Geology and Ground-Water Conditions of the Redwood Falls Area Redwood County, Minnesota

By GEORGE R. SCHINER *and* ROBERT SCHNEIDER

CONTRIBUTIONS TO THE HYDROLOGY OF THE UNITED STATES

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CONTENTS

	Page
Abstract	R1
Introduction	2
Purpose and scope	2
Methods of investigation	2
Previous reports	3
Acknowledgments	3
Well-numbering system	4
Geography	5
Location	5
Culture	5
Climate	6
Topography and drainage	6
Geology	7
Summary of geologic history	7
Geologic units and their water-bearing properties	9
Precambrian System	9
Precambrian bedrock surface	11
Cretaceous System	12
Quaternary System	12
Pleistocene deposits	12
Recent deposits	17
Ground water	17
Occurrence	18
Movement	19
Water levels	20
Recharge	22
Discharge	22
Evapotranspiration	23
Springs	23
Aquifer tests	24
General	24
Test at site of well 112.36.14aaa1	25
Test at site of well 112.36.12bbd1	26
Test at site of well 112.36.25abb3	27
Present well development	27
Domestic and stock	28
Municipal	31
Availability of water	31
Surface water	33
Quality of water	34
Summary	40
Well logs	40
Literature cited	43
Index	45

ILLUSTRATIONS

Plates are in separate volume]

PLATE 1. Topographic map of part of report area.
2. Map of area showing surficial geology and Precambrian basement rock.
3. Map showing bedrock surface and sections through report area.
4. Map showing contours on the piezometric surface.
5. Hydrographs of observation wells and graph of monthly precipitation.
6. Hydrograph of observation well 113.36.35add1 and graphs of precipitation and temperatures.
7. Drawdown caused by pumping well 112.36.14aaa1.
8. Drawdowns caused by pumping well 112.36.12bbd1.
9. Drawdowns caused by pumping well 112.36.25abb3.
10. Map showing availability of water and location of wells and test holes.
11. Map of vicinity of Redwood Falls showing location of wells and test holes.

		Page
FIGURE	1. Diagram showing method of numbering wells	R4
	2. Index map showing report area	5
	3. Location of wells used during test pumping of well 112.36.12bbd1	26
	4. Location of wells used during test pumping of well 112.36.25abb3	28
	5. Theoretical drawdown in an aquifer due to pumping a well 350 gpm	32
	6. Theoretical drawdown in an aquifer due to pumping a well 700 gpm	32

TABLES

		Page
TABLE	1. Water-bearing characteristics of geologic units in the Redwood Falls area, Minn	R10
	2. Selected wells in the Redwood Falls area	29
	3. Chemical analyses of waters in the Redwood Falls area	36
	4. Elements, substances, and characteristics commonly found in ground water	38
	5. Selected logs of wells and test holes in the Redwood Falls area	41

CONTRIBUTIONS TO THE HYDROLOGY OF THE UNITED STATES

GEOLOGY AND GROUND-WATER CONDITIONS OF THE REDWOOD FALLS AREA, REDWOOD COUNTY, MINNESOTA

By George R. Schiner and Robert Schneider

ABSTRACT

The Redwood Falls area includes about 80 square miles in southwestern Minnesota and is about 100 miles west of Minneapolis and St. Paul. Its surface is a gently undulating glacial-drift plain, interrupted in part by the large Minnesota River valley and the tributary Redwood River valley. The drift plain was laid down by the Des Moines lobe of the Wisconsin Glaciation and consists chiefly of ground moraine and several subdued recessional moraines. The glacial drift rests either on Precambrian gneiss or on thin patches of Cretaceous sedimentary strata that overlie the Precambrian bedrock.

The glacial drift consists principally of till and some outwash and ranges in thickness from 0 to about 260 feet. It is the chief source of ground water, yielding small supplies almost anywhere in the area and large supplies in at least two places. Where the drift is absent, thin, or impermeable, small yields commonly are obtained from the Precambrian bedrock.

The most notable aquifers in the area are three buried outwash deposits that are associated with a conspicuous southeastward-trending buried bedrock valley. The tops of the aquifers occur about 70, 120, and 200 feet below the land surface, and their maximum known thicknesses are about 25, 55, and 45 feet, respectively. The aquifers are confined largely by relatively impermeable till; however, owing to the movement of water through the till, the drift may be regarded as a hydraulic unit.

The main source of recharge to the ground-water reservoir is local precipitation, and most of the natural discharge is by evapotranspiration. The water table ranges in depth from 0 to about 30 feet below the land surface.

Aquifer tests were made on the three outwash aquifers to determine their hydraulic characteristics. The coefficient of transmissibility (T) of the 200-foot aquifer is about 126,000 gpd (gallons per day) per ft, and the coefficient of storage (S) is about 0.0002. The T and S values of the 120-foot aquifer are about the same as for the 200-foot aquifer. For the 70-foot aquifer the value of T is about 70,000 gpd per ft, and S is about 0.0007. The data suggest that when the artesian head in the aquifers is lowered by pumping, recharge is induced by leakage from the confining beds.

The 120-foot aquifer is considered the best known source of ground water in the area. The city of Redwood Falls has used this aquifer for its water supply since August 1955 and, in 1960, pumped about 106 million gallons from it. The water level in the aquifer had stabilized by late 1956; considerable additional water probably can be obtained from the aquifer. Although the 70-foot aquifer is not as extensive or as thick as the one at 120 feet, large amounts of water probably can be obtained from this aquifer also. The 200-foot aquifer is narrow, elongate, and irregular in form and appears to be very permeable only locally.

Chemical analyses show that water from the glacial-drift aquifers is primarily of the bicarbonate type, is hard, and contains an excessive amount of iron. In places water from the Precambrian bedrock is much softer than water from the drift.

INTRODUCTION

PURPOSE AND SCOPE

This study of the geology and ground-water conditions in the Redwood Falls area, Minnesota, was made by the United States Geological Survey in cooperation with the city of Redwood Falls as part of a Statewide program in cooperation with the Division of Waters Minnesota Department of Conservation. The objective of the program is to evaluate the ground-water resources of the State, so that these resources can be developed most economically and can be utilized to the maximum extent. In many parts of the State, economic growth is restricted by inadequate knowledge of the availability of water supplies.

The geologic and hydrologic conditions in the Redwood Falls area are fairly representative of those of a large region of southwestern Minnesota, adjacent to the Minnesota River. In much of this region, relatively thin unconsolidated glacial deposits of low permeability directly overlie crystalline rocks; consequently, ground-water supplies are generally small. The findings of this investigation can probably be applied effectively in evaluating the ground-water resources of other parts of the Minnesota River valley area.

METHODS OF INVESTIGATION

The fieldwork, begun in the period 1952–54, consisted of collecting and studying the available geologic and hydrologic data pertaining to the area. Well drillers, well owners, and municipal officials were contacted for information in connection with a well inventory. A piezometric surface map was constructed from water-level measurements in selected wells. Periodic water-level measurements were made in observation wells, and aquifer tests were made at three sites to determine the hydraulic characteristics of the water-bearing strata. Chemical analyses of ground water from selected wells were made in the Survey's laboratory at Lincoln, Nebr. Basic data concerning surface water was compiled.

A reconnaissance map of the surficial geology was made using aerial photographs (scale about 3 inches to the mile), and subsurface geologic conditions were determined from records and logs of water wells and test holes. Through the cooperation of the city of Redwood Falls, Survey geologists obtained geologic and hydrologic data by logging 25 test holes in the field. The test holes were drilled by the hydraulic-rotary method, and an electric log was run in each hole with a single-point resistance logger, which also recorded spontaneous potentials.

The altitudes of the wells controlling the piezometric map were obtained by instrumental leveling; others are from the U.S. Geological Survey Redwood Falls (Minn.) topographic quadrangle map (pl. 1). All altitudes are in reference to mean sea level.

During July and August 1952, 64 electrical-resistivity profiles were made to delineate the bedrock topography and to locate water-bearing deposits of potential value as sources of water supply. The work was done by the Geophysics Branch of the Survey. The profiles showed heterogeneity of the glacial deposits and similarity of the resistivity characteristics of the basal section of the glacial deposits, the highly weathered crystalline basement rock, and the sedimentary bedrock formations. The data were used as a general guide in the compilation of a bedrock contour map.

The work was under the immediate supervision of the junior author, who was formerly district geologist for Minnesota.

PREVIOUS REPORTS

The earliest report on the general geology of Redwood County was by Upham (1884, p. 562–588), and it included a section on water-well data. Reports on the geology and underground waters of southern Minnesota by Hall and others (1911) and by Thiel (1944) included sections on Redwood County. A description of the report area is included in Leverett's (1932) study on the regional glacial geology of Minnesota and parts of adjacent states. Lund (1956) described the Precambrian igneous and metamorphic rocks of the Minnesota River valley. In 1947 a report was made on the water supply, distribution system, and sewage disposal for the city of Redwood Falls by the G. M. Orr Engineering Co., Minneapolis, Minn. This report contained information on wells and test holes.

ACKNOWLEDGMENTS

Much of the data on which this report is based was obtained through the cooperation of well owners, well drillers, civil officials, and private citizens. Their interest and cooperation are greatly appreciated.

The author especially thanks Mr. G. W. Stocking, former Redwood Falls city engineer, and Mr. Elwood Fagen, water superintendent, for their assistance.

WELL-NUMBERING SYSTEM

Wells and test holes in Minnesota are numbered by the U.S. Geological Survey in accordance with the U.S. Bureau of Land Management's system of subdivision of the public lands. The first segment of a well or test-hole number indicates the township north of a base line; the second, the range west of the principal meridian; the third, the section in which the well or test hole is situated. The lowercase letters a, b, c, and d, following the section number, locate the well within the section. The first letter denotes the 160-acre tract, the second the 40-acre tract, and the third the 10-acre tract as shown in figure 1. The letters are assigned in a counterclockwise direction, beginning in the northeast quarter. Within each 10-acre tract, consecutive numbers beginning with 1 are added as suffixes in the order in which the wells were recorded.

Figure 1 is a sketch indicating the method of numbering wells in a section. Number 112.36.25ddb1 identifies the first well recorded in NW¼SE¼SE¼ sec. 25, T. 112 N., R. 36 W.

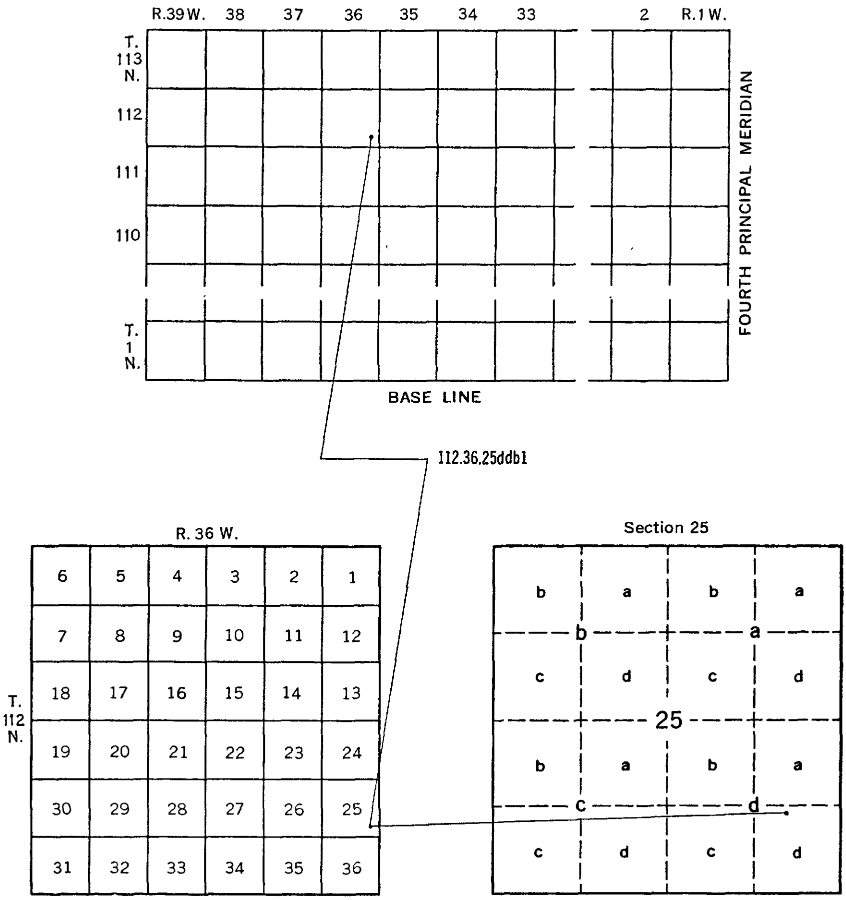

FIGURE 1.—Diagram of section showing method of numbering wells.

GEOGRAPHY

LOCATION

The Redwood Falls area is in southwestern Minnesota, and it occupies about 80 square miles of the northeastern part of Redwood County. It is about 100 miles west of Minneapolis and St. Paul and is bounded approximately by lat 44°28′ and 44°35′ N. and long 95°02′ and 95°15′ W. (fig. 2). Redwood Falls, the only city in the county and the county seat, is in the common corners of Tps. 112 and 113 N. and Rs. 35 and 36 W.

