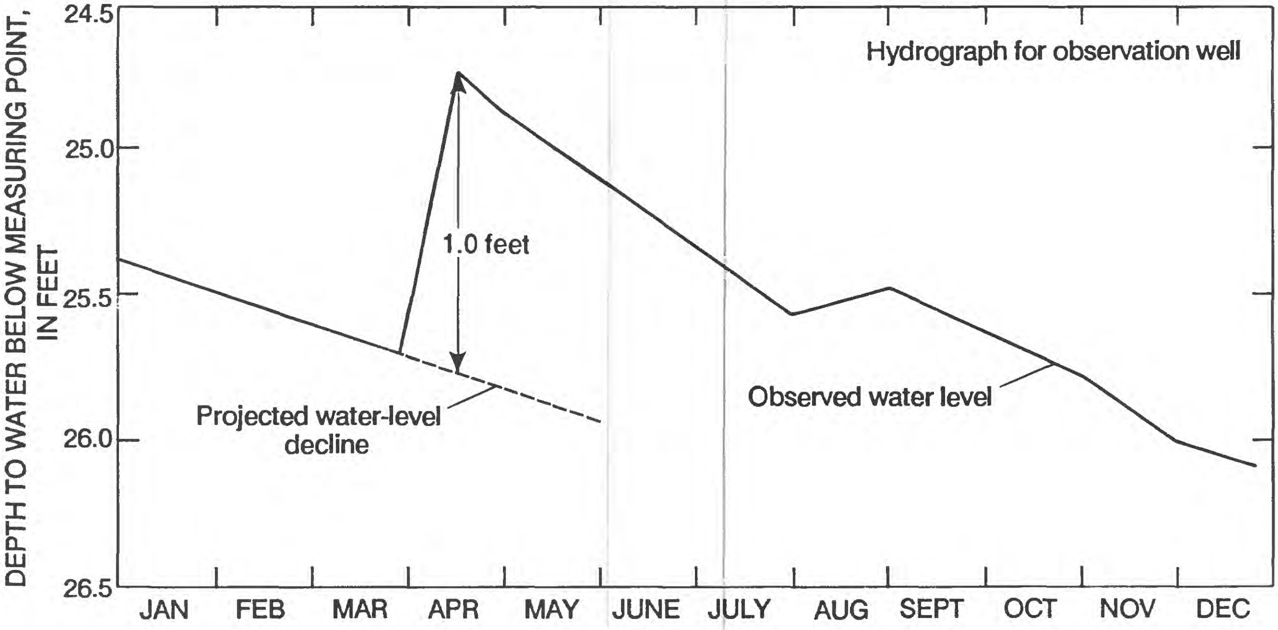
Ground water moves into and out of the study area primarily where confined-drift aquifers extend beyond the boundaries of the study area. Ground-water flow into the study area is from the west and southwest and flow out of the study area is to the north and east. Measured hydraulic gradients indicate that flow from areas outside the study area is not significant.

Areal Recharge

Recharge to the ground-water system is predominantly from precipitation, and is greatest in areas where the unconfined-drift aquifer is present (fig. 6). Recharge commonly is greatest in the spring during periods of snowmelt, spring rain, and low evapotranspiration, but can also be significant during autumn rainfall. Conversely, rates of ground-water recharge are usually low in the summer and winter because precipitation is lost by evapotranspiration or is held as snowpack.

Recharge rates can be estimated from continuous water-level measurements from observation wells (Rasmussen and Andreason, 1959). The method assumes that all water-level rises in the well result from recharge to the aquifer and the rate of recharge per year equals the sum of individual water-level rises within the year multiplied by the specific yield of the aquifer. The water-level rise calculated by this method is based on a lower line projecting the recession line of the hydrograph to the date at which the peak occurred (fig. 18). The calculated recharge rate then represents the total ground-water recharge that occurred during the period. The corrected recharge rate equals the difference between the peak stages and the projected water-level declines, multiplied by the specific yield of the surficial aquifer for all recharge events during the year. Annual recharge was computed for 1986-87 using a hydrograph from an observation well completed in the unconfined-drift aquifer at Bemidji. Areal recharge, assuming a specific yield of 0.2 (Myette, 1986), was estimated at 4 in/yr. This value is consistent with values of recharge published by Helgesen (1977) for an area about 50 mi to the south. Results from model simulations suggest that a recharge rate of from 4 to 8 in/yr produce the best matches between model-simulated and measured water levels in wells.

Although recharge to the ground-water system is greatest where the unconfined-drift aquifer is present, significant quantities of recharge also occur where till is present at land surface. Because till has a lower hydraulic conductivity than sand, recharge is generally reduced. Model calibration indicated that recharge to areas where glacial till is present at land surface varies depending on the source of the glacial till. In areas where Wadena lobe till is exposed, generally to the south of the sand plain, a recharge rate of 4 to 8 in/yr was found to produce the best match between model-simulated and measured water levels in wells. In areas where the Des Moines lobe till is exposed, north of the sand plain, a recharge value of 0 to 4 in/yr produced the best results. Model results confirmed that the rate of recharge in the sand-plain aquifer is similar to the rates calculated from water-level data in the unconfined-drift aquifer. The estimates of significant recharge in the areas south of the sand plain are probably related to the sandy texture of till in that area and to areas of internal drainage in kettles and depressions in the moraines.



Recharge (largely from snowmelt and early spring rain)
= (water-level rise) x (estimated specific yield)
= (1.0 feet) x (0.2)
= 0.2 feet
= 2.4 inches

Figure 18.--Example of hydrograph demonstrating method of estimating recharge to unconfined-drift aquifer during spring

Discharge

Discharge from the ground-water system occurs by leakage to streams, lakes, and swamps, evapotranspiration, and withdrawals by wells.

Ground-water discharge to streams, lakes, and swamps

A significant percent of discharge from the ground-water system is to rivers and streams. This discharge component was estimated by several measurements (February 10-12, 1988) of base-flow discharge in the Clearwater and Mississippi Rivers. Total streamflow gain in a 39.7 mile reach of the Mississippi River between Lake Itasca, in Clearwater County, and Lake Bemidji, in Beltrami County, (fig. 7) was measured at 64 ft^3/s (cubic feet per second). Total streamflow gain in a 19.9-mile reach of the Clearwater River between the town of Bagley, in Clearwater County, and the town of Aure, in Beltrami County, was approximately 23 ft^3/s. Gain in streamflow in Grant Creek from its source northwest of Wilton to near Wilton, a 5.6-mile reach, was measured at 12.3 ft^3/s. Discharge to these rivers depends on the (1) thickness of the riverbed material, (2) vertical hydraulic conductivity of the riverbed material, and (3) hydraulic-head differences between the aquifer and the river. In general, ground-water discharge to rivers exceeds leakage from rivers into the ground-water system. An exception often is during periods of high spring streamflow. The amount of ground water discharged from the aquifers to the streams, as simulated by the ground-water-flow model, compares favorably with the values of baseflow discharge given above. Measurements of ground-water discharge to lakes and to swamps were not made during this study.

Evapotranspiration

Evapotranspiration is a combination of direct evaporation from surface water and soil moisture plus transpiration of water by plants. The amount of ground-water loss to evapotranspiration depends on water availability (depth to the water table below land surface), solar energy supplied, air temperature, and humidity of the air. The rate of evapotranspiration is assumed to be a maximum of 20 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 study area was 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. This seasonal variation in ground-water loss to evapotranspiration is approximately the same from year to year, provided the vegetation does not change significantly. Ground-water losses to evapotranspiration are probably greatest in the eastern part of the study area where large surface-water bodies are present and depth to ground water is shallow.

Ground-water use

Public water supply is the major use of ground water in the Bemidji-Bagley area and comprises both municipal and private waterworks (Lee Trotta, U.S. Geological Survey, St. Paul, Minn., written commun., 1988). There are three municipal waterworks in the study area; Bemidji, Bagley, and Cass Lake. Bemidji alone withdrew 441.6 Mgal (million gallons) in 1985. Together the three municipal waterworks withdrew 531 Mgal of ground water at a per capita rate of 111 gal/d (gallons per day) in 1985.

The study area has at least 11 private waterworks. The 8 largest reported withdrawals of ground water totaling 2.75 Mgal in 1985. Most of the water withdrawn was used to supply trailer parks. Privately-supplied industrial water use in the study area included egg processing and the manufacture of particleboard and paperboard products. About 29.4 Mgal of ground water was withdrawn for these purposes in 1985.

Irrigation is a major use of water in the study area. Major crops (mostly potatoes) required 31.7 Mgal of ground-water irrigation. The average potato field received about 2.2 in. in 1985 and 3.8 in. in 1986. Noncrop irrigation (for nursery, landscaping, cemetery, and golf course purposes) required 22.8 Mgal of ground water.

Beltrami County withdrew 693.5 million gallons of ground water for rural-domestic purposes and 87.6 Mgal of ground water for consumption by livestock in 1985. A detailed description of water use in the study area is given in Appendix A.

Theoretical Maximum Yield of Wells in Confined and Unconfined-drift Aquifers

The theoretical maximum yields of wells in the uppermost confined-drift aquifer were estimated using a chart developed by Meyer (1963) which relates well diameter, specific capacity, and the coefficients of transmissivity and storage to well yield. The relation shows that, for confined aquifers (storage coefficients less than about 0.005), large differences in storage coefficient correspond to relatively small differences in specific capacity. Therefore, inaccurate estimation of aquifer storage is not a serious limiting factor in estimating theoretical well yields. The relation shows that, for transmissivities of approximately 270 to 13,000 ft^2/d, the ratio of transmissivity (ft^2/d) to specific capacity (gal/min) is about 320 to 1. The ratio is larger for greater transmissivities. Therefore, for confined aquifers with transmissivities of 13,000 ft^2/d or less, the specific capacity can be approximated by dividing the transmissivity by 320. The theoretical maximum well yield at a specific site can then be estimated by multiplying the specific capacity by the available drawdown. The theoretical maximum well yield for unconfined-drift aquifers was computed directly by multiplying the specific capacity (pumping rate divided by drawdown) by the available drawdown. The estimates of theoretical maximum well yield included in this report were based on the following assumptions:

1. The aquifer is homogeneous, isotropic, and infinite in areal extent.
2. The well is screened through the entire thickness of the aquifer, is 100 percent efficient, and has a diameter of 4 in.
3. The well is pumped continuously for 24 hours (confined aquifer) or until steady-state conditions occurred (unconfined aquifer).
4. Available drawdown is depth to water minus depth to screen (depth to top of the aquifer for confined aquifers).
5. Effects of recharge, hydrologic boundaries, and other pumping wells are negligible.
6. Storage coefficients are 0.2 for unconfined and 0.0002 for confined aquifers.

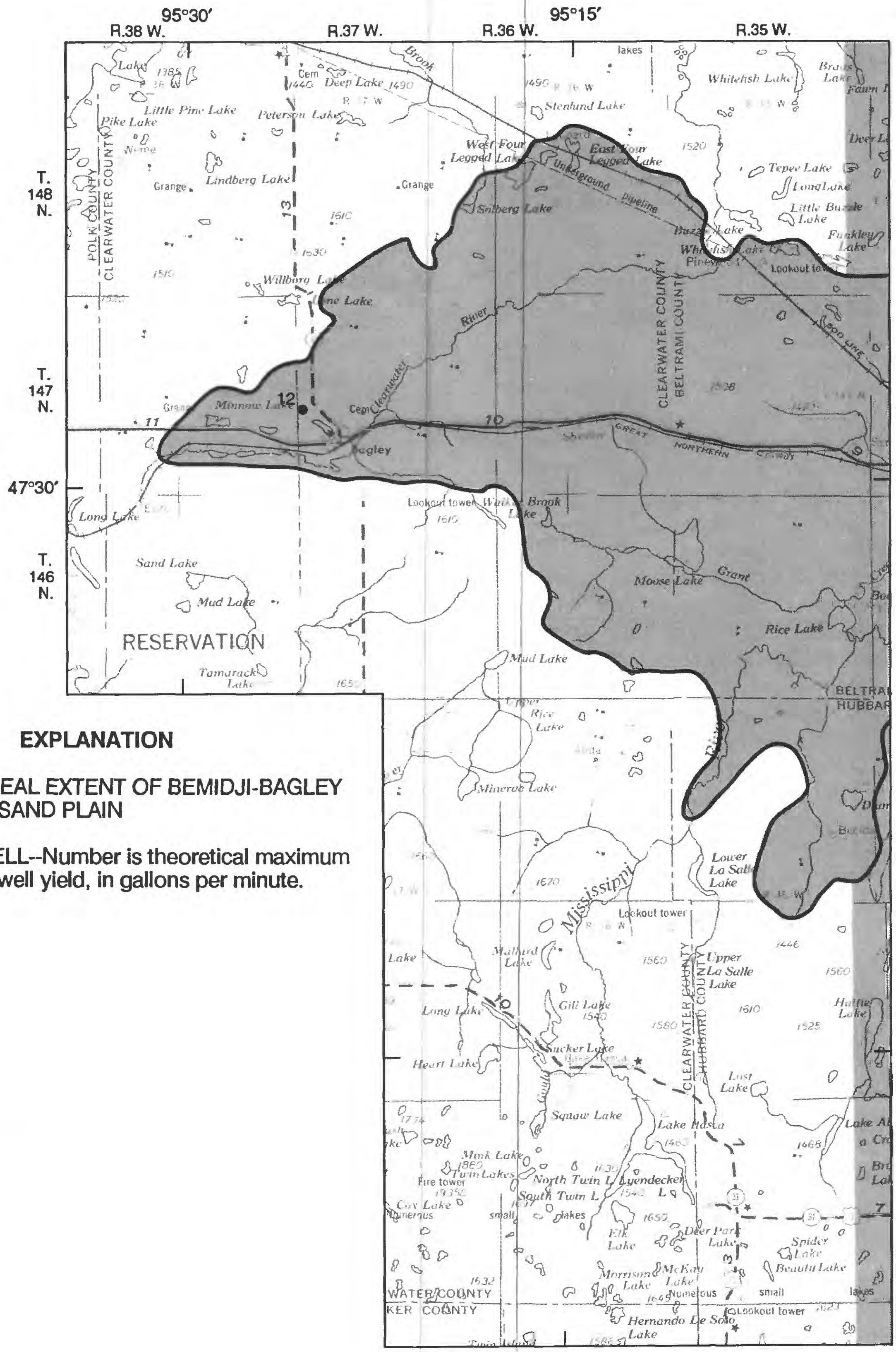
Local variations in aquifer hydraulic properties, recharge, proximity of the well to other pumping wells, effects of hydrologic boundaries (for example, rivers or the edge of the aquifer), well diameter and efficiency, and duration of pumping will cause local deviation from theoretical maximum yields.

The theoretical maximum well yields for the uppermost confined-drift and unconfined-drift aquifers are intended to show only general conditions and relative differences in water-yielding capability (figs. 19 and 20). Well yields for the unconfined-drift aquifer may be significantly lower than shown on the map in areas where drawdown significantly reduces the saturated thickness of the unconfined-drift aquifer. The maps cannot be used for accurate projection of well yields at a given location.

The areas of greatest theoretical maximum yield coincide with areas of greatest transmissivity. High-capacity wells generally are best located in these areas. Theoretical maximum well yields, computed from specific capacity values, range from 10 to 300 gal/min in the unconfined-drift aquifer and from less than 10 to about 2,100 gal/min in the confined-drift aquifer.

GROUND-WATER QUALITY

Chemical constituents dissolved in ground water are derived mainly from materials (soil, glacial drift, and rock) through which water flows. Ground-water quality varies in response to changes in residence time, length of flow path, temperature, precipitation, and chemical reactions with minerals and aquifer materials. Ground-water quality can also be influenced by chemicals introduced to ground-water systems by human activity such as direct discharges of chemicals to the ground-water system or nonpoint sources of chemicals related to land-use activities. Chemical constituents occurring naturally in ground-water can, in some instances, be the same as those introduced from human activities. Chloride is derived naturally from chloride-bearing minerals but can also be introduced to ground water systems from human and animal wastes and by leaching from deicing chemicals. Other chemicals, particularly manmade organic chemicals such as pesticides, herbicides, and solvents, have no naturally occurring source, and can be solely attributed to specific human activities.



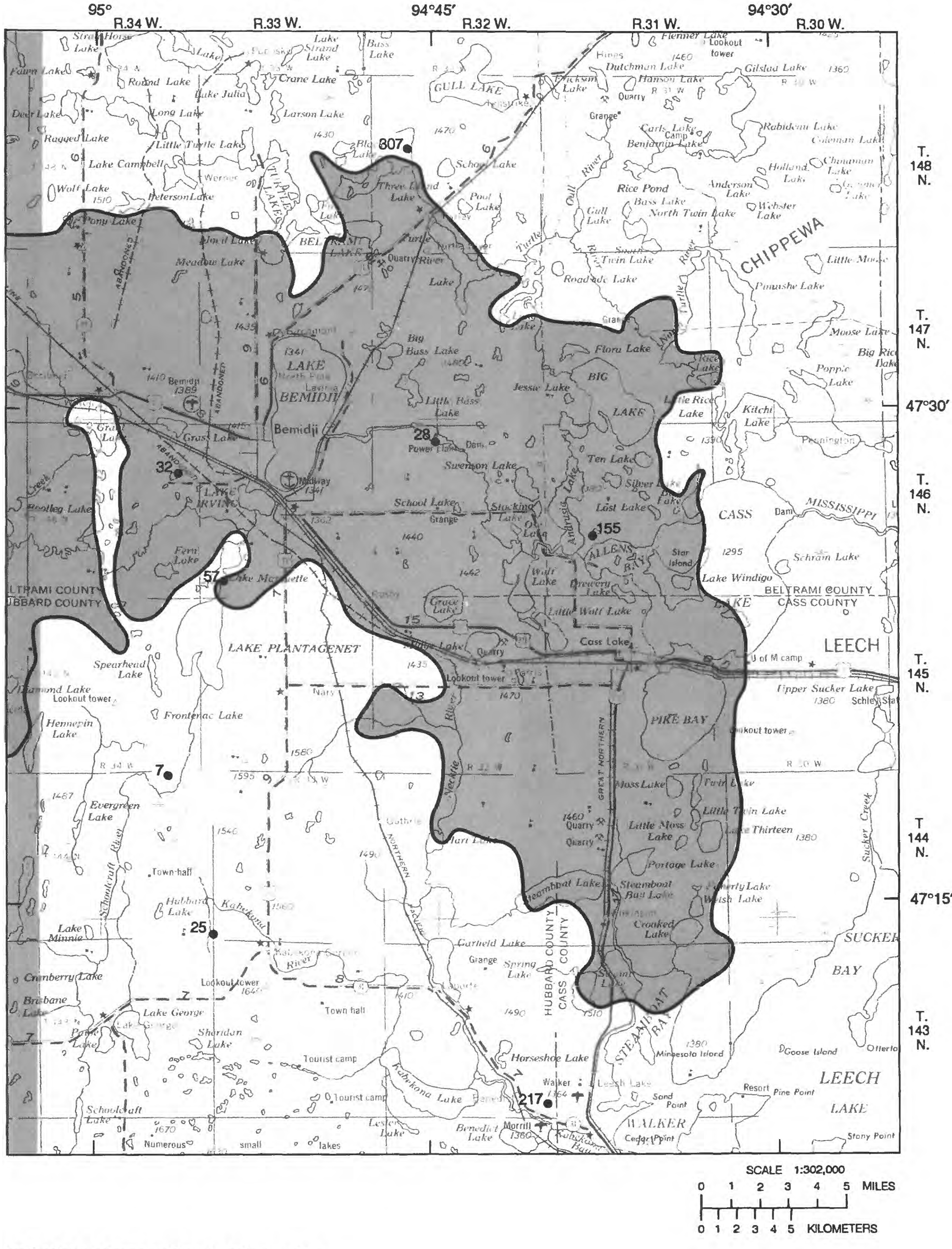
EXPLANATION

AREAL EXTENT OF BEMIDJI-BAGLEY SAND PLAIN

217 ● WELL--Number is theoretical maximum well yield, in gallons per minute.

Base from U.S. Geological Survey
Bemidji 1:250,000, 1974

Figure 19.--Theoretical maximum



well yield of unconfined-drift aquifer

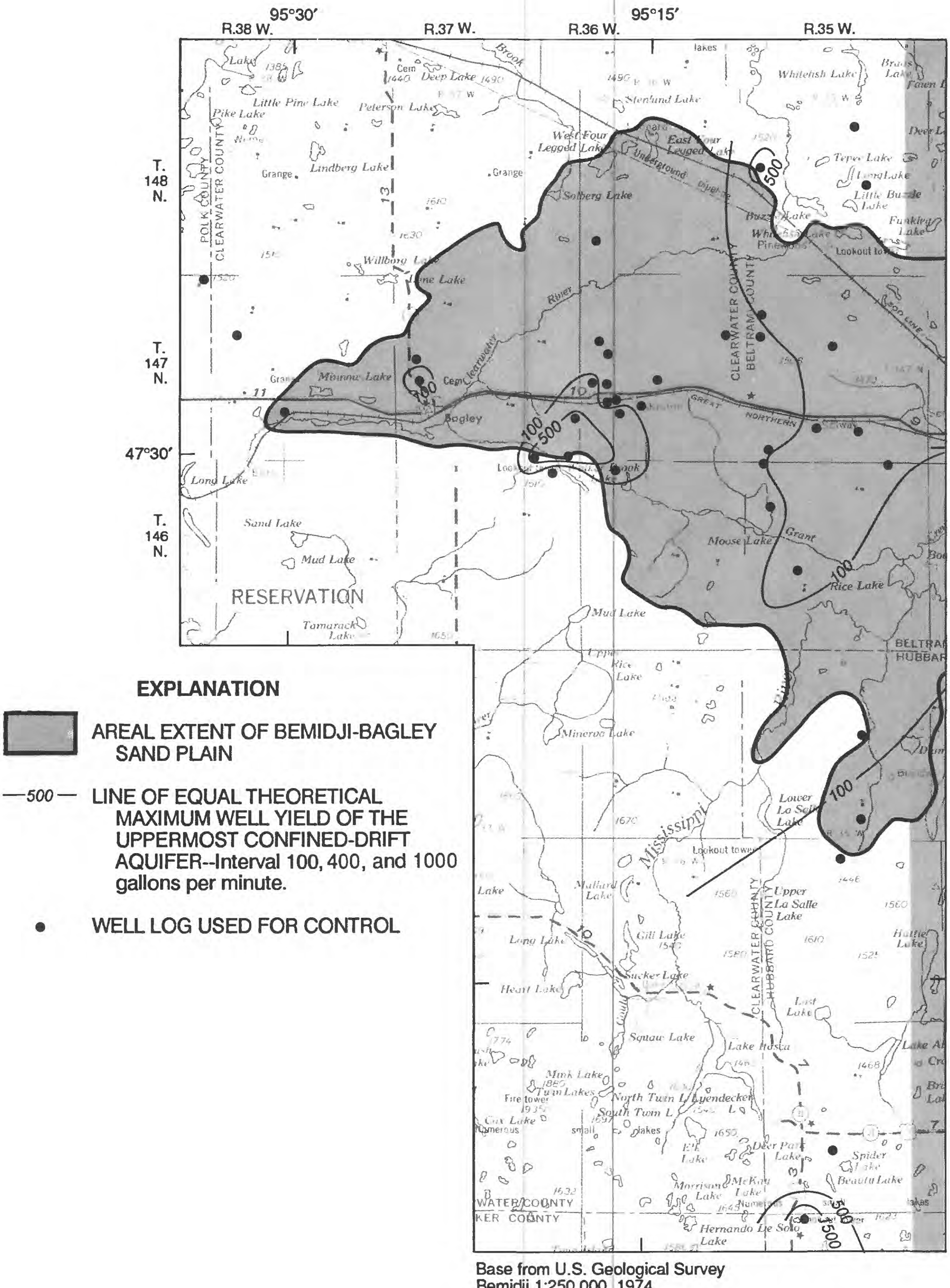
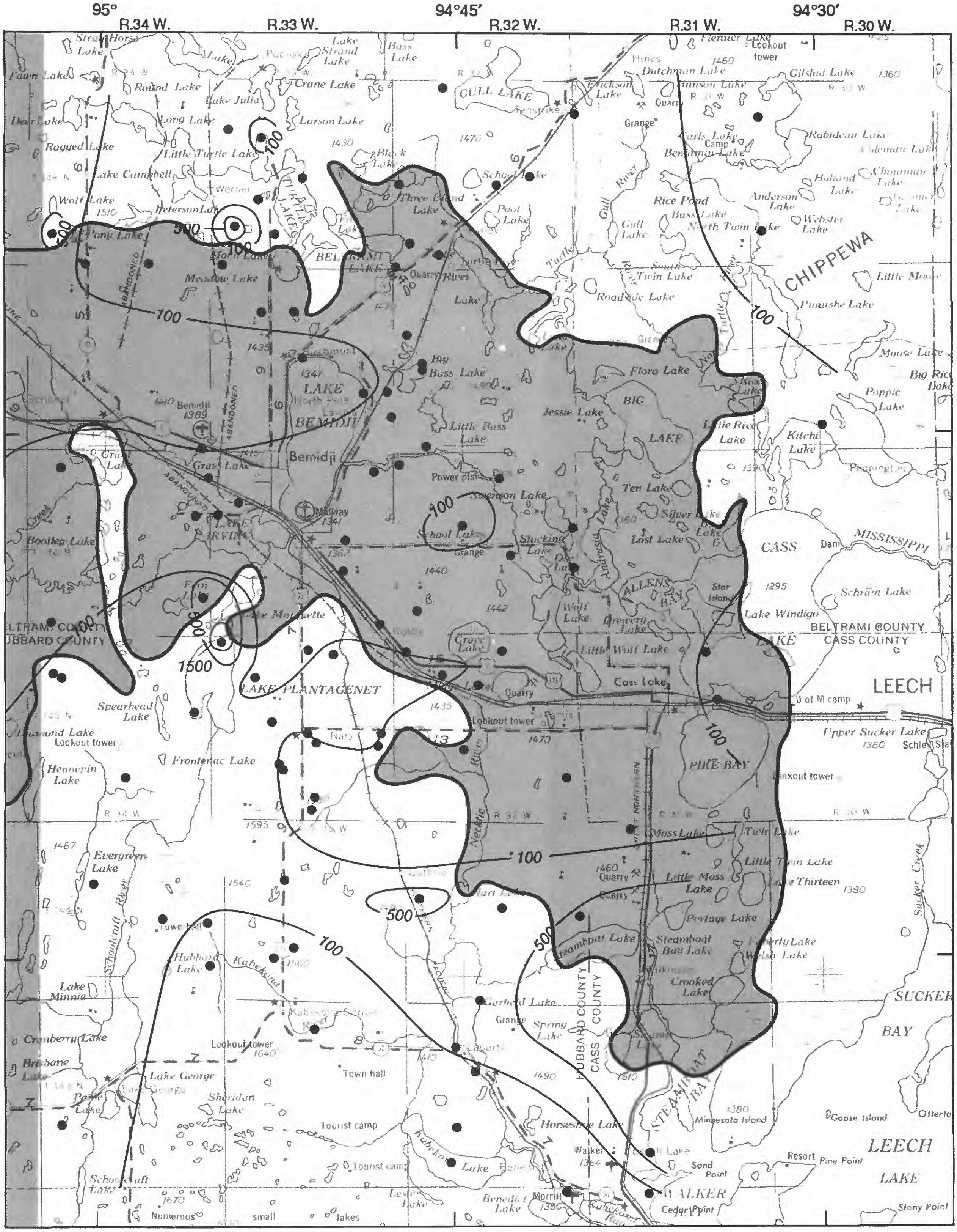


Figure 20.--Theoretical maximum



well yield of confined-drift aquifer

Water samples were collected from observation wells completed in the unconfined-drift aquifer, and from domestic-supply wells completed in the uppermost confined-drift aquifer. These samples were used to determine general ground-water quality, to test the assumption that ground-water quality is affected by land-use practices, to determine seasonal changes in water quality, and to provide baseline hydrologic and water-quality data for use in future assessments of long-term trends.

Sampling Procedures

A total of 68 wells were randomly selected from the observation wells in four land-use areas (agricultural, commercial, forested, and residential), and from the domestic-supply wells (fig. 21). All wells were sampled for an identical group of "indicator constituents" (table 1). Data from analyses of water for these "indicator constituents" were used to evaluate and compare the general ground-water quality from the unconfined-drift and uppermost confined-drift aquifer and to test the assumption that statistical differences exist in the quality of ground-water between the various land-use areas. In addition, waters from wells in several of the land-use groups were analyzed for additional constituents considered likely to be present because of land-use activities in each area.

