INVESTIGATION OF ARTIFICIAL RECHARGE OF AQUIFERS IN NEBRASKA

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations 80-93

Prepared in cooperation with

OLD WEST REGIONAL COMMISSION

NEBRASKA WATER RESOURCES CENTER,
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Large withdrawals of ground water for irrigation are causing progressive declines of ground-water levels in some areas of Nebraska. An investigation was conducted to determine the technical feasibility of artificially recharging aquifers through wells and by surface spreading. The experiments showed that large quantities of water can be recharged through wells and by surface spreading if conditions are favorable. In the well experiments, about 0.5 billion gallons of water was withdrawn from a well near the Platte River and recharged through a well into a Pleistocene sand and gravel aquifer near Aurora where ground-water levels are declining. The recharge rate was about 730 gallons per minute during two tests of 6 and 8 months duration. There was no evidence of clogging due to chemical reaction, air entrainment, or bacterial growth. Some clogging of the aquifer did occur in the immediate vicinity of the recharge well due to a small amount of fine sediment in the recharge water. Analysis of water-level buildup in the recharge well during the 6-month test indicated that recharge could have continued at a rate of about 700 gallons per minute for several years before rehabilitation of the recharge well would have been necessary. Infiltration rates from surface-spreading experiments ranged from 0.5 feet per day in loess-covered plain to 11 feet per day in sandhills. Perching layers of low permeability existed at each site and could cause problems in recharging.

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

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PREFACE

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, succeeded by Dr. Gary L. Lewis as Acting Director of the Nebraska Water Resources Center, were project directors; William F. Lichtler, U.S. Geological Survey, was the 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 surface-spreading 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.

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)
bushel (bu) (U.S.)	0.03524	cubic meter (m^3)
foot (ft)	0.3048	meter (m)
square foot (ft^2)	0.0929	square meter (m^2)
square foot per day (ft^2/d) (transmissivity) $(ft^3/d)/ft$	0.0929	square meter per day (m^2/d) $(m^3/d)/m$
cubic foot (ft^3)	0.0283	cubic meter (m^3)
cubic foot per second (ft^3/s)	28.32	liter per second (L/s)
gallon (gal)	0.003782	cubic meter (m^3)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
inch (in.)	25.4	millimeter (mm)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.590	square kilometer (km^2)
pound (lb)	0.4536	kilogram (kg)
pound per square inch ($lb/in.^2$)	6895	pascal (Pa)
degree Fahrenheit (°F)	(°F -32)0.556	degree Celsius (°C)

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INVESTIGATION OF ARTIFICIAL RECHARGE OF GROUND WATER IN NEBRASKA

BY

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

ABSTRACT

Large withdrawals of ground water for irrigation are causing progressive declines of ground-water levels in some areas of Nebraska. An investigation was conducted to determine the technical feasibility of artificially recharging aquifers through wells and through surface spreading by means of impoundments, pits, and canals. Information gained from a literature search and from preliminary tests was used to design several artificial-recharge experiments. The experiments showed that large quantities of water can be recharged through wells and by surface spreading if conditions are favorable.

In the well experiments, about 0.5 billion gallons of water from an aquifer recharged by the Platte River was transported 3 miles by pipeline and recharged through a well into a Pleistocene sand and gravel aquifer near Aurora where ground-water levels are declining. The recharge rate was about 730 gallons per minute during two tests of 6 and 8 months duration. The rise in ground-water levels due to recharge extended more than a mile from the recharge well in both tests.

The pattern of ground-water-level buildup during the 8-month test was similar to that during the 6-month test. Two-thirds of the way through the test the rate of water-level buildup in the recharge well increased greatly because casing failure allowed a large amount of sediment to enter the well.

Although the chemical quality of the recharge water was markedly different from that of the native aquifer water, no evidence of clogging due to chemical reaction was detected; also, there was no evidence of clogging due to air entrainment or bacterial growth. Evaluation of water-level changes in the recharge well and in observation wells during the 6-month test indicated some clogging of the aquifer in the immediate vicinity of the recharge well due to a small amount (0.04 milligram per liter) of fine sediment in the recharge water. Analysis of water-level buildup in the recharge well during the 6-month test indicated that recharge could have continued at a rate of about 700 gallons per minute for several years before rehabilitation of the recharge well would have been necessary.

In surface-spreading experiments, the maximum sustained infiltration rates from a 24-foot-diameter ring infiltrometer set in loess at the well-recharge site near Aurora were about 0.5 foot per day during a 140-day test. The recharge water caused water levels in a perched zone of saturation at depths between 36 and 38 feet to rise 15 feet, to within 21 feet of the surface, indicating that if the test had continued or if the impoundment area had been larger, the water level in the perched zone of saturation might have risen to the surface thereby reducing the infiltration rate.

The maximum sustained infiltration rate from a similar experiment in the Sand Hills near Tryon was 11 feet per day. Perching layers also retarded downward infiltration and caused lateral movement of water in the subsurface at this site.

Infiltration rates from re-use pits near the Aurora site ranged from 0.01 to 1.60 feet per day, indicating that the permeability of the subsurface material is extremely variable and that perching layers probably are absent in some areas.

Flow measurements in an irrigation canal excavated in loess near Farwell indicate an infiltration rate of 0.36 foot per day from a 2.7-mile reach.

INTRODUCTION

Ground-water levels are declining progressively in many aquifers in Nebraska (Pederson and Johnson, 1979). If this trend continues, the yields of wells in these aquifers eventually will become inadequate for municipal, irrigation, or industrial uses. If this occurs, many wells completed in the upper parts of the aquifers will become dry, and the economic impact of the depletion of ground-water resources will be severe in many areas.

The cause of progressive declines of ground-water levels is a long-term excess of withdrawal compared with recharge. Such declines can be corrected by reducing withdrawals, by capturing natural discharge, by increasing recharge, or by a combination of these methods. This report discusses only methods of increasing recharge.

Purpose and Scope

The purpose of this investigation was to assess the feasibility of various artificial methods of increasing aquifer recharge, particularly methods that might be applicable to Nebraska. The primary objectives of the investigation were:

(1) to document and evaluate existing recharge systems through literature review;

(2) to develop criteria for determining sites where artificial recharge may be feasible;

(3) to assess 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.

To accomplish these objectives and the purpose of the investigation, a literature search of reports on artificial recharge was made and persons working on artificial-recharge projects were contacted. Also, experiments were conducted at sites typical of widespread areas where increased recharge is needed or likely to be needed in the future. The well-recharge experiment was designed to obtain detailed information on the extent of the area affected by a recharge well, quantities of water that could be recharged, problems that might inhibit recharge, and recharge techniques most likely to be practical. The surface-spreading experiments were designed to determine infiltration rates under differing conditions, variation of rates with time, and information on the movement of the water after it infiltrates the land surface.

During the first 2 years of this investigation, documentation and evaluation of existing recharge systems and development of criteria for determining sites where artificial recharge may be feasible virtually were completed (Lichtler and others, 1979). Preliminary tests were made to select appropriate test sites for experimental artificial recharge facilities. Construction was begun at sites near Aurora and Tryon, Nebr. Long-term experiments were begun at the Aurora site.

During the second 2 years of this investigation, several well-recharge tests, including tests of 6 and 8 months duration, were made. Records of water-level buildup and water-quality characteristics were obtained from the recharge well and from observation wells located from 2 inches to nearly a mile from the recharge well.

Recharge by surface spreading was studied at facilities installed near Aurora and near Tryon, in an existing canal in the Farwell Irrigation District, and in several reuse pits near the Aurora site.

Methods of Artificial Recharge

Artificial recharge may be accomplished by direct or indirect methods. The two most common direct methods are recharge through wells and surface spreading.

Recharge through wells is used commonly 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 of water from the surface to the aquifer usually is too low for recharge by surface spreading to be feasible. Also, well recharge may be the only feasible method of artificial recharge where little land is available.

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 depends 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 cleaned by scraping, plowing, or disking to reestablish the permeability of the surface materials. Use of the recharge-spreading basins generally is an economical method of artificial recharge where there are no low-permeability layers between the land surface and the aquifer.

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

Indirect methods of artificial recharge involve 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 level 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.

Factors Affecting Recharge by Wells

Most of the problems in recharging through wells, especially in aquifers composed of fine-grained material, involve excessive buildup of water levels in the recharge well because of clogging of the well screen or aquifer. If the recharge water is not low in suspended solids, air, and microorganisms, and is not chemically compatible with the natural ground water and the aquifer material, clogging can cause a recharge operation to be infeasible.

Under ideal conditions a well will accept recharge water at least as readily as it will yield water by pumping. 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 in the well, and 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 pumping. Actual conditions, however, are seldom ideal. Factors in nature that alter the ideal conditions in regard to artificial recharge through wells include differences in the physical and chemical quality and temperature between the recharge water and the native water, rearrangement of the gravel-pack material or the aquifer material near the well because of changes in direction of flow, and changes in aquifer response caused by changes in saturated thickness of the aquifer during pumping and recharge operations. Buildup of water levels in recharge wells is usually, but not always, greater than corresponding drawdowns during pumping.

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

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

(2) Entrained air in the recharge water, which is 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 both of the following (Sniegocki, 1963a, p. 7): simple blocking of the air bubbles by sand grains; and the Jamin effect (Smith and Crane, 1930; Gardescu, 1930). The Jamin effect results from the fact that a capillary tube which contains restrictions and is filled with a chain of alternate air bubbles and water is capable of sustaining a finite pressure gradient without allowing fluid movement. A sand-and-gravel aquifer probably acts as a series of interconnected capillary tubes containing many restrictions and the forces created by the Jamin effect prevent the movement of the entrained air after it has been introduced into the aquifer.

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

Gas may be liberated from solution if the recharge water is warmed by contact with the native ground water, resulting in clogging similar to that caused by air entrainment. If the two waters are approximately the same temperature or if the recharge water is warmer than the ground water, this is usually not a problem.

(3) Microbial growth in a well. Such growth produces slimes or other products that can clog recharge wells and aquifers. The effects of these products are similar to those of suspended sediment in reducing the transmissivity of the aquifer and increasing water-level buildup in the recharge well. Ground water normally is nearly free of microbes and should not clog the well by microbial growth during recharge unless it is contaminated during transit to the recharge well.

(4) Chemical reactions between the recharge water and the native ground water, the aquifer material, or both. Such reactions can cause precipitation of insoluble matter that can clog the screen, the pores of the aquifer, or both. The effects of the precipitate are similar to those of suspended sediment in clogging the well and aquifer, reducing the transmissivity of the aquifer and thereby causing greater than normal buildup of water levels in the recharge well.

The chemical reactions causing precipitation commonly are complex and temperature sensitive. A knowledge of the dissolved chemical constituents of the native and recharge waters and their chemical equilibra, the water temperatures, and any changes in the composition of the waters with time are necessary to accurately predict potential problems from chemical precipitation.

(5) Ionic 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. When freshwater is recharged into an aquifer containing saline water the ion concentration of the native water is decreased, reducing the electrostatic attraction between the clay particles and permitting them to disperse and form a nearly impermeable barrier near the well bore. Reduction of the ionic concentration during an artificial recharge experiment at Norfolk, Va., apparently caused a 90-percent reduction in the specific capacity of a recharge well after just 6 days of operation. The recharge water came directly from the city of Norfolk's distribution system and had a very low salinity and sediment content (Brown and Silvey, 1977).

(6) Iron precipitation. Such precipitation can occur in a well if iron-rich water is aerated or exposed to other oxidizing conditions. Soluble ferrous iron is oxidized to the insoluble ferric form. The resulting iron compounds 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-reducing 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 greater viscosity than the native water. This greater 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.

Factors that can cause the buildup of water levels in the recharge well to be less than the corresponding drawdown in a discharging well include the following:

(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 the higher water levels that result when a water-table aquifer is recharged;

(3) Recharge water that is unsaturated with respect to calcium carbonate. Such water can dissolve parts of a carbonate aquifer or calcium carbonate in a sand-and-gravel aquifer, thereby increasing the size of the pores and channels and increasing the transmissivity and storage capacity of the aquifer. Other chemical reactions also may 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, during a period of years they could become significant.

Factors Affecting Recharge by Surface Spreading

Recharge by spreading basins is most effective where there are no impeding layers between the land surface and the aquifer and where clear water is available for recharge; however, a more turbid water can be tolerated than with well recharge. The most common problem in recharging by surface spreading is clogging of the surface material by suspended sediment in the recharge water, by microbial growth, or by both. 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 scarification. Clogging of the surface by microbial growth can usually be controlled by allowing the basin to dry periodically, which will then allow the organic material to oxidize. This practice requires the basin to be inoperative for varying lengths of time.

History and 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, Great Britain, and Spain. 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 also is practiced to keep saltwater from intruding freshwater aquifers. In England, intermittent percolation through soil helps to purify river water that is as much as one-third wastewater effluent. Israel has reclamation projects that use percolation to process wastewater from the city of Tel Aviv. Israel also is a leader in the use of wells for recharge.

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 ground-water levels were noted, people have been concerned about depleting the ground-water resources and have been looking for ways to augment natural recharge.

The current investigation was an outgrowth of 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. Some of the objectives of the UBBNRD study were incorporated into this current study. Work elements were assigned to avoid duplication and to allow personnel assigned to each study to concentrate in greater detail on their assignment.

Well-recharge systems in Nebraska

The only previous scientific well-recharge experiment in Nebraska was made in the Lincoln well field, Lincoln, Nebr., by Singleton (1966) as his Master of Science 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 Dakota Sandstone underlying the Lincoln well field was physically feasible and that this recharge would depress and displace saltwater in the aquifer. Prolonged pumping in the field had induced saltwater to move into the producing wells from deeper and more westerly parts of the aquifer. The principal water supply of Lincoln is now (1979) 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.

Five aquifer tests consisting of 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-ft) of water was recharged during the tests at a rate of about 420 gal/min. The longest continuous injection was 24 days. Pumping tests were made before and after the recharge tests and no change in transmissivity of the aquifer was detected. This indicated that little or no clogging occurred in the aquifer away from 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 was 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 chemically 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 liquefaction 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 with modifications 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 during 1977 and have been redeveloped periodically to remove accumulated sediment.

A second cooling-water recharge operation is located at an anhydrous ammonia plant 0.5 mi 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 million gallons 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 systems in Nebraska

There have been no significant surface-spreading operations solely for recharge in Nebraska prior to the current (1977-79) 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, locally known as the Tri-county area. Ground-water levels in the Tri-county area rose as much as 99 ft between 1940 and 1978 (Pederson and Johnson, 1979, p. 70). This type of artificial recharge also occurs in Lincoln County, 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 increase evapotranspiration losses, cause water logging of the land, and pollute ground water. Lining canals can help where seepage causes problems.

Conjunctive use of water, whereby seepage 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.

DESCRIPTION OF EXPERIMENTAL SITES

Although many reports on artificial recharge have been written, most deal with conditions significantly different than those in the selected sites in Nebraska. The experiments conducted as part of this investigation were designed to determine, under conditions typical of large areas, the rates at which water can be recharged through wells or through surface-spreading techniques, how these rates change with time, and physical problems that might develop during extended periods of recharge. Such information is needed by planners who must evaluate the economic feasibility of artificial recharge, and its applicability in areas where conditions are similar to those in the selected sites.

Only one site was selected for well-recharge experiments, partly because of expense and partly because the composition of the major aquifers in Nebraska tend to be somewhat uniform. This tends to make results of the experiments readily transferable to other areas. Two sites were selected for surface-spreading experiments. One was in the plains and dissected plains region and one was in the Sand Hills region. Locations of the sites are shown in figure 1.

The materials above the aquifers are much different in the two regions and consequently present different hydrologic conditions. Together, the regions comprise more than one-half of the area in Nebraska; therefore, data obtained in the experiments should have broad application.

Aurora Site

The experimental artificial-recharge site located near Aurora, Nebr., was used for well-recharge and surface-spreading experiments to determine the technical feasibility of the methods. The Aurora site is in east-central Nebraska in Hamilton County, in the Nebraska Plain (Lugn, 1935). The general physiography of this county 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

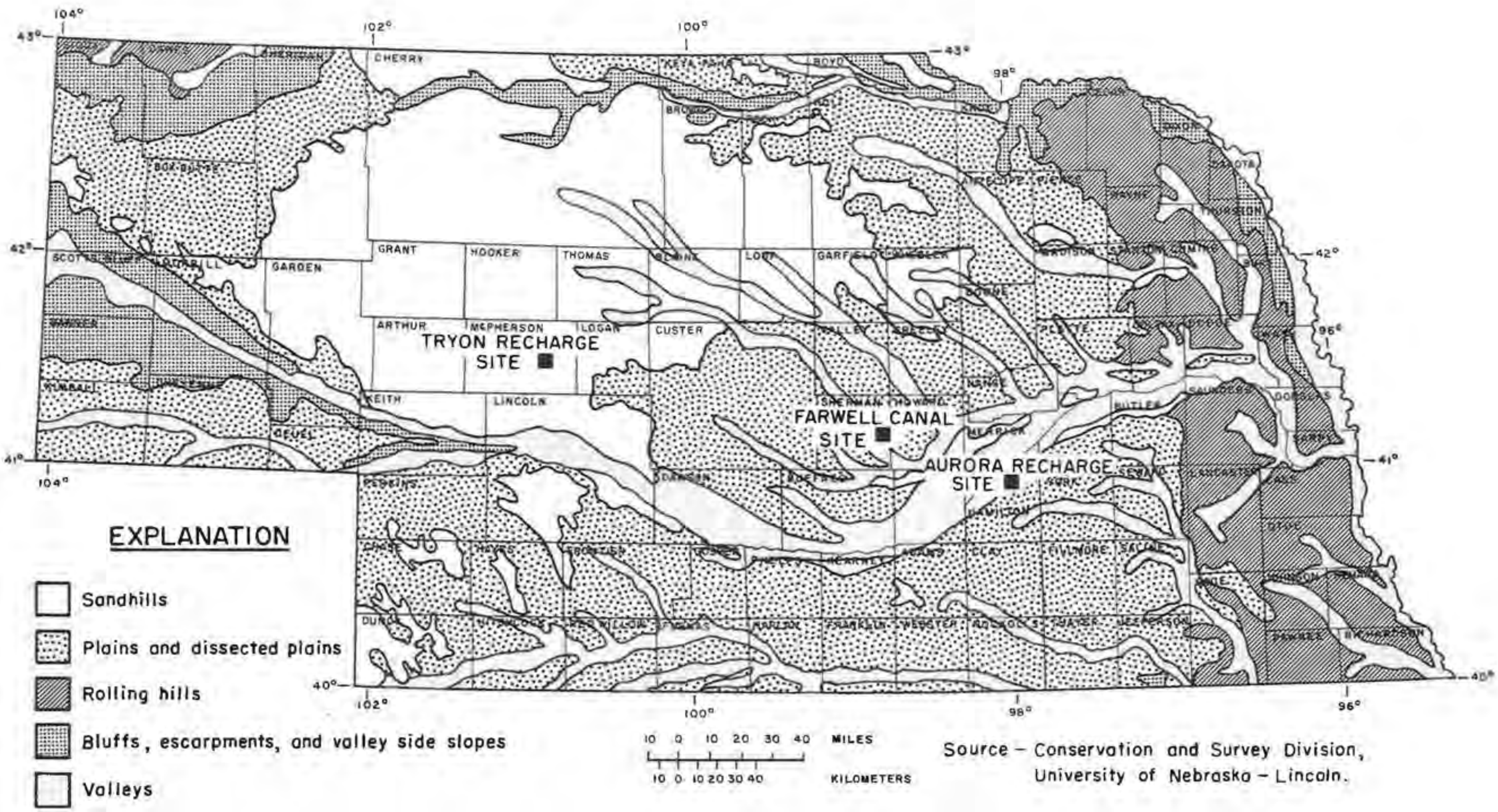

Figure 1.--Location of experimental sites in relation to topographic regions of Nebraska.

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 site, which includes both the withdrawal well and the recharge well, is on the upland in the Big Blue River basin near its divide with the Platte River basin (fig. 2). The withdrawal well is very near the divide between the basins and within 0.5 mi of the Platte River. This site was selected for the withdrawal well because it is typical of areas where the Platte River is in hydrologic connection with the Pleistocene sand-and-gravel aquifer.

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

Land surface altitude at the withdrawal-well site is approximately 1,871 ft, or about 86 ft above river level (fig. 3). The recharge well is 3 mi east of the withdrawal well. The altitude at this well is approximately 1,847 ft, or 24 ft lower than at the withdrawal well. 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 caused by large withdrawals for irrigation in the Big Blue River basin (fig. 4). However, chemical analyses of ground-water samples at the recharge-well site were very different from Platte River water, indicating that river water either had not yet displaced native water or it had been greatly modified in transit.

A generalized lithologic log (fig. 5) 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 and sandy silt; 75-90 ft, medium quartz sand; 90-200 ft, mostly medium to very coarse sand, plus varying amounts of gravel; 200-250 ft, fine sand with layers of sandy silt, medium sand, and gravelly sand. Lithologic and geophysical logs of the recharge-well site were used to locate accurately the depths of the contacts between aquifer and nonaquifer materials to ensure proper emplacement of the well screen.

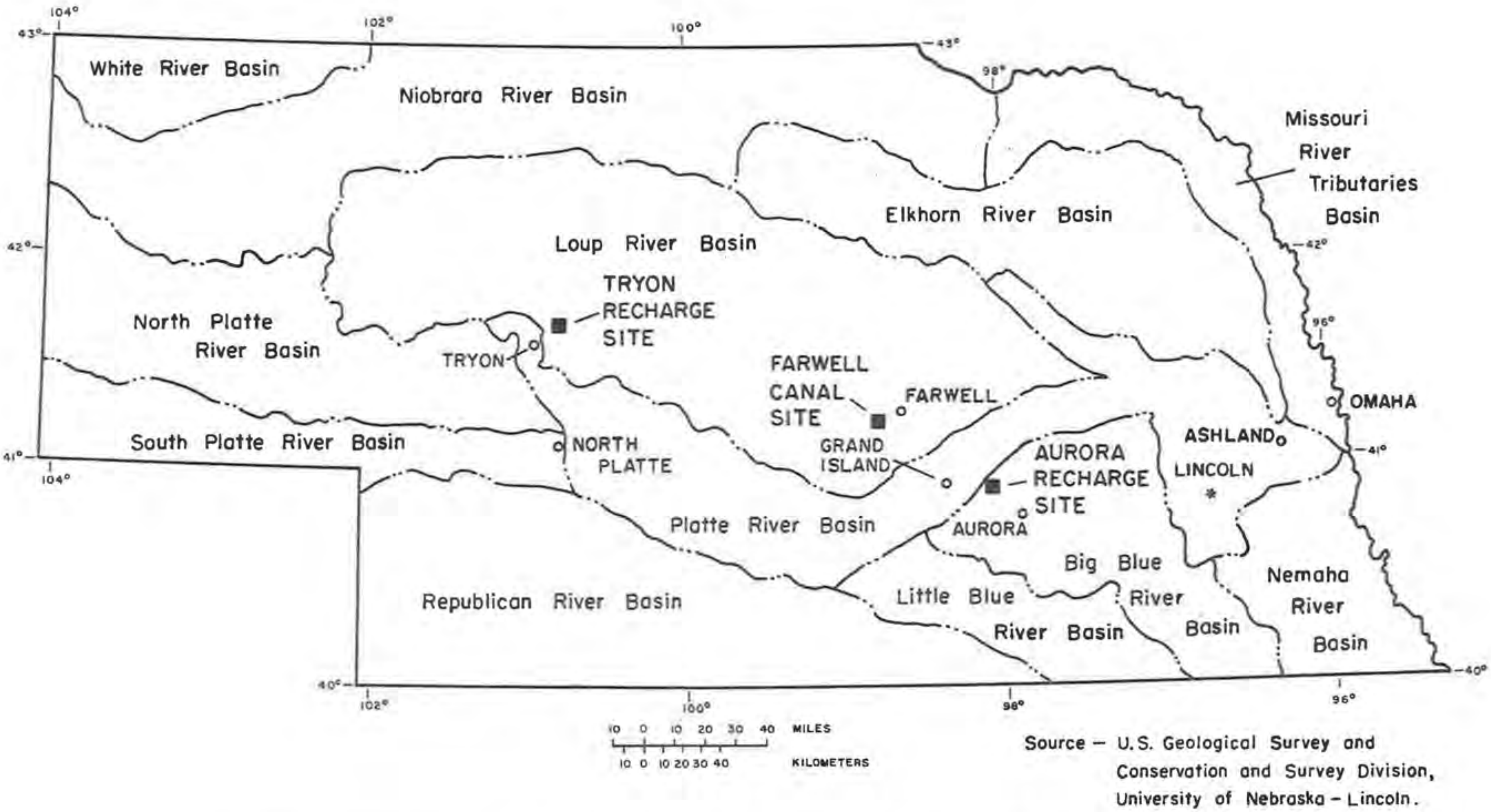

Figure 2.--Locations of recharge sites in relation to drainage basins of Nebraska.

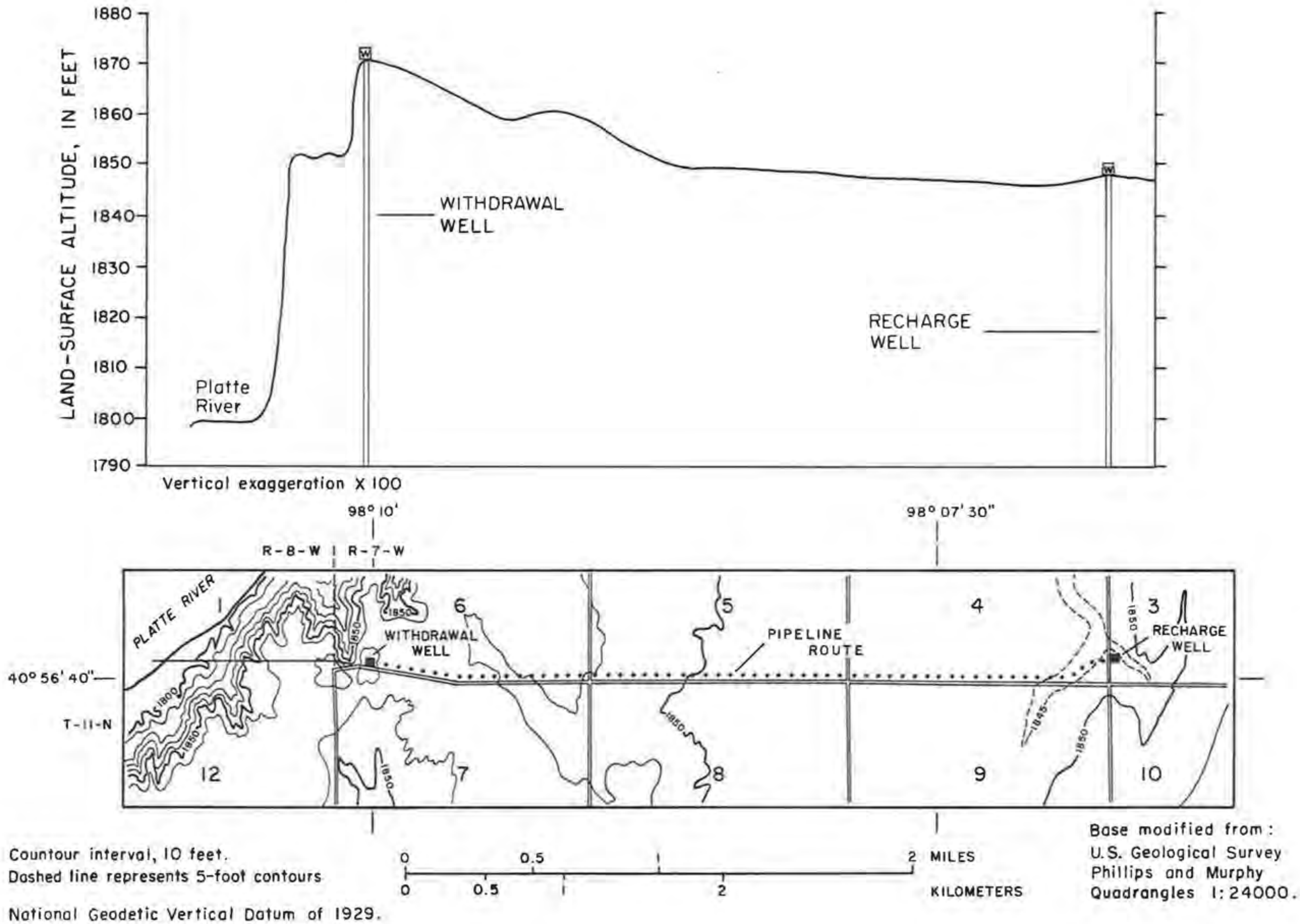

Figure 3.--Land-surface altitude and route of pipeline used in artificial-recharge experiment near Aurora.

