GEOLOGY AND GROUND-WATER CONDITIONS AT MINOT, NORTH DAKOTA

By

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North Dakota Ground-Water Studies No. 6

Prepared in cooperation between the Geological Survey, U. S. Department of the Interior; the City of Minot; the North Dakota State Geological Survey; and the North Dakota State Water Conservation Commission.

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CONTENTS

	Page
Abstract--	1
Introduction--	7
Purpose and scope of the investigation-------------	7
Previous work--------------------------------------	8
Acknowledgments------------------------------------	10
Location and general features of the area----------	11
Geology and occurrence of ground water------------------	13
Chemical analyses of water in and near Minot------------	19
Hydrology of the aquifer at Minot-----------------------	26
General discussion of the problem------------------	26
Ground-Water development and use-------------------	32
History of development-----------------------	32
Amount of Water used-------------------------	35
Long-period production--------------------	35
Daily production--------------------------	41
Water-level fluctuations---------------------------	42
General--------------------------------------	42
Long-period water-level changes--------------	42
Seasonal fluctuations------------------------	46
Daily fluctuations---------------------------	47
Relation between ground-water use and water levels--	50
Pumping tests--------------------------------------	52
Collection of data---------------------------	52
Arrangement of data for computation of transmissibility and storage coeffecients-------	54
Formulas and methods for computing transmissibility and storage coefficients-----------	55
Fundamental basis of formulas----------------	55
The Thiem formula----------------------------	57
The Theis non-equilibrium formula------------	59
Summary of results of pumping tests-----------	60
Specific capacities of wells at Minot--------------	63
Recharge---	65
Storage--	70
Safe yield of the aquifer--------------------------	70
Possibility of artificial recharge with river water-	73
Records of wells--	74
Logs of wells and test holes----------------------------	88

ILLUSTRATIONS

		Page
Figure 1.	Map showing location of Minot with respect to physiographic features in North Dakota.	13
Figure 2.	Map of Minot and vicinity showing surface geology and location of wells and test holes.	16
Figure 3.	Graphic logs of test holes and wells in the Souris River Valley in and near Minot.	18
Figure 4.	Daily high and low water levels and daily pumpage from wells in Minot area.	In pocket
Figure 5.	Water levels in observation wells during pumping test on Minot city supply wells 3 and 4	47
Figure 6.	Water levels in Northern States Power Co. wells, October 7 to 14, 1944	49
Figure 7.	Relation between ground-water consumption and water levels.	52
Figure 8.	Semi-log plot of drawdown at observation wells vs. distance from pumping well.	59
Figure 9.	Semi-log plot of recoveries at observation wells vs. distance from pumped well	59
Figure 10.	Semi-log plots of drawdown at observation wells vs. time since pumping began Minot city supply well No. 3 .	60
Figure 11.	Semi-log plots of recoveries at observation wells vs. time since pumping stopped at Minot city supply well No. 4.	60
Figure 12.	A. Water levels in wells at Minot. B. Monthly average and annual average pumpage at Minot. C. Monthly average gage height on Souris River above Minot. D. Monthly precipitation at Minot.	In pocket

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ABSTRACT

The investigation of the ground-water resources in the vicinity of Minot was begun in 1944 by the U. S. Geological Survey in cooperation with the City of Minot and the North Dakota State Geological Survey and was concluded under cooperation between the U. S. Geological Survey and the North Dakota State Water Conservation Commission. Its purpose was to determine the ground-water resources of the area and especially the hydrologic and hydraulic characteristics of the sand and gravel aquifer from which the City of Minot obtains its water supply, and to forecast as nearly as practicable the quantity of water that can be produced from the aquifer in and near the city without ultimate overdevelopment.

The Fort Union formation, of earliest Tertiary Plaeocene age, is the bedrock of the region. It is covered with river alluvium, sand and silt deposits of glacial Lake Souris, and glacial drift ranging in thickness from 0 to 250 feet or more. A few small exposures of the bedrock are found along the valley of the Souris River and the Riviere des Lacs.

Locally ground water for domestic supplies is obtained from sand and gravel in the glacial drift, and from lignite and sandstone beds of the Fort Union formation, but in the Souris River Valley most of the ground water is obtained from sand and gravel beds in the valley fill. So far as is known, no supplies are derived from formations underlying the Fort Union in this area, although small supplies of rather highly mineralized water could probably be obtained from other formations at depths exceeding 1,000 feet.

The fill in the Souris River Valley consists of glacial till, sand and gravel of glacio-fluvial origin, silts and clays deposited in glacial Lake Souris, and Recent river alluvium. Domestic and stock wells obtain water from various aquifers in the valley fill but the principal aquifer in the fill is that from which the municipal and large industrial supplies are obtained. It is a sand and gravel body of glacio-fluvial origin reached at depths of about 100 feet below the present valley floor. This aquifer is variously interconnected with other aquifers in the drift and in the overlying alluvium. Its linear extent is not known but it probably extends many miles both upstream and downstream from the City of Minot. Additional test drilling is needed to determine the possibilities of obtaining other large ground-water supplies along its course.

In general, the water from the Fort Union formation is softer but much more highly mineralized than that from other sources. The municipal water from the principal aquifer is substantially similar in chemical character and concentration to the river water. Its iron content is objectionably high but it is otherwise satisfactory for general purposes.

The average production of ground water from the principal aquifer is estimated to have been about 600,000 gallons a day in 1928, increasing to 880,000 gallons a day in 1931 and to about 2,390,000 gallons a day in 1946. The highest monthly production was in August 1946, when pumpage amounted to 114.1 million gallons or an average of 3.69 million gallons a day for the month. The maximum daily production of the three large users of ground water occurred on June 21, 1946, and amounted to 4,255,000 gallons.

The original water levels in the aquifer at Minot were 2 to 3 feet above the level of the water in the Souris River. As new ground-water developments were made, the later level in the aquifer was lowered. The decline amounted to about 9 feet by 1928 and to about 27 feet by 1938. In 1946 the average high monthly water level was about 34 feet lower than the original water levels. The lowering of water levels is almost directly proportional to the rate of withdrawal of ground water from the aquifer.

Seasonal fluctuations in the water levels are the result of variations in the amount of water pumped, the water levels trending downward in the months when the pumpage is high and recovering when the pumpage is reduced. The difference between high and low water levels in 1945 was 9.42 feet at the city supply well No. 2. In 1946 the difference was 11.48 feet.

Daily water-level fluctuations in wells in the principal aquifer result chiefly from changes in barometric pressure and from interference effects of pumping wells.

Only occasionally when the Souris River is at a high stage do the water levels fluctuate in such a manner as to indicate seasonal or intermittent recharge to the aquifer. However, such fluctuations occuring at other times, if comparatively small, could be masked by fluctuations due to changes in pumping and to barometric-pressure changes.

The average coefficient of transmissibility of the aquifer was computed from pumping tests to be about 250,000 gpd/ft. and the average coefficient of storage was computed to be about .00034.

There are three sources of recharge to the aquifer: (1) Direct penetration of the rainfall in the valley to the water table in shallow contributing aquifers: (2) ground-water discharge into the aquifer from the Fort Union formation by lateral movement into the valley and probably by upward percolation from deeper horizons; and (3) downward percolation of Souris River water. Of these three sources of recharge, the river appears to be the most important contributor.

It is concluded that the aquifer at Minot is not overdeveloped. The perennial "safe yield" will depend largely upon the specific capacities of the producing wells. The specific capacities of the municipal and industrial wells at Minot average more than 20 gpm/ft. If wells having specific capacities of 20 gpm/ft. are pumped at a rate of about 700 gpm, it is indicated that a yield of about 3.5 million gallons a day (annual average) probably can be obtained from the aquifer without lowering the pumping water levels excessively.

In order that the production may be thus increased it is apparent that the net recharge must continue to increase with lowering water levels as it has in the past. There is no reason to believe that this will not occur but there is always some possibility that conditions in the recharge areas are such as to prevent increasing the recharge rates by the necessary amounts. For this reason careful water-level records should be maintained on a few of the observation wells. Production probably will increase slowly and the water-level records will indicate overpumping of the aquifer, if it should occur, before it becomes serious.

In the event that it should become necessary, surface water from the Souris River could be used as a supplemental source of supply or could be used in artificially recharging the aquifer by directing the surface water underground through wells.

INTRODUCTION

Purpose and scope of the investigation

The investigation of the ground-water resources in the vicinity of Minot was begun by the U. S. Geological Survey in the summer of 1944 in cooperation with the City of Minot and the North Dakota State Geological Survey. The investigation was continued subsequently with funds provided by cooperation between the U. S. Geological Survey and the North Dakota State Water Conservation Commission.

The purpose of the investigation was to determine the ground-water resources in the vicinity of Minot and especially to determine the hydrologic and hydraulic characteristics of the sand and gravel aquifer from which the City of Minot obtains its water supply, and to forecast as nearly as practicable the quantity of ground water that can be produced from the aquifer in and near the City of Minot without ultimate overdevelopment. The investigation involved a study of the geology in the area in the vicinity of Minot: the collection and study of data from existing wells; the study and correlation of climatic and streamflow data; and the study and interpretation of pumping tests, pumping records, and water-level fluctuations. Eight test holes were drilled to obtain data on the width and thickness of the aquifer. Unfortuanately some of the holes failed to reach the depths required to furnish this information. Pumping tests were made on several wells to determine the coefficients of storage and transmissibility of the aquifer.

The results of the study are of chief interest to the City of Minot and other users of ground water in the area. However, it is hoped that it will prove to be a basic contribution to the proposed more general study of the ground-water resources of Ward County and to the ground-water studies now being undertaken by the Bureau of Reclamation and other Government agencies in connection with the Missouri-Souris development program.

Previous work

A number of publications dealing with the geology in the Minot area and in adjacent areas, with special reference to the coal resources of the region, have been published. The latest of these studies was made by Andrews 1/ , who lists references to earlier studies of this nature. Upham 2/ referred to some of the glacial features of glacial Lake Souris, but did not describe in detail any of the features of the area. Simpson 3/ described the general features of the geology and ground-water occurrence in North Dakota and included a more detailed description of the geology and ground-water occurrence in Ward County under the section dealing with county reports. In this section he also made special reference to the ground-water development at Minot. 4/

1/ Andrews, D.A., Geology and coal resources of the Minot region, North Dakota; U.S. Geol. Survey Bull. 906-B, pp. 46-48, 1939.
2/ Upham, Warren, the glacial Lake Agassiz: U.S. Geol. Survey Mon. 25, 1896
3/ Simpson, H.E., Geology and ground-water resources of North Dakota U.S. Geol. Survey Water-Supply Paper 598, 1929
4/ Simpson, H.E., op. cit., pp. 254-256

Acknowledgments

The investigation was performed under the general supervision of O.E. Meinzer, Geologist in Charge of the Division of Ground Water, until his retirement from the Federal service. The work was continued under the supervision of his successor, A.N. Sayre. In North Dakota, the investigation was under the general supervision of A. L. Greenlee, geologist in charge until his resignation from the Federal service, when he was succeeded by P.E. Dennis, district geologist. Field work and technical study of the problems was begun by A. M. Morgan, geologist, who was detailed to the work from Wyoming. The investigation was continued by the writer after Mr. Morgan's return to Wyoming.

Information and data were gathered from many sources and splendid cooperation was had from all parties contacted in the field. Special acknowledgements due J.W. Bliss, City Manager of Minot, Lloyd Wilhelm, City Engineer, S.K. Swenkenson, Minot Superintendent of Public Works, and other employees of the City of Minot for their assistances and cooperation throughout the investigation. Acknowledgement is due the well drillers of the area and the employees of the Great Northern Railway Company, the Northern States Power Company, the Minot Flour Milling Company, and others for furnishing records and data of importance to the investigation. Many helpful suggestions and data were obtained from members of the Geologic Branch of the U.S. Geological Survey who were working in the area during the progress of the investigation. Acknowledgement is also due to the members of the North Dakota State Water Conservation Commission and to Wilson M. Laird, State Geologist, for their cooperation throughout the investigation.

Location and general features of the area.

The City of Minot is located in the valley of the Souris River in Ward County in the northwestern part of North Dakota. The population within the corporate city limits was 16,577 in 1940, according to the U.S. Bureau of the Census. The population in the city and additions not incorporated was estimated by the Minot Association of Commerce to be 19,484 in 1946. The city is located on the main lines of two railroads, the Great Northern and the Minneapolis, St. Paul and Sault Ste. Marie. Three interstate paved highways enter Minot, U.S. 2 from the east and west, U.S. 52 from the northwest and southeast, and U.S. 83 from the north and south.

The City of Minot is the principal shipping point and business center for most of the northwestern part of North Dakota and adjacent parts of Canada. The principal industries in the area are farming and coal mining. Wheat is the principal crop but oats, flax, barley, and rye are grown extensively. Poultry raising, dairying, beef cattle raising, and farm-products are also important industries in the area.

The climate in the Minot area in semiarid. The average annual precipitation at Minot is reported by the U. S. Weather Bureau to be 15.50 inches, based on a 54-year record, but the departures from this average may be large in any year. The annual temperature range may amount to more than 150° F. The extreme low temperature recorded in North Dakota was -60° F., in 1936 and the highest recorded temperature was 121° F., also in 1936.

The seasonal distribution of average monthly precipitation and temperature at the Minot airport are given in the following table.

Average monthly precipitation and average monthly temperature at Minot, North Dakc

Month	Average precipitation (inches)	Average Temperature (° F)
Jan.	0.37	6.6
Feb.	0.43	10.2
Mar.	0.61	23.6
Apr.	1.22	40.8
May	2.16	53.1
June	3.11	65.1
July	2.05	68.8
Aug.	1.92	65.6
Sept.	1.60	56.4
Oct.	0.91	43.8
Nov.	0.66	27.4
Dec.	0.46	13.1
Year	15.50	39.7

The City of Minot is located in the western part of the Drift Prairie plain of the Central Lowland province and just northeast of the Missouri escarpment (see Fig. 1)

The Missouri escarpment divides Ward County into two nearly equal portions. Except in the valleys of the Souris River and the Riviere des Lacs, the Drift Prairie in this section is a northeastward-sloping, gently rolling plain marked here and there with sloughs. The valley of the Souris River is entrenched more than 200 feet below the surface of the plain in the vicinity of Minot.

The City of Minot is located chiefly in the valley of the Souris River, although a considerable part of the residential district lies upon the plain south of the valley. The ground-water study was largely confined to the Souris River Valley and the alluvial beds which partly fill it.

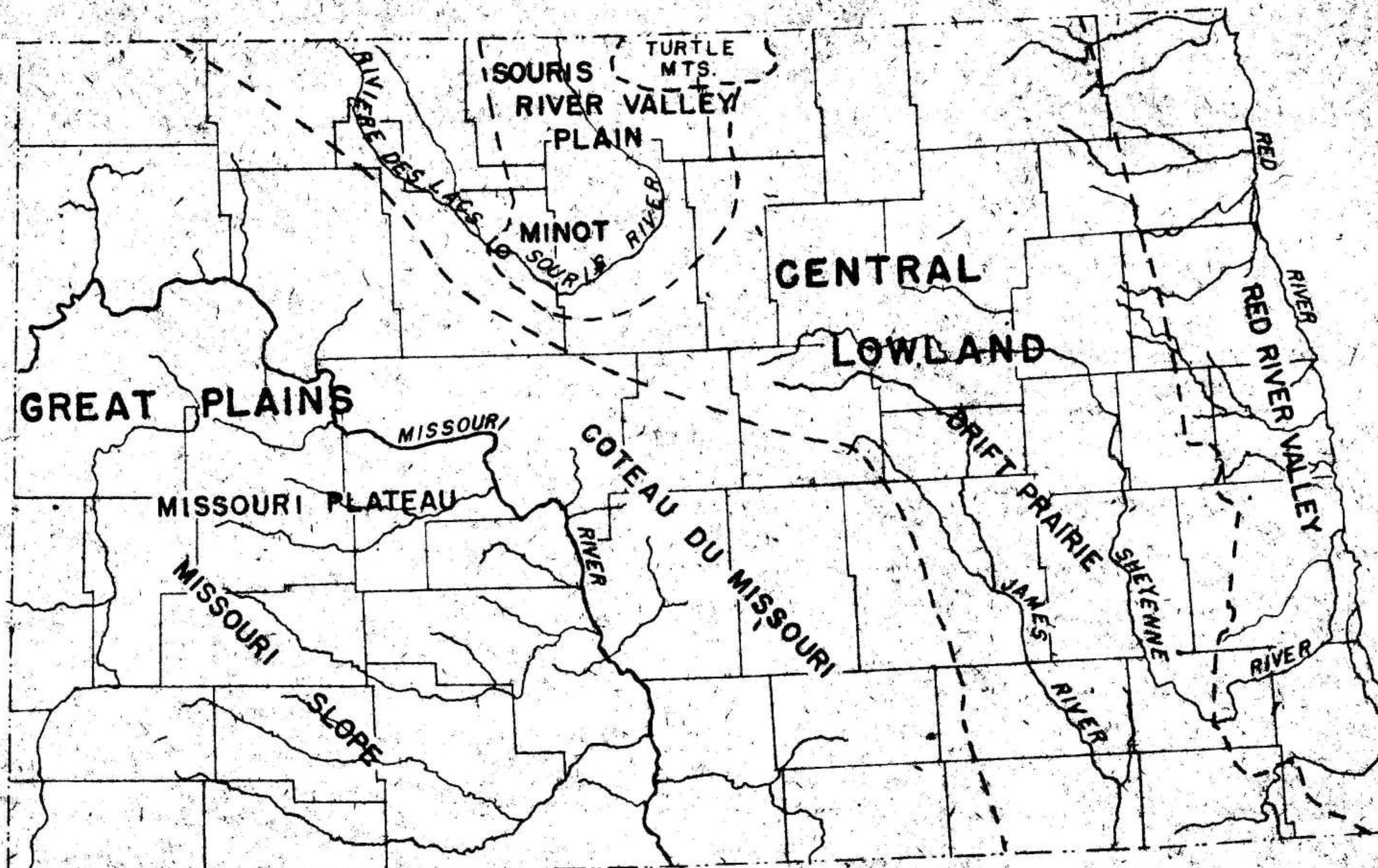


FIGURE I. MAP SHOWING LOCATION OF MINOT WITH RESPECT TO PHYSIOGRAPHIC FEATURES IN NORTH DAKOTA (AFTER SIMPSON)

The Fort Union formation, of Paleocene age, is the bedrock of the region but, in the vicinity of Minot, it is covered with river alluvium, sand and silt deposits of glacial Lake Souris, and glacial drift. A few small exposures of the bedrock are found along the valleys of the Souris River and the Riveire des Lacs. Drilled wells obtain small to moderate supplies of water from sandstone and lignite beds of the Fort Union formation. The following log taken from Simpson's 5/ report shows the general charcter of the Fort Union formation and the distribution of water-bearing beds.