A uniform procedure was used to sample all observation wells. The sampling techniques were modified from techniques recommended by Have and Tornes (M. R. Have and L. H. Lan Tornes, U.S. Geological Survey, Minn., written commun., 1985).

A summary of the field sampling procedures follows:

1. Water levels were measured in all wells at each sampling site.
2. Wells to be sampled were flushed by pumping the well with a centrifugal pump or a positive-displacement pump.
3. The flushing rate at each well was measured.
4. Temperature, specific conductance, and pH were measured in the flushing water.
5. Two criteria were used to determine the length of time a well would be flushed before sampling. A well was pumped until at least two casing volumes of water had been removed, or until the specific conductance and temperature readings stabilized.
6. After a well was properly flushed, samples were collected with a Teflon[1] bailer.
7. Samples that did not need filtering were obtained directly from the bailer and were preserved by standard procedures. Samples for determining dissolved constituents were filtered through a 0.45-micrometer membrane, collected in the sample container, and preserved (Fishman and Friedman, 1985).
8. Preserved samples were iced and shipped daily from the field to the U.S. Geological Survey Central Laboratory in Arvada, Colorado.

[1]Use of the brand name in this report is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.

Laboratory Procedures

All samples were analyzed at the U.S. Geological Survey Laboratory in Arvada, Colorado. Inorganic constituents were analyzed by procedures outlined in Fishman and Friedman (1985). Volatile organics and pesticides were analyzed according to procedures in Wershaw and others (1983).

General Water Quality

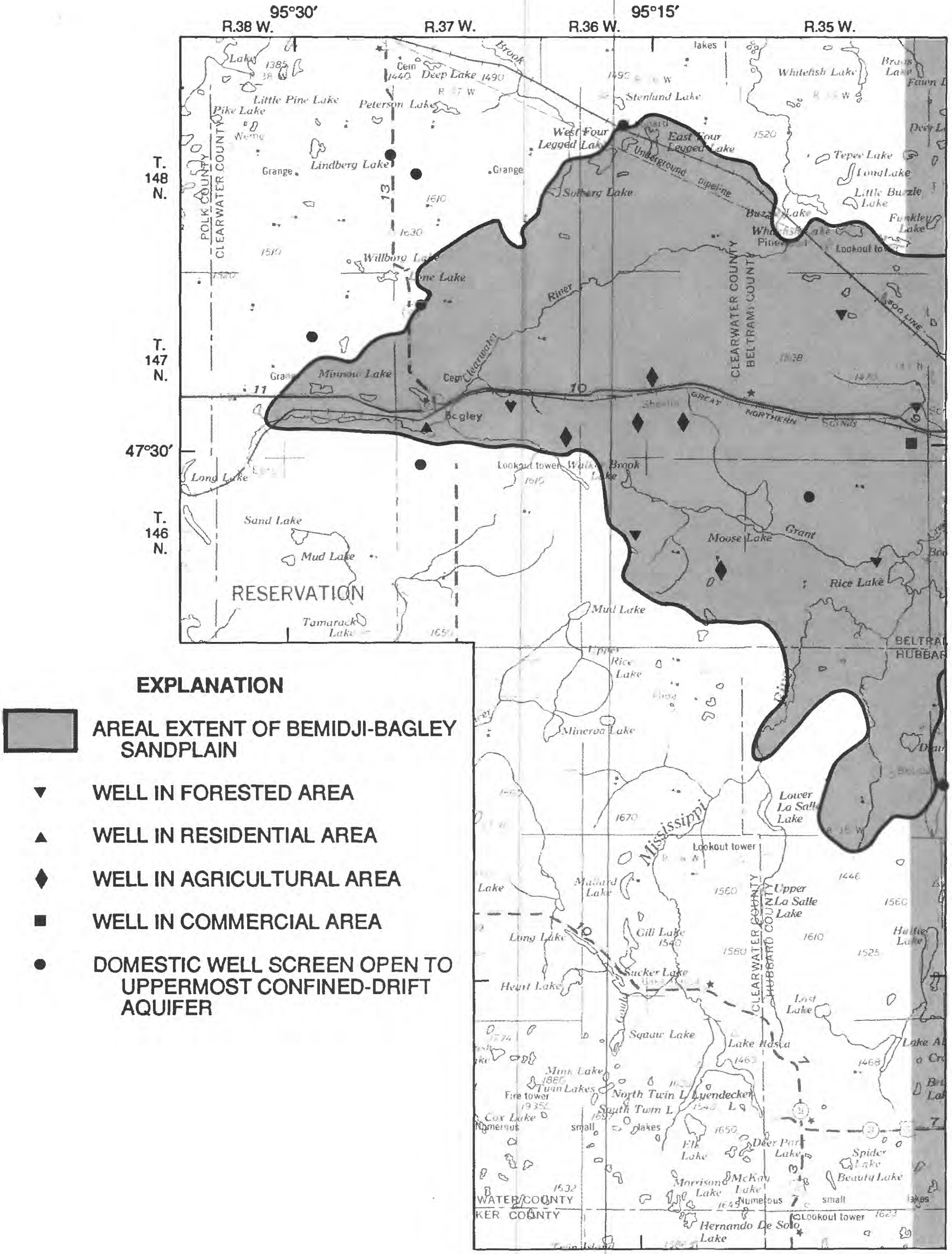
Water from both unconfined-drift and uppermost confined-drift aquifers in the Bemidji-Bagley area is very hard, averaging 267 and 309 mg/L (milligrams per liter) of $CaCO_3$, respectively. Water having a hardness equivalent greater than 180 mg/L of $CaCO_3$ is generally considered very hard (Hem, 1985). Hardness, as applied to water, is not an exact term and is generally associated with the effects observed with the use of soap or with encrustations left by water when heated. 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 is generally used (Hem, 1985).

Calcium and bicarbonate are the predominant ions in ground water from both unconfined-drift and confined-drift aquifers. A common graphical technique for presenting water-chemistry data is a trilinear diagram. These diagrams permit the representation of common cation and anion compositions of many samples on a single graph. Figure 22 contains a trilinear diagram comparing the relative chemistry of water from wells completed in the unconfined and confined-drift aquifers. The points representing cation and anion data from the lower triangles are extended to the parallelogram (Freeze and Cherry, 1979) to indicate the general type of water indicated by concentrations of cations and anions. Waters in the Bemidji-Bagley area are generally of the calcium-bicarbonate type. Calcium and bicarbonate are derived primarily from soil and rock weathering (Hem, 1985).

Waters from both aquifers generally are suitable for domestic consumption, crop irrigation, and most other uses. Concentrations of ammonia, boron, chromium, iron, manganese, phenols and atrazine locally exceed limits recommended by the MPCA (Minnesota Pollution Control Agency) (1988) for domestic consumption (table 2). Dissolved solids also locally exceed the recommended limits of MPCA (1988) for agricultural and wildlife use (table 2).

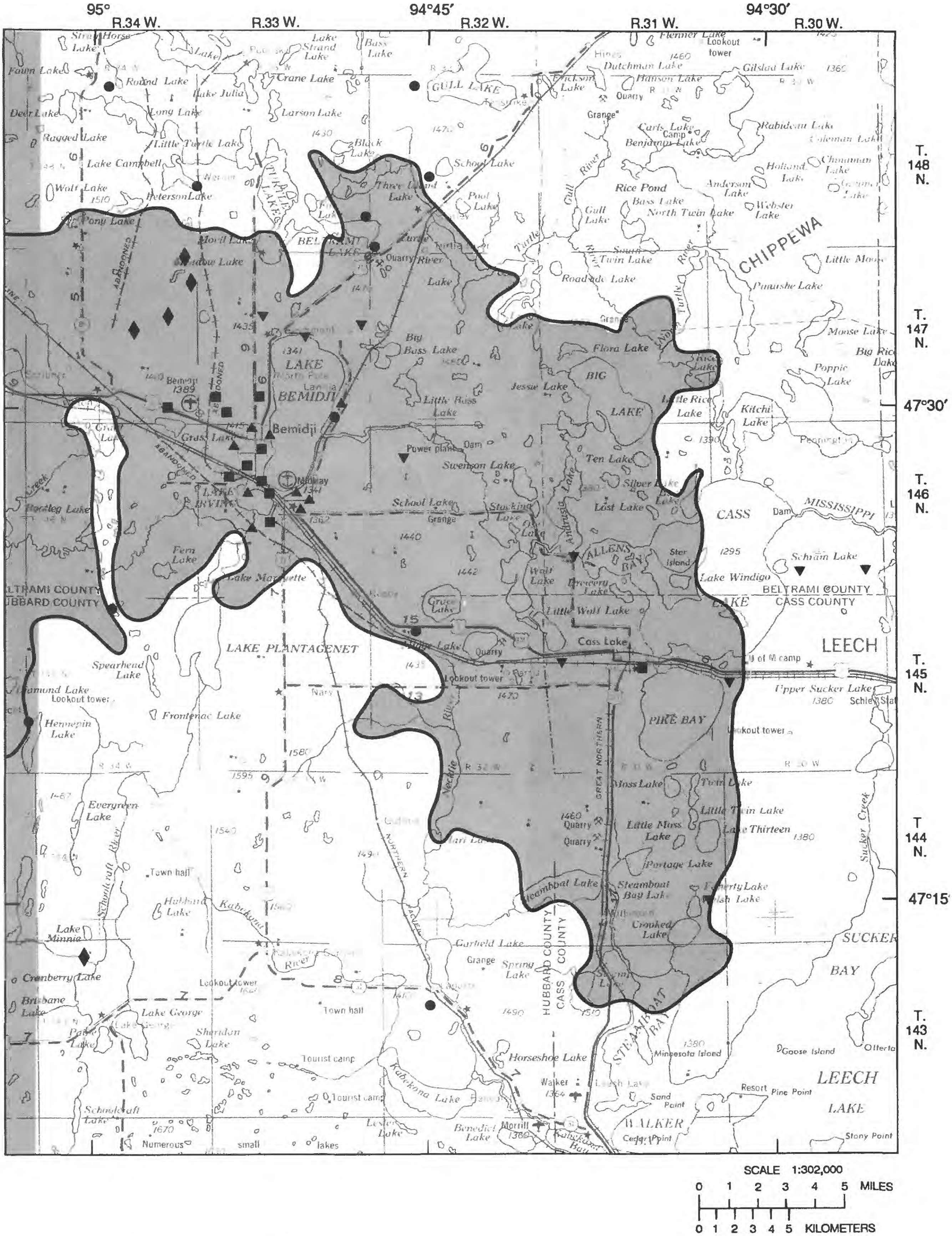
High concentrations of dissolved solids in ground water can cause well-screen encrustation and reduced well yield. Dissolved-solids concentrations in water from unconfined-drift and uppermost confined-drift aquifers frequently exceed the MPCA recommended limit for domestic use.

Dissolved iron and manganese are essential to plants and animals, but at high concentrations may cause objectionable taste, odors, and staining of plumbing fixtures. High concentrations of these ions do not adversely affect plants, but treatment of the water may be necessary prior to domestic use.



Base from U.S. Geological Survey
Bemidji 1:250,000, 1974

Figure 21.--Water-quality sampling locations



according to land-use and aquifer types.

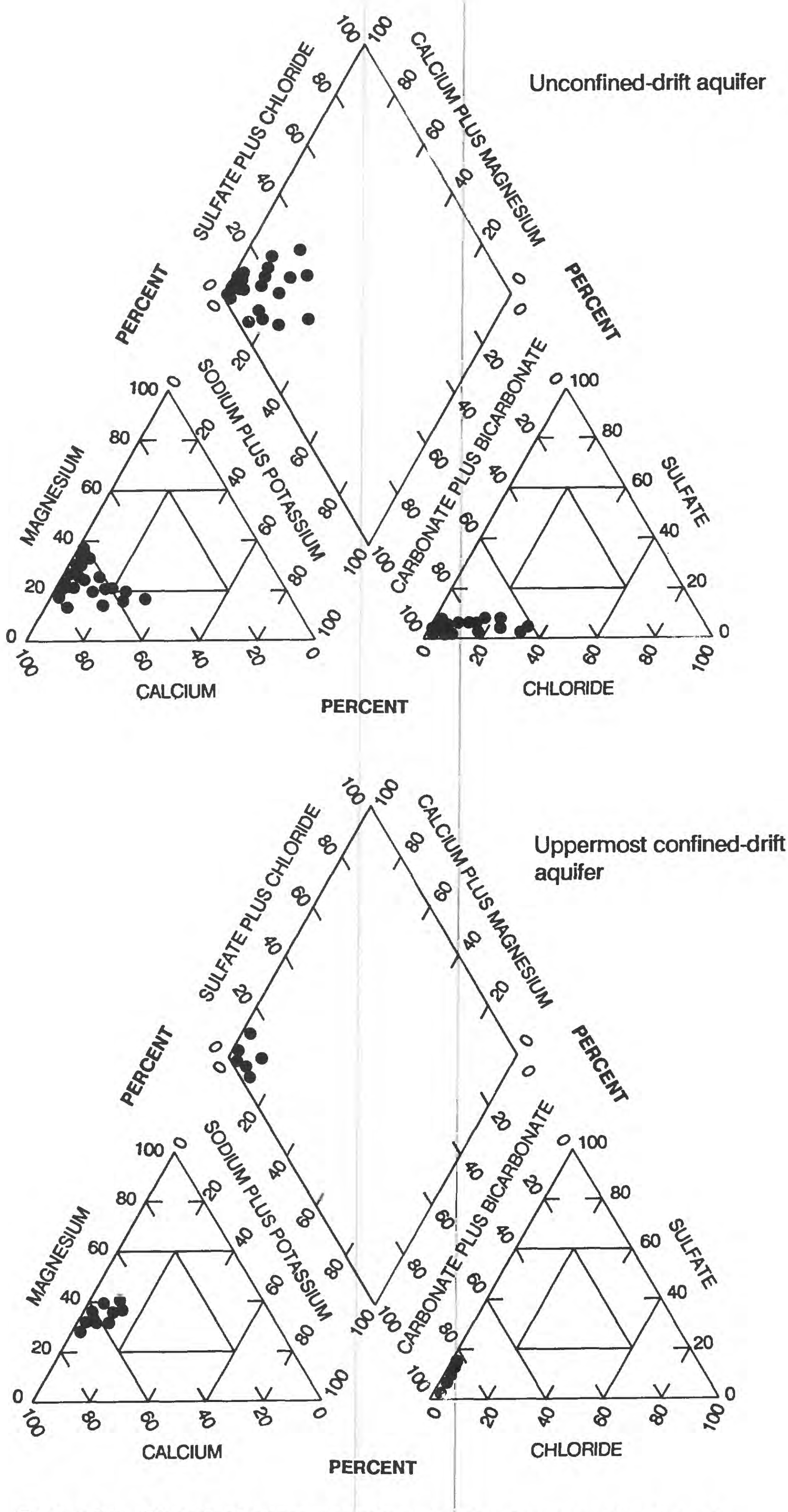


Figure 22.--Chemical characteristics of water in unconfined- and confined-drift aquifers

Table 2.--*State recommended limits for domestic consumption and agricultural and wildlife use for selected constituents in ground water*[1]*, and percentages of wells sampled where water exceeds the limits*

[mg/L, milligrams per liter; µg/L, micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius]

Constituent	Concentration		Limit type	Number of wells sampled	Percent of wells exceeding limits
			Inorganic Constituents		
Ammonia	.016	mg/l	Agriculture, Wildlife	62	56
Arsenic	.01	mg/l	Domestic consumption	33	0
Barium	1.0	mg/l	Domestic consumption	23	0
Boron	0.5	mg/l	Domestic consumption	23	4
Cadmium	.01	mg/l	Domestic consumption	23	0
Chloride	250.	mg/l	Domestic consumption	39	0
Chromium (Hexavalent)	.05	mg/l	Domestic consumption	23	9
Iron	0.3	mg/l	Domestic consumption	33	18
Lead	.05	mg/l	Domestic consumption	33	0
Manganese	.05	mg/l	Domestic consumption	23	35
Nitrate (nitrate plus nitrite as N)	10.0	mg/l	Domestic consumption	62	0
Selenium	.01	mg/l	Domestic consumption	23	0
Sulfate	250.	mg/l	Domestic consumption	62	0
			Other Constituents		
Alachlor	6.0	µg/l	Domestic consumption	13	0
Atrazine	3.0	µg/l	Domestic consumption	13	8
Cyanazine	9.0	µg/l	Domestic consumption	13	0
Metloachlor	10.0	µg/l	Domestic consumption	13	0
Metribuzin	175.0	µg/l	Domestic consumption	13	0
Simazine	35.0	µg/l	Domestic consumption	13	0
Trifluralin	2.0	µg/l	Domestic consumption	13	0
Phenol	1.0	µg/l	Domestic consumption	62	40
Dissolved solids	700	µg/l	Agriculture, Wildlife	62	8
pH	6.0-8.5	standard units	Agriculture, Wildlife	62	0
Specific conductance	1000	µS/cm	Agriculture, Wildlife	62	0

[1]Recommended limits from Minnesota Pollution Control Agency (1988).

The suitability of water for irrigation commonly is determined by relating conductivity of the water to the sodium-adsorption ratio (SAR), which can be used to classify the water in terms of its sodium and salinity hazards. This classification system was developed by the U.S. Salinity Laboratory (1954). The SAR is determined by the following relation where constituent concentrations are expressed in milliequivalents per liter:

$$SAR = \frac{\text{Sodium}}{\sqrt{(\text{Calcium} + \text{Magnesium})/2}} \qquad (1)$$

A high SAR value indicates that irrigation can destroy soil structure and thereby reduce permeability.

Salinity is directly related to the concentrations of dissolved solids in water. High salinity concentrations endanger plants by reducing the amount of water absorbed by roots. Waters from the uppermost confined-drift and unconfined-drift aquifers exhibit a potentially low sodium hazard and a medium to high salinity hazard (fig. 23).

The chemistry of water from the unconfined-drift and from the uppermost confined-drift aquifers is generally similar. Figure 22 shows that common cations and anions plot in the same general areas of the diagram for both aquifers. This similar grouping of data shows that major cations and anions in water samples from the unconfined and confined-drift aquifers are of similar concentration and indicates that some mixing of water between the aquifers probably occurs.

Subtle differences exist between the chemistries of waters from the two aquifers. Analyses for waters from the unconfined-drift aquifer are more scattered than those for the confined-drift aquifer on the trilinear diagram, possibly indicating that water from the unconfined-drift aquifer is affected by outside factors such as influences from various land uses.

Waters from the uppermost confined-drift aquifer generally have greater specific conductances; higher total dissolved solids; and greater concentrations of alkalinity, bicarbonate, magnesium, sodium, potassium, fluoride, and silica than have waters from the unconfined-drift aquifer (table 3). These higher concentrations of naturally occurring constituents in waters from the uppermost confined-drift aquifer may occur because of the longer flow paths and longer residence times of water in the confined-drift aquifer as compared to the unconfined-drift aquifer. Longer residence times in the uppermost confined-drift aquifer compared to the unconfined-drift aquifer may reflect (1) the possible discontinuity of the confined-drift aquifer and the low ground-water-flow velocities produced by that discontinuity; and (2) the greater depth of burial that results in long flow paths. The combined effect is to increase the water-mineral contact time, thereby increasing mineral dissolution and the concentrations of chemical constituents in the ground water. Higher concentrations for listed constituents may also be caused by longer residence time in ground water where recharge to the uppermost confined-drift aquifer is through till in the highland (morainal) area bordering the unconfined-drift aquifer.

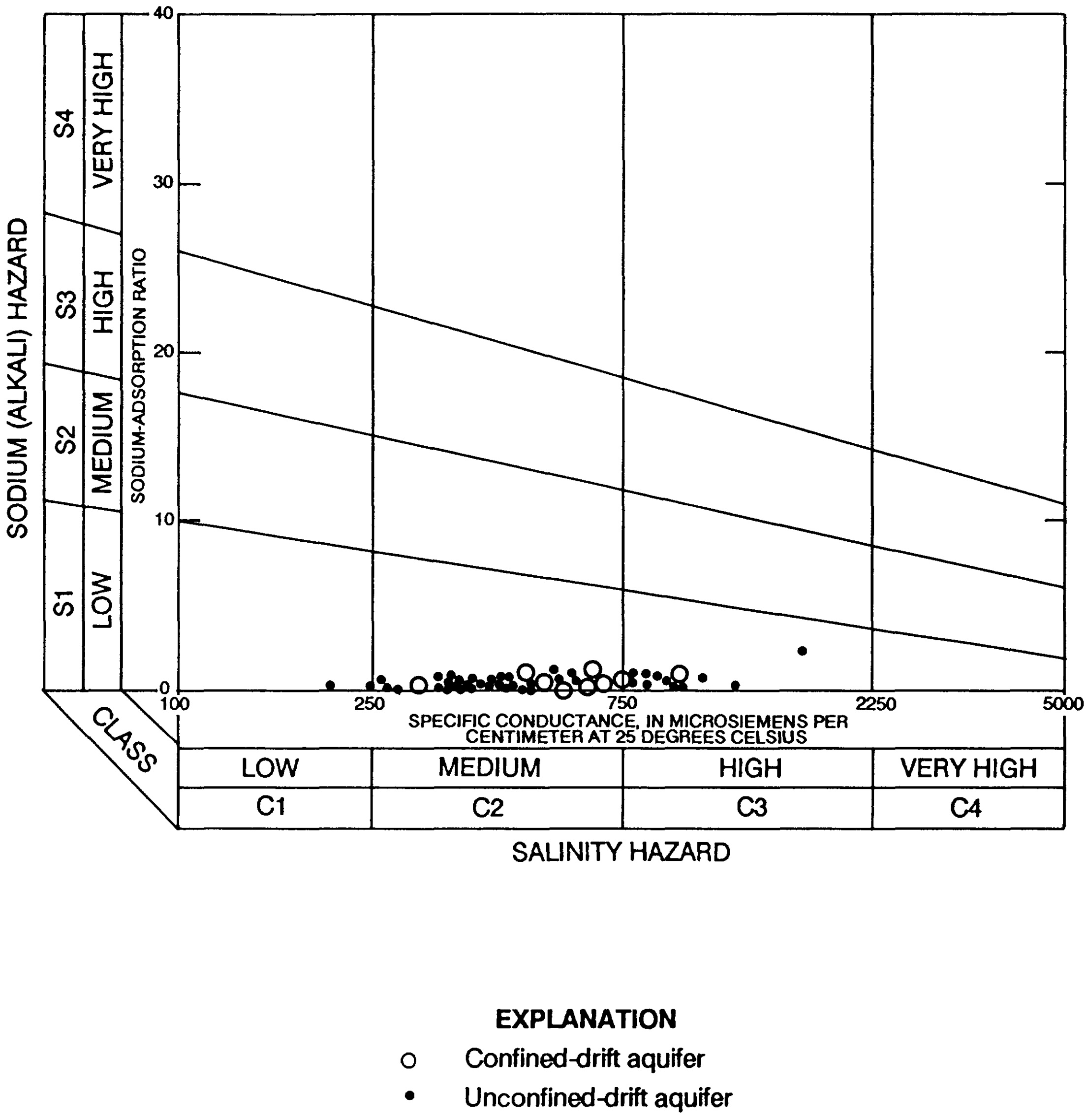


Figure 23.--Suitability of water from unconfined and confined-drift aquifers for irrigation in terms of sodium and salinity hazards

(U.S. Salinity Laboratory, 1954)

Table 3.--*Statistical comparison of water-quality data for wells completed in unconfined-drift and confined-drift aquifers*

[mg/L, milligrams per liter; µg/L, micrograms per liter; °C, degrees Celsius; µS/cm, microsiemens per centimeter at 25 degrees Celsius; field, determined at sampling site; --, not determined; <, less than]

Chemical constituent or property	Unconfined aquifers						Confined aquifers					
	Number of samples	Mean	Standard deviation	Minimum-Maximum	Median	Number of samples less than reporting level	Number of samples	Mean	Standard deviation	Minimum-Maximum	Median	Number of samples less than reporting level
Temperature (°C)	49	10.6	2.5	7.5-18	9.5	0	13	10.7	2.3	7.5-15.0	11.5	0
Specific conductance (µS/cm)	47	568	276	208-1800	460	0	13	549	146	320-890	546	0
pH (Standard units)	49	--	--	6.6-8.3	7.4	0	13	--	--	7.0-8.1	7.6	0
Dissolved solids, residue at 180 °C, (mg/L)	35	331	164	129-1020	281	0	13	340	93	227-583	325	0
Alkalinity, field (mg/L as $CaCo_3$)	49	246	88.0	92.0-470	232	0	13	330	97.0	196-520	330	0
Bicarbonate, field (mg/L as HCO_3)	35	308	107	112-578	302	0	13	410	110	239-629	410	0
Nitrogen, ammonia, dissolved (mg/L as N)	49	.32	1.3	<.010-8.5	.02	11	13	--	.346	<.010-1.20	.18	2
Nitrogen, ammonia plus organic, dissolved (mg/L as N)	49	1.1	2.1	<.20-14	.50	5	13	--	.39	<.20-1.5	0.5	3
Nitrogen, nitrite plus nitrate, dissolved (mg/L as N)	42	1.3	1.9	<.10-7.8	.39	13	13	--	.083	<.10-.34	.10	18
Phosphorus, dissolved (mg/L as P)	47	.06	.12	<.010-.690	.020	2	13	--	.0147	<.005-.057	.0065	6
Phosphorus, ortho dissolved (mg/L as P)	47	.050	.110	<.001-.690	.020	2	13	.0084	.0084	<.001-0.50	.005	2

Table 3.--*Statistical comparison of water-quality data for wells completed in unconfined-drift and confined-drift aquifers*--Continued

Chemical constituent or property	Unconfined aquifers						Confined aquifers					
	Number of samples	Mean	Standard deviation	Minimum-Maximum	Median	Number of samples less than reporting level	Number of samples	Mean	Standard deviation	Minimum-Maximum	Median	Number of samples less than reporting level
Calcium, dissolved (mg/L as Ca)	48	77	29	31-190	70	0	13	80.1	17.3	10-130	77	0
Magnesium, dissolved (mg/L as Mg)	48	18.2	9.53	4.50-64.0	17.0	0	13	27.8	11.6	15-60	25	0
Sodium, dissolved (mg/L as Na)	48	15.3	34.2	1.1-230	3.5	0	13	7.85	7.26	1.4-29	4.85	0
Potassium, dissolved (mg/L) as K	48	2.5	5.1	.4-3.6	1.4	0	13	2.63	1.31	.3-5.7	2.4	0
Chloride, dissolved (mg/L as Cl)	49	25	58	.50-380	3.4	0	13	1.3	1.8	.3-6.4	.6	0
Sulfate, dissolved (mg/L as SO4)	49	9.93	5.13	2.10-25.0	9.3	0	13	14.5	23.3	0.9-88.0	6.1	0
Fluoride, dissolved (mg/L as F)	48	.1	.04	.1-0.3	.1	0	13	.24	.25	.1-1.2	0.2	0
Silica, dissolved (mg/L as SiO2)	48	21.	6.8	1.9-43	20	0	13	23	3.3	18-29	23	0
Phenols, total (µg/L)	46	3	6	<1-40	2	10	13	2	.87	<1-3	2	5

Water in the unconfined-drift aquifer generally has higher mean concentrations of dissolved ammonia plus organic nitrogen, dissolved nitrate plus nitrite, dissolved chloride, dissolved phosphorus, dissolved orthophosphorus, and dissolved phenols (table 3). Elevated concentrations of these constituents are related to land-use practices. The effect of these practices on water quality of the unconfined-drift aquifer appears to be more pronounced than that of the confined-drift aquifer, probably because of the proximity of the unconfined-drift aquifer to land surface and the lack of low-permeability materials that could isolate the unconfined-drift aquifers from direct infiltration of recharge. Increased nitrate concentrations can result from infiltration of runoff from livestock feedlots, domestic septic systems, and fertilizers. Studies conducted by Myette (1984) near Staples, Minn., indicate that concentrations of nitrate and chloride generally are greatest in samples from the shallowest part of the surficial aquifer (near the water table). This indicates that water containing elevated levels of nitrate and chloride moves vertically to the water table and then laterally, discharging primarily to streams and lakes, rather than moving deeper into the ground-water system. Only a minor amount of vertical mixing occurs within the saturated part of the unconfined-drift aquifer. This is because hydraulic conductivities are greater horizontally than vertically and relatively short flow paths exist in these systems.

Ground-Water Quality Related to Specific Land Uses

In addition to analyses for constituents sampled in common among all land-use-type and aquifer-type groups, water from wells completed in the unconfined-drift aquifer in commercial, residential, and agricultural land-use groups was analyzed for specific groups of constituents whose possible occurrence might be related to land-use activities in those areas.