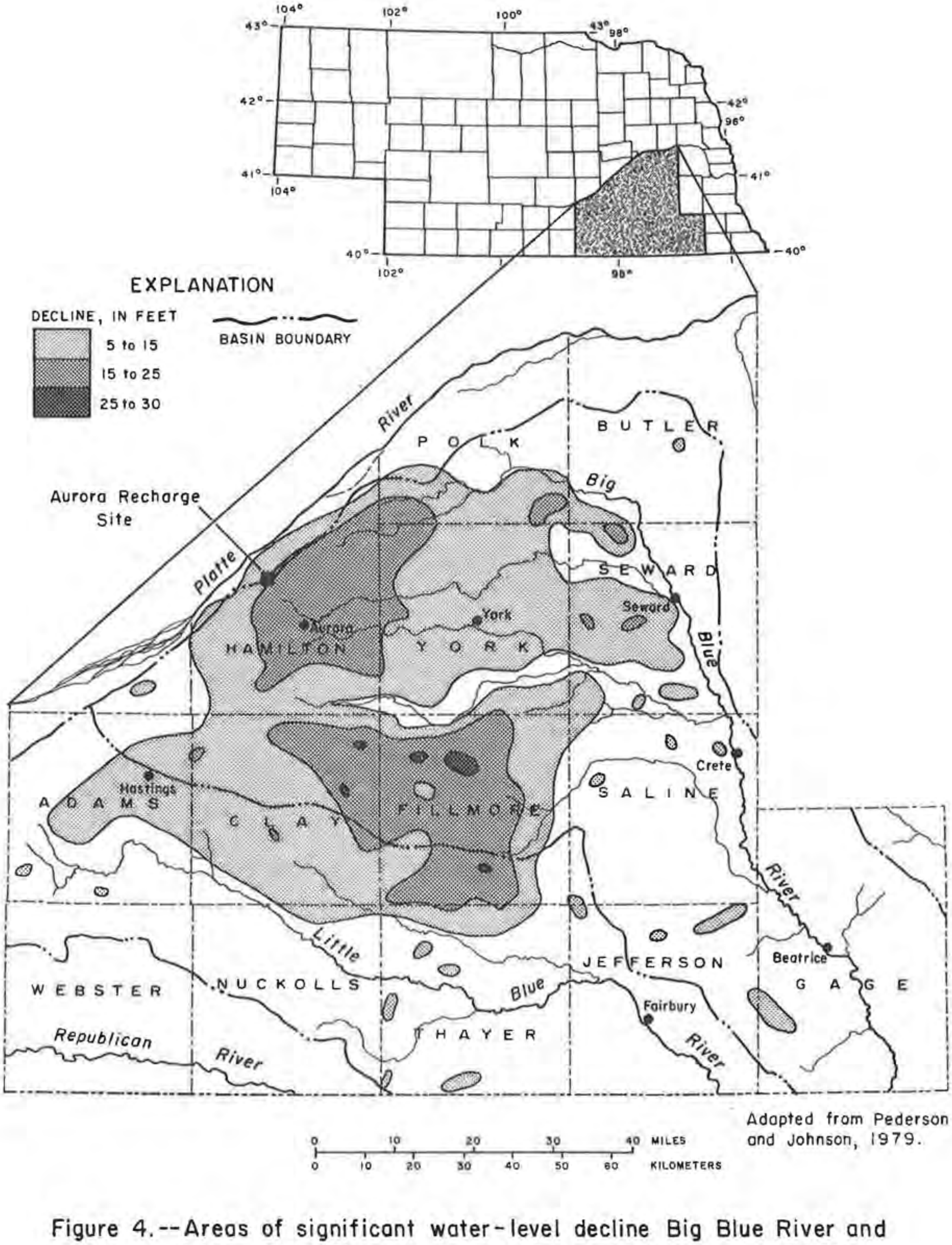

Figure 4.--Areas of significant water-level decline Big Blue River and Little Blue River basin area from 1950 to spring 1978.

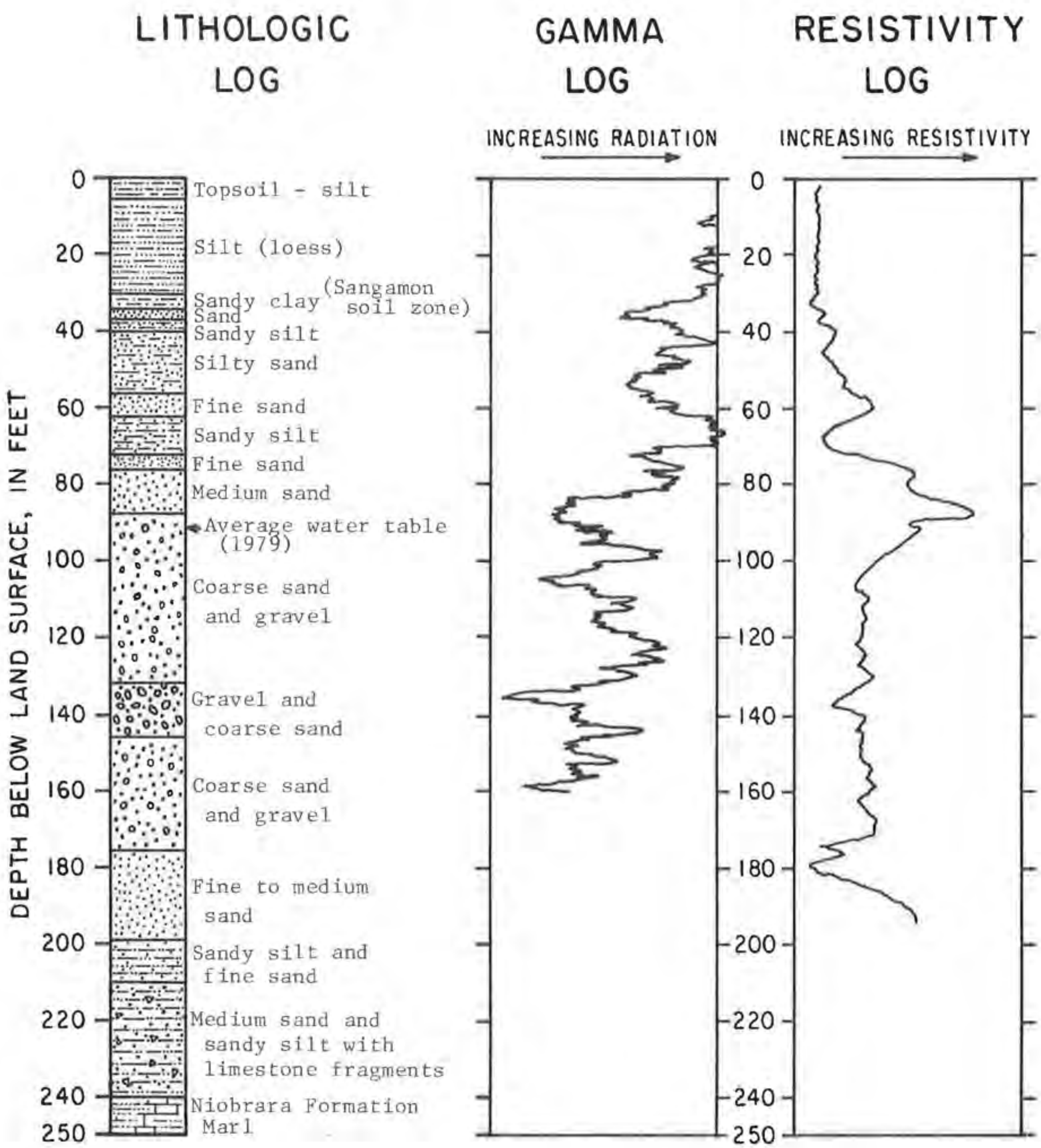

Figure 5.--Generalized lithologic and geophysical logs of permanent artificial-recharge site near Aurora.

Tryon Site

A second experimental artificial-recharge site involving surface spreading was located at the University of Nebraska Sand Hills Agricultural Laboratory near Tryon in west-central Nebraska. The Tryon site is in the Sand Hills region (Lugn, 1935) that includes most of north-central Nebraska (fig. 1) and extends a short distance into South Dakota. The surface topography of the region is mostly sand dunes stabilized by a grass cover. Viewed from the air, most of the Sand Hills region appears to be a choppy sea, each hill resembling a wind-driven wave (Keech and Bentall, 1971). Interspersed among the dunes are flat-floored valleys. The sand that forms the dunes and that floors the interdune valleys constitutes a nearly continuous deposit.

The Ogallala Formation of late Tertiary age underlies the entire Sand Hills region and consists of interlayered stream sediments, lake-bed deposits, and possibly windblown sediments with a total thickness of several hundred feet in some places. At the Tryon experimental site, the top of the Ogallala Formation is approximately 300 ft below the land surface. The principal water-bearing zone used in the area is just above the Ogallala between 270 and 300 ft below the land surface. The static water level is about 120 ft below the land surface. The material from the land surface to the aquifer is fine to medium sand with a semi-consolidated sandstone layer at 90 ft below the land surface (fig. 6).

EXPERIMENTS IN RECHARGE THROUGH WELLS

Major emphasis during the investigation was placed on well-injection methods of artificial recharge. This was done because of the interest of many people, including farmers, politicians, scientists, and manufacturers, in well recharge in Nebraska.

Selection of Permanent Site

Preliminary tests were made during 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.

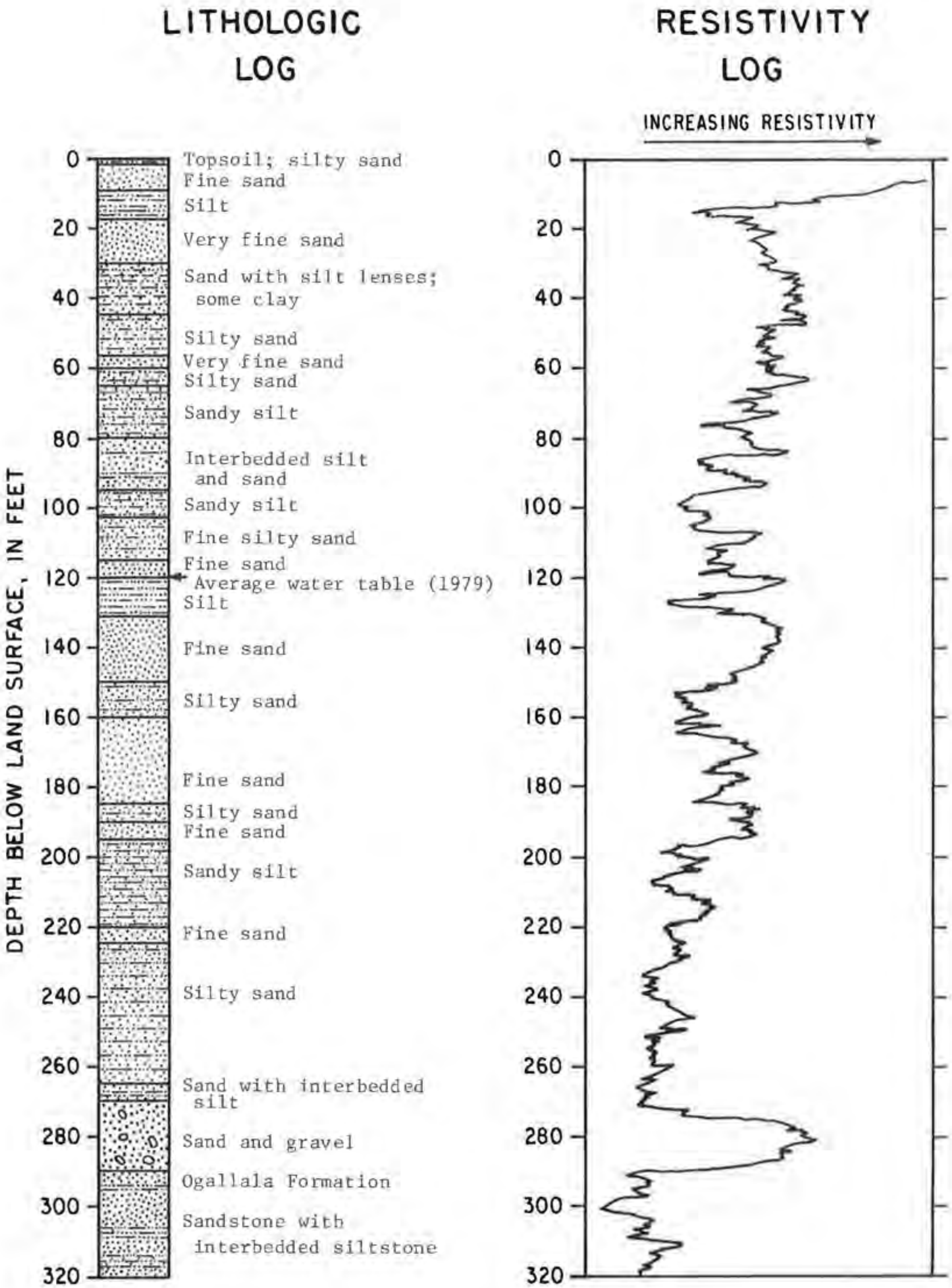

Figure 6.--Generalized lithologic and geophysical logs of Sand Hills site, Tryon.

The Big Blue River basin in southeastern Nebraska was selected as a preliminary 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; 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 similar 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 during November 17-18, 1975, to determine the characteristics of the recharge well and the surrounding aquifer. An explanation of pumping tests is included in a later section titled "Testing the System." Observation wells to monitor water levels were installed at distances of approximately 8, 66, and 200 ft from the recharge well and a water-level recorder was installed on an unused irrigation well 0.25 mi from the recharge well. Sediment, bacteria, and dissolved-chemical concentrations of the water from the recharge well were monitored to provide background information prior to the test.

The supply well was connected to the recharge well with 10-inch irrigation pipe. More than 1 million gallons of water chemically similar to Platte River water was injected into the aquifer during December 3-5. Water levels and quality of the injection water were monitored as during the pumping test. The water level in the recharge well increased rapidly during the first several hours of the test but then nearly stabilized (fig. 7). If clogging of the aquifer or screen had been a major problem, the water level in the injection well would have continued to build up throughout the test.

A post-injection pumping test was made during 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 similar in shape and roughly proportional to the graph of drawdowns from the pumping tests (fig. 8). Comparison of results of the post-injection (December 9-10) pumping test with those of the preinjection (November 17-18) pumping test (table 1) indicate that the transmissivity had not changed significantly.

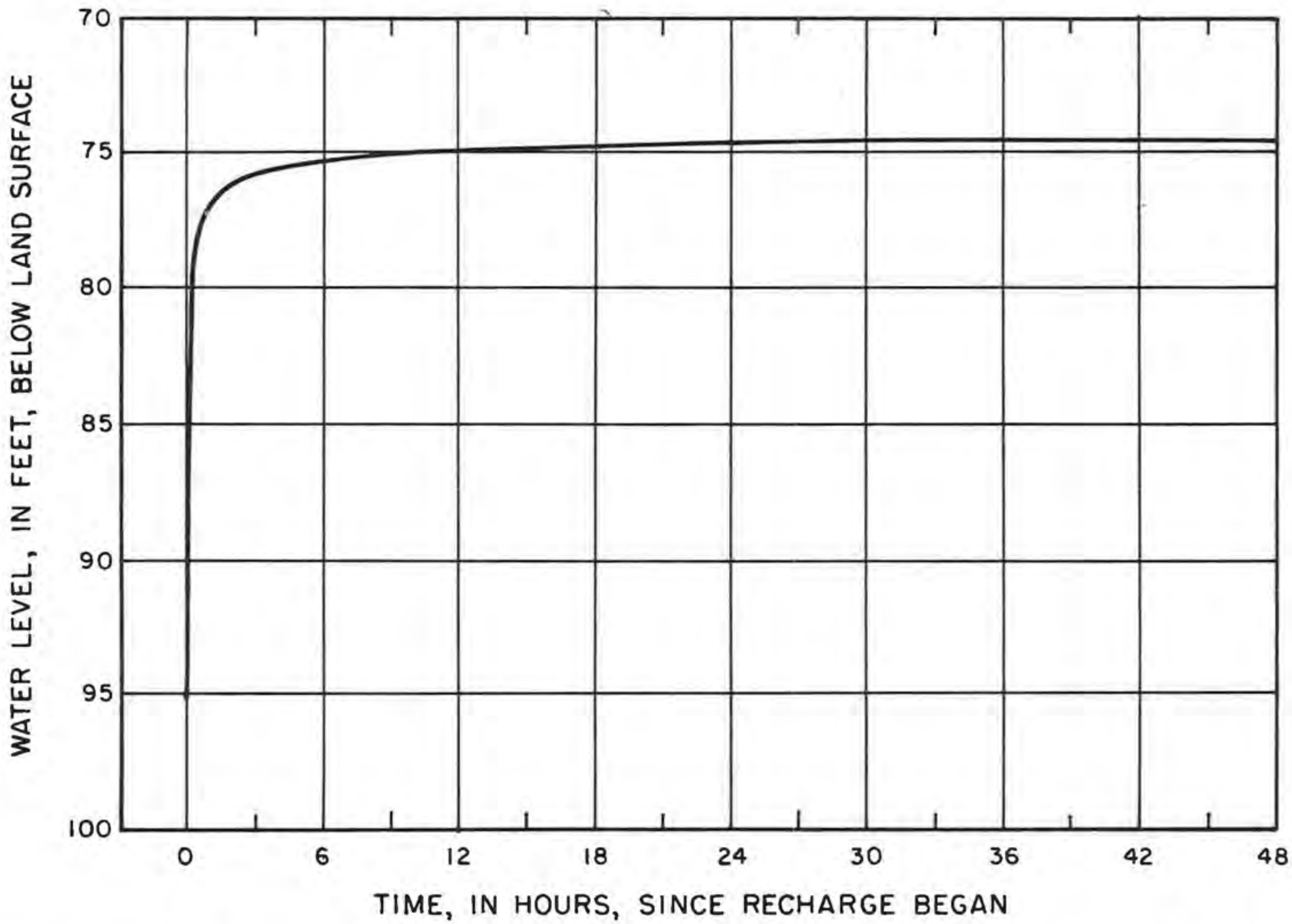

Figure 7.--Buildup of water levels in recharge well at preliminary test site near Aurora, December 3-5, 1975

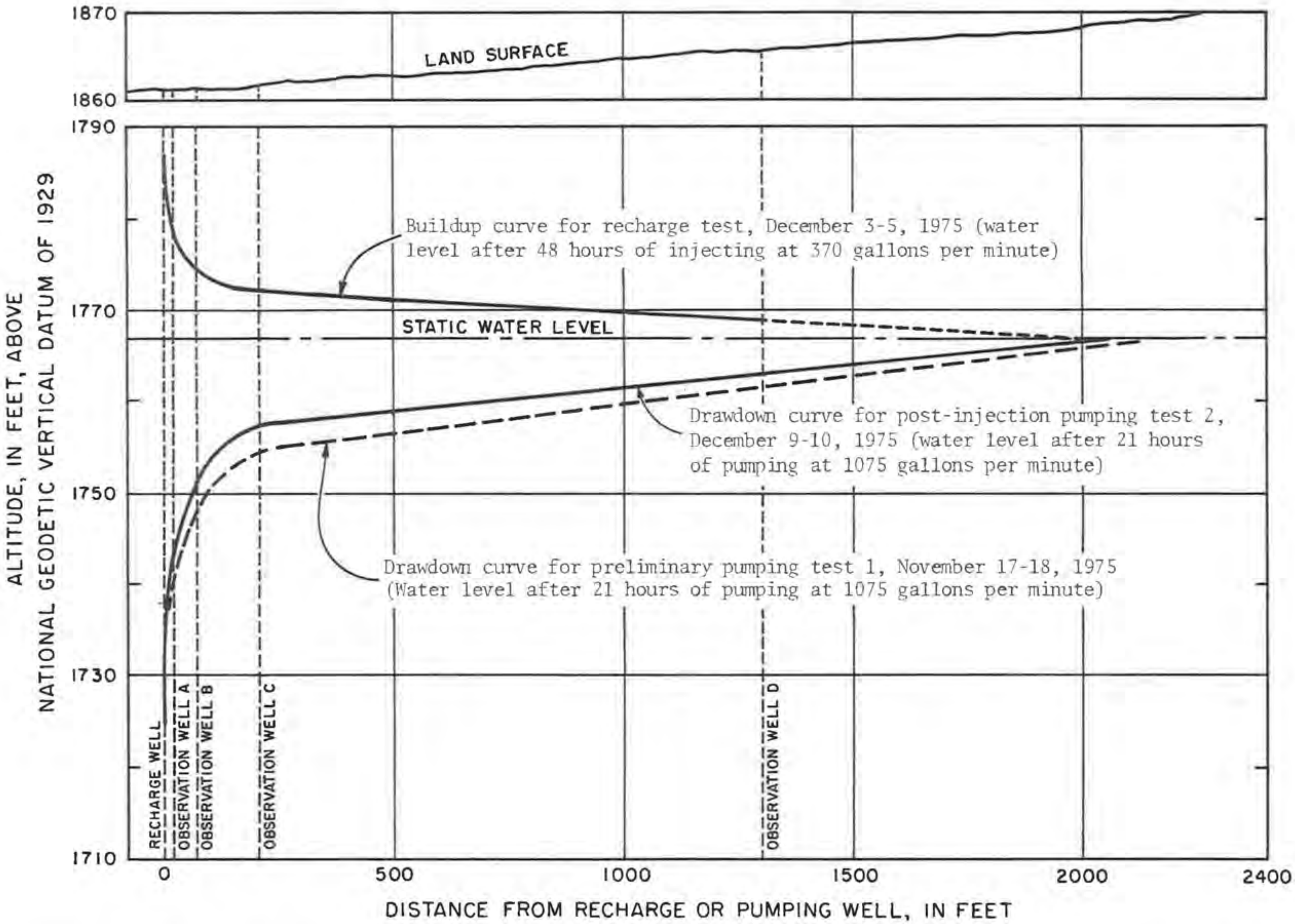

Figure 8.--Comparison of water-level changes during pumping and recharge tests at peliminary test site near Aurora.

Table 1.--Results of aquifer tests at preliminary test site near Aurora

Well designation	Screened interval (ft)	Distance from pumped well (ft)	Transmissivity[1] (ft^2/d)	Storage coefficient[2]	Maximum drawdown (ft)	Maximum buildup (ft)
Pumping test 1 - November 17-18, 1975, recharge well pumped 21 hr at 1,065 gal/min						
Recharge	110-220	0	-----	-------	----	----
Observation A	173-176	8	6,800	0.0003	26.8	----
Observation B	173-176	66	6,800	.0003	16.6	----
Observation C	173-176	200	7,100	.0003	11.2	----
Recharge test - December 3-5, 1975, recharge well injected 48 hr at 370 gal/min						
Recharge	110-220	0	-----	------	----	18.9
Observation A	173-176	8	6,600	0.0001	----	11.2
Observation B	173-176	66	6,700	.0002	----	7.0
Observation C	173-176	200	6,900	.0002	----	4.8
Pumping test 2 - December 9-10, 1975, recharge well pumped 21 hr at 1,055 gal/min						
Recharge	110-220	0	6,600	------	45.4	----
Observation A	173-176	8	6,900	0.0003	26.3	----
Observation B	173-176	66	6,800	.0005	15.9	----
Observation C	173-176	200	6,800	.0005	9.9	----

[1] The rate at which water is transmitted through a unit width of the aquifer under a unit hydraulic gradient at the prevailing temperature.

[2] The volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in hydraulic head.

Analyses of the pumping-test data were made by use of leaky-aquifer type curves (Lohman, 1972, p. 30). This method was used because lithologic samples obtained during construction of the observation wells showed a semiconfining layer near the top of the aquifer that made the aquifer semiconfined during the period of the test. The analyses indicated that the principal sand-and-gravel aquifer in the vicinity of the recharge well at the preliminary site has a transmissivity of about 7,000 ft^2/d [52,000 (gal/d)/ft] and a storage coefficient of about 0.0004 (table 1).

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 yielded considerable sand and fine gravel when the well was pumped at high rates. The water pumped from the supply well initially had a high sediment concentration, therefore it was discharged onto the ground and water was used for recharge only when it became relatively clear. The computed quantity of sediment injected into the recharge well was 2.5 lb. The sediment removed during the post-injection pumping test was 5.5 lb, or about twice the quantity 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 post-injection 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 recharge well accepted a significant quantity of water without impairing the performance of the well or the aquifer. This result indicated that there was a reasonable chance that a longer test would be successful; therefore, this area was considered suitable for the permanent recharge test site. Requirements for a permanent test site are that conditions be representative of a much larger area, that the site be readily accessible and that experiments can be conducted within the constraints of available time and money. The information gained from the first test was used not only in selecting the permanent test site but also in designing the permanent well-recharge system which is located near the preliminary site (fig. 9).

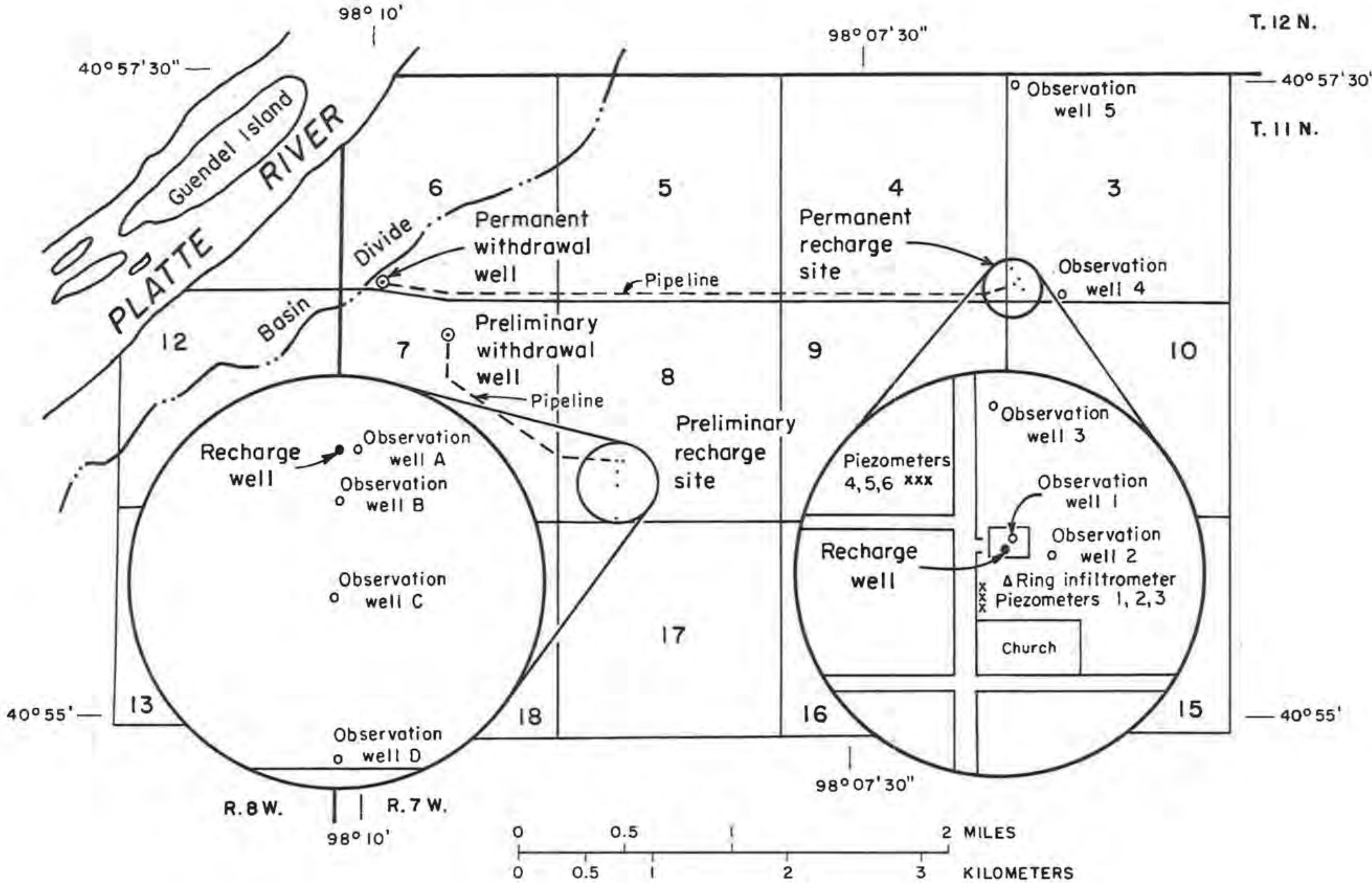

Figure 9.--Location of wells at artificial-recharge sites near Aurora.