Log of the Minneapolis, St. Paul & Sault Ste. Marie Railway well at Ryder

	Thickness (feet)	Depth		Thickness (feet)	Depth
Drift (?)	54	54	Shale	2	301
Clay and boulders	27	81	Coal and water	2	303
Coal	2	83	Shale	35	338
"Slate"	42	125	Sandy shale	23	361
Coal and water	12	137	Shale	9	370
"Slate	31	168	Coal	6	376
Shale	39	207	Shale	27	403
Coal	5	212	Coal and water	5	408
"Slate"	22	234	Shale	4	412
Rock	2	236	Coal	2	414
"Slate"	9	245	Shale	6	420
Coal	1	246	Coal	1	421
"Slate"	18	264	Shale	16	437
Shale	18	282	"Slate"	31	468
Coal	6	288	Hard Rock	5	473
Shale	8	296	Shale	3	476
Coal and Water	3	299	Coal	6	482

5/ Simpson, H.E., op. cit., p. 251

	Thickness (feet)	Depth		Thickness (feet)	Depth (feet)
Shale	1	483	Sand and Shale	11	543
Shale and coal	2	485	Coal	1	544
"Slate"	5	490	Shale	1	545
Shale	6	496	Sand and Shale	16	561
Coal	2	498	Coal and water	4	565
Shale	7	505	Shale and water	3	568
"Slate"	27	532	[illegible]		

The general charcter of the formation underlying the Fort Union to a total depth of 3,980 feet is given in the following log of an oil test well drilled in the SW¼ sec. 4, T. 155 N., R. 85 W., as adaptedhere from Simpson's report 6/

Generalized record of the DesLacs Western Oil Co. well

Character of strata penetrated	Depth (feet)
Glacial Drift	0-50
Gray, rather calcareous sandy clay with streaks of limestone, sandstone, and lignite. Hard layer, with show of gas beneath, reported by driller at 210 ft.	60-590
Lignite	590-598
Sandy clay, in part calcareous.	598-900?
Fine quartz sand, reported by drillers to show oil.	900?-920
Dark sandy calcareous shale, containing lignite and fragments of limestone	920-960
Gray muddy shale.	960-1,050
Gray sandy clay, with some carbonaceous matter	1,050-1,075
Gray gumbo, with fragments of light-colored limestone	1,075-1,125
Gray fine-grained shaly sandstone	1,125-1,160
Gray soft sticky shale.	1,160-1,300
No cuttings; reported by driller as sandstone, with good show of oil and gas.	1,300-1,340
Light-gray shale, with calcareous layers	1,340-1,900?
No cuttings; reported by driller as "limestone , with good show of oil".	1,900?-1,905
Gray shale	1,905-1,960

6/ Simpson, H.E., op. cit. pp. 252-253

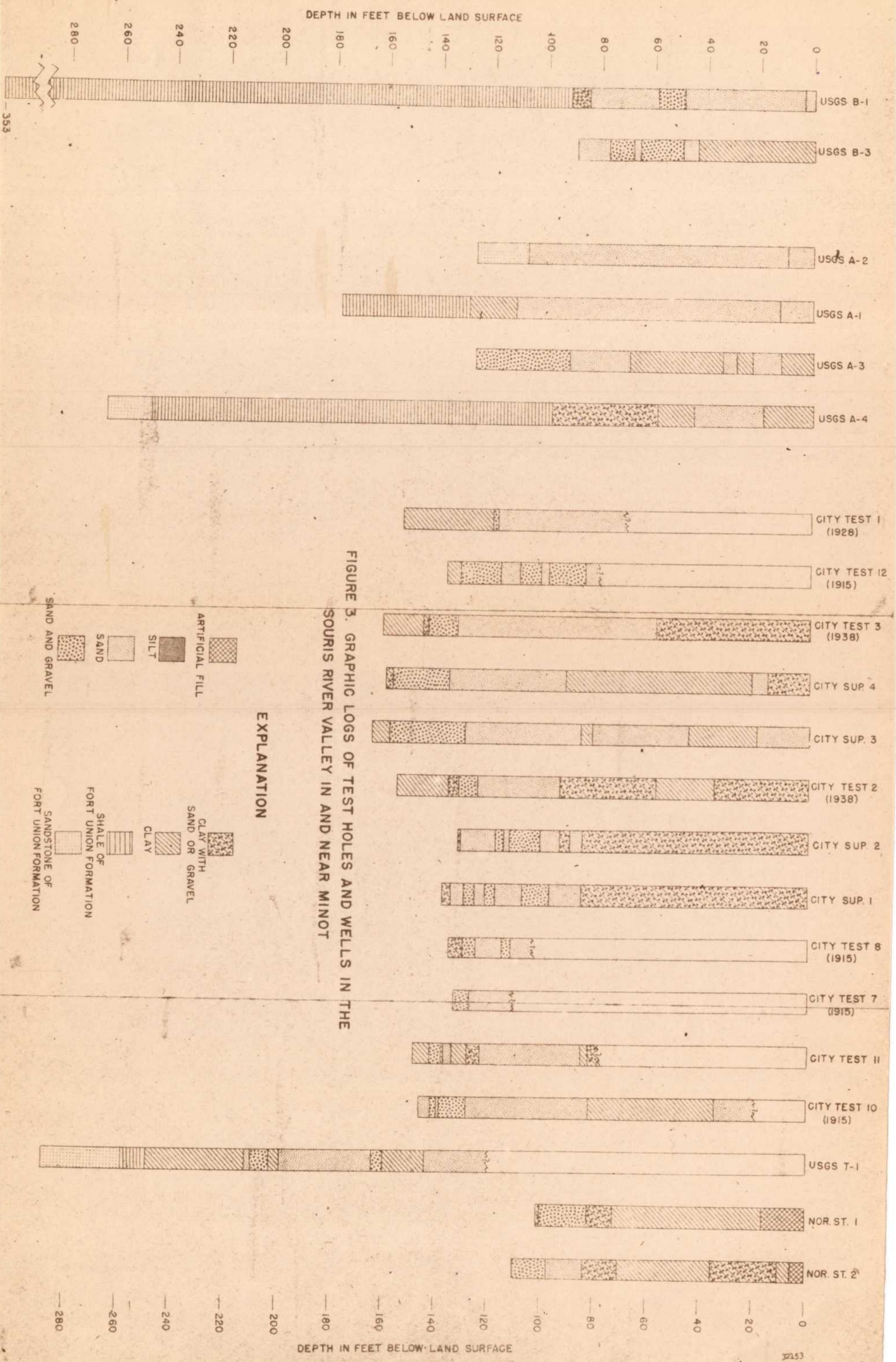


FIGURE 3. GRAPHIC LOGS OF TEST HOLES AND WELLS IN THE SOURIS RIVER VALLEY IN AND NEAR MINOT

Generalized record of the Des Lacs Western Oil Co. well (cont'd.)

Character of strata penetrated	Depth (feet)
Light-gray shaly limestone, with fragments of fossils	1,960-1,980
Gray shale, with calcareous layers	1,980- ?
Whitish clay	? -2,165
Gray, rather calcareous shale	2,165-2,300
Gray calcareous shale and limestone	2,300-2,320
According to driller's report there is sandy shale and sandstone, showing 1 to 10 barrels of oil a day, between 2,300 and 2,310 feet, which may correspond to the gas sand of the gas field at Glendive, Mont.	
Gray calcareous shale:fragments of fossils at 2,650 feet	2,320-2,800
Gray shaly limestone, with Ostrea and Inoceramus	2,820-2,830
Whitish shaly limestone	2,830-2,833
Gray crumbly shale	2,833-2,878
Blue Limestone with Inoceramus and Ostrea congesta	2,878-2,900
Dark crumbly calcareous shale	2,900-3,133
Blue limestone containing pyrite and fossils at 2,995-3,030 feet	
Driller reports sandstone showing 1 to 10 barrels of oil a day at 3,040-3,043 feet.	
Blue limestone with Baculites Inoceramus, and Ostrea	3,133-3,140
Dark-blue to black calcareous shale and limestone, with Ostrea congesta and abundant fragments of thick-shelled Inoceramus	3,140-3,400
Dark gummy, somewhat calcareous shale	3,400-3,476
Dark-gray, rather splintery shale, fragments of fossils	3,476-3,500
Dark, rather gummy shale	3,500-3,650
According to driller, limestone and limey shale at 3,460-3,560	
Dark hard massive, fairly calcareous shale	3,650-3,856
Gray limestone	3,856-3,860
Dark massive shale	3,860-3,880
Massive gray limestone	3,880-3,890
Dark hard shale and limestone with Inoceramus	3,890-3,909
Quartz sand, called Dakota sandstone by driller	3,909-3,924
Hard dark, rather calcareous shale, with Inoceramus	3,924-3,980

The local surface geology at Minot and the location of wells and Test holes in the vicinity are shown in figure 2.

Locally in the uplands, ground water for domestic supplies is obtained from the Fort Union formation and from sands and gravels in the glacial drift The existing wells in the Fort Union formation and in the drift have small yields. However, in other areas of the State, lignite and sandstone beds in the Fort Union formation and bodies of gravel and sand in the drift yield large quantities of water. Test drilling in the Minot area has not been extensive enough to determine whether or not such supplies may be present there.

In the Souris River Valley most of the wells obtain water from sands and gravels in the valley fill. A few wells in the valley obtain supplies from the Fort Union formation. So far as is known, no supplies are derived from formations underlying the Fort Union in this area, although some of the underlying formations would probably yield small supplies.

The fill in the Souris River Valley consists of till, sand, and gravel and glacio-fluvial origin, silts and clays deposited in glacial Lake Souris, and Recent river alluvium. The log of U.S.G.S. test hole T-1 indicates that the valley fill extends to 258 feet below the present valley floor at this location.

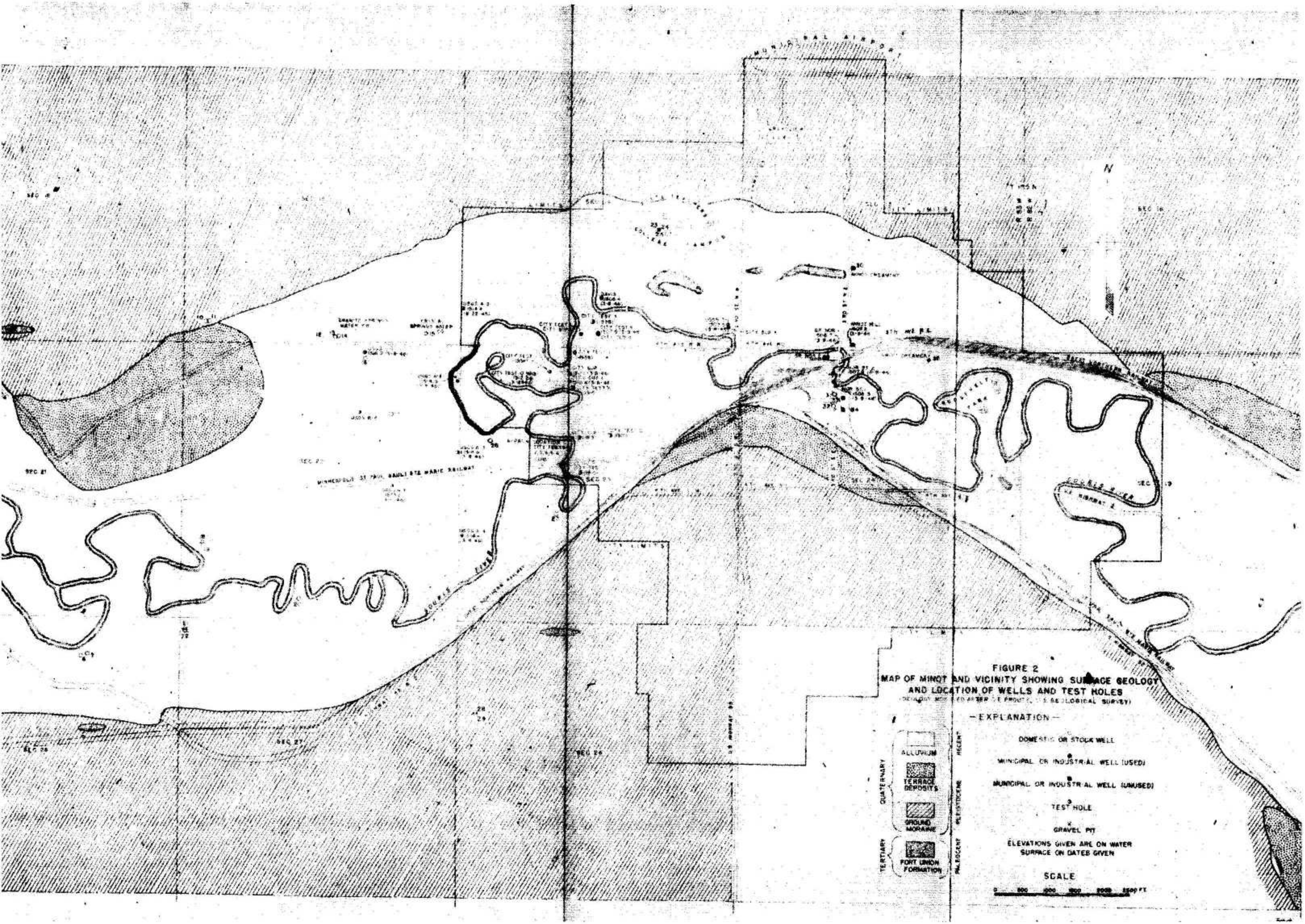


FIGURE 2
MAP OF MINOT AND VICINITY SHOWING SURFACE GEOLOGY AND LOCATION OF WELLS AND TEST HOLES

Domestic and stock wells obtain water from various depths in the valley fill but the principal aquifer from which the municipal and large industrial supplies are obtained is a sand and gravel body of glacio-fluvial origin reached at a depth of about 100 feet below the valley floor. This sand and gravel is variously interconnected with sands in the drift and in the overlying alluvium in such a manner that it may receive recharge from rainfall and from the river, as well as from ground-water discharge by lateral and upward flow from beds in the Fort Union formation. The most productive part of this aquifer is found in about the middle of the Souris River Valley at Minot and follows roughly a course between U.S.G.S. test B-2, U.S.G.S. test A-3 the city supply wells, U.S.G.S. test T-1 and the Great Northern supply wells. Some wells near the south side of the valley have failed to produce supplies adequate for creameries and other small industries. On the other hand, the well at Minot State Teachers College, at the northern edge of the valley, produces about 30 gallons a minute from a 6-inch well 200 feet deep. This well is reported to have produced 180 gallons a minute when pumped by air lift, the air being injected into the well at a depth of 160 feet.

The linear extent of this aquifer is not known but it probably extends many miles both upstream and downstream from the City of Minot. Addtional test drilling is needed to determine its extent and the possibilities of obtaining other large ground-water supplies, such as the one at Minot, at other sites along its course.

The hydrologic properties of the aquifer are discussed in detail in following sections. Graphic logs of many of the wells and test holes drilled in the valley are shown in figure 3. Written logs of wells and test holes and records of many of the wells in the vally are given at the end of this report.

CHEMICAL ANALYSES OF WATER IN AND NEAR MINOT

Twenty-nine Chemical analyses of water in and near Minot are given in the following table. Twelve are from wells drawing water from the valley fill in the Souris River Valley in Minot, two are from the Souris River, eight are from shallow wells drawing water from the glacial drift outside the valley and seven are representative of the waters derived from the Fort Union formation.

In general, the water from the Fort Union formation is much more highly mineralized than that from the other sourses, the preponderant constituents being sodium bicarbonate and sodium sulfate. The Fort Union water is generally much softer than the water from the other sources. On the other hand, the waters from the glacial drift generally contain less sodium bicarbonate than the water from the other sources but are relatively high in calcium and magnesium sulfate. The river water will flucuate considrably in quality, being less highly mineralized during flood stage than during periods of low flow, but there is a substantial similarity between the two analyses given for the river water and those for the waters from wells in the valley fill.

CHEMICAL ANALYSES OF WATER

Well or other source	Owner	Location m/	Date of analyses	Source of analyses	Aquifer	Total dissolved solids	Silica (SiO_2)	Iron (fe)
City Water a/	City of Minot	City of Minot	May 23, 1921	b/	c/	1,135	29	2.6
City supply well No. 1	do	do	Jan. 15, 1932	d/	c/	657	--	1.0
City supply well No. 2	do	do	Jan. 15, 1932	d/	c/	924	--	2.0
City supply well No. 3	do	do	Jan. 15, 1932	d/	c/	1,555	--	2.3
City supply well No. 1	do	do	Feb. 1, 1940	e/	c/	742	28	1.75
City supply well No. 2	do	do	Feb. 1, 1940	e/	c/	648	26	2.3
City supply well No. 3	do	do	Feb. 1, 1940	e/	c/	1,220	30	2.3
City supply well No. 4	do	do	Feb. 1, 1940	e/	c/	1,262	26	3
City supply well No. 5	do	dd	Sept. 20 1946	e/	c/	1,147	--	0.1
No. 24 (fig. 2)	State Teachers College	do	May 23 1921	b/	c/	1,454	29	3.2

a/ Composite sample, city wells No. 1 and No. 2 in use

b/ Simpson, H. E. Geology and ground-water resources of North Dakota: U.S. geol. Survey Water-Supply Paper 598, pp. 304-305, 1929

c/ Well drawing from Souris River valley fill

d/ Dr. G.A. Abbott, University of North Dakota, Grand Forks, N. Dak.

e/ First District Health Unit, Minot, North Dakota

m/ Locations according to township, range, and section given thus: 11-155-85 refers to Sec. 11, T. 155 N., R. 85 W.

IN AND NEAR MINOT. PARTS PER MILLION

Alumina (Al_2O_3)	Calcium (Ca)	Magnesium (Mg)	Sodium & Potassium (Na+K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Total hardness as ($CaCo_3$)	Total alkalinity as $CaCO_3$
---	56	27	353	799	68	200	---	251	------
---	37	18	182	536	17	76	---	166	------
---	75	31	248	704	96	124	---	315	------
---	93	28	473	982	143	300	---	347	------
3	58	24	111	468	35	46	.75	243	384
3	60	21	85	406	48	28	.80	236	333
3	56	25	262	677	67	133	.73	245	555
---	52	27	247	648	105	153	.50	316	531
---	106	33	290	744	144	190	---	390	610
---	125	56	320	742	291	232	---	542	------

Well or other source	Owner	Location m/	Date of analysis	Source of analysis	Aquifer	Total dissolved solids	Silica (SiO_2)	Iron (Fe)
Northern States Power Co. well No.1	Northern States Power Co.	City of Minot	Jan. 31, 1945	f/	c/	1,378	27	0.7 h/
Northern States Power Co. Well No. 2	Northern States Power Co.	do	Jan. 31, 1945	f/	c/	1,026	14	7.7 h/
Souris River	---------	do	Sept. 27, 1945	f/	--	1,110	10	7.7 h/
Souris River	---------	do	Oct. 10, 1945	f/	--	1,110	8	7.0 h/
Des Lacs Public School	School	Des Lacs 11-155-85	May 24, 1921	b/	g/	2,548	19	.11
Stredvick Well	S. Stredvick	Berthhold 21-156-87	1938?	j/	g/	368	18	.1
Johnson Well	B. Johnson	do	1938?	j/	g/	1,597	31	.6
Ryder School #1	School	Ryder 10-151-86	1938?	j/	g/	945	20	0
Ryder School #2	School	do	1938?	j/	g/	837	26	.02
Ryder School #3	School	do	1938?	j/	g/	1,006	25	0.3

h/ Simpson, H. E., Geology and ground-water resources of North Dakota: U.S. Geol. Sur. Water-Supply Paper 598, pp. 304-305, 1929.
c/ Well drawing from Souris River valley fill.
f/ Northern States Power Company, Minot, North Dakota
g/ Shallow well in glacial drift.
j/ Abbott, G.A. and Voedisch, F.W. The municipal ground-water supplies of North Dakota: North Dakota Geol. Sur. Bull. 11 pp. 84-85, 1938.
m/ Locations according to township, range and section given thus: 11-155-85 refers to Sec. 11, T. 155 N., R. 85 W.

IN AND NEAR MINOT, PARTS PER MILLION

Alumina (Al_2O_3)	Calcium (Ca)	Magnesium (Mg)	Sodium & Potassium (Na + K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Total hardness as $CaCO_3$	Total alkalinity as $CaCO_3$
---	137	56	268	637	284	209	---	572	522
---	72	32	238	544	190	125	---	311	446
---	99	45	239	567	245	154	---	434	465
---	99	49	227	573	219	160	---	448	469
---	406	158	105	403	1,465	26	---	1,660	---
14	69	32	6.1	295	56	10	1	306	243
8.1	288	113	32	523	774	14	1.1	1,185	428
9	20	91	145	359	346	13	0	430	294
8	19	77	147	378	252	34	0	368	306
8.6	23	82	187	408	326	60	0	403	334

CHEMICAL ANALYSES OF WATER

Well or other source	Owner	Location m/	Date of analysis	Source of analysis	Aquifer	Total dissolved solids	Silica (SiO_2)	Iron (Fe)
Ole Olness well	Ole Olness	Ryder 10-151-86	1938?	j/	g/	1,509	28	.02
Sig Olness well	Sig Olness	do	1938?	j/	g/	2,385	24	.2
Berthold Park well	Park	Berthold 21-156-87	1938?	j/	k/	2,131	19	2.4
Berthold School well	School	do	1938?	j/	k/	3,004	45	8
Berthold City well	City of Berthold	do	1938?	j/	k/	2,391	20	.3
Kenmare City well	City of Kenmare	Kenmare 17-160-88	1938?	j/	k/	1,380	19	.6
Soltz well	M. Soltz	Des Lacs 11-155-85	May 24, 1921	b/	k/	2,244	16	1.7
Gunther well	H.W. Gunther	Des Lacs 21-155 85	July 5, 1921	b/	k/	2,345	15	.75
McKee well	Geo. McKee	Des Lacs 17-155-85	July 5, 1921	b/	k/	2,300	14	.94

b/ Simpson, H. E., Geology and ground-water resources of North Dakota: U.S. Geol. Survey Water Supply Paper 598, pp. 304-305 1929

g/ Shallow well in glacial drift.

j/ Abbott, G.A., and Voedisch, F. ., The municipal ground-water supplies of North Dakota: North Dakota Geol. Survey Bull. 11, pp. 84-85, 1938.

k/ Well drawing from the Fort Union formation.

m/ Locations according to township, range, and section given thus: 11-155-85 refers to Sec. 11, T. 155N., R. 85 W.

