ARTIFICIAL-RECHARGE INVESTIGATION NEAR AURORA, NEBRASKA

2-YEAR PROGRESS REPORT

Open-File Report 79-1492

Prepared in cooperation with:
Old West Regional Commission
Nebraska Water Resources Center, Institute of Agriculture and Natural Resources, The University of Nebraska-Lincoln
Nebraska Natural Resources Commission

UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

ARTIFICIAL-RECHARGE INVESTIGATION NEAR AURORA, NEBRASKA 2-YEAR PROGRESS REPORT

By William F. Lichtler, David I. Stannard, and Edwin Kouma

Open-File Report 79-1492

Prepared in cooperation with:
Old West Regional Commission
Nebraska Water Resources Center, Institute of Agriculture and Natural Resources, The University of Nebraska-Lincoln
Nebraska Natural Resources Commission

Lincoln, Nebr.

1979

Acknowledgments

This investigation was funded largely by a contract grant from the Old West Regional Commission to the Nebraska Water Resources Center of The University of Nebraska-Lincoln. The U.S. Geological Survey, the Nebraska Natural Resources Commission, and the Nebraska Water Resources Center also contributed to the funding.

Dr. Kenneth A. Blackburn, Old West Regional Commission, was Project Coordinator; Dr. Millard W. Hall, director of the Nebraska Water Resources Center, was project director; William F. Lichtler, U.S. Geological Survey, was principal investigator; and David I. Stannard and Edwin Kouma, Nebraska Water Resources Center, were project engineers.

The authors appreciate the help of the many individuals whose interest and cooperation greatly facilitated the investigation. Special thanks are extended to Mr. and Mrs. Kenneth Herrold and Mr. and Mrs. Eugene Gustafson who permitted the use of their properties for construction of wells and seepage facilities. Special thanks are also extended to Keith Gustafson for use of irrigation equipment and to farmers and landowners who permitted construction of the pipeline across their land--especially Mr. and Mrs. Judson Griffith who were greatly inconvenienced by pipeline construction through their front yard.

CONTENTS

	Page
Abstract	1
Introduction	1
Purpose and scope of the investigation	2
Methods of artificial recharge	3
Problems in artificial recharge	4
Previous investigations	5
Nebraska	5
Well-recharge systems	5
Surface spreading	7
Current investigation	8
Description of the experimental site	8
Recharge through wells	11
Water levels in recharge wells	15
Preliminary injection tests	18
Selection of permanent recharge site	23
Installation of the system	26
Withdrawal well	30
Recharge well	30
Pipeline	32
Observation wells	32
Testing of the system	32
Pumping test	32
Recharge tests	36
Monitoring of the system	37
Results of first long-term test	42
Recharge through water spreading	45
Aurora site	47
Instrumentation	48
Results of tests	51
Criteria for successful artificial recharge	53
Artificial recharge through wells	55
Artificial recharge by surface spreading	56
Conclusions	56
References	58

ILLUSTRATIONS

		Page
Figure 1.	Map of drainage basins of Nebraska and location of recharge site	9
2.	Map of topographic regions of Nebraska	10
3.	Diagram of pipeline route of artificial-recharge experiment near Aurora, Nebr	12
4.	Map showing changes in ground-water levels in Nebraska between 1950 and 1977	13
5.	Generalized geologic and geophysical logs of permanent artificial recharge site near Aurora	14
6.	Graph showing comparison of water-level changes during pumping and recharge tests at preliminary test site near Aurora	20
7.	Buildup of water levels in recharge well at preliminary test site near Aurora, December 3-5, 1975	21
8.	Diagram of artificial-recharge sites near Aurora	24
9.	Map showing specific conductance of ground water in Hamilton County, Nebraska, 1969	27
10.	Graphs of grain-size analyses from withdrawal-well site--test hole No. 3 near Aurora	28
11.	Graphs of grain-size analyses from recharge-well site--test hole No. 4 near Aurora	29
12.	Schematic diagram of permanent recharge-well installation	31
13.	Diagram of permanent well-recharge system near Aurora	33
14.	Graph of drawdown in observation wells during pumping test March 2-4, 1977, at permanent recharge-test site near Aurora	35
15.	Graph of pressures in piping of permanent recharge well	38
16.	Profile of water-level buildup February 1978 in wells during recharge at the permanent site near Aurora	43
17.	Graphs of water-level rise in wells caused by recharging 155 million gallons of water at the permanent recharge site near Aurora	44
18.	Photograph of surface-spreading installation near Aurora	49
19.	Diagram of typical air-permeability installation	52
20.	Graph showing changes in seepage rate from 24-foot-diameter pan at recharge site near Aurora	54

TABLES

	Page
Table 1. Results of aquifer tests at Aurora site in Hamilton County, Nebr.	22
2. Chemical analysis of water from the Platte River near Grand Island, Nebr., and selected wells in Hamilton County, Nebr.	25
3. Sediment data	40
4. Bacteria data from tests at permanent well-recharge site, Aurora, Nebr.	46

SELECTED FACTORS FOR CONVERTING INCH-POUND UNITS TO INTERNATIONAL SYSTEM (SI) METRIC UNITS

The International System (SI) is a consistent system of metric units adopted by the Eleventh General Conference of Weights and Measures in 1960. Selected factors for converting inch-pound units used in this report to SI metric units are given below.

Multiply inch-pound units	By	To obtain SI units
acre	4047	square meter (m^2)
acre-foot (acre-ft)	1233	cubic meter (m^3)
foot (ft)	.3048	meter (m)
foot per day (ft/d)	.3048	meter per day (m/d)
foot per mile (ft/mi)	.3048	meter per mile (m/mi)
gallon (gal)	.003785	cubic meter (m^3)
gallon per minute (gal/min)	.00006309	cubic meter per second (m^3/s)
gallon per day (gal/d)	.003785	cubic meter per day (m^3/d)
inch (in)	25.4	millimeter (mm)
mile (mi)	1.609	kilometer (km)
pound (lb)	.4536	kilogram (kg)
pound-force per square inch (lbf/in^2)	6895	pascal (Pa)
square foot per day (ft^2/d)	.3048	square meter per day (m^2/d)
square mile (mi^2)	2.590	square kilometer (km^2)
degree Fahrenheit (°F)	(°F -32) 5/9	degree Celsius (°C)

ARTIFICIAL-RECHARGE INVESTIGATION NEAR AURORA, NEBRASKA
2-YEAR PROGRESS REPORT

By W. F. Lichtler, D. I. Stannard, and E. Kouma

ABSTRACT

This report presents the results of the first 2 years of a 4-year investigation of potential for artificial recharge and recharge methods that might be used to mitigate excessive aquifer depletion in Nebraska.

A Quaternary sand-and-gravel aquifer near Aurora, Nebr., was recharged by injecting water through a well at a rate of approximately 730 gallons per minute for nearly 6 months. Total recharge was 530 acre-feet. Recharge was intermittent during the first 2 months, but was virtually continuous during the last 4 months. Buildup of the water level in the recharge well was 17 feet. The rate of buildup indicates that the well could have accepted water by gravity flow at more than 3,000 gallons per minute for at least 1 year. The cause of a continuing slow rise in water levels in the recharge well in contrast to nearly stable water levels in observation wells as close as 10 feet from the recharge well is as yet uncertain. The recharge water and the native ground water appeared to be chemically compatible.

Infiltration rates from 24-foot-diameter surface impoundments ranged from 0.04 to 0.66 feet per day. The higher rates may have resulted in part from leakage down incompletely sealed holes that were drilled to install monitoring equipment.

The investigation, including a report on the entire project, is scheduled for completion by 1980.

INTRODUCTION

Ground-water levels are declining progressively in many aquifers in Nebraska. If this trend continues, the yields of many wells in these aquifers eventually will become inadequate for municipal, irrigation, or industrial uses. As this occurs, many wells completed in the upper parts of the aquifers will become dry. The economic impact of the depletion of ground-water resources will be severe in many areas.

The cause of the progressive decline of ground-water levels is a long-term excess of withdrawal over recharge. The imbalance can be corrected by reducing withdrawals, by capturing natural discharge, by increasing recharge, or by a combination of all three mechanisms. This report discusses methods of artificially increasing recharge.

Purpose and scope of the investigation

The purpose of this investigation is to assess the feasibility of various methods of artificially increasing aquifer recharge, particularly methods that might be applicable to Nebraska. The primary objectives of the investigation are: (1) to document and evaluate existing recharge systems through extensive literature review, (2) to develop criteria for selection of sites where artificial recharge may be feasible, (3) to assess the practicability of artificial recharge in selected areas, and (4) to determine the amounts of water moving into aquifers from the land surface through well recharge, impoundment, and canal systems.

This report is a progress report on the 4-year investigation and a final report on the first 2 years. The investigation, as originally proposed, was to be of 4-year duration and was planned accordingly. However, because of charter restrictions placed on the Old West Regional Commission (OWRC), the principal funding agency, the time period was reduced to 2 years. The OWRC recognized that more time was needed and strongly encouraged the participants to seek an extension of the project at the close of the original 2-year period which ended December 31, 1977. The 2-year extension was granted in November 1977.

During the first 2 years, some work was done toward fulfilling all of the primary objectives. Documentation and evaluation of existing recharge systems and development of criteria for selecting sites where artificial recharge may be feasible were essentially completed. Preliminary tests were made to select appropriate sites and experimental artificial-recharge systems were constructed near Aurora, Nebr. Long-term experiments were begun at these demonstration sites, but none were completed within this first 2-year period. This report deals almost exclusively with the selection of sites for, constuction of installations for, and preliminary results of these experiments.

Data were obtained to determine the amount of water moving into aquifers from the land surface, but analyses were incomplete at the close of the initial 2-year period.

Methods of artificial recharge

Artificial recharge may be accomplished by direct or indirect methods. The two most common direct methods are surface spreading and recharge through wells. Surface spreading consists of directing water from a stream or reservoir to places where it will flow or stand in basins on permeable material that will allow the water to seep to an aquifer. The water is sometimes diverted to trenches or pits to speed infiltration.

In surface spreading the infiltration rate is dependent on the depth of water on the surface, permeability of the material between the land surface and the aquifer, and the geochemical, biological, and physical changes that take place in the water and in the material through which the water moves. Usually a spreading basin is modified to operate as a slow sand-filter system constructed on natural material. When infiltration rates decline due to clogging of the surface material by suspended sediment or organic growth, the basins are allowed to dry. The basins are then rejuvenated by scraping, plowing, or disking to re-establish the permeability. Use of the recharge spreading basins generally is an economical method of artificial recharge where there are no low-permeability layers between the surface and the aquifer.

Waste water, such as sewage effluent, may be used as a source of recharge water. Use of the recharge spreading basins in some places provides a highly economical method of improving the quality of water.

Recharge through wells is the method commonly used where layers of material with low permeability exist between the land surface and the top of the aquifer. At such places, the rate of vertical movement from the surface to the aquifer usually is too low for recharge by surface spreading to be feasible.

Indirect methods of artificial recharge include inducing flow of surface water into an aquifer by pumping wells. Lowering the water level in the aquifer below the level of hydraulically connected streams, lakes, or ponds causes water to infiltrate into and recharge the aquifer. Similarly, when the potentiometric surface of a leaky artesian aquifer declines to a stage lower than that of an underlying or overlying aquifer, water will move through the confining beds into the pumped aquifer. Indirect artificial recharge usually is an unintentional byproduct of the development of the ground-water resources of an area.

Problems in artificial recharge

Problems encountered with artificial recharge vary with diverse geologic and hydrologic conditions. Under ideal conditions a well will recharge as much water as it will yield. That is, if a well will yield 1,000 gal/min with 30 ft of drawdown, it should accept as recharge 1,000 gal/min with 30 ft of buildup of water level in the well. In practice, however, conditions are seldom ideal and the buildup of water levels in recharge wells usually is greater than corresponding drawdowns during pumping; in some situations, however, it may be smaller. Excessive buildup of water levels can cause a recharge operation to become infeasible.

The principal cause of excessive buildup of water levels is clogging of the well screen or the aquifer by (1) suspended sediment or organic particles in the recharge water, (2) entrained air, (3) microbial growth, (4) chemical precipitation, (5) swelling of clay minerals, (6) ion-exchange reactions that result in clay-particle dispersion, (7) biochemical changes in the water involving iron-reducing bacteria and sulfate-splitting organisms or other microbes, and (8) precipitation of iron as a result of aeration.

One disadvantage of recharge through wells, especially in aquifers composed of fine-grained material, is that the recharge water must be low in suspended solids, air and bacterial content, and must be chemically compatible with the natural ground water and the aquifer material. A second disadvantage is that well-recharge systems usually are expensive; however, in some situations they may be less expensive than surface-recharge systems.

Recharge by spreading basins is most effective where there are no impeding layers between the land surface and the aquifer and where good-quality water is available for recharge; however, a poorer quality of water can be tolerated than with well recharge. The most common problem is clogging of the surface material by suspended sediment in the recharge water and (or) microbial growth. In coarse-grained material, fine suspended sediment may move 18 inches or more into the soil, making its removal difficult. Cultivation of the land surface usually increases the retention of suspended materials in the upper inch of the soil to more than 90 percent. This facilitates their removal by scraping or restoration of the surface by scarification. Clogging of the surface by microbial growth can usually be controlled by allowing the basin to dry periodically, which will then cause the organic material to oxidize. This practice requires the basin to be inoperative for varying lengths of time.

PREVIOUS INVESTIGATIONS

Artificial recharge to augment potable ground-water supplies is widely practiced in Europe, especially in Sweden, Germany, and the Netherlands, and to a lesser extent in France, Spain, and United Kingdom. Percolation of surface water through the soil reduces the color and certain chemical constituents, eliminates the suspended matter, and reduces the cost of treatment. In the Netherlands, California, and other coastal areas around the world, artificial recharge through wells is also practiced to keep saltwater from intruding into freshwater aquifers. In England, intermittent percolation through soil helps to purify river water that is as much as one-third waste-water effluent. Israel has reclamation projects that use percolation to process waste water from the city of Tel Aviv. Israel is also a leader in the use of wells for recharge.

Nebraska

Artificial recharge has been accomplished at a few localities in Nebraska by well-recharge and surface-spreading techniques. Several such operations are discussed below.

Well-recharge systems

The only previous scientific well-recharge experiment in Nebraska was made in the Lincoln well field, Lincoln, Nebr., by Singleton (1966) as a Masters thesis at the University of Nebraska. The work was under the supervision of Ralph R. Marlette, Associate Professor of Civil Engineering at the University of Nebraska-Lincoln.

The objective of the investigation was to show that artificial recharge through injection wells into the Cretaceous Dakota Sandstone underlying the Lincoln well field was physically feasible and that this recharge would depress and displace salty water in the aquifer. Prolonged pumping in the field had induced water to move into the producing wells from deeper and more westerly parts of the aquifer where the natural water is salty. The principal water supply of Lincoln is now (1978) a well field in the Platte River valley near Ashland; however, it is desirable to use the Lincoln field for brief periods to meet peak summer demands. As a routine process started in 1966, freshwater from the Ashland field is recharged to the aquifer at Lincoln when surplus water is available. Because water moves slowly through the aquifer, most of the recharge water remains in the area of the Lincoln well field and is available to meet peak demands.

Three pumping tests and two recharge tests were conducted in the Lincoln well field between March and November 1965. A total of 22 million gallons (67.5 acre-feet) of water was recharged at a rate of about 420 gal/min. The longest continuous injection was 24 days. Pumping tests were run before and after the recharge tests and no change in transmissivity of the aquifer was detected. This indicates that little or no clogging occurred in or near the injection well during recharge. Analysis of water-level changes in observation wells indicated that 86 percent of the water recharged during the 24-day test remained within 1,100 ft of the recharge well.

The conclusion reached from the experiment was that it was successful and that artificial recharge through wells in the Lincoln well field is physically feasible. In evaluating reasons for the success of the experiment, the following factors were noted: (1) no air was allowed to mix with the recharge water; (2) the recharge water from the Ashland treatment plant was free of suspended sediment and bacteria; (3) the recharge water was compatible with the water in the aquifer. No adverse chemical reactions occurred, such as precipitation, clay dispersion or swelling caused by ion exchange, or biochemical changes.

Most other well-recharge operations in Nebraska are closed systems involving return of ground water used for cooling purposes. One such operation is near Aurora, Nebr. A 100-foot-deep, concrete-cased well was drilled in 1964 to supply cooling water used during the liquification of anhydrous ammonia. A similar well was drilled to return the water to the aquifer. The initial operation of the return well was unsatisfactory, probably because the water was allowed to cascade into the well thereby entraining air. A second return well was drilled in 1965; however, modifications were made in the design to eliminate air entrainment. The return wells recharged the aquifer at a combined rate of 200 gal/min. The limited success of this recharge operation probably resulted from air remaining in the aquifer even though the wells were pumped and redeveloped. If a wetting agent had been used during redevelopment, it might have helped to remove the air. Another possible problem was clogging caused by sediment in water from the withdrawal well. The wells were in use in 1977 and have been redeveloped periodically to remove accumulated sediment.

A second cooling-water recharge operation is located at an anhydrous ammonia plant one-half mile from the first plant. At this site water is withdrawn at a rate of 250 gal/min from a 230-foot-deep, 4-inch-diameter, steel-cased well with shutter screen. The temperature of the water is increased about 20°F before it is returned to the aquifer through a

147-foot-deep, 4-inch-diameter, steel-cased well with shutter screen. The system began operating in 1973 and through 1976 the recharge well has needed cleaning only once; this was in the summer of 1976 and it was accomplished by pumping the well. About 7 Mgal were pumped; however, as the water was used to pressure test a new ammonia tank, it is doubtful if that much pumpage was needed to clean the well.

This recharge system was successful because (1) it was a closed system with no exposure of the water to air or other contamination; (2) the wells were designed so the screen openings matched the grain size of the aquifer to keep suspended sediment in the recharge water to a minimum; (3) the recharge water was of the same chemical composition as the receiving water, therefore no significant chemical reactions occurred.

Surface spreading

There have been no significant surface-spreading operations solely for recharge in Nebraska prior to the current (1978) studies. However, artificial recharge of ground water occurs as a byproduct of surface irrigation in many parts of the State. The largest area where this type of artificial recharge occurs is in Kearney, Phelps, and Gosper Counties, Nebr., locally known as the Tri-county area. Ground-water levels in the Tri-county area rose as much as 97 ft between 1940 and 1976 (Ellis and Pederson, 1977, p. 2). This type of artificial recharge has also occurred near Farwell in Sherman and Howard Counties, in Frontier, Red Willow, and Hitchcock Counties, and in other smaller areas. Most of the recharge in these areas is seepage from canals, ditches, and reservoirs or seepage of excess irrigation water applied to cropland. This type of artificial recharge can be detrimental if it is not part of an overall water-management system. It can waste valuable water, cause water logging of the land, and pollute ground water. Lining canals can help where seepage causes problems.

Conjunctive use of water, whereby the seepage water is pumped for irrigation or other uses, can prevent excessive buildup of water levels. However, conjunctive use may not prevent contamination of ground water through leaching of fertilizer and pesticides from irrigated fields. This problem usually can be alleviated by careful scheduling of irrigation to prevent excessive application of water.