The permanent withdrawal well was located on the Eugene Gustafson farm about 0.5 mi 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 the Platte River is a large potential source of recharge water and 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 consistently yielded water with a chemical composition nearly identical to that of Platte River water. Also, the water level in the irrigation well had not changed significantly during the last 20 years even though there was extensive 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 indicated that in this area the river was effectively recharging the aquifer for a distance of at least 0.5 mi from the river, but that appreciable river recharge had not occurred several miles inland. Chemical analyses of water from irrigation wells corroborated the above conclusion.

Although water from the river and water from the permanent withdrawal well had about the same concentrations of major dissolved chemical constituents (table 2), the river water contained much greater concentrations of suspended sediment, organic matter, dissolved and entrained air and bacteria, than did the well water. Therefore, to take advantage of natural filtration, recharge water was withdrawn from the well rather than directly from the river. This eliminated the need for an expensive water-treatment plant as is commonly needed in well-recharge systems. Also, water was withdrawn from a well rather than from the river in order to utilize the aquifer under and near the river as a temporary storage reservoir for recharge water. Because the river is dry periodically, it is not dependable as a recharge supply. However, by utilizing the vast storage capacity of the aquifer under and near the river, water for recharge is available at all times of the year, so that efficient use can be made of the recharge facilities. The partly depleted aquifer under and near the river is replenished when flow in the river resumes.

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, analyses indicative of the degree of mineralization were made of the water from selected existing wells in the Big Blue River basin. A site on the Kenneth Herrold farm 3 mi east of the withdrawal well met the criteria of accessibility and water quality. This site is 500 ft north of the Monroe church on a small plot of virgin prairie near the headwaters of the Big Blue River.

Table 2.--Chemical analysis of water from the Platte River near Grand Island and selected wells in Hamilton County
[mg/L = milligrams per liter; ug/L = micrograms per liter]

Constituents	Units	Platte River (Avg. 1975)	Prelim. with-drawal well 10-10-75	Prelim. re-charge well 10-10-75	Platte River (Avg. 1976)	Perm. with-drawal well 9-3-76	Perm. re-charge 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	Co - Pt unit	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
Nitrite plus nitrate, as N	mg/L	.36	.31	1.9	.47	.69	160
pH	pH unit	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	--	--
Sodium-adsorption ratio (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	**umho/cm	878	1130	561	796	842	2410
Sulfate	mg/L	233	340	53	224	210	440

* Tons per acre-foot
** Micromhos per centimeter at 25° C.

Water samples from domestic wells 500 ft west, 600 ft southeast, and 1,000 ft northeast of the site had specific conductances of 670, 790, and 670 umho/cm (micromhos per centimeter at 25°C), respectively. These specific conductances are within the range found in Hamilton County, which is a typical area of the Big Blue River basin (fig. 10). The chemical composition of typical Big Blue River basin ground water, however, was significantly different from Platte River water. This was important, as it was necessary to determine if Platte River-type water was compatible with native ground water in the Blue River basin.

The selected site for the well-recharge experiment seemed nearly ideal because recharge water similar in chemical quality to Platte River water was available near an apparently typical Big Blue River basin ground-water area, thus making the results of experiments directly applicable in much of the Big Blue River basin. When the permanent recharge well was installed, water of different quality than expected was discovered. The effects of large differences in water quality between water from the permanent withdrawal well and that in the permanent recharge well are discussed in a subsequent section (p. 62).

The enthusiastic support of the farmers in the area plus a good road system assurred ready access to the site. The proximity of the source of the recharge water to the area to be recharged made the experiment financially possible.

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. Cores were taken at intervals with thin-walled Shelby tubes. When the auger reached its depth limit of about 125 ft, a hydraulic rotary drill was used to obtain additional 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 by Johnson Division, UOP, to determine the depths to be screened, the proper type of gravel pack, and the optimum screen-slot size. The size distribution of the aquifer materials is shown in figure 11 for the site of the withdrawal well and in figure 12 for the site of the recharge well. The graphs can help assess the technical feasibility of artificial recharge in other locations if size-distribution information is known.

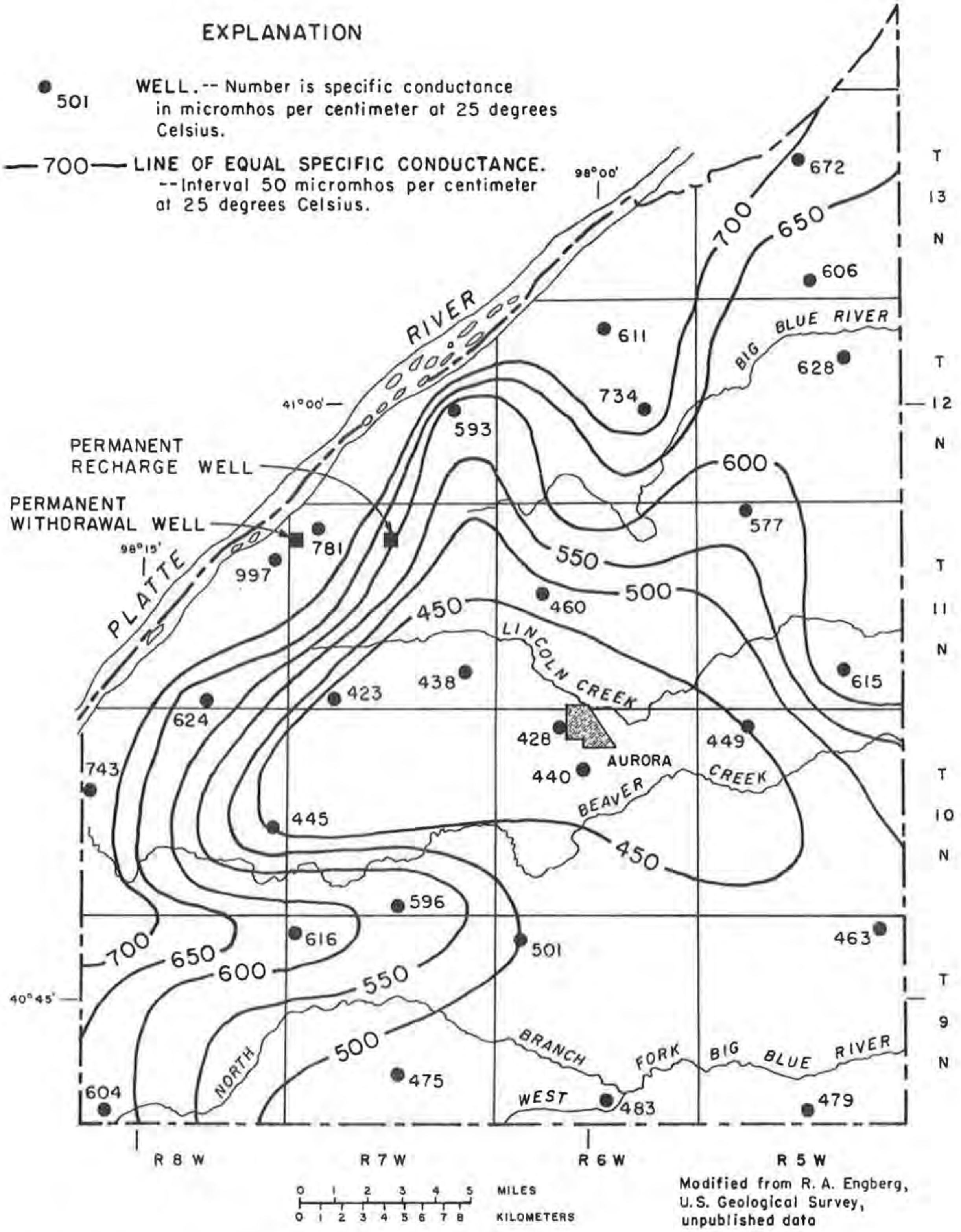

Figure 10.--Specific conductance of ground water in Hamilton County, 1969.

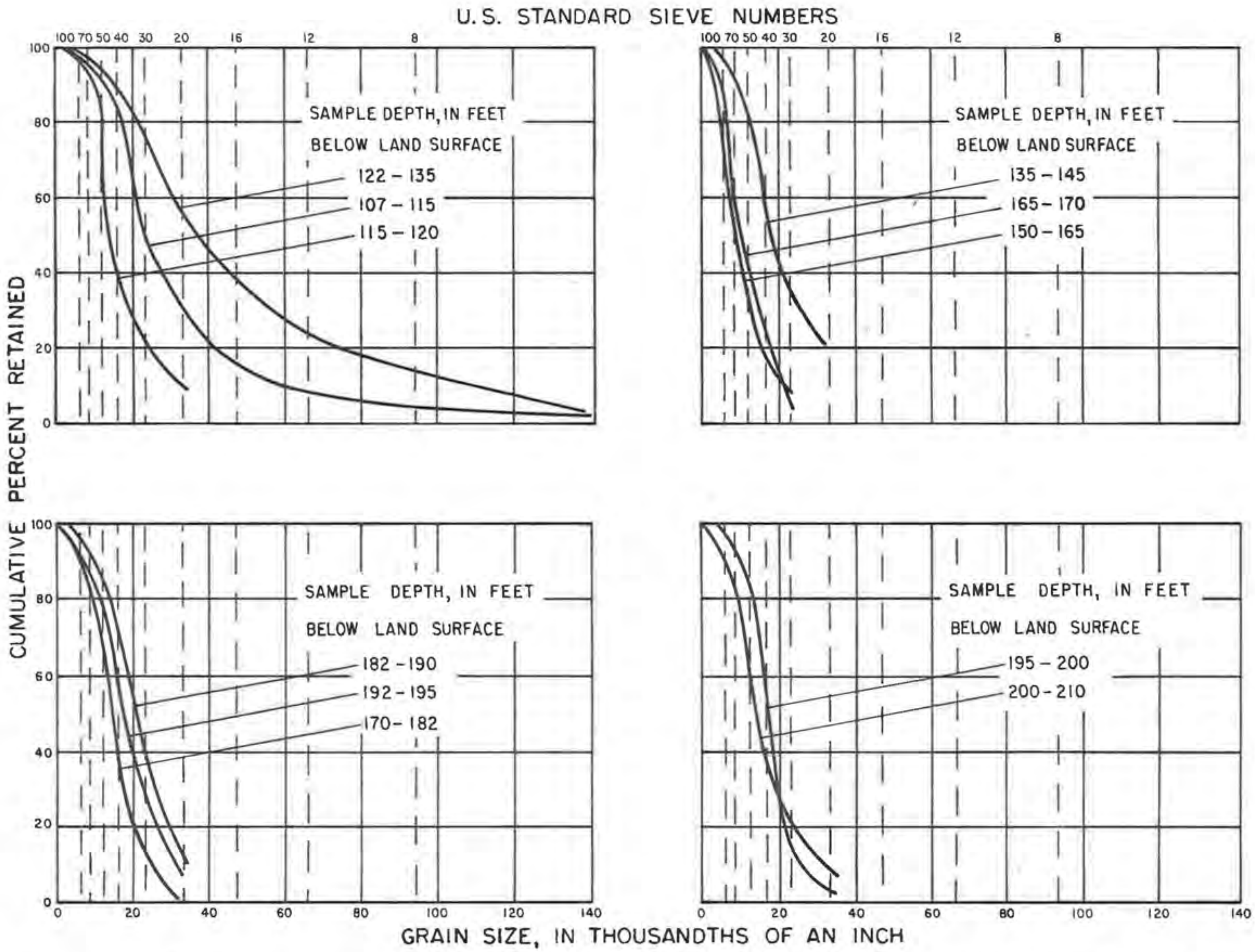

Figure 11.--Grain-size analysis of aquifer material from test hole 3 at withdrawal-well site near Aurora. (Analyses by Johnson Division, UOP)

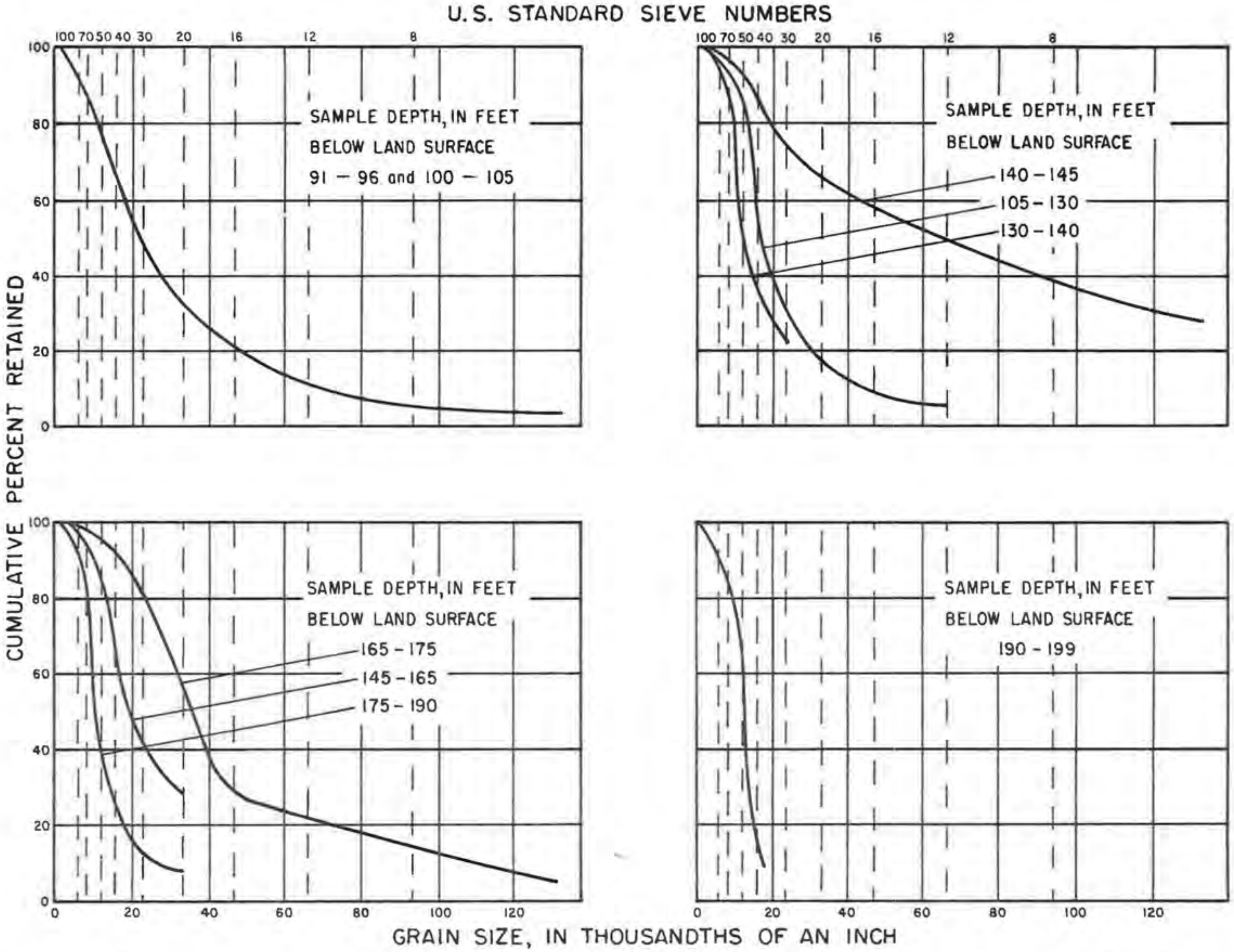

Figure 12.--Grain-size analysis of aquifer material from test hole 4 at recharge-well site near Aurora. (Analyses by Johnson Division, UOP)

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 screen[1] between depths of 140 ft and 190 ft and between 203 ft and 213 ft. The interval between 190 ft and 203 ft was cased with blank steel because the sediment contained fine-grained material which would be difficult to screen out. The medium- to coarse-grained material from 103 ft 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- to 3/16-inch gravel. It was developed by pumping, surging, and swabbing for 50 hours and was pumped at approximately 1.5 times the desired production rate to obtain water as sand-free as possible for recharge. A 50-horsepower electric motor on a 5-stage vertical turbine pump was installed in the well.

Recharge well

The recharge well (fig. 13) is 18 inches in diameter and 201 ft deep. It is screened with 40-slot (0.04-inch openings) Johnson Irrigator screen from 100 ft to 180 ft. The entire thickness of the aquifer was screened because during recharge operations the water level in the recharge well is above the top of the aquifer so that the entire thickness of the aquifer can be utilized for recharge. The interval from 180 to 201 ft is blank steel casing sealed at the bottom. This section houses a 50-horsepower submersible pump. The pump, used for aquifer testing and water sampling, 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.

For tests before June 1978, four injection tubes with gate valves at the top were installed in the well, each to a depth of 105 ft. Two of these tubes were 3 inches, one was 2½ inches, and one was 1½ inches in diameter. Different sized tubes were installed so that the best combination of sizes could be determined experimentally to insure

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

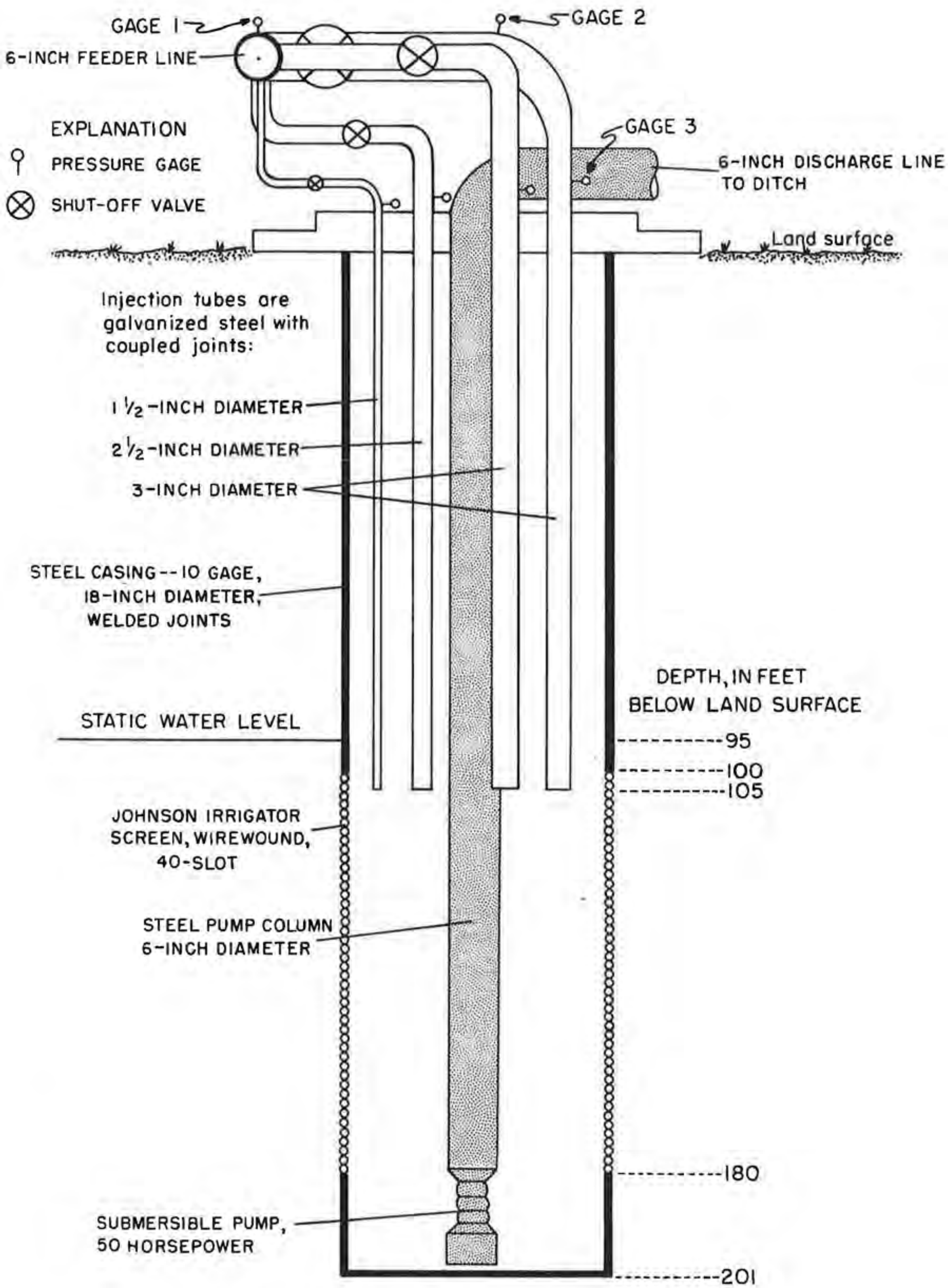

Figure 13.--Permanent recharge-well installation.

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 in an attempt 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 13, was installed to provide access for a continuous water-level recorder, a current meter, and for chlorinating the well.

For tests between June 1978 and July 1979, the 105-foot-deep tubes were replaced by two injection tubes with gate valves installed in the recharge well to a depth of 185 ft. It was determined from the first tests that one 3-inch diameter tube and one 2-inch diameter tube would provide the proper back pressure to maintain positive pressure on the system. The tubes were placed below the screen in an attempt to improve the accuracy of current-meter measurements of the velocity profile in the well during recharge. The baffles had been displaced during installation in the well and thus had proved ineffective in eliminating distortion in the velocity profile caused by discharge of water from the injection tubes. Installing the tubes below the screen did not improve the accuracy of the velocity measurements probably because the tubes, pump column, and power cord in the well caused an extremely nonuniform flow pattern in the well.

Pipeline

The withdrawal and recharge wells were connected by a 3-mile long, 12-inch diameter, low-pressure (22 $lb/in.^2$) plastic pipeline that was buried below frostline to enable operation throughout the year (fig. 14). The pipeline was equipped with a surge tank, air-vacuum relief valves and pressure-relief valves to protect the line from damage. The eastern end of the line was equipped with a shut-off valve located in a pit inside a 20- by 22-foot building that also housed the recharge well and an observation well. A 6-inch diameter steel line equipped with flow meters, shut-off valve, and sampling outlets connected the 12-inch line to the injection tubes and to a bypass line which discharged to a nearby ditch. Before the start of recharge operations, the system was disinfected with a strong solution of calcium hypochlorite (HTH 70).

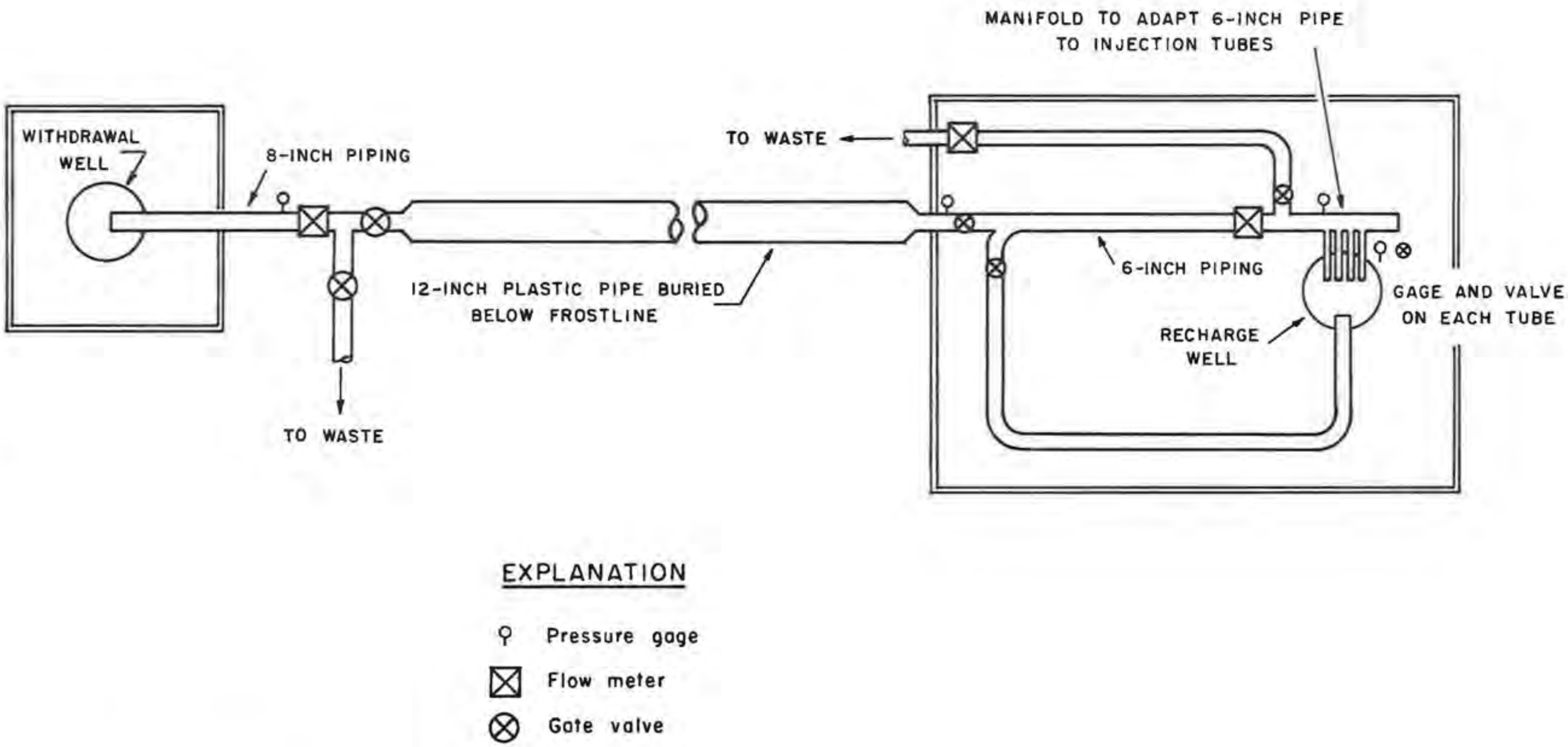

Figure 14.--Permanent well-recharge system near Aurora.

Observation wells

Six-inch diameter observation wells, equipped with continuous recording gages were installed at distances of 10, 90, 316, 1,322, and 4,527 ft from the recharge well to record changes in water level (fig. 9). The 6-inch observation wells were screened in the same interval as the recharge well. In addition, a 1¼-inch observation well was installed in the gravel pack 2 inches 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 were located approximately 140 and 215 ft from the injection well. The piezometer nests were installed to obtain water-quality samples and to measure water levels in different parts of the aquifer.

Continuous water-level recording gages were installed on two existing irrigation wells for the second long-term test (November 20, 1978, to July 20, 1979). These wells (observation wells 6 and 7, fig. 20) were located 2,200 and 3,000 ft from the recharge well.

Testing the Well-Recharge System

Several tests were made of the well-recharge system, partly to verify preliminary data obtained for aquifer characteristics and partly to check the equipment and design of the system. A pumping test was made to help determine aquifer characteristics in the vicinity of the permanent recharge well before any water was injected into the aquifer. This was followed by two short-term recharge tests. Following subsequent longer recharge tests, two more pumping tests were made to determine the effects of recharge on the aquifer. Results of data analyses for the pumping tests are presented in table 3.