Alumina (Al_2O_3)	Calcium (Ca)	Magnesium (Mg)	Sodium and potassium (Na + K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Total hardness as $CaCO_3$	Total alkalinity as $CaCO_3$
6.0	36	138	277	444	436	285	0	661	364
5.7	52	202	376	532	849	413	0	965	436
6	119	79	508	820	893	87	3	628	672
7.6	9.6	15	1,065	1,065	1,351	19	1.6	101	874
5.6	13	12	968	2,030	1.5	354	3	80	1,665
9.1	21	16	527	1,180	95	137	1.6	117	968
---	10	3.4	920	1,954	2.6	294	---	39	---
---	16	48	882	2,152	31	110	---	60	---
---	---	---	---	1,920	30	106	---	---	---

HYDROLOGY OF THE AQUIFER AT MINOT

General discussion of the problem

An "aquifer" is any rock formation or stratum that will yield water in sufficient quantity to be of importance as a source of supply. 7/ There is a number of aquifers in the Minot area, including one or more in the Fort Union formation, one or more shallow aquifers in the drift, and a highly permeable aquifer of glacio-fluvial origin which occurs in the drift of the Souris Valley at a depth of about 100 feet in the vicinity of Minot. The latter is the only known aquifer in the area that will produce sufficient quantities of water to be of importance as a principal source for municipal and industrial purposes. It has furnished water for the City of Minot since 1917 and has been the prinicipal source of water for the Great Northern Railroad at Minot since 1929 and for the Northern States Power Company since 1931. Because of its importance as a source of water for municipal industrial, and other uses, this aquifer received most attention during the investigation and considerable quantitative work was done to determine the amount of water that could be produced from it in the vicinity of Minot without eventual depletion of the supply; to determine whether overdeveolpment of the supply had already occurred or whether additional deveolpment would be justified and how much; and to determine its hydraulic characteristics as a means of predicting the yield , drawdown, and interference effects to be expected from new wells drilled in the aquifer.

7/ Meinzer, O.E. The occurrence of ground water in the United States U.S. geol. Survey Water-Supply Paper 489, p. 52, 1923.

As the data to be presented in the following sections refer principally to this important aquifer, it will be convenient to refer to it simply as "the aquifer" and if references are made to any of the other aquifers in the area the distinction will be made clear.

The aquifer is composed of sand, gravel and cobbles of glacio-fluvial origin. In the vicinity of Minot it is overlain with till, with silts and clays of glacial Lake Souris, and with Recent river alluvium. The water is thus confined by an overburden of relatively impermeable material The water in the aquifer occurs under confined or "artesian" conditions, although it does not rise above the land surface and so does not support flowing wells. The aquifer is about 50 feet thick in the vicinity of Minot and is from 2,000 to 3,000 feet wide where test-hole sections were drilled across it. Its linear extent is not known. There is evidence that the aquifer is interconnected with some of the local, near-surface sand bodies in such a way as to receive water from them, and through them from the river.

A brief discussion of the hydrologic principles considered in the solution of ground-water problems probably will be helpful to the reader in determining the relationship of the various data to the general problem. The following discussion is taken from a paper by Theis. 8/

"all ground water of ecomomic importance is in process of movement through a porous rock stratum from a place of intake or recharge to a place of disposal. Velocities of a few tens or a few hundreds of feet a year are probably those most commonly met with in aquifers not affected by wells.

8/ Theis, Charles V., The source of water derived from wells; Civil Engineering pp. 277-280, May 1940

This movement has been going on through a part of geologic time. It is evident that on the average the rate of discharge from the aquifer during recent geologic time has been equal to the rate of input into it. Comparatively small changes in the quantity of water in the aquifer, with accompanying changes in water level, may occur as the result of temporary unbalance between discharge by natural processes and recharge, but such fluctuations balance each other over a complete season or climatic cycle. Under natural conditions, therefore, previous to development by wells, aquifers are in a state of approximate dynamic equilibrium. Discharge by wells is thus a new discharge superimposed upon a previously stable system, and it must be balanced by an increase in the recharge of the aquifer, or by a decrease in the old natural discharge, or by a loss of storage in the aquifer, or by a combination of these.

"Recharge to the aquifer may result from the penetration of rainfall through the soil to the water table, or by seepage from streams or other bodies of surface water, or by movement vertically or laterally from another ground-water body. Two possible conditions in the recharge area must be considered. The potential recharge rate may be so large...as to exceed the rate at which water can flow laterally through the aquifer. In this case the aquifer becomes overfull and available recharge is rejected. The water table stands at or near the surface in the recharge area. In such a case it is evident that is use of ground water by means of wells can increase the rate of underground flow from the area, more water is available to replenish the flow.

"On the other hand , the possible rate of recharge may be less than the rate at which the aquifer can carry the water away. The rate of recharge in this case is governed (1) by the rate at which the water is made available by precipitation . or by the flow of streams. or (2) by the rate at which water can move vertically downward through the soil to the water table and thus escape evaporation. In recharge areas of this latter type, none of the recharge is rejected by the aquifer.

"In attempting to determine where the water discharged by wells comes from, or, more accurately, what process serves to balance the hydralic system after the new discharge of the wells is imposed on it, this difference between rejected recharge and unrejected recharge must be kept clearly in mind. If water is rejected by the aquifer in the recharge area under natural conditions, then pumping of wells may draw more water into the aquifer. On the other hand, no matter how great the normal recharge, if under natural conditions none of it was rejected by the aquifer, then there is no possibility of balancing the well discharge by increased recharge, except the use of artificial processes such as water spreading.

....

"Ground water flows through an aquifer according to the simple law by Darcy in 1856. The rate of flow is proportional to the pressure (hydraulic) gradient in the water.......

"Under Darcy's law there is only one way of reducing the flow in the areas of natural discharge or of increasing the flow in the area of recharge. This is by changing the pressure gradient or the thickness of saturation of the aquifer in those areas, which in turn means changing the height to which the water levels rise in wells throughout the area between the producing wells and the areas of natural recharge or discharge. This means a lowering of water level everywhere between the wells and the areas of natural discharge or recharge. In turn this means a reduction of storage in the aquifer and an abstraction of water from it.

"There are two fundamental physical properties of any aquifer which largely control the movement of water through it. The first is the ease with which it transmits the water. This characteristic of the aquifer as a whole is called the coefficient of transmissibility and is defined as the number of gallons of water that will pass in one day through a vertical strip of the aquifer 1 foot wide under a unit pressure (hydraulic) gradient.

"The other important characteristics of the aquifer is the amount of water that will be released from storage when the head in the aquifer falls. This has been called the coefficient of storage and is defined as the amount of water in cubic feet that will be released from storage in each vertical column of the aquifer having a base 1 foot square, when the water level falls 1 foot. For non-artesian aquifers the coefficient of storage is nearly identical with the specific yield of the material of the aquifer. For artesian aquifers the coefficient depends on the compressibility of the aquifer or of included or stratigraphically adjacent shaly beds and is much smaller."

The quantitative determination of the safe yield of the aquifer, then, requires the collection and study of data on natural discharge and artificial discharge by wells, on water levels and water-level fluctuations to determine the effects of rainfall and stream flow in recharging the aquifer, and on the hydraulic characteristics of the aquifer. The coefficient of transmissibility and the coefficient of storage generally can be determined readily by means of pumping tests. The artifical discharge of water by wells can be obtained by direct measurement or, if actual measurement records are not available, it is often possible to estimate the production from related data such as power-consumption records for the pumping plants or time records of operators. Direct Direct Measurements of natural recharge and discharge are often impractical if not impossible to obtain, and so these quantities often must be calculated or inferred from data on water levels, discharge from wells, hydraulic gradients, and the coefficients of transmissibility and storage It should be apparent that very short records on water levels and water consumption are usually inadequate for a satisfactory solution of the problem and often many years of water-level and production records are required before reliable predictions can be made.

Ground-water development and use

History of development

Prior to the development of the municipal ground-water supply by the City of Minot, there were no individual ground-water developments of importance in the Minot area. Most of the wells in the area supplied only the relatively small domestic needs of individual families. In the Souris River Valley the wells tapped the shallow aquifers in the valley fill, or in some places where the shallow aquifers did not yield sufficient water or water of good quality, the wells were drilled to deeper aquifers in the drift or to water-bearing horizons in the Fort Union formation. Probably a few of the wells in the area tapped the important sand and gravel aquifer which now furnishes large quantities of water for municipal and industrial purposes. Simpson 9/ lists a number of wells drilled in and near Minot but does not give the dates when the wells were drilled or put into use. Some industrial wells are included in this list. A few of these wells apparently tapped the principal aquifer but it is not indicated that the production of water from these wells was very large. The production from a shallow well owned by the Great Northern Railway Company is given as 15,000 gallons a day.

9/ Op. cit., p. 260

Treated water from the Souris River was used for municipal and most industrial purposes but seasonal low flows in the Souris River and increasing water demands made this source of supply inadequate and undesirable. Consequently, the city undertook a test-drilling program in 1915 in a search for a possible ground-water supply. The test drilling was conducted with the advice and assistance of H. E. Simpson, then State Geologist of North Dakota. The investigation led to the discovery of the important sand and gravel aquifer in the river valley. As a result, city supply well No. 1 was constructed in 1916 and by October 1917 the city had switched entirely from surface water to ground water for municipal purposes. A second well, city supply well No. 2 was drilled in 1918. These wells were the principal ground-water developments in the area until 1929, when the Great Northern Railway Company drilled wells to the aquifer to obtain water for engine boilers. In 1930 and 1932 the Northern States Power Company drilled wells to the aquifer to obtain auxilary cooling-water supplies. City supply well No. 3 was drilled in 1931 and city supply well No. 4 in 1939 to meet increased demands on the municipal supply. The two new wells furnished the prinicipal part of the municipal demands after this time, the older wells being used only occasionally as auxiliary supplies. City supply well No. 2 was later abandoned entirely because of trouble with the screen. A fifth supply well was drilled by the city in 1946 but had not been put into use as late as July 1947 because of difficulty in obtaining pumping equipment.

The municipal supply and the industrial supplies of the Great Northern Railway Company and the Northern State Power Company are the only large ground-water developments that have been made in the area. However, a number of smaller industrial supplies have been developed. These inculde supplies of the Crystal Springs Water Company, the Granite Springs Water Company, the Minot State Teachers College, the Swift Creamery, the Minot Creamery, White's Creamery, the Minot Flour Milling Company, and the Peoples Ice Company (Davis well). Not all these wells tap the principal aquifer. Wells of the Crystal Springs Water Company and the Granite Springs Water Company are in a shallow aquifer northwest if the main part of town. The water in this aquifer is unconfined but the water level is considerably below river level and the aquifer is so connected with the principal aquifer that the water contained in both is considered to be part of the same supply. The Minot State Teachers College has three wells, two in the valley fill and one in the Fort Union formation. The two in the valley fill may not penetrate the principal aquifer, but the water taken from them probably is a part of a ground-water body which recharges the principal aquifer.

The other industrial wells are in the principal aquifer. The Minot Mill Well and the Davis well are not being used. The Davis well was drilled to obtain for making ice but ice made from the water was objectionably discolored and the well was little used and was soon abandoned.

Amount of water used

Long-period production: From 1916 to 1929, when the supply wells of the Great Northern Railway were constructed, the only important ground-water development was the Minot City wells. No detailed records are available to indicate the amount of ground water used by the city during this period. However, a clipping from a local newspaper dated August 11, 1934, makes the following comment: "Under the river source system, water conditions became acute in Minot in 1915, when the flow in the river shrank to 325,000 gallons per day, which was scarecely half of the normal daily pumpage for that period." A "Report on water supply at Minot, Ward County, North Dakota", dated September 19, 1928, from the Division of Sanitary Engineering of the North Dakota Department of Health, states: " "The City of Minot obtains its water supply from two wells. These wells are about 100 yards from each other and drilled to a depth of 134 feet. The water is pumped directly to a reservoir of three-million gallon capacity. The water consumption is about 700,000 gallons per day. There are about 1,600 connections to the system and practically all connections metered." Simpson 10/ estimated the average daily water consumption as 600,000 gallons. These estimates indicated that the average daily consumption during the period was fairly constant between 600,000 and 700,000 gallons a day.

The following table gives the estimated monthly pumpage from Minot city wells for the period from July 1930 through December 1946. These figures represent the total pumpage from all the city wells. Most of the water was metered at the wells but from 1932 through 1939 the water pumped from the city supply well No 3 was estimated from the number of hours the pump was operated each month.

10/ Op. cit., p. 270

Monthly pumpage from city wells, 1930-1946
Millions of gallons

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Ave.
1930							61.3	41.2	33.6	42.9	26.6	26.7	
1931	24.5	21.5	24.2	29.3	36.0	40.4	41.6	20.6	13.4	27.1	20.5	21.0	26.7
1932	23.3	22.3	24.2	23.8	27.6	30.7	38.4	39.0	29.3	24.4	23.8	23.5	27.[illegible]
1933	23.3	21.8	26.7	26.3	26.5	33.9	38.5	37.1	30.3	25.1	23.3	24.8	28.[illegible]
1934	23.1	22.0	26.2	26.6	39.6	31.0	48.4	45.9	31.2	31.5	26.9	28.7	31.[illegible]
1935	31.4	27.4	30.0	28.6	31.5	40.6	47.2	43.2	39.7	36.0	29.6	29.8	34.[illegible]
1936	29.5	30.5	35.0	32.2	43.2	70.4	72.0	55.0	41.9	38.7	24.6	34.5	42.[illegible]
1937	44.2	32.0	35.2	35.9	42.2	45.6	63.1	60.4	39.3	33.7	32.2	35.9	41.[illegible]
1938	37.1	32.9	40.4	30.2	39.8	38.7	45.5	47.6	41.0	33.2	27.7	27.9	36.8
1939	27.3	24.4	28.2	26.7	44.8	43.5	45.9	41.1	37.2	29.4	26.9	25.9	33.3
1940	26.3	25.0	26.6	24.7	30.8	40.5	48.1	48.4	44.7	31.7	28.0	27.9	33.6
1941	26.5	24.4	29.5	29.1	34.6	41.7	45.8	46.0	27.7	28.0	24.5	28.5	32.1
1942	27.9	25.5	26.7	25.2	28.2	36.3	40.2	33.6	30.4	29.8	26.5	27.5	29.8
1943	26.2	22.6	15.0	26.7	30.9	41.8	33.3	37.9	32.9	30.7	25.0	26.7	29.1
1944	25.1	23.9	25.0	24.0	32.2	29.9	46.3	35.4	30.3	34.5	26.3	26.2	29.9
1945	39.7	35.5	25.6	27.3	29.5	32.8	36.3	38.4	33.8	25.3	29.2	30.4	32.0
1946	32.2	28.7	33.5	56.7	46.2	51.5	52.5	49.4	41.1	44.5	33.0	33.3	41.[illegible]
Ave.	28.3	26.5	28.2	29.5	35.2	40.5	47.3	42.3	34.0	32.8	26.7	28.1	

The average monthly pumpage increased from a low of about 27 million gallons in 1931 to about 42 million gallons in 1936. After the peak consumption in 1936, the pumpage dropped gradually to about 29 million gallons in 1943. A sharp rise in consumption came during 1946, when the average monthly pumpage was about 42 million gallons.

The population increase in Minot from 1930 to 1940 was only 478, the population being 16,099 in 1930 and 16,577 in 1940. However, by 1946 the population had increased to 19,484, according to the Minot Association of Commerce figures. This population increase accounts for part of the increased pumpage since 1931. However, the high consumption in 1936, 1937, 1938, and 1946 was due chiefly to unusually hot, dry wheather during the summers of those years, when relatively large amounts of water were used for irrigating lawns and gardens, for air conditioning, and for other uses.

There is a marked seasonal fluctuation in the amount of water used. The three months of highest consumption are June, July, and August, whereas the consumption is generally low during the five months from November through March. The highest monthly pumpage recorded was 72.0 million gallons in July 1936. The lowest recorded monthly pumpage was 15.0 million gallons in March 1943.

Estimates of monthly production of ground water from the Great Northern Railway wells from July 1938 through December 1946 are given in the following table. These figures were estimated by multiplying the hours the pump was operated each month by the discharge rate. The discharge rate was not always constant and changes in the pumping rate were estimated from records of the amount of chemicals used in treating the water and from notes kept by the pump operator. The pumping rates applied average about 30,000 gallons an hour.

Monthly pumpage from Great Northern Railway wells, 1938-1946
(Millions of Gallons)

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1938							12.2	15.6	17.8	20.5	16.0	16.0
1939	16.6	15.8	15.3	13.2	12.0	12.2	14.4	16.8	16.2	16.1	13.2	11.8
1940	12.4	12.7	13.4	15.5	16.3	16.1	14.2	16.0	17.0	15.3	16.7	16.9
1941	17.0	14.4	15.5	13.2	14.8	13.7	18.1	16.9	16.7	18.5	18.6	18.7
1942	19.1	17.8	19.8	17.3	17.8	18.6	19.5	20.8	19.8	17.8	18.4	18.5
1943	18.1	17.1	18.9	15.0	15.4	16.1	14.8	14.8	15.2	18.1	17.5	19.0
1944	17.9	16.5	17.9	14.7	13.8	13.6	15.8	18.4	17.4	19.7	20.3	18.4
1945	17.9	15.2	16.5	15.9	3.1	0	0	5.8	11.9	12.8	16.3	16.6
1946	16.6	14.5	15.7	10.2	11.4	8.9	9.5	12.6	14.7	15.7	15.3	17.1

The water pumped from the railroad wells is treated and used for boiler water. Facilities are available for using river water when desirable. In 1943, river water was used entirely during part of May, during June and July, and during part of August. This switch was made because of a scarcity of certain chemicals needed to treat the well water. Production from the railroad wells was highest in 1943, 1944, and 1945, owing probably to the extra rail traffic during the war years. The average production during the 8-year period 1939-1946 was about 16 million gallons a month.

Estimates of the monthly production of ground water from the Northern States Power Company wells from January 1940 through December 1946 are given in the following table. These figures were estimated by multiplying the hours the pumps operated each month by the discharge rate. The discharge rate of the pumps has not been measured for several years. At the time the pumps were instlled the No. 1 well produced 500 gallons a minute and the No. 2 well produced 800 gallons a minute. In estimating the production given in the table these pumping rates were reduced 20 percent to allow for probable reduction of efficiency through wear and for lowered water levels. Thus the production rate of well No. 1 was taken as 400 gallons a minute and that of well No. 2 as 640 gallons a minute.

Monthly pumpage from Northern States Power Co. well, 1940-1946
(Millions of gallons)

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1940	0	0	0	0.	4.4	23.8	22.5	11.6	21.9	14.5	1.9	6.7
1941	18.7	16.1	18.1	4.0	16.6	19.7	35.5	35.6	20.6	12.9	0	0
1942	1.0	7.3	9.9	0	7.3	29.1	36.2	29.6	28.8	17.6	13.3	14.3
1943	15.4	10.7	5.9	0	0	0	0	0.2	2.4	23.9	8.5	9.4
1944	0	0	0	0	8.3	4.6	8.8	0.3	0	0.9	0	0
1945	0	0	0	0	0	11.1	33.5	36.0	30.9	26.9	3.8	2.3
1946	2.6	0.6	0.3	0	3.5	33.5	25.8	46.1	10.9	9.1	0.6	0

The water pumped from the Northern States wells is used for condensing water in steam-turbine units. Facilities are available for switching from well water to river water. River water is used when there is sufficient flow and when the water temperature is as low as or lower than that of well water. Consequently, the greatest use of well water ordinarily occurs during the months of June, July, August, and September, when the temperature of the ground water is considerably lower than that of the river water.

In addition to the ground water used by the three large consumers, it is estimated that other industrial ground-water use and domestic use in the area will amount to about 200,000 gallons a day or about 6 million gallons a month. The following table shows the estimated total monthly ground-water use in the area from 1940 through 1946. This table includes the consumption of the three large users plus an estimated 6 million gallons a month consumed by others.

Estimated total monthly consumption of ground water at Minot, 1940-1946 (Millions of gallons)

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Ave.
1940	44.7	43.7	46.0	46.2	57.6	86.3	90.8	82.0	89.6	67.5	52.5	57.5	63.5
1941	68.2	60.9	69.1	53.2	72.0	81.1	105.4	104.6	72.0	65.5	49.1	53.2	71.0
1942	54.0	56.6	62.4	48.5	59.3	89.9	101.9	90.0	85.0	71.2	64.2	66.3	70.6
1943	65.7	56.4	45.8	47.7	52.3	64.0	54.1	59.0	56.5	78.7	57.0	61.1	58.0
1944	49.0	46.4	48.9	44.7	60.2	54.1	76.7	60.0	53.7	61.1	52.6	50.6	54.8
1945	63.6	56.6	48.1	49.2	38.6	49.9	75.9	86.1	82.6	70.9	55.3	54.2	60.9
1946	57.4	49.8	55.5	72.9	67.1	99.9	93.9	114.1	72.8	75.3	54.9	56.4	72.5
Ave.	57.7	53.0	53.6	51.8	58.1	75.0	85.6	85.3	73.2	70.0	55.1	57.0	64.4

The highest total production during the 7 years 1940-1946 occurred in 1946, when the average monthly pumpage amounted to about 73 million gallons or an average of about 2.4 million gallons a day. The highest monthly consumption was in August 1946, when the pumpage amounted to about 114 million gallons or an average of about 3.7 million gallons a day for the month. The year of lowest consumption during the period was 1944, when the average monthly pumpage was about 55 million gallons or an average of about 1.8 million gallons a day. The lowest consumption was in May 1945, when pumpage amounted to only 39 million gallons or an average of about 1.2 million gallons a day for the month.