Agricultural Areas

Water from wells in agricultural land-use areas were analyzed for arsenic and lead (formally used as pesticides) and for a group of common organic pesticides (Triazine group) (table 4). Arsenic and lead concentrations did not exceed recommended drinking water limits of the MPCA (1988) in any waters from agricultural-area wells. One organic pesticide (atrazine) was identified in one well in Clearwater County (Appendix C). The concentration of atrazine detected in this well was low (2.9 μg/L) (micrograms per liter), which is less than the recommended limit for drinking water (Minnesota Department of Health and Minnesota Department of Agriculture, 1988) (table 2).

Commercial Areas

Water from wells sampled in commercial land-use areas was analyzed for heavy metal ions and for a group of volatile organic compounds commonly used for commercial and industrial purposes (table 5). Several volatile organic compounds (methylene chloride, trichlorofluoromethane, 1,2-transdichloroethylene, and dichlorodifluoromethane) were identified at low concentrations in several wells in the Bemidji area. Although the concentrations were low, these compounds in drinking water are inherently toxic to humans. There are

Table 4.--*Statistical summary of water-quality data for wells completed in unconfined-drift aquifer in agricultural land-use areas for lead, arsenic, and common organic pesticides*

[Reporting level is the lowest measured concentration of a constituent that may be reliably reported using a given analytical method. The reporting level is set somewhat higher than the detection limit. All constituents in micrograms per liter unless noted. [1] All analyses for this constituent were less than reporting level. mg/L, milligrams per liter; --, not determined; <, less than]

Constituent	Number of samples	Mean	Standard deviation	Minimum-Maximum	Median	Reporting level	Number of samples less than reporting level
Carbon, organic total (mg/L)	13	6.3	3.0	2.5-10	6.2	.1	0
Arsenic, dissolved (as As)	13	1.	.8	<1-4	1	1	7
Iron, dissolved (as Fe)	13	20	10	10-40	20	10	0
Lead, dissolved (as Pb)[1]	13	--	--	--	--	.1	13
Propazine, total [1]	13	--	--	--	--	.1	13
Simetryne, total[1]	13	--	--	--	--	.1	13
Trifluralin, total [1]	13	--	--	--	--	.1	13
Simazine, total[1]	13	--	--	--	--	.1	13
Prometone, total[1]	13	--	--	--	--	.1	13
Prometryne, total[1]	13	--	--	--	--	.1	13
Atrazine, total	13	--	--	<.1-2.9	.1	.1	12
Alachlor, total recoverable[1]	13	--	--	--	--	.1	13
Cyanazine, total[1]	13	--	--	--	--	.1	13
Ametryne, total[1]	13	--	--	--	--	.1	13
Metribuzin, total recoverable[1]	13	--	--	--	--	.1	13
Metolachlor, total recoverable[1]	13	--	--	--	--	.1	13

Table 5.--*Statistical summary of water-quality data for wells completed in unconfined-drift aquifer in commercial land-use areas for heavy metals and volatile-organic compounds*

[Reporting level is the lowest measured concentration of a constituent that may be reliably reported using a given analytical method. The reporting level is set somewhat higher than the detection limit. All constituents in micrograms per liter unless noted. [1]All analyses below reporting level; mg/L, milligrams per liter; --, not determined; <, less than.]

Constituent	Number of samples	Mean	Standard deviation	Minimum-Maximum	Median	Reporting level	Number of samples less that reporting level
Arsenic, Dissolved (as As)	13	4	4	<1-14	1	1	2
Barium, dissolved (as Ba)	13	130	100	22-290	118	2	0
Boron, dissolved (as B)	13	40	30	<10-120	30	10	1
Cadium, dissolved (as Cd)	13	--	--	<1-3	1	10	9
Chromium, dissolved (as Cr)	13	--	--	<10-310	<10	10	10
Iron, dissolved (as Fe)	13	4290	6280	<3-20000	1130	3	1
Lead, dissolved (as Pb)	13	--	--	<5-10	<5	5	11
Manganese, dissolved (as Mn)	13	950	1400	1-4800	450	1	0
Aluminum, dissolved (as Al)	13	19	7	<10-30	20	10	2
Selenium, dissolved (as Se)	13	1	.3	<1-2	1	1	2
Dichlorobromomethane, Total[1]	13	--	--	--	--	3.0	13
Carbontetrachloride, Total[1]	13	--	--	--	--	3.0	13
1,2,-Dichloroethane, Total[1]	13	--	--	--	--	3.0	13
Bromoform, Total[1]	13	--	--	--	--	3.0	13
Chlorodibromomethane, Total[1]	13	--	--	--	--	3.0	13
Chloroform, Total[1]	13	--	--	--	--	3.0	13
Toluene, Total[1]	13	--	--	--	--	3.0	13
Benzene, Total[1]	13	--	--	--	--	3.0	13
Chlorobenzene, Total[1]	13	--	--	--	--	3.0	13
Chloroethane, Total[1]	13	--	--	--	--	3.0	13
Ethylbenzene, Total[1]	13	--	--	--	--	3.0	13
Methylbromide, Total[1]	13	--	--	--	--	3.0	13
Methylchloride, Total[1]	13	--	--	--	--	3.0	13
Methylenechloride, Total	13	--	--	<3-27	<3	3.0	12
Tetrachloroethylene, Total[1]	13	--	--	--	--	3.0	13
Trichlorofluoromethane, Total	13	--	--	<3-4	<3	3.0	12

Table 5.--*Statistical summary of water-quality data for wells completed in unconfined-drift aquifer in commercial land-use areas for heavy metals and volatile-organic compounds*--Continued

Constituent	Number of samples	Mean	Standard deviation	Minimum-Maximum	Median	Reporting level	Number of samples less that reporting level
1,1-Dichloroethane, Total[1]	13	--	--	--	--	3.0	13
1,1-Dichloroethylene, Total[1]	13	--	--	--	--	3.0	13
1,1,1-Trichloro-ethane, Total[1]	13	--	--	--	--	3.0	13
1,1,2-Trichloro-ethane, Total[1]	13	--	--	--	--	3.0	13
1,1,2,2-Tetrachloro-ethane, Total[1]	13	--	--	--	--	3.0	13
1,2-Dichlorobenzene, Total[1]	13	--	--	--	--	3.0	13
1,2-Dichloropropane, Total[1]	13	--	--	--	--	3.0	13
1,2-Transdichlor-ethylene, Total	13	4	--	<3-17	--	3.0	12
1,3-Dichloropropane, Total[1]	13	--	--	--	--	3.0	13
1,3-Dichlorobenzene, Total[1]	13	--	--	--	--	3.0	13
1,4-Dichlorobenzene, Total[1]	13	--	--	--	--	3.0	13
2-Chloroethylvinyl-ether, Total[1]	13	--	--	--	--	3.0	13
Dichlorodifluoro-methane, Total	13	--	--	<3-6	--	3.0	12
Trans-1,3-Dichloro-propene, Total[1]	13	--	--	--	--	3.0	13
Cis 1,3-Didhloro-propene, Total[1]	13	--	--	--	--	3.0	13
1,2-Dibromoethylene, Total[1]	13	--	--	--	--	3.0	13
Vinylchloride, Total[1]	13	--	--	--	--	3.0	13
Trichoroethylene, Total[1]	13	--	--	--	--	3.0	13
Mercury, Dissolved (as Hg)	13	.2	.2	<.1-1.1	0.1	.1	3
Styrene, Total[1]	13	--	--	--	--	3.0	13
Xylene, Total recoverable[1]	13	--	--	--	--	3.0	13

few State or Federal drinking-water or health standards for these organic compounds. Their presence in water from observation wells installed for this study is probably related to localized sources near the wells.

Heavy-metal concentrations in water from wells in commercial land-use areas were generally less than limits for domestic consumption and agriculture and wildlife use set by MPCA (1988), except for isolated occurrences of chromium, iron, and manganese (Appendix C).

Residential Areas

Water from wells completed in the unconfined-drift aquifer in residential land-use areas was analyzed for heavy metals in addition to the constituents sampled for in common among all groups (table 6). Except for isolated occurrences of chromium and manganese, concentrations of metals in water from wells in this land-use type group were all below concentrations acceptable for domestic consumption and for agricultural and wildlife uses as set by the MPCA (1988).

Relation Between Water Quality and Land Use

A statistical comparison of common chemical constituents in water from wells in each land-use and aquifer-type group is shown in table 7. Concentrations are generally greater in water from wells completed in commercial and residential land-use areas than in water from wells in agricultural and forested land-use areas. For example, mean values of temperature, ammonia plus organic nitrogen, phosphorus, calcium, sodium, potassium, chloride, sulfate, silica, dissolved solids, and specific conductance are generally greater for wells in commercial and residential land-use type areas than for wells in forested and in agricultural land-use type areas. The mean values of ammonia nitrogen, magnesium, and fluoride are generally greater for wells in commercial land-use type areas than for wells in forested and agricultural land-use type areas. The mean value of nitrogen (NO_2 + NO_3, dissolved) is generally greater for wells in residential land-use type areas than for wells in forested and agricultural land-use type areas.

The relationship between land use and ground-water quality is further illustrated by box and whisker plots (figures 24-26). Corresponding plots of the several constituents from wells completed in the confined-drift aquifer also are shown for comparative purposes. These plots graphically illustrate the median (50th percentile) and quartile values (25th and 75th percentiles). Also, the range of adjacent data that are less than 1.5 times the interquartile distance (range between the 25th and 75th percentile points) above the 75th or below the 25th quartile value are represented by the "whiskers". Outlier values are also shown on these plots as outlying points.

These plots are included to illustrate the relation between land use and the general chemistry of ground water in the unconfined-drift aquifer. Similar relations exist for ammonia plus organic nitrogen, phosphorus, calcium, sodium, potassium, chloride, silica, magnesium, and fluoride. These data suggest that land use may be affecting the quality of water in the unconfined-drift aquifer.

Table 6.--*Statistical summary of water-quality data for wells completed in unconfined-drift aquifer in residential land-use areas for heavy metals*

[All constituents in micrograms per liter. [1]All analyses below reporting level. --, not determined; <, less than]

Constituent	Number of samples	Mean	Standard deviation	Minimum-Maximum	Median	Reporting level
Arsenic, dissolved	10	2	.5	<1-2	1	1
Barium, dissolved	10	50	10	40-70	50	10
Boron, dissolved	10	40	20	<10-80	40	10
Cadmium, dissolved[1]	10	--	--	--	--	10
Chromium, dissolved	10	30	30	<10-90	10	10
Iron, dissolved	10	240	720	<3-2300	10	3
Lead, dissolved[1]	10	--	--	--	--	5
Manganese, dissolved	10	69	180	1-590	8	1
Aluminum, dissolved	10	10	5	<10-20	10	10
Selenium, dissolved[1]	10	--	--	--	--	1
Mercury, dissolved	10	.1	.1	<.1-0.2	.1	.1

Table 7.--*Statistical summary of water-quality data by land-use and aquifer-type group*

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

	Temperature (degrees Celsius)	Specific conductance (µS/cm)	pH (standard units)	Alkalinity, field, (mg/L as $CaCO_2$)	Bicarbonate, field, (mg/L as HCO_3)	Nitrogen, dissolved, (mg/L) as N		
						Ammonia	Ammonia plus organic	Nitrite plus nitrate
Number of samples	68	65	62	62	55	68	61	61
Mean								
Agricultural	10.0	381	--	210	260	.02	.37	1.8
Commercial	10.9	718	--	290	360	1.0	2.0	1.2
Confined aquifer	10.7	549	--	330	410	.25	.54	6.1
Forested	9.6	431	--	250	330	.03	.45	.10
Residential	11.5	561	--	230	300	.02	1.0	3.0
Median								
Agricultural	9.5	345	7.6	190	230	.02	.30	1.0
Commercial	10.0	592	7.3	270	340	.08	.70	.45
Confined aquifer	11.5	546	7.6	330	410	.16	.40	.10
Forested	9.5	420	7.4	240	310	.09	.59	.29
Residential	9.5	605	7.5	222	280	.02	.50	2.5
Standard deviation								
Agricultural	2.2	101	--	72	89	.01	.18	1.6
Commercial	2.5	397	--	110	140	2.4	3.5	1.5
Confined aquifer	2.3	146	--	97	110	.34	.38	.08
Forested	0.9	153	--	100	120	.10	.41	.30
Residential	3.8	185	--	55	69	.01	1.5	2.6
Minimum-Maximum								
Agricultural	7.5-14.0	208-555	7.3-8.1	92-310	110-380	.01-0.05	<.20-0.70	<.10-4.5
Commercial	8.0-17.0	275-1800	6.6-7.9	140-440	170-530	.02-8.5	.30-14	<.10-1.7
Confined aquifer	7.5-15.0	320-890	7.0-8.1	196-520	240-630	.01-1.2	<.20-1.5	<.10-0.30
Forested	8.0-11.	221-825	6.8-8.3	110-470	130-580	.01-.26	<.20-1.8	<.10-0.97
Residential	7.5-17.5	290-890	6.9-7.9	180-370	220-450	.01-0.04	.30-5.4	<.10-7.8

Table 7.--*Statistical summary of water-quality data by land-use and aquifer-type group*--Continued

	Phosphorus, dissolved, (mg/L as P)	Phosphorus, ortho, dissolved, (mg/L as P)	Calcium, dissolved, (mg/L as Ca)	Magnesium, dissolved, (mg/L as Mg)	Sodium, dissolved, (mg/L as Na)	Potassium, dissolved, (mg/L as K)
Number of samples	64	68	67	67	67	68
Mean						
Agricultural	.03	.02	62	16	3.6	1.64
Commercial	.08	.06	94	21	34	4.59
Confined aquifer	.02	.02	72	24	23	2.43
Forested	.02	.01	71	18	2.8	1.51
Residential	.10	.09	80	16	18	12.97
Median						
Agricultural	.03	.02	57	14	2.7	1.30
Commercial	.02	.01	90	18	19	1.80
Confined aquifer	.01	.01	74	24	5.6	2.40
Forested	.03	.02	70	19	3.2	1.30
Residential	.06	.05	78	16	17	1.40
Standard deviation						
Agricultural	.02	.02	20	4.77	2.7	1.15
Commercial	.19	.18	40	13.28	59	9.14
Confined aquifer	.03	.02	29	13.80	51	1.40
Forested	.02	.02	20	10.51	2.2	0.77
Residential	.13	.12	5.1	3.71	12	1.10
Minimum-Maximum						
Agricultural	<.01-0.07	<.01-.06	31-99	9.30-23.00	1.4-12	0.40-4.70
Commercial	<.01-0.69	<.01-.69	43-190	9.80-64.00	1.9-230	0.60-36.00
Confined aquifer	<.01-0.13	<.01-.11	.5-130	0.11-60.00	1.4-220	0.30-5.70
Forested	<.01-0.08	<.01-.06	33-110	4.50-43.00	1.1-10.	0.60-3.20
Residential	<.01-0.40	<.01-.40	55-130	11.00-23.00	2.3-41	0.70-4.30

Table 7.--***Statistical summary of water-quality data by land-use and aquifer-type group***--Continued

	Chloride, dissolved, (mg/L as Cl)	Sulfate, dissolved, (mg/L as SO_4)	Flouride, dissolved, (mg/L as F)	Silica, dissolved, (mg/L as SiO_2)	Phenols, total, (μg/L)	Solids, dissolved, residual at 180 degrees Celsius (mg/L)	Organic Carbon, total (mg/L as C)
Number of samples	68	68	61	63	62	61	60
Mean							
Agricultural	3.6	6.9	.1	19	2	240	6.3
Commercial	50	12	.2	26	2	437	12
Confined aquifer	1.32	14	.2	23	2	347	2.4
Forested	6.7	8.5	.1	17	4	280	7.4
Residential	40	13	.1	22	4	343	6.9
Median							
Agricultural	2.8	6.2	.1	19	2	208	6.2
Commercial	25	14	.1	23	1	366	9.4
Confined aquifer	0.6	6.4	.2	23	1	325	1.9
Forested	1.4	7.8	.1	20	2	272	11
Residential	34	12	.1	22	2	357	5.7
Standard deviation							
Agricultural	3.7	2.5	.0	5.0	1	66	3.0
Commercial	95	6.8	.1	8.2	2	232	0
Confined aquifer	1.7	22	.2	3.4	1	100	1.9
Forested	19	3.2	.0	5.8	11	93	2
Residential	33	4.5	.0	4.9	6	104	5.1
Minimum-Maximum							
Agricultural	.5-15	3.6-12	<.1-0.1	11-27	<1-4	147-374	2.5-10
Commercial	.60-380	2.1-25	<.1-0.3	17-43	<1-8	174-1020	4.3-44
Confined aquifer	.30-6.4	.9-88	<.1-1.2	18-29	<1-3	227-583	.5-6.1
Forested	.60-73	4.0-14	<.1-0.2	1.9-23	<1-40	129-454	2.4-4.8
Residential	6.5- 93	8.2-21	<.1-0.2	16-29	<1-20	218-508	<.1-19

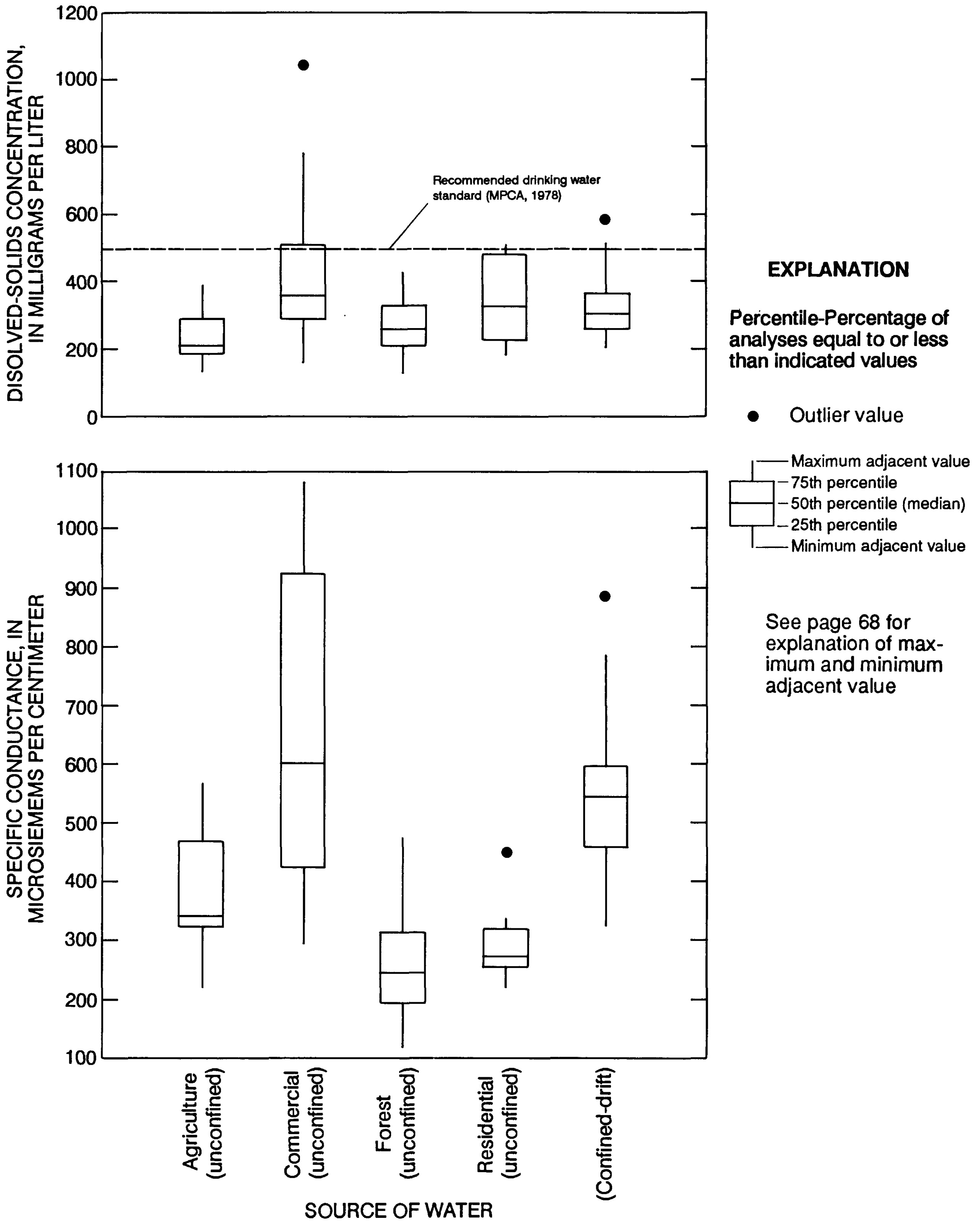


Figure 24.--Concentrations of dissolved solids and specific conductance in ground water from uppermost confined-drift aquifer and from various land-use areas in unconfined-drift aquifer

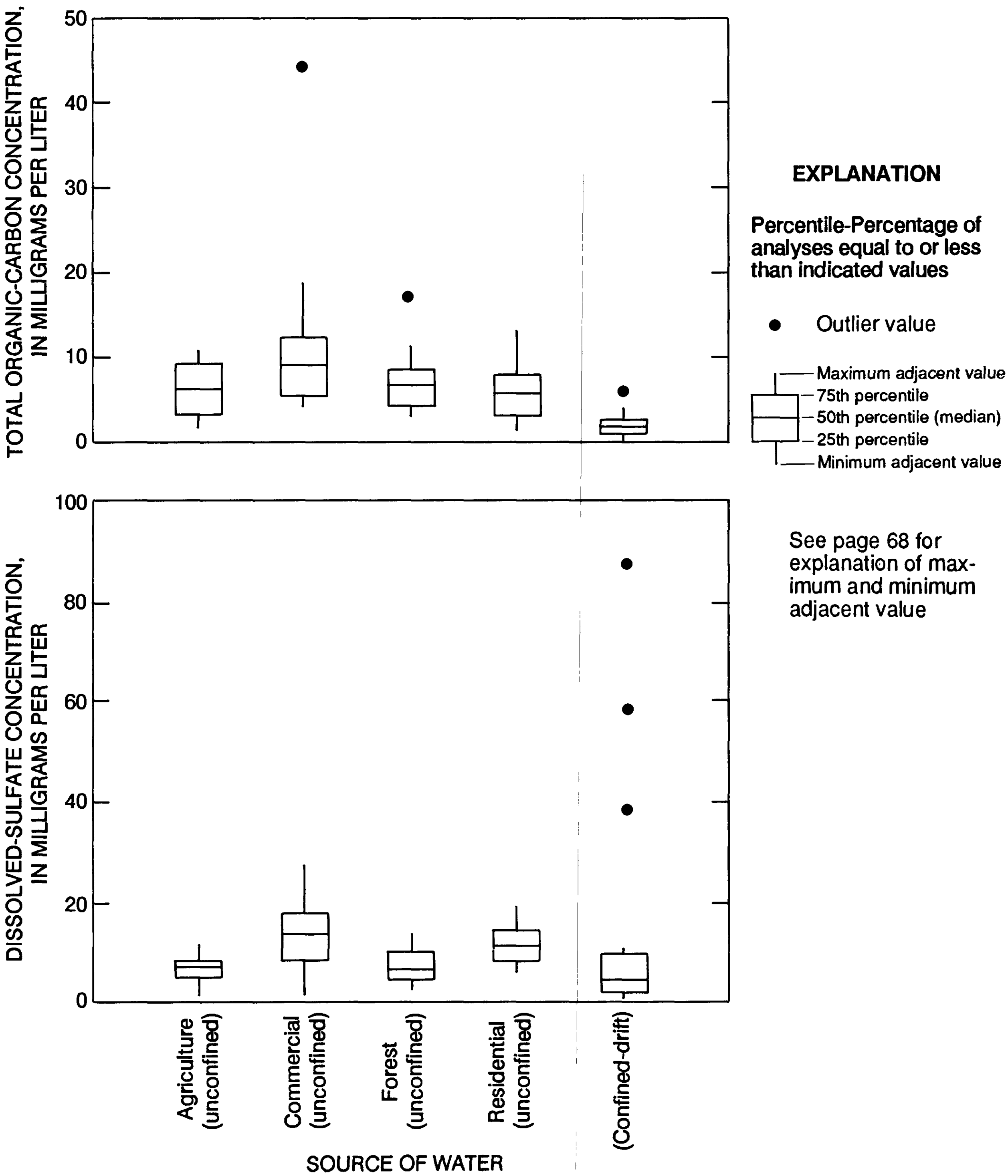


Figure 25.--Concentrations of total organic carbon and dissolved sulfate in ground water from uppermost confined-drift aquifer and from various land-use areas in unconfined-drift aquifer

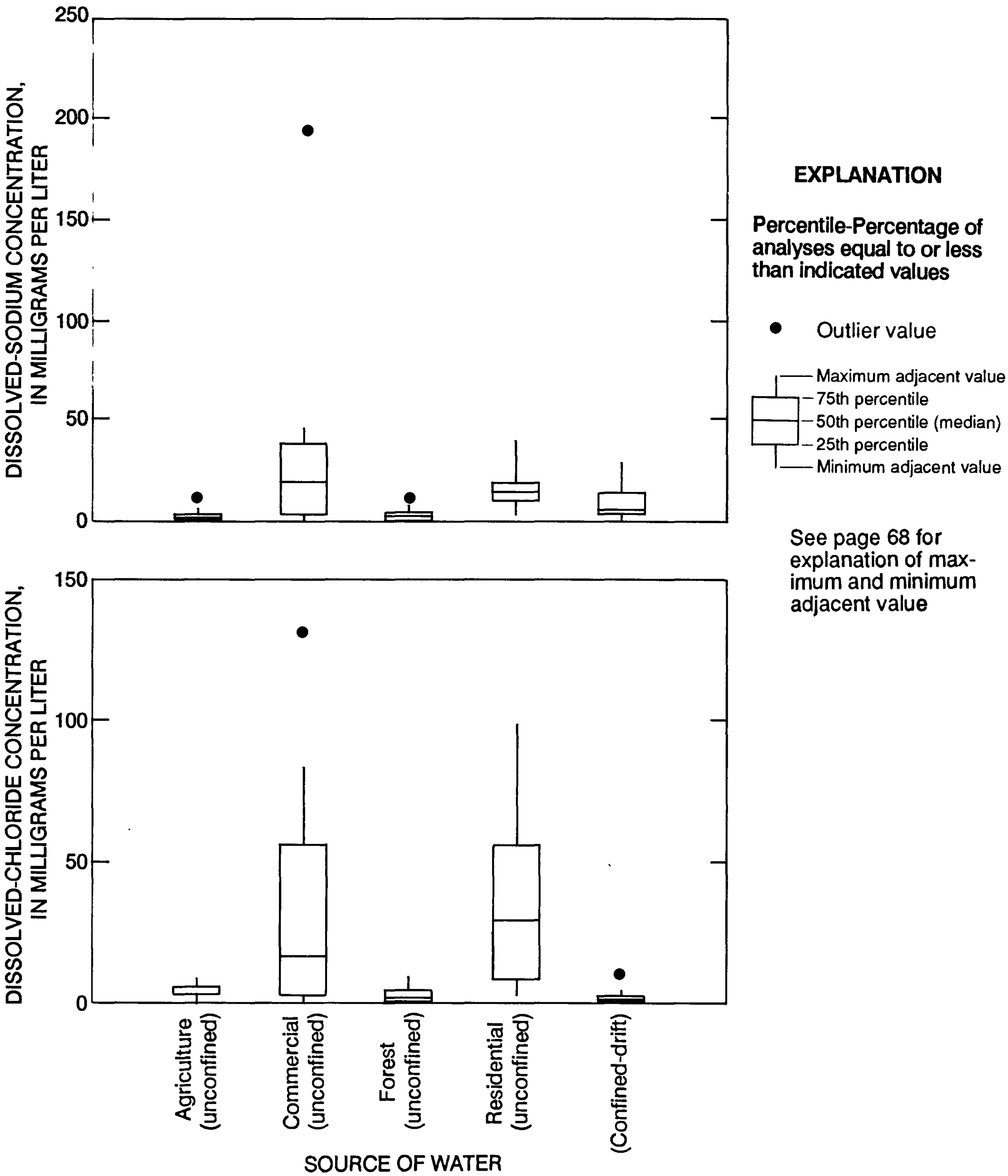


Figure 26.--Concentrations of dissolved chloride and dissolved sodium in ground water from uppermost confined-drift aquifer and from various land-use areas in unconfined-drift aquifer

Trilinear diagrams of common cations and anions for waters from the unconfined-drift aquifers from each land-use type group further illustrate this relationship (fig. 27). The relative scatter in these plots indicates greater variability in common-ion concentrations in water from wells completed in commercial and residential land-use type groups than in water from wells completed in agricultural and forest land-use type groups. This suggests that a land-use impact may exist. Land-use activities in the areas of more intensely-used land use (residential and commercial land-use type areas) appear to result in greater variability in the concentrations of common cations and common anions than in areas of less intensely used land use (agricultural and forest land-use type groups).