Pumping tests

The fluctuations of the water levels in an aquifer in response to pumping or recharge are controlled by the hydraulic characteristics of the aquifer and by any boundary conditions that exist. Aquifer tests help determine these characteristics 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.

Characteristics affecting hydraulic response of an aquifer include transmissivity and storage coefficient. Transmissivity is a measure of the ability of the aquifer to transmit water and is defined as the rate

Table 3.--Results of aquifer tests at the permanent test site near Aurora

Well designation	Screened interval (feet)	Distance from pumped well (feet)	Transmissivity (ft^2/d)	Storage coefficient	Maximum drawdown (feet)	Specific capacity (ft^2/min)
Pumping test 1 - Mar. 2-4, 1977, recharge well pumped 48 hr at 880 gal/min (Depth to water at start, 98.22 ft)						
Recharge	100-180	0	------	---------	10.3	10.4
Observation 1	100-180	10	13,000	0.19	8.1	------
Observation 2	100-180	90	13,000	.07	4.5	------
Observation 3	100-180	316	17,000	.04	2.2	------
Pumping test 2 - May 16-18, 1978, recharge well pumped 43 hr at 850 gal/min						
Recharge	100-180	0	------	---------	13.1	8.4
Observation 1	100-180	10	16,000	0.11	7.2	------
Observation 2	100-180	90	13,000	.13	3.9	------
Observation 3	100-180	316	14,000	.09	1.7	------
Piezometer 5	130-135	212	15,000	.06	2.6	------
Pumping test 3 - Aug. 14-17, 1979, recharge well pumped 70 hr at 940 gal/min						
Recharge	100-180	0	------	---------	-------	6.5
Observation 1	100-180	10	16,000	0.23	7.5	------
Observation 2	100-180	90	18,000	.06	4.2	------
Observation 3	100-180	316	18,000	.13	1.9	------

at which water is transmitted through a unit width of the aquifer under a unit hydraulic gradient at the prevailing water temperature. The storage coefficient characterizes the "reservoir" response of an aquifer and relates water-level changes to the amount 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 hydraulic head.

The methods used to determine these aquifer characteristics assume that the aquifer is homogeneous, isotropic, and areally extensive, and flow is laminar and entirely radial. Few aquifers meet all these criteria; however, if the physical characteristics of the aquifer and confining beds in the area affected by a pumping well are known, the reliability of pumping-test results can be evaluated. Examination of geologic samples from many wells in the area of the Aurora site indicate that the aquifer fulfills the assumptions to a reasonable degree.

The pumping test to help determine aquifer characteristics in the vicinity of the permanent recharge well prior to injection of recharge water was made during March 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 tests were plotted on log-log graph paper. The resultant curves were analyzed using delayed-yield type curves (Lohman, 1972) applicable to aquifers under water-table conditions (fig. 15). It is significant that the aquifer at the preliminary site only 2 mi away was under semiconfined conditions, whereas at the permanent site conditions were water table. The difference illustrates the fact that the characteristics of the Quaternary aquifer can vary considerably within relatively short distances.

Analysis of the data from the March 2-4 pumping test at the site of the permanent recharge well (table 3) indicated a transmissivity of about 15,000 ft^2/d [112,000 (gal/d)/ft]. The storage coefficient as determined from the curves ranged from 0.19 to 0.04. The considerable variations in this coefficient may be due to slow drainage which causes greater error in the computations for the more distant observation wells than for the nearby wells. If the test had been of sufficient duration (perhaps months would be required), there would have been time for water to drain more completely from the more distant sediments in the cone of

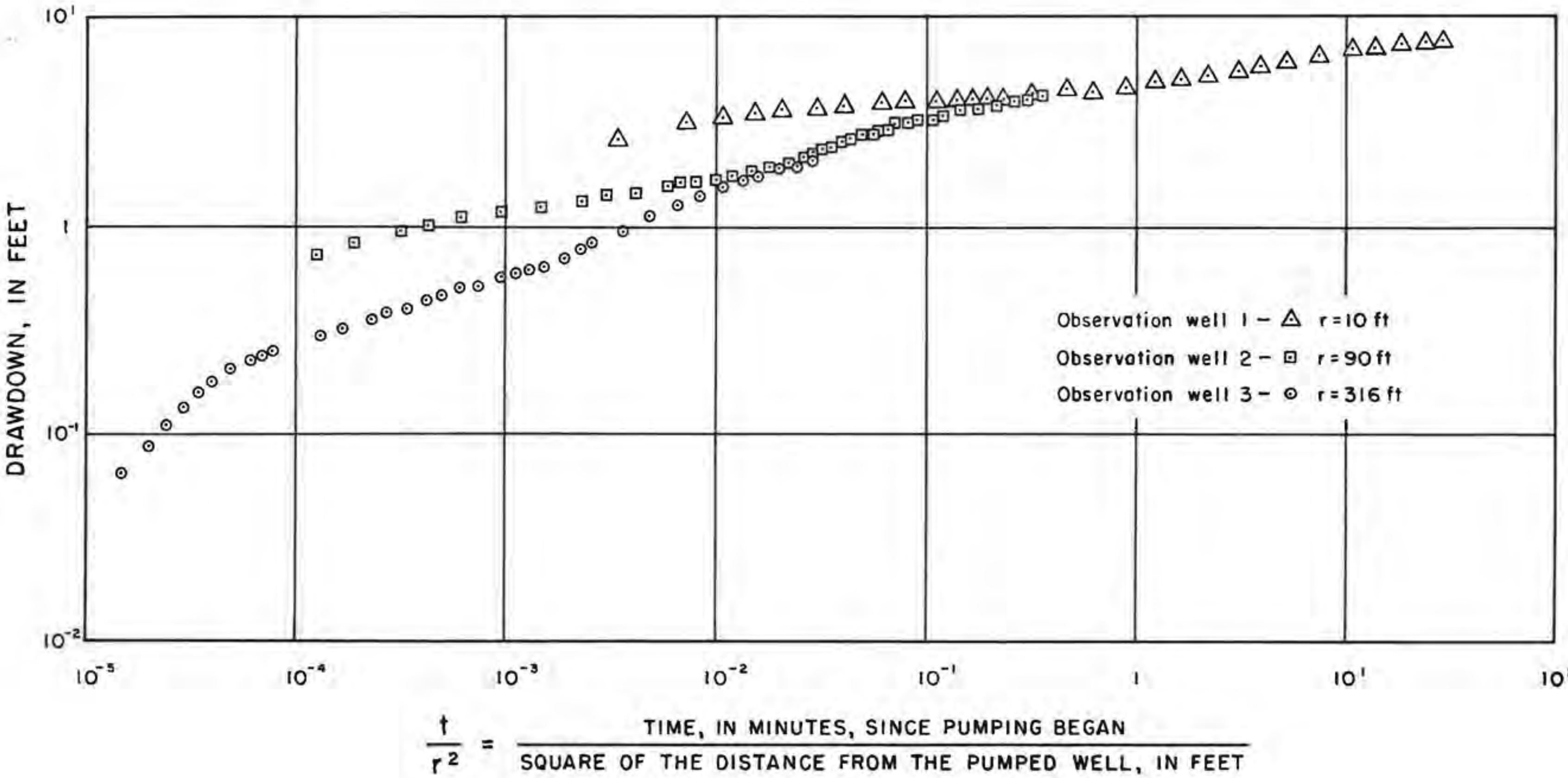

Figure 15.--Time-drawdown curves for observation wells during pumping test at permanent recharge site near Aurora on March 2-4, 1977.

depression and this effect probably would have been minimized and the storage coefficients probably would have been nearer the value of 0.19 obtained from the nearest well. This value is reasonable for a clean sand and gravel aquifer.

Pumping tests also were made during May 16-18 and August 14-17 following the first and second long-term recharge tests, respectively. These pumping tests were made to assess the effects of recharging on the aquifer. The results given in table 3 show that recharging had little effect on the aquifer coefficients.

The concentration of sediment in the water removed from the recharge well during the pumping test of March 2-4 was about 0.3 mg/L (milligram per liter) for a total of 6.3 lb (table 4). The sediment yield decreased during pumping.

Recharge tests

Water was first injected into the permanent recharge well on March 18, 1977, to see if the system, especially the injection tubes, was functioning properly. The tubes were arranged in manifold from the 6-inch piping within the building (fig. 13). The injection-tube system was designed to use 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. 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 injection rate for the March 18 test was 700 gal/min, the maximum output of the system. Excessive vibration, cavitation, and hydraulic head loss occurred between the 6-inch pipe and the top of the well. With one 3-inch and the 1½-inch valve open, the pressure head in the 6-inch pipe was 13 lb/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.

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

Table 4.--Sediment pumped from or injected into permanent recharge well

Period covered				Pumped from well				Injected into well			
				Length of period (hour)	Average pumping rate (gal/min)	Sediment concentration (mg/L)	Sediment (pound)	Length of period (hour)	Average pumping rate (gal/min)	Sediment concentration (mg/L)	Sediment (pound)
1977											
3-2	1055	3-4	1015	47.3	880	0.300	6.3	------	-------	--------	--------
3-16	1347		1440	1.0	1010	2.36	1.05	------	-------	--------	--------
	1440		1530	1.0	1010	1.29	.56	------	-------	--------	--------
5-17	1815		2130	------	-------	--------	-------	3.3	755	0.548	0.67
	2130	5-18	0900	------	-------	--------	-------	11.5	755	.138	.60
	0900	5-19	0600	------	-------	--------	-------	21.0	755	.019	.15
	0600	5-20	0200	------	-------	--------	-------	20.0	755	.030	.23
	0200		1215	------	-------	--------	-------	10.2	755	(a)	--------
7-18	1725		1745	.3	1000	75.5	12.59	------	-------	--------	--------
	1745		1815	.5	1000	6.34	1.58	------	-------	--------	--------
	1815		2025	2.2	1000	3.36	3.64	------	-------	--------	--------
	2041	7-19	0130	4.8	1000	.976	2.35	------	-------	--------	--------
7-20	1052	7-21	0140	14.8	970	.433	3.11	------	-------	--------	--------
	0140		1255	11.2	970	.505	2.76	------	-------	--------	--------
	1255	7-22	0030	11.6	970	.157	.88	------	-------	--------	--------
	0030		1220	11.8	970	.181	1.04	------	-------	--------	--------
	1220		1605	3.8	970	.190	.35	------	-------	--------	--------

7-27	1130		1340	------	-------	--------	-------	2.2	975	.324	.50
	1340	7-28	0025	------	-------	--------	-------	10.7	975	.190	1.00
	0025		2230	------	-------	--------	-------	22.1	975	(a)	--------
	2230	7-29	1357	------	-------	--------	-------	15.4	975	(a)	--------
8-24	0956		1730	------	-------	--------	-------	(b)	975	(a)	--------
	1730	9-1	0130	------	-------	--------	-------	175.5	750	(a)	--------
	0130	9-10	1845	------	-------	--------	-------	257.2	885	(a)	--------
	1845	9-14	0245	------	-------	--------	-------	80.0	760	(a)	--------
	0245	9-24	1200	------	-------	--------	-------	249.3	760	(a)	--------
1977		1978									
11-23	1200	1-6	1200	------	-------	--------	-------	1056.0	745	.052	20.46

a Metricel filter pad lost weight in the filtering process; precise concentration could not be determined, but probably did not exceed 0.01 mg/L.

b Before injection.

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 July 18-22 and an additional 3 Mgal were withdrawn July 27-29. To determine what, if any, chemical reactions had taken place as a result of mixing recharge water with native aquifer water, a sample of the first water pumped was taken on July 18. The chemical analysis of this water (table 5) shows that the water in the vicinity of the recharge well had been diluted significantly by the recharge water. However, no evidence can be seen in the analyses to indicate that chemical reactions likely to cause clogging of the well screen or the aquifer had occurred.

Testing of the system indicated that the system was functioning adequately and that clogging of the recharge well was not detectable, at least in short-term tests. Pumping tests showed that the computed transmissivity of the aquifer at the permanent well site was approximately twice that at the preliminary site. The computed storage coefficient at the permanent site was several hundred times that at the preliminary site, reflecting the semiartesian conditions at the preliminary site versus water-table condition at the permanent site.

Monitoring the System

Careful monitoring of the system provides 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, in the aquifer, or in both. Monitoring of water levels is required to detect and quantify excessive buildup should it occur in the recharge well or in the surrounding aquifer. Monitoring of both water levels and water quality is required to help determine probable causes of clogging.

The water-level monitoring system consisted 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. During the second long-term test, gages also were installed on two irrigation wells. Locations of these wells with respect to the recharge well were described earlier. The 6-inch observation wells were used to monitor aquifer response to pumping or recharge. Comparison of changes in these wells to changes in

Table 5.--Chemical analyses of water from wells at permanent site near Aurora
[Concentrations in milligrams per liter, except as indicated]

Constituent	Recharge well a/ 4-13-77	With-drawal well b/ 5-19-77	Recharge well c/ 7-18-77	Obser-vation well 1a/ 4-22-77	Obser-vation well 1 11-3-77	Forsman well 1-22-76	Forsman well 9-14-76
Alkalinity	230	190	210	240	200	203	235
Bicarbonate	280	230	260	290	240	247	286
Boron d/	--------	100	90	60	120	-------	-------
Calcium	520	91	280	700	90	91	560
Carbonate	--------	-------	-------	-------	-------	-------	-------
Chloride	36	26	30	50	24	6.8	39
Color (units)	--------	1	1	2	1	-------	-------
Fluoride	--------	0.5	0.4	0.3	0.4	-------	-------
Noncarbonate hardness	1,400	110	690	2,000	110	86	1,500
Total hardness	1,700	300	900	2,200	300	290	1,800
Iron d/	40	10	100	20	10	10	10
Magnesium	88	17	49	110	19	15	88
Manganese d/	40	8	20	20	4	10	30
Nitrate + nitrite as N	270	0.73	120	330	0.82	9.2	260
pH (units)	--------	-------	-------	-------	8.2	-------	-------
Phosphorus	--------	0.08	0.03	0.21	0.04	-------	-------
Potassium	21	5.6	11	27	5.4	7.5	22
Dissolved solids	--------	-------	1,600	-------	590	-------	-------
Dissolved solids, ton/acre-foot	--------	-------	2.1	-------	0.80	-------	-------
Sodium-adsorption ratio (SAR)	1.0	1.9	1.3	1.0	2.0	0.8	1.0
Silica	--------	18	23	27	19	-------	-------
Sodium	90	74	89	110	80	30	95
Specific conductance e/	3,240	900	2,020	4,320	870	670	3,260
Sulfate	680	220	460	870	230	110	830

a/ Native water
b/ Recharge water
c/ Mixture of native and recharge water
d/ Microgram per liter
e/ Micromho per centimeter at 25°C.

the recharge well gives an indication of the extent of clogging of the aquifer in the immediate vicinity of the recharge well during recharge. Comparison of water levels in the gravel pack observation well to water levels in the recharge well indicates the degree of clogging of the well screen.

Monitoring of water quality consisted of the following:

(1) Periodic 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 L (liters) of water through a 0.45-μm (micrometer) filter and determine the suspended-solids load from the difference in the dry weight of the filter before and after filtration. 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 slightly in error; that is, the weight of the filter pad after filtration was less than before filtration. The problem was solved by substituting special Gelman Teflon filters that do not dissolve in water or volatilize during drying.

(2) Continual monitoring of specific conductance and temperature and periodic monitoring of dissolved oxygen concentration and pH, of water injected into or pumped from the recharge well. A probe designed to measure these four properties was connected to a Martek Mark V water-quality analyzer and installed so that water flowed over it continuously. Any two of the properties could be recorded at a given time and the other two could be read periodically. Changes in specific conductance and temperature were considered to be good indicators of change in water quality; therefore, these two properties 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 (American Public Health Association, 1971, p. 679), of the total bacterial concentration of water injected into and 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. These analyses were needed 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.

Results of First Long-Term Test

The first long-term recharge test was started on September 13, 1977. It was planned originally to continue for 60 days, but after 9 days and periodically thereafter until October 31 it was interrupted by power outages. The problem finally was tracked to a shorting of the power company's transmission lines and was corrected. Except during a 16-hour power failure November 8-9 caused by a snowstorm, recharge was continuous from October 31, 1977, to April 9, 1978.

About 635 acre-ft (207 Mgal) of water was recharged to the aquifer from September 13, 1977, to April 9, 1978, at a rate of 700-756 gal/min with a buildup of water levels in the recharge well of 19 ft. The buildup resulted in development of a cone of elevation that extended slightly more than a mile from the recharge well (fig. 16). Of the 19 ft of buildup in the recharge well, approximately 60 percent occurred during the first few days of recharge (fig. 17). During September and October, recharge was intermittent because of power interruptions; however, from October to April, recharge was nearly continuous at an average rate of 732 gal/min with an additional increase in water levels in the recharge well, after the first few days, of 7.6 ft. If this rate of increase (1.3 ft/mo) is projected for an additional 6 months and there is no lowering of water levels by artificial means such as pumping, then a total buildup of about 27 ft would occur during the first year of recharge.

The static water level in the recharge well was about 95 ft below land surface; therefore, if the rate of buildup of 27 ft/yr at 732 gal/min continued, it would be possible to recharge a single well at a rate more than three times the stated rate or nearly 2,400 gal/min for a year before the water level in the recharge well 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 nearby observation wells stabilized; this indicated that increased hydraulic-head differential was necessary to move water away from the recharge well. Because the quantity and quality of the water was unchanged, this showed that clogging was reducing the transmissivity of the aquifer in the vicinity of the recharge well. Water levels in the recharge well and the 1¼-inch observation well in the filter pack were virtually identical, indicating no significant clogging of the well screen during this test. Therefore, the clogging probably was in the aquifer between the recharge well and

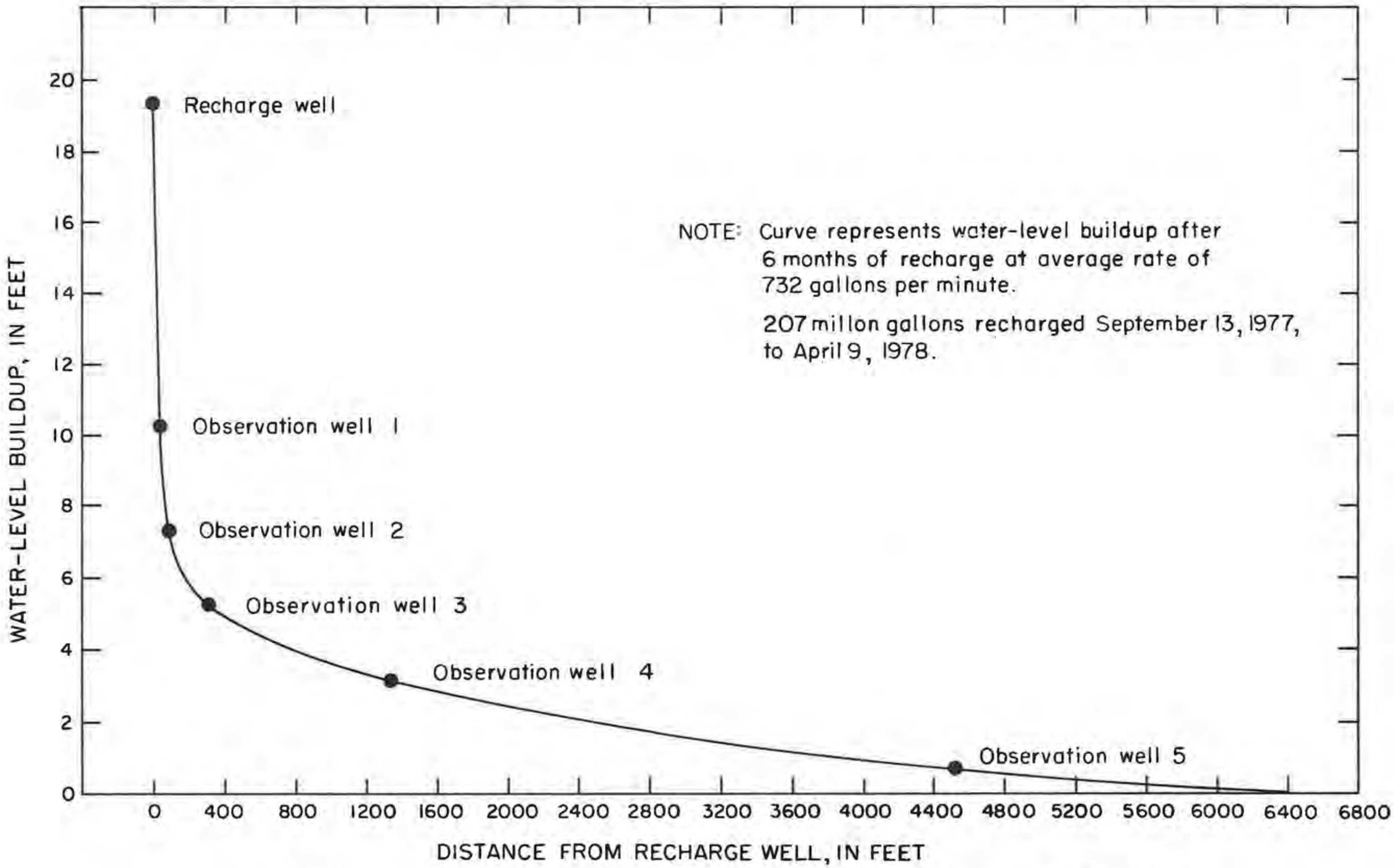

Figure 16.--Profile of water-level buildup in wells at Aurora site, April 9, 1978.

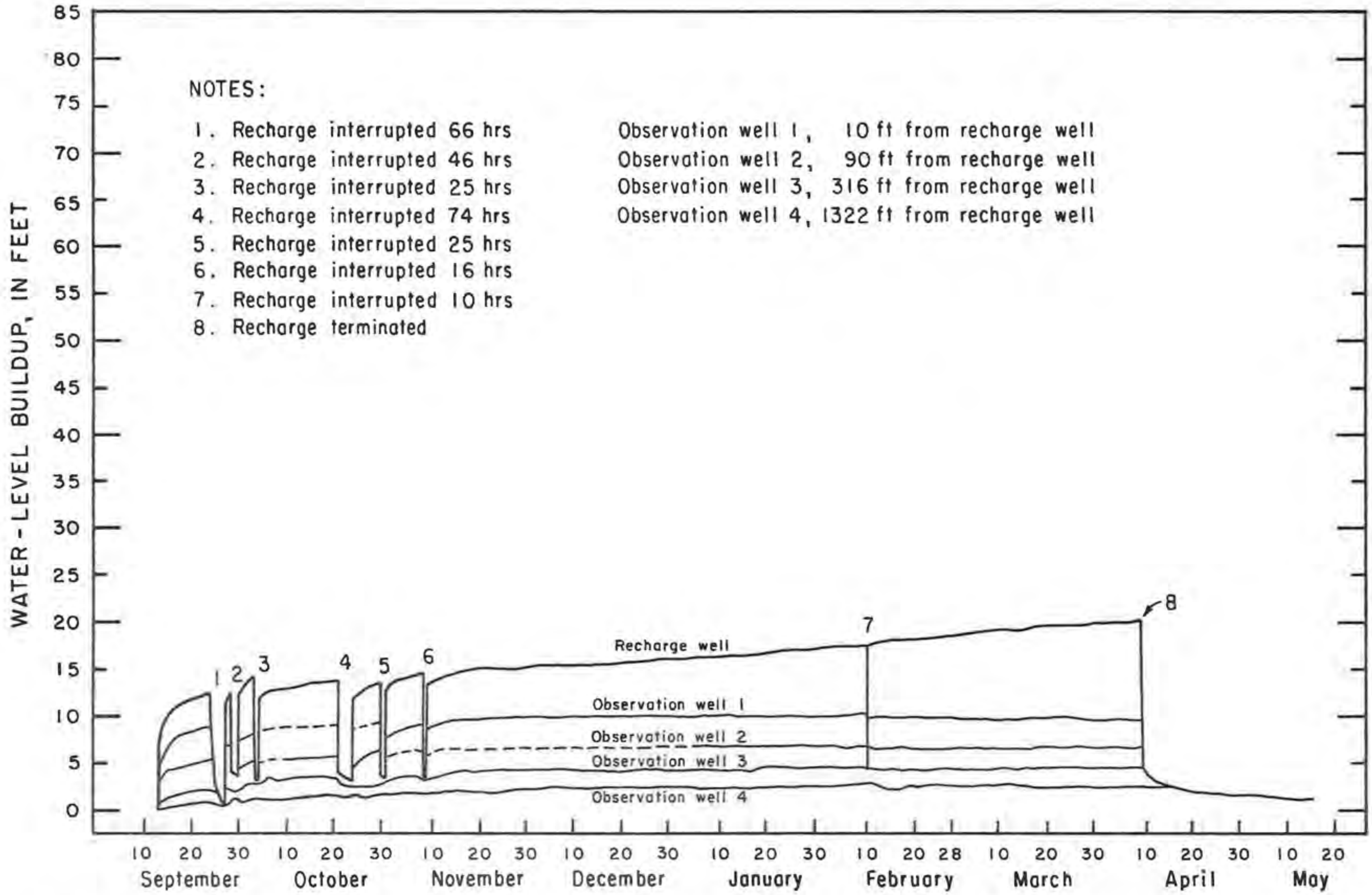

Figure 17.--Measured water-level buildup caused by recharging 207 million gallons, Aurora, first long-term test.

the observation well 10 ft away. The buildup of the water level in the recharge well caused increasing back pressure on the withdrawal-well pump and caused the recharge rate to decline (fig. 18).

A plot of the buildup of water levels in the recharge well and observation wells 1 to 4, adjusted to reflect a constant recharge rate of 730 gal/min during the first long-term test, is shown in figure 19. This rate is near the average rate of recharge for the first test (732 gal/min) and exactly the average rate of recharge for the second long-term test.

The graphs in figure 19 show that the water-level buildup in observation wells 1 to 4 had virtually stabilized by the end of November 1977, but the buildup in the recharge well continued after that time at a rate of about 1 ft/mo until the pump was repaired on February 10, 1978. During the next month, the water-level buildup was about 2.6 ft or a rate of more than 2.5 times the rate from December 1 to February 10. The rate of buildup then gradually returned to slightly more than 1 ft/mo.

The cause of the increase in clogging rate after February 10, 1978, is not known, but it may have been due to a slight increase in the sediment concentration of the recharge water caused by shifts in the gravel pack as a result of removing and reinstalling the withdrawal well pump.

Several possible causes of clogging in the aquifer were considered. These included:

(1) Chemical reactions - Analysis of water samples taken early in the test (11-3-77) from observation well 1, 10 ft from the recharge well, showed the chemical quality of the water to be virtually identical to recharge water (5-19-77), indicating that native ground water had been flushed more than 10 ft from the recharge well. (See table 5.) Therefore, it is unlikely that any chemical reactions were occurring between the recharge water and the resident ground water. The aquifer material is mostly quartz sand and gravel which is quite unreactive, so it also is unlikely that significant chemical reactions could take place between the recharge water and the aquifer material. Therefore, chemical reactions were not a likely cause of the clogging.