CURRENT INVESTIGATION

Interest in artificial recharge of ground water in Nebraska goes back many years. Ever since large-scale irrigation began in the early 1950's and progressive declines of water levels were noted, people in the State have been concerned about depleting the ground-water resources and have been looking for ways to augment natural recharge.

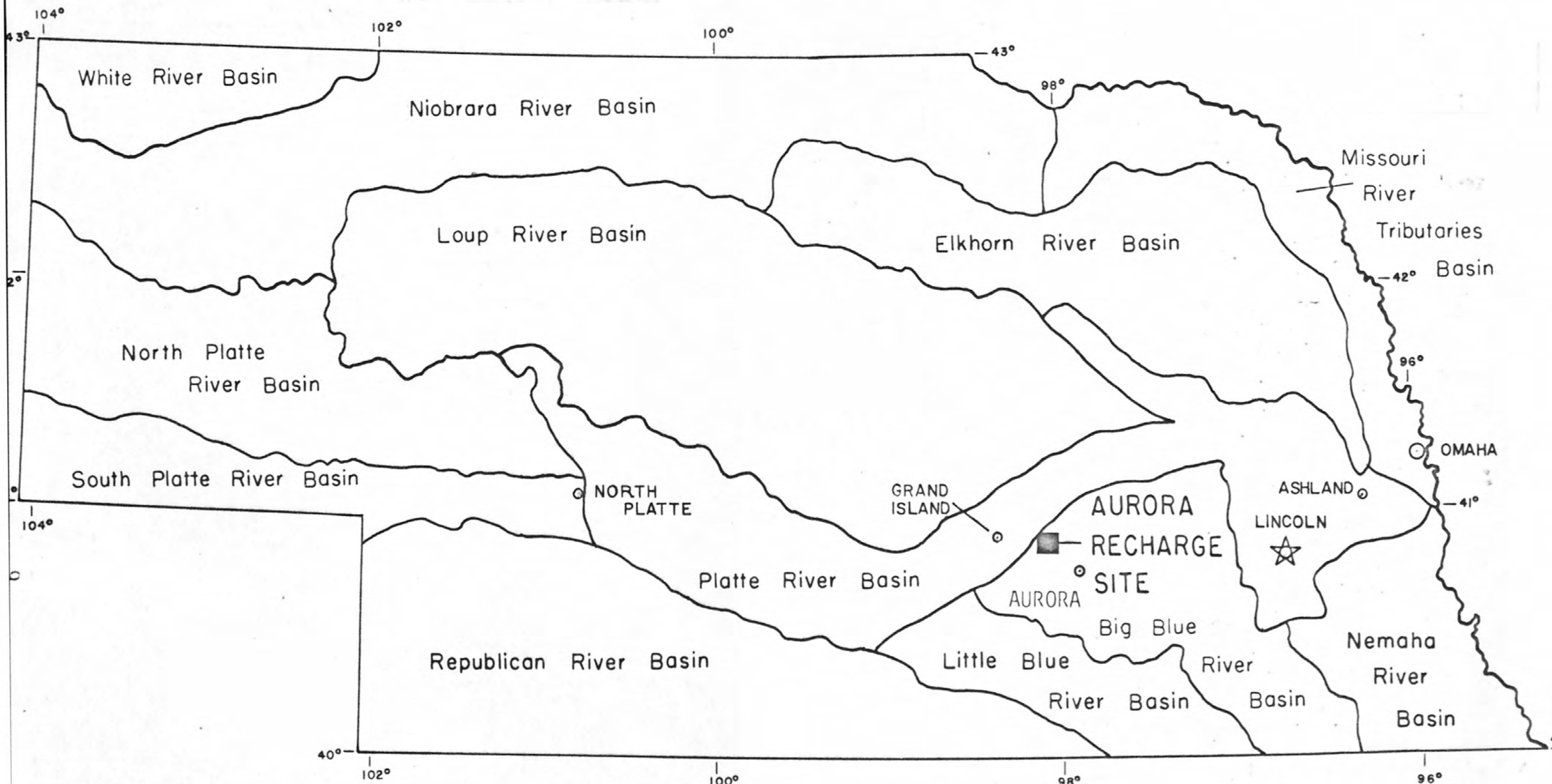
The forerunner of the current investigation was a contract between the Agricultural Engineering Department of the University of Nebraska and the Upper Big Blue Natural Resources District (UBBNRD). This contract called for a review of the literature on artificial recharge and field studies on several methods of recharge. Before the study in the UBBNRD was completed, work was started in late 1975 on the current investigation funded largely by the Old West Regional Commission. Many of the objectives of the UBBNRD study were incorporated into this study. Work elements were assigned to avoid duplication and to allow each study to concentrate in greater detail on its assignment.

Description of the experimental site

An experimental artificial-recharge site located near Aurora, Nebr., (fig. 1) is used for a well-recharge and a surface-spreading experiment.

The Aurora site is in east-central Nebraska in Hamilton County, in the Nebraska Plain (Lugn, 1935). The general physiography of this county (fig. 2) is that of an almost level eastward-sloping plain that has been modified slightly by stream erosion and wind action (Keech, 1962). The Platte River, which forms the northwest boundary of the county, has eroded a broader and deeper valley than have other streams in the county. The Platte valley lies at an average depth of about 100 ft below the general level of the upland.

The Aurora experimental site, which includes both the withdrawal well and the recharge well, is located on the upland in the Big Blue River basin near its divide with the Platte River basin. The withdrawal well is very near the basin divide and within one-half mile of the Platte River. This location was selected for the withdrawal well because here the Platte River is in hydrologic connection with the Pleistocene sand-and-gravel aquifer.



Source — U.S. Geological Survey and Conservation and Survey Division, University of Nebraska — Lincoln.

Figure 1.--Drainage basins of Nebraska and location of recharge site.

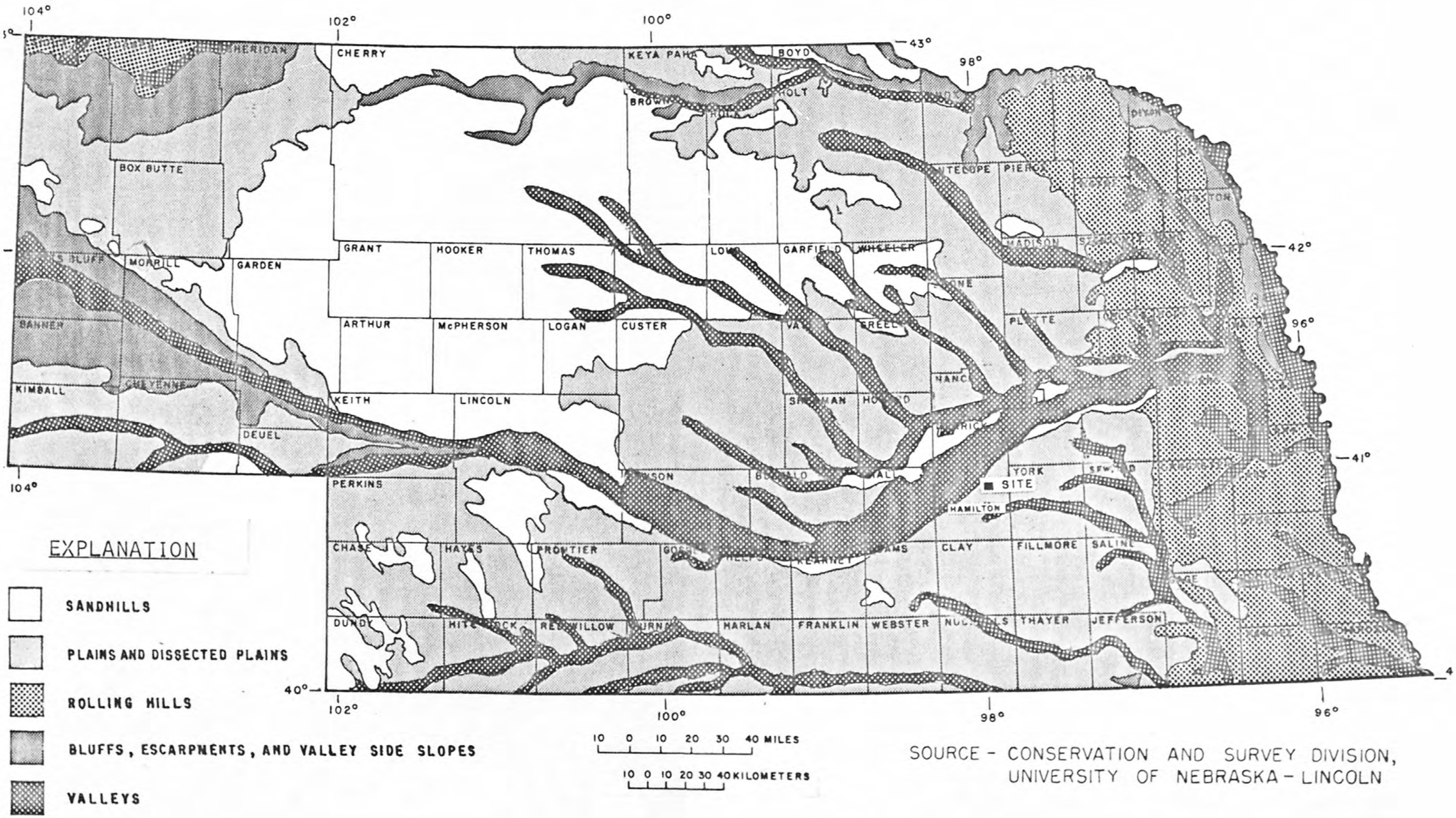


Figure 2.--Topographic regions of Nebraska.

Ground-water levels and the chemical quality of water from irrigation wells at similar distances from the Platte River indicate that the aquifer underlying the withdrawal-well site receives recharge from the Platte River. This suggested that the chemical quality of the water available for use in the experiment would be similar to that of Platte River water and therefore of a quality suitable for use in this experiment.

The recharge well is 3 mi east of the withdrawal well. Land-surface altitude at the withdrawal-well site is approximately 1,871 ft above National Geodetic Vertical Datum of 1929, or about 86 ft above river level. The altitude at the recharge well is approximately 1,847 ft NGVD or 24 ft lower than at the withdrawal well (fig. 3). The withdrawal well is 213 ft deep and the recharge well is 180 ft deep.

The static ground-water level at the recharge-well site also is about 24 ft lower than at the withdrawal well, indicating an eastward water-table gradient of at least 8 ft/mi. Seepage from the Platte River undoubtedly has been moving toward the recharge-well site for years, and the rate of movement has accelerated recently in response to the increased decline of water levels (fig. 4) caused by large withdrawals for irrigation in the Big Blue River basin. However, chemical analyses of ground-water samples indicate that Platte River seepage probably has not yet reached the recharge-well site.

A generalized geologic log of formations at the recharge-well site indicates the following: 0-30 ft, loess (wind-blown silt); 30-34 ft, fossil soil zone; 34-75 ft, fine quartz sand with thin layers of silty sand; 75-90 ft, medium quartz sand; 90-200 ft, medium to very coarse sand, plus varying amounts of gravel; 200-255 ft, fine sand with layers of sandy silt, medium sand, and gravelly sand. Geologic and geophysical logs of the recharge-well site are shown in figure 5.

Recharge through wells

Major emphasis during the first 2 years of this investigation was placed on well-injection methods of artificial recharge. This was done because of the extensive interest in well recharge and to allow for extended periods of recharge.

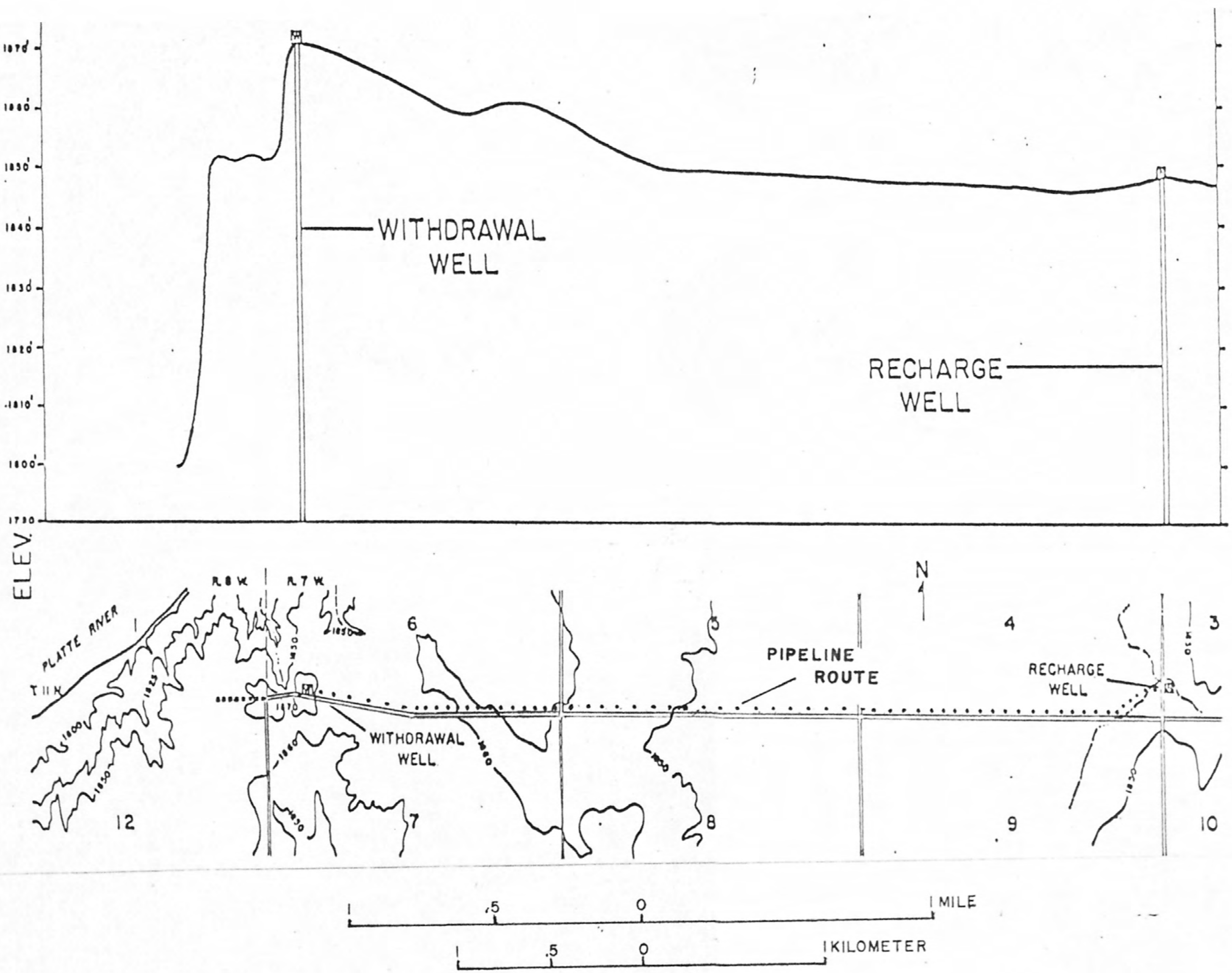


Figure 3.--Pipeline route of artificial-recharge experiment near Aurora.

Source - U.S. Geological Survey and Conservation and
Survey Division, University of Nebraska-Lincoln.

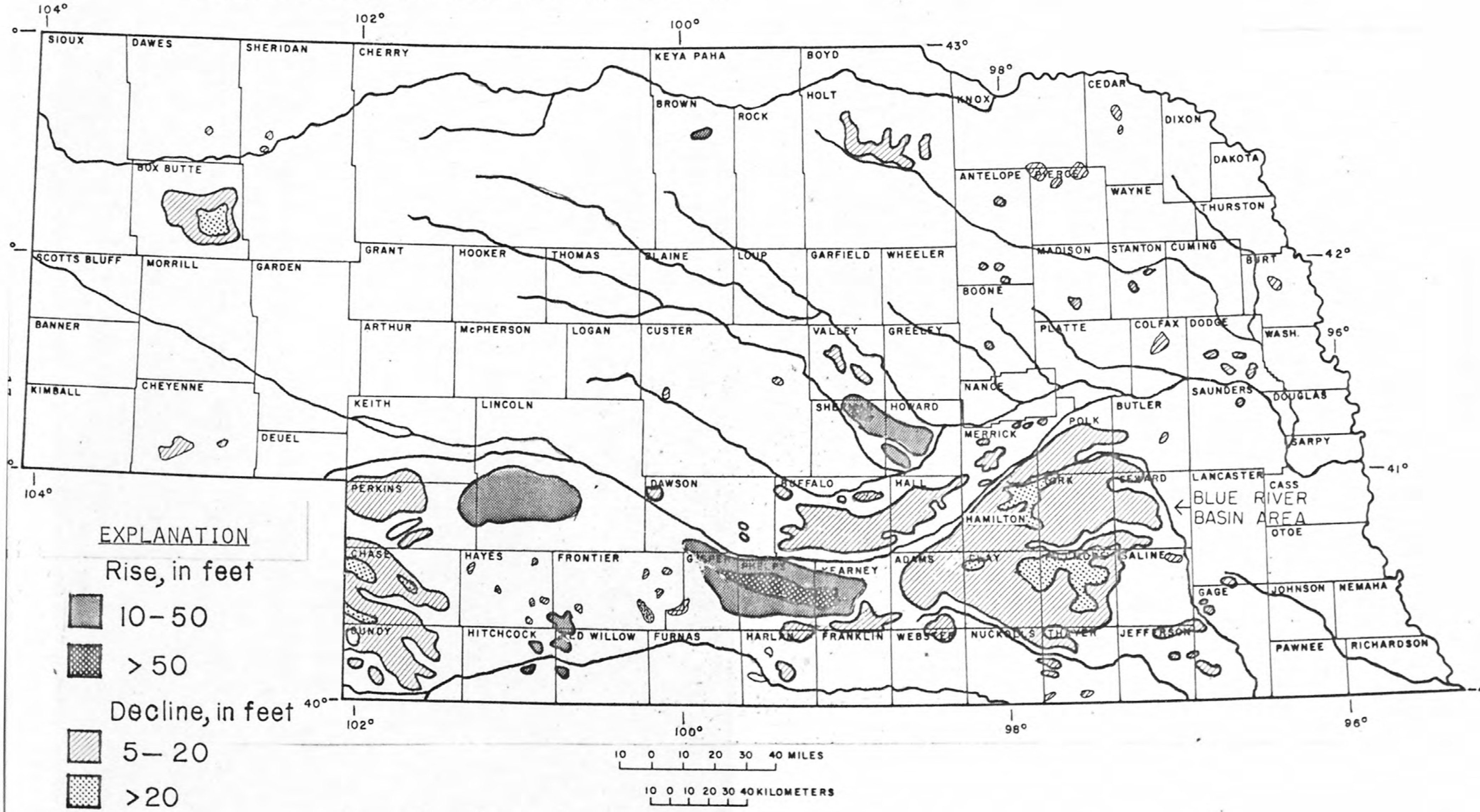


Figure 4.--Changes in ground-water levels in Nebraska between 1950 and 1977.