CULTURE

In 1960 the population of Redwood County was 21,718, and that of Redwood Falls was 4,285. Redwood Falls is the center of a rich agricultural region in which the main crops are corn, soybeans, oats, and flaxseed. Granite for building stone is quarried at Morton, about 6

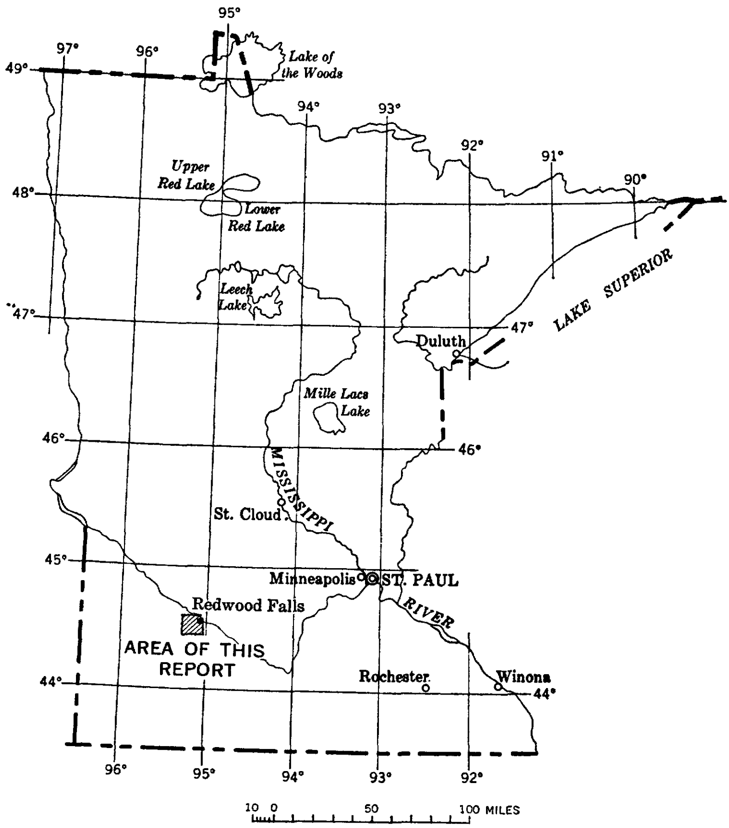

FIGURE 2.—Index map of Minnesota showing the location of the Redwood Falls area.

miles east of Redwood Falls. Shale is quarried from the bluff of the Minnesota River about 4 miles east of Redwood Falls and is used for coloring bricks manufactured at Springfield, Minn., about 20 miles to the southeast. Kaolinized gneiss that crops out in the area was used in the manufacture of paint in about 1868–69, but production costs were excessive and its manufacture was discontinued. About 10 percent of the city's electrical power is produced by a municipally-owned hydroelectric plant on the Redwood River.

The area is served by U.S. Highway 71, State Highways 19 and 93, and by the Chicago and North Western Railway, and the Minneapolis & St. Louis Railway.

The Federal Aviation Agency maintains an emergency airfield and a weather station about 1½ miles east of Redwood Falls.

CLIMATE

The climate of the Redwood Falls area is continental, characterized by wide variations in temperature, scanty winter precipitation, normally ample summer rainfall, and a general tendency to extremes in all climatic features. The main influence on the climate of the area is the succession of high and low pressure cycles that continually sweep across the Northern States from west to east.

For the period 1931–55, the mean monthly temperatures at Redwood Falls ranged from a high of 74.9°F in July to a low of 14.3°F in January and averaged 45.9°F. The mean monthly precipitation ranges from 0.57 inch in January to 4.14 inches in June and averages 23.4 inches annually. The monthly precipitation for the period 1952 through 1956 is shown graphically on plate 5. Daily precipitation and maximum and minimum daily temperatures for 1955 are shown on plate 6.

In Redwood County the major crops are grown from May to August, during which time about 55 percent of the annual rainfall is received. The average number of days without killing frost is about 150.

TOPOGRAPHY AND DRAINAGE

The Redwood Falls area is in the Western Young Drift section of the Central Lowland province (Fenneman, 1938, p. 559). Except for the Minnesota River valley and part of the Redwood River valley, the report area is a smoothly rolling plain underlain by glacial deposits and interrupted by belts of low knolls and ridges. The region is poorly drained, and there are many intermittent shallow ponds and sloughs (swampy depressions). The term "till plain" is used by Fenneman (1938, p. 571–572) to describe this type of glacial topography.

The highest land altitude, about 1,075 feet, is in the southwestern part of the area; the lowest, about 820 feet, is in the Minnesota River valley (pl. 1). The average altitude of the upland surface is about 1,020 feet.

Belts of knolls and ridges, termed moraines, trend southeastward and eastward; some are almost imperceptible on the topographic map and others are prominent. Locally, they may be as much as about 40 feet in height (NE¼ sec. 10, T. 112 N., R. 36 W., and SE¼ sec. 16, T. 112 N., R. 35 W.; see pl. 1).

The southeast-trending Minnesota River drains the area, and its valley is one of the most conspicuous topographic features. Near the village of North Redwood, the Minnesota River valley is about 200 feet deep and 1½ miles wide; however, the Minnesota River occupies only about a 200-foot-wide meandering channel. The valley floor contains many knobs of crystalline rock and numerous small lakes and ponds. Small gullies are common along the steep valley walls. Adjacent to the south bluff of the Minnesota River valley and along the upland surface is a belt about a mile wide that is noticeably flatter than the general surface of the till plain.

A large terrace along the south side of the Minnesota River extends from the SE¼ sec. 4 to the NW¼ sec. 24, T. 113 N., R. 36 W. It is about 4 miles long and ¾ of a mile wide at its widest point.

The Redwood River is tributary to the Minnesota River and flows northeastward in a shallow valley until it crosses a high in the crystalline basement rock in the NW¼ sec. 1, T. 112 N., R. 36 W. At this place there is a waterfall about 30 feet in height. Below the waterfall, for a distance of about half a mile, the meandering river has cut a gorge into the weathered basement rock, forming bluffs more than 100 feet high. The Redwood River valley ranges in width from about one-eighth of a mile within the gorge to more than three-quarters of a mile beyond the gorge. Above the falls the greatest width of the valley is about a quarter of a mile.

Ramsey Creek and that part of Crow Creek in the report area are in relatively shallow valleys. A small waterfall is formed where Ramsey Creek crosses the crystalline basement rock high in the SE¼ sec. 36, T. 113 N., R. 36 W.

GEOLOGY

SUMMARY OF GEOLOGIC HISTORY

The highly complex Precambrian crystalline rocks in the Redwood Falls area are among the oldest known in geologic history and are a subsurface extension of the Precambrian Shield of Canada. The ancient surface on these rocks has been deeply weathered and eroded. No evidence has been found in this area to suggest that deposition occurred between the Precambrian and Cretaceous; therefore, if pre-Cretaceous sediments were deposited, they have been completely removed by erosion. In places the deeply weathered Precambrian surface is capped by a lateritic layer (rocks having a high content of the hydroxides of iron and aluminum) which suggests that at least part of the weathering occurred when the climate was warm and moist, probably during the late Mesozoic Era. In late Cretaceous time, shallow seas encroached from the west and deposited clay, silt, and sand; deltaic, lacustrine, and bog sediments also were deposited. If sediments were deposited between late Cretaceous and Pleistocene time they also were removed by erosion.

During the Pleistocene Epoch, continental glaciers advanced and retreated across the region several times. Although only Wisconsin drift has been recognized in the Redwood Falls area, Leverett (1932, p. 14–35) identified drifts of Nebraskan, Kansan, and Illinoian age in Minnesota. It is possible, therefore, that glaciers advanced over the area during one or more of those stages. The Des Moines ice lobe covered the region during the Cary and Mankato stades of the Wisconsin, moving southward from Canada through the valleys of the Red and Minnesota Rivers to the vicinity of Des Moines in central Iowa (Leverett, 1932, p. 56–57; Flint, 1955, p. 133).

As the Des Moines lobe receded and halted in successive steps, recessional moraines were formed along the edges of the ice. Long halts in the recession were marked by topographically prominent morainic systems, whereas brief halts were marked by subdued moraines. The Antelope moraine (Leverett, 1932, p. 103–104), which was formed during a brief halt in the last retreat of the glacier, extends from eastern Grant County, S. Dak., to the Minnesota valley near the eastern border of Redwood County. Although the moraine is not continuous beyond this point, Leverett (1932, pl. 3) has mapped a section of it on the north side of the Minnesota valley. According to Leverett, the main part of the moraine follows the north side of the Redwood River valley. Near the city of Redwood Falls the moraine probably splits into narrow fingerlike ridges (pl. 2).

The present Minnesota valley began to form during the retreat of the Des Moines lobe. Schwartz and Thiel (1954, p. 272) state that the occurrence of several successively younger outwash plains along the Minnesota valley indicates that the valley was formed by a glacial melt-water river at the margin of the ice. As the ice continued to retreat north and west, the melt waters eventually carved a channel upstream as far as Big Stone Lake, about 80 miles northwest of the Redwood Falls area. Further retreat of the ice resulted in the formation of Glacial Lake Agassiz in the north-sloping Red River valley.

The Minnesota River valley was probably shallow before drainage from Lake Agassiz began and before a rock barrier between St. Paul and Fort Snelling (near Minneapolis) was eroded away. Remnants of the rock barrier can be seen at St. Anthony Falls in the present Mississippi River channel at Minneapolis. Leverett (1932, p. 102) estimates that the valley was deepened at least 100 feet after the barrier was removed. The river that flowed from Lake Agassiz southward is known as the Glacial River Warren. When Lake Agassiz began to drain northward, the water level of the lake was lowered enough to stop the flow of Glacial River Warren across the continental divide at Browns Valley, Minn. (north of Big Stone Lake, about 110 miles northwest of Redwood Falls). The Minnesota River now occupies a narrow meandering channel in the floor of its valley and is one of the country's best examples of an underfit stream. The Redwood River was probably formed as a tributary stream to the Glacial River Warren.

Except for some stream erosion, the glacial topography has been little modified since retreat of the last glacier. Sediments consist mostly of flood-plain and lake and swamp deposits.

GEOLOGIC UNITS AND THEIR WATER-BEARING PROPERTIES

A brief summary of the water-bearing characteristics of the geologic units in the Redwood Falls area is given in table 1, and the availability of ground water is shown on plate 10. The surficial distribution of all the geologic units is shown on the geologic map (pl. 2). Because the Quaternary alluvium and swamp deposits are generally thin, their full extent is not shown.

PRECAMBRIAN SYSTEM

Crystalline rocks of Precambrian age form the basement complex in the area, and they are a part of the Laurentian Upland or Precambrian Shield. These rocks are overlain in most places by Pleistocene or Recent deposits; they are locally overlain by Cretaceous strata.

The Precambrian rocks are part of a group of granites and granite gneisses that crop out in the Minnesota and Redwood River valleys, and are termed the Morton quartz monzonite gneiss (Lund, 1956, p. 1482). Lund (1956) and Goldich (1938) have described in detail the Precambrian rocks in the Redwood Falls area. Lund tentatively assigned the granite gneisses of the Minnesota River valley to late pre-Huronian or Huronian age.

The Precambrian rocks show various stages of alteration, ranging from relatively fresh rock to a deeply weathered clayey mass. The degree of weathering is not uniform, being controlled in part by jointing. The depth of weathering ranges from 0 to about 100 feet.

TABLE 1.—*Water-bearing characteristics of geologic units in the Redwood Falls area, Minn.*

System	Series or Epoch	Geologic unit		Approximate maximum thickness (feet)	Description	Water-bearing characteristics
Quaternary	Recent	Alluvial and swamp deposits.		(?)	Clay, silt, sand, and gravel.	Yields may be sufficient for domestic and stock use in places.
	Pleistocene	Glacial drift	Till	200	Heterogeneous and unsorted material ranging in size from clay to boulders. Contains sand and gravel lenses.	Yields little or no water to wells in most places. Yields may be sufficient for domestic and stock use.
			Outwash	55	Sorted and stratified deposits of clay, silt, sand, gravel, cobbles, and boulders.	Small to large yields, depending on thickness, extent, and permeability. Yield of about 800 gpm obtained in a pumping test.
Cretaceous	Upper	Shale, silt, and possibly sand		15	Predominantly soft shale and some silt. Commonly includes carbonaceous material.	Not determined.
Precambrian				(?)	Quartz monzonite gneiss. Fresh to highly weathered and decomposed.	May yield small supplies in some areas and no water in others. Water obtained from weathered and creviced sections may be sufficient for domestic and stock use.

Unweathered Precambrian bedrock crops out at the falls of the Redwood River in the SE¼SW¼SE¼ sec. 36, T. 113 N., R. 36 W., and the SW¼NE¼NW¼ sec. 1, T. 112 N., R. 36 W. It varies in color from pink to dark gray and has bands of light and dark-colored minerals showing a general mineralogical segregation. Pegmatites, quartz veins, and fine-grained granitic dikes commonly cut the rock. Macroscopic constituents include quartz, pink to red potassium feldspar, light-colored plagioclase, biotite, and magnetite. The knobs of unweathered Precambrian bedrock exposed in the floor of the Minnesota valley are similar to the outcrop at the falls; one example is in the NE¼NE¼NE¼ sec. 32, T. 113 N., R. 35 W. (pl. 2).