(2) Air entrainment - Positive pressure was maintained in the piping throughout the recharge test to eliminate the possibility of air entering the recharge water through leaks in the system. The first water through the piping system was run to waste until the dissolved

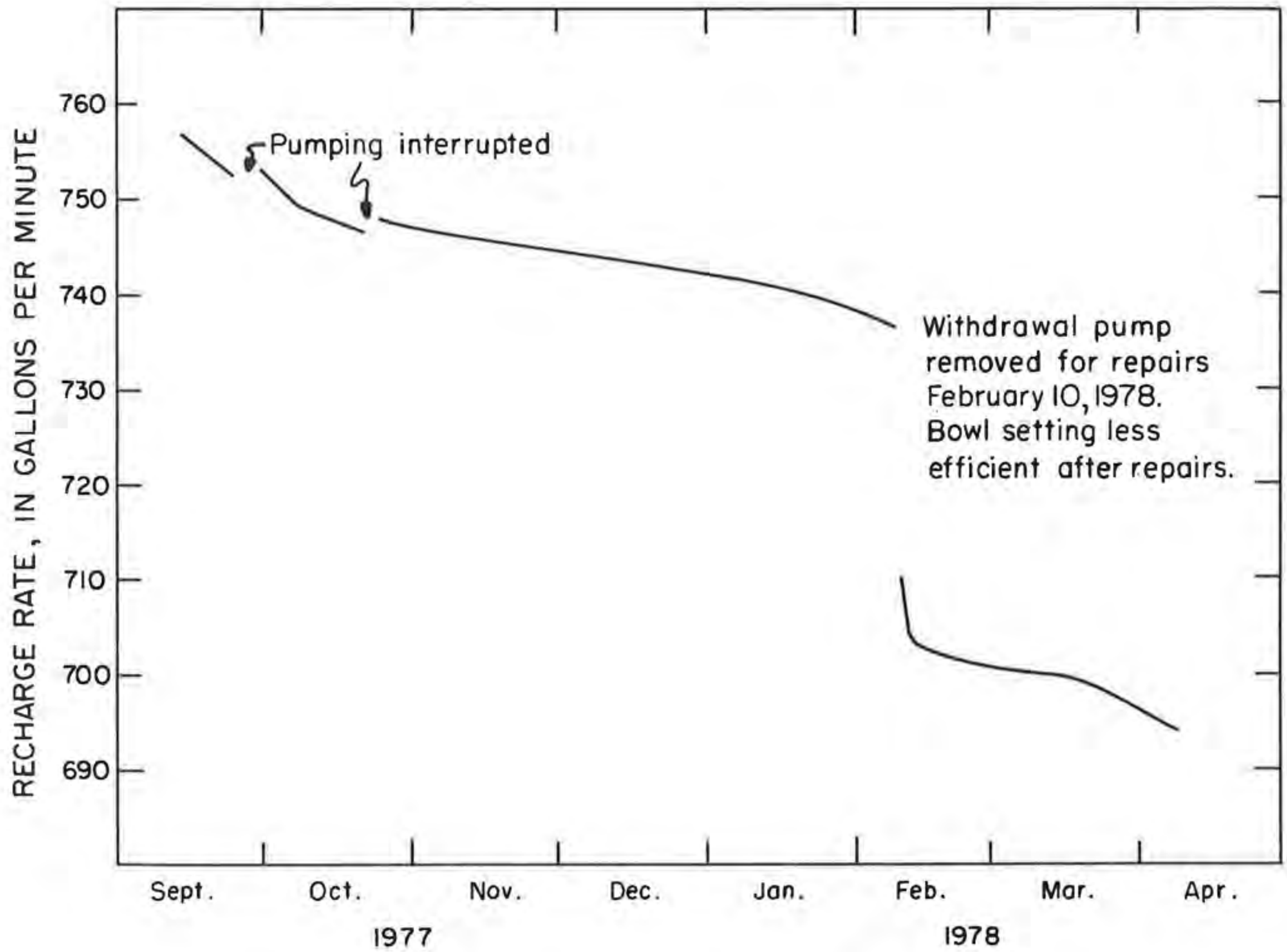

Figure 18.--Changes in recharge rate during first long-term test--Aurora site.

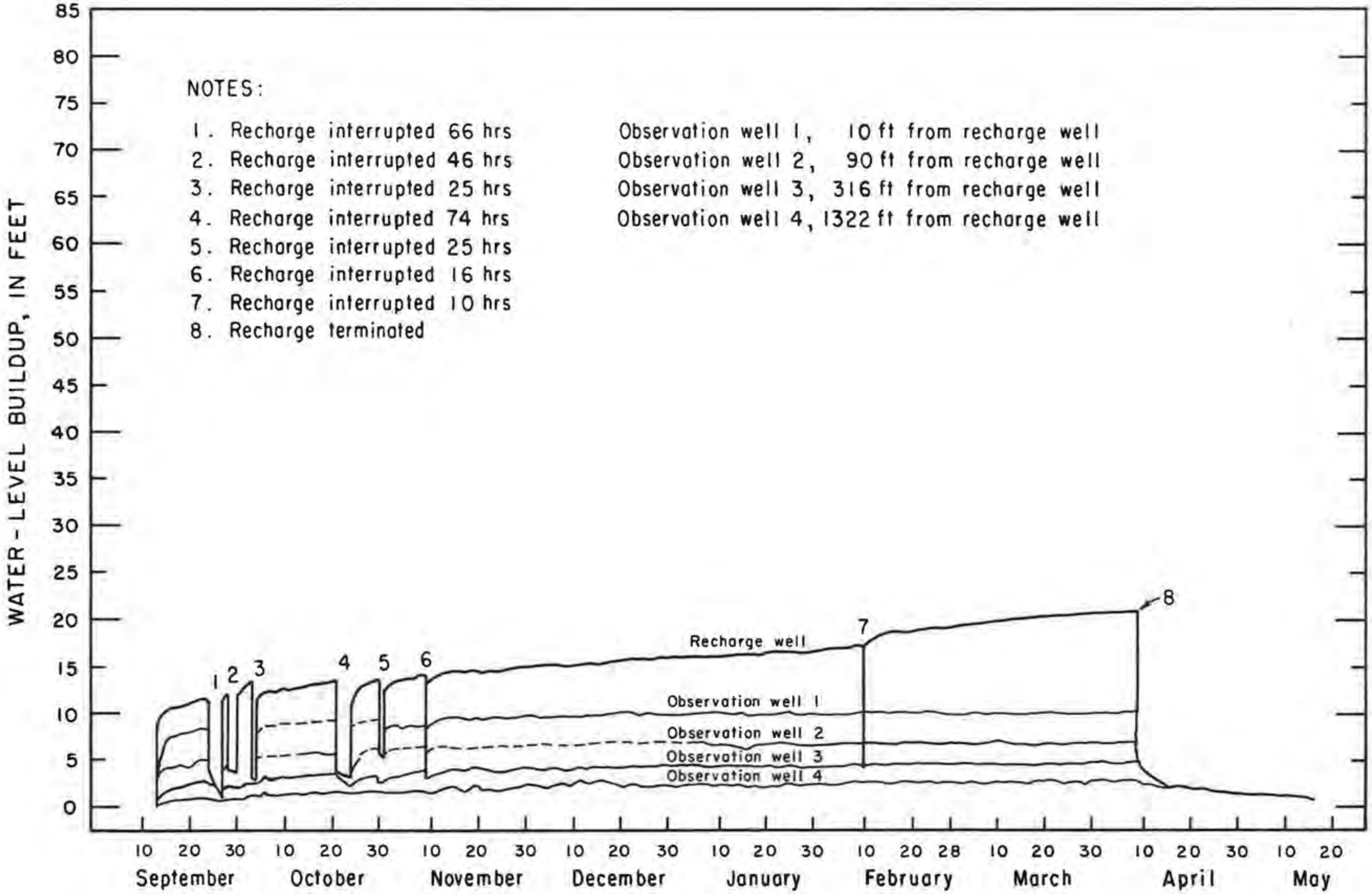

Figure 19.--Water-level buildup, adjusted to a constant recharge rate of 730 gallons per minute, caused by recharging 207 million gallons — Aurora site, during first long-term test.

oxygen concentration decreased to less than 2 mg/L. The temperature and pressure conditions were similar where the recharge water was withdrawn from the aquifer near the Platte River and where it was used to recharge the aquifer in the Big Blue River basin. Thus the emergence of dissolved gas from solution due to temperature and pressure changes was minimal. Based on the above, neither entrained air nor the emergence of dissolved gases was a likely cause of clogging.

(3) Bacterial growth - The total bacteria count in the recharge water from the withdrawal well generally was less than 2,000 colonies per 100 mL (milliliters) (table 6) during the first long-term recharge test. It tended to increase as recharge operations continued. The increase probably was due to growth of bacteria in the pipeline and the wells. The system was chlorinated with HTH 70 before the start of recharge operations; however, power outages caused temporary interruptions of recharge several times during the early part of the test. The interruptions allowed air and probably air-born bacteria to enter the pipeline, and as the recharge water was not chlorinated, bacterial growth could have occurred in the piping system due to this source of contamination. Evidence that bacterial growth did occur in the withdrawal well was seen in the greenish-colored water that was pumped to waste at the withdrawal end of the pipeline after the well had not been pumped for several weeks; however, the greenish water persisted for only a few seconds after start of pumping. The bacteria probably grew because the static water in the well was exposed to air.

Clogging of a recharge well by low concentrations of bacteria is poorly documented; however, Ehrlich (Reeder, Wood, Ehrlich, and Ren Jen Sun, 1976, p. 50) states, "Absence of oxygen, as is typical of most deep ground water, precludes the existence of air-breathing animals, and lack of sunlight excludes plants from ground water. Although many species of bacteria flourish under anoxic conditions, the organic content of most ground water is insufficient to sustain a bacterial population."

No slime was noted coming from the continuous sampling hose, and samples collected from various depths in the recharge well at a later date during recharge had a low bacteria count. All evidence indicates that bacteria probably were not a significant cause of clogging during the first long-term recharge test.

(4) Suspended sediment - In the early recharge tests, sediment in the recharge water was discounted as a cause of clogging in the recharge well because the sediment concentration appeared to be extremely low. The sediment concentration of the recharge water was measured by filtering

Table 6.--Bacteria data from tests at permanent recharge-well site, Aurora

Well sampled	Date	Time	Colonies per 100 mL	Remarks
			Data from preliminary tests	
----------	3-8-77	----	--------	Recharge well chlorinated
----------	3-9-77	----	--------	Withdrawal well and pipeline chlorinated; recharge well flushed
----------	3-10-77	----	--------	Withdrawal well and pipeline flushed
----------	3-16-77	----	--------	Recharge well pumped for 1.7 hours
Recharge	3-17-77	0835	175	Recharge well pumped for 3.5 hours
Do------	--do---	0928	260	
Do------	--do---	1032	250	
Withdrawal	5-17-77	2300	650	Start 2½-day recharge test at 1815
Do------	5-18-77	1830	365	
Do------	5-19-77	1700	335	
Recharge	7-18-77	1725	14,500	Start recharge well pump at 1715
Do------	--do---	1752	2,520	
Do------	--do---	2109	1,025	
----------	----------	----	--------	Recharged intermittently for 2½ months
			Data from first long-term test	
----------	10-31-77	----	--------	Start continuous recharge test
Withdrawal	1-11-78	1600	135	
Do------	1-27-78	1430	500	
----------	2-1-78	----	--------	Shut down for 10 minutes
Withdrawal	2-7-78	1500	1,650	Recharge water just before entering well
Do------	3-8-78	1230	1,380	Do.
Do------	3-21-78	1200	9,350	Do.
Recharge	5-11-78	1400	256	Collected with sampling pump; well had been idle for 32 days
Withdrawal	1-3-79	1400	650	Recharge water collected just before entering well
Do------	1-23-79	1300	1,150	Do.
Recharge	1-24-79	1330	145	Collected from 70 ft below water surface

21 L of water through a 0.45-μm Metricel filter. The water was withdrawn from the bottom of the 6-inch piping just before the water entered the well. The filter pads were oven-dried and weighed before and after filtering. The apparent sediment concentration 45 minutes after the start of a 66-hour recharge test on May 17-20, 1977, was 0.548 mg/L; however, after 5 hours of recharging it had decreased to 0.138 mg/L, and after 24 hours of recharging it had decreased to 0.019 mg/L. After 64 hours no sediment was detected. The calculated amount of sediment pumped from the recharge well was 17 times the calculated amount injected into the well and the specific capacity was increased slightly.

During a 6-month recharge test started September 13, 1977, all sediment determinations appeared negative during the first 20 days, reaching apparent negative values of as much as -0.0075 mg/L. As a result of the difficulty with the Metricel filters, Gelman Teflon membrane filters were used beginning on December 20, 1977. Tests run on the teflon filters showed no loss of weight due to washing or heating.

A pumping test was made during May 16-18, 1978, in the recharge well after termination of the first long-term recharge test. Analysis of the data showed that the general transmissivity of the aquifer, as determined by water-level changes in the observation wells, had not changed as a result of recharge (table 3). However, the specific capacity of the recharge well had decreased about 20 percent (10.4 to 8.4 ft^2/min of drawdown) from the pre-recharge specific capacity (table 3). This tends to confirm the data from the water-level buildup that clogging occurs in the immediate vicinity of the recharge well.

The exact cause or causes of clogging in the recharge well were not clear after the first long-term recharge test. Sediment was suspected as the principal cause, partly from the sediment data, but mostly from elimination of other causes. Therefore, it was decided to run a second long-term test to try to pinpoint the cause of clogging.

Results of Second Long-Term Test

A second long-term recharge test was made during 1978-79. Approximately 247 million gallons of water was recharged to the aquifer from November 20, 1978, to July 20, 1979, at an average rate of 730 gal/min. The buildup resulted in development of a cone of elevation extending more than a mile from the recharge well (fig. 20).

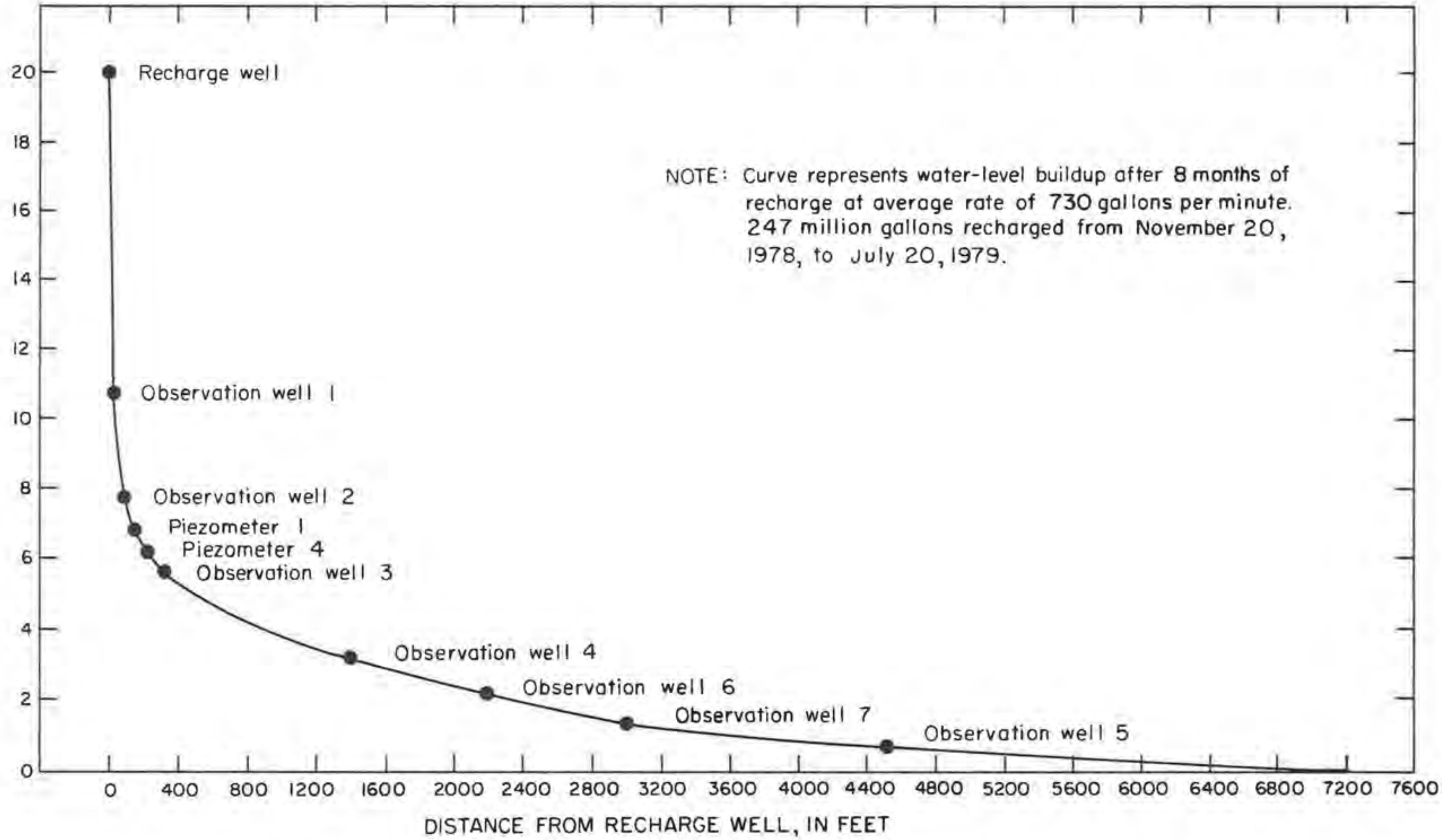

Figure 20.--Profile of water-level buildup in wells at Aurora site, July 20, 1979.

The pattern of water-level buildup in the recharge well in the second long-term test was similar to that in the first long-term test. The initial buildup rate was slightly greater in the second test (fig. 21) than in the first (fig. 17), partly because the recharge rate was slightly higher during the early part of the test and probably partly because of residual clogging from the first test. Comparison of figures 19 and 22, which show buildup adjusted to a constant recharge rate, indicate that most of the increased buildup in the second test was due to residual clogging. As in the first test, the recharge rate declined as the test progressed due to back pressure caused by the buildup of the water level in the recharge well. The actual buildup rate as recorded is shown in figure 21. The water-level buildup adjusted to a constant recharge rate of 730 gal/min, which was the average recharge rate for the second long-term test, is shown in figure 22. The graphs in figure 22 show that the buildup in observation well 1 virtually stabilized by mid-January 1979 but that the buildup in the recharge well continued at a rate of 2.0 ft/mo from January 15 to April 21, at a rate 4.5 ft/mo from April 21 to June 10, and at a rate of 16.2 ft/mo from June 13, after a 2-day shutdown due to power interruptions, to June 28. After June 28 until the termination of the test on July 20, the buildup rate, not including the shutdown on July 15-16, averaged about 73 ft/mo.

The dramatic increase in buildup rate was accompanied by an equally dramatic increase in the sediment concentration of the recharge water. Coarse sand and fine gravel were collected from the sampling line. This sediment was much too large to have passed through the 0.03-inch screen of the withdrawal well.

Downhole television camera surveys made in the recharge and withdrawal wells after the termination of the test, showed coarse sand and gravel coating the inside of the recharge-well screen and at least one hole in the casing of the withdrawal well. There was a 4-foot accumulation of sediment in the bottom of the recharge well that consisted mostly of medium to coarse sand, gravel, and a few small pebbles.

The visible hole in the casing of the withdrawal well was 5 ft above the static water level (90 ft below the land surface) and water from a perched zone above the aquifer could be seen flowing into the well. It is likely that the water flowing into the well in conjunction with vibrations from the pump caused sand, gravel, and pebbles from the surrounding gravel pack to enter the well and be sucked into the turbine pump and delivered to the recharge well.

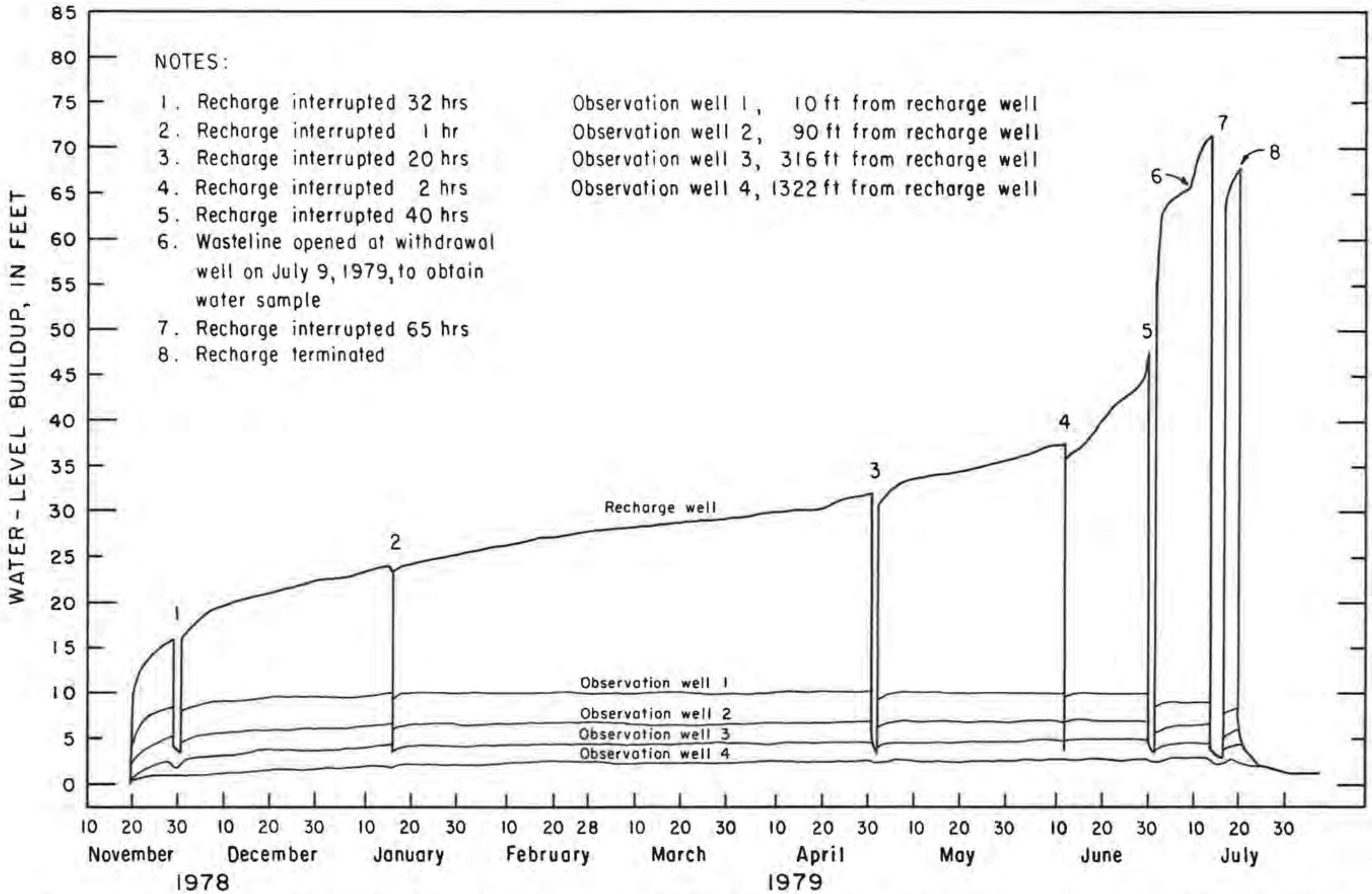

Figure 21.--Measured water-level buildup caused by recharging 247 million gallons - Aurora site, second long-term test.

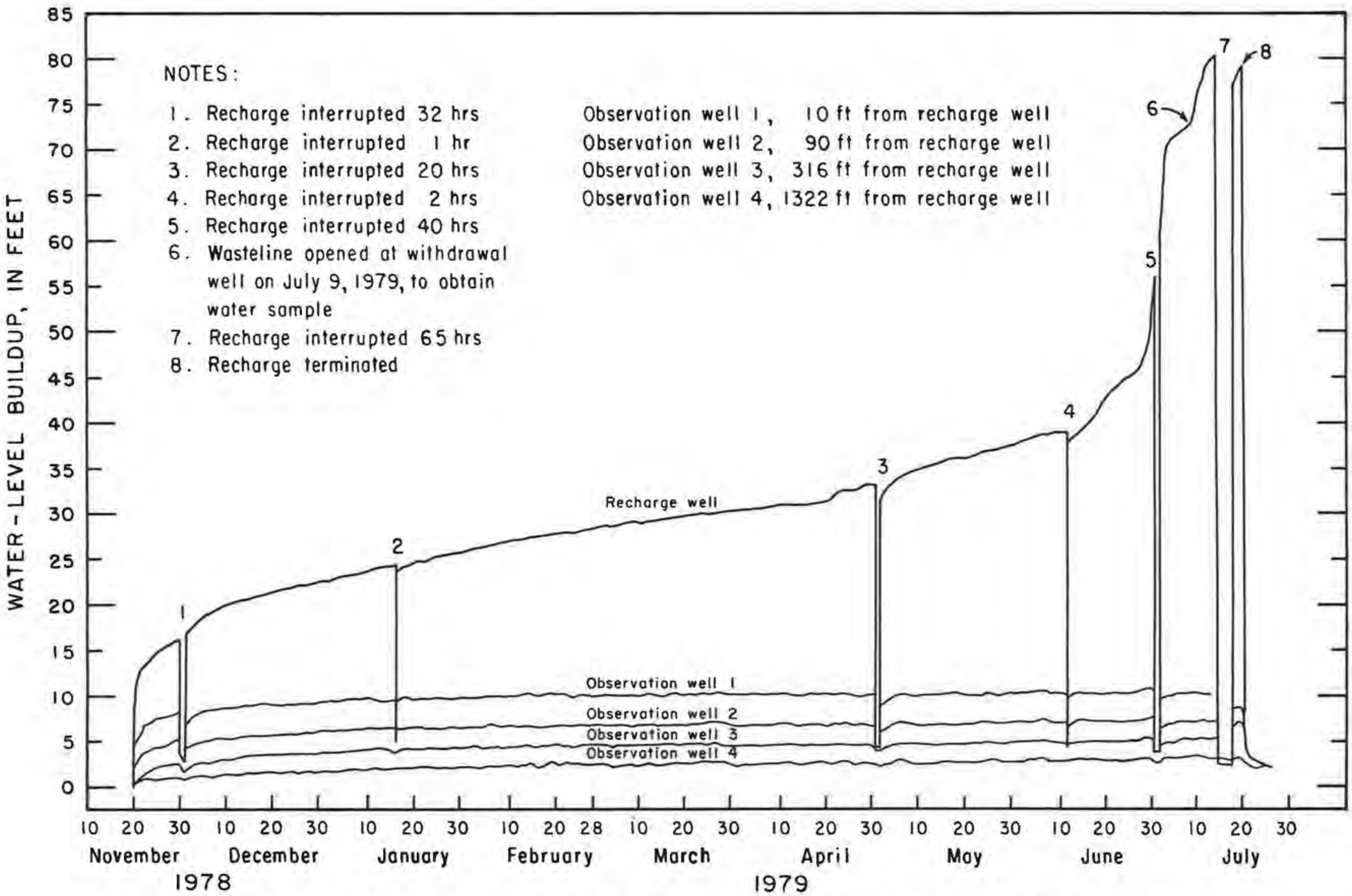

Figure 22.--Water-level buildup, adjusted to a constant recharge rate of 730 gallons per minute, caused by recharging 247 million gallons - Aurora site, second long-term test.

The failure of the casing, which had an anticipated life of at least 20 years, created some problems in correlating sediment concentration with water-level buildup, although the general correlation through mid-April can be seen in figure 23. It is likely that sediment entered the withdrawal well through the casing hole and was carried to the recharge well in a nonuniform manner as the gravel pack periodically collapsed against the outside of the casing in the vicinity of the hole. Therefore, the water samples taken for sediment analysis do not indicate the true average sediment load entering the well. The total calculated load entering the recharge well was 75 lb, but the sediment found in the bottom of the well equaled about 800 lb. The 800 lb does not include fine sediment carried through the screen into the gravel pack and the aquifer; therefore, the total sediment entering the recharge well was in excess of that amount.

It is not known when the hole in the casing of the withdrawal well began to develop, but from the buildup graph of the recharge well (fig. 23), it appears that the hole began contributing sediment to the recharge well in mid-April 1979. The effect of the sporadically increasing sediment load entering the recharge well on water-level buildup is evident in figure 23 and tends to support the conclusion that sediment was the principal cause of clogging in the recharge well.

Special efforts were made during the second long-term test to determine the dissolved oxygen of the water through use of a Martek water-quality analyzer. The efforts proved less than satisfactory because the instrument was insensitive at concentrations less than about 2 mg/L. Measurements made by the Winkler method on March 22 and April 2, 1979, indicated concentrations of 0.03 and 0.02 mg/L, respectively; whereas, the Martek readings were 1.26 and 0.85 mg/L. Probably the very low concentrations are representative of most of the test.