Daily production: The daily ground water production from the Minot City wells, the Great Northern Railroad wells, the Northern State Power Company wells and the total daily production from wells during the period from July 1944 through December 1946 are shown graphically in figure 4. During this period the masimum daily production from the city wells was about 2.6 million gallons on July 25, 1944. The maximum daily pumpage from the Great Northern wells was estimated at 776,000 gallons and occurred on November 28, 1944. Maximum daily production from the Northern States wells was estimated at about 1.5 million gallons and was pumped on 13 days in June, 11 days in July, all of August, and 6 days in September in 1946. The maximum daily production of the three users during this period was about 4.25 million gallons, on June 21, 1946. If the maximum daily production of all three users had occurred at the same time, the maximum daily use would have been nearly 5 million gallons.

Water level fluctuations

General

Water level fluctuations in an aquifer are the results of changes in the natural forces acting upon the aquifer and its continued water (such as changes in barometric pressures) and changes in the amount of water stored in the aquifer. Changes in storage in the aquifer result from variations in the rate of recharge to the aquifer or from changes in the rate of discharge from the aquifer, by either natural or artificial means. Drawdowns caused in the aquifer by pumping wells indicate a change in the amount of water contained in the aquifer in the area where the drawdowns occur. Water-level fluctuations over a number of seasons may indicate whether the aquifer is being overused under certain rates of use or that it is being used at less than its maximum capacity, as the case may be. Indications as to the amount of recharge reaching the aquifer and the source of the recharge are obtained by a study of the water level fluctuations in conjunction with data on precipitation, water use, stream flow, etc.

A discussion of the water level fluctuations in the aquifer at Minot is given in the following sections.

Long period water level changes

A few water-level measurements were made at the time the test drilling was done by the city in 1915 and in subsequent years, and water-level measurements were made in each of the city supply wells when they were drilled. Water-level measurements were also made when the Great Northern Railroad well No. 1 was drilled and when the Northern States Power Company wells were drilled.

These few measurements are the only water-level records available prior to 1933. In 1933, 1934, 1935, and 1936, more or less regular water-level measurements at approximately monthly intervals were made by the Northern States Power Company in their wells. For the period between 1936 and 1942 no water-level records are available, except for a few made by the Northern States Power Company in the fall of 1938. In 1942 the city of Minot began making frequent water-level measurements in the Davis well and these measurements were continued by the city until July 1944, when the present investigation was begun.

Figure 12-A shows the individual measurements which were made during the period from 1916 through 1946 and also the average monthly water level at the Davis well from 1942 to 1946 and the average monthly water level in city supply well No. 2 for the period from September 1944 through 1946. The water levels are plotted as elevation of the water surface above mean sea level.

These records indicate that the original undisturbed water level in the aquifer in the vicinity of Minot was about 1,544 to 1,545 feet above mean sea level or from 2 to 3 feet above river elevation. After use of ground water was begun by the city, the water levels declined considerably. Apparently the decline in water level amounted to about 9 feet by 1928. The Great Northern wells were installed at this time and the first of the Northern States Power Company wells was drilled in 1930. A new well was drilled by the city in 1931 and the second Northern States well was put down in 1932. The use of ground water was increased by these developments and the water levels declined sharply. By 1936 the highest yearly water levels in the area were about at an elevation of 1,517 feet, as indicated by measurements in the Northern States

Power Company wells. This represented a decline of about 18 feet during the 8 years from 1928 to 1936, whereas the decline was only 9 feet during the 12 years prior to 1928. The total decline in water level from the original water level in 1915 was 27 feet by 1936.

The following table gives the monthly average and annual average of water-level measurements in Minot city supply well No. 2 and in the Davis well during the period 1942-1946.

Monthly average of water-level measurements in wells in Minot (Feet above mean sea level)

	Minot city supply well No.2			Davis well				
	1944	1945	1946	1942	1943	1944	1945	1946
Jan.		1,512.8	1,510.8	1,508.7	1,505.8	1,508.7	1,510.6	1,508.7
Feb.		1,511.8	1,511.0	1,508.7	1,505.9	1,510.3	1,509.6	1,510.1
Mar.		1,514.0	1,510.7	1,508.0	1,506.2	1,510.7	1,511.4	1,508.3
Apr.		1,513.7	1,511.0	1,509.0	1,507.3	1,511.1	1,512.2	1,508.8
May		1,514.5	1,509.7	1,509.4	1,509.6	1,511.7	1,512.5	1,508.0
June		1,514.2	1,507.7	1,506.9	1,516.6	1,511.4	1,514.3	1,504.0
July		1,511.7	1,505.6		1,514.4	1,511.1	1,510.0	1,501.6
Aug.		1,509.8	1,504.4		1,510.8	1,510.2	1,507.4	1,500.0a/
Sept.	1,512.0	1,508.8		1,504.9	1,509.7	1,509.8	1,508.2	
Oct.	1,512.1	1,509.7	1,507.7	1,504.6	1,508.3	1,509.8	1,506.5	1,505.7a/
Nov.	1,512.6	1,510.0	1,507.7	1,505.8	1,508.2	1,510.6	1,507.4	1,505.9a/
Dec.	1,513.8	1,510.8		1,505.7	1,508.1	1,511.2	1,508.1	
Ave.		1,511.8	1,508.6	1,507.2	1,509.2	1,510.6	1,509.9	1,506.1

a/ Estimated from city supply well No. 2

The highest monthly average water level in the Davis well in 1942 was 1,509.4 feet in May, representing a decline of about 35 feet from the original water levels in the area and a decline of about 8 feet from the water levels in the Northern States Power Company wells in 1936. As will be discussed in a later section, the low water levels at this time, compared to the earlier 1936 levels, were due principally to the greater ground-water use in 1942. In 1943 the water levels in the Davis well rose sharply, resulting in a high monthly average level of 1,516.6 feet in June, which is about the same as the 1936 water levels in the Northern States wells. This sharp rise was due in part to decreased pumpage but was principally caused by recharge from the Souris River, which was at high stages during April, May, and June 1943. The water levels lowered rapidly during July, August, and September. The highest monthly average water level in 1944 was 1,511.7 feet in May, but in 1945 the water levels again rose sharply and the highest monthly average water level for this year was 1,514.3 feet above sea level in June. The Souris River was not at an unusually high stage and the precipitation was not unusually high prior to the rise in water level in 1945. The total ground-water use was low at this time, however, so that the rise was due principally to decreased pumping. The highest monthly average water level in 1946 was 1,510.1 feet above sea level in February. This level is about 34 feet lower than the original water levels.

The annual average water level in the Davis well was 1,507.2 feet in 1942 and increase to 1,509.2 feet in 1943 and 1,510.6 feet in 1944. The average water level declined to 1,509.9 feet in 1945 and 1,506.1 feet in 1946.

The average level of 1,506.1 feet in 1946 was the lowest annual average water level for the 5 year period 1942-1946. The changes in annual average water level are almost directly proportional to the changes in the annual pumpage (see fig. 7).

Seasonal fluctuations

Seasonal fluctuations in the water levels seem to be due chiefly to changes in pumping, the water levels trending downward in the months when pumping is heavy and recovering when pumping is reduced. Only occasionally when the Souris River is at a high stage do the water levels fluctuate in such a manner as to indicate seasonal or intermittent recharge to the aquifer. However, such fluctuations occurring at other times, if comparatively small, could be masked by fluctuations due to changes in pumping and changes in barometric pressure. Referring to figure 4, it is apparent that the water levels in all the observation wells are affected by pumping from wells of all the large users. The stage of the water levels is a function of the total pumpage in the area and is not caused by the pumping from any indivivual well in the area. The magnitude of the seasonal fluctuations in 1945 and 1946 is shown in the following table:

Highest and lowest recorded water levels in three wells in Minot in 45 & 46

Well	Highest recorded water level a/	Lowest recorded water level a/	Difference (feet)	Highest recorded water level a/	Lowest recorded water level a/	Differednce (feet)
Minot city supply well No. 2	39.42	48.86	9.42	43.13	54.61	11.48
Davis well	35.25	48.20	12.95	42.26	51.92	9.66
Minot Mill well	40.48	53.39	12.91	-----	-----	-----

a/ Depth to water, in feet below land surface

Daily fluctuations

Water level fluctuations in wells in the principal aquifer result chiefly from changes in barometric pressure and from interference effects of pumping wells. Figure 5, which shows the waterlevel fluctuations in 11 wells during the time when pumping tests were being conducted on city supply wells 3 and 4, illustrates the nature of these flucuations

Barometric effects on the water levels are pronounced, except in the Davis well and in U.S.G.S. test hole A-3. It is beleived that the Daivs well is near a boundary where the confined water is connected with shallow water under water table conditions. Barometric effects are generally imperceptible where the ground water is unconfined or where confined water is near to areas of unconfined water and so connected with it that the barometric effects are controlled by the water levels in the unconfined area. The reason for the lack of pronounced barometric effects at U.S.G.S. test A-3 is not clear. There was some change of water level in this well during the pumping test, but neither barometric effects nor interference effects from the pumping can be definitely recognized. It is probable that the well was nearly plugged, so that changes in pressure caused water to move in and out of it only very slowly.

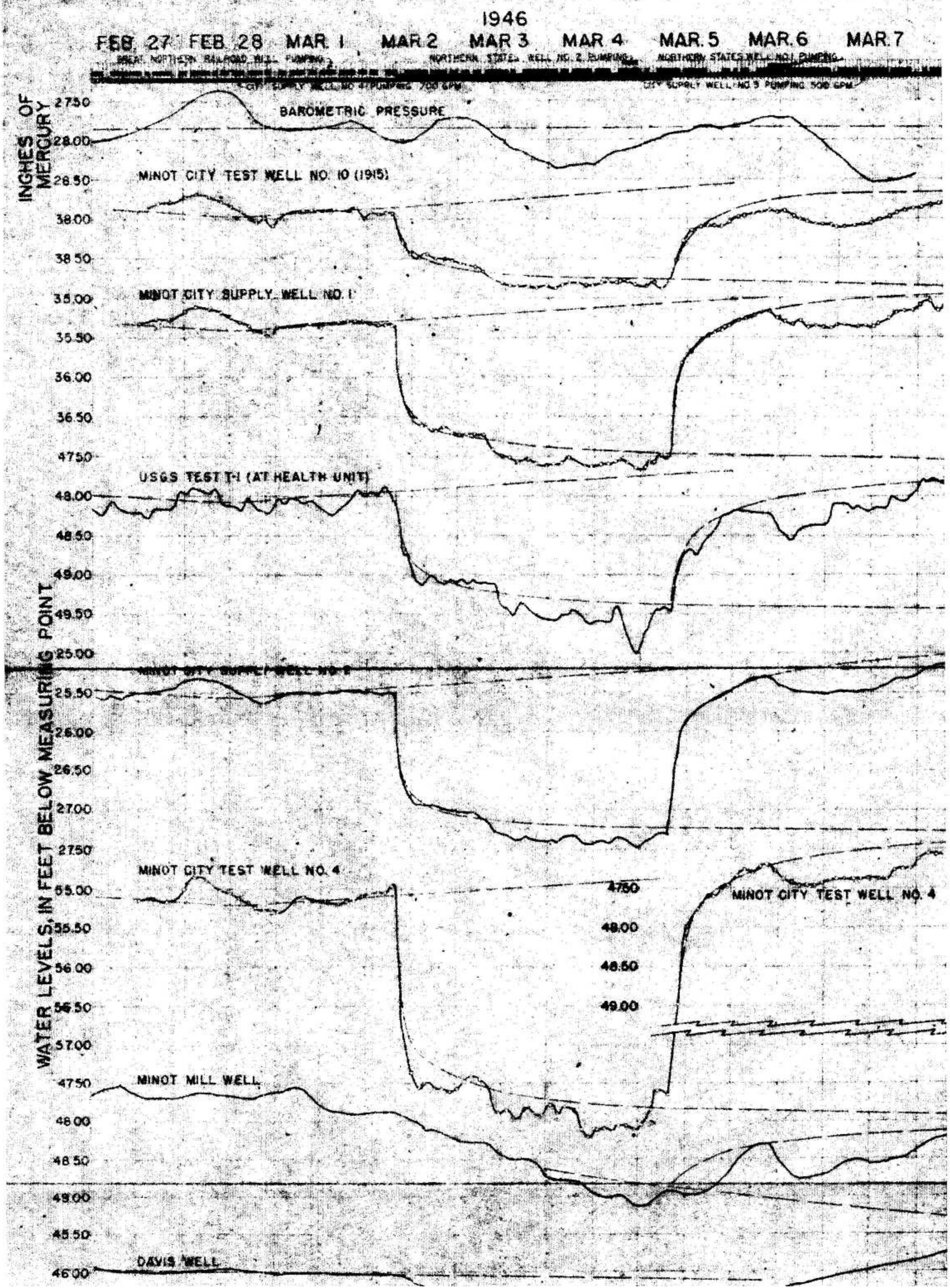
Pronounced interference effects from pumping city supply wells No. 3 and 4 were observed in all the wells shown except U.S.G.S. tests A-1, A-3, A-4 and B-3.

The magnitude of the interference in different wells due to pumping city supply well No. 3 at 500 gallons aminute for 72 hours is given below:

Interference at observation wells due to pumping city supply well No. 3 at 500 gallons a minute for 72 hours.

Observation well	Distance to city supply well No. 3 (feet)	Interference (feet)
City test No. 4	320	2.92
Davis well	800	1.18
City supply well No. 2	770	2.01
City supply well No. 1	920	1.88
Minot city test No. 10(1915)	1,270	1.14
U.S.G.S Test T-1 (Health Unit	2,760	1.64
Minot Mill well	5,060	1.0 (estimated)

This table indicates that the interference effects extend quite large distances from the pumped well. Even so, intereference effects were not recognized at U.S.G.S. test A-1 though barometric effects were quite pronounced. U.S.G.S. test A-4 was cased only to one of the shallow sands and intereference effects were not to be expected in this well. However, the water is confined and the well shows barometric fluctuations. U.S.G.S test B-3 was cased to 90 feet but it is possible that the screen was not placed opposite the principal aquifer or that interference effects were stopped by some local condition before reaching the area of this well.


1946
FEB. 27
FEB. 28
MAR. 1
MAR. 2
MAR. 3
MAR. 4
MAR. 5
MAR. 6
MAR. 7
GREAT NORTHERN RAILROAD WELL PUMPING
NORTHERN STATES WELL NO. 2 PUMPING
NORTHERN STATES WELL NO. 1 PUMPING
CITY SUPPLY WELL NO. 4 PUMPING 700 GPM
CITY SUPPLY WELL NO. 3 PUMPING 500 GPM
INCHES OF MERCURY
BAROMETRIC PRESSURE
27.50
28.00
28.50
MINOT CITY TEST WELL NO. 10 (1915)
38.00
38.50
35.00
MINOT CITY SUPPLY WELL NO. 1
35.50
36.00
36.50
47.50
USGS TEST T-1 (AT HEALTH UNIT)
48.00
48.50
49.00
49.50
25.00
25.50
26.00
26.50
27.00
27.50
MINOT CITY TEST WELL NO. 4
55.00
55.50
56.00
56.50
57.00
47.50
48.00
48.50
49.00
MINOT CITY TEST WELL NO. 4
MINOT MILL WELL
47.50
48.00
48.50
49.00
45.50
DAVIS WELL
46.00
WATER LEVELS, IN FEET BELOW MEASURING POINT

Interference effects due to pumping the railroad wells and the Northern States Power Company wells can be recognized at Minot city test No. 4, city supply well No. 1, city supply well No. 2, and Minot city test No. 10 (1915), although the effects are slight and are often masked by effects of barometric changes and by the effects of changes in pumping at the city wells. The interference effects from the railroad and power company wells are quite pronounced at U.S.G.S. test T-1 (health unit) and at the Minot Mill well, but during the pumping tests of February 27-March 7, 1946, the recognizable interference effect at these wells did not exceed half a foot.

The slow reaction of the Davis well to the pumping from the city wells supports the idea that this well is near a boundary where the aquifer becomes unconfined.

Figure 6 shows water levels in the Northern States Power Company wells from October 7 to October 14, 1944. The power company well No. 2 was pumped for 24 hours, from 9 a.m. on October 10 to 9 a.m. on October 11. The interference effect at well No. 1 caused by pumping well No. 2 is clearly shown. The minor fluctuations in water levels are due principally to interference from the Great Northern Railway well, the high points representing the water levels at times when the railroad well was idle.

Daily high and low water levels in various wells are shown in figure 4, covering the period from August 1944 through December 1946. Fluctuations shown on this graph appear to be due largely to the effects of pumping. A few anomalies are present which cannot be explained by changes in pumping, such as the sharp rise in the water level in the Davis well during the first part of June 1945. Immediately after this rise in water level, the water level fluctuations due to pumping increased sharply in magnitude. The water levels in other observation wells did not react in like manner. It is believed that this rise was not due to effective recharge, as might be supposed, but to the geology of the aquifer. Thus the ground water in an area near the well might have been under water-table conditions until the water level rose within about 40 feet of the land surface. At this point the water level reached a confining bed and confined or artesian conditions developed in the area previously unconfined. Owing to the decreased specific yield, the water level rose more rapidly than before and interference effects from pumping wells became more pronounced. Following the rise, the pumping in the area increased and the water level declined nearly as rapidly as it had risen.

Relation between ground-water use and water levels

There is, apparently, a proportional relationship between the annual average water levels in the aquifer at Minot and the annual average production of water. The relation between water levels at Minot and the ground-water production is shown in figure 7. The data from which this graph was constructed are given in the following table. The data for the years 1942 through 1946 are computed annual water levels at the Davis well and annual average ground-water production at Minot.

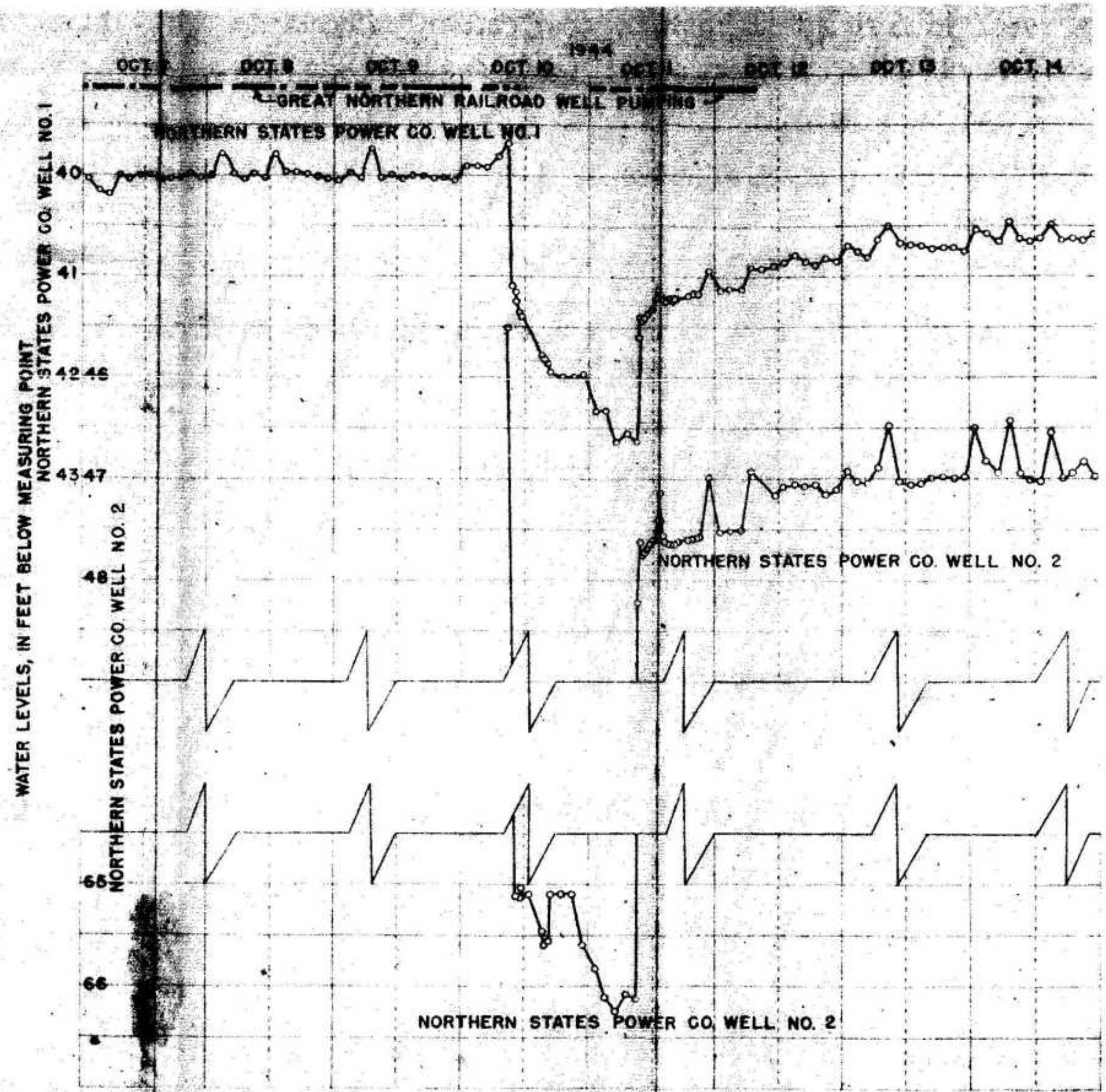


FIGURE 6
WATER LEVELS IN NORTHERN STATES POWER CO. WELLS
OCTOBER 7 TO OCTOBER 14, 1944

Annual average water level and annual average ground-water production in the Minot area

	Annual average ground water use (millions of gallons a day)	Annual average water level (feet above sea level)
1915	0.00	1544.5 d/
1928	0.60 a/	1535.7 d/
1930	0.85 b/	1522.5 d/
1931	0.88 c/	1528.5 d/
1942	2.32	1507.2 e/
1943	1.91	1509.2 e/
1944	1.80	1510.6 e/
1945	2.00	1509.9 e/
1946	2.39	1506.1 e/

a/ Estimate from H. E. Simpson

b/ Author's estimate of city pumpage

c/ Pumpage from city wells only

d/ Based on single water-level observation (various wells).

e/ Annual average water level at Davis well.