Deeply weathered bedrock typically is brown and may be observed in the SE¼SE¼ sec. 36, T. 113 N., R. 36 W., and in the SW¼SW¼ sec. 31, T. 113 N., R. 35 W. At these locations at least 50 feet of the rock is disintegrated to a highly fragmented mass. Other exposures showing approximately the same degree of weathering include a knob in the Minnesota River valley in the NE¼SW¼NE¼ sec. 30, T. 113 N., R. 35 W., and the gorge of the Redwood River in the SW¼NE¼SW¼ sec. 31, T. 113 N., R. 35 W., and the SW¼SW¼NE¼ sec. 36, T. 113 N., R. 36 W.

Where highly weathered, the bedrock is largely a soft kaolinitic clay and is usually blue or green when first exposed, as by gully erosion or by drilling (gully in the NW¼NW¼NW¼ sec. 31, T. 113 N., R. 35 W.). Eventually its color changes to a yellow ash or glistening white (road cut in the SW¼NW¼SW¼ sec. 29, T. 113 N., R. 35 W.).

An outcrop of Precambrian rock having a thick kaolinized zone at its surface forms the north bluff of the Redwood River in Alexander Ramsey Park, northeast of the park shelter area in the SE¼NW¼NE¼ sec. 36, T. 113 N., R. 36 W. It consists of light-gray to white kaolinized gneiss adjacent to less weathered greenish-gray gneiss along what appears to be a fault line. At least 50 feet of the kaolinitic material is exposed, and less weathered bedrock extends another 50 feet to the base of the stream.

Goldich (1938, p. 26) describes the mineralogy of the residual clay formed from the gneiss as follows:

The residual clays are composed chiefly of kaolinite and quartz, the latter derived from the original mineral of the gneiss. Other original minerals are not common. Besides the kaolinite and other clay minerals not positively identified, iron oxides, siderite, leucoxene, and a chlorite-like mineral are weathering products.

A bauxitic laterite usually caps the kaolinized bedrock where it has not been deeply eroded by glaciation or where it is overlain by Cretaceous strata. This laterite is hard and gray, contains brown and red pisolitic structures, and is as much as 4 feet thick in places along the bluff of the Minnesota River.

Yields of wells completed in the Precambrian crystalline rock are erratic. Some wells may yield sufficient water for domestic and stock supplies from fractures in the rock or from the colluvium on the weathered rock surface.

PRECAMBRIAN BEDROCK SURFACE

A map showing generalized contours on the Precambrian bedrock surface (pl. 3) was prepared from test-hole data, drillers' logs, well records, and a study of outcrops. The most significant feature of the bedrock surface is the valley whose axis trends southeast and passes through the NE¼ sec. 14 and through sec. 13, T. 112 N., R. 36 W., sec 19, and the SW¼ sec. 20, and sec. 28, T. 112 N., R. 35 W. In sec. 13, T. 112 N., R. 36 W., the valley is incised at least 150 feet into the bedrock and is at least 4 miles wide. Glacial deposits fill the valley and generally cover the Precambrian surface topography; consequently, except for the areas where the overlying deposits are thin, the buried Precambrian surface has little or no expression in the form of the land surface.

The altitude of the bedrock surface ranges from about 790 feet in the buried valley to approximately 1,000 feet at the falls of the Redwood River. The crest of the falls, in the SW¼NE¼NW¼ sec. 1, T. 112 N., R. 36 W., is part of a local bedrock high that trends southeast. However, the regional slope of the bedrock probably is northeast toward the Minnesota River. The approximate depth to bedrock may be obtained by referring to plates 1 and 3, subtracting the altitude of bedrock given on plate 3 from the altitude of the land surface given on plate 1.

CRETACEOUS SYSTEM

The Cretaceous strata in the Redwood Falls area are classified Late Cretaceous in age (Hall and others, 1911, p. 144–145; Thiel, 1944, p. 369) and are mapped as covering most of the area (Grout and others, 1932). However, information obtained in this investigation from test holes, well logs, and a study of outcrops in the area indicates that the Cretaceous strata are thin and their distribution is patchy. Cretaceous strata crop out locally along the bluffs of the Minnesota and Redwood River valleys (pl. 2). They may cover large areas in the subsurface, but they are extremely difficult to distinguish from the overlying Pleistocene deposits that are derived in part from the Cretaceous sediments. The maximum thickness of the Cretaceous strata in the report area is about 15 feet; the average thickness is less than 3 feet.

The fact that much of the Cretaceous sediments are clayey and carbonaceous, suggests a lagoonal or near-shore environment of deposition. Upham (1884, p. 577–579) described lignitic material of Cretaceous age in the SE¼NW¼SW¼ sec. 30, T. 113 N., R. 35 W. and in the remains of an old caved "coal mine" where the material was mined in 1868 or 1869. A bed of lignite about 3 inches thick crops out near the mine in a 1-foot layer of gray lignitic plastic clay. Beneath the clay is the lateritic layer frequently found on the Precambrian bedrock surface.

Beds of silt and shale totaling 15 feet in thickness are exposed in the SW¼NE¼SE¼ sec. 33, T. 113 N., R. 35 W. The outcrop consists of a highly weathered gray calcareous silt, at least 5 feet thick, that grades laterally into about 15 feet of soft gray shale.

None of the wells inventoried were definitely known to be completed in the Cretaceous strata and, therefore, the water-bearing properties of the Cretaceous in the report area are not known. However, Cretaceous strata yield small to moderate supplies of water in other parts of Redwood County.

QUATERNARY SYSTEM

PLEISTOCENE DEPOSITS

About 90 percent of the land surface in the Redwood Falls area is glacial drift (pl. 2). "Glacial drift" is a general term for all the material that was deposited by glaciers either directly from the ice or from its melt waters. It may be classified into two general types; till and glacioaqueous deposits. Till constitutes the bulk of the drift and consists of a mass of heterogeneous rock fragments ranging in size from clay particles to large boulders, deposited chiefly underneath the ice and little or not at all sorted by water. Glacioaqueous deposits are formed by the combined action of ice and water; consequently, there is considerable variation in the degree of sorting and stratification in these deposits. Ice-contact and outwash deposits are types of glacioaqueous deposits and, although they make up a small percentage of the drift in this area, they are the principal sources of water.

Although glacial drifts older than the Wisconsin have been mapped in southwestern Minnesota, Iowa, and South Dakota, no evidence of their presence was found in the report area. Leverett (1932, p. 14–22) recognized Nebraskan and Kansan drifts in southwestern Minnesota. R. V. Ruhe (written communication, 1950) identified drifts of Nebraskan and Kansan age in northwestern Iowa, and Flint (1955, p. 34) tentatively assigned drifts in northeastern South Dakota and northwestern Iowa to the Nebraskan, Kansan, and Illinoian. The criteria that Flint (1955, p. 31–32) believes to be characteristic of pre-Wisconsin tills in this region—scarcity of large-size rock fragments, pronounced compaction, conspicuous chemical alteration, and distinctive dark hue—have not been observed in the Redwood Falls area. If pre-Wisconsin glacial deposits occur in the area, they probably are in small isolated patches.

The Wisconsin Glaciation has been divided into four stades: The Iowan, Tazewell, Cary, and Mankato (Leighton, 1933). These stades have been identified in southern Minnesota, eastern South Dakota and northern Iowa (R. V. Ruhe, written communication, 1950), and they represent prominent ice advances during the Wisconsin Glaciation. However, buried loess deposits or buried soil zones, which are indicative of multiple glaciation, were not observed in the report area. The only evidence of multiple glaciation in the area is the occurrence of widespread sheets of outwash deposits separated by four till units (section *C–C′*, pl. 3). Providing the surficial till in the area is Mankato in age, the four till units may represent the Iowan, Tazewell, Cary, and Mankato stades of the Wisconsin Glaciation. It is also possible that all the drift in the area was deposited during brief oscillations of an ice sheet in one or more of the late Wisconsin stades.

The surface on the drift in the Redwood Falls area is characterized by swell and swale topography and consists mostly of ground moraine and some recessional moraines. Ground moraine is drift that has been deposited beneath a glacier and is characterized by a plain of low

712–187—64——3

relief. A recessional moraine is a thickened belt of drift, commonly ridgelike, that may contain outwash. The recessional moraine forms at or near the edge of the ice during a halt in the general recession of an ice sheet. The distribution of recessional and ground moraines in the area is shown on plate 2. The narrow fingerlike moraines extending east and southeast from the Redwood River are probably part of Leverett's (1932, p. 103) Antelope moraine, which was formed during the retreat of the Mankato Stade of the Wisconsin Glaciation. According to Leverett, the Antelope moraine can be traced from the west, between Ramsey Creek and the north side of the Redwood River, almost to Redwood Falls. However, the moraine is not conspicuous in the report area, possibly because the topography has been modified by stream erosion.

According to Leverett (1932, p. 105), the southeast-trending moraines between the Antelope moraine and the Minnesota valley, east of Belview (about 6 miles west of Delhi, pl. 1), are probably part of a group of moraines that was formed by gradual melting of a very narrow ice tongue.

The greatest known drift thickness in the Redwood Falls area, 263 feet, is in the NW¼NW¼SE¼ sec. 13, T. 112 N., R. 36 W., where it fills the deepest part of the bedrock valley. The drift is very thin or absent where the Minnesota and Redwood Rivers have eroded into bedrock. The surficial drift is generally light to dark gray, except in the upper part where it is oxidized to a yellow or yellowish brown. The depth of oxidation may be as much as 50 feet, but the average is about 15 to 30 feet below land surface. The lower limit of oxidation is fixed by the depth of active percolation of oxygenated water. The depth of weathering depends principally upon the type and structure of drift materials as well as climate, topography, and vegetation. Although the drift is generaly heterogeneous, a typical section composed of till would be similar to the following idealized section:

Depth (feet)	*Description*
1–4+	Surficial soil, black, noncalcareous to calcareous, silty and clayey; contains some pebbles.
?	Drift, chemically decomposed; gray to yellowish brown, silty, sandy, gravelly; very thin and not clearly evident; present locally.
4–5±	Drift, oxidized and leached, but otherwise little altered; yellowish brown, silty, sandy, gravelly; contains some boulders.
5–30±	Drift, oxidized; contains primary calcium carbonate; yellowish brown, silty, sandy, calcareous; commonly contains some boulders.
30 to bedrock	Drift, unaltered, light to dark gray, silty, sandy, gravelly, calcareous, compact; contains some boulders.

The composition of till is determined by the formations over which the glacier passes. Although large rock fragments are conspicuous, most of the till in the area consists of clay, silt, and sand. The fine texture of the till suggests the glacier that deposited it moved over a surface composed of soft unconsolidated formations such as shale and clay. The following table shows that the most abundant pebble in the till is limestone; granite and shale pebbles are the next most numerous. The sources of the granite and shale pebbles are probably the Precambrian and Cretaceous bedrock underlying western and southwestern Minnesota. The limestone probably was derived from the Paleozoic strata in northwestern Minnesota and southern Manitoba.

Pebble counts of till samples

Location	*Dominant rock types (percentage of pebbles in sample)*
SW¼SE¼SW¼ sec. 17, T. 112 N., R. 36 W.	Limestone (59), granite (24), shale (7), basalt (4).
NE¼NE¼NW¼ sec. 20, T. 112 N., R. 36 W.	Limestone (42), granite (21), shale (11), sandstone (15).
NE¼NE¼NE¼ sec. 20, T. 112 N., R. 36 W.	Limestone (46), granite (13), shale (31), quartzite (5).
NW¼NW¼NE¼ sec. 36, T. 113 N., R. 36 W.	Limestone (50), granite (25), shale (7), basalt (7).
SE¼NW¼SW¼ sec. 36, T. 113 N., R. 36 W.	Limestone (31), granite (14), shale (31), sandstone (13).

Although thick sections of till are exposed in road cuts and stream valleys, slumping and weathering minimize the number of good exposures. Well-defined sections are exposed along the south bank of the Redwood River in secs. 1 and 2, T. 112 N., R. 36 W., and along the bluffs of the Redwood River from the NE¼ sec. 36, T. 113 N., R. 36 W. to the S½ sec. 30, T. 113 N., R. 35 W. The numerous deep gullies that cut the steep bluffs of the Minnesota River, east of Redwood Falls, also expose good sections of till.

Glacioaqueous deposits consisting almost entirely of outwash are the chief source for ground water in the Redwood Falls area. The outwash was deposited by glacial melt-water streams that were subject to extreme changes in volume, sediment load, and channel characteristics. It consists of distinctly to obscurely stratified beds of clay and silt and any combination of angular to rounded sand, gravel, cobbles, and boulders. However, the bulk of the outwash is composed of sand and gravel; clay is usually a minor constituent. Very fine sediments are held in suspension by moving water; therefore, the melt-water streams that deposited the outwash in this area also carried away most of the clay and silt. Bodies of outwash occur in a variety of sizes and shapes ranging from small lenses to large, thick sheets. They may be found intimately associated with till in almost any relationship because of the complex depositional environment that prevailed at the ice front.

Much of the outwash now buried in the Redwood Falls area was covered by readvancing ice sheets. Consequently, the upper part of an outwash deposit may have been scraped away or ploughed up by the ice and redeposited as a gravelly till. Buried outwash is not usually evident from the form of the surface topography or the drainage pattern in this area; however, it can be mapped by studying well records and test-hole information. Under certain conditions supplementary information on its occurrence may be obtained by geophysical exploration methods such as electrical resistivity.