Readings from the Martek analyzer were useful in indicating that concentrations were consistently very low during most of the test and that little air was entrained in the recharge water. Readings were as high as 5-6 mg/L in the first water through the pipeline; however, this water was discharged to the ditch and water was not allowed into the recharge well until the concentrations decreased to less than 2 mg/L. As in the first test, the temperatures and pressures in the aquifer were similar where the water was withdrawn and where it was recharged; therefore, there should have been little or no emergence of dissolved gases.

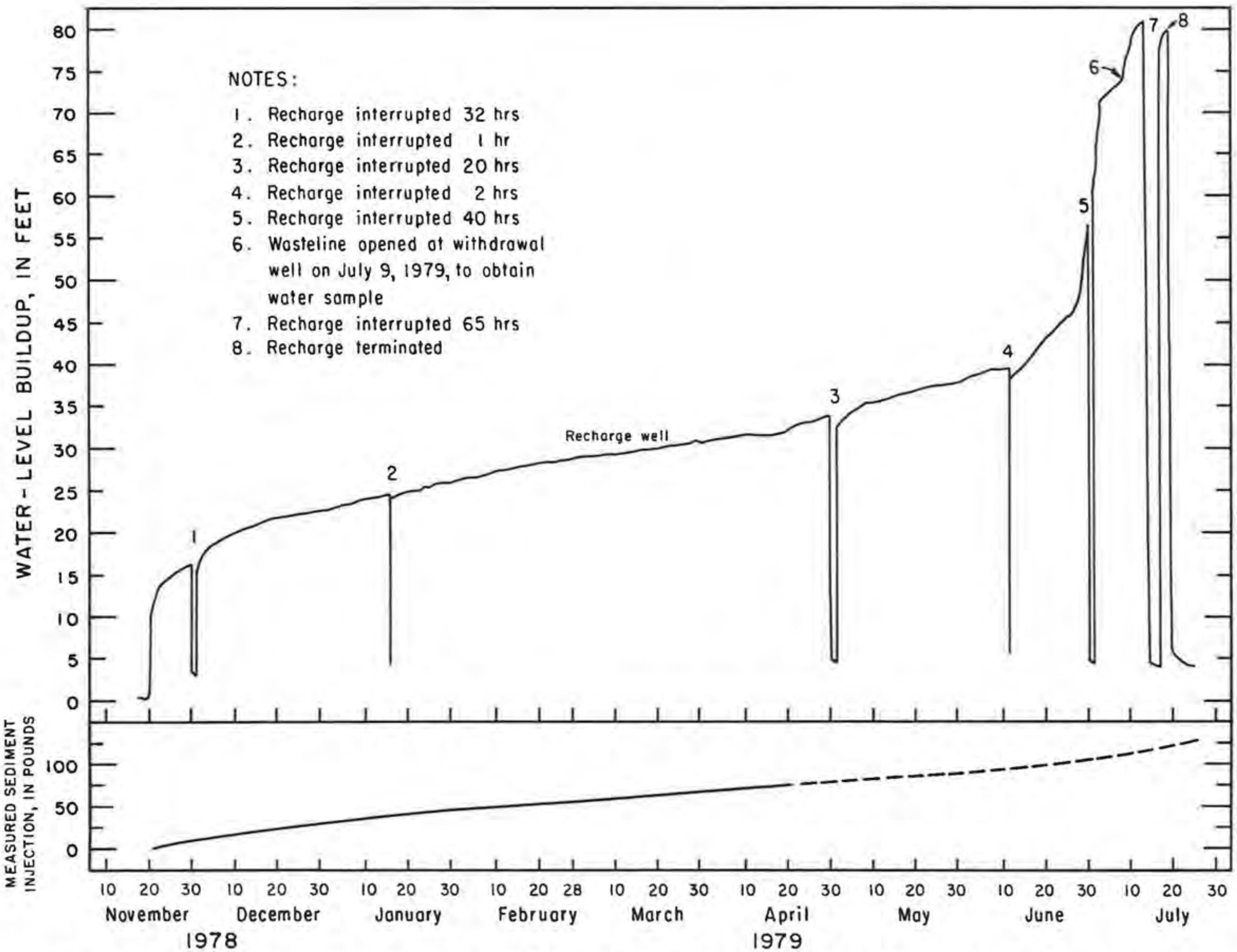

Figure 23.--Water-level buildup in recharge well, adjusted to 730 gallons per minute, and sediment injected into recharge well - Aurora site, second long-term test.

The number of bacteria in the recharge water was determined as in the first test (table 6). In addition, water samples were collected from within the casing of the recharge well for bacterial analysis. The samples were collected with a small sterilized bottle that was opened 5 ft below the water level in the well (75 ft below the land surface). The samples were analyzed by Dr. Thomas L. Thompson, professor at the School of Life Sciences, University of Nebraska-Lincoln. Dr. Thompson reported that he found no Gallionella or Leptothrix bacteria in the sample. He identified some chromobacterium and slime formers, but in his opinion nothing that would cause clogging in a well. There was a little mold growth which indicated slight outside contamination of the sample. Although bacterial growth in the recharge well cannot be ruled out entirely as a cause of clogging of the aquifer, the bacterial analysis and the condition of the inside of the well, as revealed by the television survey made 3 days after the termination of recharge, indicate that bacterial growth was not a significant cause of clogging.

The second long-term recharge test substantially verified the principal conclusion of the first long-term recharge test, that large quantities of clean water can be recharged through a well at a rate of 730 gal/min or more if the water and the aquifer are compatible. Entrained or dissolved air, bacteria, and chemical reactions did not appear to present any problems; however, even very small quantities of suspended sediment in the recharge water caused some clogging of the recharge well during the test period.

It appears likely that under any practical system of large-scale artificial recharge through wells, provision would have to be made to redevelop the recharge wells periodically. Pumping of the recharge well did not improve appreciably the specific capacity of the recharge well.

Anomalous Ground-Water Quality at Aurora Site

The survey of the specific conductance of ground water in Hamilton County during 1969 showed that the specific conductance ranged from 423 to 997 umho/cm (fig. 10). A more detailed survey was made in January 1976 of that part of Hamilton County selected as a possible site for the well-recharge experiment. The specific conductance of the water from the three wells closest to the location selected for the recharge well were 670 umho/cm (Mrs. Forsman's well 454 ft to the west-northwest), 793 umho/cm (Monroe church well 500 ft to the southeast), and 668 umho/cm (Kenneth Herrold's well 1,120 ft to the northeast). These specific conductances were within the range generally found in ground water in Hamilton County and the Big Blue River basin.

The recharge well was drilled at the same time that the withdrawal well was drilled and the pipeline constructed. When water samples were collected and analyzed during development of the recharge well, the specific conductance, surprisingly, was 2,410 umho/cm, which was higher than any ground water previously sampled in the area and much higher than Platte River water that generally is less than 1,000 umho/cm. Repeated sampling gave the same results. The nitrate concentrations were among the highest ever found in ground water in the State (160 mg/L, table 2); concentrations in water from most wells in the area were less than 10 mg/L and those in Platte River water in the area generally were less than 1 mg/L.

When the highly mineralized water was discovered at the recharge-well site on September 3, 1976, the nearby private wells were resampled. The specific conductances of the water in the Monroe Church well and the Herrold well had not changed appreciably since January; however, the specific conductance of the water in the Forsman well had increased from 670 to 3,260 umho/cm (table 5). The nitrate concentration in the water from this well also had increased from 9.2 to 260 mg/L, and the sulfate concentration similarly had increased from 110 to 830 mg/L.

Discussions with Mrs. Forsman revealed that her water softener had not functioned efficiently during and for some time after each irrigation season (July to August) for a number of years, but functioned properly during the rest of the year. The apparent malfunction of the water softener was probably caused by a great increase in the mineralization of the water during and immediately after the irrigation season. The increase in mineralization in water from the Forsman well appears to be directly related to drawdown of the water table caused by sustained pumping from an irrigation well about 1,200 ft to the northwest. By the next January, the specific conductance of water in the Forsman well was a normal 678 umho/cm.

In March 1977 water samples from the Forsman well were collected and analyzed for several days before a planned 48-hour pumping test of the recharge well. The specific conductance of the samples ranged from 675 to 678 umho/cm. However, a sample collected from the Forsman well after 42 hours of pumping had a specific conductance of 2,820 umho/cm. The specific conductance of samples collected at intervals after termination of the test gradually decreased until they returned to normal 3 days after the test. The specific conductance of the water from the recharge well during the pumping test varied from 3,000 to 3,420 umho/cm.

A possible explanation of the phenomenon detected in the Forsman well is that a layer of highly mineralized water exists in the upper part of the aquifer in the vicinity of the well. With normal pumping of the domestic well of only a few gallons per minute, the water was not drawn into the well; however, heavy pumping lowered the water table to or below the top of the screen and allowed the mineralized water to enter the well.

The source of the highly mineralized water that existed in the vicinity of the recharge well before the start of the recharge experiment is not known. Samples of the water from the recharge well were analyzed for nitrate isotope ratios by Dr. Roy Spalding, professor and hydrochemist at the University of Nebraska-Lincoln. Dr. Spalding reported that the ratio was 3.9, which indicated that the source of nitrate in the water was not human or animal waste. Fertilizer is an unlikely source because the recharge well is located in a plot of virgin prairie that had no significant application of fertilizer. In addition, none of the irrigation wells, many of which are located in corn fields that have received heavy applications of fertilizer for many years, yielded water with nitrate concentrations anywhere nearly as high as those of water from the recharge well.

A likely source of the highly mineralized water is, so-called, "geologic nitrate", or nitrate derived from organic matter buried perhaps thousands of years ago. The recharge well is only about 100 ft south of a shallow, mostly dry slough that is part of the headwaters of the Big Blue River. Organic matter associated with an ancestral course of the slough may be the source of the excessive nitrate. Evidence to support this possibility was detected during a 66-hour recharge test conducted during May 17-20, 1977. The mineralization of water from observation well 3, located 316 ft north of the recharge well, increased 50 percent as recharge progressed but decreased during sustained recharge later in 1977. It seemed as if a body of highly mineralized water had been pushed by recharge water north from the vicinity of the slough to observation well 3, and that further recharge had pushed the mineralized water beyond observation well 3.

The discovery of the body of highly mineralized water in the vicinity of the recharge well after it was too late to select a different site caused considerable consternation. However, subsequent events showed that the mineralized water did not interfere significantly with the principal objectives of the investigation for two reasons.

First, analysis of water samples collected from observation well 1, 10 ft from the recharge well, showed that native ground water had been flushed at least 10 ft from the recharge well during the early part of the first long-term test; therefore, chemical reactions could not have taken place between native and recharge water in the immediate vicinity of the well after the early part of the first long-term test.

Water-level measurements in the observation wells indicated that all clogging occurred less than 10 ft from the recharge well, so chemical reactions between the dissimilar water were not a significant factor in the long-term recharge operations. If chemical reactions were not a factor in the high mineral concentrations found in the vicinity of the recharge well, it is unlikely they would be a factor in the lower concentrations found in more typical Big Blue River basin ground water.

Second, although the concentrations were higher than those typical of Big Blue River basin ground water, the type of constituents were similar, so the same type of reactions likely would occur. A water sample collected subsequent to the 66-hour recharge test during May 17-20, 1977, contained a mixture of native and recharge water. Chemical analysis of this sample (table 5) did not show the formation of any compounds that would likely cause clogging of the well. Therefore, it is unlikely that there would be adverse chemical reactions between Platte River-type water and typical Big Blue River basin-type ground water.

Tracer Tests

A tracer test to determine the rate of movement of recharge water in the aquifer was conducted at the Aurora well-recharge site in November 1977. Injection of the tracers began at 1640 hours on November 7. At the start of the test, water had been recharged continuously to the aquifer at a rate of 750 gal/min since October 31, 1977. Records of water levels in the observation wells showed that reasonably steady flow conditions existed at the start of the test. Recharge continued at the same rate for 30 hours before a snowstorm interrupted power for 16 hours after which recharge was resumed at the same rate.

Tracers used -- Five tracers were injected simultaneously into the recharge well. The principal tracer was bromide introduced as sodium bromide (NaBr). This tracer was selected because of low natural concentrations in the aquifer, the conservative nature of the bromide ion, the ease of analytically determining trace concentrations, and its nontoxicity.

The remaining four tracers were fluorocarbon species which were used to test their suitability as tracers. Results of the fluorocarbon tracer tests are given by Thompson and others (1978).

Water samples were collected from observation wells 1 and 2 using low displacement (0.01-0.08 gal/min) pressure lift pumps installed at depths of 105, 115, and 125 ft in observation well 1 and 145 and 170 ft in observation well 2. Description of the operation of these pumps is given by R. F. Middleburg (U.S. Geological Survey, written commun., 1976) and Signor (1978). These pumps yield a semicontinuous flow of water. Water samples from piezometers P1, P2, P3, P4, P5, and P6 were obtained using airlift pumps constructed with a short length of ½-inch pipe attached to a pressure line and a sampling line.

In addition to collecting samples for laboratory analysis to determine bromine concentration, on-site analyses were made using a specific ion bromide electrode and a digital voltmeter. The on-site analyses were used as indicators of bromide arrival at the observation points to determine the optimum frequency of sampling. Analytical accuracy was determined by blind analysis of samples of known concentration supplied by the U.S. Geological Survey laboratory in Arvada, Colo., and by splitting samples for dual analysis by the laboratory and project personnel.

Results.--Bromide concentrations increased to greater than natural concentrations in observation wells 1 and 2 and in piezometers P2 and P3. (See fig. 9 for well location.) The times of arrival of maximum concentration of bromide showed that, radially, the aquifer is not completely homogeneous. Although piezometer P3 is 52 ft farther from the recharge well than observation well 2, the tracer arrived at piezometer P3 first and the maximum concentration was higher than in observation well 2. This indicates preferential permeability in the direction of piezometer P3. Comparison of the concentration values obtained from piezometer P3 screened in the top of the aquifer and nearby piezometer P2 screened in the middle of the aquifer show that the aquifer is not homogeneous vertically in the direction of piezometers P3 and P2. However, the nearly identical values for the two sampled depths within the screened interval in observation well 2 show that the aquifer is reasonably homogeneous vertically in that direction. Flow possibly is radially symmetrical except in the direction of piezometer P3.

The maximum concentration of the bromide tracer, which was equal to the injection concentration, appeared in observation well 1 about 1½ hours after the start of injection; however, the first significant increase in bromide concentration appeared after only 11 minutes. At observation well 2, 90 ft from the recharge well, the maximum concentration (87 percent of the injection concentration) arrived about 66 hours after the start of injection. The first significant increase occurred 24 hours after the start of injection. The arrival times of the fluorocarbon tracers at the observation wells agreed very closely with the arrival times of the bromide tracer.

At piezometer P3, 142 ft from the recharge well, the maximum bromide concentration detected (29 percent of the injection concentration) occurred at the 105- to 110-foot level after only 24 hours. Because piezometer P3 is a greater distance from the recharge well than observation well 2 (142 versus 90 ft), it was assumed that it would arrive at piezometer P3 later than at observation well 2. Therefore, piezometer P3 was not sampled until 21 hours after the start of tracer injection. However, by then the bromide had already arrived at the 105- to 110-foot level in piezometer P3. A likely explanation is that an elongated lense of coarse gravel connects piezometer P3 to the recharge well and permits more rapid flow of recharge water in that direction.

The time required for detection of the first change in water level resulting from recharge and the actual arrival of recharge water at various distances from the recharge well are listed in table 7. Although, as noted previously, water does not move uniformly through the ground, the data in the table give an indication of the relative speed of pressure waves and the actual speed of movement of the water.

EXPERIMENTS IN RECHARGE THROUGH WATER-SPREADING SYSTEMS

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. Water-spreading can be accomplished by flooding or spraying the land surface, by impounding water in shallow excavations, by diverting water into canals, 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, a layer with low permeability through which the water must pass generally controls the rate of downward movement. This controlling layer can be at the land surface or at any depth between the surface and the aquifer and is not necessarily the layer with the lowest permeability. If the controlling layer is at considerable depth, its effect on recharge may not become apparent until long after the start of artificial recharge operations.

Table 7.--Approximate time of first change in water level and arrival time of bromide tracer at observation wells due to recharge at Aurora site

Well measured or sampled	Distance and direction from recharge well	Time required for detection	
		Change in water level	Arrival of tracer
Observation well 1	10 ft northeast	1 second	11 minutes
Observation well 2	90 ft east-southeast	5 seconds	24 hours
Piezometer P3	142 ft south-southwest	9 seconds	21 hours
Observation well 3	316 ft north	15 seconds	Not observed

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 1-2 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 or drilled 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-ft 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 commonly is used on basins that operated well originally but have decreased infiltration capacity because of clogging by sediment, bacterial growth, or both.

Alternate wetting and drying of a recharge basin is often used in place of, or in conjunction with, scarification. The drying process kills most microorganisms, which clog the soil, and hastens the decomposition of their bodies and the slimes they have created. 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.

Ring-infiltrometer tests, made as part of the investigation, used ground water, which was almost sediment free, to avoid the need of settling areas or retention basins to remove debris and to reduce the need for scarification and wetting and drying. The tests were designed to locate possible perching layers that would retard downward movement of water and to determine which layer would probably control recharge rates in a large-scale recharge operation. This information can help in evaluating the feasibility of surface spreading as a method of recharge in many areas of Nebraska and possibly elsewhere.

Aurora Site

Equipment for a water-spreading experiment was installed near the well-recharge site 8 mi northwest of Aurora. 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 locations are near the recharge well partly because the well site is representative of large areas in the Blue River basin and partly to facilitate comparison of the effectiveness of well injection and water-spreading methods of artificial recharge. No attempts were made to find locations with highly permeable soil because the objective of the experiment was to test the recharge capabilities of typical Blue River basin materials. A 1927 soils map (the latest available) indicates that the soil at the site is Hastings silt loam, which includes 56 percent of the soils in Hamilton County (Goke and Buchannon, 1927). Aspects of the geology of the area are shown in figure 5.

Instrumentation

The ring infiltrometer (fig. 24) was formed by bolting together sections of corrugated steel into 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

Figure 24.--Surface-spreading installation near Aurora.

to minimize leakage. A water supply was obtained using a 1½-inch plastic hose from a 180-foot-deep well at the Monroe church about 400 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 from rainfall and losses due to evaporation.

A 1½-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 and was caused by a 6-inch clayey sand layer at a depth of 38 ft.

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 infiltrometer. 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.

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 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 obtaining neutron logs at the same time that adjacent "undisturbed" core samples were taken for analyses of moisture content at a laboratory established at the site. By logging a hole periodically and comparing the logs, it is possible to determine the movement of a wetted front as it moves downward to the aquifer.

Tensiometers, which use porous cups, were installed inside the ring at depths of 2, 6, 12, 24, 36, and 48 in. below the land surface. Porous cups equipped with sampling tubes were placed within the ring at depths of 6, 22, 37, 53, and 79 ft below the land surface. The holes drilled to implant the tensiometers and the porous cups were sealed with bentonite. The purpose of the tensiometers was to monitor the movement of the wetted front in the first few feet below land surface. The cups, equipped with sampling tubes, were used to collect water samples from the unsaturated zone or perched saturated zones for chemical analysis. A vacuum was placed on these porous cups to draw in moisture from outside the cups. When sufficient volume had entered the cups, air pressure was applied to one of two hoses connected to the cups, 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 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 7-inch hole to a depth of 95 ft and emplacing short, 1½-inch-diameter screens at depths of 95, 91, 68, 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 0.5 ft 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. 25). The inclined manometer measured the air pressure in each of the various zones. By taking successive readings when the atmospheric pressure changed rapidly and comparing the readings to the atmospheric pressure at corresponding times, the air permeability of various zones was determined. The air permeability was then converted to hydraulic conductivity (Weeks, 1977).

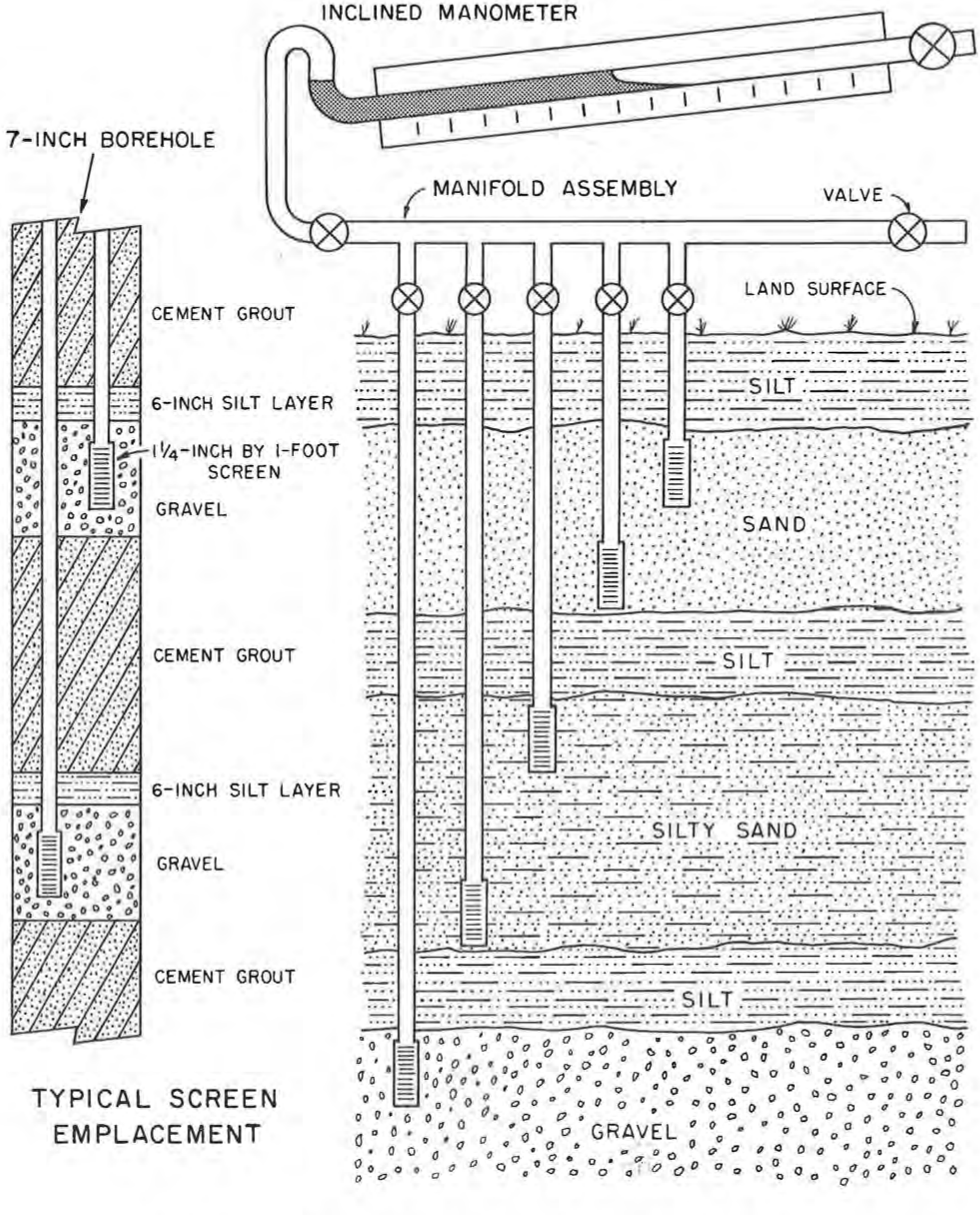

Figure 25.--Typical air-permeability installation.

The air-permeability technique is operable only above the water table, as saturated zones are virtually impermeable to air. Because the perched zone of saturation above the low permeability layer at a depth of 38 ft existed throughout the investigation, hydraulic conductivity could only be determined for the 7- to 28-foot interval. That conductivity was calculated to be 0.9 ft/d (Lappala, oral commun., 1980).

Results of tests

A preliminary test and two long-term tests using the 24-foot-diameter ring infiltrometer were conducted at the Aurora site. The preliminary test was a short-termed one 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. No monitoring devices were installed except a meter to measure the quantity of water put in the infiltrometer. Based on these data, it was decided that an adequate recharge supply could be obtained from the well at the Monroe church.

During the preliminary test, the ring infiltrometer was emplaced 1 ft below the ground surface; however, lateral seepage at the ground surface was observed for distances of as much as 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 in. below land surface 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.

For the first long-term test, the ring infiltrometer was filled with water on October 25, 1977. Initial infiltration rates, corrected to 50°F, were computed as 0.36 ft/d. The rates increased for 10 or 11 days to a maximum of 0.66 ft/d (fig. 26) and then decreased slightly for the next 3 days. The test was terminated on November 18, 1977, because of freezing weather. The duration of this test was insufficient to provide definitive answers as to the practicality of surface spreading as a method of artificial recharge in the site area.

A second long-term infiltration test was started on June 20, 1979. The same ring infiltrometer was used as in the first test. It was assumed that the soil and bentonite sealant had settled in place around the monitoring devices and would prevent any excessive seepage near the devices.

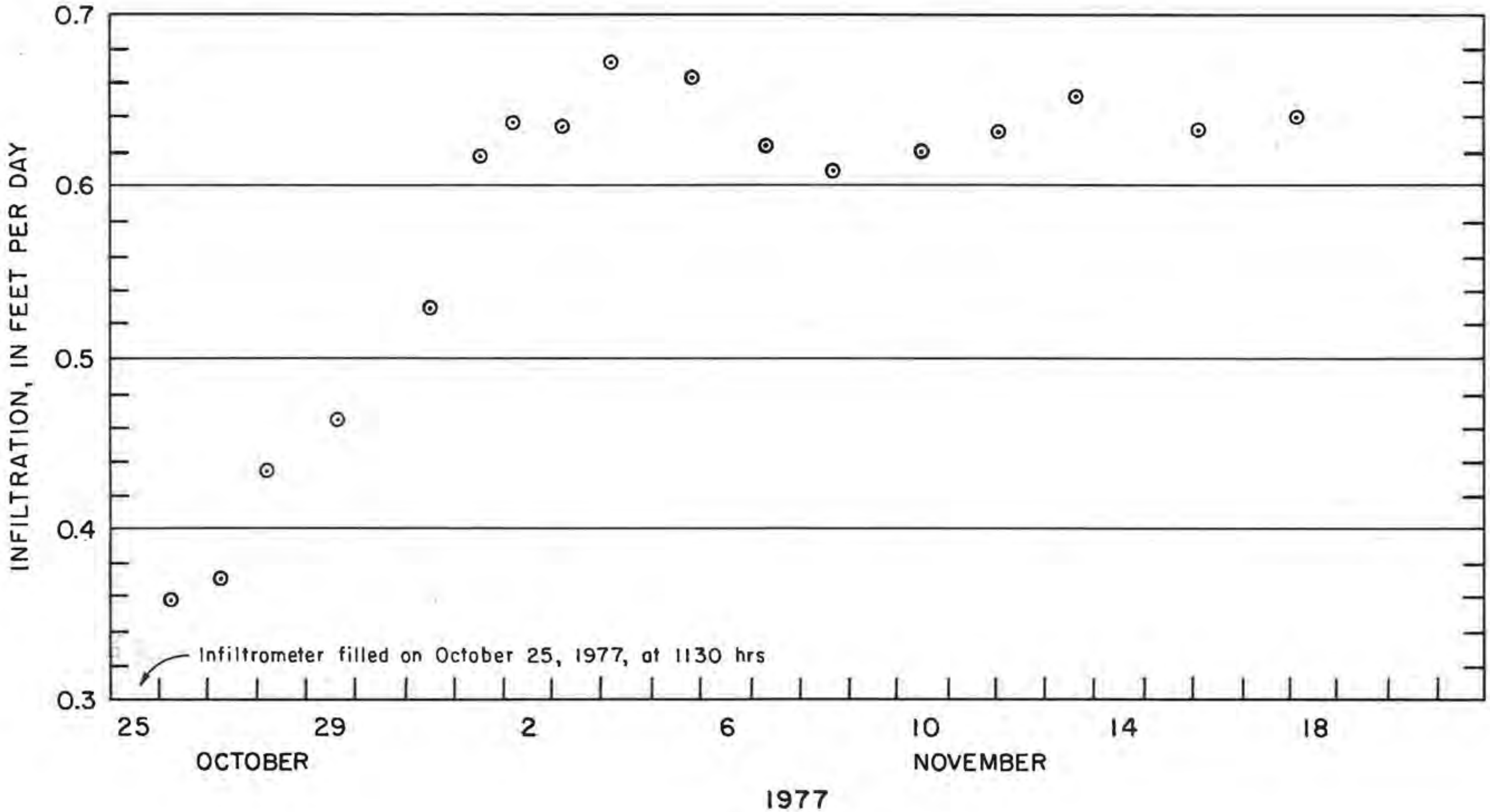

Figure 26.--Changes in infiltration rate (corrected to 50° F) from 24-foot-diameter infiltrometer, Aurora site.