Pumping tests

Collection of data

Pumping tests were made on the aquifer in the vicinity of Minot during the first part of March 1946. Data was obtained from 19 wells in the area during the pumping tests. The locations of these wells are shown on the map of the area (fig. 2). Pumpage data was obtained for Minot city supply wells Nos. 3 and 4, Great Northern Railway supply wells Nos. 1 and 2, and the Northern States Power Company supply wells Nos. 1 and 2. Four automatic water-stage recorders were in operation during the tests, on the Minot Mill well, on the U.S.G.S. test T-1 (health unit), on the Davis well, and on city supply well No. 2. Water-level measurements were made with a steel tape at frequent intervals through out the tests in the following nine wells: City test well No. 4 (just outside the pump house at city supply well No. 4), city test well No. 3 (inside the pump house at city supply well No. 3), city supply well No. 1, city test well No. 10 (1915) in Oak Park, U.S.G.S. test A-1 in Oak Park, U.S.G.S test A-3, U.S.G.S test A-4, U.S.G.S test B-1 and U.S.G.S. test B-3. Water levels were not measured in city supply wells Nos. 3 and 4 during the tests because of difficulty in getting a tape into them.

At the time the tests were made, water for the city of Minot was being supplied entirely from Minot city supply wells Nos. 3 and 4. It was not practicable to shut the supply wells down for any long time, so the following pumping regimen was carried out during the tests: Minot city supply well No. 3 was shut down and supply well No. 4 was set to pump 700 gallons a minute.

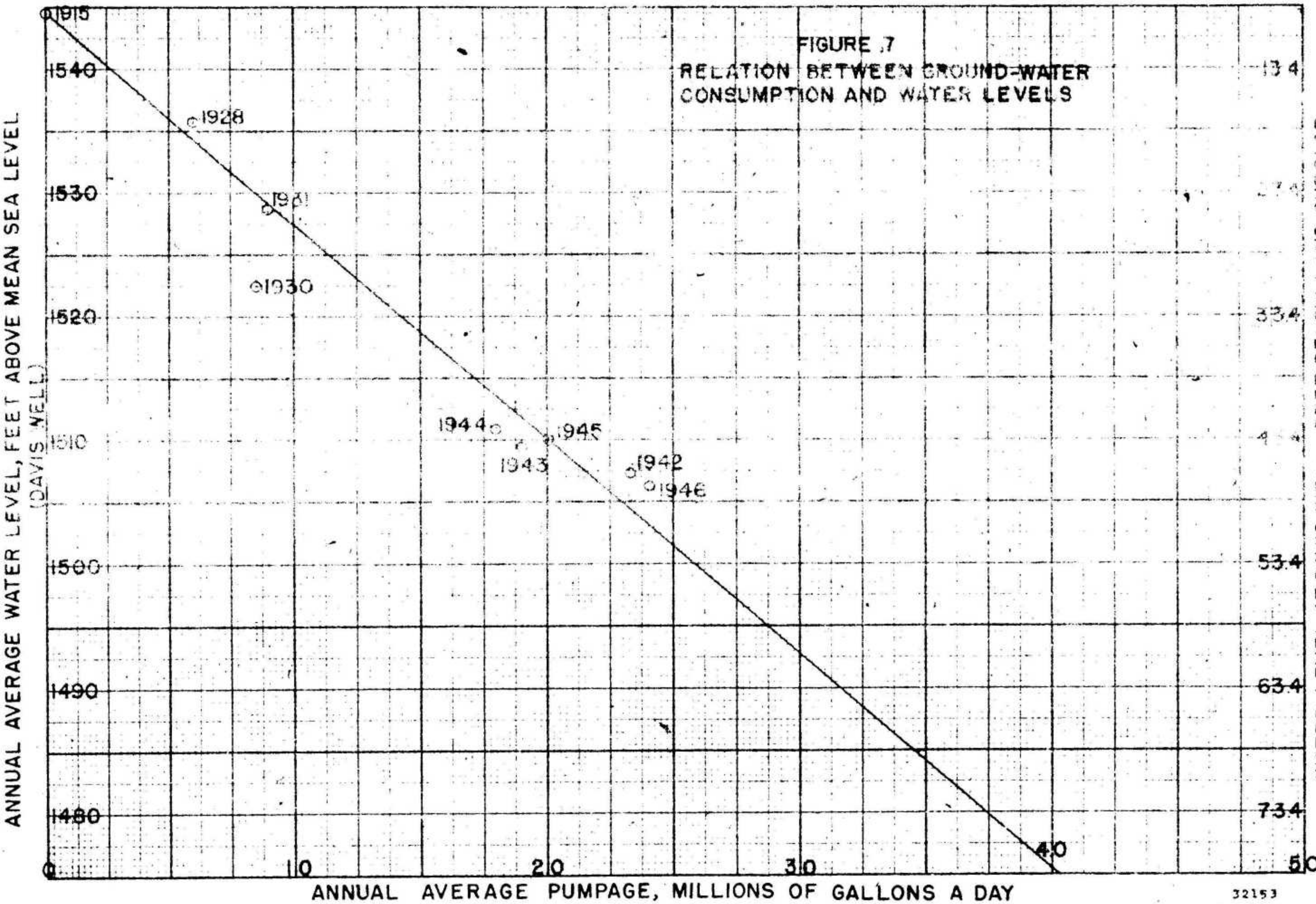


FIGURE 7
RELATION BETWEEN GROUND-WATER CONSUMPTION AND WATER LEVELS
ANNUAL AVERAGE WATER LEVEL, FEET ABOVE MEAN SEA LEVEL (DAVIS WELL)
WATER LEVEL AT DAVIS WELL, FEET BELOW LAND SURFACE
ANNUAL AVERAGE PUMPAGE, MILLIONS OF GALLONS A DAY
1915
1928
1931
1930
1944
1945
1943
1942
1946
1540
1530
1520
1510
1500
1490
1480
13.4
33.4
53.4
63.4
73.4
0
1.0
2.0
3.0
4.0
5.0

32153

This pumpage was held constant for a period of 72 hours and water levels were measured in the observation wells. At the end of 72 hours supply well No. 3 was started with a discharge rate set at 500 gallons a minute and supply well No. 4 contained pumping at 700 gal.a minute. This pumpage was continued for another 72 hours and water-level measurements were taken. At the end of the second 72 hour period supply well No. 4 was shut down and supply well No. 3 continued to pump at 500 gallons a minute for another 72 hours, at which time the test was ended.

Aside from the interference effects due to pumping the city supply wells, the water levels in the observation wells were influenced by barometric pressure changes and by interference effects due to pumping the railroad well and the Northern States Power Company wells. The Great Northern well No. 1 was pumped intermittently throughout the test but the daily draft from the well did not vary a great deal and had been fairly constant for several days prior to the test. The pumping and non-pumping periods for the Great Northern well were always distributed thoughout the day in such a way that the interference effects from this well did not create a serious handicap in interpreting the water-level data, although the effects on some of the observation wells were quite pronounced. The Great Northern well No. 2, located a short distance from well No. 1, was not pumped during the time that the test was in progress. The Northern States Power Company well No. 1 was pumped for about 6 hours on March 6 and their No. 2 well was pumped for about 4 hours on March 4.

The pumping periods were not long enough to cause serious interference effects in water levels in the observation wells. The greatest extraneous change in water level in most of the observation wells was caused by changes in barometric pressure.

Arrangement of data for computation of transmissibility and storage coefficients

Figure 5 is a graphic presentation of the data obtained during the pumping tests. It shows the time during which each of the various wells was pumped, an inverted barometric pressure curve, and the water levels in the observation wells during the pumping test. The barometric curve is inverted to show more clearly the relation between changes in barometric pressure and the water levels, as the water levels affected by barometric pressure will be low when the baromatric pressure is high and high when the barometric pressure is low. The water levels in the observation wells are shown with heavy solid lines. The smooth curves shown by light broken lines are extrapolations indicating the estimated water levels in the observation wells as they would have been had there been no interference from barometric pressure changes from the pumping of the railroad and power company wells. Satisfactory data were not obtained from city test well No. 3 and U.S.G.S. test B-1. City test well No. 3 was plugged and the water level in U.S.G.S. test B-1 was disturbed by water from melting snow that entered the well, rendering the records worthless.

Formulas and methods for computing transmissibility and storage coefficients

Fundamental basis of formulas: Computations of the hydraulic coefficients of an aquifer form water level data are made possible by the fact that single interference effects on the water levels in observation wells from various sources are simply added to each other to obtain the total interference effects from all sources. To illustrate this point, consider the water level fluctuations in city supply well No. 2, as shown in figure 4. At the beginning of the pumping test, city supply well No. 4 was set to produce 700 gallons a minute and city supply well No. 3 was allowed to remain idle. This pumping regimen was held constant for 72 hours so that the trend of the water levels under these conditions could be determined with sufficient accuracy to allow reasonable extrapolation of the trend over the succeeding 72 hour period when the pumping regimen would be changed. At the end of the first 72 hour period, well No. 3 was started and set to produce 500 gallons a minute. This new pumping regimen was continued for 72 hours. Now, the interference effect on the water level in city supply well No. 2 caused by pumping city supply well No. 3 at a rate of 500 gallons a minute is the difference between (1) what the water level would have been during the second 72 hour pumping period if the pumping regimen had not been changed, and (2) the actual water level in the well during the second 72 hour period. In other words, the drawdown in city supply well No. 2 caused by pumping well No. 3 at a rate of 500 gallons a minute is the difference between the light broken lines over the second 72 hour pumping period.

At the end of the second 72 hour pumping period, the water level trend under this pumping regimen was established well enough so that extrapolation over a third 72 hour period was possible. The city supply well No. 4 was shut off but city supply well No. 3 was allowed to continue pumping at 500 gallons a minute. This change in pumpage produced the same effect on the water levels in the observation wells that would be produced if both wells had been allowed to continue pumping but with the addition of a recharge well injecting 700 gallons a minute into the aquifer at city supply well No. 4. The difference between the light broken lines over the third 72 hour period, then, is the effect of an imaginary recharge well pumping 700 gallons a minute into the aquifer at city supply well No. 4 or, as it is generally known, it is the "recovery" caused by decreasing the discharge of city supply well No. 4 by 700 gallons a minute.

Formulas for computing the coefficients of transmissibility and storage are derived from the fundamental concept of ground water flow first stated by H.P.G. Darcy and from a consideration of the physical elements of the medium through which the water passes. Darcy experimented with the flow of water in filter sands and found that the rate of flow of water through a sand is directly proportional to the hydraulic gradient in the sand.

The formulas which have been devised for computing the coefficients of transmissibility and storage by discharging well methods are divided into two groups, the equilibrium formulas, which do not take account of the element of time and from which only the coefficient of transmissibility can be obtained; and the non-equilibrium formulas, which take into consideration the element of time and from which both the coefficient of storage and the coefficient of transmissibility can be obtained. Both types of formulas used in this report are based upon the following assumptions: The aquifer is entirely homogeneous and isotrpic (transmits water with equal facility in all directions) within the region of application; the water in the aquifer occurs under confined or artesian conditions; and the aquifer extends indefinitely in all directions away from the well so that strictly radial flow occurs within the region of application.

Because no aquifer is entirely homogeneous in character as assumed in the formulas, varying results are sometimes obtained by applying the various formulas to the same data. In some cases local inhomogeneties of the aquifer can be determined by evaluating the causes of these various results. In order to make a close approximation of the coefficients they were computed through the use of several of the formulas and methods.

The Thiem formula: The equilibrium formula used for computing transmissibility was first used in 1906 by Gunther Thiem and bears his name. The Thiem formula, arranged to give the coefficient of transmissibility form the data obtained in the pumping tests, is:

$$T = \frac{527.7\ Q \log_{10} (r_2 / r_1)}{(s_1 - s_2)}$$

Where T = Coefficient of transmissibility, the number of gallons of water which will flow in 1 day through a vertical strip of the aquifer 1 foot wide under unit hydraulic gradient, or through a section of the aquifer 1 mile wide under a hydraulic gradient of 1 foot per mile.

Q = discharge of pumping well, gallons a minute.

r_2 = radial distance from pumped well to far observation point, feet.

r_1 = radial distance from pumped well to near observation point, feet.

s_1 = drawdown of water level, in feet, at a distance r_1 from pumped well.

s_2 = drawdown of water level, in feet, at a distance r_2 from pumped well.

In applying this formula the drawdowns in observation wells at the ends of the second and third 72 hour pumping periods were plotted against the log of the distances from the pumped well to the observation wells. If the aquifer were completely homogeneous and if there were no water level disturbances in the observation wells except interference from the pumped well, the points would fall on a straight line. Figure 8 is plotted from the drawdowns obtained by pumping city supply well No. 3 and figure 9 is plotted from the recovery caused by shutting off city supply well No. 4 To compute the coefficient of transmissibility the slope of the straight line is determined by taking the difference in drawdown over one log cycle. The slope of the line is $\frac{\log_{10}(r_2/r_1)}{(s_1 - s_2)}$

If taken over one log cycle the quantity $\log_{10}(r_2/r_1) = 1$ and $s_1 - s_2 = \Delta s$, the change in drawdown over one log cycle, and the formula becomes $T = \frac{527.7\ Q}{\Delta s}$ Values of T computed by this formula from the drawdown and recovery data shown in figures 8 and 9, based on pumping city supply wells Nos. 3 and 4, are 264,000gpd/ft. and 255,000 gpd/ft., respectively. In computing the average transmissibility as obatined from all computations, these values are given a weight of 4 because data from four of the observation wells lie very close to the desired straight line whereas data from two of the wells are definitely out of line.

The Theis non-equilibrium formula: In 1935 a paper by Theis 11/ was published, containing a non-equilibrium formula by means of which the coefficients of transmissibility and storage can be obtained form data taken during a pumping test. His formula is:

$$s = \frac{114.6\,Q}{T} \int_{u}^{\infty} \frac{e^{-u}}{u}\,du$$

where $u = \frac{1.87\,r^2 S}{Tt}$

s = the drawdown, in feet, at any point in the vicinity of a well pumped at a uniform rate.

Q = discharge of the well, in gallons a minute
T = coefficient of transmissibility, in gallons a day per foot
r = radial distance, in feet, from pumped well to point where drawdown , s, occurs.
S = coefficient of storage, a decimal fraction, the amount of water in cubic feet that will be released from storage in each vertical column of the aquifer having a base 1 foot square when the water level falls 1 foot.
t = the time the well has been pumped, in days

The solution of the equation is not readily obtained by ordinary mathematical means because the coefficient of transmissibility appears as an unknown on both sides of the integral sign. As a consequence the use of type curves is often employed for its solution. However, Jacob 12/

11/ Theis, C.V., The relation between the lowering of the piezometric surface and the tate and duration of discharge of a well using ground-water storage: Geophys. Union Trans., pp. 519-524, 1935

12/ Jacob, C.E. Drawdown test to determine effective radius of artesian well: Am. Soc. Civil Engrs. Proc., p. 636 May 1946 recently devised an approximate method for the solution of this equation which is valid for sufficiently large values of t. This method is applied to the individual observation wells in the present report. The log of the time in minutes since pumping began is plotted against the drawdown in the well in feet. For sufficiently large values of t the points will fall on a straight line on the graph. The coefficients, T and S, are computed form the straight line by means of the equations

$$T = \frac{264\ Q}{\Delta s}$$

where Δs is the change in drawdown over one log cycle, and

$$S = \frac{2.08 \times 10^{-4} T t_0}{r^2}$$

where t_0 is the time in minutes corresponding to the point where the straight line intersects the line of zero drawdown.

Figure 10 is a plot of the data obtianed while pumping city supply well No. 3 and figure 11 is a similar plot using the recovery caused by shutting off city supply well No. 4 The values of T and S computed from these curves are given in the following sections.

Summary of results of pumping tests

The following table is a summary of the several determinations of the coefficients of transmissibility and storage and weighted averages derived from them.

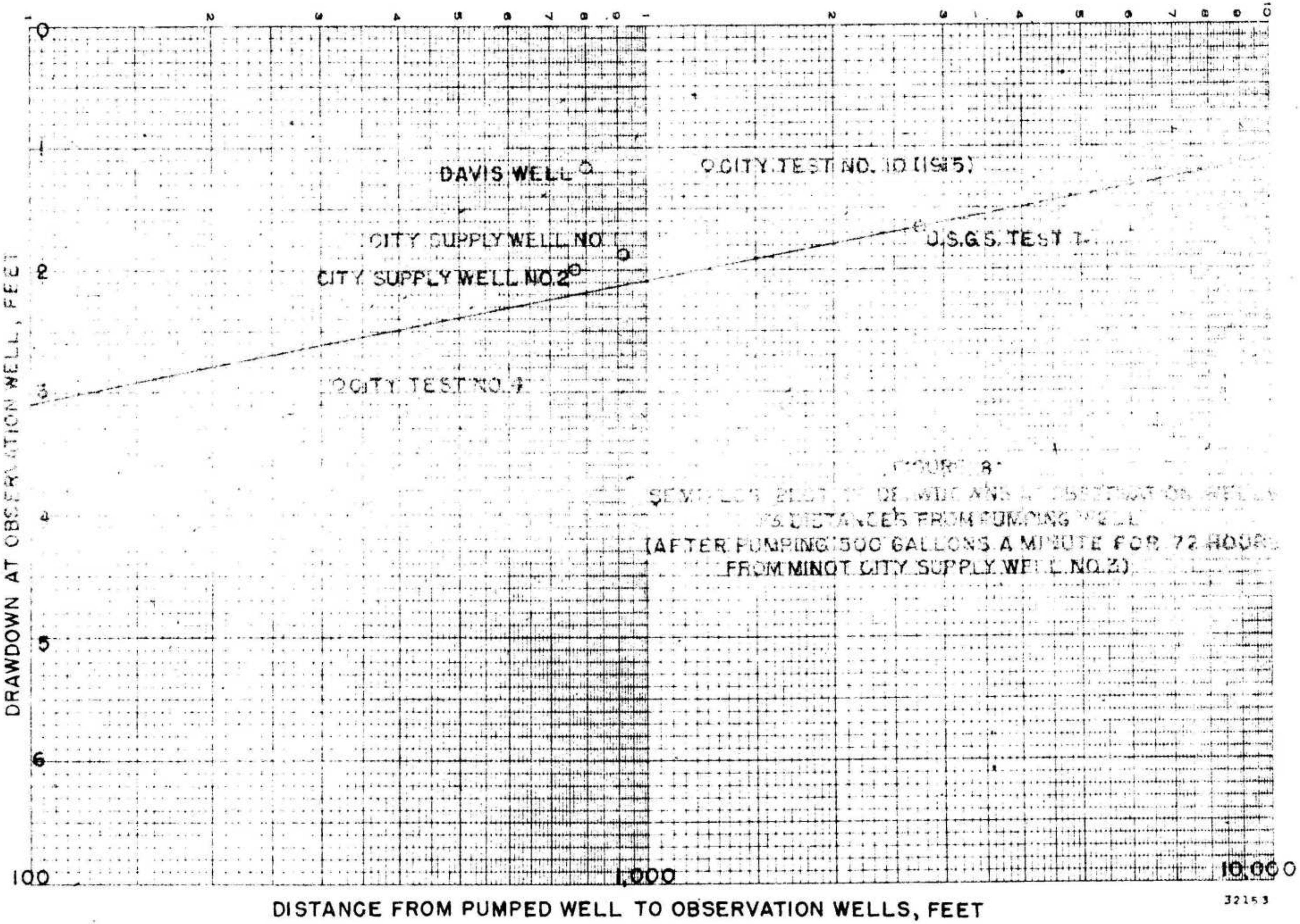


FIGURE 8
SEMI-LOG PLOT OF DRAWDOWNS [illegible] OBSERVATION WELLS
VS DISTANCES FROM PUMPING WELL
(AFTER PUMPING 500 GALLONS A MINUTE FOR 72 HOURS
FROM MINOT CITY SUPPLY WELL NO.3)