Three large buried outwash deposits were mapped (pl. 10) and are shown in the geologic cross sections of plate 3. The tops of these deposits are approximately 70, 120, and 200 feet below land surface (altitudes of about 970–980 feet, 930–940 feet, and 860 feet, respectively, on section *A–A′*, pl. 3). Geologic sections *B–B′* and *C–C′* show the 70- and 120-foot deposits respectively. The two lower deposits and probably the upper one are associated with the Precambrian bedrock valley (pl. 3). Aquifer tests were made on these three deposits to determine their water-bearing properties (see p. R24).

The water-bearing properties of outwash deposits are quite variable due to their complex mode of deposition. Well yields from the outwash range from a few gallons a minute to quantities large enough for municipal or industrial use. The maximum known yield in the area is 823 gpm from a test well. Many wells obtain sufficient water for domestic and stock use from small lenses of sand and gravel associated with the till or from sandy and gravelly parts of the till.

Surface outwash is of minor extent in the report area and it is a minor source of ground water; therefore, it is not shown on plate 2. Locally (a gravel pit in the N½NE¼SE¼ sec. 6, T. 112 N., R. 35 W.), the surface outwash is at least 12 feet thick; however, its average thickness is probably much less. The irregular distribution of the surface outwash and its association mainly with the topographically subdued area adjacent to the Minnesota River valley suggest that it was deposited during flood stages of the Glacial River Warren. The prominent terrace that extends through and covers most of sec. 14, T. 113 N., R. 36 W. (pl. 1), may include some outwash.

Ice-contact features are stratified bodies of drift deposited in contact with melting glacier ice. A poorly stratified deposit of sand and gravel, near the base of the bluff along the Minnesota River in the SW¼NE¼SE¼ sec. 33, T. 113 N., R. 35 W., may be an ice-contact deposit. Similar bodies of sand and gravel, probably ice-contact features, occur near the base of the bluff along the Redwood River in the SE¼NW¼ sec. 31, T. 113 N., R. 35 W., and the SE¼NW¼NE¼ sec. 31, T. 113 N., R. 35 W. The poorly sorted drift cropping out in a gravel pit in the SW¼SW¼NW¼ sec. 1, T. 112 N., R. 35 W., may also be an ice-contact feature. Some domestic and stock wells may tap buried ice-contact deposits.

RECENT DEPOSITS

Recent alluvium, consisting primarily of fine-grained sediments, has been deposited on the flood plains of the Redwood and Minnesota Rivers. It probably overlies Pleistocene alluvium in many places, but they are not differentiated in this report. Locally swamp deposits of Recent age probably overlie Pleistocene swamp deposits in the Redwood River and Minnesota River valleys and in the poorly drained areas on the surface of the ground moraine.

Previous to this investigation, the city of Redwood Falls had installed a series of large-diameter wells in shallow alluvium along the south side of the Redwood River valley (sec. 2, T. 112 N., R. 36 W.). One of several test holes drilled to explore this alluvium penetrated about 11 feet of sand and gravel from 4 to 15 feet below land surface in the SE¼SW¼SE¼ sec. 2, T. 112 N., R. 36 W. However, the other test holes showed that the areal extent of the deposit is relatively small; furthermore, the material is poorly sorted and its permeability is probably low.

GROUND WATER

Ground water as defined by Meinzer (1923a, p. 38) is "* * * that part of the subsurface water which is in the zone of saturation." It is the water that supplies springs and is available to wells; it discharges into lakes and streams where it maintains their stages and flows between rains and snowmelt.

The zone of saturation includes all rock materials whose interstices are filled with water at or greater than atmospheric pressure. The primary source of ground water in the Redwood Falls area is precipitation. Part of the precipitation remains on the surface and moves into streams or lakes; part is returned to the atmosphere by evaporation and transpiration; the remainder percolates into the ground.

As the water percolates downward to the zone of saturation, a part is held in the upper unsaturated materials by molecular attraction between the water and the walls of the interstices through which it passes. This water is said to be in the zone of aeration. Above the zone of saturation and, in part, continuous with it, is the capillary fringe in which water is held against the force of gravity by capillarity. The amount of water in the zone of aeration may be considerable and is dependent upon several factors, the most significant of which are the texture and thickness of the material comprising the zone. Water bound in the zone of aeration is not available to wells, but water requirements of this zone must be satisfied before infiltrating precipitation can descend by gravity to the zone of saturation. Much of the water in the zone of aeration may be withdrawn by transpiration of plants and evaporation from the soil.

Geologic formations that yield water in sufficient quantities for economic use are termed aquifers. The amount of water a rock or soil can retain or transmit is a function of its porosity and permeability. The porosity of a rock is the percentage of its total volume that is made up of interstices. Permeability refers to the capacity of a water-bearing formation to transmit water through its interstices. Most rocks are permeable to some extent, but if the interstices of a rock are large and interconnected, as in sorted sand and gravel, and water moves through them more or less freely, the material is said to be permeable. Where the interstices are very small or poorly connected, as in clay or dense crystalline rock, water moves slowly or not at all, and the material is said to be of low permeability or impermeable. Sorted sand and gravel such as that composing glacial outwash is very permeable, whereas till is relatively impermeable. In the section entitled "Aquifer Tests," permeability is defined quantitatively as a coefficient.

OCCURRENCE

Ground water in the Redwood Falls area occurs under confined (artesian) and unconfined (water table) conditions. Unconfined ground water is under atmospheric pressure and occurs in aquifers that are not encased by impermeable materials. The upper surface of the unconfined water is the water table, whose shape is usually a subdued model of the topography. The depth to the water table generally varies with time and place and depends on the local topography and the prevailing recharge-discharge relationships of the ground-water reservoir. The water table in the report area ranges from 0 to about 30 feet below the land surface. Where the water table intersects the land surface, seeps or springs normally occur and, depending upon the nature of the terrain, a lake, marsh, or stream may form. An aquifer that contains unconfined water is referred to as a water-table aquifer and wells completed in it are known as water-table wells. Only a small percentage of the wells in the area tap unconfined aquifers. These wells are completed in surficial outwash, Quaternary alluvium, or places where Precambrian bedrock crops out or is overlain by permeable material.

Ground water occurs under artesian conditions where it is confined between impermeable strata and will rise above the base of the upper confining bed. An artesian aquifer is not dewatered when it is pumped unless the water level is drawn below the bottom of the overlying confining stratum. When water is removed from an artesian aquifer, the space it formerly occupied is compensated for by the expansion of the remaining water and the compression of the aquifer that results from the reduced pressure.

Ideal water-table or confined conditions rarely, if ever, occur in nature. Most confining beds that are considered impermeable permit slow movement of ground water through them. Ground water moves with varying degrees of ease through the so-called impermeable layers of glacial drift as well as through aquifers, and the drift functions as a complex hydraulic unit. Under these conditions, the immediate response to pumping in most confined glacial-drift aquifers is a rapid lowering of pressure. However, prolonged pumping induces the slow movement of water through the fine grained confining materials, and eventually a condition of equilibrium with the water table may be attained. Under these conditions, the water might be regarded as semiconfined rather than confined. Conversely, when first pumped, aquifers that seem to be unconfined may show an immediate response to pressure changes similar to confined aquifers.

Much of the Precambrian bedrock probably contains semiconfined ground water, although reasonably good artesian conditions also may prevail in places.

MOVEMENT

Ground water moves downgradient from areas of recharge to areas of discharge. Velocities of movement may range from tens to hundreds of feet per year, depending in part on the permeability of the materials and the geologic structure. An increase or decrease in the hydraulic gradient and, therefore, a change in the rate of movement of ground water at any given place may be due to a change of permeability of the water-bearing material or to an unbalance of previously established recharge and discharge relations. For example, an increase in gradient may be caused by depressed water levels due to pumping or to a decrease in permeability.

The piezometric (pressure) surface of a water-bearing formation or aquifer may be defined as the imaginary surface that everywhere coincides with the static level of the water in the aquifer. Piezometric maps indicate the direction of ground-water flow at any given point, the direction being normal to the isopiestic lines or contours. An isopiestic line connects points on the piezometric surface having the same static level. Piezometric-surface maps also may indicate areas of ground-water recharge or discharge.

A piezometric map (pl. 4) of the Redwood Falls area was constructed from water-level measurements made during August 1953. Shallow wells were used for control points in order to construct a map showing the approximate configuration of the water table. Some wells used for control probably did not tap water-table aquifers, but their water levels probably were close to the water table and would not materially change the map. Locally, points on streams were selected to fill in the gaps that would have existed in the contours because of the lack of sufficient control wells. The actual pattern of ground-water flow in any given area may be much more complex than that which may be inferred from the generalized contours shown on plate 4.

South of the Redwood River the map shows numerous ground-water divides that coincide approximately with the surface drainage divides. Ground-water divides also are in the areas between Redwood River and Ramsey Creek and between Ramsey Creek and the Minnesota River. The close spacing of the isopiestic lines near the Redwood and Minnesota Rivers and Ramsey Creek indicates a steepening of the hydraulic gradient associated with the discharge of ground water into these streams. The highest altitudes of the piezometric surface are in the southern part of the area, and the regional gradient is toward the Minnesota River.

WATER LEVELS

Natural fluctuations of water levels in a ground-water reservoir usually represent a change in relation between the rates of recharge and discharge, and, therefore, represent changes in storage. If discharge from a ground-water reservoir exceeds recharge, the water levels will decline; if recharge exceeds discharge, the water levels will rise.

In water-table aquifers, fluctuations of water level represent water added to or removed from the aquifer. Under natural conditions, these fluctuations usually result from recharge by precipitation or discharge from seeps and springs and by evapotranspiration. In artesian aquifers, fluctuations represent changes in pressure within the system that may be caused by a variety of factors; some of the most important are (a) long-term changes in the natural rates of recharge or discharge, (b) pumping, and (c) changes in storage in overlying water-table aquifers. Other factors of minor significance, usually producing short-term fluctuations, are (a) changes in atmospheric pressure, (b) shock waves generated by earthquakes, and (c) changes in load produced by passing trains or by ocean tides.

Four observation wells were measured periodically in the Redwood Falls area; hydrographs of these wells for most of the period 1952–56 are given in plate 5. The graph of well 113.36.35add1 (47 feet deep) is considered representative of water-table fluctuations; wells 112.36.10cab1 (194 feet deep), 112.36.14aaa1 (214 feet deep; log given in table 5), and 112.36.25bda1 (150 feet deep) are artesian wells. Plate 6 shows a hydrograph of well 113.36.35add1 for 1955 and a graph of daily precipitation and daily maximum and minimum temperatures in the area as recorded at the Redwood Falls airport weather station.

The hydrograph of well 113.36.35add1 shows that most recharge occurs in the early spring, largely from snowmelt and rains. The largest increment of recharge was in 1953 when the water level rose about 7.2 feet from March to May.

Generally water levels decline through the summer chiefly because of the large draft by evapotranspiration. Heavy rainfall during the growing season may temporarily reverse the downward trend of the water level after first satisfying soil-deficiency needs. For example, in 1955 (pl. 6) the water-level decline continued although 1.77 inches of rain fell from June 28 to July 1. The downward trend probably persisted largely because of the dry condition of the soil and subsoil, which retained the precipitation and prevented it from reaching the water table. However, the 4.49 inches of rain that fell from July 4 to 11 caused the water level to rise at least 2 feet, probably because the rainfall between June 28 and July 1 satisfied most of the soil moisture deficiency and allowed a large amount of the July 4–11 precipitation to reach the water table. The pronounced draft of ground water by evapotranspiration is shown by the water-level decline during July–August 1955. Even the large amount of precipitation (4.93 inches) that fell in the period August 3–9 was not enough to reverse the downward trend until almost a week later, when the water level rose only about 0.6 foot.

The decline of water level during the summer usually continues at a lesser rate in the fall in response to the decreased use of ground water by plants. Also, a given quantity of precipitation may cause a greater rise of the water level in the fall than in the summer, provided water requirements of the zone of aeration have first been satisfied. However, the downward trend common during the summer may continue through the fall if precipitation is deficient or if an early frost accumulation impedes the infiltration capacity of the soil. Throughout the winter water levels usually continue to decline because the frozen ground prevents recharge. Schneider (1958, p. 15) points out that part of the winter decline is caused by the upward movement of

712-187—64——4

moisture in the direction of the thermal gradient. Some recharge may occur in the winter when the air temperature reaches or exceeds 32° F and frost melt descends to the water table (Schneider, 1958, p. 12). For example, on February 8 and 9 (pl. 6) the daily maximum temperature exceeded 32° F, and there was a corresponding rise in the water level.

The hydrographs of wells 112.36.10cab1, 112.36.14aaa1, and 112.36.25bda1 show that fluctuations of artesian-water levels are similar throughout the area. In general, except for magnitude, they are also similar to fluctuations of the water table. For the periods of record the hydrographs of wells 112.36.10cab1, 112.36.14aaa1, and 112.36.25bda1 showed net declines of 9.4, 8.0, and 8.8 feet, respectively. These declines probably reflect the below-average precipitation from 1954 to 1956. In well 112.36.25bda1, at least part of the pronounced decline that has occurred since July 1955 was caused by pumping (see p. R31). It is not certain whether or not the water levels in the other two wells were affected by pumping.