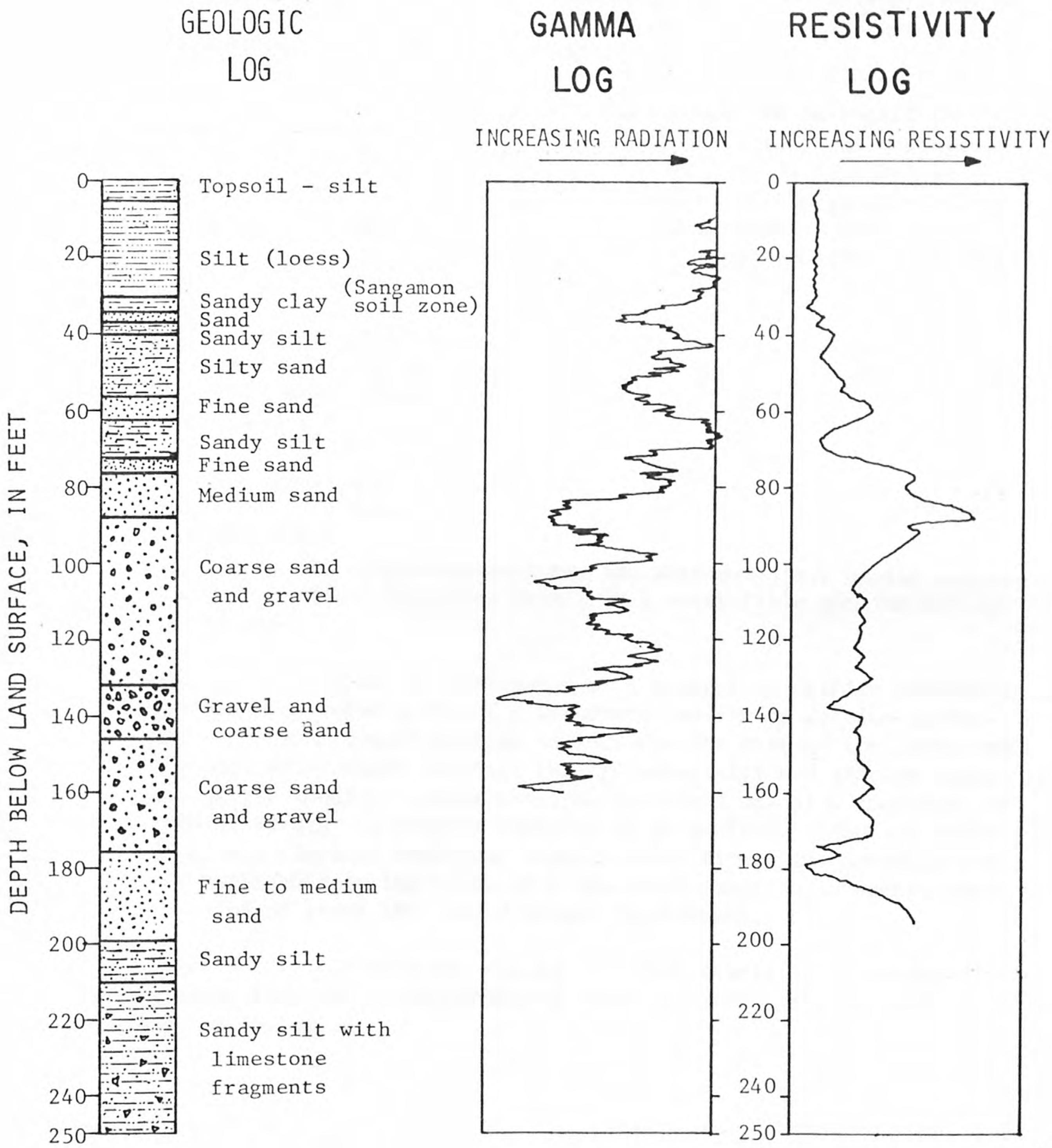


Figure 5.--Generalized geologic and geophysical logs of permanent artificial-recharge site near Aurora.

Water levels in recharge wells

Under ideal conditions, a graph of the buildup of water levels in the vicinity of a well when it is recharging should be a mirror image of a graph of the drawdown in the vicinity of the well when it is pumped, provided rates of recharge and pumping are the same.

Factors in nature that alter the ideal conditions in regard to artificial recharge through wells include (1) differences in quality between the recharge water and the native water, (2) differences in temperatures of the two waters, (3) rearrangement of the gravel-pack material or the aquifer material near the well because of changes in direction of flow, and (4) changes in aquifer response caused by differing water levels during pumping and recharge operations.

Some of the factors can tend to make the buildup of water levels less than the corresponding drawdown; however, most of them tend to make the buildup greater. Some that can make the buildup less than drawdown are as follows:

1. Recharge water that is warmer than the native ground water and therefore less viscous;

2. Increase in the saturated thickness and transmissivity of the aquifer due to rising water levels in a water-table aquifer during recharging;

3. Recharge water that is unsaturated with respect to calcium carbonate which can dissolve parts of a carbonate aquifer or calcium carbonate in a sand-gravel aquifer to increase the size of the pores and channels and thereby increase the transmissivity and storage capacity of the aquifer. Other chemical reactions may also increase the transmissivity and storage capacity of an aquifer. Solution effects from such chemical reactions usually occur slowly and normally are not noticeable during tests of a few days' duration; however, over a period of years they could become significant.

Factors that can make the buildup of water levels in a recharge well greater than the corresponding drawdown in a discharging well include the following:

1. Suspended material in the recharge water, including both organic and inorganic matter. This is a major cause of well and aquifer clogging. The material is filtered out of the water and deposited on the well screen, in the pores of the aquifer, or both. The deposited sediment reduces the area of the well-screen openings and the transmissivity of the aquifer, thereby increasing the head differential necessary to maintain a given recharge rate.

2. Air entrainment--another major cause of clogging. The exact manner in which air bubbles become lodged in the interstices of the aquifer is unknown, but the bubbles apparently have the same effect as clay particles or sand grains in that they effectively retard the passage of water. Movement of the bubbles outward from the well or upward to the water table may be prevented by one or more of the following (Sniegocki, 1963a): (a) simple blocking of the air bubbles by sand grains; (b) distortion of gas bubbles when they are forced through the capillary openings (Gardescu, 1930); and (c) a condition called the Jamin effect (Smith and Crane, 1930). The Jamin effect results from the fact that a capillary tube which contains restrictions and is filled with a chain of alternate air and water bubbles is capable of sustaining a finite pressure. A sand-gravel aquifer probably acts as a series of interconnected capillary tubes containing many restrictions and the forces created by the Jamin effect and bubble distortion act to prevent the movement of the entrained air after it has been introduced into the aquifer.

   Once air has been entrained in a sand-gravel aquifer, it dissipates very slowly with simple pumping of the well (Sniegocki, 1963a). Special redevelopment procedures involving the use of hexametaphosphate and surging and pumping are necessary to remove the bubbles before the specific capacity of an air-clogged well can be restored.

   Closely related to air entrainment is gas liberated from solution if the recharge water is warmed by contact with the native ground water. If the two waters are approximately the same temperature, this is usually not a problem.

3. Bacterial growth in a well. Such growth produces slimes or other products that can clog recharge wells and aquifers. These products act similarly to suspended sediment in reducing the transmissivity of the aquifer and increasing water-level buildup. Ground water, normally, is relatively free of bacteria; therefore, unless it is contaminated during transit to the recharge well, it should not clog the well by bacterial growth.

4. Chemical reactions between the recharge water and the native ground water and (or) the aquifer material. Such reactions can cause precipitation of insoluble matter that can in turn clog the screen and (or) the pores of the aquifer. The precipitation acts similarly to suspended sediment in clogging the well and aquifer, reducing the transmissivity of the aquifer and causing greater buildup of water levels.

   The chemical reactions causing precipitation are often complex and temperature sensitive. A knowledge of the chemical composition of the waters and their chemical equilibrium as well as their temperatures and the likelihood of changes in the composition of the waters with time are necessary to accurately predict potential problems from precipitation. Computer models are available to aid in making such predictions.

5. Ion-exchange reactions that result in dispersion of clay particles and swelling of colloids in a sand-and-gravel aquifer. Such reactions can occur when the recharge water is of different chemical composition than the native ground water, especially when freshwater is recharged into an aquifer containing water rich in sodium chloride. The reaction can disperse even a minor amount of clay and concentrate it in a nearly impermeable barrier near the well bore. An example of this type of reaction occurred during an artificial-recharge experiment at Norfolk, Va., (Brown and Silvey, 1977) where a recharge well lost 90 percent of its capacity in 6 days although the recharge water was of good quality, coming directly from the city of Norfolk's distribution system.

6. Iron precipitation. Such precipitation can occur in a well if iron-rich water is exposed to aeration or other oxidizing conditions. Soluble ferrous iron is oxidized to the insoluble ferric form. The resulting iron salts clog the aquifer much the same as suspended particles do.

7. Biochemical changes in the recharge water and ground water involving iron-reducing bacteria or sulfate-splitting organisms. Such changes can cause clogging under certain conditions. If the recharge water and the recharge system are kept free of bacteria, this should not be a problem.

8. Differences in temperature between recharge and aquifer water. When water that is cooler than the native ground water is injected into an aquifer, the recharge water has a higher viscosity than the native water. This higher viscosity requires a greater buildup in the recharge well to move cool water at the same rate as warmer

water. In a test in a sand-and-gravel aquifer at Grand Prairie, Ark., Sniegocki (1963b, p. 8) determined that the specific capacity of a recharge well decreased approximately 30 percent when the temperature of the recharge water was reduced from 66° to 43°F.

Preliminary injection tests

A preliminary injection test was made in November-December 1975 as part of the test-site-selection process to obtain information for the design of a permanent well-recharge system. Of particular interest during the preliminary test was whether any major problems, such as incompatibility of the different waters, would make it impractical to install a permanent system.

The Big Blue River basin in southeastern Nebraska was selected as the location for a test site because (1) an extensive, prolific, and widely used aquifer exists in the area, (2) progressive water-level declines caused by large withdrawals for irrigation are widespread (fig. 4), and (3) the Platte River, a potential source of water suitable for recharge, flows nearby. The specific site in Hamilton County was selected because an existing irrigation well that yields water nearly identical in chemical composition to Platte River water was available as a supply well, and another irrigation well about a mile away that yields water similar in chemical composition to ground water in the Big Blue River basin was available as a recharge well. The hydrologic setting at this recharge well is representative of much of the Big Blue River basin, thus the experimental results obtained in the test should be applicable to many sites in the basin.

A pumping test was conducted on November 17-18, 1975, to determine the characteristics of the recharge well and the surrounding aquifer. Observation wells to monitor water levels were installed at distances of approximately 8 ft, 66 ft, and 200 ft from the recharge well and a water-level recorder was installed on an unused irrigation well one-quarter mile from the recharge well. Sediment, bacteria, and dissolved-chemical contents of the water from the recharge well were monitored to provide baseline information on conditions prior to the test.

The supply well was connected to the recharge well with 10-inch irrigation pipe. More than 1 Mgal, chemically similar to Platte River water, was injected into the aquifer December 3-5. The same parameters, including quality of the injection water, were monitored as during the pumping test.

A postinjection pumping test was made on December 9-10 to determine the effects that injection had on the recharge well and the surrounding aquifer. The same parameters were monitored as previously. Results of this recharge experiment showed there was no significant plugging of the well or aquifer at this preliminary site during the short test. The graph of the buildup was nearly a mirror image of that of the pumping tests, and results of the postinjection pumping test indicate that the aquifer coefficients had remained unchanged (figs. 6, 7).

Analyses of the pumping-test data indicate that the principal sand-and-gravel aquifer in the vicinity of the recharge well has a transmissivity of about 6,600 ft^2/d [50,000 (gal/d)/ft] and a storage coefficient of about 0.0005 (table 1). The storage coefficient and water-level responses indicate that the aquifer is a leaky artesian aquifer at this site, that is, the confining bed overlying the aquifer is semipermeable. Analyses of drill cuttings from the observation wells showed a layer of silt near the top of the aquifer.

The water level before pumping began was above the top of the silt layer. Pumping in the first few seconds of the test lowered the water level below the silt layer in the vicinity of the pumping well, and thereafter during the test the aquifer was leaky artesian. If the test had been conducted for a longer period of time, the water above the silt layer would have drained to the underlying part of the aquifer and the aquifer response would have more nearly reflected water-table conditions.

The concrete-cased supply well yields considerable sand and fine gravel when the well is pumped at high rates. The first water pumped from the supply well contained the highest sediment content, and therefore it was discharged onto the ground; only when the water became relatively clean was it used for recharge. The computed sediment load injected into the well during recharge was 2.5 lb. The sediment removed during the postinjection pumping test was 5.5 lb, about twice the amount injected.

The recharge water was injected through the bowls of the turbine pump in the well at 370 gal/min. Some sand in the recharge water lodged in the bowls of the pump and created a momentary problem when the pump was started for the postinjection pumping test. If the recharge operation had been longer, the pump bowls might have become sand locked. Therefore, it is especially important when recharging through a pump column that the recharge water be as sand-free as possible.

The performance of the irrigation well was not impaired by the recharge operations.

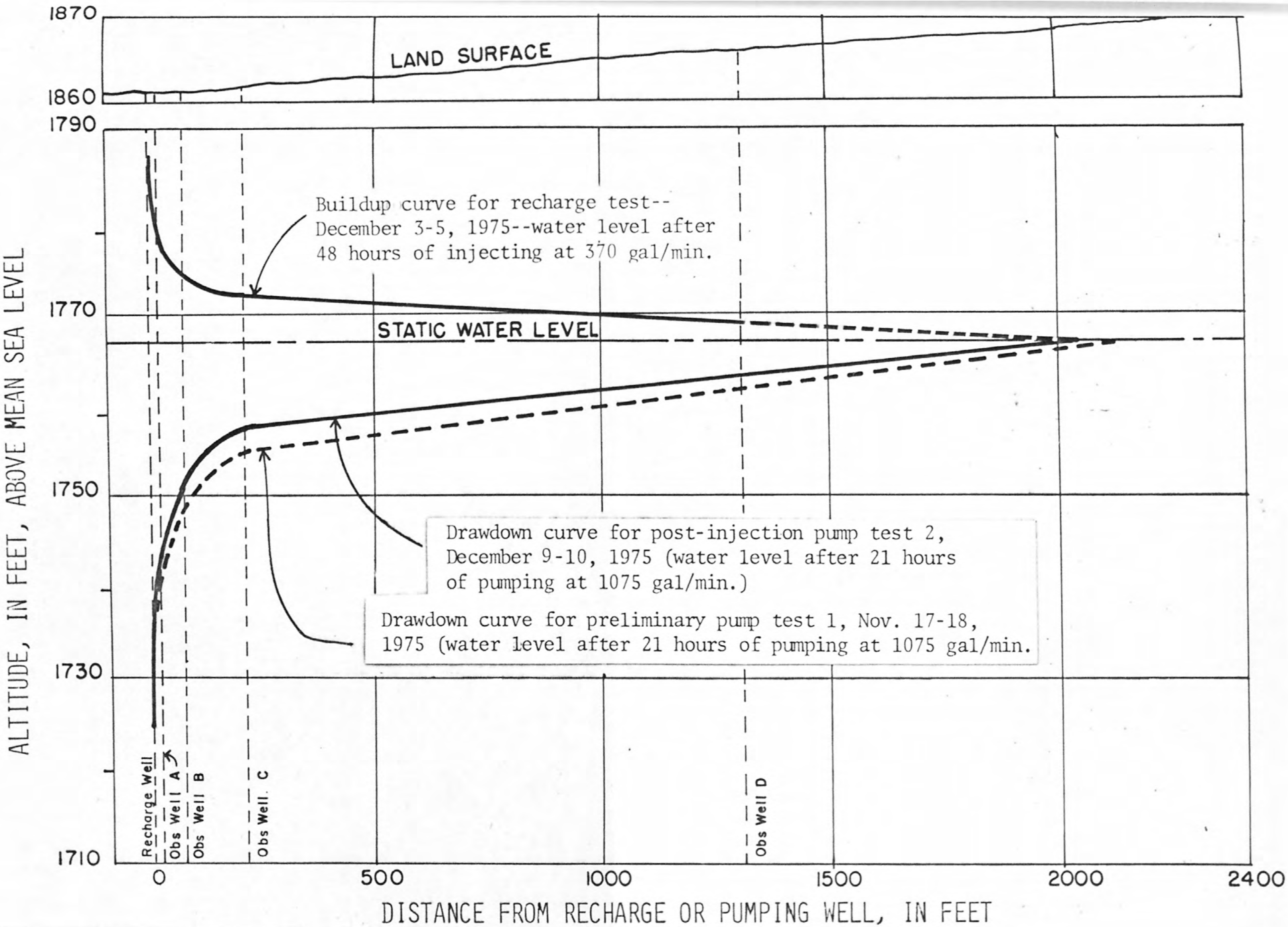


Figure 6.--Comparison of water-level changes during pumping and recharge tests at preliminary test site near Aurora.

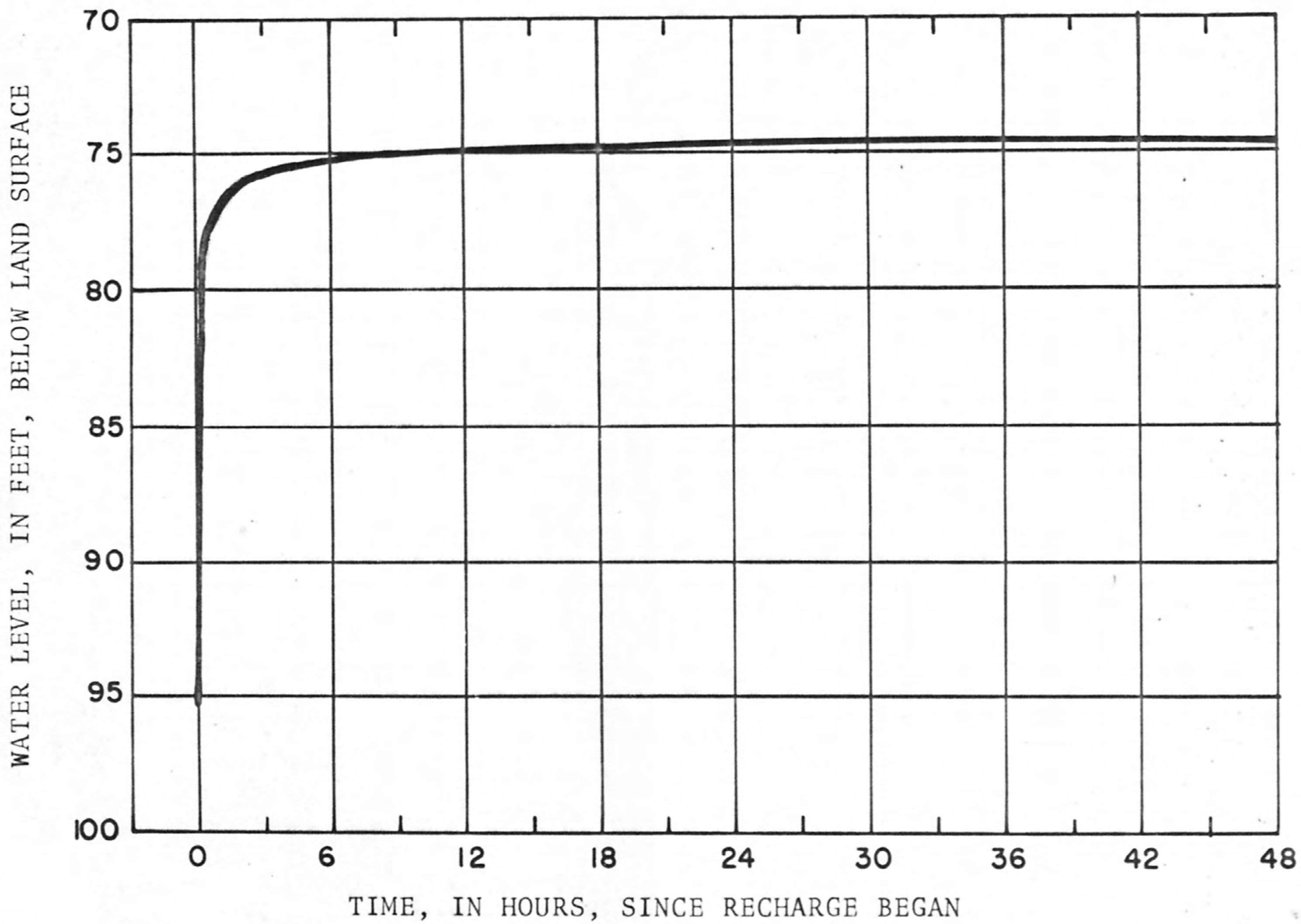


Figure 7.--Buildup of water levels in recharge well at preliminary test site near Aurora, December 3-5, 1975.