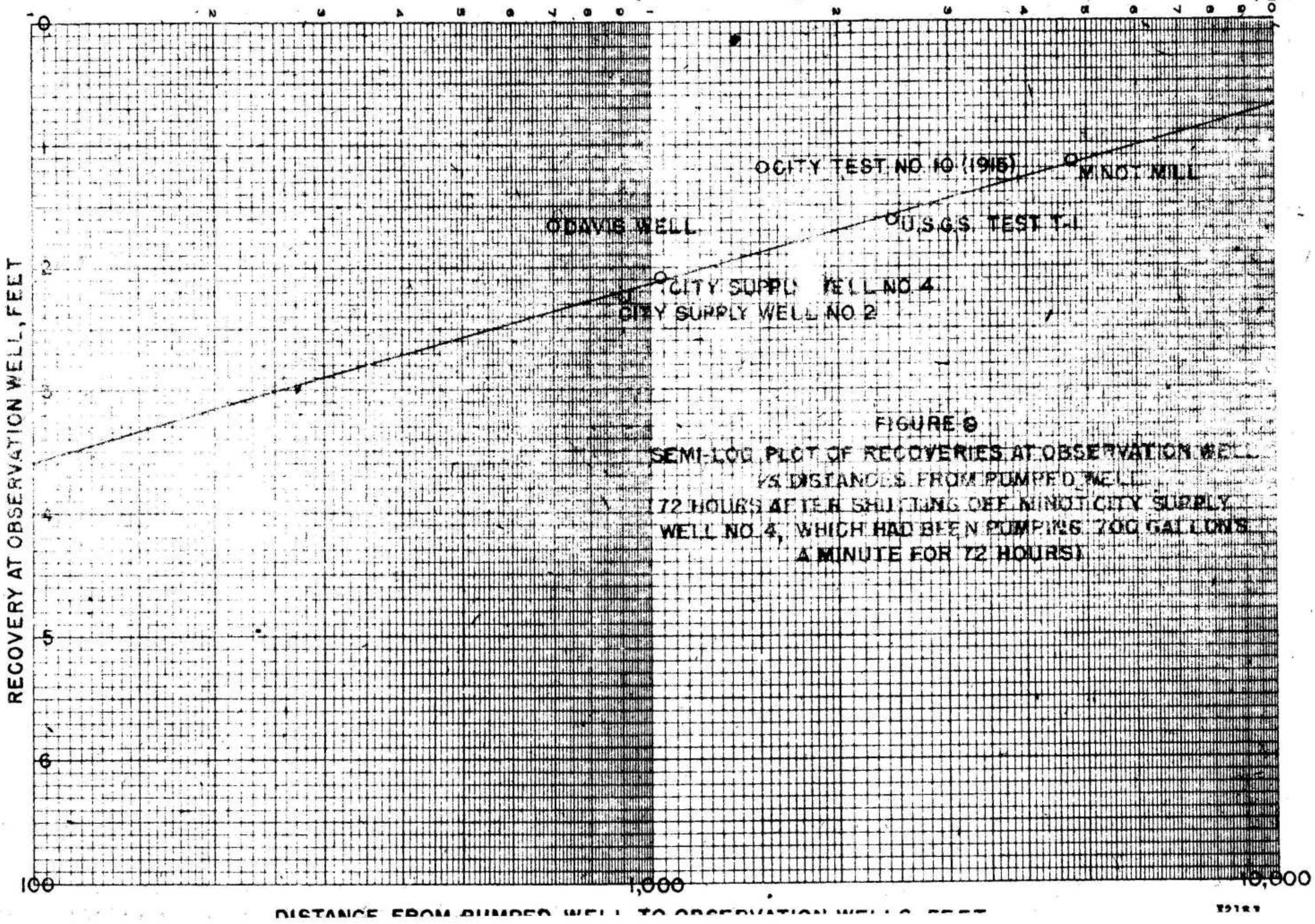


FIGURE 8

SEMI-LOG PLOT OF RECOVERIES AT OBSERVATION WELL VS DISTANCES FROM PUMPED WELL 72 HOURS AFTER SHUTTING OFF MINOT CITY SUPPLY WELL NO. 4, WHICH HAD BEEN PUMPING 700 GALLONS A MINUTE FOR 72 HOURS.

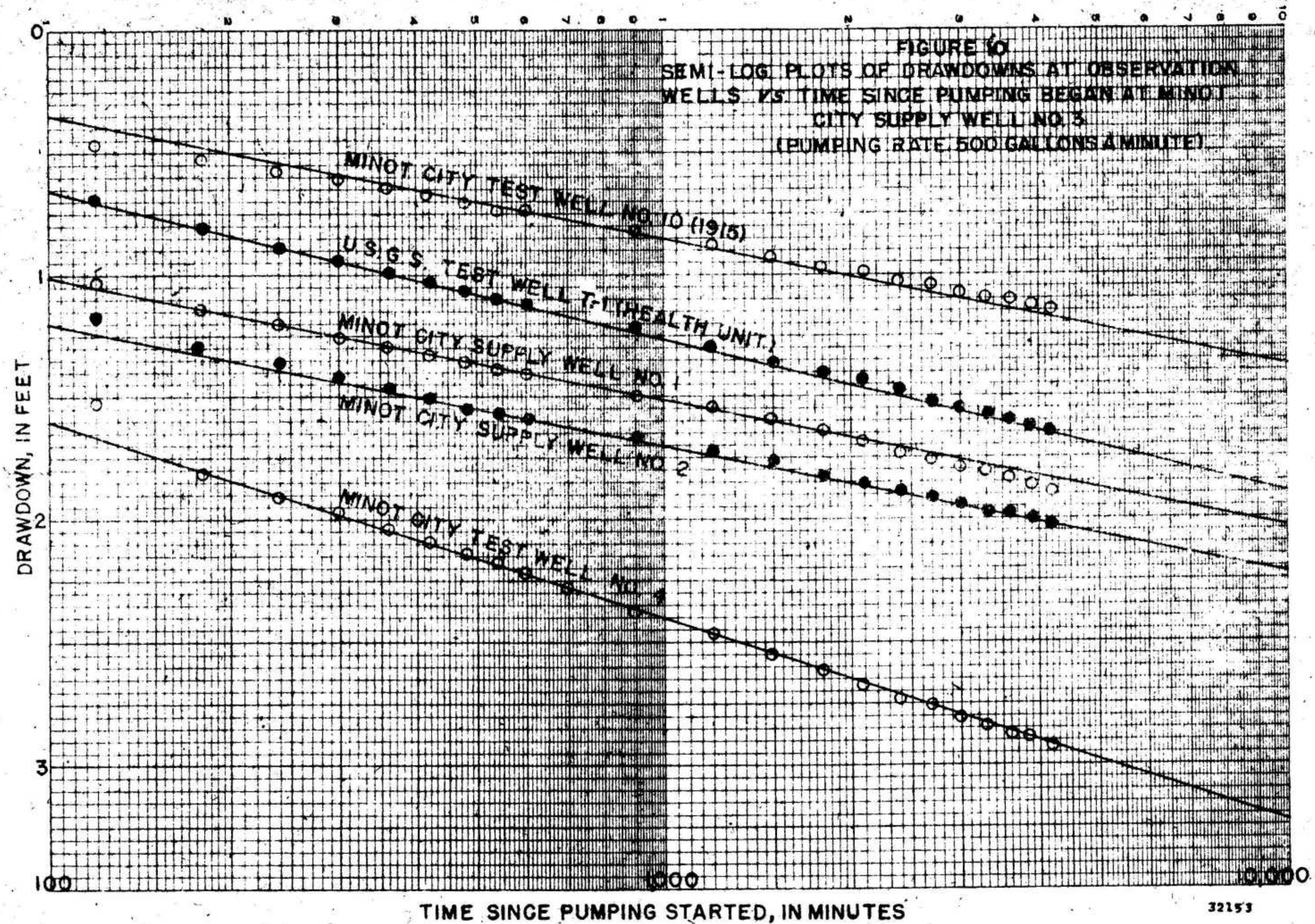
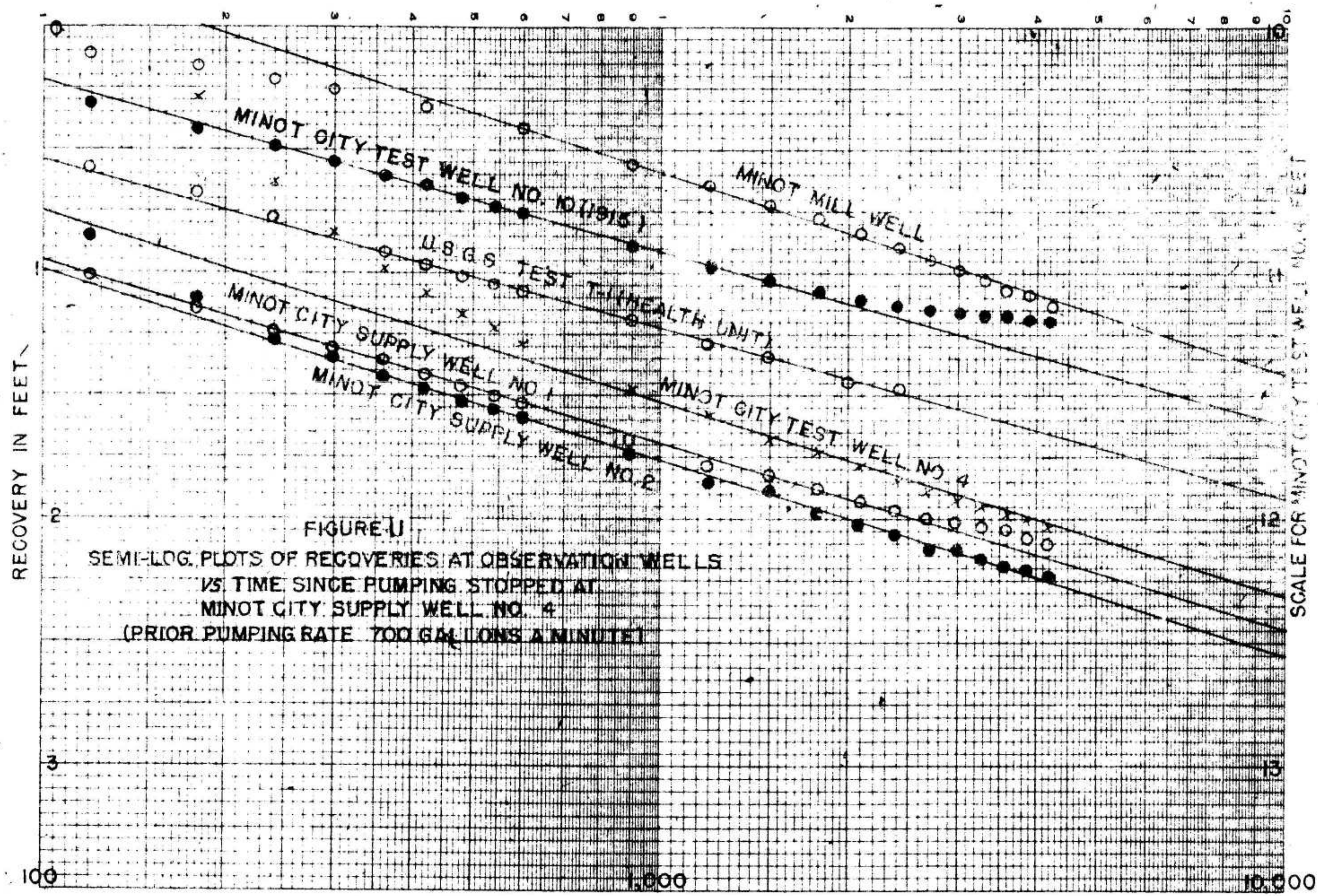


FIGURE 10
SEMI-LOG PLOTS OF DRAWDOWNS AT OBSERVATION WELLS vs TIME SINCE PUMPING BEGAN AT MINOT CITY SUPPLY WELL NO 3
(PUMPING RATE 500 GALLONS A MINUTE)
MINOT CITY TEST WELL NO 10 (1915)
U.S.G.S. TEST WELL T-1 (HEALTH UNIT)
MINOT CITY SUPPLY WELL NO. 1
MINOT CITY SUPPLY WELL NO. 2
MINOT CITY TEST WELL NO. 4
DRAWDOWN, IN FEET
0
1
2
3
100
1000
10,000
TIME SINCE PUMPING STARTED, IN MINUTES
32153



RECOVERY IN FEET
SCALE FOR MINOT CITY TEST WELL NO. 4, FEET
MINOT CITY TEST WELL NO. 10 (1915)
MINOT MILL WELL
U.S.G.S. TEST T-1 (HEALTH UNIT)
MINOT CITY SUPPLY WELL NO. 1
MINOT CITY SUPPLY WELL NO. 2
MINOT CITY TEST WELL NO. 4
FIGURE U
SEMI-LOG PLOTS OF RECOVERIES AT OBSERVATION WELLS
VS. TIME SINCE PUMPING STOPPED AT
MINOT CITY SUPPLY WELL NO. 4
(PRIOR PUMPING RATE 700 GALLONS A MINUTE)
0
1
2
3
10
11
12
13
100
1,000
10,000

Summary of determinations of transmissibility and storage coefficients

By equilibrium formula
(All available observation wells)

T=264,000 gpd/ft., City supply well No. 3 pumping (wt. of 4 allowed)
T=255,000 gpd/ft., from recovery caused by shutting (wt. of 4 allowed) off city supply well No. 4

By approximate non-equilibrium formula
(individual observation wells)

Observation well	From drawdown caused by pumping city supply well No.3		From recovery caused by shutting off city supply well No. 4	
	T gpd/ft.	S	T gpd/ft.	S
City test well No. 10 (1915)	259,000	.00069	264,000	.0011
City supply well No.1	259,000	.000067	246,000	.00025
City supply well No.2	259,000	.000041	237,000	.00032
City test well No. 4	163,000	.00035	237,000	5.92x10-13
USGS test at health unit	216,000	.000049	268,000	.00015
Minot Mill well	-------	-------	225,000	.00037

Weighted average of all values for T = 248,000 gpd/ft.

Weighted average of all values for S = .00034

The variation in the computed values of T and S is due chiefly to the fact that the actual conditions in the aquifer do not meet entirely the assumptions upon which the formulas are based. As in all stream-laid deposits, the transmissibility and coefficient of storage will differ from place to place. However, the transmissibility at any particular spot is of little value in making computations with respect to the aquifer as a whole.

For this purpose an average value of the coefficients for the whole aquifer is desired. It is beleived that the weighted averages of the coefficients given in the table are of the correct order of magnitude and approximate the average characteristics of the aquifer in the vicinity of the present well field.

The computed values of transmissibility range from a low of 163,000 to a high of 268,000 gpd/ft. The range in computed values of coefficient of storage is even greater, the low being 5.92 x 10-13 and the high being 0.0011.

The low storage coefficient of 5.92 x 10-13 is significant, for this value is smaller than would be obtained if nothing but the elasticity of water were effective in creating storage. The same data from which this low storage coefficient was commuted indicated a transmissibility of 237,000 gpd/ft., which is about in line with the computed average transmissibility. This arrangement indicates that the drawdown at city test well No. 4 during the period was excessive for the transmissibility involved. The excessive drawdown was not caused by screen loss or by poor well construction in city well No. 4, as the observation well is 11.5 feet away from the pumped well. There appear to be at least two possible causes for the excessive drawdown: (1) city supply well No. 4 and the adjacent test well may be in a local area of low transmissibility such that interference effects due to pumping city supply well No. 4 extend out to an area of higher transmissibility which ultimately controls the rate of decline of the water level in the well and in the test well.

(2) The excessive drawdown may be the result of only partial screening of the water-bearing formation at the supply well. According to available records, the well is screened only between 125 and 155 feet, although sand and sand and gravel was penetrated through the entire interval between 92 and 158 feet.

Specific capacities of wells at Minot

The "specific capacity" of a well is its rate of yield per unit of drawdown of the water level in the well, generally expressed as gallons a minute per foot of drawdown. The term is applied only to wells in which the drawdown in water level is approximately proportional to the production. Thus the specific capacity of a well which yields 500 gallons pwe minute when the water level in the well is lowered 20 feet is $\frac{500 \text{ gpm}}{20 \text{ feet}} = 25$ gpm per ft. As the drawdown in a well increases as pumping continues, the specific capacity is only an approximate quantity, and it is convenient for comparative purposes to use the drawdown after a 1-day pumping period in computing the specific capacity.

Specific capacities were not obtained for all the large producing wells in the Minot area. Pumping water levels could not be measured in city supply well No. 1. Supply well No. 2 has been abandoned and was not pumped during the course of the investigation and no old records of pumping water levels are available for estimating the specific capacity of this well. The Great Northern Railway well No. 2 is a standby well only a few feet from the No. 1 well and was not pumped during the investigation. Discharge measurements could not be obtained in the Northern States Power Company wells.

The specific capacities for city supply wells 3 and 4 were measured during the investigation. The specific capacities of the Northern States well were estimated form draw-down discharge measurements obtained at the time the wells were drilled. The specific capacity of the Great Northern Railway well No. 1 was estimated from water level measurements made by the writer. The specific capacity of the city supply well No. 5 was estimated from the results of a 1 day pumping test made by the drilling contractor upon completion of the well, as reported by the city officials.

Specific capacities of wells at Minot

Well	Specific capacity gpm/ft.
City supply well No. 3	6.2
City supply well No. 4	21
City supply well No. 5	150
Great Northern Railway Well No. 1	25
Northern States Power Co: Well No. 2	18

Recharge

There are three sources of recharge to the aquifer in the Souris River Valley: (1) Direct penetration of the rainfall in the valley to the water table in shallow contributing aquifers and possible direct rainfall penetration to the principal aquifer in some areas along the stream; (2) ground water discharge into the aquifers from the Fort Union formation by lateral movement into the valley and probably by upward percolation of water from deeper horizons: and (3) downward percolation of Souris River water directly into the aquifer in certain areas and percolation of river water into contributing shallow aquifers in areas where the river crosses them..Of these three sources of recharge, the river appears to be the most important contributor to the water supply in the aquifer.

The average annual precipitation at Minot is 15.50 inches, as reported by the U. S. Weather Bureau, based on a 54 year period. Under the most favorable conditions, only a small percentage of the annual precipitation will percolate downward through the soil to reach the water table. Assuming that 10 percent of the average annual precipitation can reach the water table in the valley areas where the soil conditions are favorable for recharge (estimated as not over 10 percent of the valley area), the contribution to the ground water supply through direct penetration of precipitation amounts to about 4.3 acre-feet per mile of valley per year. The average ground water production at Minot during the past 7 years was about 772,800,000 gallons a year or 2,380 acre feet a year.

Thus, the direct penetration of the precipitation in the valley to the ground-water body is probably small compared to the amount of ground water used and is a negligible factor insofar as recharge to the aquifer is concerned.

Many of the wells drilled in the Fort Union formation on the uplands in the Minot area encounter water bearing beds at elevations above the bedrock floor in the Souris River Valley, and flowing wells are obtained from the Fort Union formation in the valley. Water levels in wells on the uplands are generally from 100 to 150 feet higher than the river surface. Therefore, opportunity exists for recharge to the aquifer in the valley by lateral movement of ground water from the Fort Union formation into the valley and probably by upward percolation of ground water from deeper water bearing horizons in that formation.

The amount of ground water contributed to the aquifer from the Fort Union formation cannot be accurately calculated from present information. Chemical analyses of the water from the principal aquifer made while the ground-water development was still very small indicate that it was never as highly mineralized as typical water from the Fort Union formation. Furthermore, the mineralization of the water from the principal aquifer has not increased with development and there is some evidence that the mineralization may have decreased somewhat in recent years. Thus, although the hydraulic gradients toward the valley in the Fort Union formation probably have been increased to some extent by lowered water levels in the principal aquifer, the increased contribution from the

Fort Union formation has not been sufficient to increase the minerali- zation of the water in the aquifer. The relatively low mineralization of the water in the principal aquifer indicates that only a small percentage of the water has been contributed by the Fort Union beds.

The principal source of recharge to the aquifer is evidently from the downwards seepage of surface water into the aquifer or into con- tributing shallow aquifers. The follwoing table gives the monthly and annual flow in the Souris River at a gaging station 3½ miles west of Minot, in acre-feet.