RECHARGE

Most of the recharge to the ground-water reservoir in the Redwood Falls area is derived from downward percolation of local precipitation. The amount of precipitation that infiltrates the reservoir is determined principally by the duration, intensity, and type of precipitation, the density and types of vegetation, the season, the topography, and the porosity and permeability of the soil and underlying formations. Much of the land in the report area consists of clayey soil, and its flat to moderately rolling surface is poorly drained. Consequently, runoff is impeded, and recharge from precipitation is facilitated. It was estimated from a study of daily precipitation records and hydrographs for the period 1953–56, that about 10 percent of the average precipitation of 23.7 inches recharged the ground-water reservoir. This amounts to about 40 million gallons of water added annually to each square mile of the ground-water reservoir area. Some additional recharge undoubtedly occurs by lateral ground-water movement from adjacent areas. The amount of recharge received by influent surface-water seepage is probably small.

DISCHARGE

Ground water in the Redwood Falls area is discharged by natural and artificial means. Natural discharge takes place by evaporation from shallow water-table ponds and sloughs, evaporation from the soil and transpiration of plants (collectively referred to as "evapotranspiration"), through seeps and springs along streams, and by ground-water movement from the report area in the direction of the hydraulic gradient. Artificial discharge is by pumping from wells and through artificial drains (canals), which also facilitate the removal of ground water by evaporation and transpiration (See p. R23).

EVAPOTRANSPIRATION

Evapotranspiration is the term used to describe the combination of soil and vegetal discharge of ground water into the atmosphere. According to Meinzer (1923b, p. 48–49):

> * * * Soil discharge of ground water is discharge through evaporation directly from soil or rocks. The water is, for the most part, lifted by capillarity from the zone of saturation nearly to the surface, where evaporation takes place. Obviously discharge of this kind can occur only where the water table is close to the surface * * *. Vegetal discharge of ground water is discharge through the physiologic functioning of plants. The water may be taken into the roots of the plants directly from the zone of saturation or from the capillary fringe, which in turn is supplied from the zone of saturation. It is discharged from the plants by the process of transpiration. The depths from which plants will lift ground water vary greatly with different plant species and with different soils and conditions of water supply. Investigations show that certain kinds of plants will lift ground water from depths as great as 50 feet.

Most of the evapotranspiration in the Redwood Falls area results from the cultivation of corn and small grains. In connection with studies of the consumptive use of water by irrigated corn, Rhoades and Nelson (1955, p. 395–396) stated that corn may use more than about 650,000 gallons per acre during the growing season; a single corn plant in full leaf may transpire 8 gallons of water in a week. Because irrigation tends to increase consumptive use by evaporation, these figures may be somewhat high for the report area where irrigation is not practiced; however, they serve to indicate the high order of magnitude of water consumption by this crop. Blaney (1955, p. 343–345) estimated the consumptive use of water for small grains under irrigation in Colorado as about 400,000 gallons per acre. For humid areas such as Redwood Falls, this value is at least 10 percent too high.

It is estimated that, for the period 1953–56, about 80 percent of the average annual rainfall in the Redwood Falls area was lost by evapotranspiration.

SPRINGS

A spring results from the natural discharge of ground water from a rock or soil upon the land surface or into a body of surface water. Springs are divided into different classes on the basis of various characteristics; the two most common types in the Redwood Falls area are gravity and contact springs. Gravity springs occur where the water table crops out, and contact springs form at the exposed contact of a relatively permeable formation that overlies an impermeable formation. Many of the latter type are formed at the contact of the more permeable oxidized till and the relatively impermeable unoxidized till. Both types of springs are numerous along the valley walls of the Minnesota and Redwood Rivers and Ramsey Creek. The discharge from springs in the Redwood Falls area is directly related to precipitation; because ground-water storage above the level of discharge is small, springs cease to flow in dry periods. The amount of water discharged by springs was not determined, but it is small in comparison to discharge by evapotranspiration.

Marshy areas occur locally, particularly along stream channels, largely as the result of ground-water discharge, though in most places the point or points of discharge cannot be readily identified.

AQUIFER TESTS

GENERAL

Effects of withdrawal of water from an aquifer can be predicted only if the hydraulic characteristics of the aquifer are known. These characteristics can be determined by aquifer tests or controlled pumping tests, in which the cone of depression produced by pumping is mathematically analyzed. Coefficients of transmissibility (T) and storage (S) may be computed by standard methods of analysis described by Wenzel (1942, p. 88–89), Theis (1935, p. 522), Cooper and Jacob (1946), and Jacob (1946). The effectiveness of an aquifer is determined by these coefficients. The coefficient of transmissibility may be expressed as the number of gallons of water, at the prevailing water temeprature, that will pass in 1 day through a vertical strip of the aquifer 1-foot wide and extending the saturated height of the aquifer, under a hydraulic gradient of 100 percent. The coefficient of storage of an aquifer is defined as the volume of water it releases from or takes into storage per unit surface area of the aquifer per unit change in the component of head normal to that surface. Another coefficient used to describe the water-bearing characteristics of earth materials is the coefficient of permeability which is defined by the Geological Survey as the rate of flow of water in gallons per day through a cross section of 1 square foot, under a hydraulic gradient of 100 percent, at a temperature of 60° F. In the field the prevailing water temperature is used, and the value is called the "field coefficient of permeability." The average field coefficient of permeability is equal to the coefficient of transmissibility divided by the saturated thickness of the aquifer.

The above-mentioned computations for T and S are based, in part, on the following idealized conditions: (1) The aquifer is homogeneous, isotropic (permeability is the same everywhere), and of infinite areal extent, (2) the discharging well penetrates the full thickness of the aquifer, and (3) the coefficient of transmissibility does not change (the saturated thickness remains constant). It is not possible for all these conditions to be met in the field, but it has been found that in general the performance of a well, or well field, relates directly to the transmissibility and storage coefficients computed by these methods. Values of T and S determined from a pumping test can be used to predict the short-term yield from a well or well field, to determine the efficiency of individual wells, and to plan the spacing of wells.

Pumping tests were made in each of three glacial-outwash aquifers in the area. Water-level measurements were made for several hours before each test, to obtain the trend of the water levels before pumping started. The test wells were then pumped at a constant rate of discharge for a specific time while water-level measurements were made. After pumping ceased, recovery measurements were made.

TEST AT SITE OF WELL 112.36.14aaa1

In October 1953 an aquifer test was made by pumping well 112.36.14aaa1. Well 112.36.13bbc1, about 780 feet southeast of the pumped well, was used as an observation well. (See pl. 10 for locations of wells.) The pumped well was 4 inches in diameter, 214 feet deep, and was completed with 5 feet of screen. It was pumped with an air compressor at an average rate of 86 gpm for 25 hours, and the discharge was measured volumetrically in a stock tank. Water-level measurements were made with a steel tape. Plate 7 shows the hydrograph of observation well 112.36.13bbc1 during the test. Well 112.36.11ada2, about 4,000 feet north of the pumped well, also was measured during the test. Although the water level was lowered 0.70 foot, the well was found to be partly plugged and the data could not be used in the analysis. The test was first started October 13, 1953, but after 250 minutes of pumping, the compressor failed; the test was restarted on October 14.

In the vicinity of wells 112.36.14aaa1 and 112.36.13bbc1, the aquifer is about 44 feet thick and extends from a depth of 199 to 243 feet. The aquifer probably pinches out about 4,200 feet to the north, inasmuch as test hole 112.36.11aad2 penetrated Precambrian bedrock 151 feet below the land surface and a test hole (112.36.11ada1) about 3,800 feet north of the test well did not indicate sand or gravel below a depth of 104 feet. The aquifer may extend in a narrow belt over a considerable area (area 3 on pl. 10).

The coefficient of transmissibility at the test site is about 126,000 gpd per ft and the coefficient of storage is about 0.0002. The field coefficient of permeability is about 3,000 gpd per sq ft. Although the aquifer is highly permeable at the test site, its average permeability is probably much lower.

The test data were analyzed for the presence of hydraulic boundaries by techniques similar to those described by Ferris (1948). In less than an hour of pumping, the cone of depression expanded to a discharge boundary, about 2,000 feet from the observation well. During the last part of the test, other discharge boundaries were indicated at indeterminate distances. These boundaries may represent the aquifer's pinching out against the southwest or northeast walls of the bedrock valley or a reduction in the permeability of the aquifer at a distance from the test site.

TEST AT SITE OF WELL 112.36.12bbd1

In June 1954 an aquifer test was made by pumping municipal well 112.36.12bbd1 at an average rate of 267 gpm. This well is 12 inches in diameter and is screened from 80 to 92 feet. Discharge measurements were made with a propeller-type meter. Water-level measurements were made in observation wells 112.36.12bbd2 and 112.36.12bad2 with a steel tape; observation wells 112.36.12bbd3 and 112.36.12bca1 were fitted with recording gages that made continuous records of the water levels. Figure 3 shows the locations and distances between the wells at the test site and plate 8 shows the hydrographs of the observation wells during the test.

The pumped and observation wells tap a deposit of glacial outwash as much as 27 feet thick. The pumped well and the observation well

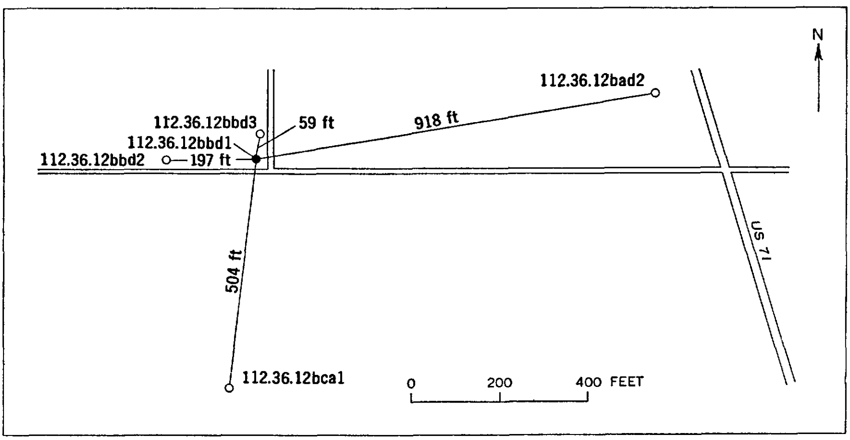

FIGURE 3.—Map showing location of wells used during test pumping of well 112.36.12bbd1, about ¼ mile south of Redwood Falls. Open circles represent observation wells.

59 feet away (112.36.12bbd3) penetrated 27 feet of sand and gravel at a depth of 66 to 93 feet. Test-hole data indicate that the outwash deposit extends over a large area south and southeast of Redwood Lake; however, the thickness and permeability of the outwash appear to be somewhat variable. (See cross sections *A–A′* and *B–B′*, pl. 3).

The average value of *T* is about 70,000 gpd per ft and the value of *S* is about 0.0007. If the average thickness of the outwash in the test area is assumed to be 20 feet, the average field coefficient of permeability is about 3,500 gpd per sq ft.

The analysis of the test data for observation well 112.36.12bbd2 suggests that pumping induced recharge near the end of the test. This may have been caused by the cone of depression reaching a more permeable part of the aquifer, by leakage from the confining strata, or by a combination of both. Data from observation well 112.36.12bad2 indicated a discharge boundary in less than half an hour at a distance of about 1,300 feet from the well.

TEST AT SITE OF WELL 112.36.25abb3

A third test was run in August 1954 by pumping well 112.36.25abb3 with a turbine pump at an average rate of 823 gpm. The well was 12 inches in diameter and had 40 feet of screen from about 142 to 182 feet. Water-level measurements were made with a steel tape in wells 112.36.24dbc1, 112.36.25abb1, and 112.36.25bda1. Well 112.36.25abb2 was equipped with a recording gage. Water-level measurements in the pumped well were made with an electric gage and the discharge rate was measured with an orifice and manometer. Figure 4 shows the locations and distances between the wells, and plate 9 shows the hydrographs of the wells during the test. The aquifer is at least 3 miles long and 1½ miles wide; in places it is about 55 feet thick (area 1, pl. 10).

The coefficient of transmissibility is about 126,000 gpd per ft, and the storage coefficient is about 0.00025. The average thickness of the aquifer in the test area is about 50 feet, the average field coefficient of permeability about 2,500 gpd per ft.

The test data indicated a recharge boundary on all the observation wells within half an hour after pumping started. This recharge may be due to an increase in the permeability of the aquifer at some distance from the test site, or possibly leakage from the confining strata.

PRESENT WELL DEVELOPMENT

The location, depth of wells, and information on water levels in the report area are shown on plates 10 and 11. A description of selected wells is given in table 2. Data on area wells not included in table 2 are available from the Geological Survey, St. Paul, Minn.

DOMESTIC AND STOCK

Nearly all the residents of the Redwood Falls area depend upon ground water for domestic and farm purposes. Most domestic and stock wells in the area obtain water from buried outwash deposits; some tap surficial ice-contact deposits, surficial outwash deposits, or bedrock (table 2).