Table 1.--Results of aquifer tests at Aurora site in Hamilton County, Nebr.

Well designation	Screened interval (ft)	Distance to observation well (ft)	Transmissivity (ft^2/d)	Storage Coefficient	Leakance (ft/d)	Maximum buildup or drawdown (ft)
Tests at preliminary site						
Pumping test 1 - Nov. 17-18, 1975, recharge well pumped 21 hr at 1075 gal/min						
Recharge	110-220	0	--	--	--	--
Observation A	173-176	8	5,860	0.000737	0.675	26.8
Observation B	173-176	66	7,220	.000215	.123	16.6
Observation C	173-176	200	8,810	.000176	.046	11.2
Recharge test - Dec. 3-5, 1975, recharge well injected 48 hr at 370 gal/min						
Recharge	110-220	0	4,260	0.00335	0.789	18.9
Observation A	173-176	8	4,810	.000962	.555	11.2
Observation B	173-176	66	6,060	.000239	.103	7.0
Observation C	173-176	200	6,510	.000248	.076	4.8
Pumping test 2 - Dec. 9-10, 1975, recharge well pumped 21 hr at 1075 gal/min						
Recharge	110-220	0	4,910	0.00106	0.899	45.4
Observation A	173-176	8	5,750	.000830	.662	26.3
Observation B	173-176	66	6,310	.000482	.298	15.9
Observation C	173-176	200	6,700	.000596	.312	9.9
Test at permanent site						
Pumping test 1 - Mar. 2-4, 1977, recharge well pumped 48 hr at 880 gal/min						
Recharge	100-180	0	--	--		11.3
Observation 1	100-180	10	13,400	0.190	(Not	8.1
Observation 2	100-180	90	13,400	.074	analyzed)	4.5
Observation 3	100-180	316	17,000	.042		2.2

Selection of Permanent Recharge Site

The results of the preliminary well-recharge test indicated there was a reasonable chance that a longer test would be successful; therefore, a permanent recharge site was selected. The information gained from the first test was used in designing the permanent well-recharge system which is located near the preliminary site (fig. 8).

One of the objectives of the project is to determine the suitability of Platte River water for recharge in the Big Blue River basin. The permanent withdrawal well is located on the Eugene Gustafson farm about one-half mile from the Platte River and about 100 ft east of the divide between the Platte River basin and the Big Blue River basin. This site was selected because information on file with the U.S. Geological Survey showed that an irrigation well on the Gustafson farm 3,000 ft from the chosen site and about the same distance from the river yields water with a chemical composition similar to that of Platte River water. Also, the water level in the irrigation well had not changed significantly in the last 20 years even though there was heavy ground-water withdrawal in the area for irrigation. In contrast, water levels in irrigation wells several miles from the river in areas of similarly large ground-water withdrawals had declined more than 25 ft. This fact indicated that in this reach the river was effectively recharging the aquifer for a distance of at least one-half mile from the river. Chemical analyses of water from the irrigation well corroborated the above conclusion.

Although the dissolved chemical constituents in water from the permanent withdrawal well were about the same as those in river water (table 2), the overall quality of the two waters differed in an important way. The river water contained suspended sediment, organic matter, dissolved and entrained air and bacteria, in addition to dissolved chemical constituents. The recharge water was withdrawn from a well rather than directly from the river so that natural filtration through the ground removed the sediment, organic matter, air, and bacteria from the river water before it was withdrawn for use in recharge. This procedure eliminated the need for an expensive water-treatment plant as is commonly needed in well-recharge systems. Another reason for withdrawing water from a well rather than from the river was to utilize the aquifer under and near the river as a temporary storage reservoir for recharge water. The river becomes dry periodically and therefore is not wholly dependable as a recharge supply. By utilizing the vast storage capacity of the aquifer under and near the river, water for

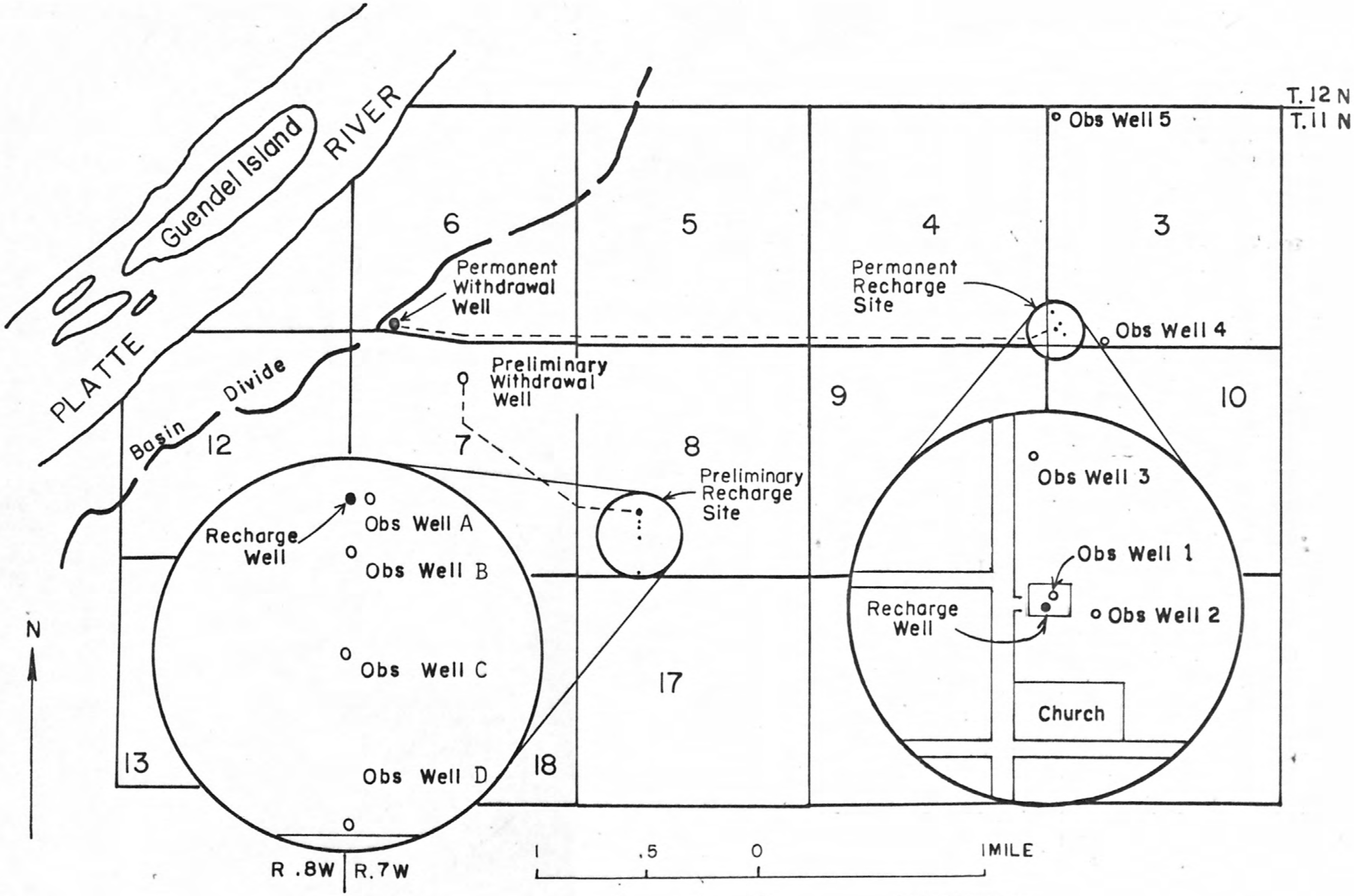


Figure 8.--Artificial-recharge sites near Aurora.
[Obs well, Observation well]

Table 2.--Chemical analysis of water from the Platte River near Grand Island, Nebr., and selected wells in Hamilton County, Nebr.

Constituent or characteristic	Units	Platte River (Average 1975)	Preliminary withdrawal well 10-10-75	Preliminary recharge well 10-10-75	Platte River (Average 1976)	Permanent withdrawal well 9-3-76	Permanent recharge well 9-3-76
Alkalinity	mg/L	182	240	237	182	178	229
Bicarbonate	mg/L	223	292	289	221	217	279
Boron	ug/L	140	110	40	147	--	--
Calcium	mg/L	67	110	71	70	86	360
Carbonate	mg/L	0	0	0	0	--	--
Chloride	mg/L	29	33	6.1	28	26	25
Color		7	2	2	8	--	--
Fluoride	mg/L	.5	.5	.4	.5	--	--
Noncarbonate hardness	mg/L	100	130	0	86	110	940
Total hardness	mg/L	282	370	230	267	290	1200
Iron	ug/L	15	0	10	11	60	20
Magnesium	mg/L	24	23	12	23	18	65
Manganese	ug/L	21	160	10	11	60	60
Nitrate and nitrite	mg/L	.36	.31	1.9	.47	.69	160
pH		8.0	6.9	7.0	8.0	--	--
Phosphorus	mg/L	.05	.11	.20	.06	--	--
Potassium	mg/L	12	7.3	6.1	12	5.6	18
Dissolved solids	mg/L	588	791	356	568	--	--
Dissolved solids	*	.80	1.1	.48	.77	--	--
SAR		2.1	2.5	.8	2.1	1.9	.7
Silica	mg/L	22	22	28	22	--	--
Sodium	mg/L	83	110	28	80	73	58
Specific conductance	**	878	1130	561	796	842	2410
Sulfate	mg/L	233	340	53	224	210	440

* Ton per acre-foot.

** Micromhos per centimeter at 25°C.

recharge was available at all times during the year, resulting in the most efficient use of the facilities. The partly depleted aquifer under and near the river was replenished when flow in the river resumed.

The effects of the striking differences in water quality between water from the permanent withdrawal well and that in the permanent recharge well will be discussed in a subsequent report on this project. The differences include nitrate concentrations 232 times greater in water from the permanent recharge well and specific conductance, total hardness, calcium, and magnesium concentrations more than twice those in water from the permanent withdrawal well.

In order to locate an accessible site for the recharge well where the quality of the ground water is reasonably typical of ground water in the Big Blue River basin, an analysis was made of the conductance of the water in selected existing wells in the Big Blue River basin. Conductance indicates the degree of mineralization of water. A site on the Kenneth Herrold farm 3 mi east of the withdrawal well met the criteria. This site is 500 ft north of the Monroe Free Evangelical Church on a small plot of virgin prairie near the headwaters of the Big Blue River.

Water samples from domestic wells 500 ft west, 600 ft southeast, and 1,000 ft northeast of the site had conductivities of 670, 790, and 670 micromhos per centimeter, respectively. Figure 9 shows that these conductances are within the range found in Hamilton County, which is a typical area of the Big Blue River basin. The chemical composition, however, was significantly different from that of the Platte River water. This was important as it is necessary to determine if Platte River water is compatible with native ground water in the Blue River basin.

Installation of the system

Before installation of the permanent well-recharge system, test holes were drilled at both the withdrawal- and recharge-well sites. A hollow-stem auger was used to obtain samples from land surface to the water table and as far into the aquifer as was possible with the auger rig. Cores were taken at intervals by the thin-walled shelby-tube method. When the auger rig reached the limit of its capability (about 125 ft), a hydraulic rotary rig was brought in to obtain samples to a depth of 255 ft.

Geophysical logs were made in the bore hole and sand-size analyses were made of the aquifer material to determine the depths to be screened and the optimum screen-slot size. The size distribution of the aquifer materials is shown in figures 10 and 11.

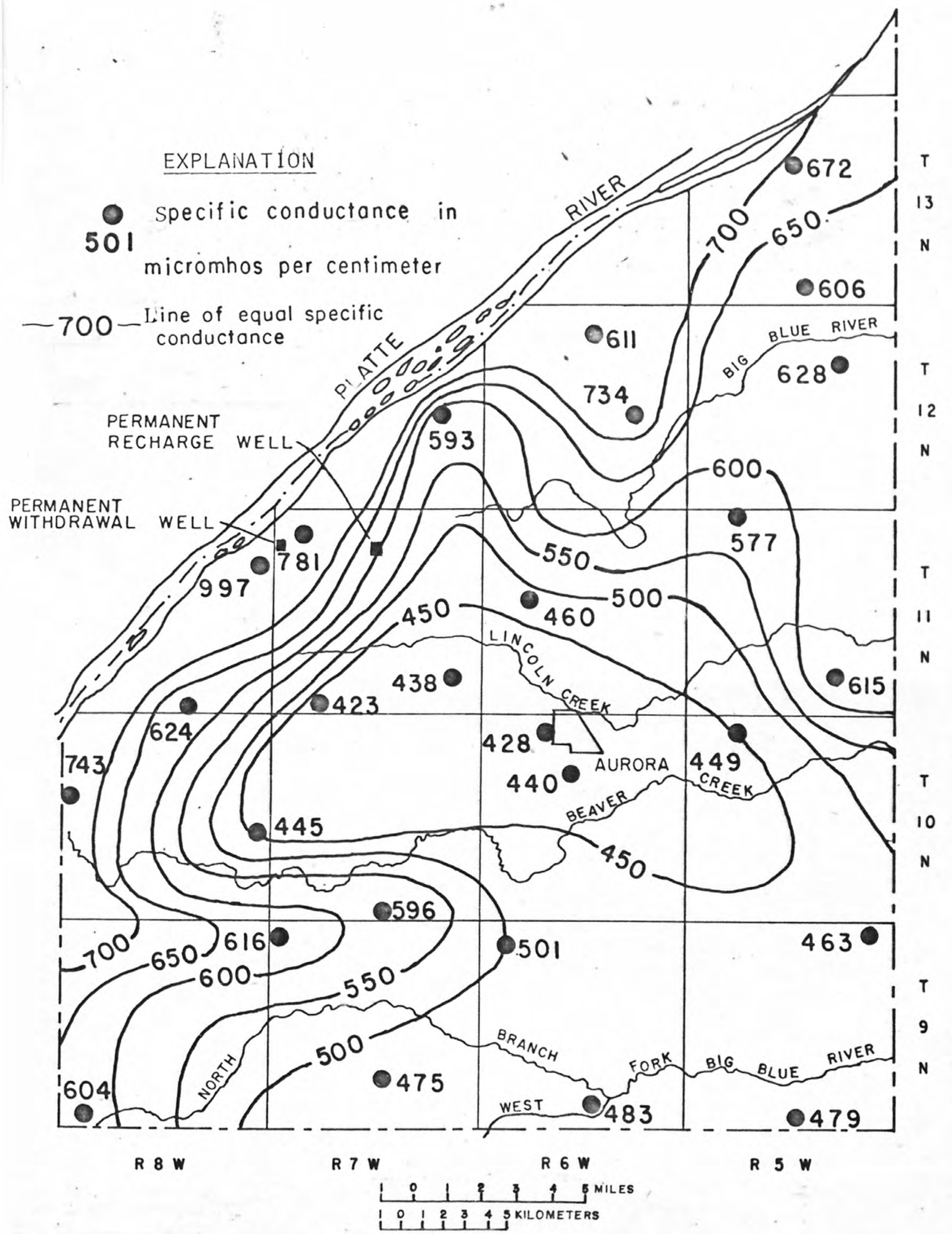


Figure 9.--Specific conductance of ground water in Hamilton County, Nebr., 1969.

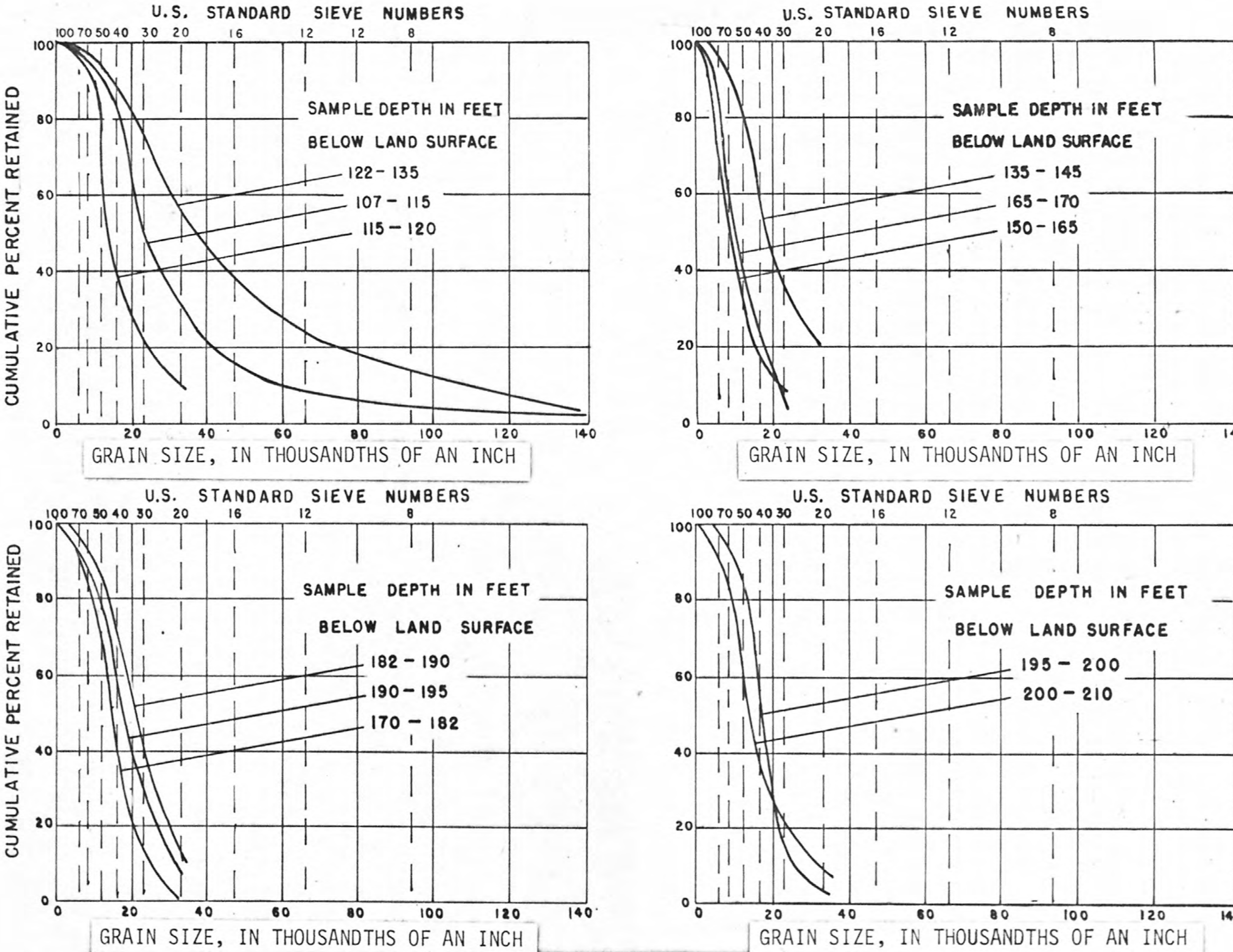


Figure 10.--Grain-size analyses from withdrawal-well site--test hole No. 3 near Aurora.
(Analyses by Johnson Division, United Oil Products Co.)