Discharge of the Souris River above Minot
(acre-feet)

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Total
1935	a/	a/	508	561	4,000	18	1,060	264	0	a/	a/	a/	6,411 b/
1936	a/	a/	a/	3,590	1,610	4,860	3,050	4,270	325	a/	a/	a/	17,705 b/
1937	a/	a/	0.2	76	850	13	a/	a/	a/	a/	a/	a/	989 b/
1938	a/	a/	2,080	6,090	25	0	345	1,880	2,100	1,840	51	223	14,634 b/
1939	6.1	0	10,090	22,440	162	361	21	.99	0	5,370	157 c/	123 c/	38,781
1940	25 c/	29 c/	23	5,430	374	15	1,900	3,610	4.2	2.8	0	0	11,411
1941	0	0	1.8	8,480	201	1,130	99	29	74	1,120	1,050	116	12,301
1942	21	2.8	477	4,170	413	66	117	68	290	26	25	0	5,676
1943	0	0	9,210	104,400	60,840	30,720	16,410	5,400	876	159	142	922	229,079
1944	9,090	7,980	5,340	8,470	996	12,390	8,110	7,850	7,090	6,940	7,100	5,200	86,556
1945	5,260	4,440	5,870	1,830	1,150	825	208	52	0	27	163	82	19,907
1946	73	30	1,780	8,730	3,020	113	926	2.2	2,620				

a/ Discharge not measured

b/ Partial sum.

c/ Discharge estimated

It is apparent that the annual discharge of the Souris River during the period covered by the table has been more than sufficient to recharge the aquifer by the necessary amount, although low or zero flow has occurred several times for a period of several consecutive months. During low-flow period, some river pondage may be available for ground-water recharge or the water pumped from the wells may be taken from ground-water storage in the valley.

Evidence of exceptional amounts of recharge to the aquifer from the river has been recognized in the water level fluctuations only once, during May, June and July 1943 when the water levels in the Davis well rose to unusually high levels. The high water levels persisted only a short time, however. This rise in water levels was evidently caused by the unusually high stage of the river during April, May, June and July of that year. Any fluctuations in water levels caused by recharge when the river is at ordinary stage are so masked by fluctuations due to pumping and barometric pressure changes as to be unrecognizable

In the immediate vicinity of Minot, the rate of recharge through seepage to the aquifer is likely to be quite constant so long as there is any water in the river because the present water levels in the aquifer are a considerable distance below the river level. This is also true of the water levels in the unconfined aquifer penetrated by U.S.G.S. tests A-2 and B-1 and at U.S.G.S. test A-1 where sandy sediments exist from the river level to the top of the gravel of the principal aquifer. However the aquifer may be recharged by the stream at points throughout a number of miles of its length both upstream and downstream. Lowering of the water levels in the aquifer may increase the hydraulic gradients from these points and also may increase the effective length of stream over which recharge may occur and thus further increase the rate of recharge to the aquifer.

Storage

The amount of ground water in storage in the Souris River valley deposits is not definitely known because the linear dimensions of the principal aquifer and the areas of contributing shallow aquifers in the valley have not been determined. The straight-line relationship between ground water use and water levels shown in figure 7 indicates that most of the ground water produced in the area during the past two decades probably has been derived through replenishment by natural recharge and that only a small amount of this water has been derived from storage in the aquifer, although the ground-water storage is probably great enough to support pumpage for at least several months without causing serious additional or permanent lowering of the water levels. Ground-water storage is available to support the ground-water developments during seasons when replenishment is reduced by dry weather or for other reasons.

Safe yield of the aquifer

The relationship between water levels and pumpage from the aquifer shown in figure 7 indicates that the aquifer has not been overdeveloped as yet and that production of water at present rates will not cause a serious lowering of the water levels. The amount that pumpage can be increased over present rates depends upon several factors, such as type of well construction, location of wells in the aquifer, and the continuance of increasing recharge rates with lowering water levels.

There is a wide range in the specific capacities of the existing wells in the area. If the water levels are lowered too much, the rate at which water can be pumped from the wells of low specific capacity will be reduced and it is possible that the production from these wells might become so low that the usefulness of the wells would be entirely destroyed, although the wells of higher specific capacities would still produce large quantities of water.

Although there is not sufficient data to permit a rigerous estimate of the safe yield of the aquifer, a reasonable esimate of the yield to be expected under certain conditions can be made in the following manner:

The pumping water levels might be considered as at least approaching a dangerously low stage if the regional pumping water levels were drawn below the artesian confining beds or the tops of the well screens, say to an elevation of about 1,440 feet. The seasonal low water level at the Davis well in 1945 and 1946 was about 5 feet lower than the average water level fot the same years. Increased pumpage would probably increase this difference between average annual and low annual water level because maximum pumpage occurs during the summer months. An allowance of about 10 feet prbably should be made for this factor. In addition, an allowance for additional drawdown in the vicinity of the pumping wells should be made. It is estimated on the basis of the specific capacities of the present wells (see page 74) and the high transmissibility of the formation (see p. 71) that with 7 to 10 wells each pumped intermittently at about 700 gpm, about 35 feet should be allowed for this item.

Thus the annual average water level at the observation wells should not be lower than 1,440 + 10 + 35 = 1,485 feet. Referring to figure 7, an annual average production of about 3.5 million gallons a day would be indicated for an annual average water level of 1,485 feet at the Davis well. The yield of the aquifer under this arrangement would then be about 3.5 million gallons a day (annual average) representing an increase of about 45 percent over the 1946 pumpage and an increase of about 65 percent over the 1942-1946 average pumpage.

If it were desired to pump a larger number of wells with specific capacities of about 20 gpm per ft. at rates of less than 700 gpm or else abandon them in favor of wells of higher specific capacities the yield under the above-described limitations could safely be increased still further.

In order that the production may be safely increased up to the amount stated, it is apparent that the net recharge must continue to be increased in proportion to the depth to water in the vicinity of the well field as it apparently has been in the past. There is no reason to believe that this will not occur, but there is always some possibility that conditions in the recharge areas are such as to prevent increasing the rechrage rates by the necessary amounts. For this reason, careful water level records should be maintained on a few of the observation wells. Production will probably increase slowly and, if over-pumping of the aquifer should occur, the water level records should indicate this condition before the overproduction becomes so great as to be immediately serious.

Possibility of artificial recharge with river water

In the event that production of water at Minot should increase to such an extent that further increases in production from the wells would be impractical, surface water from the Souris River could be used as a supplemental source of supply, either by pumping treated river water directly into the city water system or by artificially recharging the ground-water supply by directing the water underground through the supply wells during times when they are not in use or through especially constructed recharge wells.

The relatively constant temperature of the ground water, which is lower than that of surface water in the summer, would be reduced still further, and the relatively constant chemical character of the ground water might be improved, by artificially recharging the aquifer during the winter months when the temperature of the surface water is lowest. An economic advantage would also result because of the higher water levels and consequent smaller pumping lifts which would be induced by artificial recharge.

Experience has shown that the water used for artificial recharge through wells should be free from silt and organisms such as algae because clogging of screens and the adjacent sand or gravel may result, with consequent impairment of the efficiency of the recharge wells. For this reason it is usually necessary to use filtered and sometime chlorinated water for recharging through wells

It is also possible that artificial recharge by water spreading would be feasible in areas such as that in the vicinity of U.S.G.S. tests A-2 and B-1, where sandy sediments exist from near the surface to depths of 90 to more than 120 feet and where water levels are approximately 40 feet below the land surface. Additional water recharged in these areas would ultimately reach the principal aquifer.

Well No.	Owner	Location in T.155 N. R. 83 W.	Use a/	Driller	Year completed	Diameter inches	Depth feet	Type	Chief aquifer
1	Cass	NE¼NW¼ Sec. 21	S	Peterson	1942	18	24	--------	Fine Black sand
2	do.	NE¼NW¼ Sec. 21	D	do.	---	36	17	-------	Sand
3	C. E. Ward	NW¼NW¼ Sec. 21	D	-----	1936	84	25	Dug.	Gravel
4	do.	NW¼NW¼ Sec. 21	S	-----	-----	48	25	do.	------
5	Behm	NE¼NW¼ Sec. 28	D	Behm	1940	4	32	Bored	Sand
6	Sorenson	NW¼NE¼ Sec. 28	D,S.	Peterson	1929	6	18	-----	Gravel
7	do.	NW¼NE¼ Sec. 28	D	do.	1943	6	17	-----	do.
8	A. Chris-tenson	SE¼SW¼ Sec. 15	S	do	1937	1½	50	Driven	------
9	do.	SE¼NW¼ Sec. 15	D	-----	1942	1½	50	do.	------
10	C. I. Peterson	SW¼SW¼ Sec. 15	D	Reinholtz	1935	4	370	Drilled	------
11	do.	SW¼SW¼ Sec. 15	D	-----	1939	4	500	do.	------
12	Buchholz	SW¼SE¼ Sec. 15	D	Maynard Oothovdt	1936	3	340	do.	------
13	L. Schoon-over	SW¼SE¼ Sec. 15	D	Louis Ellis	1936	2	52	-----	Sand and gravel

Water Temperature °F	Water level, feet below land surface	Remarks
44	16.36 Aug. 1944	Equipped with windmill. Water reported ha:
49	15.0 Aug. 1944	Equipped with hand pump. Water reported hard
44	----------	Equipped with hand pump. Water reported hard.
44	----------	Equipped with, hand pump. Water reported hard
44	----------	Sand point driven to 35 ft. Equipped with 1/ H.P. electric motor. (Water reported good, nc very hard)
--	----------	Sand point driven to 21 ft. Equipped with $\frac{1}{2}$ H.P. electric motor. Water reported good . Adequate.
55	----------	Equipped with $\frac{1}{2}$ H.P. electric motor. Water re ported good. Adequate.
47	----------	Equipped with hand pump. Water reported hard with iron stain.
46	----------	Equipped with hand pump. Water reported hard with iron stain.
--	Flow	Encountered about 2 ft. of lignite at 60 ft. Water reported soft, with soda taste and yell stain
--	-------	Equipped with $\frac{1}{2}$ H.P. Electric motor. Water reported soft.
--	Flow	Equipped with $\frac{1}{2}$ H.P. electric motor. Water reported soft but contains gas; highly mineralized.
--	Reported 40 ft	Granite Springs Water Co. well. Water sold in Minot for drinking water. Well dug 40 ft. an sand point driven rest of way. Average use from two wells is about 2,000 gpd. Equipped with 1 H.P. electric motor. Water reported moderately hard.

RECORDS OF

Well No.	Owner	Location in T. 155 N R. 83 W	Use a/	Driller	Year completed	Diameter inches	Depth Feet	Type	Chief Aquifer
14	L. Schoonover	SW¼SE¼ Sec. 15	D	Louis Ellis	1936	2	46	-----	Sand and gravel
15	Crystal Springs Water Co.	SE¼SE¼ Sec. 15	D	----	----	--	47	-----	Sand
USGS B-1	In county road right of way	NW¼NE¼ Sec. 22	T	U.S. Geol. Survey	1945	6	353	Drilled	Sand
16	---------	NW¼NE¼ Sec. 22	D	----	----	--	---	------	------
USGS A-1	City of Minot	NE¼NE¼ Sec. 22	T	U.S. Geo. Survey	1945	4	178	Drilled	Sand and gravel
17	R.A. Gifford	NW¼NE¼ Sec. 22	D	----	----	--	28	------	Coarse sand
USGS B-2	In county road right of way	SW¼NE¼ Sec. 22	T	Layne-Western Co. of Minn.	1945	4	59	Drilled	Sand and gravel
USGS A-3	In county road right of way	SE¼NE¼ Sec. 22	T	U.S. Geol. Survey	1945	4	128	do.	Sand and gravel
USGS B-3	Oscar Olson	NE¼SE¼ Sec. 22	T	do	1945	4	90	do.	Sand and gravel
18	Mrs. I Peterson	NW¼SW¼ Sec. 22	D	S.R. Peterson	1939	6	30	do.	Sand
19	do.	NW¼SW¼ Sec. 22	D	do.	1936	6	33	do.	Sand

WELLS (Cont.)

Water Temperature °F	Water level feet below land surface	Remarks
---	Reported 40≠	Granite Springs Water Co. well. Water sold in Minot for drinking water. Well dug to 40 ft. and sand point driven rest of way. Equipped with 1 H.P. electric motor. Water reported moderately hard.
---	Reported 42≠	Water sold in Minot for drinking water. Average use about 1,000 gallons a day.
---	41.97 Mar. 8, 1946	Weak flow at 353 ft. Well plugged with cement to shut off flow. Put in 93 ft. 2 in. black pipe to preserve for observation well. Measuring point, top of coupling on 2 in. pipe at land surface. See log.
---	----	Original location of Granite Springs Water Co.
---	See fig 4	Cased with 112 ft. 4 in. standard pipe. Measuring point, top of collar on 4 in. casing. 0.60 ft. above land surface. See log and pumping test
47	--------	Equipped with hand pump. Water reported moderately hard, with a little iron stain.
---	--------	Well cased with 50 ft. 2 in. black pipe but sanded above water level. Log not published
---	See fig. 4	Cased with 3 in. casing. Measuring point, top of collar on 4 in. casing 2.50 ft. above land surface. See log and pumping tests.
---	See fig. 4	Well cased with 83 ft. 2 in. black pipe. Measuring point, top of collar on 2 in. black pipe, 1.30 ft. above land surface. See log and pumping tests.
46	--------	Equipped with hand pump. Water reported hard, with iron stain.
48	--------	Equipped with hand pump. Water reported hard, with iron stain.

RECORDS OF

Well No.	Owner	Location in T.155 N. R. 83 W.	Use a/	Driller	Year Completed	Diameter inches	Depth feet	Type	CHIEF AQUIFER
20	Mrs. J.N. Johnson	SE¼SW¼ Sec. 22	D	------	1936	6	25	Bored and driven	Sand (20-25)
21	C.G. Leite	NW¼NW¼ Sec. 27	D.S.	C.G. Leite	1944	6	19	Dug and driven	Fine black sand
22	do	NW¼NW¼ Sec. 27	U	----	1935	20	19	Dug	Sand at bottom
23	Minot State Teachers College	NW¼SE¼ Sec. 14	I	C.A. Simpson	1936	6	640	Drilled	Fort Union formation
24	do	NW¼SE¼ Sec. 14	I	Rein-holtz	1919	6	200	do	27 ft. of gravel in bottom
25	Do	NW¼SE¼ Sec. 14	I	C.A. Simpson	1936	10	197	do	12 ft. of gravel in bottom
USGS A-2	City of Minot	SW¼SW¼ Sec. 14	T	Layne-Western Co. of Minn.	1945	4	127	do.	Sand
Davis	Davis	SW¼SE¼ Sec. 14	U	------	----	8	----	do	Sand and gravel
City test3 (1938)	City of Minot	SE¼SW¼ Sec. 14	T	McCarthy Well Co.	1938	--	161	do	Sand gravel

WELLS (CONT.)

Water temperature (°F)	Water level feet below land surface	Remarks
--	12.95 Aug. 1944	Equipped with 1/3 H.P. electric motor. Water reported hard, with iron stain. Bored to 17 ft. and sand point driven to 25 ft.
45	15+or- Aug. 1944	Equipped with hand pump. Water reported soft, good. Well dug to 17 ft. and sand point driven rest of way.
--	14.42 Aug. 1944	Well not in use at present. Water reported good.
--	Flow	Water contains some gas.
--	51.02 June 19, 1945	Reported to have pumped 180 gpm with air lift when air is injected 160 ft. below land surface Measuring point, top of 5-in. casing liner, 2.5 ft. above land surface. See chemical analysis.
--	------	Well equipped with pump but not used very much
--	39.58 June 25, 1945	See log.
--	See fig. 4,9,11	Measuring point top of 8 inch casing, 1.00 ft. above land surface. Well drilled to furnish water for making ice but was not used because ice made from the water was milky and discolored. well is now equipped with water-stage recorder Measuring point, top of casing 1.00 ft. above land surface.
--	------	See log and chemical analysis.

Well No.	Owner	Location in T. 155 N. R. 83 W	Use a/	Driller	Year completed	Diameter Inches	Depth Feet	Type	Chief Aquifer
City Test 3	City of Minot	SE¼ SW¼ Sec. 14	T	McCarthy well Co.	1931	5	160?	Drilled	Sand and gravel
City Supply Well 3	do	SE¼ SW¼ Sec. 14	C	do	1931	20	158	do	Sand and gravel
City Test 4	do	SW¼ SE¼ Sec. 14	T	do	1938	5	163	do	Sand and gravel
City supply Well 4	do	SW¼ SE¼ Sec. 14	C	do	1939	30	160	do	Sand and gravel
USGS T-1	do	SE¼ SE¼ Sec. 14	T	U.S. Geol. Survey	1945	4	288	do	Sand and gravel
City supply Well 5	do	SE¼ SE¼ Sec. 14	C	Layne Western Co. of Minn.	1946	24	145	do	Sand and gravel
City test 2 (1938)	do	NE¼ NW¼ Sec. 23	T	McCarthy Well Co.	1938	5	155	do.	Sand and gravel

WELLS (Cont.)

Water temperature (°F)	Water level feet below land surface	Remarks
----	----	
----	----	Gravel-packed well. Outside casing 20 in. diameter. Inside casing 12 in. diameter. Well screened lower 28 ft. Pea gravel pack between screen and aquifer and between casings. See log and chemical analysis.
----	See figs. 4 and 11	Measuring point, top of plug in well casing, 0.30 ft. below land surface. See log.
----	----	Gravel-packed well. Outside casing 30 in., inside casing 15 in. diameter. Well screened between 125 and 155. Pea gravel pack between screen and aquifer and between casings. See log and chemical analysis.
----	See figs. 4 and 9	Cased with 134 ft. of 2 in. pipe and 88 ft. of 4 in. casing. Recorder installed over well during the period of pumping test. Measuring point, top of collar on 4 in. casing, 0.40 ft. above land surface. See log and pumping test
----	----	Gravel-packed well about 10 ft. south of U.S.G.S. T-1. Outside casing 24 in. diameter to 112 ft. Inside casing 12" diameter with 30 ft. of screen on bottom to 145 ft. Packed with pea sized gravel between screen and aquifer and between casings. Reported to have pumped 600 gpm for a 24 hr. period with a drawdown of about 4 ft.
----	----	See log.

RECORDS OF

Well No.	Owner	Location in T 155 N R 83 W	Use a/	Driller	Year completed	Diameter inches	Depth Feet	Type	Chief aquifer
City Supply Well 2	City of Minot	NE¼NW¼ Sec. 23	U	McCarthy Well Co.	1918	12	132	Drilled	Sand and gravel
City Supply Well 1	do	NE¼NW¼ Sec. 23	C	do	1916	10	132	do	Sand and gravel
City test 8 (1915)	do	NE¼NW¼ Sec. 23	T	do	1915	5	135?	do	Sand to fine coarse
City test 1 (1938)	do	NE¼NW¼ Sec. 23	T	Do	1938	5	154	do	Sand and gravel
City test 10 (1915)	do	NW¼NW¼ Sec. 23	T	do	1915	5	126?	do	Sand and gravel
26	O. Olson	SW¼NW¼ Sec. 23	D	----	1883	14	27	---	Sand
City test 2,3,4, 5, and 6 (1915)	City of Minot	SW¼NW¼ Sec. 23	T	McCarthy Well Co.?	1915	5	---	Drilled	----
City test 7 (1915)	do	SE¼NW¼ Sec. 23	T	do	1915	5	133?	do	Sand and gravel
City test 12 (1915)	do	SW¼NE¼ Sec. 23	T	do	1915	5	130?	do	Sand and gravel

WELLS (Cont.)

Water Temperature °F	Water level feet below land surface	Remarks
----	See figs. 4, 9, 11	Equipped with 40 ft. of screen in bottom of well. Well abandoned because of bad screen. Now equipped with automatic water stage recorder. Measuring point top of recorded shelf, 14.88 ft. below land surface. See log and chemical analysis.
----	See fig. 4	Equipped with 40 ft. of 9 in. screen. Reported to have pumped 890 gpm with 7½ ft. of draw-down after pumping 48 hrs. Measuring point, hole in elbow of discharge pipe, 10.76 ft. below land surface. See log and chemical analysis
----	--------	See log.
----	--------	See log.
----	See figs. 4 and 11	See log
45	--------	Equipped with hand pump. Water reported hard, with iron stain. Well adequate for farm purposes. Never goes dry.
----	--------	See log
----	------	See log
----	--------	See log.