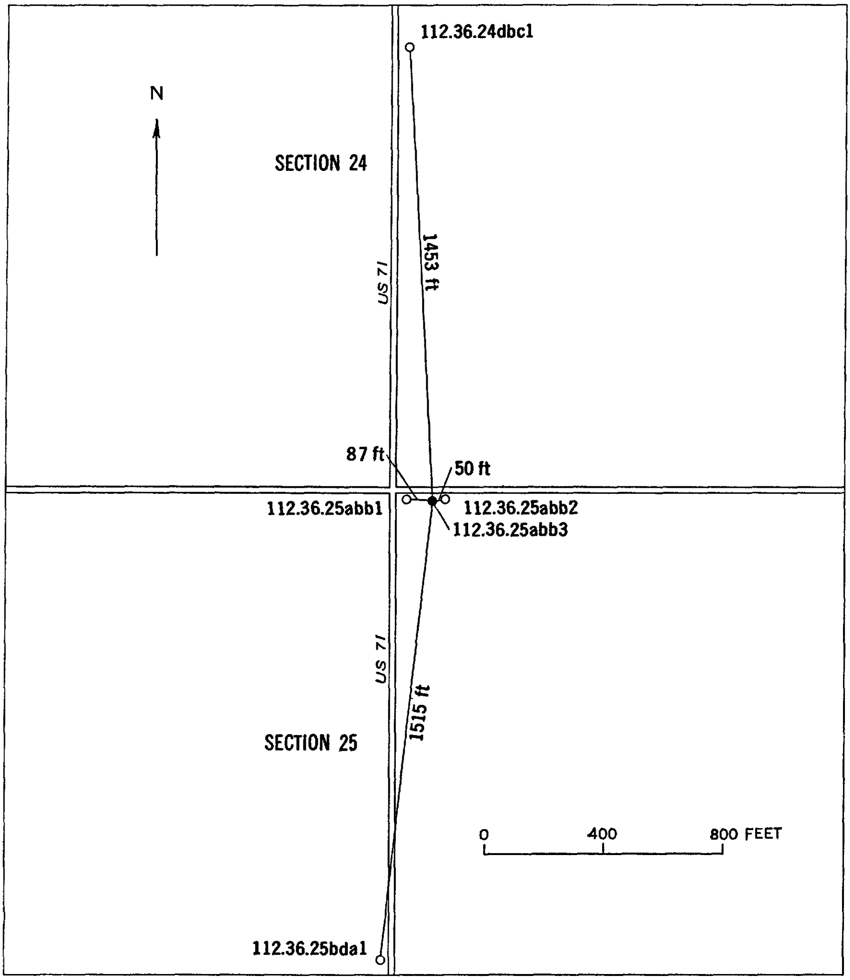

FIGURE 4.—Map showing location of wells used during test pumping of well 112.36.25abb3, about 3 miles south of Redwood Falls. Open circles represent observation wells.

TABLE 2.—*Selected wells in the Redwood Falls area*

Type of well: B, Bored; Dr, Drilled; Du, Dug.
Depth of well below land surface: Measured depths are given in feet and hundredths of a foot; reported depths are given in feet.
Geologic source: A, alluvium of Quaternary age; Ud, undifferentiated glacial drift of Pleistocene age; O, glacial outwash of Pleistocene age; p€, rock of Precambrian age.
Water level: Measured water levels are given in feet and hundredths of a foot; reported water levels are given in feet.
Use of water: D, domestic; N, not used; O, observation of water-level fluctuations; P, public supply; S, stock.
Remarks: C, chemical analysis given in table 3; H, hydrograph shown on plate 5; I, well inadequate; L, log given in table 5 or shown on plate 3.

Well No.	Owner or tenant	Type of well	Depth of well below land surface (feet)	Diameter of well (inches)	Water-bearing zones				Water level		Use of water	Remarks
					Top (feet below land surface)	Thickness (feet)	Material	Geologic source	Feet below land surface	Date of measurement		
112.35.15ccb1	E. E. Wetmore	B	52	32			Fine sand	Ud	13.81	8-26-53	D, S	I
28ccb2	Helen and Edgar S. Lewis	Dr	182	5	180	2	Crystalline rock	p€	29.63	8-25-53	D, S	
32daa1	Frank Weeks	B	60	28				Ud	25.02	9-1-53	D, S	
33bbb1	A. Mell	Dr	212	5	198	14	Crystalline rock	p€	55		D, S	
112.36.1dca1	Milo Palmer	Dr	53.00	6	37.5	0.5	Fine gravel	Ud	10.78	8-26-53	D	
2dda2	City of Redwood Falls		20.00				Sand and gravel	A	17.52	8-27-53	P	
7bda1	Gus Nelson	B	52	36				Ud	33.09	4-8-53	D, S	I
10cab1	Thomas A. Whittet	Dr	194	5	189	5	Coarse gravel	O	38.49	8-20-53	O, D, S	L, C, H
12bbd1	City of Redwood Falls	Dr	92	12			Sand and gravel	O	67		P	C
12bbd2	do	Dr	86.90	4	73	26	do	O	68.06	6-2-54	N	L
14aaa1	do	Dr	214.00	4	199	44	do	O	31.66	8-20-53	O	L, C, H
14ada2	Frank Boots	B	69.00	24				Ud	26.35	8-20-53	N	
25abb3	City of Redwood Falls	Dr	180	12	122	60	Sand and gravel	O	50.68	7-27-54	P	C
25bad1	S. L. Park	B	60					Ud	18		N	
25bda1	City of Redwood Falls	Dr	150	2	124	39	Sand and gravel	O	44.18	5-22-54	O	L, H
27bcc1	B. Oscar Nelson	Dr	130	5			Decomposed crystalline rock.	p€	28.00	8-28-53	D, S	L, C
34caa2	E. G. Barenthin	B	90	36				Ud	4.27	8-19-53	S	I
36cdd2	T. S. Balko	B	55	24			Gravel	Ud	20		D, S	I
113.35.18ccc1	John W. Hoepner	Dr	40	5			Crystalline rock	p€	4.73	8-20-53	N	
29bcc2	Mrs. Mary Hoskens		20				do	p€	6.70	9-20-53	D	I
29caa1	North Redwood School	Dr	114	5	4	110	do	p€			P	C
34dcb1	Dr. S. F. Ceplecha	Dr	172.00	6	70	102	do	p€	69.65	5-29-53	D	C
113.36.13ccc1	Frank Moritz	B	45	24			Sand	Ud	39		D, S	
21ddd1	Edward Eis	Du	10				Fine sand	Ud	5		S	I
24dcb1	H. Amberg	B	65	36			Gravel	Ud	36.22	8-26-53	D, S	
25ccc1	do	Du	10.00	36				Ud	7.47	8-26-53	N	
26acb1	Fred Lechner	B	85	24				Ud	20.10	8-19-53	D, S	I
28ddd1	Bernard Bliss	B	28	26				Ud	10		D, S	
34baa1	Leroy E. Woodford	B	65.00	26				Ud	13.73	8-26-53	D, S	
35add1	George A. Cady	B	46.90	32				Ud	4.67	8-18-53	O, D	H
35ccd2	Jerry Mahoney	Dr	164	5	130	34	Crystalline rock	p€	80		D, S	I

Most of the farm wells are drilled or bored; a few are hand dug. In recent years an increasing number of wells have been drilled. The bored wells range in diameter from 12 to 48 inches and most are completed with concrete casing, whereas, the drilled wells range in diameter from 4 to 6 inches and are finished with steel casing. Well screens are not ordinarily used in either type well, although the use of screens would probably increase the yields of the wells and minimize the possibility of the wells being plugged by silt or fine sand.

Bored wells provide a large storage capacity in the well; consequently, they are useful where the aquifer is thin or of low permeability. Large yields are seldom obtained from the bored wells, because for the most part, they can penetrate only the top of the aquifer owing to the method of construction. Furthermore, if completed just below the water table, the bored wells may go dry when the water table declines during dry periods or during the winter. Drilled wells can penetrate the full thickness of an aquifer; consequently, they are more dependable and usually yield larger quantities of water. From the standpoint of sanitation, drilled wells are more desirable than bored wells because there is generally less opportunity for surface contaminants to enter them.

The efficiency of a well is determined by its construction and pumping equipment, which can result in widely differing yields from the same aquifer. Many wells are reported to be inadequate even though the aquifer is capable of yielding adequate quantities of water. There may be many reasons for the inadequacy, but a common difficulty is that the drop pipes do not extend far enough below the static water level. For example, a well may be 70 feet deep and have a drop pipe 40 feet in length that extends 15 feet below the static water level. If the water level draws down to the end of the drop pipe, it is obvious that 30 feet of water remains in the well.

The amount of water required from a well varies according to the needs of the users and, as the need increases, present well supplies eventually may be regarded as inadequate. The following table is one of many that gives the average daily requirements of water for farm and domestic supplies (Anderson, 1955, p. 38). It is recognized that, as living standards rise and mechanization increases, water requirements for farm and domestic use will increase.

Daily requirements of water for farm and domestic supply

Consumer	*Requirement (gallons)*
Family members, for all purposes including kitchen and bath (each)	35
Horses (each)	10
Cattle, nonmilk-producing (each)	12
Cattle, milk-producing (each)	25–30
Hogs (each)	2
Sheep (each)	1½
Chickens (100)	4

MUNICIPAL

Prior to this investigation, the city of Redwood Falls obtained its water supply from a group of shallow wells on the south bank of Lake Redwood about half a mile southwest of the city and from a deeper well (112.36.12bbd1) about three quarters of a mile south of the city (pl. 11). The shallow wells are completed in alluvium, average about 20 feet in depth, and are about 10 feet in diameter. Well 112.36.12bbd1 is completed in glacial outwash at a depth of 92 feet.

The city stores its water in three ground-level storage reservoirs having a total capacity of 577,000 gallons and in an elevated steel tank having a 100,000-gallon capacity. Approximately 87 million gallons of water were pumped from wells in 1955; by 1960 the annual pumpage was about 106 million gallons, an increase of about 20 percent in 5 years.

On the basis of information obtained during this investigation, the city installed well 112.36.25abb3 in 1955 and 112.36.25aaa1 in 1957. These wells, 170 and 180 feet deep, are completed in the same outwash deposit and are approximately 2,250 feet apart. Well 112.36.25aaa1 is the principal producing well; the other is for standby purposes. All other wells are on a standby or inactive status.

AVAILABILITY OF WATER

The general availability of ground water in the Redwood Falls area is summarized on plate 10. Only a small part of the area has been investigated by test drilling. Consequently, in many places where adequate wells are completed at shallow depths, little or no information is available on the occurrence of deep aquifers. It is possible that there are aquifers in the area capable of yielding large supplies of water other than those delineated in plate 10. It appears that the best area for further exploration is in the buried bedrock valley. However, owing to the variable extent and character of glacial outwash, controlled test drilling and test pumping should precede any contemplated large ground-water development.

The theoretical drawdowns that may be expected at several distances from wells pumping continuously from ideal aquifers with the specified characteristics are shown in figures 5 and 6. The assumed values of T and S are those obtained from the two aquifer tests made in areas 1 and 2 (figs. 3, 4, and pl. 10). The hydraulic coefficients computed from the test in area 1 are similar to those computed from the test in area 3.

The drawdown in a pumped well or a well affected by pumping is directly proportional to the discharge rate of the pumped well. Therefore, the drawdown caused by a well in an artesian aquifer having a T value of 126,000 gpd per ft and an S value of 0.00025, and pumping 350 gpm, would be half that shown on figure 6. The total drawdown at any specified location affected by more than one pumping well is equal to the sum of the drawdowns of the wells affecting that location. It should be pointed out that the theoretical drawdowns indicated on figures 5 and 6 are based on the assumption that the aquifers receive no recharge, are homogeneous, and are of infinite areal extent. However, glacial aquifers usually are heterogeneous and of limited extent; therefore aquifer-test data would be expected to reveal boundaries of various types. Despite this situation, figures 5 and 6 may be used as rough guides in planning the spacing of additional wells.

The direction of the deviation between the theoretical drawdown and the actual drawdown may indicate the type of boundary that causes the deviation. If, after a considerable period of pumping, the actual drawdown is less than the theoretical drawdown, a recharge

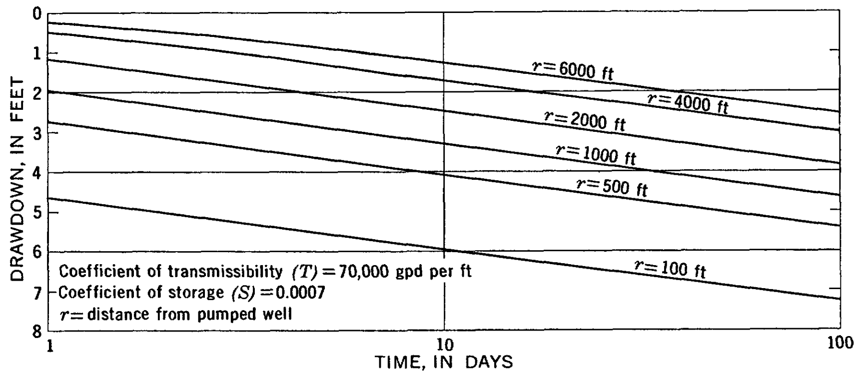

FIGURE 5.—Theoretical drawdown at several distances from a well pumping 350 gpm from an ideal aquifer.

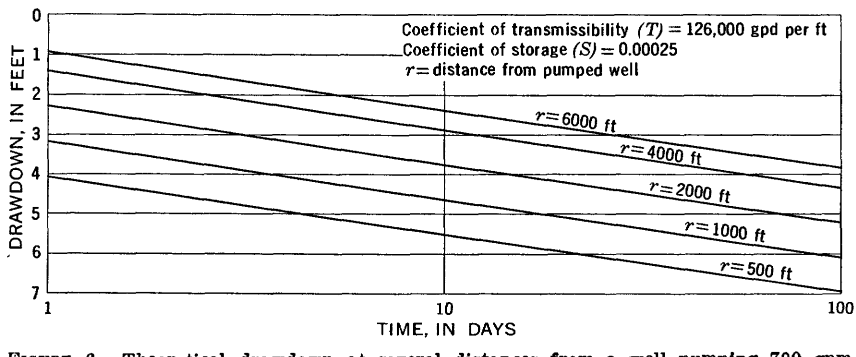

FIGURE 6.—Theoretical drawdown at several distances from a well pumping 700 gpm from an ideal aquifer.

boundary is suggested. A discharge boundary would be indicated if the actual drawdown was greater than the theoretical drawdown.