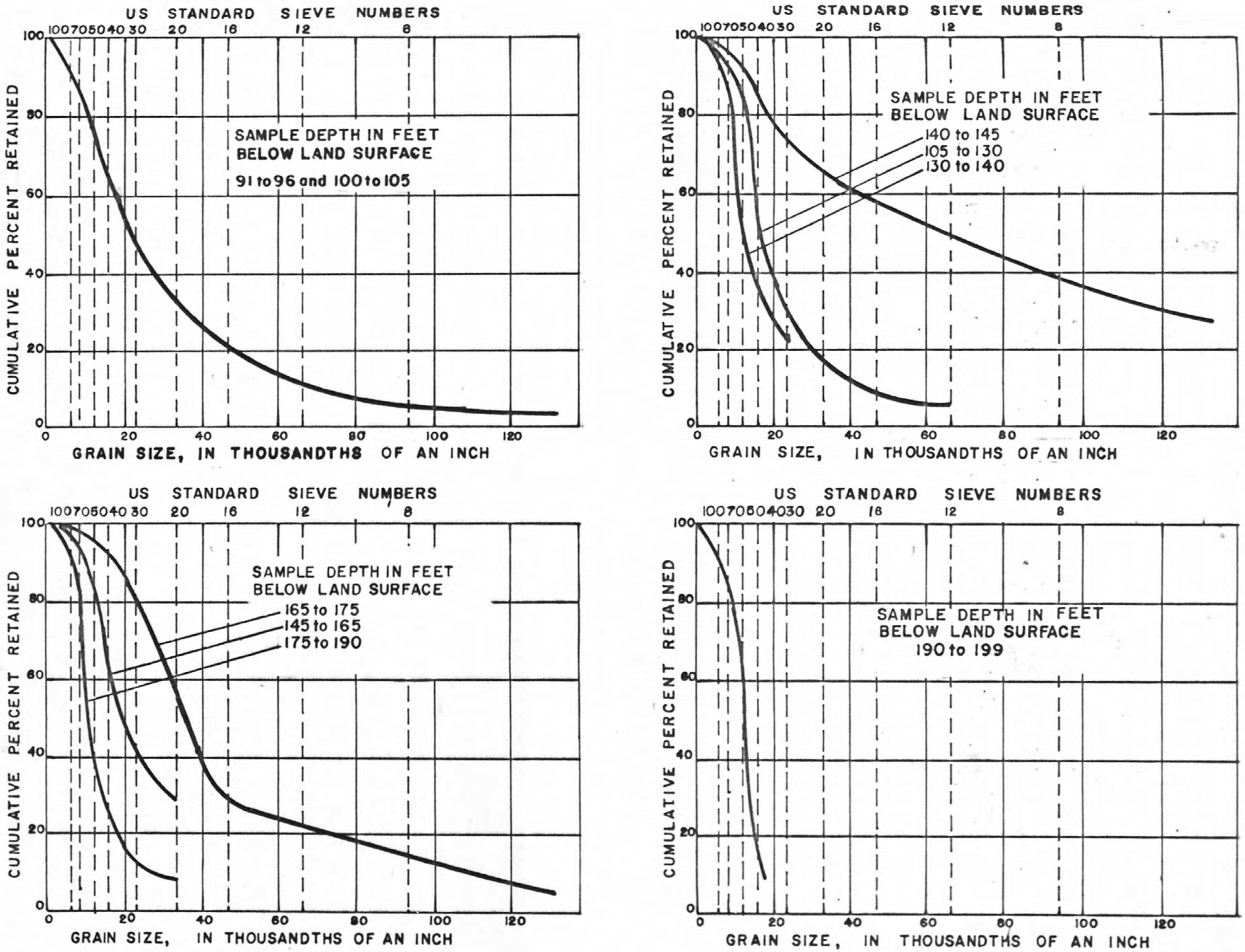


Figure 11.--Grain-size analyses from recharge-well site--test hole No. 4 near Aurora. (Analyses by Johnson Division, United Oil Products Co.)

Withdrawal well

The withdrawal well is 16 inches in diameter and 213 ft deep. It is screened with 30-slot (0.03-inch openings) Johnson Irrigator[1/] screen between depths of 140 to 190 ft and between 203 to 213 ft. The interval between 190 to 203 ft was cased with blank steel because the strata contained fine-grained material which would be difficult to screen out. The medium- to coarse-grained material from 103 to 140 ft was not screened because the water level in the aquifer adjacent to the well was expected to be drawn down to approximately 140 ft during pumping. The well was finished with a 6-inch thick filter pack of 1/32-inch to 3/16-inch gravel. It was developed by pumping, surging, and swabbing for 50 hours and was pumped at approximately one and a half times the desired production rate to obtain water as sand-free as possible. A 50-horsepower electric motor on a 5-stage vertical turbine pump was installed in the well.

Recharge well

The recharge well (fig. 12) is 18 in. in diameter and 200 ft deep. It is screened with 40-slot (0.04-inch openings) Johnson Irrigator screen between depths of 101-181 ft. The entire thickness of the aquifer was screened because during recharge operations the water level in the recharge well rises above the top of the aquifer so that the entire thickness of the aquifer could be utilized for recharge. The interval from 181 to 201 ft is blank steel casing sealed at the bottom. This section houses a 50-horsepower submersible pump. The pump was installed in the bottom of the well to avoid interference with the injection tubes and measuring devices in the upper part of the well.

Four injection tubes equipped with gate valves were installed in the well, each to a depth of 105 ft. Two of these tubes were 3 in., one was 2½ in., and one was 1½ in. in diameter. Different-sized tubes were installed so that the best combination of sizes could be determined experimentally to insure positive pressure, yet not exceed the design pressure of any part of the system. The injection tubes were connected by manifold to a 6-inch feeder line. Baffles were hung below the injection tubes to break up the injection streams and enable more accurate measurements of flow velocities in the screened section of the well. A 4-inch tube, not shown in figure 12, was installed to provide access for a continuous water-level recorder, a current meter, and for chlorinating the well.

1/ Use of brand name is for identification purposes only and does not imply endorsement.

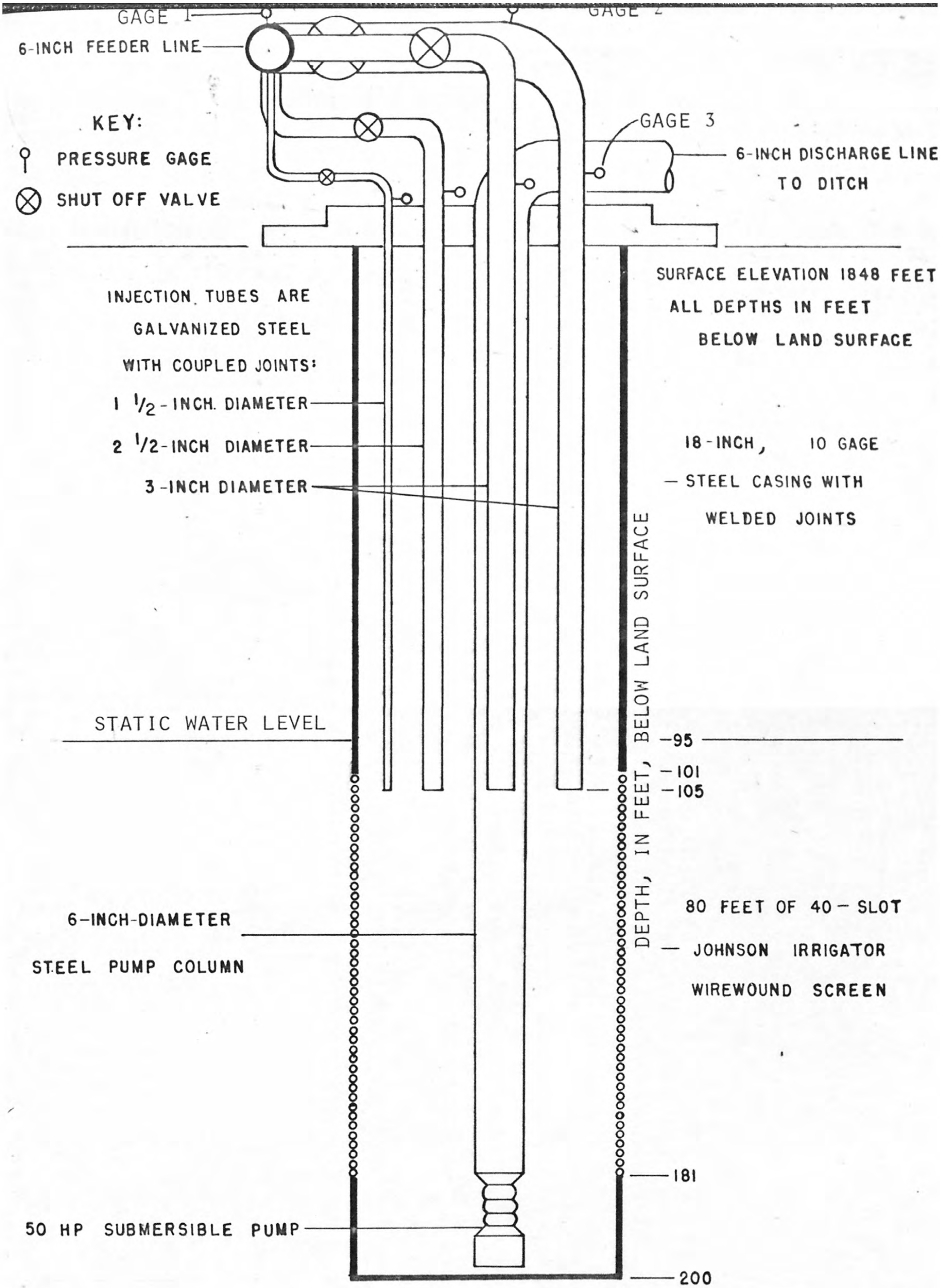


Figure 12.--Permanent recharge-well installation.

Pipeline

The withdrawal and recharge wells are connected by a 3-mile-long, 12-inch-diameter, low-head (22 lbf/in^2) P.V.C. pipeline that is buried below frostline. The pipeline is equipped with a surge tank, air-vacuum relief valves and pressure-relief valves. The eastern end of the line is equipped with a shut-off valve located in a pit inside a 20- by 22-foot building that also houses the recharge well and an observation well. A 6-inch-diameter steel line equipped with flow meters, shut-off valve, and sampling outlets connects the 12-inch line to the injection tubes and to a bypass line which discharges to a nearby ditch (fig. 13). Before the start of recharge operations, the system was disinfected with a strong solution of HTH70 granular chlorine.

Observation wells

Six-inch-diameter water-level observation wells, equipped with continuous-recording gages, are installed at distances of 10, 90, 316, 1,322, and 4,527 ft from the recharge well. In addition, a 1¼-inch observation well is installed in the gravel pack 2 in. from the recharge well. Two piezometer nests, each consisting of three 5-inch wells with 4-foot screened sections in the upper, middle, and lower parts of the aquifer, respectively, are located approximately 140 ft and 215 ft from the injection well.

Testing of the system

Several tests were run on the system, partly to verify preliminary data obtained on aquifer characteristics and partly to check out the equipment and design of the system. A pumping test was made to determine aquifer characteristics in the vicinity of the permanent recharge well. This was followed by two short-term recharge tests.

Results of data analyses are presented for the pumping test; however, analyses of the recharge tests were not complete by the end of the initial 2-year period.

Pumping test

The fluctuations of the water levels in an aquifer, in response to pumping or recharge, are controlled by the hydraulic coefficients of the aquifer and by any boundary conditions that exist. Aquifer tests are used to determine these coefficients by relating the rate and amount of drawdown in the pumping well and observation wells to rate of discharge, time since pumping began, and distance from the pumping well.

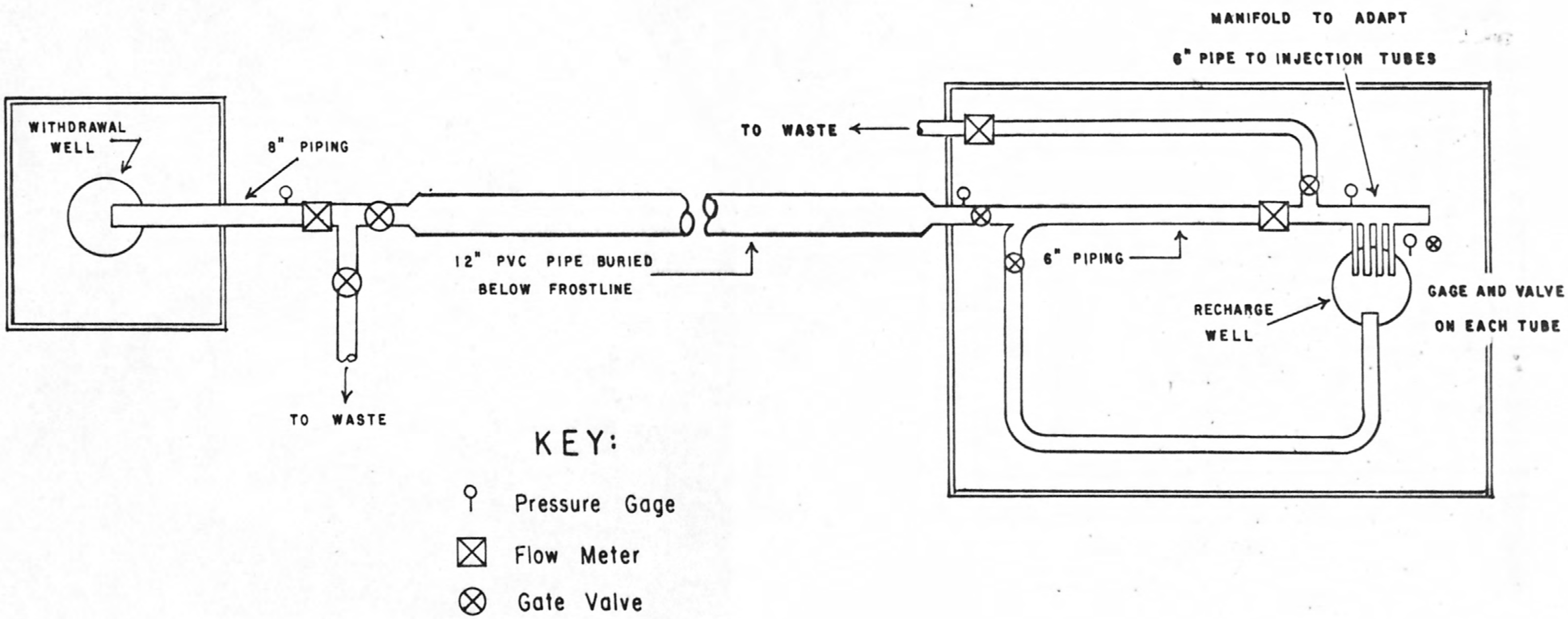


Figure 13.--Permanent well-recharge system near Aurora.

Characteristics affecting hydraulic behavior of an aquifer are transmissivity, storage coefficient, and leakance. Transmissivity is a measure of the ability of the aquifer to transmit water and is defined as the rate at which water is transmitted through a unit width of the aquifer under a unit hydraulic gradient (1 ft/ft) at the prevailing water temperature. The storage coefficient characterizes the "reservoir" behavior of an aquifer and relates water-level changes to actual amounts of water taken from or added to storage. It is defined as the volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head. Leakance is the amount of water transmitted through a confining bed which overlies or underlies an aquifer and is defined as the rate at which water will flow through a unit area per foot of head difference at the prevailing temperature.

The methods used to determine aquifer coefficients assume that the aquifer is homogeneous, isotropic, and areally extensive, and that flow is laminar and entirely radial. Few aquifers meet all these criteria; however, if the physical characteristics of the aquifer and confining beds are described, the coefficients help to describe the hydrologic characteristics of the aquifer.

The pumping test to determine aquifer characteristics in the vicinity of the permanent recharge well was made during Mar. 2-4, 1977. The recharge well was pumped at an average rate of 880 gal/min for 48 hours and drawdown was measured in the recharge well, the 1¼-inch well in the gravel pack, and in the five 6-inch observation wells. Corrections were made for changes in pumping rate, water-level changes caused by barometric fluctuations, and regional change in ground-water levels.

The corrected drawdown data from the pumping test were analyzed using delayed-yield type curves (Lohman, 1972) which are applicable to aquifers under water-table conditions. (See fig. 14.) It is significant that the data from the preliminary pumping test only 2 mi from the permanent site fit the leaky-aquifer type curves, indicating semiartesian conditions. This illustrates the fact that the characteristics of the Quaternary aquifer can vary considerably over relatively short distances.