A control ring was installed nearby in the same manner as the instrument ring except that no monitoring devices were emplaced. The control ring was added to check the assumption that no excessive infiltration was occurring through the holes drilled to emplace the monitoring devices. The data from the second test is summarized in figure 27. The infiltration rate decreased during the first few days as cracks and voids in the surface material filled up or swelled shut. Then the infiltration rate gradually increased as air in the unsaturated material was driven out or dissolved by the recharge water. The infiltration rate from the control ring (fig. 28) increased more rapidly than the rate from the instrumented ring (fig. 27) indicating that excessive infiltration did not occur through the seals around the instrumentation holes.

Why the infiltration rate from the control ring increased faster than that for the instrumented ring and was higher at the conclusion of the test (0.54 versus 0.40 ft/d, October 28, 1979), is not known, but one possibility is that residual buildup of algae in the soil from the 1977 test decreased the infiltration rate from the instrumented ring. Algal growth occurred more rapidly in the instrumented ring than in the control ring. A second possibility is that the bentonite seal around the control ring was not as effective as it was around the instrumented ring, permitting greater lateral infiltration. However, examination of the soil around both rings did not indicate this.

The implication of the first hypothesis, that is, that residual algae from previous recharge cycles caused a faster algal buildup and lower infiltration rates even after 19 months of drying, is that infiltration rates in a large-scale surface-spreading operation could decrease from initial rates even if the basin were allowed to go dry periodically.

During the first infiltration test, the water level in the piezometer emplaced in the perched zone of saturation above a depth of 38 ft was measured periodically, but during the second test it was recorded continuously. The record shows (fig. 27) that the water level in the 1¼-inch piezometer reacts to rainfall and barometric fluctuations as well as to seepage from the infiltrometer. The reaction to rainfall and seepage is controlled to some degree by antecedent conditions of soil moisture, but reaction to changes in infiltration from the infiltrometer occurred within 1 to 3 days of wetting or drying.

During the first test, which lasted 24 days, the water level in the piezometer rose about 3.5 ft. During the second test, which lasted 134 days, the water level rose 12 ft. The actual rise due to artificial

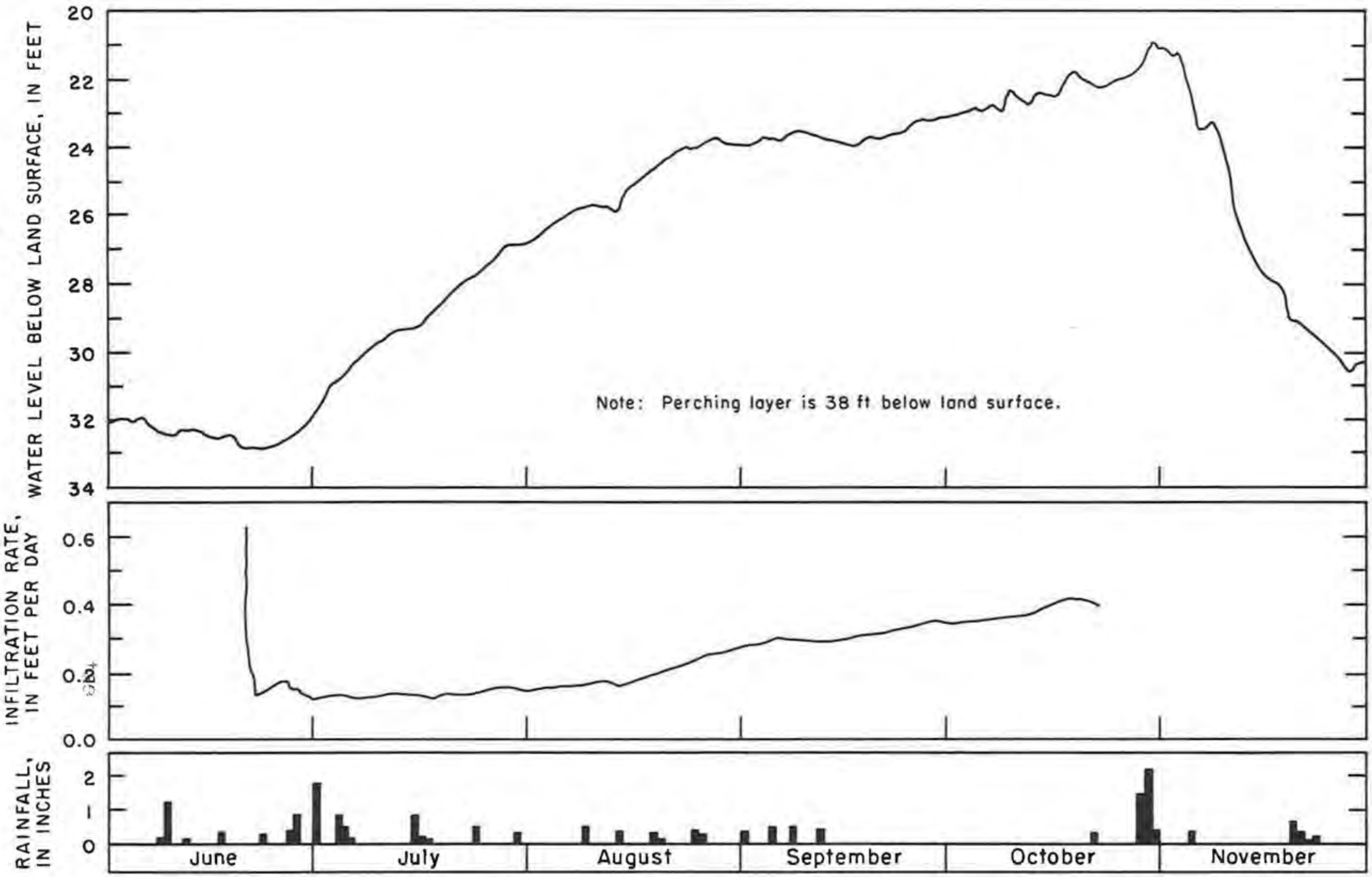

Figure 27.--Relationship between water level in perched zone, infiltration rate, and rainfall--surface-spreading site near Aurora, 1979.

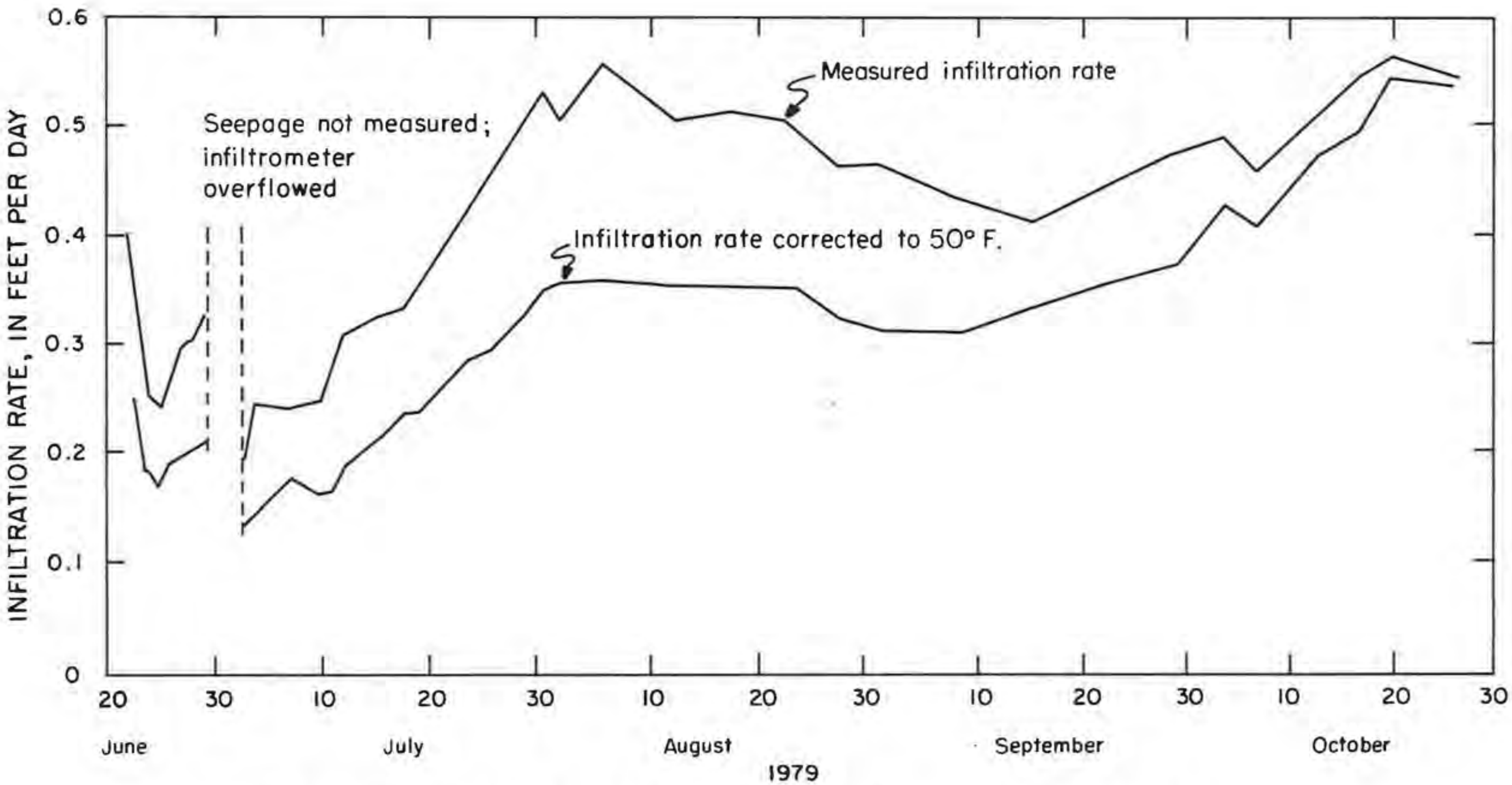

Figure 28.--Infiltration rates from control-ring infiltrometer, Aurora site.

recharge was somewhat greater than 12 ft because the water level was declining at the start of recharge. The water level was still rising when freezing weather caused termination of the test.

The area of the base of the saturated mound that built up on the less permeable zone at 38 ft was not determined. However, the fact that the mound continued to rise indicates that it was still expanding and that the less permeable layer was not yet transmitting downward a volume of water equal to that moving downward from the ring infiltrometer. As the area of the mound and the hydraulic head on the less permeable layer are much greater than the area of the ring infiltrometer (0.01 acre) and the hydraulic head above land surface (1 ft), the permeability of the 38-foot layer must be much less than that of any layers near the land surface. Therefore, the permeability of the layer at a depth of 38 ft will control the per-unit-area recharge rate in any long-term, large-scale surface-spreading type of artificial-recharge operation at this site.

Conclusions are that at the Aurora site, large-scale surface spreading probably would not be technically feasible because of less permeable layers at depth. Small-scale surface spreading or spreading through ditches might be feasible. Some areas within a few miles of the site may be suitable for recharge because the less permeable layers seem to be absent. In comparison, well recharge probably is technically feasible.

Tryon Site

Water-spreading tests were conducted at the University of Nebraska Sand Hills Agricultural Laboratory near Tryon. This site is very much different, geohydrologically, from the Big Blue River basin. Groundwater supplies are abundant at the present time (1979), because rainfall can readily infiltrate to aquifers; however, water-resource development is accelerating and shortages undoubtedly will occur in the future.

Instrumentation

A 25-foot-diameter ring infiltrometer similar to the one at the Aurora site was installed at the Tryon site (fig. 29). The ring was installed to a depth of 14 in. The edge of the ring was sealed with bentonite to minimize lateral leakage. A water supply was obtained from a 4-inch well drilled for the purpose 270 ft from the ring.

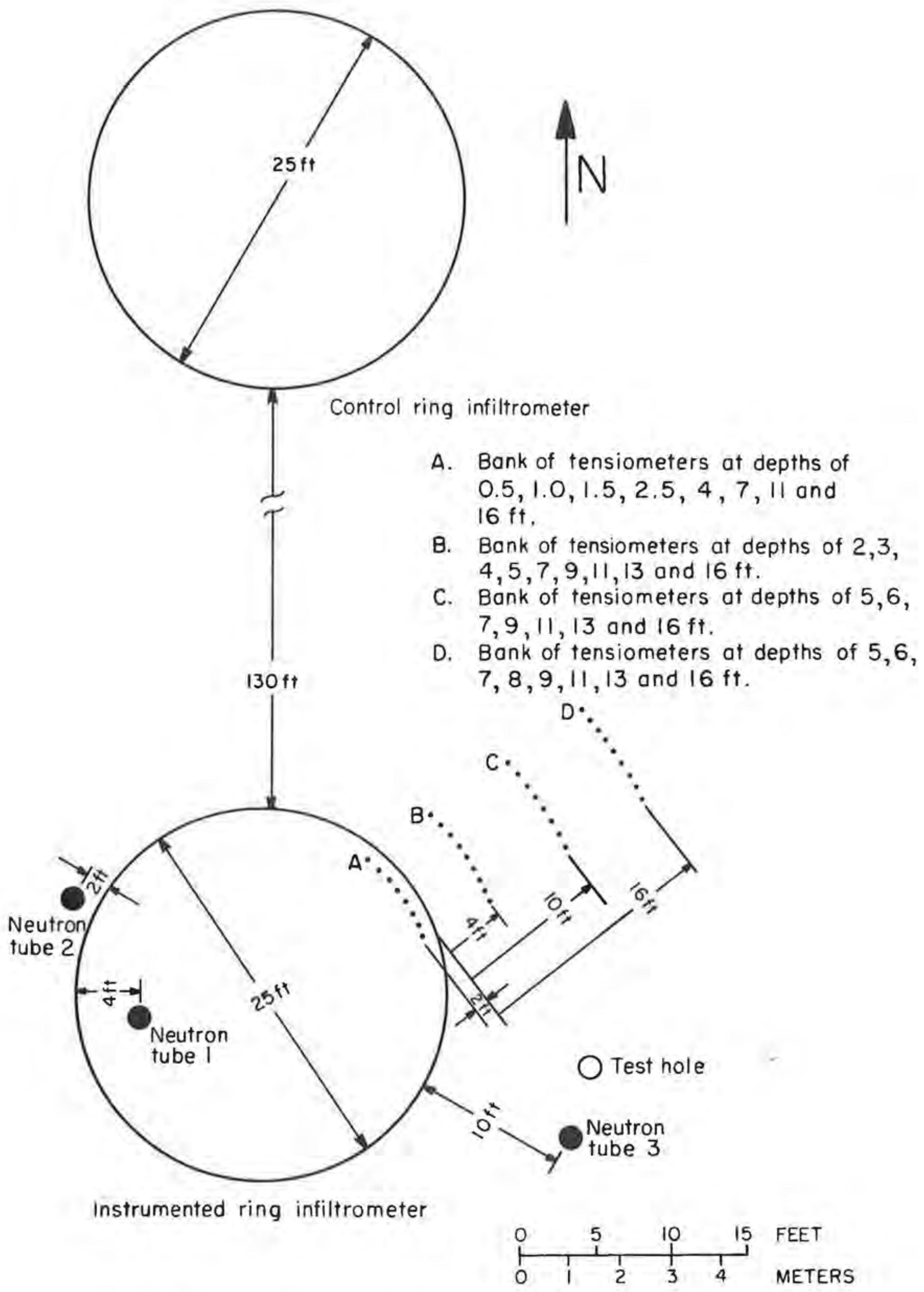

Figure 29.--Artificial-recharge site near Tryon.

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

Three neutron-probe access tubes were constructed by augering 2½-inch-diameter holes to depths of about 94 ft. A 2½-inch-diameter black-iron, threaded-and-coupled pipe (tube) with a solid-drive point was then driven to near 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, one was installed 2 ft from the ring, and one was installed 10 ft from the ring. The access tube inside the ring was installed to measure downward movement of recharge water under the ring and the two outside were installed to measure both downward and lateral movement of water as at the Aurora site.

For the first infiltration test on August 23, 1978, eight tensiometers were installed inside the ring at depths 0.5, 1, 1.5, 2.5, 4, 7, 11, and 16 ft below land surface. Porous cups were installed at depths of 6.75, 40, 40.9, 66.7, and 81.7 ft below land surface.

Because of dramatic evidence of lateral movement of recharge water obtained during the first test, banks of tensiometers were subsequently installed at distances of 4, 10, and 16 ft from the edge of the ring to monitor this lateral movement. The depths and locations of these tensiometers and ones installed earlier are shown in figure 30.

The tensiometers were to be used to monitor water movement near the surface and the porous cups were to be used to collect water samples from the unsaturated zone or perched saturated zones for chemical analysis as at the Aurora site. Whereas, bentonite had been used to seal the holes at the Aurora site, expansive cement was used at this site.

A continuous core was collected to a depth of 90 ft from a test hole drilled about 5 ft from neutron hole 3. Moisture content was determined at 5-foot intervals or change of lithology. A neutron log was made at the same time in neutron hole 3 and the information from the core hole was used to calibrate the neutron log. The test hole was left open for possible installation of an air-permeability experiment. A non-instrumented ring infiltrometer, similar in design to the instrumented one, was installed 130 ft north of the instrumented one as a control.

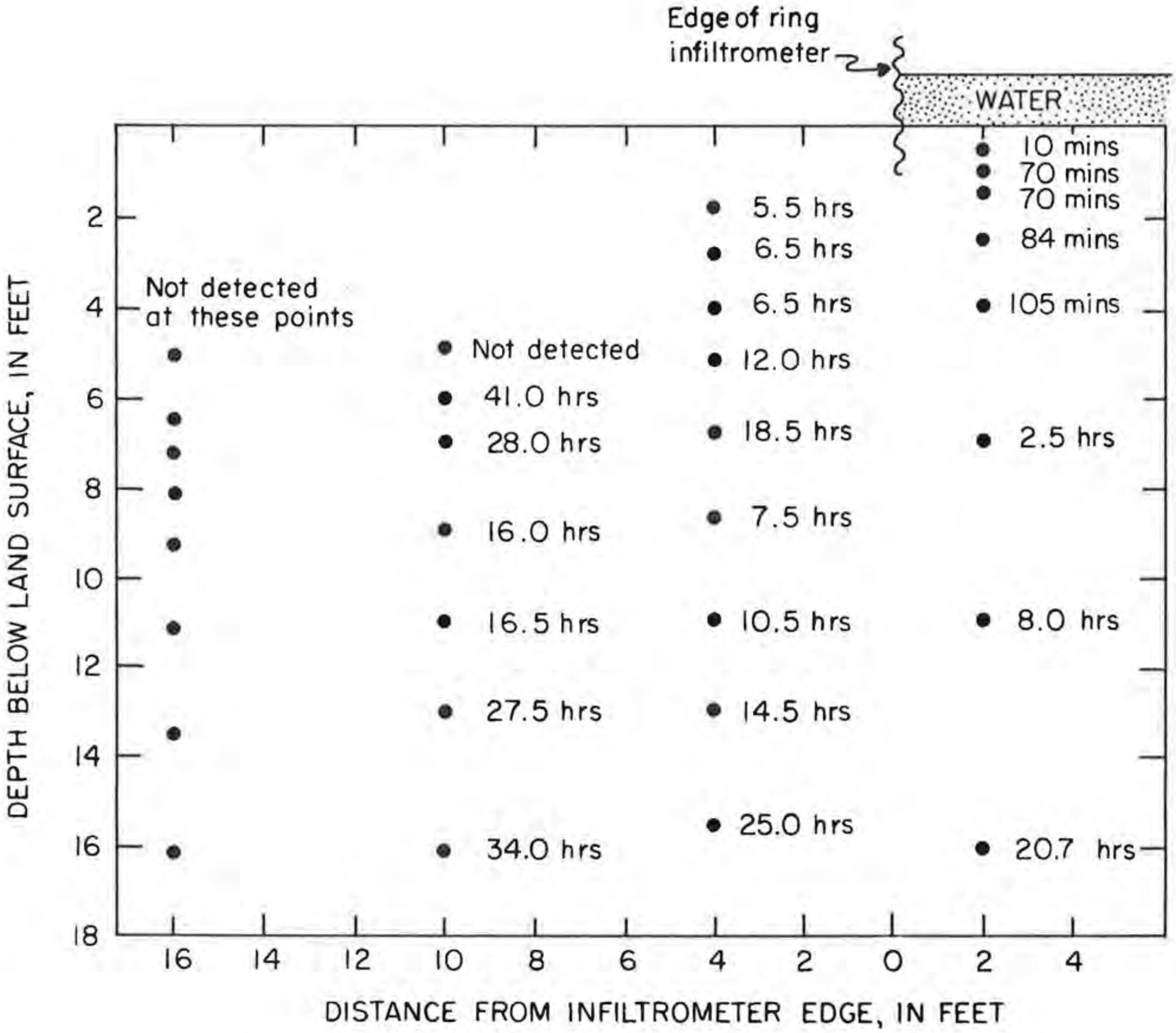

Figure 30.--Time of arrival of wetted front at tensiometers, Tryon site, second test.

Results of tests

Three tests using the 25-foot-diameter ring infiltrometer were conducted at the Tryon site. The tests were designed to monitor lateral and vertical movement of recharge water and variations with time in the infiltration rate.

Lateral movement of water.--The first test started on August 23, 1978. Initial infiltration rates were about 8.2 ft/d and gradually declined to 6.3 ft/d by August 25. On August 25, water suddenly began spouting from the nearby open test hole. A bucket that had been covering the hole was propelled several feet in the air. The 3,670 gal of water that had been in the ring infiltrometer rapidly drained through a hole about 2 ft inside the ring and gushed out the test hole 9 ft from the ring.

Subsequent inspection revealed an open passageway from inside the ring to a point in the test hole about 10 ft below land surface. This passageway had been formed by infiltrating water that had moved laterally along the top of a less permeable layer about 10 ft below the surface. During the 30-hour test, the infiltrating water that ran down the test hole was able to erode a passageway a distance of 11 ft horizontally and 10 ft vertically to the point inside the ring. The less permeable layer was not apparent on first examination of material from the test hole but was apparent on closer inspection. The passageway and the part of the test hole not filled with sand during the draining of the ring were filled subsequently with expansive cement.

The second test was started on September 12, 1978. The arrival time of the wetted front at the indicated points are shown in figure 30. The times indicate that the water did not move uniformly downward and outward from the ring infiltrometer. For example, at the bank of tensiometers 4 ft from the ring, the wetted front arrived at the 8.5-foot depth before it arrived at the 6.7-foot depth. This was caused by the nonhomogeneity of the material. Water moved downward beneath the ring and then flowed laterally along the top of the less permeable layer faster than it diffused outward and downward from the surface by gravity and capillarity. Similarly, at the bank 10 ft from the ring, water arrived at the 9.1- and 11.1-foot depths before it arrived at the 7-foot depth.

Arrival of the wetted front was not detected at the bank 16 ft from the ring during the test. It is possible that water did not move 16 ft laterally in the top 16 ft; however, recurring air bubbles in the 16-foot bank of tensiometers interferred with the moisture tension measurements so it is also possible that a small amount of recharge water did move to the vicinity of the 16-foot bank.

If it is assumed that the lateral edge of the wetted zone was symmetrical and was between 10 and 16 ft from the edge of the ring at the 10-foot depth and that capillary diffusion was small, then the 10-foot layer transmitted water downward at a rate only 31 to 19 percent as fast per unit area as the surface layer. The area of infiltration inside the ring was 491 ft^2 and the area of infiltration at the 10-foot depth within 10 to 16 ft from the ring was 1,590 to 2,550 ft^2.

The hydraulic head of water at the surface was 1 ft; however, the hydraulic head on the 10-foot layer was not known accurately, therefore the exact relationship of the permeabilities of the surface layer and the 10-foot layer was not determined. Differences in the permeabilities of various subsurface layers would have to be considered if any large-scale surface-spreading recharge operation was contemplated. Failure to do so could result in lower recharge rates than anticipated and possible water logging of nearby areas.

The distances that water spreads laterally on less permeable layers at greater depths was not determined; but evidence of ponding, to be discussed in the section on vertical movement, indicates that lateral movement was probably much more than 10 ft.

Vertical movement of water.--The vertical movement of water through the unsaturated zone was monitored to a depth of 82 ft by use of the neutron probe. Logs showing relative moisture content with depth on several selected dates are presented in figure 31. Because lateral movement of the recharge water was so pronounced near the land surface, the logs from the access tube inside the ring and the access tube 2 ft from the ring were nearly identical; therefore, only those from the access tube inside the ring are shown in figure 31. The log from the access tube 10 ft from the ring was apparently affected by water moving down the test hole which was 5 ft from the access tube and, therefore, was not reliable.

The first log in figure 31 was made before the ring infiltrometer was filled with water on September 12, 1978. Subsequent logs, made after the infiltrometer was filled can be compared in the figure with the original log to determine increases in moisture content with time at depths in the unsaturated zone. Comparison of the logs for different dates shows that recharge water moved downward about 85 ft in 58 days but not at a uniform rate. For example, the wetted front moved down 36 ft during the first 10 days of the test but took 20 days to move down an additional 26 ft. The logs indicate the water moved downward until it encountered "perching" layers of lower permeability at about 42 ft. There the water built up a zone of saturation until sufficient hydraulic

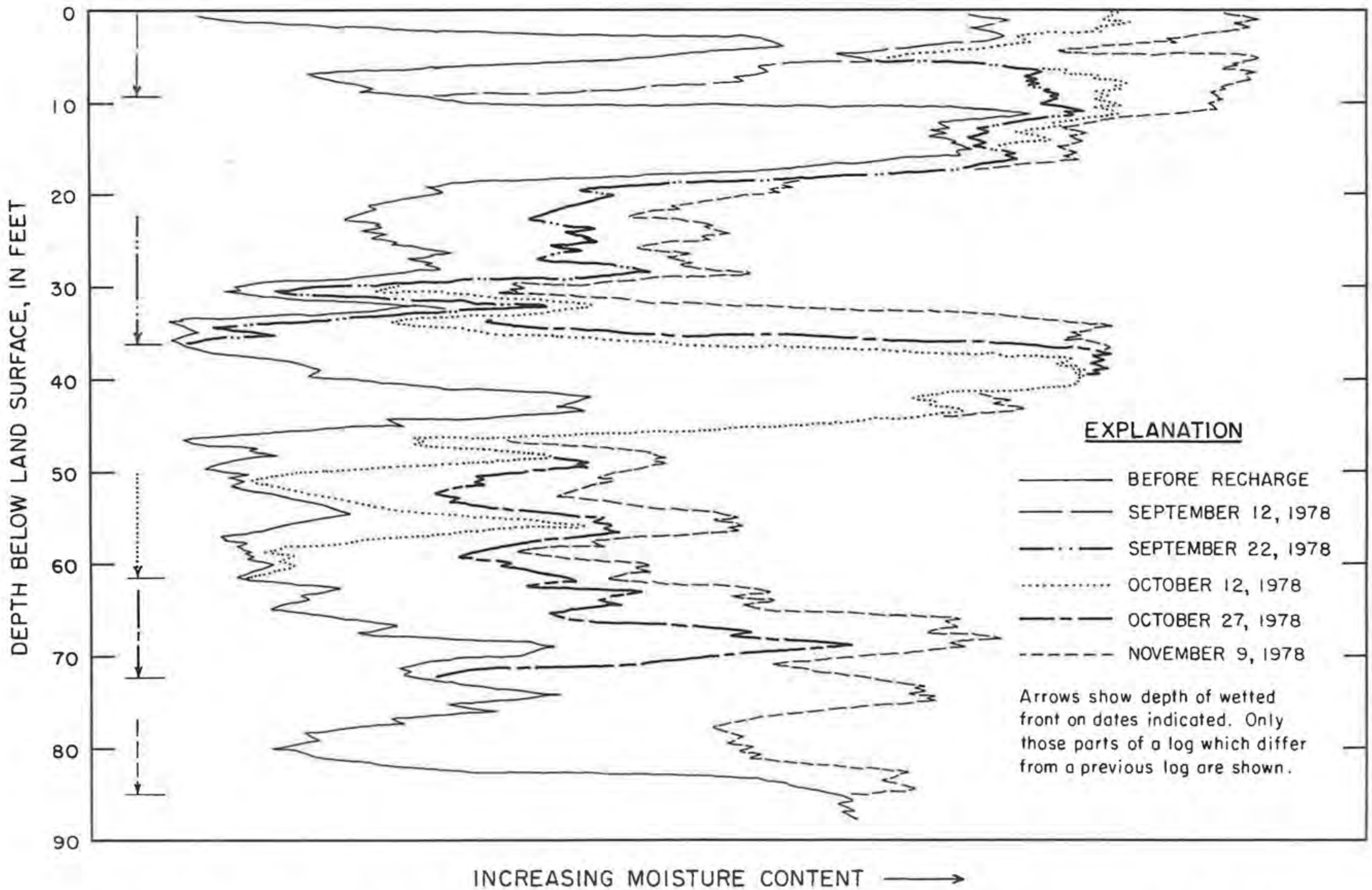

Figure 31.--Neutron logs showing relative moisture content below infiltrometer near Tryon, second test, 1978.

head was achieved to force it through the perching layer at the prevailing rate of infiltration. The effects of prominent perching layers are apparent where the front remained stationary for several days (fig. 32) at depths of approximately 42 and 58 ft.