The null hypothesis that no differences exist in ground-water quality among water from wells completed in different land-use type groups from the unconfined-drift aquifer was tested with a non-parametric statistical technique (Kruskal-Wallis test) (Walpole and Meyers, 1978). The test is a generalization of the Wilcoxon two-sample test extended to the case of more than two samples. It was used to test the null hypothesis that independent samples are from identical populations. The test is a nonparametric procedure for testing the equality of medians when the assumption that the samples are selected from normally-distributed populations may not be valid. The method involves converting observations for a particular parameter, chloride concentration for example, from all land-use categories to rank and summing the ranks for each parameter for each land-use type group.

The computed statistic becomes, and is computed as:

$$h = \frac{12}{n(n+1)} \left[\sum_{i=1}^{k} \frac{r_i^2}{n_i} \right] - 3(n+1) \qquad (3)$$

where:

n = total number of observations in all samples,

n_i $(i = 1,2,\ldots.k)$ = the number of observations in the i^{th} sample,

r_i = sum of ranks for the i^{th} sample, and

h = test statistic.

The h statistic has approximately a Chi-square distribution with k-1 degrees of freedom, when each sample contains at least 5 observations. If h falls in the critical region $h > \chi^2_\alpha$ with k-1 degrees of freedom and significance level, α, the null hypothesis (that samples are from identical populations) is rejected at that particular level of significance. Otherwise, the hypothesis is accepted.

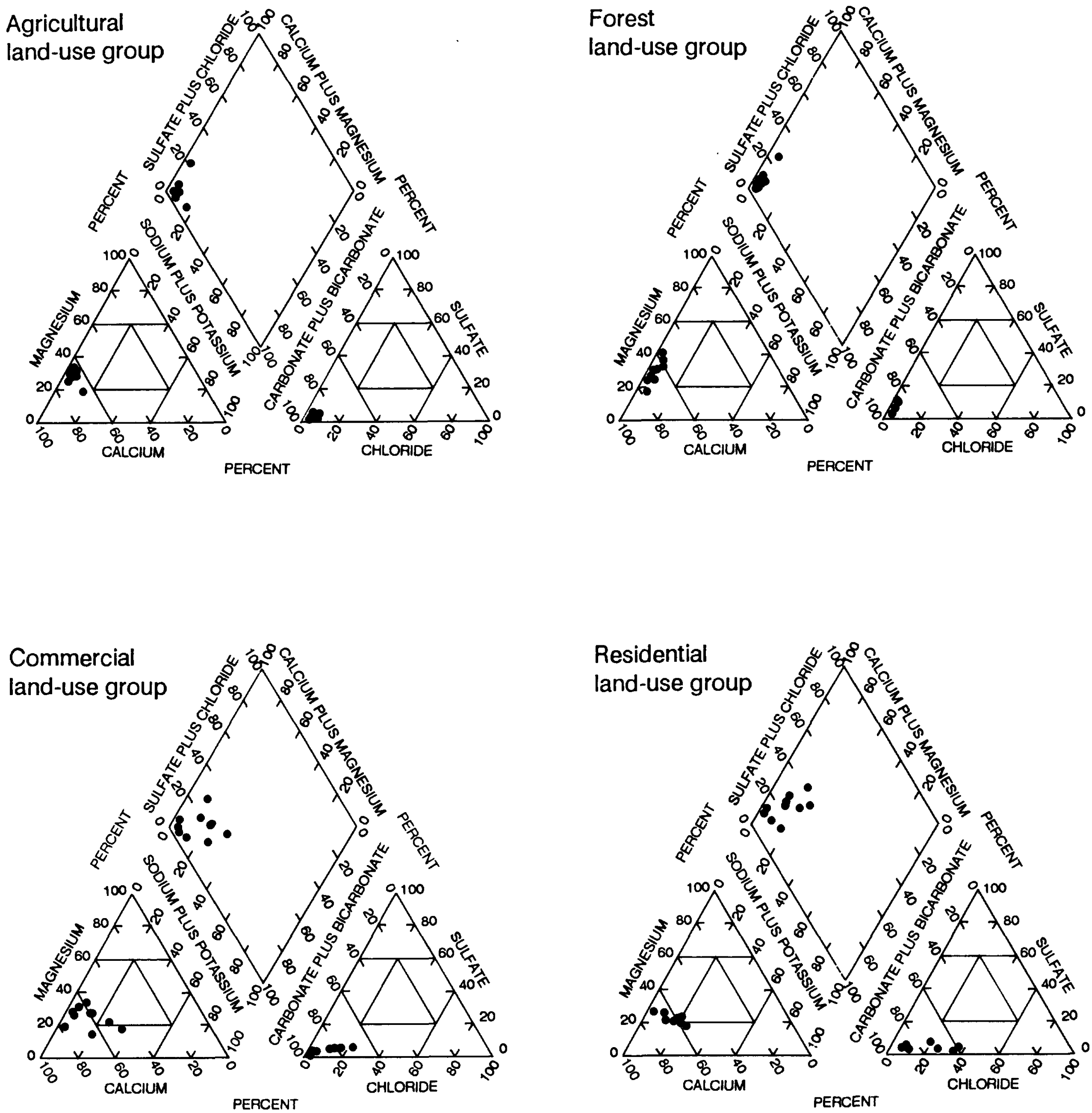


Figure 27.--Chemical characteristics of water in unconfined-drift aquifers from various land-use areas

The Kruskal-Wallis test was used to test the assumption that analyses sampled in common in all land-use type groups from the unconfined-drift aquifer were from the same population. After calculation of the h statistic for all parameters, χ^2_α value of 7.81 was determined from published tables using a 0.05 level of significance with three degrees of freedom. Using this value to define a critical region, evidence to reject the hypothesis that all analyses are from the sample population was available. The results, shown in table 8, suggest that, for 12 of the 21 constituents sampled in common among all land-use type groups, the hypothesis that samples were from identical populations could be rejected (table 8). These statistical data are further evidence that land use influences ground-water quality in the unconfined-drift aquifer. Although this statistical technique does not identify the particular land-use type group or groups that are statistically different, evaluation of the tabular data shown in table 8 and figures 24-27 suggest that the differences exist between commercial residential and forest agricultural land-use type areas. Water from the unconfined-drift aquifer in areas of commercial and industrial land use tend to have elevated concentrations of many constituents relative to those concentrations in areas of agricultural and forested land use.

Isotope Analyses for Identification of Nitrogen Sources in Ground Water

Variations in naturally-occurring nitrogen-isotope ratios were determined for samples from four wells in an attempt to identify the source of nitrogen in ground water from wells completed in the unconfined-drift aquifer in each of the four land-use type groups. This work was conducted as part of a larger study to identify the sources of nitrogen in ground water in Minnesota (H. W. Anderson, U.S. Geological Survey, St. Paul, Minn., written commun., 1987).

Variations in naturally occurring nitrogen-isotope ratios ($^{15}N/^{14}N$) have been used by Kohl and others (1971) to identify sources of nitrate in surface water. Kreitler and others (1978), Gormly and Spalding (1979), and Flipse and Bonner (1985) have used nitrogen-isotope ratios in studies of ground water. Nitrogen-isotope ratios are used to define delta ^{15}N values, which quantify the relative abundance of ^{15}N isotope in various compounds where:

$$\text{delta } ^{15}N = \left[\frac{^{15}N/^{14}N \text{ Sample} - {}^{15}N/^{14}N \text{ Standard}}{^{15}N/^{14}N \text{ Standard}}\right] 1000 \qquad (2)$$

The $^{15}N/^{14}N$ isotope ratio used as a standard is that of nitrogen in air. The delta ^{15}N values are calculated based on equation (2) and expressed in parts per thousand.

Table 8.--*Kruskal-Wallis test (0.05 level of significance) of hypothesis that water-quality samples for four different land-use types were from identical populations*

[Null hypothesis is that no differences exist in ground-water quality among waters from wells completed in different land-use type groups in the unconfined-drift aquifer. mg/L, milligrams per liter; μg/L, micrograms per liter; μS/cm, microsiemens per centimeter at 25 degrees Celsius; field, value determined at sampling site; lab, value determined in a laboratory]

Constituent	Number of wells analyzed	Kruskal-Wallis H statistic	Test of null hypothesis
Temperature, water	49	4.5	accept
Specific conductance	47	17	reject
pH, field	49	0.30	accept
Alkalinity, total, field	37	7.0	accept
Bicarbonate, field	35	6.1	accept
Nitrogen, ammonia, dissolved	49	20	reject
Nitrogen, ammonia plus organic, dissolved	49	17	reject
Nitrogen, nitrite plus nitrate dissolved	42	19	reject
Phosphorous, dissolved,	47	9.9	reject
Phosphorous, ortho, dissolved	49	15	reject
Calcium, dissolved	48	12	reject
Magnesium, dissolved	48	5.3	accept
Sodium, dissolved	48	20	reject
Potassium, dissolved	48	6.7	accept
Chloride, dissolved	49	25	reject
Sulfate, dissolved	49	18	reject
Fluoride, dissolved	48	6.1	accept
Silica, dissolved	48	12	reject
Phenols, total	46	5.2	accept
Solids, dissolved, residue at 180 degrees Celsius	49	16	reject
Carbon, organic,	49	7	accept

Anderson (U.S. Geological Survey, St. Paul, Minn., written commun., 1987) has compiled published data related to delta ^{15}N for ground water from several land-use types. These data indicate that delta ^{15}N values less than +4.0 parts per thousand indicate a predominance of nitrate from a commercial fertilizer source, while values greater than +9.0 parts per thousand indicate a source from human or animal waste. Delta ^{15}N values between 4.0 and 9.0 may represent a mixing of effects from the two main sources.

Ground water from four wells representing wells completed in the unconfined-drift aquifer under each of four land-use type groups (agricultural, commercial, forest, and residential) were sampled. Delta ^{15}N values ranged from 0.38 to 3.88, suggesting that commercial fertilizer is a primary source of nitrogen in water from all four land-use types.

Seasonally Variability in Ground-Water Quality

One well from each land-use and aquifer-type group was sampled during each of the four seasons in 1987-88 to examine the effect of seasonal changes on concentrations of chemical constituents (table 9). Few easily identifiable trends are present in these data. The values of pH appear to be lowest in the late summer and fall. Seasonal changes in concentrations of chemical constituents are assumed to be minimal.

Quality-Control

Several quality-control measures were used to test for variability introduced into the water-quality results by sampling, shipment, and analysis. Duplicate sampling of waters from one well in each of the land-use and aquifer-type groups (table 10) demonstrated that the results of nearly all parameters were reproduced within 10 percent. TOC (total organic carbon) and phosphorus were the principal exceptions.

For most samples, the cation-anion balances agreed within 5 percent. These quality-control results indicate that sampling and analytical techniques were effective for obtaining precise and accurate results for all parameters except total organic carbon.

Table 9.--*Seasonal water-quality data for selected wells*

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

Station number, Location, and Local name	Date	Temperature, water, degrees Celsius	Specific conductance (µS/cm)	pH (standard units)	Alkalinity, total, FET, field (mg/L as $CaCO_3$)	Alkalinity, total, IT, field (mg/L as $CaCO_3$)
472300094231800	10-14-87	9.5	390	7.7	220	220
145.29.8	01-15-88	8.0	275	8.3	148	--
NAT. FOR. E.,NO. 1	04-05-88	--	--	--	--	--
472409094592200	09-03-87	8.5	374	7.4	206	210
145.34.3 CBB	10-19-87	7.5	373	7.8	212	212
COLEMANN	01-18-88	--	380	7.8	212	--
	04-06-88	--	--	--	--	--
472652094532000	08-25-87	8.0	290	7.7	182	182
146.33.20 ADC	10-14-87	9.0	358	7.9	184	184
SLINEY	01-18-88	8.0	388	7.8	202	--
	04-06-88	--	--	--	--	--
472907095084100	08-29-87	8.5	312	7.8	--	--
146.33.20 DDC	10-13-87	--	307	8.0	--	151
LUNDBERG	01-15-88	8.0	295	8.3	148	--
	04-06-88	--	--	--	--	--
472925094525200	07-30-87	9.4	593	7.7	248	--
146.34.4 BDB	10-16-87	8.5	694	7.1	278	278
DNR IN TOWN	01-20-88	--	590	--	--	--
	04-05-88	--	--	--	--	--

Station number	Date	Nitrogen, dissolved, (mg/L) as N: Ammonia	Ammonia plus organic	Nitrite plus nitrate	Phosphorous, dissolved (mg/L as P)	Phosphorous, ortho, dissolved (mg/L as P)	Carbon, organic, total (mg/L as C)	Calcium, dissolved (mg/L as Ca)
472300094231800	10-14-87	0.02	<0.20	0.67	--	0.04	--	68.00
	01-15-88	.04	.40	.25	--	.00	--	74.00
	04-05-88	.02	.20	.30	--	.03	--	61.00
472409094592200	09-03-87	<.01	<.20	.30	0.04	.03	0.7	60.00
	10-19-87	.02	.30	.34	.04	.01	--	61.00
	01-18-88	.01	.20	.32	--	.03	--	60.00
	04-06-88	.01	<.20	.32	.04	.03	--	61.00
472652094532000	08-25-87	.01	.30	1.20	.07	.05	4.9	58.00
	10-14-87	.01	<.20	1.30	--	.06	--	59.00
	01-18-88	.02	<.20	1.80	--	.06	--	65.00
	04-06-88	.05	.40	2.40	--	.04	--	66.00
472907095084100	08-29-87	<.01	.30	4.50	.03	.02	5.9	46.00
	10-13-88	.02	.20	4.20	--	.02	--	43.00
	01-15-88	--	--	3.50	--	--	--	34.00
	04-06-88	.11	.60	4.30	--	.02	--	45.00
472925094525200	07-30-87	.40	.70	--	<.01	<.001	4.3	--
	10-16-87	--	.60	--	--	.01	--	98.00
	01-20-88	.03	.30	4.70	--	<.001	--	82.00
	04-05-88	.13	.70	4.10	<.005	.001	--	66.00

Station name	Date	Magnesium, dissolved (mg/L as Mg)	Sodium, dissolved (mg/L as Na)	Potassium, dissolved (mg/L as K)	Chloride, dissolved (mg/L as CL)	Sulfate, dissolved (mg/L as SO4)	Solids, dissolved, residue at 180 degrees Celsius, (mg/L)
472300094231800	10-14-87	14	2.4	0.8	1.0	7.6	241.0
	01-15-88	15	2.8	1.0	2.7	13	246.0
	04-05-88	13	2.2	.7	1.1	9.1	222.0
472409094592200	09-03-87	16	2.3	1.0	0.6	11	233.0
	10-19-87	15	--	1.0	.9	8.0	229.0
	1-18-88	16	1.9	.9	.6	8.6	226.0
	04-06-88	16	--	.9	.7	8.5	220.0
472652094532000	08-25-87	13	2.3	1.4	6.5	8.2	218.0
	10-14-87	13	1.9	1.6	10	8.4	224.0
	01-18-88	14	1.9	1.3	9.1	8.5	252.0
	04-06-88	15	2.1	1.7	9.1	9.3	250.0
472907095084100	08-29-87	14	2.1	1.0	3.2	6.1	200.0
	10-13-87	13	2.6	1.4	4.5	6.1	183.0
	01-15-88	14	2.7	--	--	--	193.0
	04-06-88	13	2.9	1.5	3.9	14	195.0
472925094525200	07-30-87	--	--	--	40	14	438.0
	10-16-87	27	19	2.1	61	22	355.0
	01-20-88	22	19	1.8	30	15	366.0
	04-05-88	20	14	1.8	18	13	314.0

Table 10.--*Results of chemical analyses of duplicate samples for quality assurance and quality control*

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

Sample number	Station number	Date	Time	Location township, range, section	Temperature, water degrees Celsius	Temperature, air degrees Celsius	Pressure (mm of Hg)
1	473044095043500	08-04-87	1800	147.35.36 BBC	9.5	23	--
2	473044095043501	08-04-87	1800	147.35.36 BBC	10.0	23	--
3	472729094505500	08-13-87	1030	146.33.15 DBD	8.5	25	745
4	472720904505501	08-13-87	1030	146.33.15 DBD	8.5	25	745
5	471546094331700	08-17-87	1500	144.31.25 BBC	9.5	23	740
6	471546094331701	08-17-87	1500	144.31.25 BBC	9.5	23	740
7	471222094445800	09-03-87	1200	143.32.17 AAA	12.5	20	--
8	471222094445801	09-03-87	1200	143.32.17 AAA	12.5	20	--
9	473423095241800	07-31-87	1200	147.37.06 AAA	13.0	30	740
10	473423095241801	07-31-87	1200	147.37.06 AAA	12.0	31	740

Table 10.--*Results of chemical analyses of duplicate samples for quality assurance and quality control*--Continued

Sample number	Specific conductance (µS/cm)	pH (standard units)	pH, lab (standard units)	Alkalinity, total, field (mg/L as CaCO3)	Alkalinity, carbonate IT, field (mg/L CaCO3)	Bicarbonate, IT, field (mg/L)	Nitrogen, ammonia dissolved (mg/L as N)	Nitrogen, ammonia plus organic dissolved (mg/L as N)	Nitrogen, nitrite plus nitrate dissolved (mg/L as N)
1	697	7.0	7.5	435	437	533	0.18	0.6	<0.10
2	697	7.0	--	435	437	533	.19	1.2	<.10
3	467	7.8	7.8	214	216	264	<.01	.6	4.50
4	467	7.8	7.8	214	216	264	<.01	1.0	4.70
5	260	7.3	7.5	108	108	132	.01	.7	<.10
6	260	7.5	7.5	108	--	132	.01	.7	<.10
7	555	7.5	7.6	--	344	419	.08	<.2	<.10
8	555	7.5	7.6	--	344	--	.08	<.2	<.10
9	380	7.4	7.9	270	--	--	<.01	.4	--
10	420	--	7.8	229	--	--	.03	.7	--

Sample number	Phosphorus, dissolved (mg/L as P)	Phorphorus, ortho, dissolved (mg/L as P)	Carbon, organic, total (mg/L as C)	Calcium, dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as Mg)	Sodium, dissolved (mg/L as Na)	Potassium, dissolved (mg/L as K)	Chloride, dissolved (mg/L as Cl)	Sulfate, dissolved (mg/L as SO_4)
1	0.01	<.001	9.4	100	25	22	1.6	6.8	12
2	.02	<.001	17	100	25	22	1.6	7.2	13
3	.08	.08	5.9	69	16	9.7	1.0	8.1	11
4	.08	.08	3.9	71	16	9.2	1.0	7.7	12
5	.02	.02	3.9	41	4.5	2.9	1.8	0.6	12
6	.02	.02	6.7	41	4.5	2.9	1.9	0.9	11
7	<.005	.00	1.0	88	27	7.1	1.9	0.4	40
8	<.005	.00	0.7	88	27	7.1	1.8	0.4	3.9
9	.05	.03	--	63	16	3.5	3.7	0.5	4.0
10	.50	.50	--	63	16	3.4	4.2	0.7	3.8

Table 10.--*Results of chemical analyses of duplicate samples for quality assurance and quality control*--Continued

Sample number	Fluoride, dissolved (mg/L as F)	Silica, dissolved (mg/L as SiO_2)	Arsenic, dissolved (µg/L as As)	Barium, dissolved (µg/L as Ba)	Boron, dissolved (µg/L as B)	Cadmium, dissolved (µg/L as Cd)	Chromium, dissolved (µg/L as Cr)	Iron, dissolved (µg/L as Fe)	Lead, dissolved (µg/L as Pb)
1	0.2	24	7	140	70	<1	310	3600	<5
2	.1	24	6	130	80	<1	10	4000	<5
3	.1	23	2	57	80	<1	10	5	<5
4	.1	22	2	53	80	<1	<10	5	<5
5	.1	1.9	--	--	--	--	--	--	--
6	.1	1.9	--	--	--	--	--	--	--
7	.2	19	--	--	--	--	--	--	--
8	.2	19	--	--	--	--	--	--	--
9	.1	20	1	--	--	--	--	33	<10
10	.1	26	1	--	--	--	--	7	<10

Sample number	Manganese, dissolved (µg/L as Mn)	Aluminum, dissolved (µg/L as Al)	Selenium, dissolved (µg/L as Se)	Dichloro-bromo-methane, total (µg/L)	Carbon tetra-chloride, total (µg/L)	1,2-Dichloro-ethane, total (µg/L)	Bromoform, total (µg/L)	Chloro-dibromo-methane, total (µg/L)	Chloroform, total (µg/L)	Phenols, total (µg/L)
1	670	20	2	<3.0	<3.0	<3.0	<3.0	<3.0	<3.0	<1
2	670	40	1	<3.0	<3.0	<3.0	<3.0	<3.0	<3.0	<1
3	2	<10	<1	<3	--	--	--	--	--	<1
4	1	<10	6	<3	--	--	--	--	--	<1
5	--	--	--	--	--	--	--	--	--	1
6	--	--	--	--	--	--	--	--	--	5
7	--	--	--	--	--	--	--	--	--	3
8	--	--	--	--	--	--	--	--	--	3
9	--	--	--	--	--	--	--	--	--	--
10	--	--	--	--	--	--	--	--	--	--

Table 10.--*Results of chemical analyses of duplicate samples for quality assurance and quality control*--Continued

Sample number	Toluene, total (µg/L)	Benzene, total (µg/L)	Chloro-benzene, total (µg/L)	Chloro-ethane, total (µg/L)	Ethyl-benzene, total (µg/L)	Methyl-bromide, total (µg/L)	Methyl-chloride, total (µg/L)	Methylene-chloride, total (µg/L)	Tetrachloro-ethylene, total (µg/L)	Trichloro-fluoro-methane, total (µg/L)	1,1-Dichloro-ethane, total (µg/L)
1	<3.0	<3.0	<3.0	<3.0	<3.0	<3.0	<3.0	<3.0	<3.0	<3.0	<3.0
2	<3.0	<3.0	<3.0	<3.0	<3.0	<3.0	<3.0	<3.0	<3.0	<3.0	<3.0
3	--	--	--	--	--	--	--	--	--	--	--
4	--	--	--	--	--	--	--	--	--	--	--
5	--	--	--	--	--	--	--	--	--	--	--
6	--	--	--	--	--	--	--	--	--	--	--
7	--	--	--	--	--	--	--	--	--	--	--
8	--	--	--	--	--	--	--	--	--	--	--
9	--	--	--	--	--	--	--	--	--	--	--
10	--	--	--	--	--	--	--	--	--	--	--

Sample number	1,1-Dichloro-ethylene, total (µg/L)	1,1,1-Tri-chloro-ethane, total (µg/L)	1,1,2-Tri-chloro-ethane, total (µg/L)	1,1,2,2-Tetra-chloro-ethane, total (µg/L)	1,2-Dichloro-benzene, total (µg/L)	1,2-Dichloro-propane, total (µg/L)	1,2-Transdi-chloro-ethylene, total (µg/L)	1,3-Dichloro-propane, total (µg/L)	1,3-Dichloro-benzene, total (µg/L)
1	<3.0	<3.0	<3.0	<3.0	<3.0	<3.0	<3.0	<3.0	<3.0
2	<3.0	<3.0	<3.0	<3.0	<3.0	<3.0	<3.0	<3.0	<3.0
3	--	--	--	--	--	--	--	--	--
4	--	--	--	--	--	--	--	--	--
5	--	--	--	--	--	--	--	--	--
6	--	--	--	--	--	--	--	--	--
7	--	--	--	--	--	--	--	--	--
8	--	--	--	--	--	--	--	--	--
9	--	--	--	--	--	--	--	--	--
10	--	--	--	--	--	--	--	--	--

Table 10.--*Results of chemical analyses of duplicate samples for quality assurance and quality control*--Continued

Sample number	1,4-Dichloro-benzene, total (µg/L)	2-Chloro-ethylvinyl-ether, total (µg/L)	Dichloro-defluoro-methane, total (µg/L)	Trans-1,3-dichloro-propene, total (µg/L)	Cis-1,3-dichloro-propene, total (µg/L)	1,2-Dibromo-ethylene, total (µg/L)	Vinyl chloride, total (µg/L)	Trichloro-ethylene, total (µg/L)	Solids, dissolved, residue at 180 degrees Celsius, (mg/L)	Mercury, dissolved (µg/L as Hg)
1	<3.0	<3.0	<3.0	<3.0	<3.0	<3.0	<3.0	<3.0	420	0.1
2	<3.0	<3.0	<3.0	<3.0	<3.0	<3.0	<3.0	<3.0	411	.1
3	--	--	--	--	--	--	--	--	281	.2
4	--	--	--	--	--	--	--	--	274	.1
5	--	--	--	--	--	--	--	--	153	--
6	--	--	--	--	--	--	--	--	159	--
7	--	--	--	--	--	--	--	--	342	--
8	--	--	--	--	--	--	--	--	343	--
9	--	--	--	--	--	--	--	--	--	--
10	--	--	--	--	--	--	--	--	--	--

Sample number	Styrene, total (µg/L)	Xylene, total recoverable (µg/L)	Specific conductance, lab (µS/Cm)	Alkalinity, lab (mg/L as CaCO3)	Propazine, (µg/L)	Trifluralin, total (µg/L)	Simetryne, total (µg/L)	Simazine, total (µg/L)
1	<3.0	<3.0	707	386	--	--	--	--
2	<3.0	<3.0	708	387	--	--	--	--
3	--	--	479	217	--	--	--	--
4	--	--	479	217	--	--	--	--
5	--	--	253	118	--	--	--	--
6	--	--	254	117	--	--	--	--
7	--	--	625	217	<.10	<.10	<.1	<.10
8	--	--	623	189	<.10	<.10	<.1	<.10
9	--	--	--	--	--	--	--	--
10	--	--	--	--	--	--	--	--

Table 10.--*Results of chemical analyses of duplicate samples for quality assurance and quality control*--Continued

Sample number	Prometone, total (μg/L)	Prometyrne, total (μg/L)	Atrazine, total (μg/L)	Alachlor, total recoverable (μg/L)	Cyanzine, total (μg/L)	Ametryne, total (μg/L)	Metribuzin, total recoverable (μg/L)	Metolachlor, total recoverable (μg/L)
1	--	--	--	--	--	--	--	--
2	--	--	--	--	--	--	--	--
3	--	--	--	--	--	--	--	--
4	--	--	--	--	--	--	--	--
5	--	--	--	--	--	--	--	--
6	--	--	--	--	--	--	--	--
7	<.1	<.1	<.10	<.10	<.10	<.10	<.10	<.10
8	<.1	<.1	<.10	<.10	<.10	<.10	<.10	<.10
9	--	--	--	--	--	--	--	--
10	--	--	--	--	--	--	--	--

SUMMARY AND CONCLUSIONS

Unconfined and shallow, confined-drift aquifers are the primary aquifers providing water to wells in a 1,600 mi^2 area that includes parts of Beltrami, Cass, Clearwater, and Hubbard Counties, Minnesota. The unconfined-drift aquifer consists of coarse sand and gravel in the north and fine sand and gravel deposits to the south. The aquifer is present near the Mississippi and Clearwater Rivers in the central part of the study area, where it underlies an area of approximately 550 mi^2. The saturated thickness of the aquifer ranges from 0 to 130 feet, and is greater than 20 ft thick over approximately 280 mi^2. Except in the Bemidji and Cass Lake areas, the aquifer is not used extensively as a source of water to wells. On the basis of estimates of horizontal hydraulic conductivity derived from specific capacity information, the transmissivity of the aquifer ranges from less than 70 ft^2/d in the south and west parts of the aquifer to greater than 8,900 ft^2/d in the area west of Bemidji. Well yields of as great as several hundred gallons per minute are possible in some areas. The scant thickness of the aquifer over most of the area limits the potential productivity of the aquifer as a potential source of ground water to wells.

The general direction of ground-water flow in the unconfined-drift aquifer is similar to the general direction of surface-water drainage, toward the Mississippi and Clearwater Rivers. These rivers are major discharge points for both the uppermost confined-drift and the unconfined-drift aquifers in the study area. Locally, flow in the unconfined-drift aquifer is toward numerous small streams, wetlands, and lakes, and may differ significantly from the regional direction of ground-water flow. The unconfined and confined-drift aquifers are separated by a fine-grained confining unit consisting of either till or lake deposits. This confining unit hydraulically separates the two aquifers. The top of the unit slopes gently to the east at about 10 ft/mi. The confining unit ranges from 1 to 340 ft in thickness.