Analysis of the data from the pumping test at the permanent recharge-well site (table 1) indicated a transmissivity of about 14,000 ft^2/d [105,000 (gal/d)/ft]. The storage coefficient as determined from the curves ranged from 0.2 to 0.04. The variations in this coefficient may be due to slow drainage which causes greater error in the more distant observation wells than in nearby wells. If the test had been of sufficient duration, this effect probably would have been minimized and the

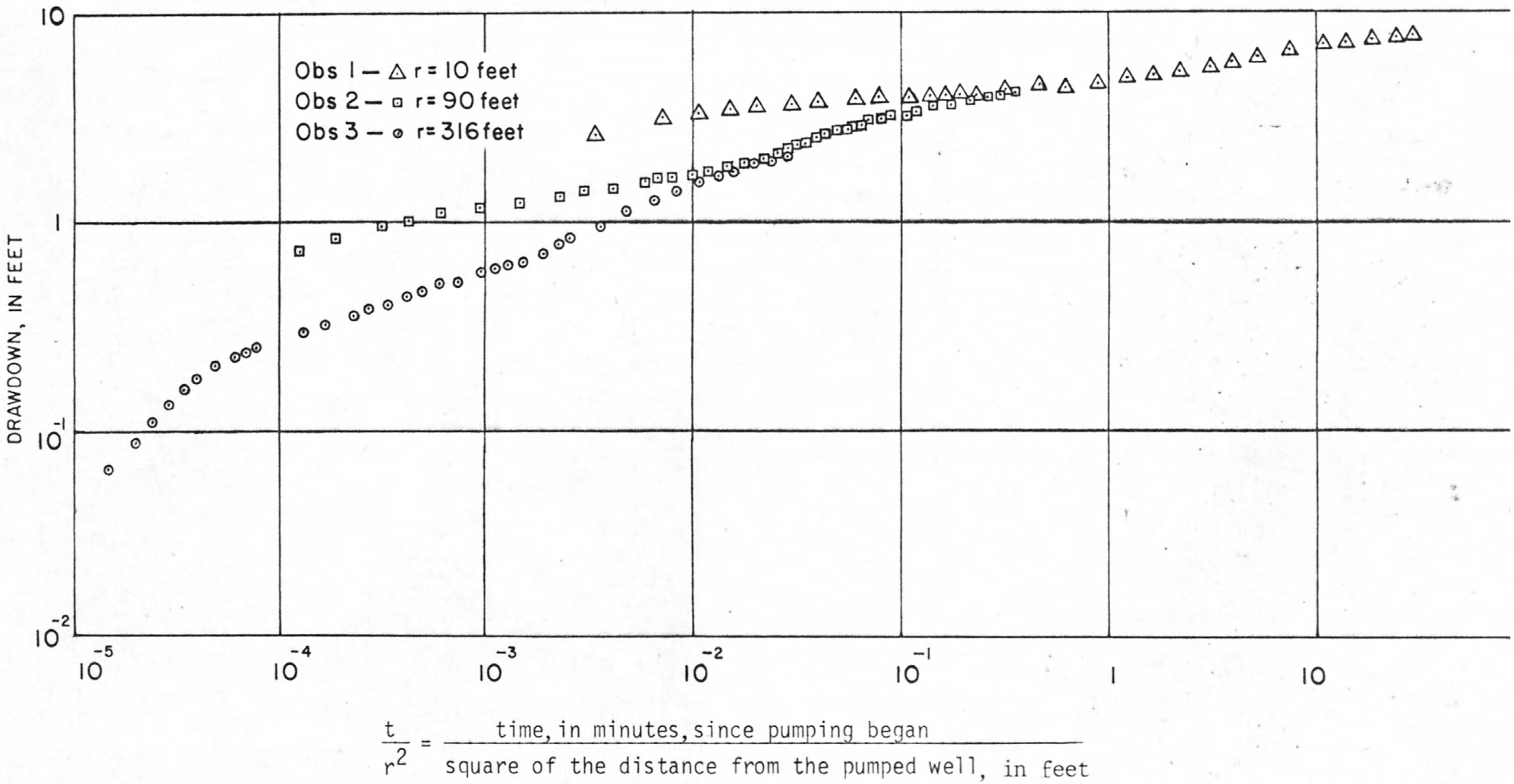


Figure 14.--Drawdown in observation wells during pumping test March 2-4, 1977, at permanent recharge test site near Aurora.

storage coefficients probably would have all been near the value of 0.2 obtained from the nearest well. This value is reasonable for a clean sand-and-gravel aquifer.

The sediment content of the water pumped from the recharge well during this pumping test was about 0.0003 grams per liter for a total of about 6 lb. The rate of sediment yield decreased during long-term pumping at a constant rate.

Recharge tests

Water was first injected into the permanent recharge well on March 18, 1977, to test the system, especially the injection tubes. The tubes were arranged in manifold from the 6-inch piping within the building (fig. 12). The injection-tube system was designed to utilize friction in the tube rather than a foot valve to maintain positive pressure (Reeder, 1975). Positive pressure is necessary to reduce gas release and to protect against air entrainment in the recharge water should a leak develop in the piping.

The injection tubes are galvanized steel with open ends. Sizes of the tubes were selected so as to obtain approximately a unit friction head loss per equal unit length of tube at the prevailing injection rate. The planned recharge rate was 1,000 gal/min; however, the exact injection rate could not be determined before the recharge system was installed. Therefore, a nest of different-sized injection tubes were installed so the proper combination of tubes could be selected by trial-and-error. Each injection tube was equipped with a gate valve equivalent to the pipe size. Pressure gages were installed on the 6-inch pipe ahead of the manifold, on the well side of the gate valves, and on each tube just above where it entered the well.

The March 18 test was made at an injection rate of 700 gal/min; excessive vibration, cavitation, and head loss occurred between the 6-inch pipe and the top of the well. With one 3-inch and one 1½-inch valve open, the pressure head in the 6-inch pipe was 13 lbf/in^2, but the pressure at the well head was negative. As a corrective measure, one of the 3-inch gate valves was replaced with a 6-inch gate valve connected to the 3-inch injection tube by a reducing elbow. With this arrangement it became possible to recharge at a rate of 750 gal/min through a single 3-inch injection tube with virtually no vibration or cavitation, and pressure remained positive throughout the system.

The pressure heads in the system 2 minutes after the start of a recharge test on October 24 were 15 lbf/in^2 at the withdrawal well, 13 lbf/in^2 at gage No. 1 in the 6-inch piping before the injection manifold, 9.5 lbf/in^2 at gage No. 2 just beyond the 6-inch gate valve, and 6.5 lbf/in^2 in gage No. 3 in the 3-inch injection tube at the well head (fig. 15). After a day of recharging at 750 gal/min, the pressures at each gage had risen about 1 lbf/in^2 and after an additional 2 months of recharging, the pressures rose approximately 1 additional lbf/in^2.

A recharge test lasting 66 hours was made during May 17-20, 1977. Water was recharged to the aquifer at a rate of about 760 gal/min for a total of about 3 Mgal or 9.2 acre-ft. The water was allowed to remain in the aquifer until July 18 after which it was pumped from the recharge well at a rate of about 1,000 gal/min. A total of 3.8 Mgal of water were withdrawn from the aquifer at this time (July 18-22) and an additional 3 Mgal were withdrawn during July 27-29. Samples of the mixed recharge-native water were taken for chemical analyses to determine what, if any, chemical reactions had taken place.

Monitoring of the system

The well-recharge experiment conducted as part of this investigation was designed to eliminate as many problems associated with well recharge as practical while keeping costs to a minimum.

Careful monitoring of the system provides the data necessary for predicting the results of long-term recharge operations. Excessive buildup of water levels in a recharge well is an indication that clogging of some kind is occurring in the well. A monitoring system, therefore, is needed to detect and measure such buildup in the recharge well and in the surrounding aquifer and to help determine probable causes of clogging.

The water-level monitoring system consists of continuous water-level recording gages on the recharge well, on five 6-inch observation wells, and on a 1¼-inch observation well in the gravel pack of the recharge well 2 in. from the well casing. Locations of these wells with respect to the recharge well were described earlier. The 6-inch observation wells are used to monitor aquifer response to pumping or recharge. Changes in water levels in these wells are compared to changes in the recharge well. Such comparison gives an indication of the extent of clogging of the aquifer in the immediate vicinity of the recharge well during recharge. Measurements of water levels in the 1¼-inch observation well are compared to water levels in the recharge well to indicate the degree of clogging of the well screen.

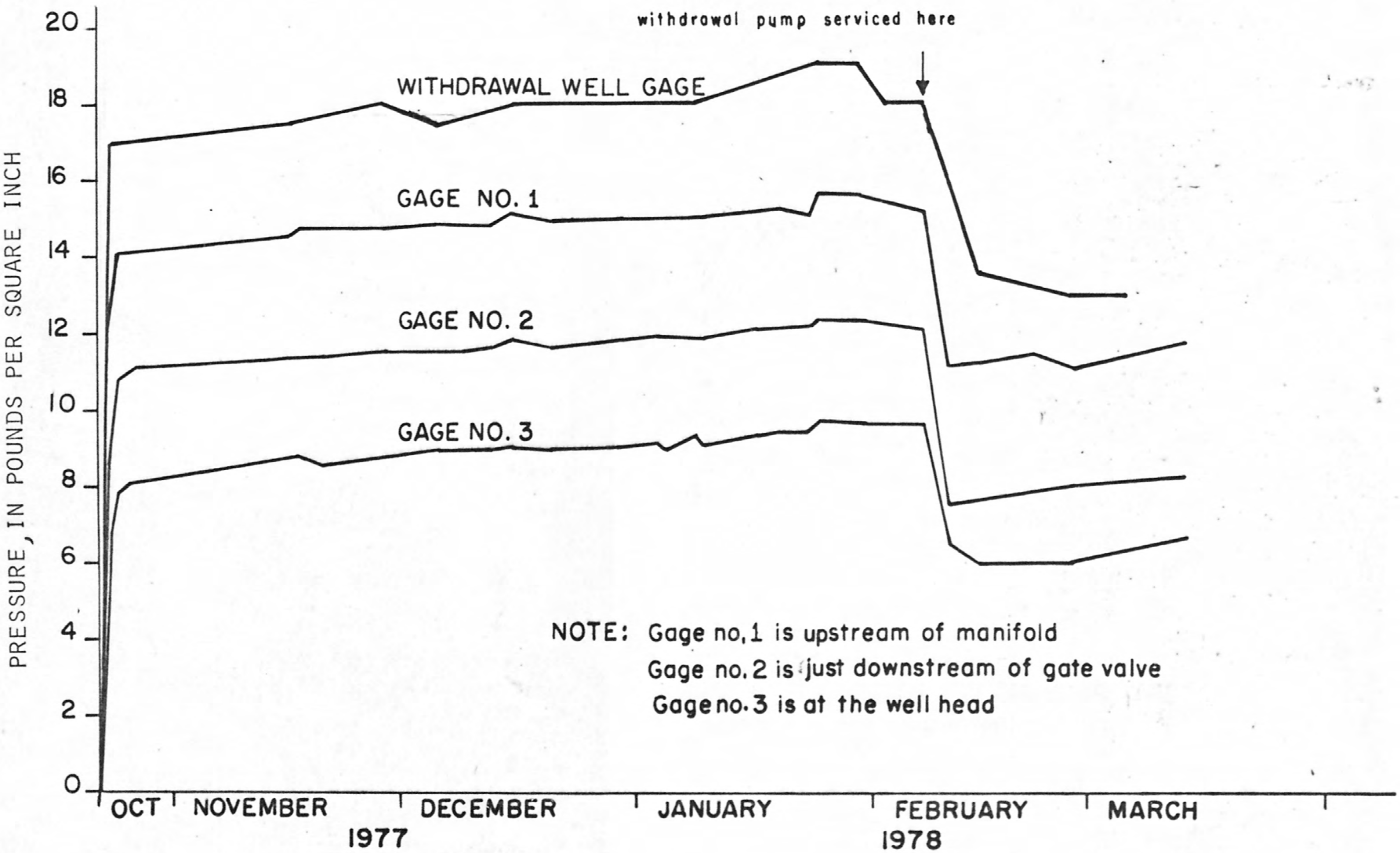


Figure 15.--Pressures in piping of permanent recharge well.

Monitoring to help determine probable causes of clogging consists of the following:

1. Periodic sampling and analysis of recharge water for suspended sediment. Sampling frequency was greatest near the beginning of a pumping or recharge test when the sediment content of the water was changing most rapidly. The procedure was to filter 20 liters of water through a 0.45-μm filter and determine the suspended solids load from the difference in the dry weight of the filter before and after filtration (table 3). Initially Gelman metracel filter pads were used; however, solution, erosion, or volatilization of minute amounts of the filter pad during filtration and drying caused the results to be somewhat in error. The problem was solved by substituting special Gelman teflon filters that do not dissolve in water or volatilize during drying.

2. Continual monitoring of conductivity and temperature, and periodic monitoring of dissolved oxygen content, and pH of the water being injected into or pumped from the recharge well. A probe designed to measure these four parameters was connected to a Martek Mark V water-quality analyzer and installed so that water flowed continuously over it. Any two of the parameters could be recorded at a given time and the other two could be read periodically. Changes in conductivity and temperature usually are the best indicators of change in water quality, therefore these two parameters usually were selected for continual recording. In addition to indicating changes in water quality with time, the data from the probe was used to indicate the optimum time for collecting water samples for more complete chemical analyses.

3. Periodic measurements, using standard methods, of the total bacterial content of water injected into and of water removed from the recharge well.

4. Sampling for chemical analyses of the recharge water, of the water pumped from the recharge well, and of water from various depths in the observation wells. This was to help determine the pattern of water movement in the ground and to detect any chemical changes that occurred as the result of mixing waters of different quality.

Table 3.--Sediment data

[Well injection, permanent artificial recharge site, Hamilton County, Nebr.]

Well sampled	Sample filtered on		Period covered				Length of period (hr)	Average pumping rate (gal/min)	Sediment concen- tration (mg/l)	Total Sediment moved (lb)
			From		To					
	Date	Time	Date	Time	Date	Time				
	1977		1977		1977					
Recharge	3/4	--	3/2	10:55	3/4	10:15	47.3	880	0.300	6.3
Recharge	3/16	13:50	3/16	13:47	3/16	14:40	1.0	1010	2.36	1.05
Recharge	3/16	14:55	3/16	14:40	3/16	15:30	1.0	1010	1.29	.56
Totals			3/16	13:47	3/16	15:30	2.0	1010	----	1.61
Withdrawal	5/17	19:00	5/17	18:15	5/17	21:30	3.3	755	.548	.67
Withdrawal	5/17	23:20	5/17	21:30	5/18	9:00	11.5	755	.138	.60
Withdrawal	5/18	18:00	5/18	09:00	5/19	06:00	21.0	755	.019	.15
Withdrawal	5/19	17:22	5/19	06:00	5/20	02:00	20.0	755	.030	.23
Withdrawal	5/20	10:13	5/20	02:00	5/20	12:15	10.2	755	*-.0001	----
Totals			5/17	18:15	5/20	12:15	66.0	755	----	1.65
Recharge	7/18	17:28	7/18	17:25	7/18	17:45	.3	1000	75.5	12.59
Recharge	7/18	17:40	7/18	17:45	7/18	18:15	.5	1000	6.34	1.58
Recharge	7/18	18:23	7/18	18:15	7/18	20:25	2.2	1000	3.36	3.64
Recharge	7/18	22:25	7/18	20:41	7/19	01:30	4.8	1000	.976	2.35
Recharge	7/20	17:15	7/20	10:52	7/21	01:40	14.8	970	.433	3.11
Recharge	7/21	09:29	7/21	01:40	7/21	12:55	11.2	970	.505	2.76
Recharge	7/21	15:42	7/21	12:55	7/22	00:30	11.6	970	.157	.88
Recharge	7/22	08:46	7/22	00:30	7/22	12:20	11.8	970	.181	1.04
Recharge	7/22	15:23	7/22	12:20	7/22	16:05	3.8	970	.190	.35
Totals			7/18	17:25	7/22	16:05	61.0	983	-----	28.30

Table 3.--Sediment data--Continued

Well sampled	Sample filtered on Date	Sample filtered on Time	Period covered From Date	Period covered From Time	Period covered To Date	Period covered To Time	Length of period (hr)	Average pumping rate (gal/min)	Sediment concen-tration (mg/1)	Total Sediment moved (1b)
	1977		1977		1977					
Withdrawal	7/27	11:41	7/27	11:30	7/27	13:40	2.2	975	.324	.50
Withdrawal	7/27	14:47	7/27	13:40	7/28	00:25	10.7	975	.190	1.00
Withdrawal	7/28	08:24	7/28	00:25	7/28	22:30	22.1	975	*-.00002	----
Withdrawal	7/29	10:25	7/28	22:30	7/29	13:57	15.4	975	*-.00015	----
Totals			7/27	11:30	7/29	13:57	50.4	975	------	1.50
Withdrawal	8/24	16:30	8/24	09:56	8/24	17:30	Before injection	975	*-.0046	----
Withdrawal	8/25	10:14	8/24	17:30	9/1	01:30	175.5	750	*-.0031	----
Withdrawal	9/7	16:13	9/1	01:30	9/10	18:45	257.2	885	*-.0075	----
Withdrawal	9/13	21:02	9/10	18:45	9/14	02:45	80.0	760	*-.0068	----
Withdrawal	9/14	08:10	9/14	02:45	9/24	12:00	249.3	760	*-.0056	----
Note:	Because of the weight loss of the metricel filters, teflon filters were used beginning on 12/20.									
Withdrawal	12/20	18:30	11/23	12:00	1978 1/6	12:00	1056.0	745	.052	20.46
	1978		1978							
Withdrawal	1/24	19:30	1/6	12:00	1/25	09:15	453.2	745	.0078	1.32
Withdrawal	1/25	23:00	1/25	09:15	1/26	13:00	27.3	745	.0040	.04
Withdrawal	1/27	03:00	1/26	13:00	1/27	17:00	28.0	745	.0039	.04

Tests are continuing (1978)

* Sediment content appears to be negative. Metricel filter pad lost weight in the filtering and (or) drying process.

Results of first long-term test

On August 24, 1977, the first long-term recharge test, planned to run continuously for 60 days, was started. The test was interrupted after 9 days, and periodically thereafter until October 31 by momentary power failures. The problem finally was tracked to a shorting of the power company's transmission lines and was corrected. Except for an 18-hour delay caused by a power interruption during a snowstorm November 8-9, recharge was continuous from October 31, 1977, to March 6, 1978.

The well-recharge tests were not concluded by the end of the first 2 years of the project (December 1977); in fact, they are continuing at the time of this writing (March 1978). Therefore, only tentative conclusions can be stated based on data collected to date.

More than 475 acre-ft (155 Mgal) of water was recharged to the aquifer from September 1977 to February 1978 at a rate of 700 to 740 gal/min with a buildup of water levels in the recharge well of 17 ft. The buildup resulted in development of a cone of elevation that extended more than a half mile from the recharge well (fig. 16). Of the 17-foot buildup in the recharge well, approximately 70 percent occurred during the first few days of recharge (fig. 17). During September and October, recharge was intermittent because of power interruptions; however, from November to February, recharge was continuous at approximately 735 gal/min with an additional increase in water levels in the recharge well after the first few days of only 3 ft. Projecting this rate of increase (1 ft/mo) for an additional 8 months, indicates a total buildup of about 25 ft/yr if there is no lowering of water levels by artificial means such as pumping for irrigation.

The static water level in the recharge well was about 94 ft below land surface; therefore, it might be possible to recharge a single well at a rate four times the stated rate, or about 3,000 gal/min for a year before the water levels would reach the land surface.

The water level in the recharge well continued to rise slowly (fig. 17) even after the water levels in the observation wells virtually stabilized. The reason for this is not known at this time but some clogging evidently occurred between the recharge well and observation well No. 1, which is 10 ft away. Water levels in the recharge well and the 1¼-inch observation well in the filter pack were virtually identical, indicating no clogging of the well screen. Therefore, the clogging probably was in the aquifer near the recharge well.