Records of

Well No.	Owner	Location in T.155 N. R. 83 W	Use a/	Driller	Year completed	Diameter inches	Depth Feet	Type	Chief aquifer
City test 11 (1915)	City of Minot	SE¼NW¼ Sec. 23	I	McCarthy Well Co.?	1915	5	148	Drilled	Sand and gravel
27	H Kettleson	NE¼SW¼ Sec. 23	D	H. Kettleson	1937	--	20	Driven	Sand
USGS A-4	In county road right of way	NW¼SW¼ Sec. 23	I	U.S. Geol. Survey	1945	4	266	Drilled	Sand (19-45)
28	S.K. Thompson	SW¼NW¼ Sec. 26	D.S.	W.C. Pagle	----	4	343	do	Shale (290-343)
29	do	SW¼NW¼ Sec. 26	--	----	1943	15	37	Bored and driven	Coarse gravel (28-37)
30	Minot Creamery	NE¼SW¼ Sec. 13	I	McCarthy Well Co.	----	10	118	Drilled	Gravel 3 feet in bottom
Minot Mill	Minot Flour Milling Co.	SE¼SW¼ Sec. 13	U	------	----	5	100?	do	Gravel
G.N. RR. 1	Grt. Nor. R.R. Co.	NE¼NW¼ Sec. 24	I	------	1929	--	----	do	Sand and gravel
G.N. RR. 2	do	NE¼NW¼ Sec. 24	I	------	1929	--	----	do	Sand and gravel
Nor. States 2	Northern States Power	NE¼NW¼ Sec. 24	I	------	1932	--	109	do	Sand and gravel

WELLS (CONT.)

Water Temperature °F	Water level feet below land surface	Remarks
---	----	See Log
51	----	Equipped with hand pump. Water reported moderately hard. Leaves scale in kettles.
---	See fig. 4	Cased with 30 ft. of 2-in. pipe. Measuring point, top of collar on 2-in. pipe, level with land surface. See log and pumping test.
50	Flow	Water reported to have soda taste. Combustib[illegible] gas escapes from water. Original static pressure reported to be about 20 lbs. per square in. above land surface. Encountered 6 ft. of coal at 75 ft., shale from 75-343
48	26+ Aug. 1944	Bored to 30 ft. and sand point driven to 37 ft. Water reported good.
---	47 Sept. 1944	Water level reported 18 ft. below land surface when drilled. Well is equipped with 12 ft. of screen. Pumps 36 gpm steadily at present.
---	See figs. 4 and 9	Well not used for 20 years. Equipped with water stage recorder. Measuring point, top of wooden well cover at square hole for recorder line, 0.20 ft. above land surface.
---	See fig. 11	Measuring point, top of west rail pump support 1 ft. below land surface. See water use records
---	-----	See water use records
----	See figs. 10 and 11	Measuring point, top of concrete pump base, 2.20 ft. above land surface. See water-use rrcords, chemical analysis and logs.

RECORDS OF

Well No	Owner	Location in T. 155 N R. 83 W.	Use a/	Driller	Year completed	Diamter inches	Depth Feet	Type	Chief
Nor. States 1.	Northern States Power Co.	NE¼NW¼ Sec. 24	I	----------	1930	---	100	Drilled	Sand and grave
31	Bridgeman Creamery	NE¼NW¼ Sec. 24	U	----------	----	---	----	do	----
32	Armour Creamery	NE¼NW¼ Sec. 24	U	McCarthey Well Co.	----	---	----	do	----
33	Whites Creamery	NE¼NW¼ Sec. 24	I	do	1932	10	70	do	Sand and gravel (47-7
34	Russell-Miller Milling Co.	NE¼NW¼ Sec. 24	U	Schultz Bros.	----	6	211	do	Gravel in bottom 20 fe
35	Swift Creamery	NW¼NE¼ Sec. 24	I	C.A. Simpson	1936	6	140	do	-----

a/ D - Domestic

S - Stock

C - Municipal supply

I - Industrial supply

U - Unused.

Water Temperature °F	Water level in feet below land surface	Remarks
---	See figs. 10 and 11	Measuring point, top of concrete pump base, 2.50 ft. below land surface; See water-use records chemical analysis, and logs.
---	---------	--
---	---------	Well was never cased for use, because no sand or gravel suitable for development of a water supply was encountered.
---	45- Sept. 1944	Original water level reported 36 ft. below surface. Pumped 190 gpm with 13 ft. of draw-down. Present use about 40,000 to 50,000 gpd.
---	----	Well abandoned 25 years. Water was insufficient in quantity for mill use and was of poor quality.
---	----	Equipped with Fairbanks-Morse cylinder pump. Reported capacity of well-200 gpm.

USGS B-1

Material Quaternary sediments	Thickness	Depth
Silt, gray-brown, some fine sand and vegetable matter	4	4
Sand, medium to coarse, clean, well-sorted and rounded, gray to light brown	5	9
Sand, coarse, well-rounded and sorted, light brown, some coal grains	14	23
Sand, medium to coarse, well-rounded and sorted light brown, some coal grains	6	29
Sand, coarse, poorly rounded, brown; contains coal, mica, pyrite, green and black quartzite and limestone	3	32
Sand, medium to coarse, well-rounded and sorted, medium brown; contains clear crystalline limestone, coal and shale grains	17	49
Sand, coarse, and fine angular gravel; contains shale, black quartzite, clear crystalline limestone, and limonite grains and pebbles	10	59
Sand, medium to coarse, fairly well rounded light brown; in part coated and cemented with limestone	5	64
Sand, coarse, light brown, angular to rounded	15	79
Sand, fine to coarse, reddish brown, well-rounded	6	85
Sand reddish brown and gray-blue clay	7	92
Fort Union formation (?)		
Silt and clay, gray-blue; caving (?) of sand and gravel	7	99
Silt and clay, gray-blue, slightly calcareous silt grains, angular, range .1 mm. to .01 mm., estimated 70% silt, 30% clay; no sand	10	109

U.S.G.S. B-1 (Cont.)

Material	Thickness	Depth
Silt and clay, gray-blue, slightly calcareous some fine sand and mica flakes	70	179
Silt and clay, gray-blue, slightly calcareous Contains vegetable matter and mica flakes	10	189
Silt and clay, gray-blue, slightly calcareous, some sand	20	209
Silt and clay, gray-blue slightly calcareous; contains a fresh-water gastropod	10	219
Silt and clay, gray-blue, slightly calcareous some vegetable matter	35	254
Silt and clay, gray-blue, slightly calcareous vegetable matter, iron-stained in part	35	284
Silt and clay, gray-blue, slightly calcareous iron-stained; limestone boulder(caved from above?)	10	294
Silt, clay, gray-blue, slightly calcareous some sand grains and mica flakes, iron-stained	49	343
Sand, so sample, Artesian water	10	353

Struck artesian water in sand between 343 and 353 feet but no samples of the sand were obtained.

U.S.G.S. A-1

Quaternary sediments

Silt, yellowish brown	13	13
Sand, very fine, light brown, and silt	19	32
Sand, medium-dark brown, with silt, gravel and coal	11	43
Sand, medium to coarse, light to dark brown coarse grains poorly rounded; contains coal, limestone, limonite, and shale grains	9	52
Sand, fine to medium, light brown	13	65
Sand, very fine to medium; dark colored grains give it a greenish brown cast; poorly rounded well-sorted, well-washed; coal and limonite grains and flakes of mica present	15	80

U.S.G.S. A-1 (Con't.)

Material	Thickness	Depth
Sand and gravel, brown; coal pebbles up to 1 inch in diameter many fragments of wood and lignite	4	84
Sand, fine to coarse, light brown; grains of shale and coal common; grains of lignite, limestone, and mica present	21	105
Sand, fine to medium, light brown; some coarse grains of shale, coal and igneous rocks; poorly rounded	7	112
Clay, blue-gray, gritty with coarse grains of sand	18	130
Fort Union formation (?)		
Clay, blue-gray, indurated, shows conchoidal fracture	20	150
Clay, blue-gray, indurated, conchoidal fracture; contains laminae	10	160
Clay, blue-gray, indurated, conchoidal fracture; contains shell fragments	18	178

U.S.G.S. A-3

Material	Thickness	Depth
Clay, gray; contains some medium grains of quartz sand	12	12
Sand, fine to medium, buff; contains some (fresh-water?) shell fragments	11	23
Clay gray, with few grains coarse sand, calcareous	6	29
Clay, sand and gravel, calcareous; much wood 44 to 45 feet	40	69
Sand, fine to medium, well-sorted	23	92
Sand, medium to coarse, and fine gravel	36	128

U.S.G.S. B-3

Material	Thickness	Depth
Quaternary sediments		
Clay, gray, well-leached, with a few grains of sand	9	9
Clay, gray, with a few sand grains fine material is slightly calcareous	20	29
Clay, gray, with a few grains of igneous rocks and coal	16	45
Sand, medium, dominantly of igneous rocks with a few shale particles well-sorted	11	56
Sand, medium to coarse, and gravel, boulder chips abundant; some of gravel larger than ¼ inch	10	66
Sand, medium to coarse; abundant coal	2	68
Sand, and gravel with pieces of coal	10	78
Sand, medium to coarse; coarse grains dominantly angular; small buff-colored grains of limestone and shale present	12	90

U.S.G.S. A-2

Sand, silty, and yellow leached clay	10	10
Sand, medium to coarse, brown; buff clay limestone, limonite and coal grains present	20	30
Sand, medium, dark brown, with a few grains of coarse sand and fine gravel	5	35
Sand, fine to medium, light brown and yellow: well-sorted	20	55
Sand, medium, silty, light brown	15	70
Sand, fine to medium, light brown	38	108
Fort Union formation (?)		
Sandstone, yellow-gray, partly cemented with calcium carbonate	19	127

City test No. 3 (1938)

Material	Thickness	Depth
Sand and clay, yellow	24	24
Clay, sandy, blue	34	58
Sand, fine, dirty	75	133
Sand, and gravel	11	144
Clay and gravel	2	146
Clay, gray	15	161

City supply well No. 3

Material	Thickness	Depth
Soil, sandy, brown	4	4
Sand, fine, silty, brown	12	16
Sand, fine, brown	4	20
Clay, dark olive drab	14	34
Clay, dark olive drab, sandy	12	46
Silt, sandy brown, with interbedded dark olive drab clay	20	66
Clay, sandy, dark olive drab	4	70
Silt, sandy, light greenish gray	12	82
Clay, dark olive drab	4	86
Sand, medium, well-rounded, brown	16	102
Sand, fine, well-sorted, gray	22	124
Sand, fine to coarse	4	128
Gravel and sand, dirty	2	130
Gravel and sand	8	138
Silt and sand, gray	2	140
Gravel and sand	18	158
Clay, brown	6	164

City supply well No. 4

Material	Thickness	Depth
Clay, sandy and loam	10	10
Sand	12	22
Clay, blue, impervious	70	92
Sand, fine	33	125
Sand, medium to coarse	11	136
Gravel and sand	6	140
Sand, gravel, and boulders	15	155
Gravel, hard-packed	3	158
Gravel and clay	2	160

U.S.G.S. T-1

Quaternary sediments		
No Log	115	115
Sand, fine to medium, with some coarse gravel, light brown	10	125
Sand, medium to coarse, brown, well-sorted	18	143
Clay, silty	16	159
Gravel, fine to coarse, and sand; contains white indurated clay pebbles	4	163
Sand, fine to medium, gray, well-sorted	35	198
Clay, gray with coarse sand and gravel	11	209
Sand, fine to medium, light brown.	2	211
Clay, bluish gray, gritty, contains some sand and gravel; calcareous	37	248
Fort Union formation (?)		
Shale, blue-gray; contains few grains of coal and medium sand; calcareous	10	258
Sandstone, gray, partly cemented	30	288

City test No. 2(1938)

Material	Thickness	Depth
Sand and clay	36	36
Clay, blue	22	58
Sand and clay	36	94
Sand, fine, hard, brown	4	98
Sand, fine, hard, black	6	104
Sand, fine, clean	14	118
Sand, fine, dirty	7	125
Sand, and gravel	8	132
Clay, sand, and gravel	4	136
Clay, blue	19	155

City supply well No.2

Clay, sand, and gravel	85	85
Sand	5	90
Sand, coarse, and clay	4	94
Sand, coarse	4	98
Sand and lignite	3	101
Sand and gravel	7	108
gravel	5	113
Sand, coarse	2	115
Sand and gravel	3	118
Sand, coarse	13	131
Clay and sand	1	132

City Supply Well No. 1

Material	Thickness	Depth
Clay, sand, and gravel	85	85
Sand, coarse	13	98
Gravel and sand	10	108
Sand, coarse, and lignite	4	112
Sand, fine to coarse	6	118
Gravel	4	122
Sand	4	126
Gravel and clay	4	130
Sand, coarse	5	135
Clay, gravelly and gumbo	3	138

City test No. 8 (1915)

Material	Thickness	Depth
No log	108	108
Sand, fine to medium, clean	2	110
Sand, medium to coarse	2	112
Sand, Coarse, and fine gravel	3	115
Sand, medium to coarse	10	125
Sand, coarse and fine gravel	5	130
Sand and clay	5	135

City test No. 1 (1938)

Material	Thickness	Depth
Sand and clay	70	70
Sand, fine, dirty	48	118
Sand and gravel	2	120
Clay	34	154

City test No. 10 (1915)

Material	Thickness	Depth
No log	19	19
Sand, fine	8	27
Sand, very fine, yellow	8	35
Clay, gray, silt	47	82
Sand, fine to medium, gray	14	96
Sand and gravel	4	100
Sand, fine to medium	8	108
Sand and gravel	10	118
Sand, fine to medium	1	119
Gravel, fine	2	121
Sand, coarse, angular	5	126

City test No. 3 (1915)

No log	7	7
Sand, fine to medium	21	28
Silt, sandy, yellow	2	30
Silt, sandy, white	5	35
Silt, gray	21	56
Sand, fine and clay	6	62
Silt, sandy, dark gray	13	75

City test No. 4 (1915)

No log	13	13
Sand, fine	1	14
Sand, very fine, white	6	20
Sand, fine, gray	23	43

City test No. 6 (1915)

Material	Thickness	Depth
No log	19	19
Quicksand	1	20
Sand, fine	15	35
Sand, fine and clay	47	82
Quicksand	16	98
Sand, fine and clay	2	100
Sand, fine	7	107
Sand, fine and clay	10	117
Sand coarse	1	118
Sand and clay	2	120
sand, coarse	1	121
Sand, fine	5	126

City test No. 7 (1915)

No log	117	117
Sand, coarse, well-sorted	10	127
Gravel and sand	6	133

City test No. 12 (1915)

No log	84	84
Sand, fine to coarse and gravel	14	98
Sand, fine to coarse	4	102
Sand, and gravel	8	110
Sand, medium to coarse	4	114
Sand and gravel	12	126
Sand and gravel, clayey	2	128

City test No. 12 (1915) (Cont.)

Material	Thickness	Depth
Sand and gravel	1	129
Sand and gravel, silty	2	131
Sand and gravel	1	132
Shale or clay, black	1	133
Clay, gray	4	137

City test No. 11 (1915)

No log	90	90
Quicksand and clay	3	93
Clay	3	96
Sand, fine clay and wood	10	106
Sand, coarse	2	108
Sand, fine	2	110
Quicksand and clay	10	120
Sand, coarse	3	123
Clay with sand and gravel	1	124
Quicksand with clay	1	125
Clay and sand	4	129
Clay and gravel	2	131
Clay, blue	3	134
Clay, sand, and gravel	7	141
Sand, fine	1	142
Clay	2	144
Sand, fine and lignite	1	145
Clay	3	148

U.S.G.S. A-4

Material	Thickness	Depth
Clay, yellow-gray, well-leached	4	4
Clay, yellow-gray, with limestone and other sand grains, calcareous	15	19
Sand, fine to coarse, and fine gravel	26	45
Clay, gray, silty, calcareous	34	79
Clay, yellow-gray to brown, gritty. Sand grains and pebbles mostly angular	20	99
Shale, blue-gray, non-calcareous	140	239
Sandstone, gray, loosely cemented	27	266

Northern States Power Company well No. 2

Fill	5	5
Clay	5	10
Clay, sandy	25	35
Clay, blue	35	70
Clay, sandy	13	83
Sand	14	97
Sand and gravel	12	109
Clay, sandy	2	111

Northern Stated Power Company well No. 1

Fill	18	18
Clay, blue	54	72
Clay, sandy	10	82
Sand and gravel	18	100
Clay, blue	2	102

32153

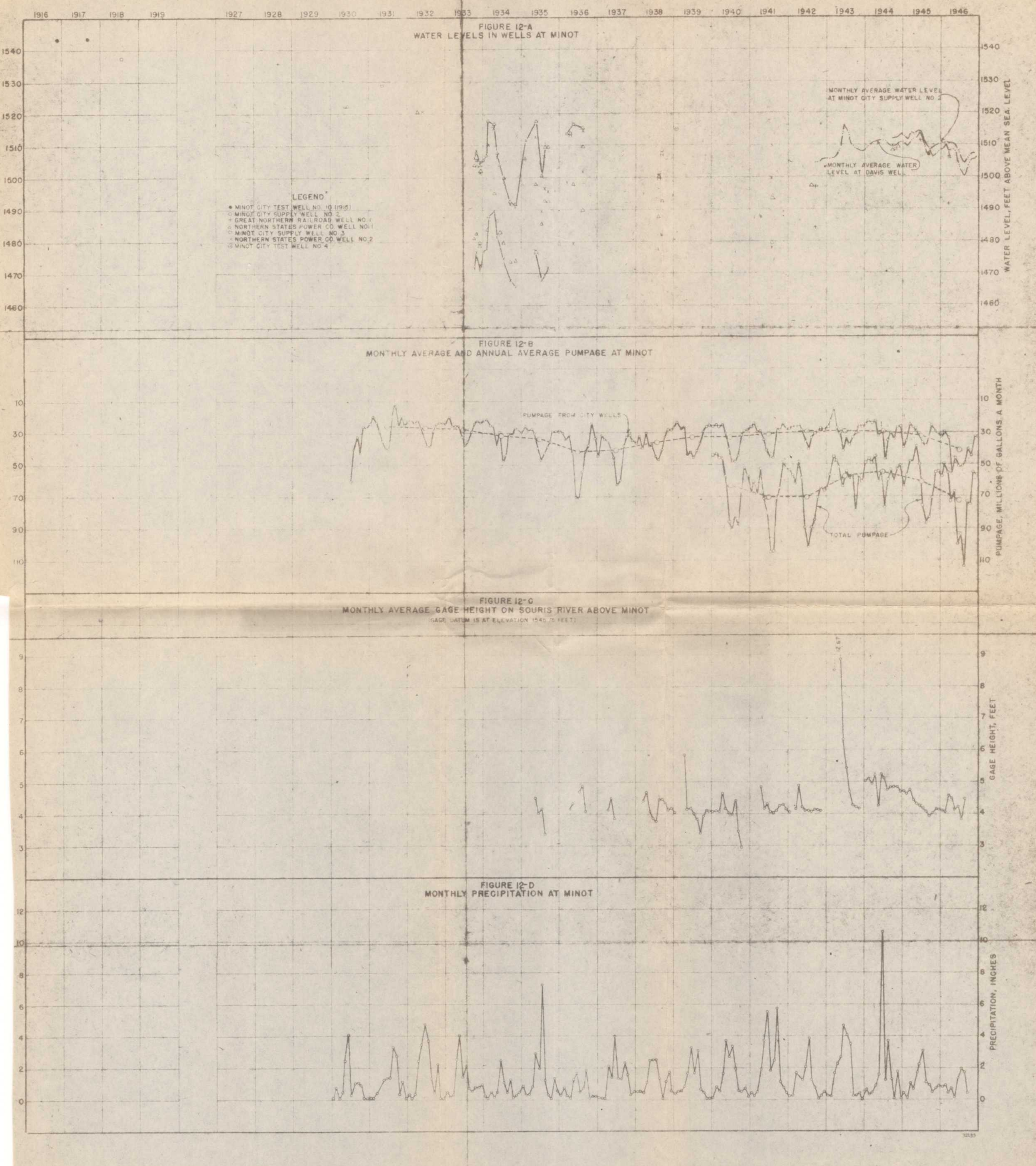


FIGURE 12-A
WATER LEVELS IN WELLS AT MINOT
LEGEND
MINOT CITY TEST WELL NO. 10 (1915)
MINOT CITY SUPPLY WELL NO. 2
GREAT NORTHERN RAILROAD WELL NO. 1
NORTHERN STATES POWER CO. WELL NO. 1
MINOT CITY SUPPLY WELL NO. 3
NORTHERN STATES POWER CO. WELL NO. 2
MINOT CITY TEST WELL NO. 4
MONTHLY AVERAGE WATER LEVEL AT MINOT CITY SUPPLY WELL NO. 2
MONTHLY AVERAGE WATER LEVEL AT DAVIS WELL
WATER LEVEL, FEET ABOVE MEAN SEA LEVEL
1916
1917
1918
1919
1927
1928
1929
1930
1931
1932
1933
1934
1935
1936
1937
1938
1939
1940
1941
1942
1943
1944
1945
1946
FIGURE 12-B
MONTHLY AVERAGE AND ANNUAL AVERAGE PUMPAGE AT MINOT
PUMPAGE FROM CITY WELLS
TOTAL PUMPAGE
PUMPAGE, MILLIONS OF GALLONS A MONTH
FIGURE 12-C
MONTHLY AVERAGE GAGE HEIGHT ON SOURIS RIVER ABOVE MINOT
GAGE HEIGHT, FEET
FIGURE 12-D
MONTHLY PRECIPITATION AT MINOT
PRECIPITATION, INCHES