The uppermost confined-drift aquifer is the primary source of ground water to wells in the Bemidji-Bagley area. The altitude of the top of the uppermost confined-drift aquifer ranges from about 1,350 ft above sea level in the Bagley area to about 1,250 ft in the Bemidji and Cass Lake areas. The thickness of the aquifer ranges from 0 to as much as 60 ft in the Bemidji area. On the basis of hydraulic-conductivity and thickness data and results from ground-water-flow model simulations, the transmissivity of the aquifer ranges from less than 100 ft^2/d in the southern and western parts of the aquifer to greater than 12,800 ft^2/d in the central portion of the area. Well yields of from 10 to 2,100 gal/min are possible in some areas. The thinness or absence of the aquifer over parts of the area limits the potential productivity of the aquifer as a source of ground water to wells.

On a regional scale, the direction of ground-water flow in the confined-drift aquifer is toward the Mississippi and Clearwater Rivers, the major discharge points for the aquifer in the study area. Ground-water divides are approximately coincidental with surface-water divides between the river systems.

Recharge to the ground-water system is predominantly from precipitation. Recharge is greatest in areas where the unconfined-drift aquifer is present. Recharge is usually greatest in the spring because of snowmelt, rain, and low rates of evapotranspiration. Assuming a specific yield of 0.2, areal discharge is estimated to be 4 to 8 in/yr in the sand-plain area.

Water samples were collected from observation wells completed in the unconfined-drift aquifer and from domestic-supply wells completed in the confined-drift aquifer throughout the study area to determine general ground-water quality, to test the assumption that ground-water quality is affected by land-use practices, to determine seasonal changes in water quality, and to provide baseline hydrologic and water-quality data for use in future assessments of long-term trends.

Waters from both the unconfined-drift and uppermost confined-drift aquifers in the Bemidji-Bagley area are very hard, averaging 267 and 309 milligrams per liter (mg/L) of $CaCO_3$, respectively. Calcium and bicarbonate are the predominant ions in ground water from both the unconfined-drift and uppermost confined- drift aquifers. Waters from both aquifers generally are suitable for domestic consumption, crop irrigation, and most other uses. Concentrations of ammonia, boron, chromium, iron, manganese, phenols and atrazine locally exceed recommended limits of the MPCA (1988) for domestic consumption. Dissolved solids locally exceed the MPCA (1988) recommended limit for agricultural and wildlife use.

Subtle differences characterize the chemistry of waters from the two aquifers. Waters from the unconfined-drift aquifer tend to group less closely than waters from the confined-drift aquifer on trilinear diagrams. This indicates that in some locations waters from the unconfined-drift aquifer are affected by outside factors such as influences from various land uses. Waters from the confined-drift aquifer generally have greater specific conductance and higher concentrations of total dissolved solids, alkalinity, magnesium, sodium, bicarbonate, potassium, silica, and fluoride than waters from the unconfined-drift aquifer. These differences may be related to the relatively long flow paths and long residence times of water in the confined-drift aquifer. The unconfined-drift aquifer generally has higher mean concentrations of dissolved ammonia plus organic nitrogen, dissolved nitrate plus nitrite, dissolved chloride, dissolved phosphorus, dissolved orthophosphorus, and dissolved phenols than the confined-drift aquifer. Elevated concentrations of these constituents may be related to land-use practices.

In addition to analyses for constituents sampled among all land-use type and aquifer-type groups, water from wells completed in the unconfined-drift aquifer in commercial, residential, and agricultural land-use groups was analyzed for individual groups of constituents whose possible occurrence might be related to land-use activities in those areas. Waters from wells in agricultural land-use areas were analyzed for arsenic and lead and for a group of common organic pesticides (triazine group). Arsenic and lead concentrations did not exceed recommended drinking-water limits of the MPCA (1978), in any waters from agricultural-area wells. One organic pesticide (atrazine at 2.9 $\mu g/L$) was identified in one well in Clearwater County.

Waters from wells in the unconfined-drift aquifer were sampled in commercial land-use areas and analyzed for heavy-metal concentrations and for a group of volatile organic compounds commonly used for commercial and industrial purposes. Several volatile-organic compounds (methylene-chloride, trichlorofluoromethane, 1,2-transdichlorethylene, and dichlorofluoromethane) were identified at low concentrations in several wells in the Bemidji area. Heavy-metal concentrations in water from wells in commercial land-use areas are generally less than recommended limits for domestic consumption and agriculture and wildlife use of the MPCA (1988), except for isolated elevated concentrations of chromium, iron, and manganese.

In residential land-use areas water from wells completed in the unconfined-drift aquifer was analyzed for heavy metals in addition to constituents sampled for in common among all groups. Except for isolated occurrences of chromium and manganese, concentrations of all metals in water from wells in this land-use type group were below concentrations acceptable for domestic consumption and for agricultural and wildlife uses as established by the MPCA (1988).

Graphical and numerical comparisons of common chemical constituents in water from wells in each land-use and aquifer-type group indicate that concentrations are generally greater in water from wells completed in commercial and residential land-use areas than in water from wells in agricultural and forested land-use areas. For example, mean values of temperature, ammonia plus organic nitrogen, phosphorus, calcium, sodium, potassium, chloride, sulfate, silica, dissolved solids, and specific conductance are generally greater for wells in commercial and residential land-use type areas than for wells in forested and agricultural land-use areas. The mean values of ammonia nitrogen, magnesium, and fluoride are generally greater for wells in commercial land-use type areas than for wells in forested and agricultural areas. The mean values of nitrogen (NO_2 +NO_3, dissolved) are generally greater for wells in residential land-use type areas that for wells in forested and agricultural land-use type areas. Box plots graphically illustrate that a relationship exists between land use and the general quality of ground water in the unconfined-drift aquifer. Trilinear diagrams of common cations and anions suggest that there is a greater variability in concentrations of these constituents in water from wells in the unconfined-drift aquifer in commercial and residential land-use areas than for wells in agricultural and forested areas.

The hypothesis that no differences exist in ground-water quality among waters from wells completed in different land-use type groups in the unconfined-drift aquifer was tested with a nonparametric technique (Kruskal-Wallis test) (Walpole and Meyers, 1978). The hypothesis could be rejected for 12 of the 21 constituents sampled among all land-use type groups.

One well from each land-use and aquifer-type group was sampled during each of four seasons in 1987-88 to examine the effect of seasonal changes on water quality. No easily identifiable trends are present in these data, and seasonal changes in concentrations of chemical constituents are assumed to be minimal.

REFERENCES CITED

Baker, D. G., and Kuenhast, E. A., 1978, Climate of Minnesota Part X, Precipitation normals for 1941-1970: Minnesota Agricultural Experimentation Station Technical Bulletin 314, 15 p.

Baker, D. G., Nelson, W. W., and Kuehnast, E. A., 1979, Climate of Minnesota Part XII, The hydrologic cycle and soil and water: Minnesota Agricultural Experimentation Station Technical Bulletin 322, 23 p.

Cleveland, W. S., 1979, Robust locally weighted regression and smoothing scatterplots: Journal of the American Statistical Assoc., 74, no. 368, p. 829-836.

Delin, G. N., 1986, Hydrogeology of confined-drift aquifers near the Pomme De Terre and Chippewa Rivers, Western Minnesota: U.S. Geological Survey Water Resources Investigation 86-4098, 90 p.

Flipse, W. J., Jr., and Bonner, F. T., 1985, Nitrogen-isotope ratios of nitrate in ground water under fertilized fields, Long Island, New York: Ground Water, v. 23, p. 59-67.

Fishman, M. J. and Friedman, L. C., 1985, Methods for determination of inorganic substances in water and fluvial sediments: U.S. Geological Survey Open-File Report 85-495, 709 p.

Freeze, R. A. and Cherry, J. A., 1979, Groundwater, Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 604 p.

Gormly, J. R. and Spalding, R. F., 1979, Sources and concentrations of nitrate-nitrogen in ground water of the Central Platte Region, Nebraska: Ground Water, v. 17, p. 291-301.

Harris, K. L., 1975, Pleistocene geology of the Grand Forks-Bemidji area, northwestern Minnesota: Ph.D. dissertation, University of North Dakota, Grand Forks, North Dakota, 142 p.

Harris, K. L., Moran, S. R., and Clayton, L., 1974, Late Quaternary stratigraphic nomenclature, Red River Valley, North Dakota and Minnesota: North Dakota Geological Survey Miscellaneous Series 52, 47 p.

Heath, R. C., 1983, Basic ground-water hydrology: U.S. Geological Survey Water-Supply Paper 2220, 84 p.

Helgesen, J. O., 1977, Ground-water appraisal of the Pineland Sands Area, Central Minnesota: U.S. Geological Survey Open-File Report 77-102, 49 p.

Hem, J. D., 1985, Study and interpretation of the chemical characteristics of natural waters: U.S. Geological Survey Water-Supply Paper 2245, 263 p.

Hobbs, H. G., and Goebel, J. E., 1982, Geologic Map of Minnesota, Quaternary Geology: Minnesota Geological Survey State Map Series S-1, 1 sheet, scale 1:500,000.

Kohl, D. H., Shearer, G. B., and Commoner, B., 1971, Fertilizer nitrogen: Contribution to nitrate in surface water in a corn belt watershed: Science, v. 174, p. 1331-1334.

Kreitler, C. W., Ragone, S. E., and Katz, B. G., 1978, $^{15}N/^{14}N$ ratios of ground-water nitrate, Long Island, New York: Ground Water, v. 16, p. 404-409.

Leverett, Frank, 1932, Quaternary geology of Minnesota and parts of adjacent states: U.S. Geological Survey Monograph 25, 658 p.

Lohman, S. W., 1972, Ground-water hydraulics: U.S. Geological Survey Professional Paper 708, 70 p.

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

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

Miller. R. T., 1982, Appraisal of the Pelican River sand-plain aquifer, western Minnesota: U.S. Geological Survey Open-File Report 82-347, 40 p.

Minnesota Department of Health and Minnesota Department of Agriculture, 1988, Pesticides and groundwater: Survey of selected Minnesota wells: Report prepared for the Legislative Commission on Minnesota Resources, February, 1988, 1988, 95 p.

Minnesota Pollution Control Agency, 1988, Minnesota code of agency rules; Standards for protection of the quality and purity of the waters of the State: Minnesota Pollution Control Agency Division of Water Quality Regulations, Minnesota Rules, chapt. 7050, 133 p.

Myette, C. F., 1984, Ground-water-quality appraisal of sand-plain aquifers in Hubbard, Morrison, Otter Tail, and Wadena Counties, Minnesota: U.S. Geological Survey Water-Resources Investigations Report 84-4080, 49 p.

Myette, C. F., 1986, Hydrogeology of sand-plain aquifers in Carlton, Kanabec, and Pine Counties, East-Central Minnesota: U.S. Geological Survey Water-Resource Investigations Report 85-4334, 66 p.

Oakes, E. L., and Bidwell, L. E., 1968, Water resources of the Upper Mississippi headwaters watershed: U.S. Geological Survey Hydrologic Investigations Atlas, HA-278, 4 sheets, scale 1:250,000.

Preusser, A., 1984, Computing contours by successive solution of quintic polynomial equations: Association for Computing Machinery on Mathematical Software, v.10, no.4, p. 463-472.

Prudic, D. E., 1982, Hydraulic conductivity of a fine-grained till, Cattaraugus County, New York: Ground Water, v. 20, no. 2, p. 194-204.

Rasmussen, W. C. and Andreasen, G. G., 1959, Hydrologic budget of the Beaver Dam Creek Basin, Maryland: U.S. Geological Survey Water Supply Paper 1472, 106 p.

Sackreiter, D. K., 1975, Quaternary geology of the southern part of the Grand Forks and Bemidji Quadrangles: University of North Dakota, Grand Forks, North Dakota, unpublished, Ph.D. dissertation, 147 p.

Schubbe, D. L., 1988, Hydrology of the Spearhead Lake Area, Hubbard County, Minnesota: South Dakota School of Mines and Technology, Rapid City, South Dakota, unpublished, MS. thesis, 76 p.

Siegel, D. I., and Winter, T. C., 1980, Hydrologic setting of Williams Lake, Hubbard County, Minnesota: U.S. Geological Survey Open-file Report 76-81, 237 p.

Sims, P. K., 1970, Geologic Map of Minnesota: Minnesota Geological Survey Miscellaneous Map Series, Map M-1, 1 sheet, scale 1:1,000,000.

U.S. Salinity Laboratory, 1954, Diagnosis and improvement of saline and alkali soils: U.S. Department of Agriculture Handbook 60, 160 p.

Walpole, R. W., and Myers, R. H., 1978, Probability and statistics for engineers and scientists, MacMillan Publishing Co., Inc., New York, 580 p.
Wershaw, R. L., Fishman, M. J., Grabbe, R. R., and Lowe, L. E., 1983, Methods for the determination of organic substances in water and fluvial sediments: U.S. Geological Survey Open-File Report 82-1004, 173 p.
Wright, H. E., Jr., 1972, Quaternary history of Minnesota: in P. K. Sims and G. B. Morey, eds., Geology of Minnesota: A Centennial Volume, Minnesota Geological Survey, p. 515-547.
Wright, H. E., Jr., 1973, Tunnel valleys, glacial surges, and subglacial hydrology of the Superior Lobe, Minnesota; in The Wisconsin Stage: Geological Society of America Memoir 136, p. 251-276.
Wright, H. E.,Jr., Matsch, C. L., and Cushing, E. J., 1973. Superior and Des Moines Lobes: in The Wisconsin Stage: Geological Society of America Memoir 136, p. 153-185.
Wright, H. E., Jr. and Ruhe, R. V., 1965, Glaciation of Minnesota and Iowa; in H. E. Wright and D. G. Frey, eds., The Quaternary of the United States, University Press, Princeton, New Jersey, p. 29-41.

APPENDIX A.--WATER USE

by Lee Trotta

Public Supply

Public water supply is the major use of ground water in the Bemidji-Bagley area and comprises both municipal and private waterworks. There are three municipal waterworks in the study area; Bemidji, Bagley, and Cass Lake. Bemidji alone withdrew 441.6 Mgal in 1985. Together these three municipal waterworks withdrew 531 Mgal of ground water at a rate of 111 gal/d per capita in 1985. This rate of use includes deliveries to industrial and commercial users and is slightly below the State average of 175 gal/d per capita and the national average of 183 gal/d per capita. One of the larger publicly supplied industries in Bemidji is potato processing.

There are at least 11 private waterworks in the study area. The eight largest withdrew 2.75 Mgal in 1985. Those that withdraw over 10,000 gal/d require appropriation permits and must report monthly pumpage to the Minnesota Department of Natural Resources. Most of the water withdrawn was used to supply trailer parks.

Total public-supply withdrawals for 1985 were about 559 Mgal, all from ground water. The City of Cass Lake also withdrew 8.5 Mgal of surface water in 1985 for temporary pipeline and tank testing.

Industrial

Privately supplied industrial water use in the study area included egg processing and the manufacture of particleboard and paperboard products. About 29.4 Mgal of ground water was withdrawn for these purposes in 1985. Also, about 18.4 Mgal of surface water was withdrawn for the manufacture of ready-mixed concrete products in 1985. Some water may be withdrawn to dewater sand and gravel pits for mining, but none was reported in 1985.

Commercial

There is little privately supplied commercial water use in the study area. One establishment had a commercial-use permit and withdrew 0.8 Mgal of ground water during 1985. Smaller privately-supplied commercial establishments were not required to report.

Hydroelectric-Power Generation

The single hydroelectric plant in the study area withdrew about 48,910 Mgal of surface water from the Mississippi River in order to produce 2.671 gigawatt hours of electricity in 1985. Although this represents greater than 96 percent of all the water withdrawn in the study area, essentially all this water was returned to the river.

Irrigation

Irrigation is a major use of water in the study area. Most sprinkler irrigation is consumed by the crops or lost to evaporation. Wild rice irrigation however, uses flooding techniques that allow a certain amount of seepage to ground water.

Withdrawals to irrigate wild rice amounted to 40.2 Mgal of surface water in 1985. These withdrawals were divided among 3 permit holders irrigating 230 acres of wild rice. The study area's average paddy received about 6.5 in. of water in 1985.

Other major crops (mostly potatoes) required 31.7 Mgal of ground-water irrigation. Six permit holders reported irrigating a total of 497 acres in 1985. The average potato field in the area received about 2.2 in. in 1985 and 3.8 in. in 1986.

Noncrop irrigation (for nursery, landscaping, cemetery, and golf course purposes) required 22.8 Mgal of ground water and 15.5 Mgal of surface water in 1985. The average golf course applied a total of about 3.4 in. in 1985.

Total reported irrigation withdrawals in the study area were about 110.2 Mgal, split evenly between surface water and ground water. This equals only 5 percent of Beltrami County's estimated irrigation withdrawals. The difference between reported and estimated withdrawals is that estimated totals are made by assigning withdrawals to known irrigators if reported withdrawals do not exist. This assigned withdrawal volume is based on information reported in previous years. Incorporating such an estimation technique adds 149.3 Mgal to the 1985 total in the study area, resulting in an estimated 259.5 Mgal of irrigation withdrawals.

Recreational

This category of water use is not systematically tracked by the State, except at State parks, waysides and ski areas. In the study area, there is one wayside which withdrew an estimated 0.5 Mgal of ground water and one ski area which withdrew about 1.1 Mgal of surface water for snowmaking.

Rural-Domestic and Livestock

Because the study area does not correspond to any regular political boundaries, rural-domestic and livestock water use could not be calculated. As an indication of their importance in the area, all of Beltrami County withdrew 693.5 Mgal of ground water for rural-domestic purposes in 1985. Beltrami County also withdrew 87.6 Mgal of ground water and 14.6 Mgal of surface water for consumption by livestock.

Sewage Treatment

Although several sewage-treatment facilities exist in the study area, site-specific data were not available in this category. As an indication of the category's importance, the six facilities in Beltrami County released an estimated total of 471 Mgal in 1985.

APPENDIX B.--GROUND-WATER-FLOW MODEL

A conceptually-based, ground-water-flow model was developed for this study to aid in understanding regional flow in the hydrogeologic system and the hydraulic properties of specific hydrologic units. A computer model developed by McDonald and Harbaugh (1984) was used to simulate ground-water flow in three-dimensions. The model solves finite-difference approximations to the ground-water-flow equation. The equations describe the flow of water through the 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 ground-water-flow model. The conceptual model consists of a qualitative description of the known characteristics and behavior of the hydrologic system. The major assumptions associated with the conceptual and ground-water-flow models are:

1. The unconfined-drift aquifer and the uppermost till confining unit (fig. B-1) are represented as a single model layer (layer 1).
2. The uppermost confined-drift aquifer (fig. B-1) is also represented as a single model layer (model layer 2).
3. Drift below the uppermost confined-drift aquifer (model layer 3) is simulated as consisting of 100 feet of sand and gravel material and 300 feet of glacial till.
4. Aquifers and confining units simulated are homogeneous and isotropic.
5. The water levels in major-surface water bodies do not fluctuate significantly with time and are simulated as leaky-river cells.
6. Minor streams and ditches are assumed to be insignificant points of discharge from the ground-water system and are ignored.
7. Recharge to the water table is from precipitation and can be varied depending upon the type of surficial material.
8. Leakage to the uppermost confined-drift aquifer is through the confining unit. The leakage is dependent on vertical hydraulic conductivity and thickness of confining units.
9. Evapotranspiration is accounted for by using a net value of recharge (net recharge = recharge - evapotranspiration).
10. Ground water discharge through wells is not returned to the aquifer system.

Model Design

The modeled area is coincidental with the study area and includes portions of the Mississippi and Clearwater River basins. The model simulates the unconfined-drift aquifer and surrounding areas that extend to the subbasin watershed divides. The active area of the model is about 1,050 mi^2. The model grid contains 33 rows and 51 columns (fig. B-2). A uniform, mile-square-grid spacing was used. This mile-square-grid is not precise enough to accurately simulate locations of individual wells and many streams, lakes, and rivers.

The glacial-drift system was divided into three model layers: layer 1 (the top layer) represents the surficial-outwash aquifer and the underlying uppermost confining unit; layer 2 represents the uppermost confined-drift aquifer; and layer 3 represents the remaining glacial drift below the uppermost confined-drift aquifer (fig. B-1).

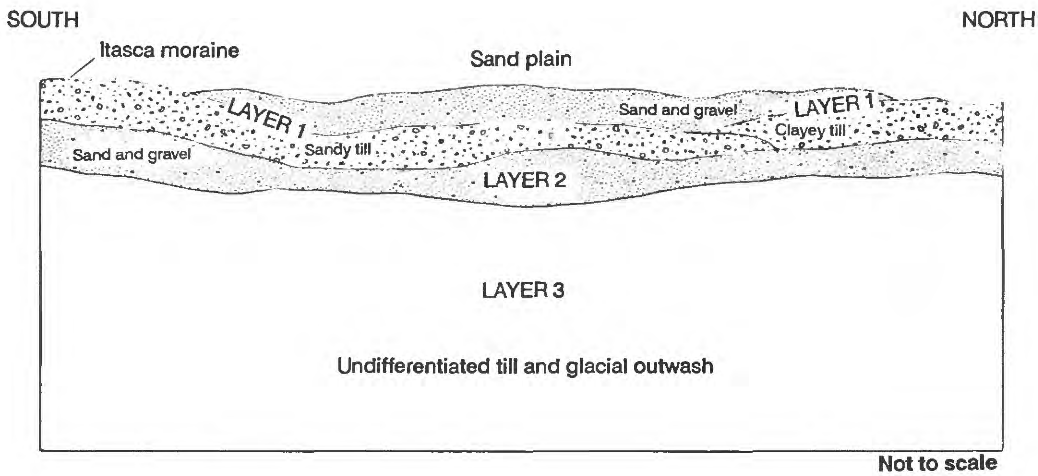


Figure B-1.--Conceptual geologic section used for ground-water-flow model construction

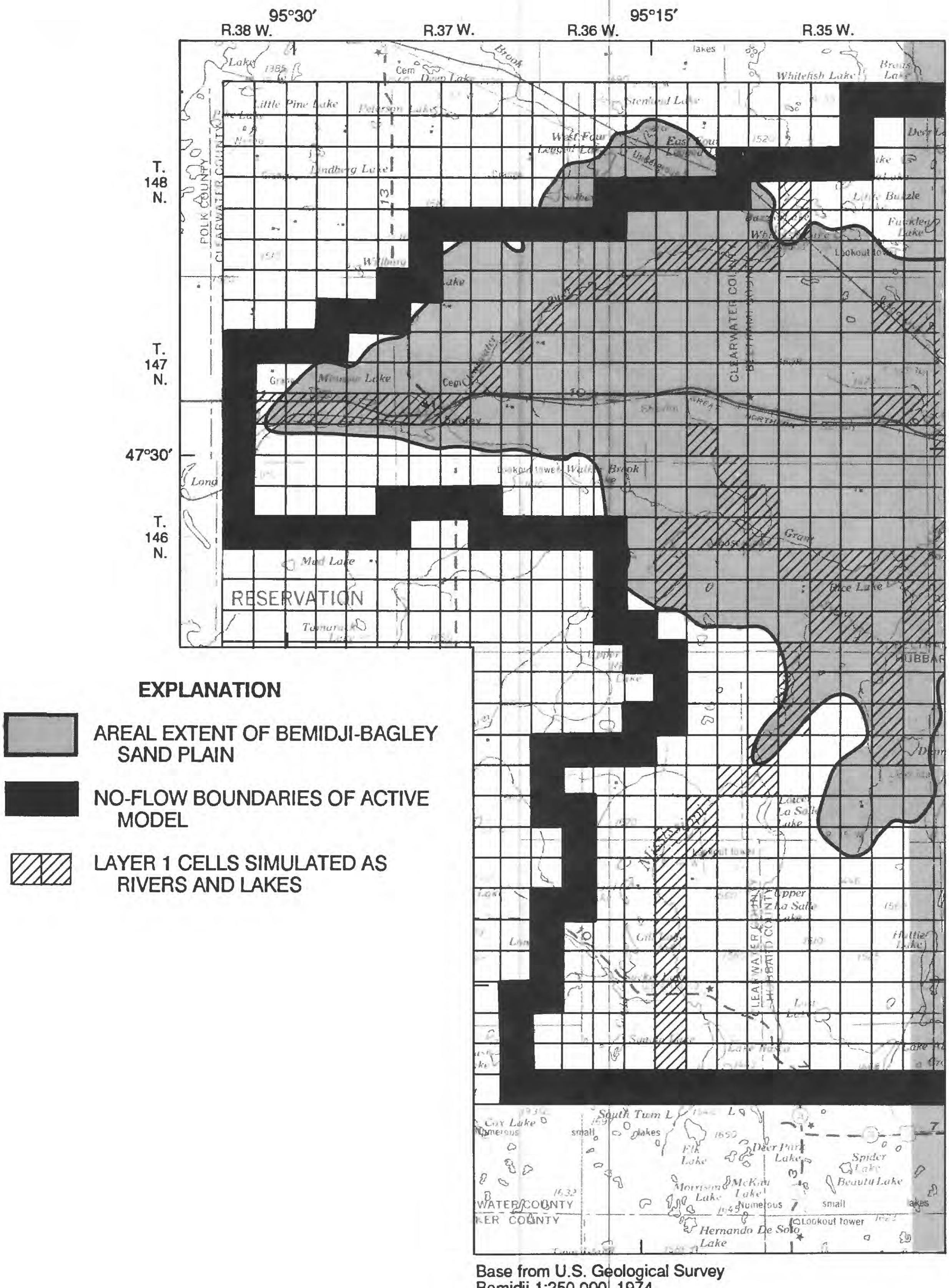
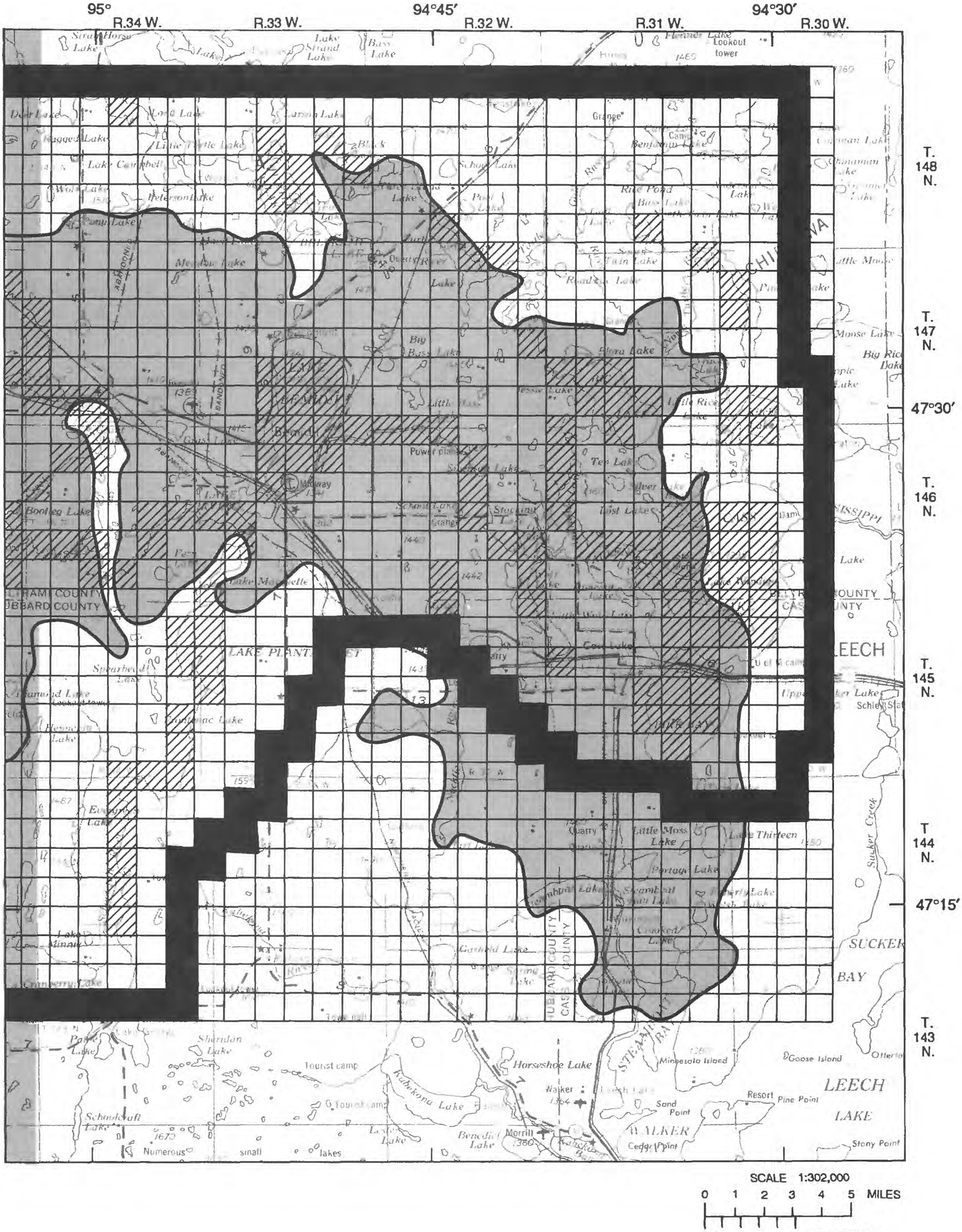


Figure B-2.--Model grid,



boundaries, and river cells

Boundaries of the active model were chosen to extend beyond the unconfined-drift aquifer boundary where possible and to simulate actual hydrologic boundaries (fig. B-2). Where possible, ground-water divides were simulated as no-flow boundaries. Where ground-water divides do not exist within the area of the model, model boundaries (no-flow boundaries) were selected to represent ground-water-flow lines. The assumption that these boundaries represent an average potentiometric surface over time was also made.