The amount of water that can be withdrawn from an aquifer without depleting it depends upon the difference between the amount of water that is discharged from it (both naturally and artificially) and the amount of recharge it receives. The greater the difference between the amount of water discharged and the amount of recharge received, the greater will be the extent of depletion.

The buried glacial-outwash aquifers in the Redwood Falls area are under artesian conditions. When an artesian aquifer is pumped, water is released from storage; prolonged pumping results in a progressive lowering of the artesian pressure. As pumping continues, the cone of depression in the artesian-pressure surface deepens and expands; the radius of the cone is determined by the physical and hydrologic properties of the aquifer and its confining beds.

Lowering the head (hydrostatic pressure) by pumping in a buried outwash aquifer could induce a significant quantity of recharge by leakage from confining strata of lower permeability. A good example of this has been described by Norris (1959), who shows that vertical leakage through till is an important source of recharge to a buried-valley aquifer at Dayton, Ohio.

The outwash aquifer in area 1 (pl. 10) is the best known source of ground water in the area. The city of Redwood Falls has been using this aquifer as its only source of water since August 1955. The rate of pumping of the municipal wells appears to be balanced by recharge and the diversion of water that would have been discharged, because the water level has more or less stabilized since late in 1956.

The aquifer tested in area 2 (pl. 10) is not as extensive or as thick as the aquifer in area 1; nevertheless, considerable additional water probably could be obtained in this area from adequately constructed and properly spaced wells. The piezometric surface map (pl. 4) indicates that when well 112.36.12bbd1 is pumping, it captures ground water that normally would have discharged into the Redwood River. It is reported that since well 112.36.12bbd1 has stopped pumping, the discharge from springs has increased considerably in the Redwood River valley, north of the well.

SURFACE WATER

As previously mentioned, the Redwood Falls area is drained by the Minnesota River and its tributary, the Redwood River.

The nearest gaging station on the Minnesota River is at Montevideo, Minn., about 40 miles northwest of Redwood Falls. The 38-year average discharge of the Minnesota River at Montevideo through 1959 is 617 cfs (cubic feet per second). Maximum discharge is 24,500 cfs on April 10, 1952. No flow is reported for several days in August–September 1933, July–September 1934, and August 1936 (Wells, 1961, p. 177).

The Yellow Medicine River is the only large stream that contributes to the flow of the Minnesota River between the Montevideo gaging station and the Redwood Falls area. Several smaller streams contribute a small amount to the flow. The 23-year average flow of the Yellow Medicine River near Granite Falls (1935–1938, 1939–1959), about 20 miles northwest of the Redwood Falls area, is 98.4 cfs. Maximum discharge is 11,800 cfs on June 18, 1957. No flow is reported for various periods in July 1931, July–September 1933, January 1948, and February 1959 (Wells, 1961, p. 178). It seems, therefore, that the average flow of the Minnesota River in the Redwood Falls area, before the addition of water from the Redwood River, is about 700 cfs.

The drainage area of the Redwood River gaging station in the NW¼SE¼NE¼ sec. 9, T. 112 N., R. 36 W. (pl. 10), is 697 square miles. The total drainage area of the Redwood River is 743 square miles. Several miles above the falls of the Redwood River the gradient of the river is about 5 feet per mile. From the falls to its junction with the Minnesota River valley, the river descends about 150 feet, mostly over rapids within the first half mile. The average discharge of the Redwood River for the 25-year period 1911–12, 1935–59 measured at the gaging station is 93.1 cfs. Maximum flow is 19,700 cfs on June 18, 1957. No flow was reported for several days in January 1940 and for part of each day August 19, 20, 1959 (Wells, 1961, p. 180). Lake Redwood is formed by a small dam built at the falls.

Ramsey Creek, a tributary to the Redwood River, and Crow Creek, a tributary to the Minnesota River, are both intermittent streams.

QUALITY OF WATER

Chemical analyses data of 26 samples of ground water and 4 samples of surface water from the Redwood Falls area are given in table 3. The ground-water samples were collected from springs and from wells ranging in depth from 29.5 to 230 feet. Table 4 lists the primary source and significance of elements, substances, and characteristics commonly found in ground water.

Water for drinking can be evaluated according to the proposed standards of the U.S. Public Health Service given in an article by

Hopkins and Gullans (1960). These standards are used by many States for rating municipal water supplies. The following is a partial list of constituents in drinking water and the proposed recommended limit of concentration.

Constituent	*Concentration (ppm)*
Iron (Fe)	0.3
Manganese (Mn)	.1
Magnesium (Mg)	50
Chloride (Cl)	250
Fluoride (F)	1.0
Sulphate (SO_4)	250
Total solids	500
Nitrates (as N)	10
Detergents (as alkyl benzene sulfonate)	.5

The chemical composition of ground water is dependent largely upon the mineral composition of the strata through which it moves and the rate of movement. Other factors such as the concentration of plant and animal life and the temperature of the region also affect the quality of natural waters. In general, waters from deep wells and wells in areas of natural discharge are more likely to be highly mineralized than waters from shallow wells and wells in recharge areas.

The heterogeneity of the glacial drift in the Redwood Falls area is reflected by the wide range of the mineral constituents in the ground water. In general, it contains large quantities of calcium and bicarbonate; calcium ranges from 46 to 518 ppm, averaging about 194 ppm and bicarbonate ranges from 207 to 543 ppm and averaged 463 ppm. The high calcium and bicarbonate content of the ground water probably reflects the highly calcareous nature of the drift in the report area. The high sulphate concentration (35 to 935 ppm, averaging 327 ppm) is typical of ground water in the glacial drift of this region.

Because most of the ground water in the Redwood Falls area is hard (84 to 994 ppm, averaging 550 ppm as $CaCO_3$) and high in iron content (0.03 to 16 ppm, averaging about 5 ppm), commercial water softeners are extensively used. However, well 113.35.34dcb1 is completed in granite, and the water has the lowest hardness (84 ppm) of those analyzed. In addition, the water from several other wells completed in the Precambrian bedrock was tested with a field kit and found to be softer than the glacial-drift waters. The relatively soft water probably results from a base-exchange process in which calcium and magnesium ions in the water were replaced by sodium and potassium ions in the decomposed rock materials.

TABLE 3.—*Chemical analyses*

[Analyst or source of data: a, R. B. Dole and F. F. Wesbrook, 1907; b, Flox Co., Minneapolis, Minn.; Survey. Analytical results in parts per million

Location	Depth of well (feet)	Analyst or source of data	Date of collection	Temperature (°F)	Silica (SiO_2)	Iron (Fe)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Manganese (Mn)
112.35.28aba1	230	f	10-29-53	50		13						1.5
36.1		a	2-18-04									
36.1		a	2-18-04									
36.1		a	3-21-05			Tr.						
36.1		a	3-21-05			Tr.						
36.2dca1	29.5	e	5-23-18			.6						1.2
36.2		e	3- 3-25			5.6						
36.2		e	11- 2-93		30		158	50	[1]26		543	
112.36.2dc		e	8-30-07		35	4.0	199	66	[1]26		542	
36.9dad1	212	f	10-20-53	48		5.1						0.65
36.10bdb1	220	f	11- 3-53	49	9.4	5.8	52	43	53	3.8	308	.16
36.10cab1	194	f	10-20-53	49	25	11	168	51	68	5.7	500	.84
36.11ada1	185.5	b	10- 2-47		22	3.1						.88
36.11ada2	166.0	f	10-20-53	49		13						.68
36.12bbd1	92	c	1- 3-52		41	5.3	518	253	186			.22
		f	10-22-53	48	31	5.4	236	40	34	8.6	538	.13
36.12daa1	90	f	10-22-53	49	31	9.6	137	40	24	6.2	494	.17
36.14aaa1	214.0	d	10-10-51			.84						1.2
		c	1- 3-52				212	172	91			
		f	10-15-53	49	27	.10	176	51	63	4.7	525	1.6
36.16aad1	185	f	10-29-53	50		16						.88
36.16dad1	155	f	10-20-53	50		3.9						.94
36.25abb3	180	f	8- 4-54	49	26	.47	231	83	101	9	509	.64
36.27bcc1	130	f	10-29-53	50		.77						.22
113.35.29caa1	114	f	10-22-53	51	15	4.5	46	18	16	4.3	207	.05
35.34dcb1	172.0	f	10-22-53	50		1.4						.09
36.36		d	10-23-50			.17						.00
36.36abb		d	10-23-50		.22	.03						
36.36		d	10-24-50		.77							
36.36		d	10-24-50		.58							

[1] Sodium, potassium calculated as sodium (Na).

of water in the Redwood area

c, General Filter Co., Ames, Iowa; d, Minnesota Department of Health; e, Thiel (1944); f, U.S. Geological except as indicated. Color on platinum-cobalt scale]

Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Boron (B)	Dissolved solids		Hardness as $CaCO_3$		Percent sodium	Turbidity	Specific conductance (micromhos at 25° C)	pH	Remarks
					Calculated	Residue at 180° C	Total	Noncarbonate					
520	4.0	------	------	------	------	1,240	702	------	------	------	1,550	7.6	
------	6.0	------	------	------	------	------	891	------	------	------	------	----	River above falls.
------	6.0	------	------	------	------	------	898	------	------	------	------	----	Do.
46	0.4	------	0.31	------	153	39	124	------	------	<7	------	----	Do.
334	4.0	------	.31	------	643	172	382	------	------	20	------	----	Do.
------	1.5	------	------	------	------	------	450	------	------	10	------	----	Color 15.
------	5.0	------	------	------	------	------	506	------	------	50	------	----	Color 10. Spring water at city.
187	12	------	------	------	732	------	------	------	------	------	------	----	Mixture of all springs in city.
361	7	0.9	------	------	972	------	------	------	------	------	------	----	Spring 1 mile south of city, east side of river.
220	3.0	------	------	------	------	786	548	------	------	------	1,140	7.8	
162	2.5	.1	4.1	0.44	488	488	307	54	27	------	761	7.7	
353	2.0	.2	5.9	.51	936	984	630	220	19	------	1,310	7.3	
735	10.3	------	------	------	------	------	684	------	------	------	------	7.6	
325	3.0	------	------	------	------	1,020	672	------	------	------	1,390	7.5	
520	3.4	------	------	------	------	------	771	------	------	------	------	6.9	
355	1.5	.2	5.8	.26	983	1,030	754	313	9	60	1,350	7.4	Color 3.
153	1.0	.3	4.1	.17	649	664	506	101	9	------	962	7.3	
310	3.0	.12	------	------	------	------	480	------	------	------	------	7.5	
330	3.4	------	------	------	------	------	436	------	------	------	------	7.9	
343	3.5	.2	.4	.48	928	978	649	218	17	0.8	1,300	7.8	
450	4.0	------	------	------	------	1,200	836	------	------	------	1,530	7.5	
445	4.0	------	------	------	------	1,180	798	------	------	------	1,540	7.5	
690	2.5	.4	8.2	.71	1,400	1,500	916	499	19	2	1,800	7.2	Color 6.
935	22	------	------	------	------	1,930	994	------	------	------	2,230	7.4	
35	8.0	.2	15	.09	264	260	189	19	15	2.2	426	7.5	
128	.4	------	------	------	------	672	84	------	------	------	1,040	8.1	
49	1.0	.18	3.8	------	------	------	260	------	------	2.4	------	7.5	Color 12; spring, Ramsey Park.
73	1.5	.12	<.1	------	------	------	280	------	------	2.2	------	7.4	Color 13; spring, Ramsey Park.
120	3.0	------	<.1	------	------	------	430	------	------	9.5	------	7.1	Color 17; log cabin area well in Ramsey Park.
43	6.0	------	.23	------	------	------	310	------	------	5.2	------	7.1	Color 18; Ramsey Falls spring well.

TABLE 4.—*Elements, substances, and characteristics commonly found in ground water*

Constituent or characteristic	*Primary source*	*Significance*
Silica (SiO_2)	Siliceous minerals	Forms hard scale in pipes and boilers. Inhibits deterioration of zeolite-type water softeners.
Iron (Fe)	The common iron-bearing minerals.	Excessive dissolved iron is likely to cause "red water" after contact with air owing to the precipitation of hydrous iron oxide. More than about 0.3 ppm will stain laundry, plumbing fixtures, and other water utensils and is objectionable for food processing and the manufacture of beverages. Larger quantities impart taste and favor the growth of iron-secreting bacteria.
Manganese (Mn)	Manganese-bearing minerals.	Less common than iron; in general has the same objectionable features; brown to black stain if more than approximately 0.1 ppm is present.
Calcium (Ca) and magnesium (Mg).	Limestone, dolomite and gypsum.	Cause most of the hardness and scale-forming properties of water; soap consuming.
Sodium (Na) and potassium (K).	Feldspars and other common minerals; ancient brines, sea water; industrial brines and sewage.	More than 50 to 100 ppm of sodium and potassium in boiler waters cause foaming. May cause other difficulties in certain specialized industrial water uses.
Boron (B)	Solvent action of ground water on various minerals.	May be injurious to crops; thus a critical factor in irrigation water.
Bicarbonate (HCO_3) and carbonate (CO_3).	Action of carbon dioxide on carbonate minerals.	In combination with calcium and magnesium forms carbonate hardness; decomposes on application of heat with attendant formation of scale and release of corrosive carbon dioxide gas.
Sulphate (SO_4)	Gypsum, iron sulfides, and other rarer minerals in many industrial wastes.	Sulphates of calcium and magnesium form hard scale. Most people cannot tolerate drinking water that contains more than 2,000 ppm sulphate. Water having more than 500 ppm sulphate may have a laxative effect on initial use.