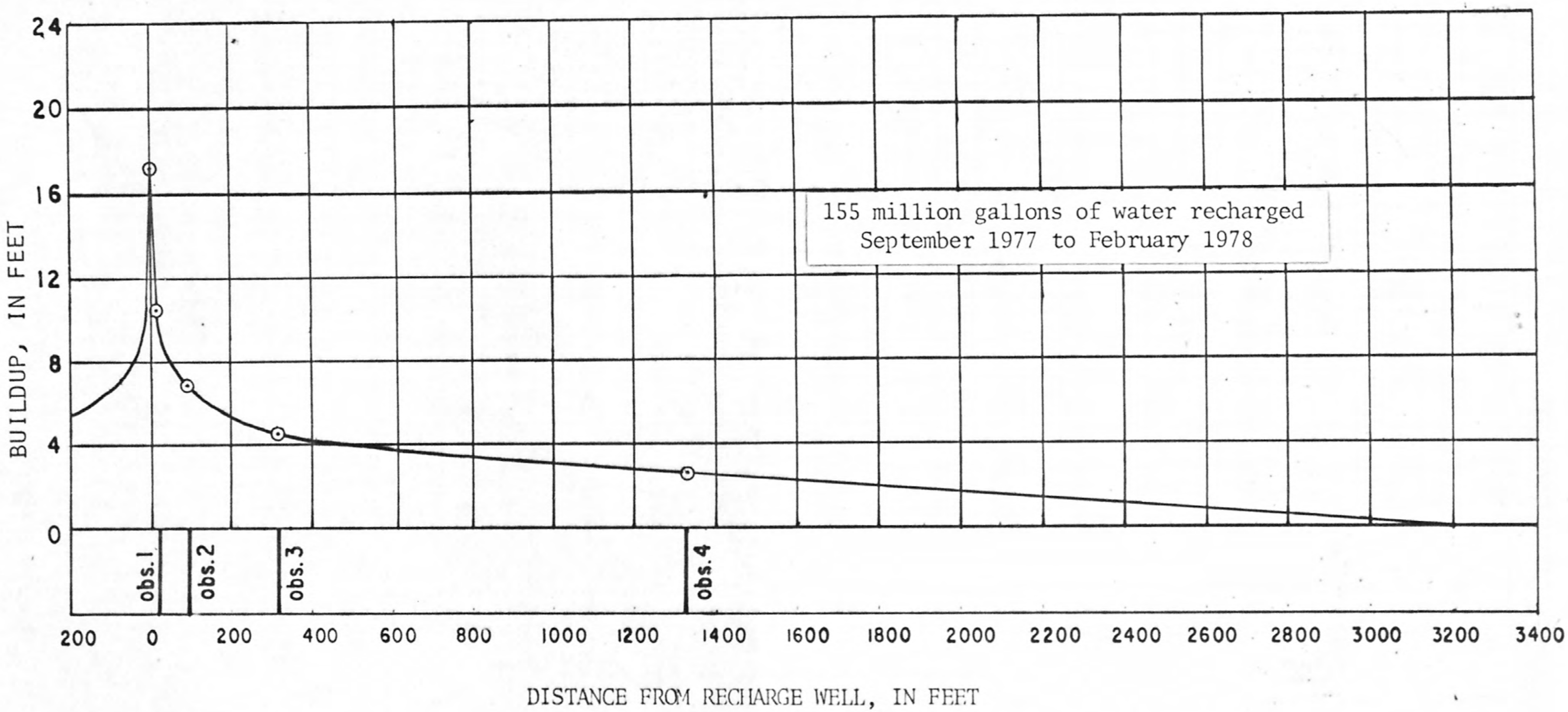


Figure 16.--Profile of water-level buildup, February 1978, in wells during recharge at the permanent site near Aurora.

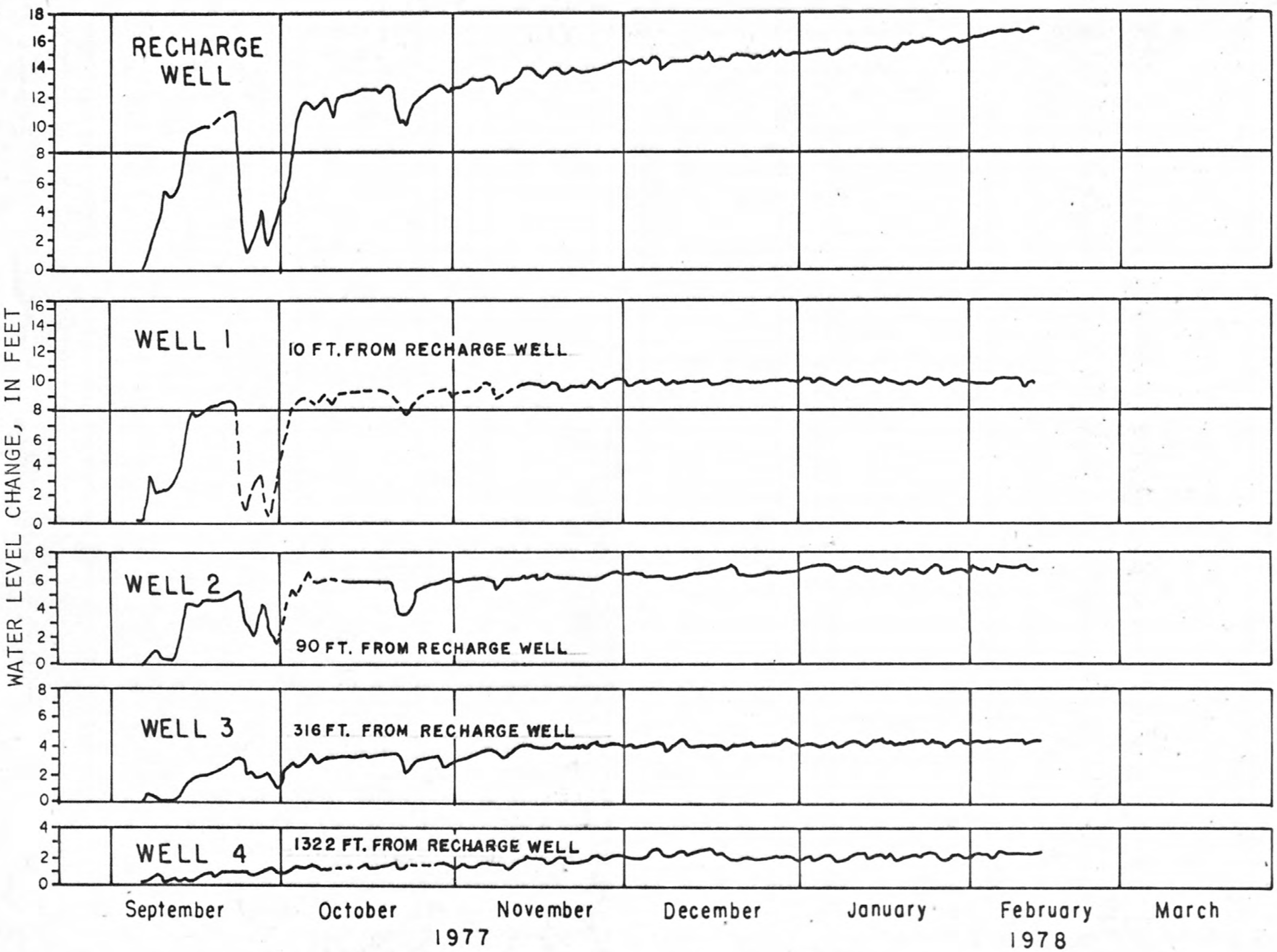


Figure 17.--Water-level rise in wells caused by recharging 155 million gallons of water at the permanent recharge site near Aurora.

A possible factor causing the clogging is air that mixed with the water when the connecting pipeline was refilled after each power interruption. The other two major causes of clogging--suspended sediment and bacteria--cannot be ruled out completely. As shown in table 3, the sediment concentrations of the recharge water, that is, water from the withdrawal well, became extremely small after 3 days of recharging and eventually approached zero. Thus, the quantity of sediment injected into the recharge well during December 1977 through early March 1978 appeared to be negligible.

The results of bacterial analyses are inconclusive. The relatively small numbers of bacteria present in the recharge water from the withdrawal well in May 1977 and January 1978 (table 4) probably had no significant effect on recharge operations. However, bacterial slime growing in the recharge well and aquifer could have caused part or all of the observed clogging. Dissolved air entering the well during intermittent recharge operations could have encouraged the growth of certain types of bacteria.

The total bacteria count in water from both the recharge and the withdrawal wells tended to increase as recharge operations continued (table 4). The increase may have been due to the growth of bacteria in the pipeline and possibly in the withdrawal well. Bacterial growth as it relates to artificial recharge will be studied further in the second half of the investigation.

Recharge through water spreading

Water spreading is herein defined as the release of water over the ground surface for the purpose of increasing the quantity of water infiltrating into the ground and percolating to the water table. It can be accomplished by flooding or spraying the land surface, by impounding water in shallow excavations, or by damming and widening natural stream channels. The rate at which water spreading increases recharge to an aquifer depends on the permeability of the materials through which the water must pass to reach the water table, the quality of the recharge water, and the quantity applied. In practice, the least permeable layer through which the water must pass generally controls the rate of downward movement. This layer can be at the land surface or at any depth between the surface and the aquifer. If the least permeable layer is at considerable depth, its effect on recharge may not become apparent until long after the start of artificial recharge operations.

Table 4.--Bacteria data from tests at permanent well-recharge site, Aurora, Nebr.

Date	Event	Well Sampled	Time Collected	Colonies per 100 ml
3/8/77	Injection well chlorinated			
3/9/77	Withdrawal well and pipeline chlorinated Injection well flushed			
3/10/77	Withdrawal well and pipeline flushed			
3/16/77	Injection well pumped for 1.7 hr			(No sample)
3/17/77	Injection well pumped for 3.5 hr	Recharge	08:35	175
3/17/77		Recharge	09:28	260
3/17/77		Recharge	10:32	250
5/17/77	Began 2.5-day recharge test at 18:15	Withdrawal	23:00	650
5/18/77		Withdrawal	18:30	365
5/19/77		Withdrawal	17:00	335
7/18/77	Started recharge well pump at 17:15	Recharge	17:25	14,500
7/18/77		Recharge	17:52	2,520
7/18/77		Recharge	21:09	1,025
8/24/77	Recharged intermittently for 2½ mo			
11/9/77	Began continuous injection test			
1/11/78		Withdrawal	16:00	135
1/27/78		Withdrawal	14:30	500
2/1/78	Shut down 10 min			
2/7/78		Withdrawal	15:00	1,650
3/8/78		Withdrawal	12:30	1,380
3/21/78		Withdrawal	12:00	9,350

Infiltration rates of recharge basins can be increased by using one or more of the following: settling areas, retention basins, diffusion wells, scarification, and alternate wetting and drying cycles.

Settling areas are low areas in recharge basins designed to collect trash and sediment washed into the basin. The upper areas, usually 1 to 2 ft above the low areas, are auxiliary infiltrating areas that receive overflow from the commonly flooded low areas.

Retention basins are used where large amounts of sediment and debris are present in the recharge water. They are used as settling basins and nearly sediment-free overflow water is discharged through pipes and flumes to nearby recharge basins. Retention basins do not require cleaning as often as recharge basins because plugging of the lining of the retention basin is not important.

Diffusion wells are wells dug below the floor of a recharge basin to enable ponded water to percolate downward to the water table. They are used where strata of low hydraulic conductivity are present beneath the land surface. The wells are commonly 10-foot-diameter precast-concrete cylinders backfilled with coarse sand and gravel and installed at sufficient depth to penetrate the restricting strata.

Scarification is the mechanical breaking up or loosening of the material on the floor of a recharge basin or the removal of a thin layer of material from the basin floor. Scarification often is used on basins that operated well originally but have decreased infiltrating capacity because of clogging by sediment and (or) bacterial growth.

Alternate wetting and drying of a recharge basin is often used in place of, or in conjunction with, scarification. The drying process kills bacteria and other organisms which clog the soil and hasten their decomposition. In addition, drying of fine-grained clogging sediment can produce mud cracks which break up the continuity of the clogging layer and increase the infiltration rate.

Aurora Site

Equipment for a water-spreading experiment was installed near the well-recharge site 8 mi northwest of Aurora, Nebr. The experiment uses a flooding-type installation enclosed by a 24-foot-diameter ring infiltrometer. The ring was implanted successively at two locations, each on virgin prairie about 100 ft from the recharge well. These sites were located near the recharge well partly to facilitate direct comparison of the effectiveness of well injection and water-spreading methods of artificial recharge and partly because the sites are representative of large areas in the Blue River basin. No attempts were made to find sites with highly permeable soil. Aspects of the geology of the area are shown in figure 5.

Instrumentation

The ring infiltrometer (fig. 18) was formed by bolting together sections of corrugated steel to form a 24-foot-diameter bottomless tank about 0.01 acre in area. The ring was installed to a depth of 18 inches into the top of a weak hard-pan layer without appreciably disturbing the native sod inside the ring. The edge of the ring was sealed with bentonite to minimize leakage. A water supply was obtained via a 1½-inch plastic hose from a 180-foot-deep well at the Monroe church about 300 ft from the ring.

A float switch maintained the water depth in the infiltrometer at 1 ft. A totalizing meter in the line measured the volume of water entering the tank. A recording rain gage and an evaporation pan were installed near the ring infiltrometer to determine gains to the pond from rainfall and losses due to evaporation.

A 1¼-inch piezometer with a 30-inch screen was installed inside the ring at a depth of 37.5 ft in a perched zone of saturation that is about 55 ft above the regional water table. The perched zone was discovered while collecting continuous shelby-tube core samples of the material above the aquifer.

Four neutron-probe access tubes were constructed by augering 2½-inch-diameter holes to depths of about 80 ft. A 2½-inch-diameter black-iron threaded-and-coupled pipe (tube) with a solid-drive point was then driven to the bottom of each hole. The part of the hole that was enlarged during the driving process was filled with bentonite to minimize leakage alongside the casing. One access tube was installed inside the ring to enable monitoring of the downward movement of water from the pond. A second tube was installed 3 ft outside the ring to enable monitoring of lateral movement of pond water through the ground. The other two tubes were installed at distances of 30 and 125 ft from the ring infiltrometer to serve as controls to enable monitoring of natural changes in the moisture content of the unsaturated zone.

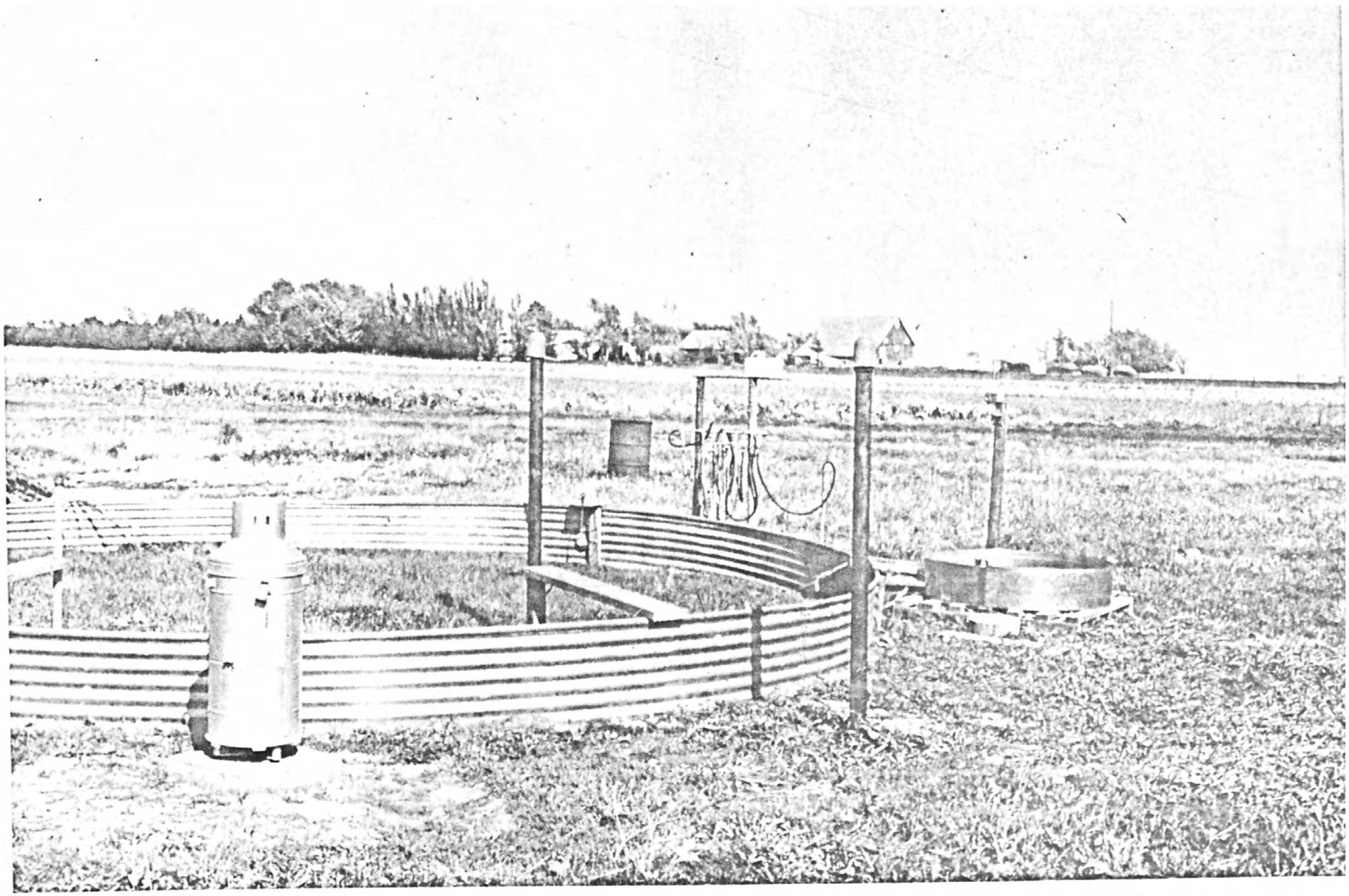


Figure 18.--Surface-spreading installation near Aurora.

The neutron probe measures the moisture content of the soil within approximately 1 ft of the access tube. The probe contains a radioactive source that sends out high-energy (fast) neutrons and a detector that measures the number of low-energy (slow) neutrons returning to the probe. Because fast neutrons are slowed by collision with the hydrogen nuclei in water, the number of slow neutrons that strike the detector is directly proportional to the moisture content of the soil. The probe is connected to a recording device that makes a continuous graphic log of the slow-neutron count as the probe is raised or lowered in the hole. The probe was calibrated to relate neutron count to moisture content by running neutron logs at the same time that adjacent "undisturbed" core samples were taken for analysis of moisture content at a laboratory on the site.

In future experiments, changes in moisture content of the soil and movement of a wetted front will be determined by periodically making neutron logs and comparing successive logs.

Tensiometers were installed inside the ring at depths of 2, 6, 12, 24, 36, and 48 in. The purpose of the tensiometers was to monitor the movement of the wetted front in the first few feet below land surface.