Geologic data compiled for this study were used to assign hydrogeologic characteristics to model cells, including the altitude of the bottom of the unconfined-drift aquifer, potentiometric surfaces of the unconfined-drift and uppermost confined-drift aquifers, and the thicknesses of the confining unit and uppermost confined-drift aquifer. Hydraulic properties for the model hydrogeologic units were estimated from data prepared for this study or adopted from published reports. Initial recharge rates were estimated by hydrograph analysis. Ground-water withdrawal data were compiled from data provided by the Minnesota Department of Natural Resources.

Model Evaluation

The model was evaluated to determine the range of values of hydrologic properties that provided simulated potentiometric heads and simulated river discharges that best matched those measured in the field. This process consisted of adjusting values of hydrologic properties within realistic limits until simulated potentiometric heads and ground-water discharge to streams acceptably matched corresponding measured values. In addition, after defining acceptable ranges of values of model-input parameters, a set of values within this range was chosen for sensitivity analysis (Table B-1). Sensitivity analysis was used to identify hydrologic properties having the greatest affect on simulated potentiometric heads and simulated river discharges. Sensitivity analysis indicates the hydrologic properties to which the model is most sensitive and therefore indicates types of additional data collection or model refinement that would most improve the model simulation of the hydrologic system.

Measured ground-water discharge to streams and reported water levels were used to determine whether model-simulated output was acceptable. The range used to define acceptable output values is described below. Base flow discharge to streams was measured at selected sites on streams in the study area in January 1987 and were compared to model-simulated ground-water discharge to streams. Because long-term stream discharge data were not available for streams in the study area, variability in base-flow was estimated from similar streams. Long-term discharge measurements from the Rum River near St. Francis, Minn. and the Clearwater River near Red Lake Falls, Minn. were used to estimate the range of variability in base flow by assuming that January measurements are a measure of the ground-water contribution to streams. For the Rum River, normal January monthly mean discharge varied from 51.5 ft^3/s (cubic feet per second) in 1934 to 529.0 ft^3/s in 1973, with a median value of 192.0 ft^3/s. For the Clearwater River, January monthly mean discharge ranged from 21.4 ft^3/s in 1940 to 220.0 ft^3/s in 1910, with a median value of 54.3 ft^3/s. These data illustrate the variability in base flow that may be expected in the study area. The streamflow gains measured during low-flow measurements in

Table B-1.--*Selected model-input parameters used for sensitivity analysis and hypothetical pumping and drought scenarios*

[--, not calculated]

	North till	South till	Sandplain	Confined aquifer	Deep drift	Stream bed	Lake bed
Recharge (inches/year)	1	7	7	--	--	--	--
Horizontal conductivity (feet/day)	.1	1.	500	500	120	1.	0.05
Vertical conductivity (feet/day)	.01	.1	100	100	.01	1.	.05

February 1988 for this study were assumed to have a possible range of variability of about plus or minus 75 percent of the measured value. Other criteria used to evaluate model hydrologic properties were the mean error of model-simulated versus measured potentiometric heads in layers 1 and 2 of the model. Because the model was used to improve an understanding of the regional flow system (as opposed to simulating local hydrologic conditions), hydrologic properties were not varied on a cell by cell basis to produce locally better matching potentiometric heads. Differences between model-simulated and measured potentiometric heads of plus or minus 10 feet were chosen as an acceptable match.

Both spatially uniform and non-uniform changes in recharge were made to determine the rate of recharge. Non-uniform changes in recharge were made in each of three zones representing differing surficial geology. The zones comprised the northern part of the study area where clay-rich till is present at land surface (north till), the southern part of the study area where sand-rich till is present at land surface (south till), and the central part of the study area where the unconfined-drift aquifer is present at land surface (sand plain). The ranges of recharge rates that provided reasonable agreement between model-simulated and measured heads and river discharges are 4 to 8 in/yr for the unconfined-drift aquifer and areas of sandy glacial till (south till) and 0 to 4 in/yr in areas of clay-rich till (north till). Sensitivity analysis indicates that all model-simulated output parameters are sensitive to recharge rates (table B-2).

Values of horizontal hydraulic conductivity were determined by varying horizontal conductivity values in model cells representing the two types of glacial till in layer 1, model cells representing sand and gravel in the unconfined-drift aquifer in layer 1, and in all model cells of layers 2 and 3. Horizontal hydraulic conductivities of 250 to 750 ft/d for the aquifers provided acceptable model-simulated heads and river discharges. The northern clay-till and southern sandy till were found to have horizontal hydraulic conductivities of about 0.1 and 1.0 ft/d, respectively. The underlying drift, which probably includes till and aquifer material, has a composite horizontal hydraulic conductivity of about 120 ft/d. The model was most sensitive to changes in the horizontal hydraulic conductivity of the aquifers (layers 1 and 2) and deep drift (layer 3) (table B-3).

Table B-2.--*Model-Computed water budget*

[--, not calculated]

Budget component	Inputs (cubic feet per second)	Outputs (cubic feet per second)
Net recharge	25,000	--
Stream leakage	1,300	26,000
Well discharge	--	200
Total	26,300	26,200

Vertical hydraulic conductivity values were changed in a similar manner. Values of 0.001 to 1.0 ft/d are considered to be acceptable values of vertical hydraulic conductivity for till units and values from 50 to 150 ft/d are considered to be acceptable for the aquifers. Sensitivity analyses indicate that vertical hydraulic conductivity of the uppermost confining unit and of deep glacial drift (layer 3) are critical parameters affecting model-simulated hydraulic heads and model-simulated discharge to streams and rivers (Table B-4).

Values of riverbed and lakebed hydraulic conductivity were determined by changing the values of these input parameters separately and simultaneously. The resulting values range from 1-10 ft/d for river beds and 0.5 to 0.005 ft/d for lakebeds. Results of sensitivity analyses for riverbed and lakebed hydraulic conductivity (table B-5) show that river discharge is insensitive to riverbed and lakebed hydraulic conductivity given the limited data and uncertainty of low-flow data available for this study. However, a decrease in riverbed hydraulic conductivity greatly increased heads in all layers.

Sensitivity analyses indicate that recharge, horizontal and vertical hydraulic conductivity of deep glacial-drift deposits (layer 3), vertical hydraulic conductivity of the confining unit and of deep glacial drift (layer 3), and riverbed conductance are the most critical hydrologic properties affecting model-simulated hydraulic heads and model-simulated discharge to streams and rivers.

Results of Model Simulation

Deep-drift aquifer units were found to be significant components of the flow system in the study area. However, little is known about their hydrologic properties. In contrast, where the surficial aquifer is less than about 20 feet thick, the model was unable to represent ground-water flow, suggesting that much of the unconfined-drift aquifer is an insignificant component of the regional-flow system because it is discontinuous and generally thin.

Table B-3.--*Sensitivity to recharge*

[In the columns under Mean Error in Computed Heads a plus sign means computed heads greater than best-fit model-computed heads; a minus sign means computed heads less than best-fit model-computed heads. In the columns under Percent Error in Computed River Discharge a plus sign means computed discharge to streams is greater than best-fit model-computed discharge; a minus sign means computed discharge is less than best-fit model-computed discharge]

Recharge values (inches/year)			Mean error in computed heads (feet)		Percent error in computed river discharge		
North till	South till	Sandplain	Layer 1	Layer 2	Mississippi River	Clearwater River	Grant Creek
0.5	3.5	3.5	-9.1	-9.5	-68	-92	-62
1.5	10.5	10.5	+8.4	+8.8	+68	+90	+67
3.0	14	14	+16.1	+16.7	+130	+175	+129
0.	7	7	-.5	-1.2	-1	-4	-4
1.5	7	7	+.2	+.6	0	+2	+2
4	7	7	+1.4	+3.0	+2	+11	+12
7	7	7	+2.8	+7.2	+5	+22	+23
1	3.5	7	-2.0	-2.2	-40	-4	-5
1	10.5	7	+1.8	+2.0	+40	+4	+4
1	14	7	+3.6	+4.0	+79	+8	+9
1	7	3.5	-6.7	-6.5	-27	-84	-61
1	7	10.5	+8.4	+6.2	+28	+85	+61
1	7	14	+12.5	+12.1	+54	+169	+121
1	4	4	-7.3	-7.3	-54	-75	-55
1	8	8	+2.6	+2.6	+24	+26	+19
1	9	9	+5.1	+5.1	+46	+51	+38
2	4	5	-4.8	+4.2	-46	-48	-31

Table B-4.--*Sensitivity to horizontal hydraulic conductivity*

[In the columns under Mean Error in Computed Heads a plus sign means computed heads greater than best-fit model-computed heads; a minus sign means computed heads less than best-fit model-computed heads. In the columns under Percent Error in Computed River Discharge a plus sign means computed discharge to streams is greater than best-fit model-computed discharge; a minus sign means computed discharge is less than best-fit model-computed discharge]

Horizontal hydraulic conductivity (feet/day)					Mean error in computed heads (feet)		Percent error in computed river discharge		
North till	South till	Sand-plain	Confined aquifer	Deep drift	Layer 1	Layer 2	Mississippi River	Clearwater River	Grant Creek
0.01	1	500	500	120	0	0	0	0	0
1	1	500	500	120	0	0	0	0	0
.1	0.1	500	500	120	0	0	0	0	0
.1	10	500	500	120	-.5	-.6	-1	-1	-1
.1	1	250	500	120	+2.2	+2.2	+2	+5	+1
.1	1	750	500	120	-1.4	+8.4	-1	-4	-2
.1	1	500	250	120	+3.5	+4.5	+7	+6	+10
.1	1	500	750	120	-1.5	-2.6	-7	-6	-7
.1	1	500	500	60	+1.2	+.6	+11	+22	+3
.1	1	500	500	180	-1.0	-.5	-9	-19	-4
.1	1	500	500	240	-1.5	-.7	-15	-30	-6

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. 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;
RO = runoff;
ET = evapotranspiration;
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.

The steady-state water budget for the calibrated model (table B-6) shows that recharge from precipitation is the major source of water to the system. Leakage to streams accounts for most of the discharge from the ground-water system.

Hydraulic-head differences between the unconfined-drift and confined-drift aquifers (layers 1 and 2) indicate that an upward component of flow occurs in areas where discharge is to lakes, rivers, and streams (fig. B-3). The distribution of model-simulated heads was in general agreement with the measured-head distribution (figs. B-4 and B-5). Model simulated heads were generally within 2 to 5 ft for the unconfined-drift aquifer and 6 to 10 ft for the confined-drift aquifer.

Effects of Hypothetical Pumping and Drought

Model simulations were conducted to determine the general effects of hypothetical ground-water development and drought scenarios on the regional ground-water system. These simulations included selected model input values that provided values of simulated heads and river discharges within 10 ft and 75 percent of measured head and river discharge, respectively. Because of the scale of the model grid, these simulations are not adequate for site specific, predictive purposes. The scenarios simulated suggest certain regional trends:

1. The effect of increased ground-water usage by municipalities was simulated by increasing the simulated pumping rate for 21 wells in the Bemidji and Bagley areas to twice the annual rate permitted by the MDNR in 1985.

Table B-5.--*Sensitivity to vertical hydraulic conductivity*

[In the columns under Mean Error in Computed Heads a plus sign means computed heads greater than best-fit model-computed heads; a minus sign means computed heads less than best-fit model-computed heads. In the columns under Percent Error in Computed River Discharge a plus sign means computed discharge to streams is greater than best-fit model-computed discharge; a minus sign means computed discharge is less than best-fit model-computed discharge]

Vertical hydraulic conductivity (feet/day)					Mean error in computed heads (feet)		Percent error in computed river discharge		
North till	South till	Sand-plain	Confined aquifer	Deep drift	Layer 1	Layer 2	Mississippi River	Clearwater River	Grant Creek
0.001	0.1	100	100	0.01	+0.5	+1.5	+1	+2	+4
.1	.1	100	100	.01	-.4	-1.0	0	-1	-3
.01	.01	100	100	.01	-.4	-.6	0	-7	-2
.01	1	100	100	.01	-.6	-.6	0	-1	-2
.01	.1	50	100	.01	0	0	0	0	0
.01	.1	150	100	.01	0	0	0	0	0
.01	.1	100	50	.01	0	0	0	0	0
.01	.1	100	150	.01	0	0	0	0	0
.01	.1	100	100	.001	+4.5	+3.3	+13	+41	+10
.01	.1	100	100	.1	-1.0	+5.3	-5	-23	-23

Table B-6.--*Sensitivity to lake-bed and river-bed hydraulic conductivity*

[In the columns under Mean Error in Computer Heads a plus sign means computed heads greater than best-fit model-computed heads; a minus sign means computed heads less than best-fit model-computed heads. In the columns under Percent Error in Computed River Discharge a plus sign means computed discharge to streams is greater than best-fit model-computed discharge; a minus sign means computed discharge is less than best-fit model-computed discharge]

Hydraulic conductivity (feet/day)		Mean error in computed heads (feet)		Percent error in computed river discharge		
Lake-bed	Stream-bed	Layer 1	Layer 2	Mississippi River	Clearwater River	Grant Creek
0.005	0.1	+29.2	+28.1	-22	-9	-26
.5	10	-3.6	+8.4	+10	-10	+3
.005	1	+2.8	+2.8	+6	+2	+6
.5	1	-.4	-.4	-1	0	-1
.05	.1	+23.1	+22.0	-29	-13	-32
.05	10	-3.3	-3.4	+8	-10	+4

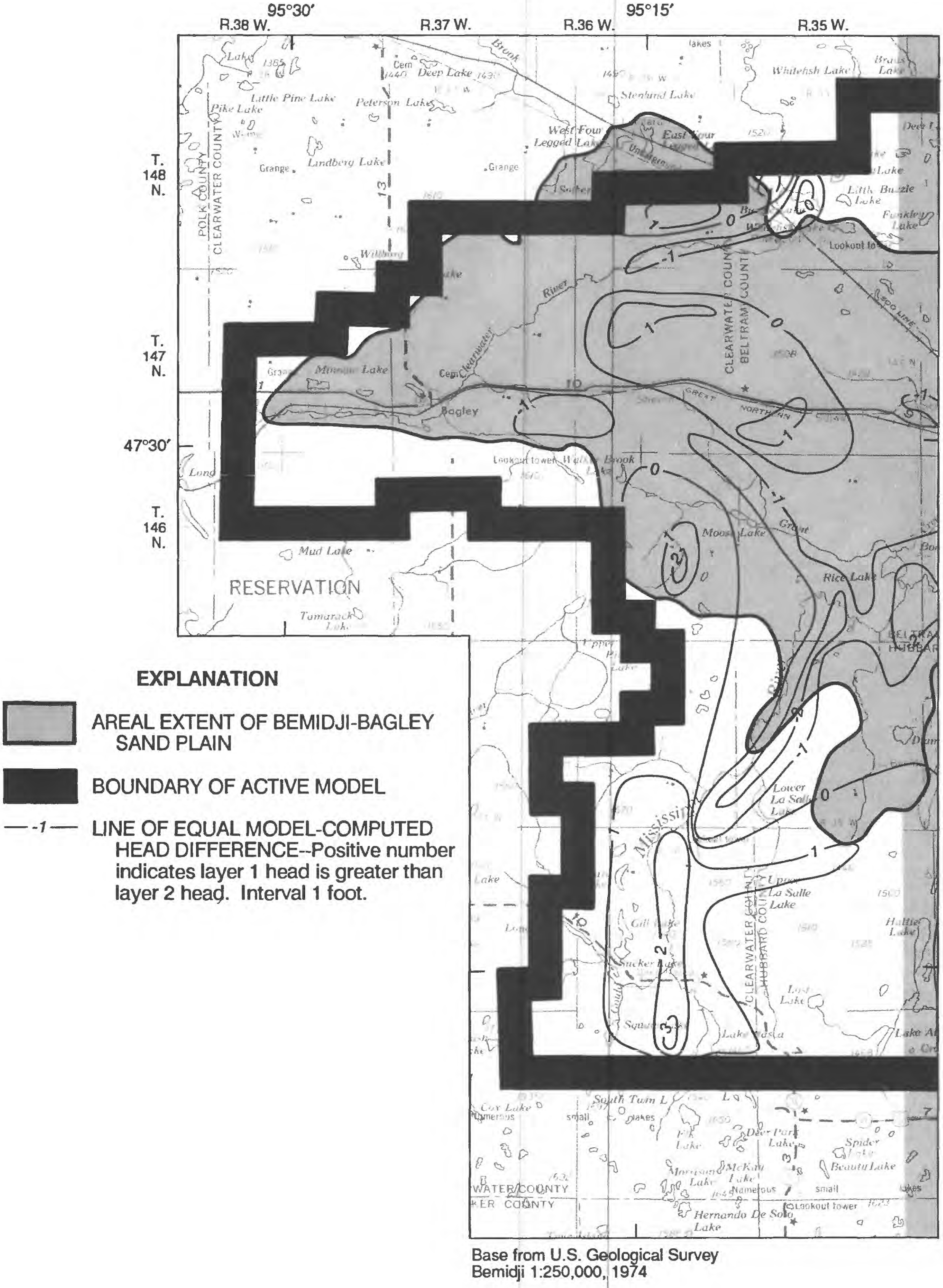
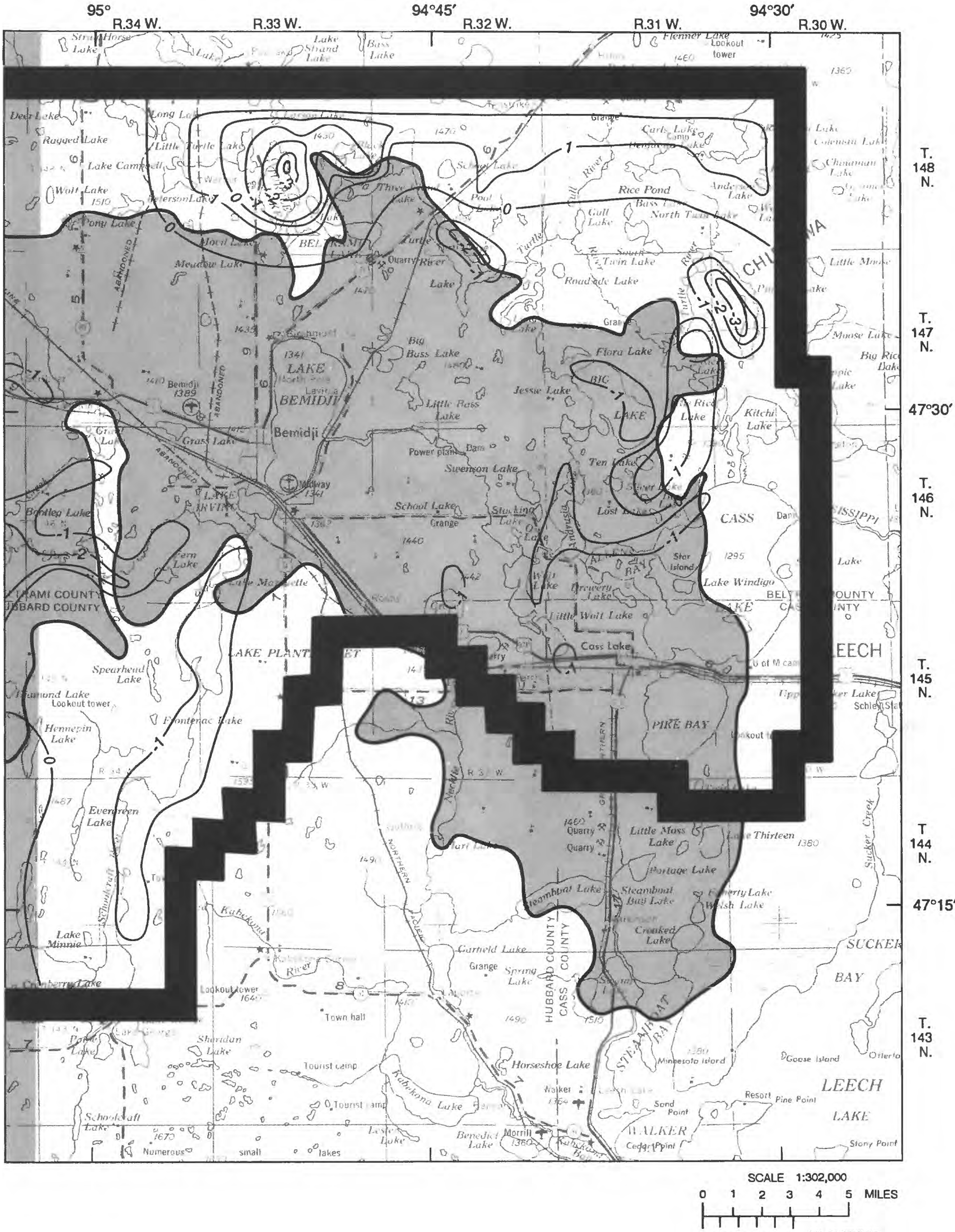
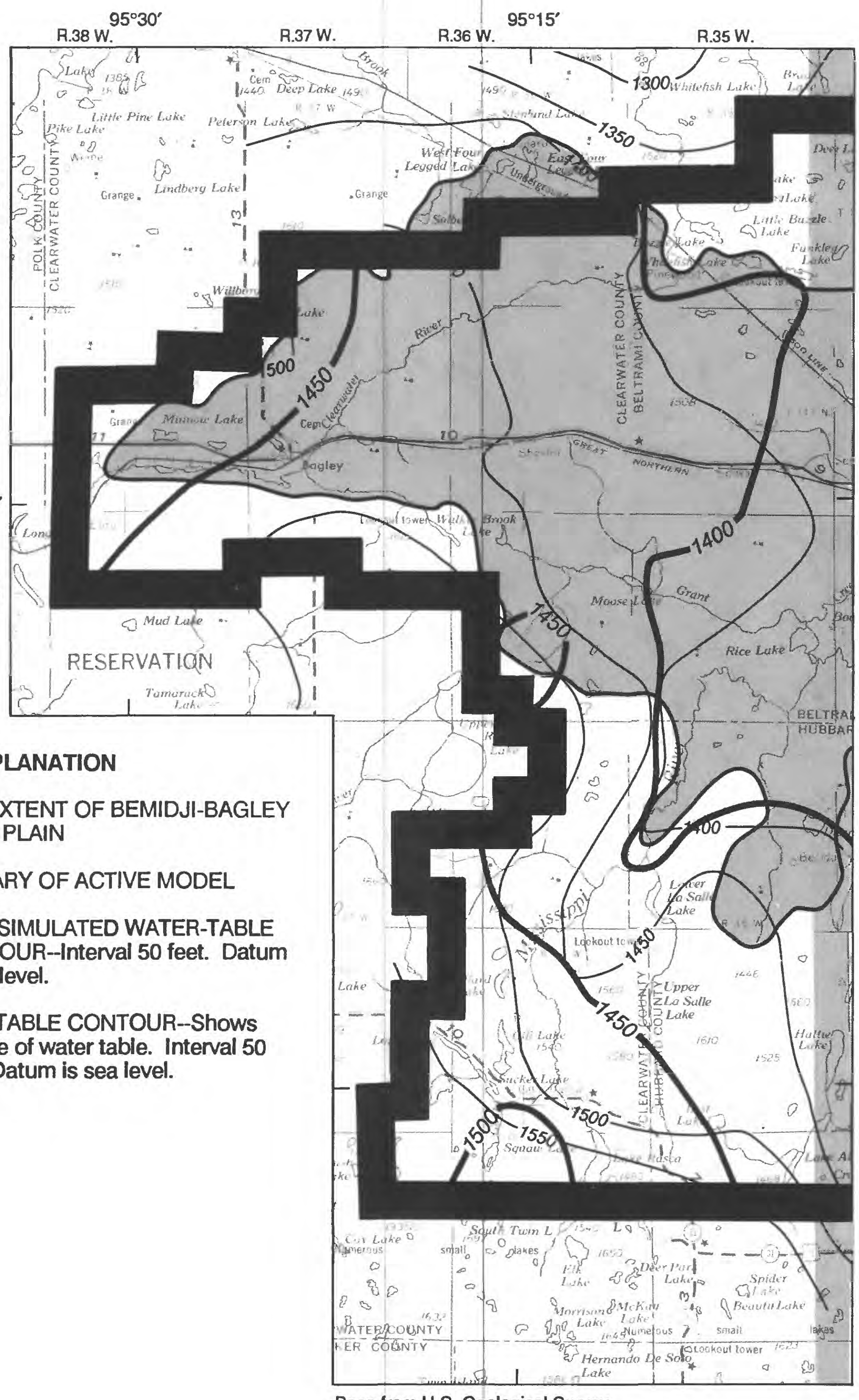


Figure B-3.--Hydraulic-head differences between unconfined-drift (layer 1) aquifer and



uppermost confined-drift (layer 2) aquifer simulated by the ground-water-flow model



EXPLANATION

AREAL EXTENT OF BEMIDJI-BAGLEY SAND PLAIN

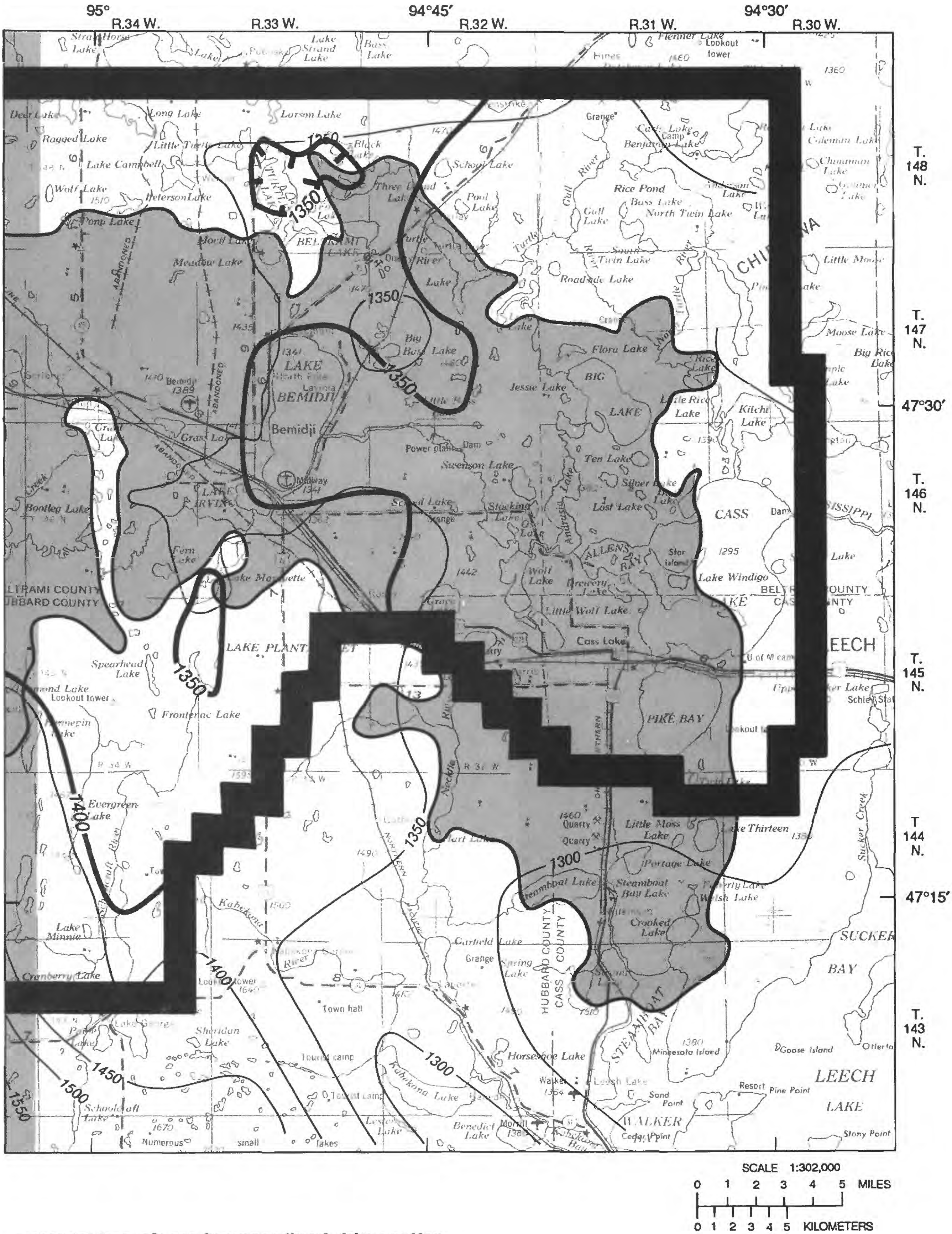
BOUNDARY OF ACTIVE MODEL

—1350— MODEL-SIMULATED WATER-TABLE CONTOUR--Interval 50 feet. Datum is sea level.