TABLE 4.—*Elements, substances, and characteristics commonly found in ground water*—Continued

Constituent or characteristic	*Primary source*	*Significance*
Chloride (Cl)	Found in small to large amounts in all soils and rocks; natural and artificial brines, sea-water, sewage.	Objectionable for various specialized industrial uses of water. Chloride in excess of about 300 ppm can be detected by persons with sensitive taste. Most people cannot tolerate drinking water that contains more than 1,500 ppm chloride.
Fluoride (F)	Various minerals	About 1.0 to 1.5 ppm apparently is desirable in reducing incidence of tooth decay. Larger amounts may cause mottling of tooth enamel of children.
Nitrate (NO_3)	Decayed organic matter, sewage, nitrate fertilizers, nitrates in soil.	Values higher than the local average may suggest pollution. There is evidence that more than about 45 ppm NO_3 may cause methemoglobinemia (infant cyanosis or "blue" babies), sometimes fatal. Water of high nitrate content should not be used for baby feeding.
Dissolved solids	Solution action of ground water on various minerals.	Most livestock apparently can tolerate as much as 10,000 ppm of total dissolved solids without injury. If the mineralization is very high, it usually requires a period of adjustment before the stock become accustomed to the water.
pH	Hydrogen-ion concentration in the ground water.	The pH is related to the corrosive characteristics of water. A pH of 7 is neutral. pH values less than 7 indicate acidic characteristics, and those greater than 7 alkaline characteristics.
Specific conductance.	Dissolved constituents in ground water which ionize.	Provides a convenient means of showing the concentration of dissolved solids in the water.
Color	Action of ground water on organic matter.	Most people object to color in drinking water. Color may stain fixtures and is objectionable in many industrial uses of water. For general purposes, color should be under 20 (platinum-cobalt scale).

SUMMARY

Except for the Minnesota River valley and the lower part of the Redwood River valley, most of the Redwood Falls area is underlain by glacial drift. The glacial drift ranges in thickness from 0 to about 260 feet and overlies either Precambrian gneiss or thin patches of Cretaceous strata, composed largely of shale. Near the center of the area there is a buried bedrock valley that trends southeast for a distance of at least 4 miles. It is incised to a depth of more than 150 feet and is filled with glacial drift.

Most wells in the area obtain water from the glacial drift. Where the drift is absent, thin, or impermeable, the wells usually tap Precambrian bedrock. Adequate domestic and stock wells can be completed almost anywhere in the drift. Two glacial-outwash aquifers capable of yielding large supplies of water are associated with the buried bedrock valley. The larger of the two aquifers is at least 3 miles long, 1½ miles wide, and as much as 55 feet thick in places. The aquifers are confined by drift composed largely of clayey till, but the drift in its entirety is considered a hydraulic unit.

Precipitation is the primary source of recharge in the area, and most of the natural discharge is by evapotranspiration. It is estimated that for the period 1953–56 about 10 percent of the average annual precipitation of 23.4 inches recharged the ground-water reservoir. Owing to the complex hydrologic and geologic characteristics of the glacial-outwash aquifers, large-scale ground-water developments should be preceded by carefully controlled test drilling and test pumping.

WELL LOGS

Table 5 contains 8 selected logs from the 57 available logs of wells and test holes drilled in the Redwood Falls area. Well cuttings of 25 test holes (pls. 10 and 11) were collected and described at the drilling sites by Survey geologists and studied later in the laboratory. All the available logs of wells and test holes shown on plates 10 and 11 may be inspected by the public at the district office of the U.S. Geological Survey, St. Paul, Minn.

TABLE 5.—*Selected logs of wells and test holes in the Redwood Falls area*

[Asterisk indicates test hole logged by Survey geologists; all other data from drillers' logs]

	Thickness (feet)	Depth (feet)
Test hole 112.35.7ccc1		
Soil, yellow	2	2
Clay, yellow	26	28
Sand, yellow	2	30
Clay, blue	8	38
Sand, gray	1	39
Clay, sandy, blue, and boulders	23	62
Clay, hard, blue	8	70
Clay, sandy, soft, blue	5	75
Sand and clay, blue	1	76
Clay and gravel, blue	17	93
Sand and gravel; soft blue clay	21	114
Clay, hard, blue, and boulders	6	120
Clay, sandy, soft, blue	2	122
Clay, hard, blue	8	130
Clay, blue	4	134
Clay, hard, blue	31	165
Clay and clayey sand	2	167
Clay, hard, blue	16	183
Clay, sandy, soft, blue	7	190
Clay, blue, and clayey sand	9	199
Sand, blue	8	207
Shale, blue; some gravel	5	212
Gneiss, decomposed, brown, green, red, yellow	2	214
Test hole 112.36.1cbb2*		
Sand, fine to medium	1	1
Clay, brown and gray	5	6
Clay and some dark-gray sand	11	17
Clay, silty, pebbly, plastic, hard, dark-gray	4	21
Clay, silty, plastic, dark-gray; contains layers of gravel	6	27
Clay, dark-gray, silty, plastic	4½	31½
Gneiss, fresh, unaltered	½	32
Test hole 112.36.2dda3*		
Soil	5	5
Clay, sandy, light-gray and brown	5	10
Clay, sandy, gray; some brown clay	6	16
Sand, fine, to medium gravel, clayey, poorly sorted; contains pelecypod shells	6	22
Boulder	1	23
Clay, dark-gray, and medium gravel	7	30
Clay, dark-gray; some medium to coarse gravel	18	48
Clay, dark-gray; some sand and gravel	14	62
Sand, fine to coarse; some gravel; clayey near bottom	15	77
Gravel, fine to medium, clayey	5	82
Clay, kaolinitic (decomposed gneiss)	10	92
Test hole 112.36.11ada1		
Clay, yellow, and rocks	30	30
Clay, sandy, blue	30	60
Clay, blue, and rocks	22	82
Sand and gravel	12	94
Clay, sandy, and rock	8	102
Sand	2	104
Clay, sandy, and rock	81	185
Gneiss	½	185½

TABLE 5.—*Selected logs of wells and test holes in the Redwood Falls area*—Con.

	Thickness (feet)	Depth (feet)
Test hole 112.36.12cba1*		
Soil, black	5	5
Till, yellow-brown	21	26
Till, dark-gray; thin sand layer from 51 to 52 ft	40	66
Sand, medium, to coarse gravel	16	82
Till, dark-gray; contains thin layers of sand and gravel	122	204
Clay, green, kaolinitic (decomposed gneiss)	6	210
Test hole 112.36.13cbb1		
Spoil bank, black	7	7
Clay, yellow	10	17
Clay, blue	36	53
Sand, clayey	2	55
Sand, blue, and clay in layers	6	61
Clay, blue, and boulders	12	73
Clay, soft, blue, and boulders	13	86
Clay, blue	51	137
Clay, sandy, soft, blue	5	142
Clay, compact, blue	26	168
Clay, soft, blue	34	202
Clay, sandy, blue	4	206
Clay, blue, and fine sand	32	238
Sand, yellow and blue	5	243
Gneiss	½	243½
Well 112.36.14aaa1		
Soil, black	2	2
Clay, yellow	11	13
Clay, yellow, and gravel	3	16
Clay, yellow	4	20
Clay, blue	31	51
Clay, sandy, yellow	3	54
Clay, sandy, blue	16	70
Sand	2	72
Clay, sandy, blue, and boulders	68	140
Clay, hard, blue	49	189
Clay, soft, blue	10	199
Sand and gravel, brown	44	243
Gneiss	½	243½
Test hole 112.36.14ada1		
Soil, black	2	2
Clay, yellow	25	27
Clay, dark-gray, and gravel	7	34
Clay, blue	40	74
Gravel, coarse, blue and yellow	3	77
Clay, sandy, blue; contains layers of sand and gravel	113	190
Clay, sandy, soft, blue; took water	63	253
Gneiss, black, red, white, hard	½	253½

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INDEX

[Italic page numbers indicate major references

	Page
Abstract	*1*
Access	*6*
Acknowledgments	*3*
Agriculture	*5*
Alluvium, description and water-bearing characteristics	*17*
Alteration, Precambrian rocks	*9*
Altitude	*7*
Antelope moraine	8, 14
Aquifers, defined	*18*
Aquifer tests, general	*24*
Artesian aquifer	*33*
Artesian conditions	*19*
Availability of water	*31*
Bauxitic laterite	*11*
Bored wells	*30*
Building stone	*5*
Capillarity	*17*
Climate	*6*
Coefficient of permeability, defined	*24*
Coefficient of storage, defined	*24*
at well 112.36.12bbd1	27
at well 112.36.14aaa1	*25*
well 112.36.25abb3	*27*
Coefficient of transmissibility, defined	*24*
at well 112.36.12bbd1	*27*
at well 112.36.14aaa1	*25*
at well 112.36.25abb3	*27*
Cone of depression at well 112.36.14aaa1	*26*
Confining beds	*19*
Contact springs, defined	*23*
Cretaceous system, description and water-bearing characteristics	*12*
Crow Creek	*34*
Culture	*5*
Deposition, Cretaceous sediments	*12*
Des Moines ice lobe	8
Discharge	*22*
Divides, ground water	*20*
Domestic and stock wells, present development	*28*
Drainage	6
Drawdown	*31*
Drilled wells	*30*
Dug wells	*30*
Electrical power	*6*
Erosion	8
Evapotranspiration, effect on water level fluctuations	*21*
general	*23*
Field coefficient of permeability, defined	*24*
at well 112.36.12bbd1	*27*
at well 112.36.25abb3	*27*
at well 112.36.14aaa1	*26*
Fieldwork, methods of investigation	*2*
Fluctuations of water levels	*20*
Geography	*5*
Geologic history, summary	*7*
Geologic units and their water-bearing properties	*9*
Geology	*7*
Glacial Lake Agassiz, origin	*8*
Glacial River Warren	*9*
Glacial topography	*6*
Glacioaqueous deposits, composition	*15*
description	*13*
Goldich, S. S., quoted	*11*
Gravity springs, defined	*23*
Ground moraine, description	*13*
Ground water	*17*
Hydraulic coeffecients	*31*
Hydraulic gradient	*20*
Ice-contact deposits, description	*13*
Ice-contact features, description and water-bearing characteristics	*16*
Introduction	*2*
Kaolinized zone, Precambrian rock	*11*
Lignite	*12*
Location of area	*5*
Meinzer, O. E., quoted	*23*
Mesozoic era, geologic history	*8*
Methods of investigation	*2*
Mineralogy, unweathered Precambrian bedrock	*10*
Minnesota River, discharge	*34*
Minnesota valley, origin	*8*
Moraines	*7*
Morton quartz monzonite gneiss	*9*
Movement of ground water	*19*
Multiple glaciation	*13*
Municipal wells, present development	*31*
Occurrence of ground water	*18*
Outwash deposits, description	*13*
water-bearing properties	*16*
Permeability, alluvium	*17*
defined	*18*

	Page
Physiographic province	6
Piezometric surface, defined	19
Pleistocene deposits, description and water-bearing characteristics	12
Pleistocene epoch, geologic history	8
Population	5
Porosity, defined	18
Precambrian bedrock, occurrence of water	19
Precambrian bedrock surface	11
Precambrian rocks, depth	9
Precambrian system, description and water-bearing properties	9
Precipitation	6
effect on discharge from springs	24
effect on recharge	22
Previous reports	3
Pumping, artesian aquifer	33
Purpose and scope of report	2
Quality of water	34
Quaternary alluvium, occurrence of ground water	18
Quaternary system, water-bearing characteristics	12
Ramsey Creek	34
Recent deposits, description and water-bearing characteristics	17
Recessional moraines, description	14
origin	8
Recharge, artesian aquifer	33
effect on water-table fluctuations	21
general	22
Redwood River, discharge	34
Requirements of water for farm and domestic supply	30
Rocks, geologic history	7
Seepage, surface-water, effect on recharge	22
general	23
Springs, discharge	33
Stratigraphic section, drift composed of till	14
idealized	14
Summary	40
Surface outwash description and water-bearing characteristics	16
Surface water	33
Swamp deposits, description and water-bearing characteristics	17
Temperature	6
Theoretical drawdown	31
Till, composition	15
description	13
Topography	6
drift	13
Water-bearing properties, geologic units	9
Water levels	20
Water table, depth	18
Weathering, depth	9
Well 112.36.121bbd1, aquifer test	26
Well 112.35.14aaa1, aquifer test	25
Well 112.36.25abb3, aquifer test	27
Well 113.36.35add1, water-table fluctuations	21
Well development, present	27
Well-numbering system	4
Wisconsin glaciation	13
Yellow Medicine River, discharge	34
Yields of wells, Cretaceous strata	12
outwash	16
Precambrian crystalline rock	11
Zone of aeration	17
Zone of saturation, defined	17