Porous cups were placed within the ring at depths of 6, 22, 37, 53, and 79 ft below the land surface. The cups were used to collect water samples from the unsaturated zone or perched saturated zones for chemical analysis. A vacuum was placed on the porous cup to draw in any moisture from outside the cup. When sufficient volume had entered the cup, air pressure was applied to one of two hoses connected to the cup, thereby forcing the water to the surface through the other hose. The chemical composition of the recharge water was different from the native water in the zone above the water table, therefore by comparing the chemistry of water at the different zones before recharge operations and at different times after the start of recharge, the downward movement of the recharge water could be monitored. In addition, changes in chemical constituents could be determined as the recharge water mixed with and (or) reacted with native water and the soil materials.

An air-permeability facility was installed near the ring infiltrometer to determine the hydraulic conductivity of the unsaturated zone (Weeks, 1977). The air-permeability facility was constructed by augering a hole to a depth of 95 ft and emplacing short, 1½-inch-diameter screens at depths of 95, 91, 68, 64, 58, 38, 35, 28, and 7 ft below land surface. The screens were connected to the surface with ¼-inch steel tubing.

Gravel was placed around the bottom screen and about one-half foot above to ensure that the screen was open to the surrounding soil. A 6-inch layer of silt was placed on top of the gravel and the hole filled with expansive cement grout to the depth where the next screen was to be emplaced. The silt layer was used to prevent the grout from penetrating the gravel. Expansive cement was used to ensure an air-tight seal in the hole. Each successive screen was emplaced in similar fashion. The depths of the screens were selected, on the basis of analyses of continuous cores, to bracket zones of low permeability.

The ¼-inch tubes were connected in manifold to an inclined manometer (fig. 19). The inclined manometer measured the air pressure in each of the various zones. By taking successive readings during times when the atmospheric pressure changed rapidly and comparing the readings to the atmospheric pressure at corresponding times, the air permeability of the various zones could be determined. The air permeability could then be converted to hydraulic conductivity (Weeks, 1977).

Results of tests

Two recharge tests, using a 24-foot-diameter ring infiltrometer, were conducted at the Aurora site. The first was a short-term test to determine the approximate infiltration rates to be expected so an adequate water supply could be designed and installed. This test lasted 8 days, August 3-11, 1976, and the average infiltration rates were approximately 0.04 ft/d. No monitoring devices were installed except a meter to measure the quantity of water put in the pond. Based on this approximate rate of infiltration, it was decided that an adequate recharge supply could be obtained from the well at the Monroe church.

In the first test the ring infiltrometer was emplaced 1 ft below the ground surface; however, lateral seepage at the land surface was observed for distances of up to 5 ft from the edge of the ring. Therefore, when the ring was moved to a new location 100 ft from the original site, it was installed to a depth of 18 inches below land surface into the top of a lower permeability "hardpan" layer in an attempt to reduce the lateral seepage. As with the first site, the narrow trench that was dug to install the ring was packed with bentonite as a seal. The greater depth of the second installation reduced but did not entirely prevent lateral seepage near the surface.

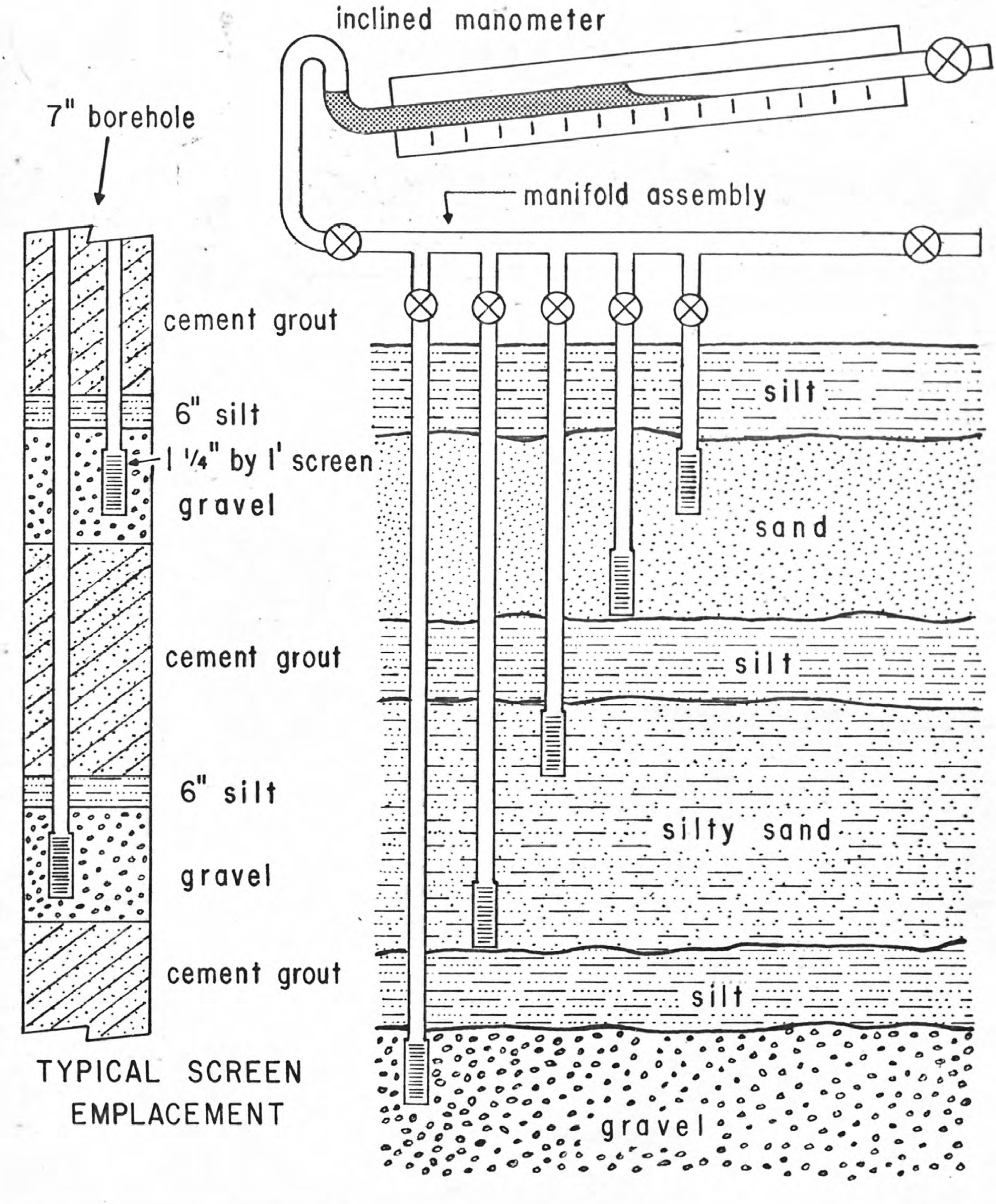


Figure 19.--Typical air-permeability installation.

For the second test the ring infiltrometer was filled with water on October 25, 1977. Initial infiltration rates, corrected to 50°F, were computed as 0.39 ft/d. The rates increased for 10 or 11 days to 0.66 ft/d (fig. 20) and then decreased slightly for the next 3 days. The test was terminated on November 9, 1977, because of freezing weather. The duration of the test was insufficient to provide definitive answers as to the practicality of surface spreading as a method of artificial recharge in the site area. However, longer tests are planned for the summer of 1979.

Certain aspects of the two tests are difficult to interpret. The two tests were located only 100 ft apart, yet the infiltration rate in the second test appeared to be about 10 times as great as in the first. The geology at the two sites appeared to be virtually identical. A possible explanation is that despite efforts to secure a tight seal around the monitoring devices, water may have leaked downward through one or more of the holes drilled to install monitoring devices at a rate higher than through the undisturbed soil. In addition, the slight decrease in infiltration rates after 10 days could be caused by wetting and swelling of the bentonite used to seal the holes, thereby reducing leakage through the holes. Special attention will be given to these problems in tests to be made during 1979.

CRITERIA FOR SUCCESSFUL ARTIFICIAL RECHARGE

Several criteria must be met if artificial recharge is to be successful: (1) a reasonably prolific aquifer must be present; (2) the aquifer must have unused storage to accept artificial recharge; (3) there must be a reasonably accessible source of recharge water; and (4) the recharge water must be of suitable quality.

A reasonably prolific aquifer must be present because there must be permeable strata present capable of accepting and yielding economically significant quantities of water. What is "reasonably prolific" will vary with many factors including the objectives of the water use. An aquifer that will not yield sufficient quantities of water for agricultural irrigation may yield sufficient quantities for domestic or municipal use.

Artificial recharge cannot be practiced unless there is a reasonably accessible source of recharge water. Many factors enter into a determination of what is "reasonably accessible". First, sufficient volume and

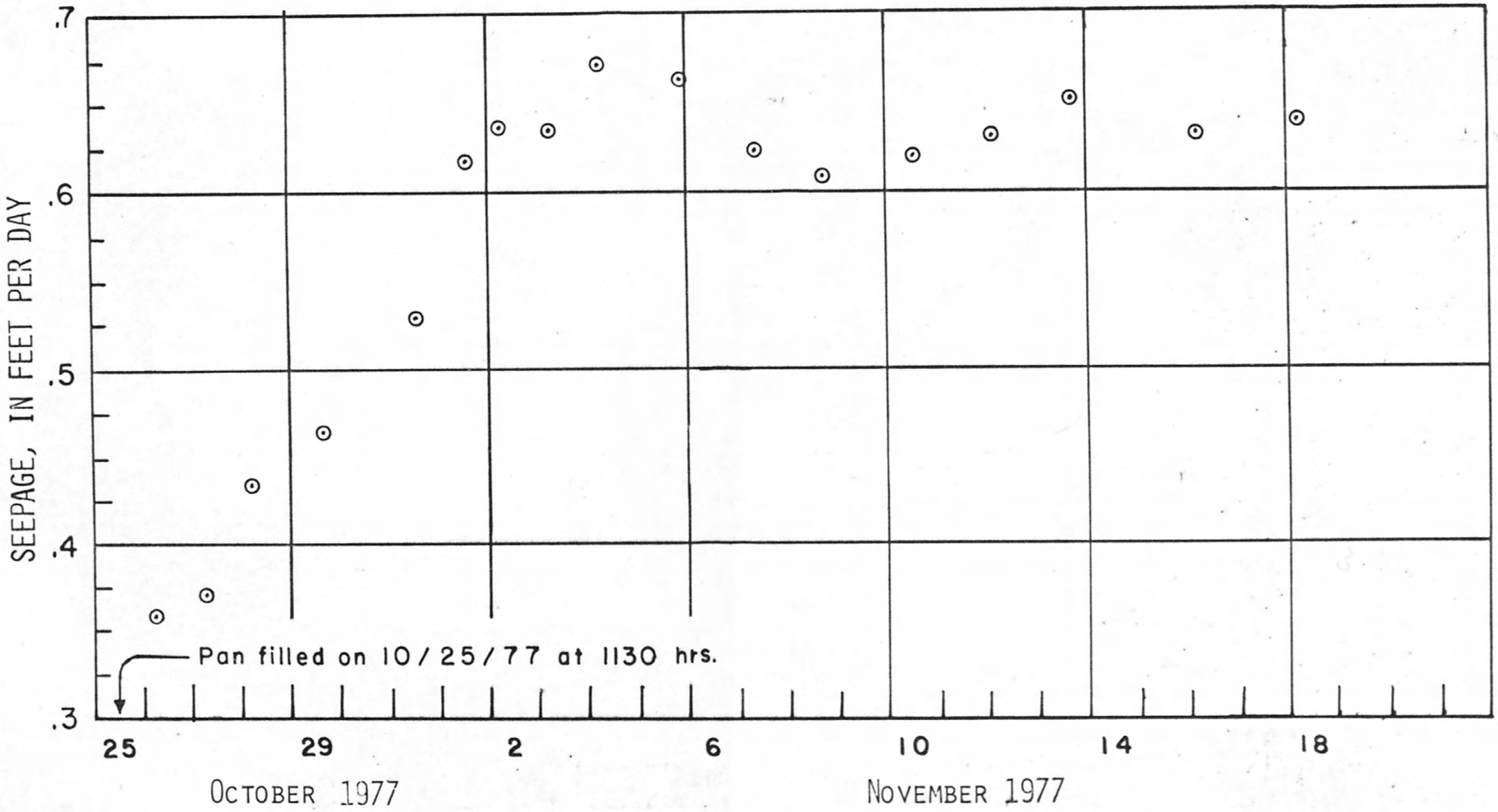


Figure 20.--Changes in seepage rate from 24-foot-diameter pan at recharge site near Aurora.

rate of flow to be practical must be available and the water must be considered surplus in the area of origin. To be considered surplus, the intended use of the water in the shortage area must have a significantly higher priority than the intended use in the area of origin. Second, the cost of transporting, recharging, and repumping the water must be equal to or less than the value of the water. The distance the water has to be transported is usually the most important factor. Third, the recharge water must be legally and socially accessible. In Nebraska, this might require modification of the present rulings on transbasin diversions and an educational program to reassure people in contributing areas that their interests will be protected.

The recharge water must be of suitable quality. Ideally, the water recharged into an aquifer should be of a quality at least as good as the usable water in the aquifer and compatible with that water. Water that is chemically incompatible with the native aquifer water, the aquifer material, or overlying materials may cause clogging problems. Suspended sediment, entrained air, and bacteria may also cause clogging problems. Water can be treated to make it acceptable for recharge, but extensive treatment is expensive and may render artificial-recharge operations economically unfeasible. The degree of treatment economically feasible may depend on the value placed on the recharged water.

Artificial recharge through wells

The four general criteria listed above for successful artificial recharge apply to artificial recharge through wells. The criterion that recharge water be of suitable quality is especially important because rehabilitation of a clogged well is often difficult or impossible. Comparison of the dissolved chemical constituents of the recharge water with those of the native water and the aquifer materials will usually determine if the recharge water is compatible. Inducing turbid recharge water to travel through a filter of several feet of sand and gravel before injection generally will solve most clogging problems associated with suspended sediment, bacteria, or entrained air.

Filtering of turbid substances can be accomplished most economically where a sand-and-gravel aquifer is in hydrologic connection with a surface source of water such as a river. Withdrawal from wells developed in the aquifer near the river will induce infiltration of river water toward the well. Periodic flood flows in the river will usually keep the infiltration surface of the river bed free of excessive buildup of sediment. Moderately turbid water can sometimes be successfully injected if the recharge wells are periodically pumped to remove sediment.

Recharge through wells (or pits extending to the aquifer) commonly is the only practical method of artificial recharge in areas where the aquifer is overlain by impermeable materials or where suitable surface or near-surface infiltrating basins are not available.

The advantages of well recharge over surface spreading are that it can be used regardless of confining layers above the aquifer; very little surface area is required; it usually is not restricted by freezing temperatures; and the water is delivered directly to the aquifer. The disadvantages are that water-quality requirements are high and capital costs may be high because of well construction.

Artificial recharge by surface spreading

The four general criteria listed previously for successful artificial recharge also apply to artificial recharge by surface spreading. An additional criterion is that the soil material between the surface and the aquifer must be sufficiently permeable to allow water to percolate rapidly to the aquifer. A minimum infiltration rate of 0.5 ft per day generally is considered essential to successful recharge operations. The quality of the recharge water usually is not as critical in surface-spreading operations as in well recharge. Infiltration surfaces are relatively large in comparison to well bores and the basins usually can be drained and cleaned periodically.

Slow seepage to the aquifer generally will remove suspended sediment and bacteria and allow entrained or dissolved gases to escape. Seepage is often used as a means of purifying polluted water.

The advantages of surface spreading over recharge through wells are lower water-treatment costs and lower capital expense. The disadvantages are that surface spreading is restricted to areas with no impermeable layers above the aquifer, and that relatively large surface areas are required. Water spreading also may be restricted by freezing conditions.

CONCLUSIONS

Data from artificial-recharge experiments at the Aurora site are still being collected so that conclusions are tentative and incomplete.

Previous tests and experiments in other States indicate that recharge through wells can be technically feasible if the water used is nearly free of suspended sediment or bacteria, if entrained air can be excluded from the recharge well, and if the water used is compatible chemically and physically with water in the aquifer.

Data obtained through December 1977 near Aurora, Nebr., indicate that water probably could be recharged to the Pleistocene aquifer through a single well at a rate of more than 3,000 gal/min for at least a year before the recharge well would need redevelopment.

Slight clogging of the aquifer in the vicinity of the recharge well appears to be occurring. The cause of the clogging is not known at this time, but sediment, bacterial action, or chemical reactions do not appear to be major causes; however, air entrainment resulting from interruptions of recharge due to power failures and bacterial action may be contributing factors. The reason or reasons why the water level in the recharge well is continuing to rise slowly while the water levels in the observation wells apparently have stabilized will be investigated in the second half of the project.

The apparent steady rate of infiltration of water into the soil through a 24-foot-diameter ring infiltrometer at Aurora, Nebr., was 0.04 ft/d in a test made in 1976. However, in a second test made in 1977, at an adjacent site, it was 0.66 ft/d. The two test sites were 100 feet apart and geologic conditions were nearly identical. The larger rate in 1977 may have been caused by leakage around subsurface monitoring devices installed for the 1977 test, whereas no monitors were installed for the 1976 test. Even though the holes drilled to install the monitoring devices were packed with bentonite in an attempt to prevent seepage down the holes, it is possible that leakage did occur.

Greater precautions to avoid short-circuiting the natural system by the installation of monitoring devices will be required for future tests. A second infiltration ring without monitoring devices will be installed near the test ring to be used as a control.

REFERENCES

Ellis, M. J., and Pederson, D. T., 1977, Groundwater levels in Nebraska, 1976: Nebraska Water Survey Paper 44, Conservation and Survey Division, The University of Nebraska-Lincoln, 96 p.

Brown, D. L., and Silvey, W. D., 1977, Artificial recharge to a freshwater-sensitive brackish-water sand aquifer, Norfolk, Virginia: U.S. Geological Survey Professional Paper 939, 53 p.

Gardescu, I. I., 1930, Behavior of gas bubbles in capillary spaces: American Institute of Mining and Metallurgical Engineers, Technical Publication 306.

Keech, C. F., 1962, Ground-water resources of Hamilton County, Nebraska: U.S. Geological Survey Water-Supply Paper 1539-N, 64 p.

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

Lugn, A. L., 1935, The Pleistocene geology of Nebraska: Nebraska Geological Survey Bulletin 10, 213 p.

Reeder, H. O., 1975, Injection-pipe system for artificial recharge: U.S. Geological Survey Journal of Research, v. 3, p. 501-503.

Singleton, Roy A., 1966, Artificial recharge of the Dakota Sandstone aquifer through a production well: Nebraska University graduate college thesis, 111 p.

Smith, W. O., and Crane, M. D., 1930, The Jamin effect in cylindrical tubes: American Chemical Society Journal, v. 52, p. 1345-49.

Sniegocki, Richard T., 1963a, Geochemical aspects of artificial recharge in the Grand Prairie Region, Arkansas: U.S. Geological Survey Water-Supply Paper 1615-E, 41 p.

_______ 1963b, Problems in artificial recharge through wells in the Grand Prairie Region, Arkansas: U.S. Geological Survey Water-Supply Paper 1615-F, 25 p.

Weeks, E. P., 1977, Field determination of vertical permeability to air in the unsaturated zone: U.S. Geological Survey Open-file Report 77-346, 171 p.