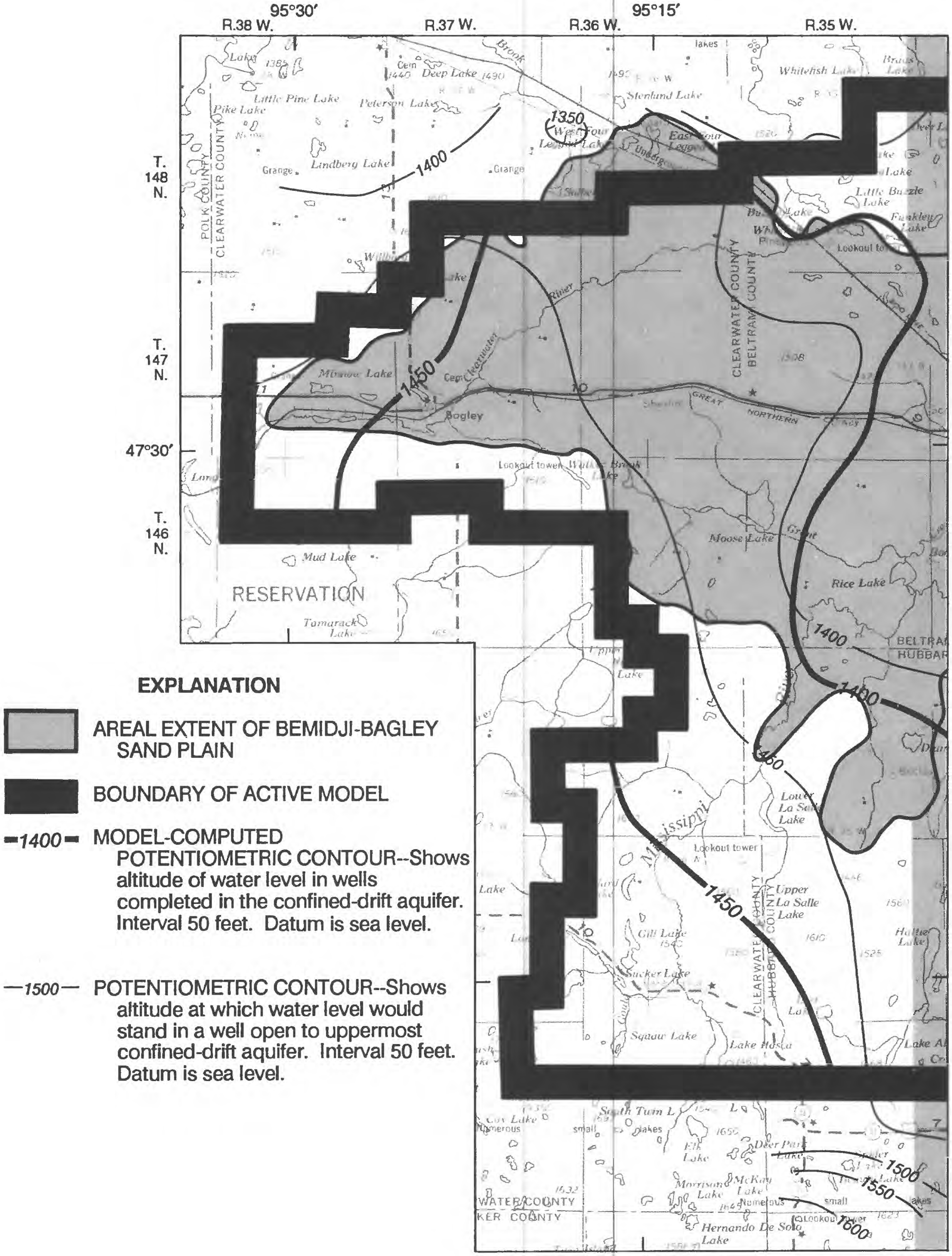
—1500— WATER-TABLE CONTOUR--Shows altitude of water table. Interval 50 feet. Datum is sea level.

Base from U.S. Geological Survey
Bemidji 1:250,000, 1974

Figure B-4.--Model-simulated and measured

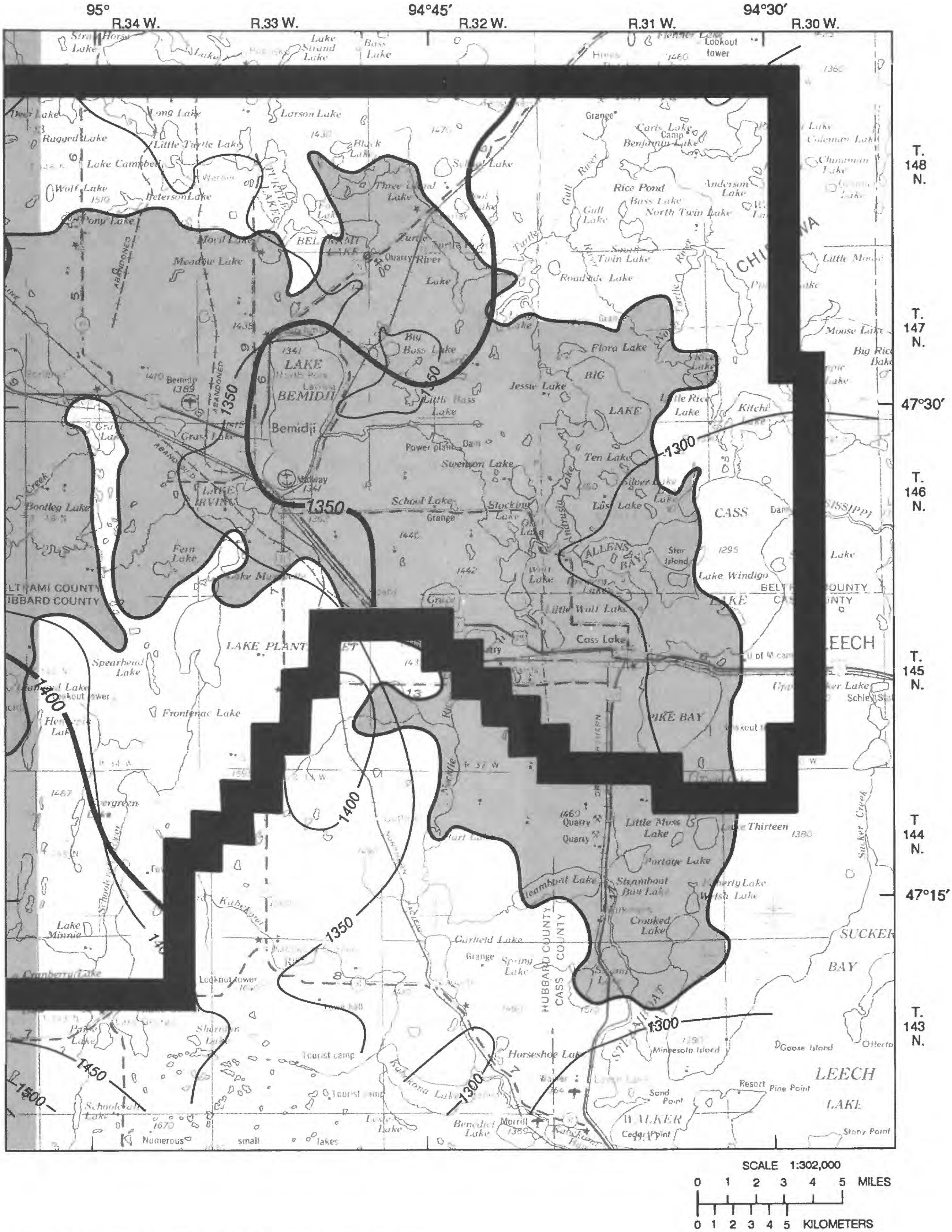


water-table surfaces in unconfined-drift aquifer



Base from U.S. Geological Survey
Bemidji 1:250,000, 1974

Figure B-5.--Model-simulated and measured potentiometric



surfaces of uppermost confined-drift aquifer

Results of the increased ground-water withdrawal by municipalities were minimal, except near Bemidji, where potentiometric heads decreased by 1 to 2 feet. The regional configuration of the potentiometric surfaces, ground-water-flow directions, and river discharges were not significantly affected by the increased municipal pumpage.

2. The effect of ground-water development for irrigation, was simulated by assuming half of all pasture and cultivated land to be irrigated with 7 in/yr. This is half the maximum rate currently permitted by the MDNR. Wells were simulated only in areas where the unconfined aquifer is more than 20 ft thick.

Declines in potentiometric heads of up to 10 feet resulted from the simulated ground-water development, but declines were generally 2 to 5 ft. Potentiometric heads in the area northeast of Bagley were the most affected because cultivated and pasture land predominates in that area. Simulated river discharge decreased by 22 percent for the Clearwater River and 14 percent for the Mississippi River as compared to measured rates for 1985.

3. The effect of drought was simulated by reducing recharge to layer 1 of the model to .5, 3.5, and 3.5 in. for the northern till, southern till, and unconfined-drift aquifer, respectively.

A reduction in recharge resulted in a significant decline in simulated potentiometric heads in the unconfined-drift aquifer and lower river discharges. The mean simulated head was 9 feet lower than the mean measured head (table B-2). Calculated river discharges were as much as 90 percent lower than the measured discharges.

APPENDIX C-WATER-QUALITY DATA

Table C-1.--*Water-quality data for wells completed in unconfined-drift aquifer in areas of agricultural land use*

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

Station number	Date	Temperature, water (°C)	Temperature, air (°C)	Barometric pressure (mm of Hg)	Specific conductance (µS/cm)	pH (standard units)	pH, lab (standard units)
471408095004300	09-04-87	7.5	19	--	332	7.6	7.9
472720095121800	08-29-87	7.5	21	--	451	7.5	7.8
472859094464000	08-26-87	12.5	17	--	345	7.6	7.7
472907095084100	08-29-87	8.5	20	--	312	7.8	8.2
	10-13-87	--	--	--	307	8.0	8.3
	01-15-88	8.0	-2	--	295	8.3	--
	01-16-88	--	--	--	--	--	8.1
473057095184000	09-04-87	14.0	19	--	535	7.3	7.3
473131095160600	08-31-87	11.0	23	--	555	7.4	7.5
473232095152900	08-31-87	11.5	23	750	360	7.4	7.5
473238094581400	08-26-87	9.5	18	--	330	7.8	8.2
473318094565300	08-28-87	10.5	21	--	501	7.6	7.8
473322094525800	08-26-87	8.5	19	--	208	8.1	8.1
473413094554300	08-26-87	8.0	19	--	485	7.6	7.5
473423095241800	07-31-87	13.0	30	740	380	7.3	7.6
473547095160800	08-31-87	9.5	22	--	315	7.3	7.9

Table C-1.--*Water-quality data for wells completed in unconfined-drift aquifer in areas of agricultural land use*--Continued

Station number	Date	Alkalinity, total, IT, field (mg/L as $CaCO_3$)	Bicarbonate, IT, field (mg/L as HCO_3)	Nitrogen, ammonia dissolved (mg/L as N)	Nitrogen, ammonia plus organic dissolved (mg/L as N)	Nitrogen, nitrite plus nitrate, dissolved (mg/L as N)	Phosphorous, dissolved (mg/L as P)	Phosphorus, ortho, dissolved (mg/L as P)	Carbon, organic, total (mg/L as C)
471408095004300	09-04-87	162.0	198	0.030	<0.2	0.32	0.02	0.02	10.
472720095121800	08-29-87	--	--	.010	.5	2.2	.02	.01	3.6
472859094464000	08-26-87	188.0	227	.030	<.2	1.7	.07	.06	8.4
472907095084100	08-29-87	--	--	<.010	.3	4.5	.03	.02	5.9
	10-13-87	151.0	--	.020	.2	4.2	--	.02	--
	01-15-88	--	--	--	--	3.5	--	--	--
	01-16-88	--	--	.030	.8	3.5	--	.02	--
473057095184000	09-04-87	302.0	368	.030	.3	<.10	.06	.06	9.4
473131095160600	08-31-87	308.0	375	.050	.5	.43	.02	<.005	6.5
473232095152900	08-31-87	200.0	244	.020	.3	.64	.03	.03	2.9
473238094581400	08-26-87	184.0	224	.020	.2	.2	.01	<.005	9.8
473318094565300	08-28-87	--	--	<.010	.7	3.4	.01	.01	3.2
473322094525800	08-26-87	92.0	112	<.010	.3	.86	.03	.02	2.5
473413094554300	08-26-87	294.0	359	<.010	.3	.31	.02	.01	9.8
473423095241800	07-31-87	--	--	<.010	.4	--	.03	.03	--
473547095160800	08-31-87	192.0	234	<.010	.3	1.9	.05	.04	3.9

Table C-1.--*Water-quality data for wells completed in unconfined-drift aquifer in areas of agricultural land use*--Continued

Station number	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)	Chloride, dissolved (mg/L as Cl)	Sulfate, dissolved (mg/L as SO_4)	Silica, dissolved (mg/L as SiO_2)	Arsenic, dissolved (μg/L as As)	Iron, dissolved (μg/L as Fe)
471408095004300	09-04-87	50	13	3.4	1.0	1.5	9.3	15	<1	7
472720095121800	08-29-87	65	23	2.3	1.3	1.5	6.4	24	<1	7
472859094464000	08-26-87	57	12	2.7	0.7	0.7	4.0	19	4	16
472907095084100	08-29-87	46	14	2.1	1.0	3.2	6.1	16	<1	9
	10-13-87	43	13	2.6	1.4	4.5	6.1	--	--	--
	01-15-88	--	--	--	--	--	--	--	--	--
	01-16-88	45	14	2.7	1.5	6.1	7.1	--	--	--
473057095184000	09-04-87	94	22	2.9	2.0	2.8	9.2	22	1	33
473131095160600	08-31-87	99	22	3.3	2.1	4.5	6.2	26	1	18
473232095152900	08-31-87	60	14	3.3	1.2	3.4	12	12	<1	33
473238094581400	08-26-87	52	9.3	12	1.7	0.7	11	11	<1	37
473318094565300	08-28-87	82	21	7.6	1.0	6.6	7.7	19	<1	6
473322094525800	08-26-87	31	9.9	1.8	0.4	15.	5.5	16	1	12
473413094554300	08-26-87	82	22	2.7	4.7	1.5	5.3	21	<1	15
473423095241800	07-31-87	63	16	3.5	3.7	0.5	4.0	27	1	33
473547095160800	08-31-87	54	13	1.4	.9	1.0	3.6	20	1	9

Table C-1.--***Water-quality data for wells completed in unconfined-drift aquifer in areas of agricultural land use***--Continued

Station number	Date	Lead, dissolved (μg/L as Pb)	Phenols, total (μg/L)	Solids, dissolved, residue at 180 °C (mg/L)	Elevation of land surface datum (feet above sea level)	Depth of well, total (feet)	Depth of water level below land surface (feet)	Specific conductance, lab (μS/cm)	Alkalinity, lab (mg/L as $CaCO_3$)	Trifluralin, total recoverable (μg/L)	Simetryne, total (μg/L)
471408095004300	09-04-87	10	3	184	1430	38	18.6	339	162	<0.1	<0.1
472720095121800	08-29-87	<10	<1	281	1462	40.5	32.2	487	248	<.1	<.1
472859094464000	08-26-87	<10	2	203	1358	14	10.7	350	187	<.1	<.1
472907095084100	08-29-87	<10	2	200	1435	40	31.6	338	150	<.1	<.1
	10-13-87	--	--	183	1435	40	--	337	148	--	--
	01-15-88	--	--	--	1435	40	34	--	--	--	--
	01-16-88	--	--	193	1435	40	--	330	153	--	--
473057095184000	09-04-87	<10	2	331	1425	8.5	3.4	580	308	<.1	<.1
473131095160600	08-31-87	<10	2	374	1445	8	2.0	636	258	<.1	<.1
473232095152900	08-31-87	<10	3	223	1465	9.5	4.1	385	197	<.1	<.1
473238094581400	08-26-87	<10	2	206	1394	14.8	9.9	355	175	<.1	<.1
473318094565300	08-28-87	<10	3	319	1390	17.5	11.1	558	224	<.1	<.1
473322094525800	08-26-87	<10	1	147	1384	20	11.9	249	91	<.1	<.1
473413094554300	08-26-87	<10	4	308	1395	24	22.2	550	200	<.1	<.1
473423095241800	07-31-87	<10	2	246	1545	16	9.22	419	250	<.1	<.1
473547095160800	08-31-87	<10	1	208	1437	18.5	13.2	358	177	<.1	<.1

Table C-1.--*Water-quality data for wells completed in unconfined-drift aquifer in areas of agricultural land use*--Continued

Station number	Date	Simazine, total (µg/L)	Prometone, total (µg/L)	Prometryne, total (µg/L)	Atrazine, total (µg/L)	Alachlor, total recoverable (µg/L)	Cyanazine, total (µg/L)	Ametryne, total	Metribuzin, total recoverable (µg/L)	Metolachlor, total recoverable (µg/L)
471408095004300	09-04-87	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
472720095121800	08-29-87	<.1	<.1	<.1	<.1	<.1	<.1	<.1	<.1	<.1
472859094464000	08-26-87	<.1	<.1	<.1	<.1	<.1	<.1	<.1	<.1	<.1
472907095084100	08-29-87	<.1	<.1	<.1	<.1	<.1	<.1	<.1	<.1	<.1
	10-13-87	--	--	--	--	--	--	--	--	--
	01-15-88	--	--	--	--	--	--	--	--	--
	01-16-88	--	--	--	--	--	--	--	--	--
473057095184000	09-04-87	<.1	<.1	<.1	<.1	<.1	<.1	<.1	<.1	<.1
473131095160600	08-31-87	<.1	<.1	<.1	2.9	<.1	<.1	<.1	<.1	<.1
473232095152900	08-31-87	<.1	<.1	<.1	<.1	<.1	<.1	<.1	<.1	<.1
473238094581400	08-26-87	<.1	<.1	<.1	<.1	<.1	<.1	<.1	<.1	<.1
473318094565300	08-28-87	<.1	<.1	<.1	<.1	<.1	<.1	<.1	<.1	<.1
473322094525800	08-26-87	<.1	<.1	<.1	<.1	<.1	<.1	<.1	<.1	<.1
473413094554300	08-26-87	<.1	<.1	<.1	<.1	<.1	<.1	<.1	<.1	<.1
473423095241800	07-31-87	<.1	<.1	<.1	<.1	<.1	<.1	<.1	<.1	<.1
473547095160800	08-31-87	<.1	<.1	<.1	<.1	<.1	<.1	<.1	<.1	<.1

Table C-2.--*Water-quality data for wells completed in unconfined drift aquifer in areas of forest land use*

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

Station number	Date	Temperature, water (°C)	Temperature, air (°C)	Barometric pressure (mm of Hg)	Specific conductance (µS/cm)	pH (standard units)	pH, lab (standard units)	Alkalinity, total, FET, field (mg/L as $CaCO_3$)	Alkalinity, total, IT, field (mg/L as $CaCO_3$)
471546094331700	08-17-87	9.5	23	740.0	260	7.3	7.5	108	108
472201094320400	08-17-87	8.0	23	740.0	476	7.3	7.8	248	248
472300094231800	10-14-87	9.5	13	--	390	7.7	7.9	220	220
	01-15-88	8.0	-15	--	275	8.3	7.8	148	--
472533094284500	08-14-87	10.0	23	745.0	221	7.9	8.4	106	108
472537094261700	08-17-87	11.0	22	740.0	333	7.4	7.7	186	186
472553094384500	09-01-87	10.5	20	--	414	7.4	7.5	250	258
472724095055200	08-27-87	10.0	20	--	525	7.2	8.0	338	332
472813095160200	09-04-87	9.5	18	--	540	7.2	7.5	462	474
473140095041200	08-27-87	10.5	20	--	452	7.3	7.7	290	292
473150095210500	08-03-87	9.0	23	750.0	825	7.7	7.5	333	334
473236094505400	08-25-87	9.5	18	--	425	7.5	7.5	234	236
	01-15-88	--	-3	--	--	--	--	--	--
473306094480000	09-01-87	9.5	20	--	366	7.6	7.8	202	204
473410095073000	08-27-87	10	21	14.0	537	6.8	7.0	--	--

Table C-2.--***Water-quality data for wells completed in unconfined-drift aquifer in areas of forest land use***--Continued

Station number	Date	Bicarbonate, FET, field (mg/L as HCO_3)	Bicarbonate, IT, field (mg/L as HCO_3)	Nitrogen, ammonia dissolved (mg/L as N)	Nitrogen, ammonia plus organic, dissolved (mg/L as N)	Nitrogen, nitrite plus nitrate, dissolved (mg/L as N)	Phosphorous, dissolved (mg/L as P)	Phosphorous, ortho, dissolved (mg/L as P)
471546094331700	08-17-87	--	132	0.01	0.6	<0.1	0.02	0.02
472201094320400	08-17-87	--	302	0.02	.4	<.1	.05	.04
472300094231800	10-14-87	--	--	0.02	<.2	.7	--	.04
	01-15-88	--	--	0.04	.4	.3	--	.002
472533094284500	08-14-87	132	--	<0.01	.5	<.1	.06	.05
472537094261700	08-17-87	--	227	<0.01	.6	.5	.02	.01
472553094384500	09-01-87	--	315	0.22	.7	<.1	.01	.01
472724095055200	08-27-87	--	412	0.24	.8	<.1	--	.02
472813095160200	09-04-87	--	578	0.06	<.2	.1	<.005	.002
473140095041200	08-27-87	--	356	0.22	.4	.2	.01	.002
473150095210500	08-03-87	--	407	0.17	.8	<.1	.05	.005
473236094505400	08-25-87	--	287	0.02	.2	1.0	.01	<.001
	01-15-88	--	--	--	--	.9	--	--
473306094480000	09-01-87	--	249	<0.01	.4	<.1	<.005	.001
473410095073000	08-27-87	--	--	0.26	1.8	<.1	.08	.06

Table C-2.--*Water-quality data for wells completed in unconfined-drift aquifer in areas of forest land use*--Continued

Station number	Date	Carbon, organic, total (mg/L as C)	Calcium, dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as Mg)	Sodium, dissolved (mg/L as Na)	Potassium, dissolved (mg/L as K)	Chloride, dissolved (mg/L as Cl)	Sulfate, dissolved (mg/L as SO_4)	Fluoride, dissolved (mg/L as F)	Silica, dissolved (mg/L as SiO_2)
471546094331700	08-17-87	3.9	41	4.5	2.9	1.8	0.6	12	0.1	19
472201094320400	08-17-87	8.9	78	17	3.1	1.2	.8	14	.1	16
472300094231800	10-14-87	--	68	14	2.4	1.6	1.0	7.6	--	--
	01-15-88	--	74	15	2.8	.8	2.7	13	--	--
472533094284500	08-14-87	5.8	33	6.4	2.8	1.0	1.8	7.1	.1	19
472537094261700	08-17-87	2.6	59	10	1.2	1.9	1.9	4.3	.1	15
472553094384500	09-01-87	17	67	19	4.2	1.8	2.6	4.7	.1	20
472724095055200	08-27-87	5.8	89	25	4.4	1.7	2.9	7.9	.1	20
472813095160200	09-04-87	7.9	98	43	1.1	2.7	1.6	7.6	.2	22
473140095041200	08-27-87	9.5	62	23	1.6	2.2	1.5	4.0	.1	21
473150095210500	08-03-87	2.4	110	36	10	2.7	73	6.3	.2	23
473236094505400	08-25-87	7.7	73	19	2.4	1.0	1.2	11	.1	20
	01-15-88	--	--	--	--	--	--	--	--	--
473306094480000	09-01-87	7.1	61	15	1.5	.8	1.7	9.6	.1	12
473410095073000	08-27-87	48	78	22	4.1	1.4	3.6	9.9	.1	19

Table C-2.--*Water-quality data for wells completed in unconfined-drift aquifer in areas of forest land use*--Continued

Station number	Date	Phenols, total (µg/L)	Solids, dissolved, residue at 180 °C (mg/L)	Elevation of land surface datum (feet above sea level)	Depth of well, total (feet)	Depth of water level below land surface (feet)	Specific conductance, lab (µs/cm)	Alkalinity, lab (mg/L as $CaCO_3$)
471546094331700	08-17-87	1	153	1300	13	7.5	253	118
472201094320400	08-17-87	2	280	1325	28	21	497	245
472300094231800	10-14-87	--	241	1323	25	15	432	222
	01-15-88	--	246	1323	25	18	420	213
472533094284500	08-14-87	40	129	1315	13	2.9	224	111
472537094261700	08-17-87	2	216	1315	13	9.2	370	190
472553094384500	09-01-87	<1	275	1308	14	4.8	473	240
472724095055200	08-27-87	2	352	1375	24	6.1	607	217
472813095160200	09-04-87	3	426	1525	36	32	732	314
473140095041200	08-27-87	2	269	1410	16	8.0	552	197
473150095210500	08-03-87	<1	454	1470	31	--	837	341
473236094505400	08-25-87	2	298	1355	20	8.9	485	170
	01-15-88	--	--	1355	21	--	--	--
473306094480000	09-01-87	<1	225	1370	14	6.5	405	163
473410095073000	08-27-87	<1	358	1400	16	5.9	500	293

Table C-3.--*Water-quality data for wells completed in unconfined-drift aquifer in areas of commercial land use*

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

Station number	Date	Temperature, water (°C)	Temperature, air (°C)	Barometric, pressure (mm of Hg)	Specific conductance (µS/cm)	pH (standard units)	Alkalinity, total, IT, field (mg/L as $CaCO_3$)	Bicarbonate, IT, field (mg/L as HCO_3)
472240094361400	08-06-87	10.5	21	750	--	6.8	326	398
472250094395300	08-06-87	9.0	22	750	345	7.5	198	241
472705094521800	08-04-87	12	23	--	1800	7.3	270	339
472750094523300	08-05-87	15	24	--	918	6.7	434	529
472816094541200	07-30-87	11	31	750	590	7.5	--	--
472818094525200	07-30-87	17	28	750	1060	7.0	--	--
472919094540700	07-29-87	9.0	28	--	1080	6.6	--	--
472925094525200	10-16-87	8.5	11	--	694	7.1	278	--
	01-20-88	--	-7	--	590	--	--	--
	07-30-87	9.4	28	750	593	7.7	--	--
473017094542400	07-30-87	9.5	31	750	550	7.9	--	--
473029094565800	08-05-87	11	23	750	275	7.6	136	166
	01-15-88	--	-3	--	--	--	--	--
473044095043500	08-04-87	9.7	23	--	697	7.0	437	533
473045094545400	08-03-87	13	25	750	440	7.4	254	310
473049094524200	07-29-87	9.0	33	750	410	7.5	--	--

Table C-3.--*Water-quality data for wells completed in unconfined-drift aquifer in areas of commercial land use*--Continued

Station number	Date	Nitrogen, ammonia, dissolved (mg/L as N)	Nitrogen, ammonia plus organic, dissolved (mg/L as N)	Nitrogen, nitrite plus nitrate, dissolved (mg/L as N)	Phosphorous, dissolved (mg/L as P)	Phosphorous, orthro, dissolved (mg/L as P)	Carbon, organic, total (mg/L as C)	Calcium, dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as Mg)	Sodium, dissolved (mg/L as Na)
472240094361400	08-06-87	0.12	1.9	<0.10	0.01	.001	19	99	14	3.4
472250094395300	08-06-87	.02	.5	.48	.04	.03	11	56	13	2.2
472705094521800	08-04-87	.03	.7	1.4	.10	.07	5.4	110	19	230
472750094523300	08-05-87	8.50	1.4	<.10	.07	.07	44	120	14	22
472816094541200	07-30-87	.11	.6	--	<.01	.001	8.0	76	18	38
472818094525200	07-30-87	4.20	4.2	--	.03	.01	11	150	20	49
472919094540700	07-29-87	1.20	1.1	--	.01	.01	13	190	64	20
472925094525200	10-16-88	--	.6	--	--	.01	--	98	27	19
	01-20-87	.03	.3	4.7	--	<.001	--	82	22	19
	07-30-87	.40	.7	--	<.01	<.005	4.3	--	--	--
473017094542400	07-30-87	.02	.5	--	.02	.01	6.4	61	13	47
473029094565800	08-05-87	.06	.4	1.7	.04	.02	5.3	43	9.8	2.1
	01-15-87	--	--	--	--	.00	--	--	--	--
473044095043500	08-04-87	.18	.6	1.9	.01	.02	9.4	100	25	22
473045094545400	08-03-87	.05	1	<.10	.03	.02	12	71	17	1.9
473049094524200	07-29-87	.04	3	--	.01	.002	5.8	63	18	4.1

Table C-3.--*Water-quality data for wells completed in unconfined-drift aquifer in areas of commercial land use*--Continued

Station number	Date	Potassium, dissolved (mg/L as K)	Cloride, dissolved (mg/L as Cl)	Sulfate, dissolved (mg/L as SO_4)	Silica, dissolved (mg/L as SiO_2)	Arsenic, dissolved (µg/L as As)	Barium, dissolved (µg/L as Ba)	Boron, dissolved (µg/L as B)	Cadmium, dissolved (µg/L as Cd)	Chromium, dissolved (µg/L as Cr)
472240094361400	08-06-87	1.2	1.0	14	32	4	150	80	<1	<10
472250094395300	08-06-87	.9	.6	5.8	20	<1	44	20	<1	<10
472705094521800	08-04-87	1.6	380	19	21	1	92	<10	<1	<10
472750094523300	08-05-87	36	63	25	43	1	290	30	<1	<10
472816094541200	07-30-87	2.8	25	16	22	1	140	40	<1	<10
472818094525200	07-30-87	5.0	81	17	35	14	300	120	2	<10
472919094540700	07-29-87	5.0	10	3.1	35	7	170	40	3	<10
472925094525200	10-16-87	2.1	61	22	--	--	--	--	--	--
	01-20-88	1.8	30	15	--	--	--	--	--	--
	07-30-87	--	40	14	--	--	--	60	--	--
473017094542400	07-30-87	2.6	52	10	20	<1	56	20	<1	<10
473029094565800	08-05-87	.6	4.8	4.2	19	1	22	20	<1	30
	01-15-88	--	--	--	--	--	--	--	--	--
473044095043500	08-04-87	1.6	6.8	12	24	7	140	70	<1	310
473045094545400	08-03-87	1.2	1.5	14	17	1	62	10	<1	<10
473049094524200	07-29-87	1.8	1.1	2.1	23	3	96	20	1	<10

Table C-3.--*Water-quality data for wells completed in unconfined-drift aquifer in areas of commercial land use*--Continued

Station number	Date	Iron, dissolved (µg/L as Fe)	Lead, dissolved (µg/L as Pb)	Manganese, dissolved (µg/L as Mn)	Aluminum, dissolved (µg/L as Al)	Selenium, dissolved (µg/L as Se)	Phenols, total (µg/L)	Solids, dissolved, residue at 180 °C (mg/L)	Mercury, dissolved (µg/L as Hg)	Elevation of land surface datum, (feet above sea level	Depth of well, total (feet)
472240094361400	08-06-87	5400	<5	4800	20	<1.	8	370	<0.1	1320	23
472250094395300	08-06-87	43	<5	13	20	<1.	<1	207	<.1	1320	23.5
472705094521800	08-04-87	13	<5	9.0	30	<1.	<1	1020	<.1	1355	14.3
472750094523300	08-05-87	8000	<5	700	20	<1.	2	580	.2	1345	10.8
472816094541200	07-30-87	2100	<10	220	<10	<1.	<1	330	.2	1343	15
472818094525200	07-30-87	12000	<10	2300	--	<1.	1	659	1.1	1342	8
472919094540700	07-29-87	20000	10	1700	10	<1.	2	787	.3	1357	30
472925094525200	10-16-87	--	--	--	--	--	--	438	--	1375	40
	01-20-88	--	--	--	--	--	--	366	--	1375	40
	07-30-87	--	--	--	--	--	4	355	.1	1375	40
473017094542400	07-30-87	<3	<10	1.0	<10	<1.	2	328	.1	1380	22
473029094565800	08-05-87	31	<5	7.0	20	<1.	1	174	.1	1381	13.5
	01-15-88	--	--	--	--	--	--	--	--	1381	18
473044095043500	08-04-87	3600	<5	670	20	2.	<1	420	.1	1407	14
473045094545400	08-03-87	88	<5	800	20	<1.	2	275	.1	1380	17
473049094524200	07-29-87	150	<10	220	30	<1.	1	240	.1	1350	21

Table C-3.--*Water-quality data for wells completed in unconfined-drift aquifer in areas of commercial land use*--Continued

Station number	Date	Depth of water level below land surface (feet)	Dichloro-bromo-methane, total (µg/L)	Carbon-tetra-chloride, total (µg/L)	1,2-Di-chloro-ethane, total (µg/L)	Bromoform, total (µg/L)	Chloro-dibromo-methane, total (µg/L)	Chloroform, total (µg/L)	Toluene, total (µg/L)	Benzene, total (µg/L)	Chloro-benzene, total (µg/L)	Chloroethane, total (µg/L)
472240094361400	08-06-87	16.88	<3	<3	<3.	<3.	<3.	<3.	<3.	<3.	<3.	<3.
472250094395300	08-06-87	15.70	<3	<3	<3.	<3.	<3.	<3.	<3.	<3.	<3.	<3.
472705094521800	08-04-87	12.78	<3	<3	<3.	<3.	<3.	<3.	<3.	<3.	<3.	<3.
472750094523300	08-05-87	5.20	<3	<3	<3.	<3.	<3.	<3.	<3.	<3.	<3.	<3.
472816094541200	07-30-87	1.29	<3	<3	<3.	<3.	<3.	<3.	<3.	<3.	<3.	<3.
472818094525200	07-30-87	3.00	<3	<3	<3.	<3.	<3.	<3.	<3.	<3.	<3.	<3.
472919094540700	07-29-87	20.9	<3	<3	<3.	<3.	<3.	<3.	<3.	<3.	<3.	<3.
472925094525200	10-16-87	31.6	--	--	--	--	--	--	--	--	--	--
	01-20-88	33.2	--	--	--	--	--	--	--	--	--	--
	07-30-87	32.52	--	--	--	--	--	--	--	--	--	--
473017094542400	07-30-87	17.76	<3	<3	<3.	<3.	<3.	<3.	<3.	<3.	<3.	<3.
473029094565800	08-05-87	--	<3	<3	<3.	<3.	<3.	<3.	<3.	<3.	<3.	<3.
	01-15-88	--	--	--	--	--	--	--	--	--	--	--
473044095043500	08-04-87	5.45	<3	<3	<3.	<3.	<3.	<3.	<3.	<3.	<3.	<3.
473045094545400	08-03-87	7.02	<3	<3	<3.	<3.	<3.	<3.	<3.	<3.	<3.	<3.
473049094524200	07-29-87	0.44	<3	<3	<3.	<3.	<3.	<3.	<3.	<3.	<3.	<3.

Table C-3.--*Water-quality data for wells completed in unconfined-drift aquifer in areas of commercial land use*--Continued

Station number	Date	Ethylbenzene, total (µg/L)	Methyl-bromide, total (µg/L)	Methyl-chloride, total (µg/L)	Methylene-chloride, total (µg/L)	Tetrachloro-ethylene, total (µg/L)	Trichloro-fluoro-methane, total (µg/L)	1,1-Dichloro-ethane, total (µg/L)	1,1-Dichloro-ethylene, total (µg/L)	1,1,1-Tri-chloro-ethane, total (µg/L)	1,1,2-Tri-chloro-ethane, total (µg/L)
472240094361400	08-06-87	<3.	<3.	<3.	<3	<3.	<3.	<3.	<3.	<3.	<3.
472250094395300	08-06-87	<3.	<3.	<3.	<3	<3.	<3.	<3.	<3.	<3.	<3.
472705094521800	08-04-87	<3.	<3.	<3.	<3	<3.	<3.	<3.	<3.	<3.	<3.
472750094523300	08-05-87	<3.	<3.	<3.	<3.	<3.	<3.	<3.	<3.	<3.	<3.
472816094541200	07-30-87	<3.	<3.	<3.	<3.	<3.	<3.	<3.	<3.	<3.	<3.
472818094525200	07-30-87	<3.	<3.	<3.	<3.	<3.	<3.	<3.	<3.	<3.	<3.
472919094540700	07-29-87	<3.	<3.	<3.	<3.	<3.	<3.	<3.	<3.	<3.	<3.
472925094525200	10-16-87	--	--	--	--	--	--	--	--	--	--
	01-20-88	--	--	--	--	--	--	--	--	--	--
	07-30-87	--	--	--	--	--	--	--	--	--	--
473017094542400	07-30-87	<3.	<3.	<3.	<3.	<3.	<3.	<3.	<3.	<3.	<3.
473029094565800	08-05-87	<3.	<3.	<3.	<3.	<3.	<3.	<3.	<3.	<3.	<3.
	01-15-88	--	--	--	--	--	--	--	--	--	--
473044095043500	08-04-87	<3.	<3.	<3.	<3.	<3.	<3.	<3.	<3.	<3.	<3.
473045094545400	08-03-87	<3.	<3.	<3.	<3.	<3.	<3.	<3.	<3.	<3.	<3.
473049094524200	07-29-87	<3.	<3.	<3.	<3.	<3.	<3.	<3.	<3.	<3.	<3.

Table C-3.--*Water-quality data for wells completed in unconfined-drift aquifer in areas of commercial land use*--Continued

Station number	Date	1,1,2,2-Tetra-chloro-ethane, total (µg/L)	1,2-Dichloro-benzene, total (µg/L)	1,2-Dichloro-propane, total (µg/L)	1,2-Transdi-chloro-ethene, total (µg/L)	1,3-Dichloro-propene, total (µg/L)	1,3-Dichloro-benzene, total (µg/L)	1,4-Dichloro-benzene, total (µg/L)	2-Chloro-ethylvinyl-ether, total (µg/L)	Dichloro-difluoro-methane, total (µg/L)
472240094361400	08-06-87	<3.	<3.	<3.	<3.	<3.	<3.	<3.	<3.	<3.
472250094395300	08-06-87	<3.	<3.	<3.	<3.	<3.	<3.	<3.	<3.	<3.
472705094521800	08-04-87	<3.	<3.	<3.	<3.	<3.	<3.	<3.	<3.	<3.
472750094523300	08-05-87	<3.	<3.	<3.	<3.	<3.	<3.	<3.	<3.	<3.
472816094541200	07-30-87	<3.	<3.	<3.	<3.	<3.	<3.	<3.	<3.	<3.
472818094525200	07-30-87	<3.	<3.	<3.	<3.	<3.	<3.	<3.	<3.	<3.
472919094540700	07-29-87	<3.	<3.	<3.	17	<3.	<3.	<3.	<3.	5.5
472925094525200	10-16-87	--	--	--	--	--	--	--	--	--
	01-20-88	--	--	--	--	--	--	--	--	--
	07-30-87	--	--	--	--	--	--	--	--	--
473017094542400	07-30-87	<3.	<3.	<3.	<3.	<3.	<3.	<3.	<3.	<3.
473029094565800	08-05-87	<3.	<3.	<3.	<3.	<3.	<3.	<3.	<3.	<3.
	01-15-88	--	--	--	--	--	--	--	--	--
473044095043500	08-04-87	<3.	<3.	<3.	<3.	<3.	<3.	<3.	<3.	<3.
473045094545400	08-03-87	<3.	<3.	<3.	<3.	<3.	<3.	<3.	<3.	<3.
473049094524200	07-29-87	<3.	<3.	<3.	<3.	<3.	<3.	<3.	<3.	<3.

Table C-3.--*Water-quality data for wells completed in unconfined-drift aquifer in areas of commercial land use*--Continued

Station number	Date	Trans-1,3-di-chloro-propene, total (µg/L)	Cis-1,3-di-chloro-propene, total (µg/L)	1,2-Dibromo-ethylene, total (µg/L)	Vinyl chloride, total (µg/L)	Trichloro-ethylene, total (µg/L)	Styrene, total (µg/L)	Xylene, total recoverable (µg/L)
472240094361400	08-06-87	<3.	<3.	<3.	<3.	<3.	<3.	<3.
472250094395300	08-06-87	<3.	<3.	<3.	<3.	<3.	<3.	<3.
472705094521800	08-04-87	<3.	<3.	<3.	<3.	<3.	<3.	<3.
472750094523300	08-05-87	<3.	<3.	<3.	<3.	<3.	<3.	<3.
472816094541200	07-30-87	<3.	<3.	<3.	<3.	<3.	<3.	<3.
472818094525200	07-30-87	<3.	<3.	<3.	<3.	<3.	<3.	<3.
472919094540700	07-29-87	<3.	<3.	<3.	<3.	<3.	<3.	<3.
472925094525200	10-16-87	--	--	--	--	--	--	--
	01-20-88	--	--	--	--	--	--	--
	07-30-87	--	--	--	--	--	--	--
473017094542400	07-30-87	<3.	<3.	<3.	<3.	<3.	<3.	<3.
473029094565800	08-05-87	<3.	<3.	<3.	<3.	<3.	<3.	<3.
	01-15-88	--	--	--	--	--	--	--
473044095043500	08-04-87	<3.	<3.	<3.	<3.	<3.	<3.	<3.
473045094545400	08-03-87	<3.	<3.	<3.	<3.	<3.	<3.	<3.
473049094524200	07-29-87	<3.	<3.	<3.	<3.	<3.	<3.	<3.

Table C-4.--*Water-quality data for wells completed in unconfined-drift aquifer in areas of residential land use*

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

Station number	Date	Temperature, water (°C)	Temperature, air (°C)	Barometric pressure (mm of Hg)	Specific conductance (µS/cm)	pH (standard units)	pH, lab (standard units)	Alkalinity, total, FET, field (mg/L as $CACO_3$)	Alkalinity, total, IT, field (mg/L as $CACO_3$)
472652094532000	08-25-87	8.0	20	--	290	7.7	7.7	182	182
	10-14-87	9.0	15	--	358	7.9	7.8	184	184
472729094505500	08-13-87	8.5	25	745	467	7.8	7.8	214	216
472740094503400	08-12-87	8.4	22	745	409	7.8	7.8	188	190
	01-15-88	--	-3	--	--	--	--	--	--
472740094512700	09-07-87	17.0	17	--	689	7.3	7.6	218	228
472757094531100	08-12-87	13.0	25	745	730	7.0	7.5	262	262
472846094533700	08-11-87	15.5	26	750	605	7.3	7.4	222	222
472938094522800	08-10-87	17.5	24	--	890	6.9	7.0	372	372
472940094531100	08-11-87	9.5	22	750	418	7.9	7.8	196	196
472949094531500	08-12-87	12.5	25	745	630	7.4	7.5	254	258
473031094490100	08-12-87	7.5	22	745	690	7.5	7.7	266	266

Table C-4.--*Water-quality data for wells completed in unconfined-drift aquifer in areas of residential land use*--Continued

Station number	Date	Bicarbonate, FET, field (mg/L as HCO_3)	Bicarbonate, IT, field (mg/L as HCO_3)	Nitrogen, ammonia, dissolved (mg/L as N)	Nitrogen, ammonia plus organic, dissolved (mg/L as N)	Nitrogen, nitrite plus nitrate, dissolved (mg/L as N)	Phosphorous, dissolved (mg/L as P)	Phosphorous, ortho, dissolved (mg/L as P)	Carbon, organic total (mg/L as C)	Calcium, dissolved (mg/L as Ca)
472652094532000	08-25-87	--	222	0.01	0.3	1.20	0.07	0.05	4.9	58
	10-14-87	--	--	.01	<.2	1.3	--	.06	--	59
472729094505500	08-13-87	--	264	<.01	.6	4.5	.08	.07	5.9	69
472740094503400	08-12-87	--	232	<.01	.4	5.3	.06	.06	5.5	55
	01-15-88	--	--	--	--	3.7	--	--	--	--
472740094512700	09-07-87	--	278	.02	.5	6.2	.08	.06	<.1	97
472757094531100	08-12-87	--	320	.03	.9	0.19	.28	.22	8.0	100
472846094533700	08-11-87	--	271	.03	1.1	7.80	.03	.03	4.3	88
472938094522800	08-10-87	--	454	.02	5.4	<.10	.40	.40	11	130
472940094531100	08-11-87	239	--	.01	.4	.36	.01	.01	19.0	62
472949094531500	08-12-87	--	315	.02	1.1	2.5	.02	.02	6.2	78
473031094490100	08-12-87	--	325	.04	.4	2.4	.02	.02	4.0	84

Station number	Date	Magnesium, dissolved (mg/L as Mg)	Sodium, dissolved (mg/L as Na)	Potassium, dissolved (mg/L as K)	Chloride, dissolved (mg/L as Cl)	Sulfate, dissolved (mg/L as SO_4)	Fluoride, dissolved (mg/L as F)	Silica, dissolved (mg/L as SiO_2)	Arsenic, dissolved (µg/L as As)	Barium, dissolved (µg/L as Ba)
472652094532000	08-25-87	13	2.3	1.4	6.5	8.2	0.1	23	2	38
	10-14-87	13	1.9	1.6	10	8.4	--	--	--	--
472729094505500	08-13-87	16	9.7	1.0	8.1	11	.1	22	2	57
472740094503400	08-12-87	12	17	.9	8.8	13	.1	21	<1	41
	01-15-88	--	--	--	--	--	--	--	--	--
472740094512700	09-07-87	19	31	1.5	85	18	.1	27	2	58
472757094531100	08-12-87	19	19	.7	57	19	.1	29	2	40
472846094533700	08-11-87	18	13	4.3	34	21	.2	18	<1	66
472938094522800	08-10-87	23	23	3.3	64	10	.1	29	1	--
472940094531100	08-11-87	11	16	1.2	13	9.1	.1	16	<1	53
472949094531500	08-12-87	18	30	1.3	59	13	.1	22	1	55
473031094490100	08-12-87	14	41	1.4	93	12	.1	16	2	48

Table C-4.--***Water-quality data for wells completed in unconfined-drift aquifer in areas of residential land use***--Continued

Station number	Date	Boron, dissolved (µg/L as B)	Cadmium, dissolved (µg/L as Cd)	Chromium, dissolved (µg/L as Cr)	Iron, dissolved (µg/L as Fe)	Lead, dissolved (µg/L as Pb)	Manganese, dissolved (µg/L as Mn)	Aluminum, dissolved (µg/L as Al)	Selenium, dissolved (µg/L as Se)	Phenols, total (µg/L)
472652094532000	08-25-87	<10	<1	<10	6.0	<5	2.0	20	<1	4
	10-14-87	--	--	--	--	--	--	--	--	--
472729094505500	08-13-87	80	<1	10	5.0	<5	2.0	<10	<1	<1
472740094503400	08-12-87	40	<1	60	14	<5	10	10	<1	2
	01-15-88	--	--	--	--	--	--	--	--	--
472740094512700	09-07-87	50	1	<10	8.0	<5	4.0	<10	<1	1
472757094531100	08-12-87	50	<1	30	6.0	<5	9.0	<10	<1	1
472846094533700	08-11-87	30	<1	10	8.0	<5	22	<10	<1	2
472938094522800	08-10-87	50	<1	<10	2300	<5	590	20	<1	3
472940094531100	08-11-87	20	<1	70	22	<5	38	20	<1	2
472949094531500	08-12-87	40	<1	<10	7	<5	<1.0	20	<1	20
473031094490100	08-12-87	<10	<1	90	8	<5	7.0	<10	<1	2

Station number	Date	Solids, dissolved, residue at 180 °C (mg/L)	Mercury, dissolved (µg/L as Hg)	Elevation of land surface (feet above sea level)	Depth of well, total (feet)	Depth of water level below land surface (feet)	Specific conductance, lab (µs/cm)	Alkalinity, lab (mg/L as $CACO_3$)
472652094532000	08-25-87	218	<0.1	1360	24	14.5	373	173
	10-14-87	224	--	1360	24	15.4	397	179
472729094505500	08-13-87	281	.2	1363	21.5	18.3	479	217
472740094503400	08-12-87	249	<.1	1365	30	24.1	434	184
	01-15-88	--	--	1365	30	--	--	--
472740094512700	09-07-87	450	.1	1350	12.5	5.10	796	191
472757094531100	08-12-87	425	<.1	1345	7	5.05	708	271
472846094533700	08-11-87	357	.2	1353	21.4	15.8	608	222
472938094522800	08-10-87	508	.1	1345	7	2.30	862	367
472940094531100	08-11-87	246	.2	1378	35	26.4	440	200
472949094531500	08-12-87	364	<.1	1360	14	7.50	631	220
473031094490100	08-12-87	448	.2	1368	38	28.0	722	213

Table C-5.--*Water-quality data for wells completed in confined-drift aquifer*

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

Station number	Date	Temperature water (°C)	Temperature air (°C)	Barometric pressure (mm of Hg)	Specific conductance (μs/cm)	pH (standard units)	Alkalinity, Total IT, field (mg/L as $CaCO_3$)
471222094445800	09-03-87	12.5	20	--	555	7.5	344
472103095030100	09-03-87	11.5	21	--	581	7.0	210
472347094461000	09-01-87	8.0	21	--	459	7.6	272
472409094592200	09-03-87	8.5	21	--	374	7.4	210
	10-19-87	7.5	7	--	373	7.8	212
	01-18-88	--	-2	--	380	7.8	--
473005095241800	08-21-87	14.0	22	--	600	7.3	470
473010094494000	09-05-87	12.0	19	--	--	7.8	240
473107095240300	08-20-87	12.0	23	745	615	7.6	390
473332095284000	08-21-87	12.0	21	--	510	7.7	306
473512094475100	09-02-87	11.5	21	--	534	7.6	304
473606094481200	08-19-87	13.0	22	745	465	7.6	338
473700094553300	09-05-87	9.0	17	--	506	7.7	278
473721094452200	08-19-87	12.0	2.3	750	--	7.3	364
473802095243100	08-21-87	7.5	22	--	890	7.2	516
473832095253300	08-21-87	8.0	22	--	750	7.5	448
473924095161100	08-20-87	15.	24	--	600	8.1	378
473957094592000	09-05-87	10.	17	--	546	7.3	328
474002094453300	09-02-87	12.5	21	--	785	7.4	468
474618095153200	08-20-87	8.5	24	--	320	7.6	196
474620095151700	08-20-87	8.5	24	--	590	7.5	--

Table C-5.--*Water-quality data for wells completed in confined-drift aquifer*--Continued

Station number	Date	Bicarbonate, IT, field (mg/L as HCO_3)	Nitrogen, ammonia dissolved (mg/L as N)	Nitrogen, ammonia plus organic, dissolved (mg/L as N)	Nitrogen, nitrite plus nitrate, dissolved (mg/L as N)	Phosphorous, dissolved (mg/L as P)	Phosphorus, ortho, dissolved (mg/L as P)	Carbon, organic total (mg/L as C)	Calcium, dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as Mg)
471222094445800	09-03-87	419	0.08	<0.2	<0.10	<.005	0.001	1.0	88	27
472103095030100	09-03-87	256	1.20	1.5	<.10	<.005	<.001	6.1	94	22
472347094461000	09-01-87	331	.04	.4	<.10	.006	.003	0.5	74	20
472409094592200	09-03-87	256	<.01	<.2	.30	.04	.03	0.7	60	16
	10-19-87	--	.02	.3	.34	.04	.01	--	61	15
	01-18-88	--	.01	.2	.32	--	.03	--	60	16
473005095241800	08-21-87	573	.03	.6	<.10	.06	.01	1.3	90	31
473010094494000	09-05-87	288	.05	<.2	<.10	.13	.11	4.5	--	--
473107095240300	08-20-87	476	.25	1.0	<.10	.006	.01	2.1	87	32
473332095284000	08-21-87	373	.40	.4	<.10	.010	.003	--	74	24
473512094475100	09-02-87	370	.20	.2	<.10	<.005	<.001	--	81	24
473606094481200	08-19-87	412	.18	1.1	<.10	.01	.011	1.1	73	22
473700094553300	09-05-87	338	.36	.5	<.10	<.005	<.005	2.5	74	25
473721094452200	08-19-87	444	.05	.4	<.10	<.005	<.005	1.7	92	31
473802095243100	08-21-87	629	.34	.8	<.10	.01	.005	2.4	130	60
473832095253300	08-21-87	547	.55	.7	<.10	4.01	.004	--	98	48
473924095161100	08-20-87	461	.02	.4	<.10	.01	.006	--	77	40
473957094592000	09-05-87	400	.16	.2	<.10	<.005	.001	1.6	80	26
474002094453300	09-02-87	575	<.01	.2	<.10	.06	.05	6.1	--	--
474618095153200	08-20-87	239	.18	.7	<.10	.01	.01	--	54	16
474620095151700	08-20-87	449	1.10	1.2	<.10	.01	.01	2.3	74	34

Table C-5.--*Water-quality data for wells completed in confined-drift aquifer*--Continued

Station number	Date	Sodium, dissolved (mg/L as Na)	Potassium, dissolved (mg/L as K)	Chloride, dissolved (mg/L as Cl)	Sulfate, dissolved (mg/L as SO_4)	Fluoride, dissolved (mg/L as F)	Silica, dissolved (mg/L as SiO_2)	Phenols, total (µg/L)	Solids, dissolved, residue at 180 °C (mg/L)	Elevation of land surface (feet above sea level)	Depth of well, total (feet)	Depth of water level below land surface (feet)
471222094445800	09-03-87	7.1	1.9	0.4	40	0.2	19	3	342	1350	94	27
472103095030100	09-03-87	4.0	3.1	0.7	3.5	.1	27	<1	362	1454	51	10
472347094461000	09-01-87	2.7	1.6	0.6	5.9	.1	18	3	281	1370	110	36
472409094592200	09-03-87	2.3	1.0	0.6	11	.1	18	2	227	1404	76	52
	10-19-87	--	1.0	0.9	8.0	--	--	--	233	1404	76	52
	01-18-88	1.9	0.9	0.6	8.6	--	--	--	229	1404	76	--
473005095241800	08-21-87	3.4	3.0	1.9	11	.2	21	<1	393	1510	90	60
473010094494000	09-05-87	--	0.3	0.4	5.9	.1	23	2	277	1360	54	3
473107095240300	08-20-87	17	2.4	6.1	0.9	.2	25	<1	400	--	170	30
473332095284000	08-21-87	8.4	2.4	0.4	1.8	.2	19	--	325	1490	152	30
473512094475100	09-02-87	6.1	2.5	0.4	6.1	.1	26	--	311	1355	74	20
473606094481200	08-19-87	5.2	2.1	0.5	2.8	.2	23	3	296	1375	105	22
473700094553300	09-05-87	4.4	2.6	0.4	1.1	.2	22	1	299	1355	68	40
473721094452200	08-19-87	3.3	2.0	1.7	11	.2	25	1	380	1360	44	22
473802095243100	08-21-87	8.6	5.7	6.4	88	.2	28	2	583	1490	85	69
473832095253300	08-21-87	29	5.0	1	61	.2	22	--	506	1460	155	9.2
473924095161100	08-20-87	14	4.8	0.9	6.9	.3	20	--	392	1450	212	--
473957094592000	09-05-87	4.5	2.5	0.3	6.4	.2	24	<1	320	1385	116	50
474002094453300	09-02-87	220.0	0.8	2.3	9.0	.2	29	1	547	1385	147	42
474618095153200	08-20-87	1.4	2.4	0.6	1.3	.2	27	--	232	--	--	--
474620095151700	08-20-87	18	3.1	0.7	1.4	.2	23	<1	358	--	356	100

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