The controlling layer governing the maximum rate of infiltration appears to be neither of the two mentioned above but all or part of an 8-foot layer between about 10 and 18 ft below land surface. At the end of the test the zone above 10 ft appeared to be saturated to the surface, whereas the zone from 18 to 31 ft appeared to be unsaturated.

The rapid buildup of a zone of saturation above the perching layer at approximately 42 ft between September 22 and October 12 is shown in figure 31. As shown by the greatly increased moisture content of the material above 36 ft between October 12 and November 9, the thickness of this saturated zone above the perching layer continued to increase until termination of the test. If the test had continued or if the ring infiltrometer had been larger, it is possible that the top of the saturated zone would have continued to rise until it merged with the overlying saturated zone at about 18 ft. If this had occurred, the new controlling layer governing infiltration rates would have been the layer at 42 ft.

Conclusions are that water can move downward 85 ft in 58 days in the Sand Hills and that, undoubtedly, it would recharge the aquifer at 120 ft. However, the sand is not uniform and zones of saturation form on less permeable perching layers causing lateral movement of water. Perching layers probably exist in many areas, and adequate geologic knowledge is necessary where surface recharge is contemplated.

Infiltration rates.--The measured infiltration rate during the second test was 8.2 ft/d during the first day (September 12), but it rapidly decreased to 3.6 ft/d by September 14 (fig. 33). The rate remained stable for a few days and then increased slowly to 6.3 ft/d by October 20, increased rapidly to 10.5 ft/d from October 23 to November 3, and then leveled off until freezing weather terminated the test on November 9. The rate decreased just before termination of the test and it might have decreased further if the test had continued.

The pattern of infiltration from the control-ring infiltrometer (fig. 34) was quite different than that from the instrumented infiltrometer (fig. 33). The rate increased and reached its maximum rapidly. For the instrumented infiltrometer, however, it decreased almost immediately and then increased slowly to its maximum. Part of the difference may be due to instrument failure after 6 hr of wetting on September 19 and 32 hr of

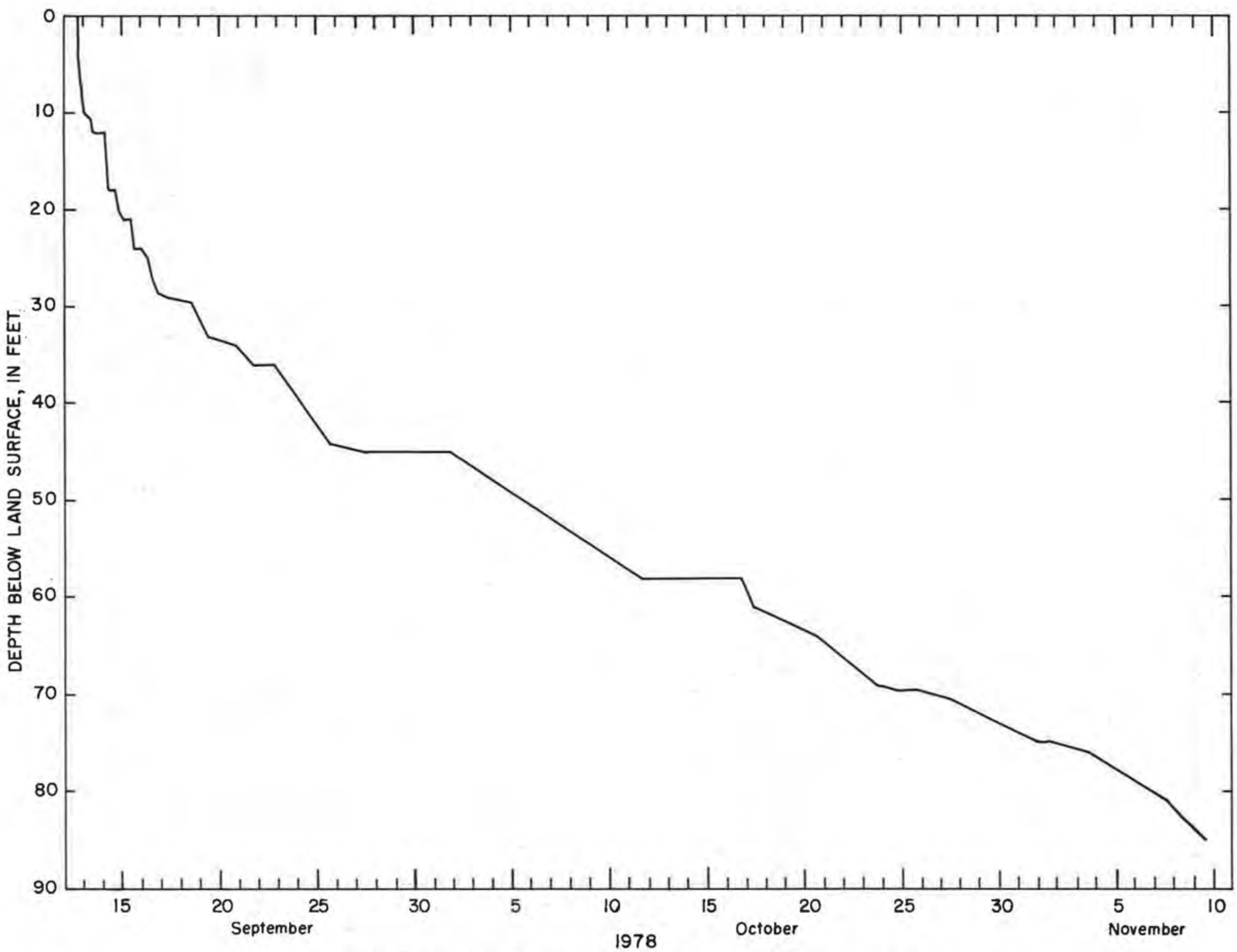

Figure 32.--Advance of wetted front below ring infiltrometer--Tryon site.

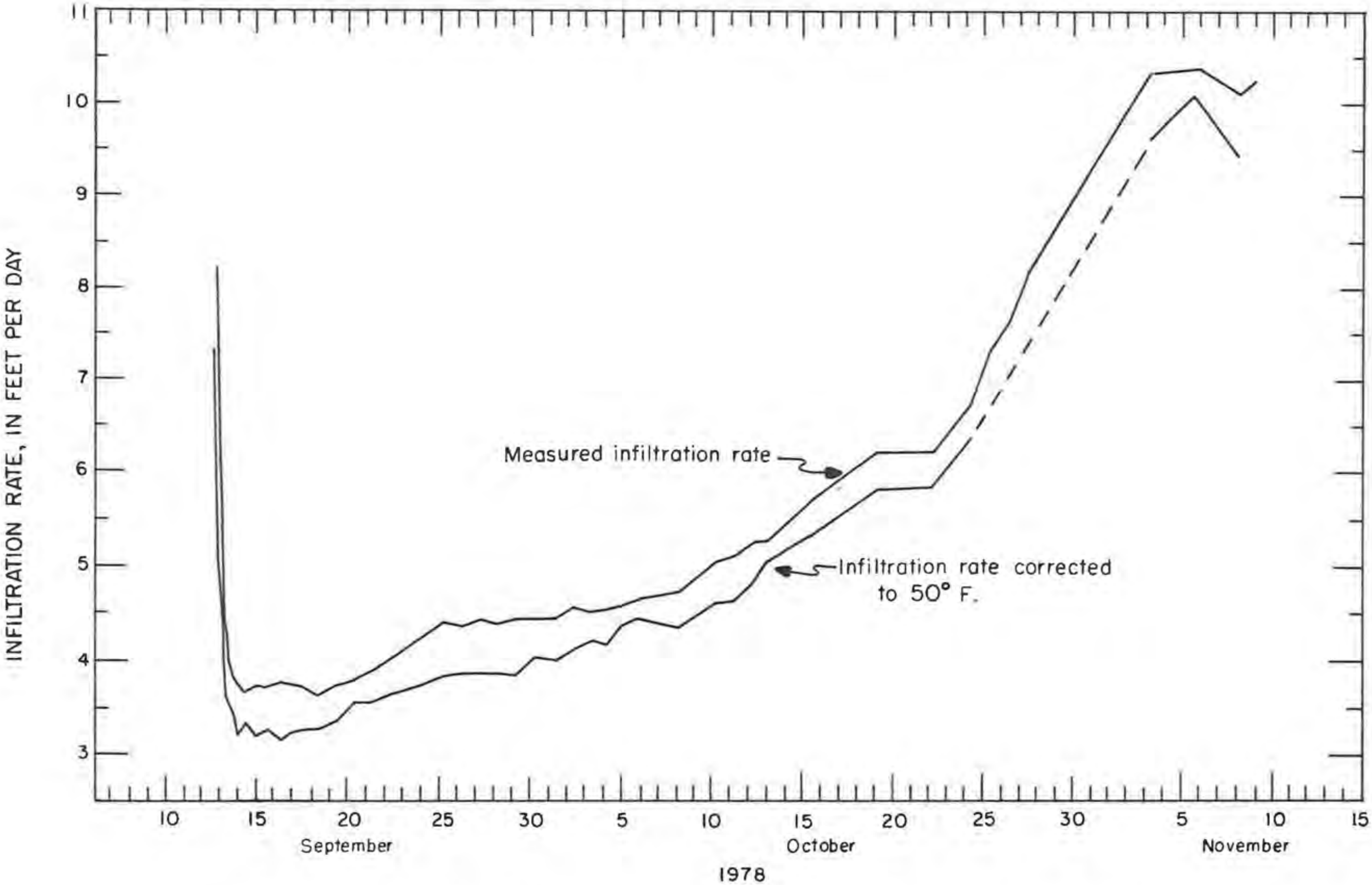

Figure 33.--Infiltration rate from ring infiltrometer, Tryon site, second test.

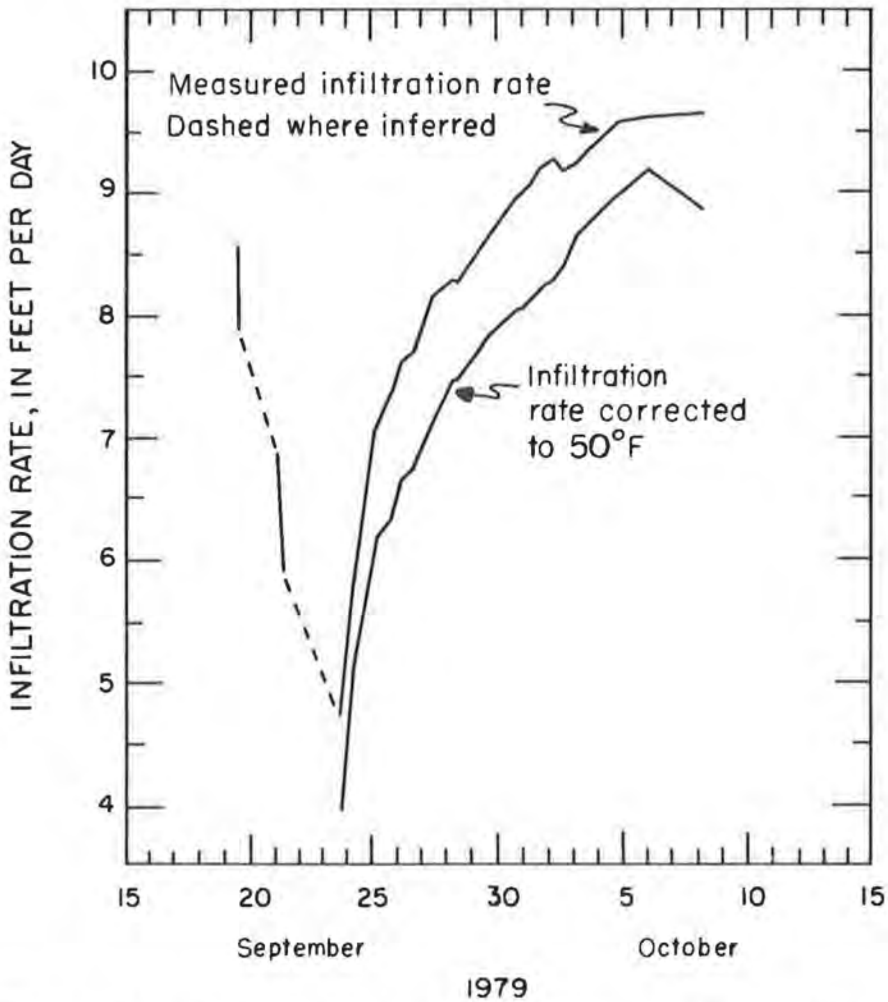

Figure 34--Infiltration rate from control-ring infiltrometer, Tryon site, second test.

wetting during September 20-21. The instrument failure allowed the infiltrometer ring to dewater for 14 hr on each occasion. It is not known what caused the rapid increase in infiltration rate early in the test as opposed to the relatively slow increase noted in figure 33 during the same time period. A possible explanation is that although the two rings were only 130 ft apart and the surface material and topography appeared similar, the near-surface materials are significantly different. Nevertheless, the apparent maximum rate of infiltration achieved at each ring was similar (9.6 ft/d for the control ring and 10.5 ft/d for the instrumented ring).

A third infiltration test was made during August-October 1979 (fig. 35). The purpose of this test was to verify the maximum infiltration rate of about 10.5 ft/d and to determine if the rate would decrease after reaching a maximum. The test was started in early August to allow more time than in the first test. Unfortunately, equipment failure caused two major interruptions; however, the test duplicated the infiltration rate of 10-11 ft/d and the rate did show a tendency to decrease after reaching a maximum. This test also was terminated by freezing weather.

The infiltration rate in the third test increased more rapidly in each segment than it did in the early part of the second test. This was probably because the sand was partly wetted from previous tests. Air had been removed from the small as well as the large interstices during the 1978 test and drainage was not yet complete from these small openings, so that it took less time to drive or dissolve the air from the interstices and allow free downward movement of the water.

The major conclusions to be drawn from the data is that subsurface materials in the Sand Hills can vary considerably in short distances and cause differing patterns of infiltration, but that rates of infiltration as high as 10 ft/d can be maintained for at least 1-2 months in the area tested. Antecedent moisture conditions of the material also can affect infiltration rates.

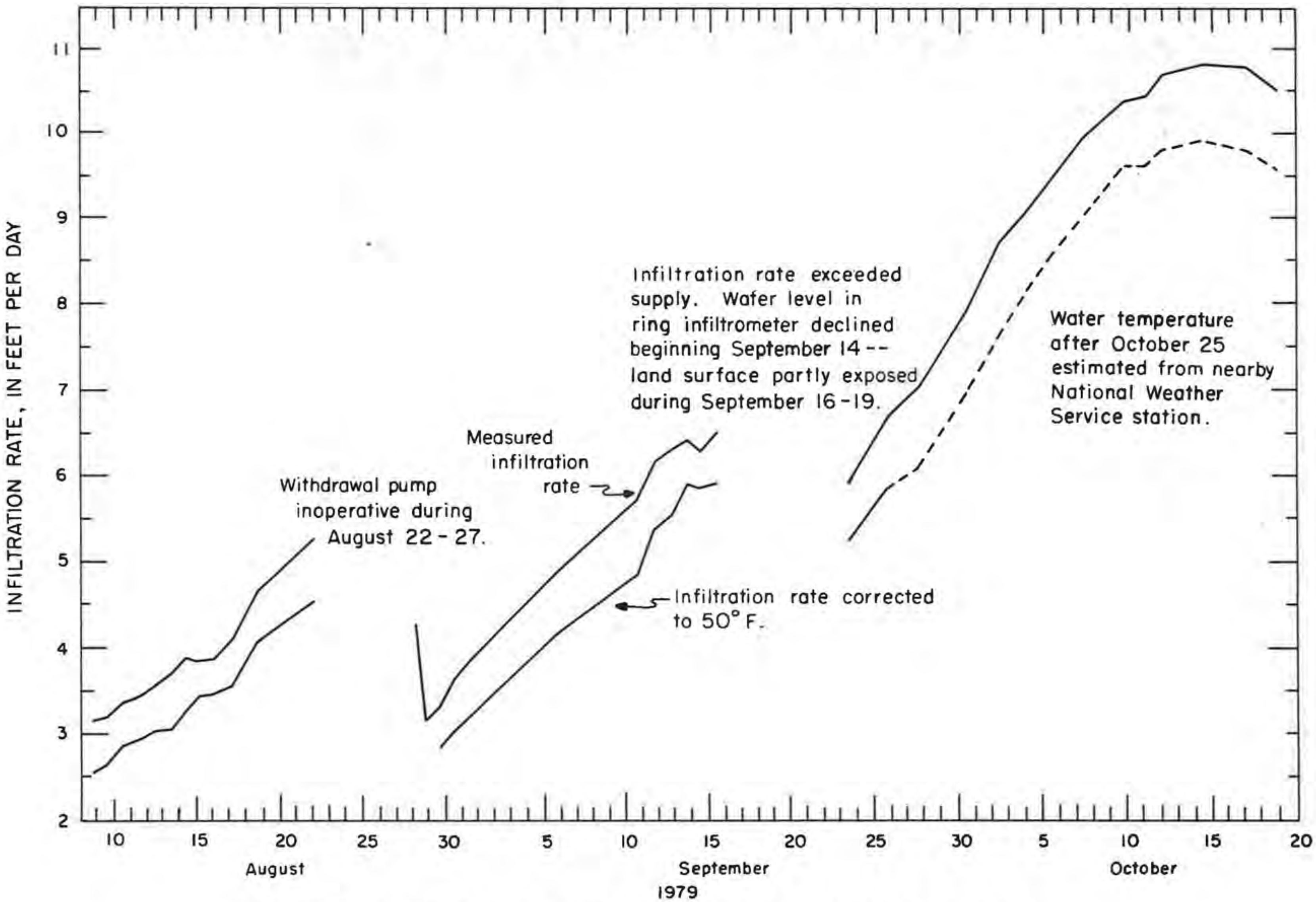

Figure 35.--Infiltration rate from ring infiltrometer, Tryon site, third test.

Tri-County Irrigation District

An unintentional form of artificial recharge by surface spreading began in 1938 in the Tri-County area which includes parts of Gosper, Phelps, and Kearney Counties. The Tri-County area was not studied as part of this investigation, but information supplied by the District is significant to the study. Surface water from the Platte River was diverted by gravity canals to irrigate farmland that had previously been operated exclusively by dryland farming, which is dependent entirely on natural rainfall. By 1973, the total irrigated acres had increased to 117,000, served by 110 mi of canals and 490 mi of distribution laterals (Robertson, Dragoun, and Sall, 1973). More than 97 percent of all the systems are unlined earth channels. Diversion of water into the systems normally begins in early April and continues until mid-October.

Since the project was initiated, water levels have risen at an average rate of about 2 ft/yr or a total of about 60 ft by 1970. The maximum rise was 90 ft in a small area. Since about 1970, the water levels have been nearly stable. The rise in water levels was due to infiltration from the miles of unlined canals and laterals and to an unknown degree to deep infiltration of excess irrigation water.

If the rise in ground-water levels had continued, water logging of the soil would have become a serious problem and an extensive drainage system may have been necessary. The solution of the potential problem of stabilizing ground-water levels was a series of fortuitous events. Prior to the extensive use of fertilizers, insecticides, and herbicides, the water supply was sufficient to produce 100 bushels of corn per acre. With the advent of hybrid varieties and application of the above practices, corn yields increased to 150 bushels per acre. This required additional water, and because the irrigation system capabilities could not be increased, farmers were forced to develop wells as an alternate source of water. The number of wells increased from about 80 in the mid 1950's to 270 by 1972. Pumpage from these wells plus pumpage from irrigation wells in areas surrounding the Tri-County area and increased natural discharge to streams and low areas had balanced the artificial recharge by the early 1970's. This conjunctive use of surface and ground water can be a very useful water-management technique in areas where geologic and hydrologic conditions are suitable.

The artificial recharge of ground water in the Tri-County area was a by-product of the surface-water irrigation system. However, under favorable geohydrologic conditions it may be possible to use infiltration from leaky canals to artificially recharge surplus surface water to an aquifer.

Farwell South Canal

Subsurface geologic conditions in the Farwell South Canal area in Sherman and Howard Counties are different than they are at the Tri-County Irrigation District. At Farwell, as at the Aurora site, low-permeability layers exist between 30 and 40 ft below land surface. Infiltration from the Farwell canals moves laterally on top of these layers to areas of lower altitude where water logging of the near-surface material has occurred. Ground-water levels have risen more than 70 ft in some areas (Frogge, 1978).

During 1978 the problem of water logging was becoming serious and consideration was being given to constructing a multi-million dollar drainage system. The transmissivity of the material above the low-permeability layers is not sufficient to allow construction of efficient irrigation wells, therefore conjunctive use of ground water and surface water is not feasible.

The Farwell canals generally are excavated in loess material that is typical of much of the surface material in Nebraska. Therefore, an attempt was made on August 29, 1978, to determine accurately the infiltration loss from a reach of canal in that District to aid in assessment of leaky canals as an artificial recharge method. After consultation with District personnel, a 2.7-mile section of Farwell South Canal that was typical of the area and contained no surface diversions was selected near Ashton, Nebr. (fig. 36).

Flow of water in the canal was measured from two bridges across the canal. A standard pigmy meter was used on an extended wading rod that could be operated from the rail of the bridge. Observations were made at 20 verticals at 1-foot intervals near the banks and 2-foot intervals in the center of the canal. Observations were made at 0.1, 0.2, 0.3, 0.6, 0.8, and 0.9 of the depth below the water surface and at 0.1 ft above the bed at each vertical. Two simultaneous measurements were made at each station (stations 9.4 and 12.1, fig. 36) by personnel using similar equipment. The measurements were made on August 8 with the downstream section measured immediately after the upstream section. During the time of measurement the water levels in the canal remained stable, as determined by continuous recording gages installed at each site, and weather conditions were ideal. The results of the simultaneous measurements were in close agreement; the difference between the calculated flows was 0.17 percent.

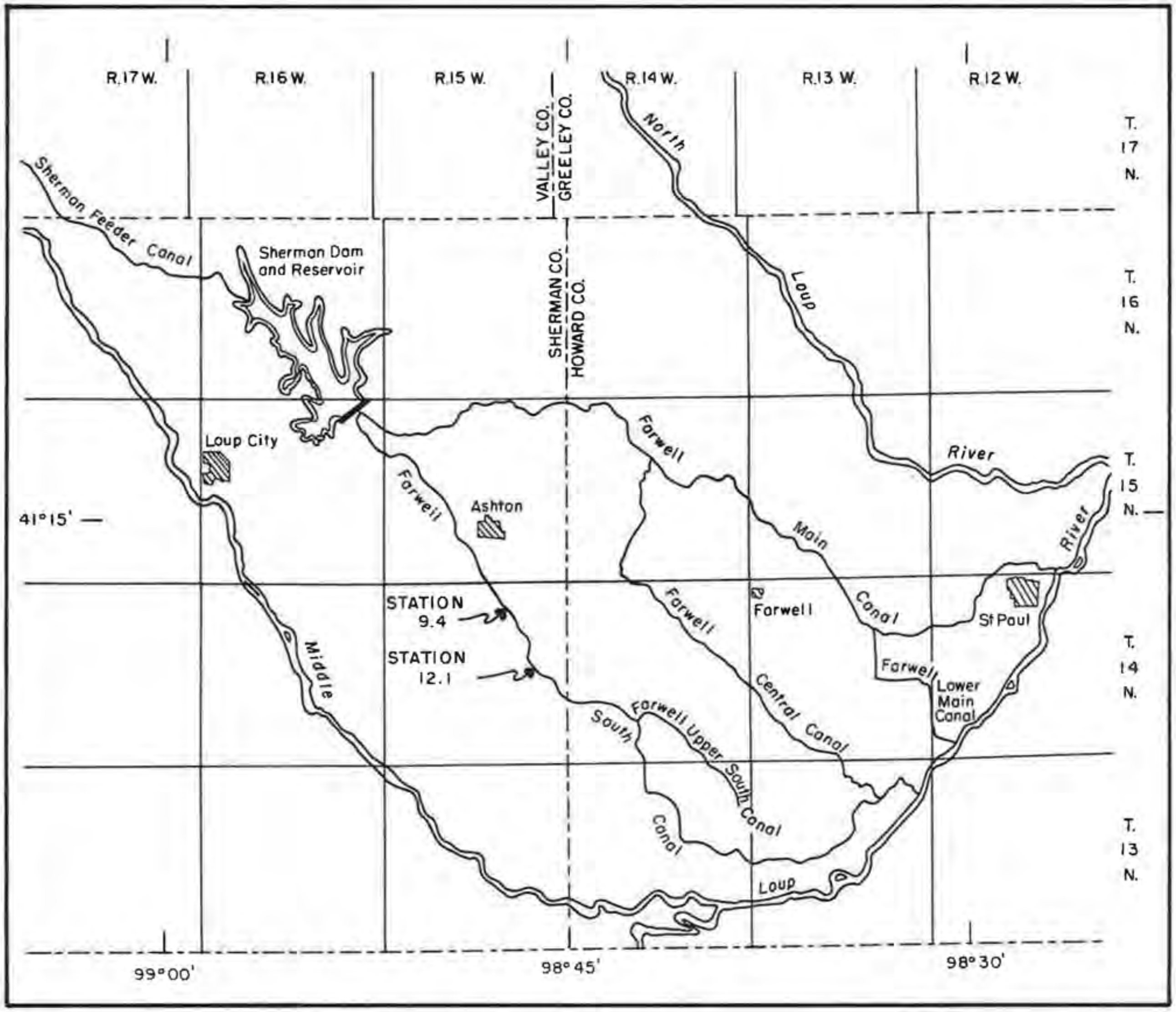

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Figure 36.--Location of measured section of canal in Farwell Irrigation Unit.

Because the same equipment and personnel were used on the same day for both upstream and downstream measurements, it is believed that there was a high degree of accuracy in measuring the difference in flow between the two stations. This degree of accuracy is higher than the degree of accuracy possible in determining the absolute quantity of flow at a given station, because the latter depends on the absolute accuracy of the meter.

Velocity profile curves (not shown in report) were drawn from the measurements in each vertical and lines of equal velocity were plotted on a cross section of the canal. Areas were then measured and multiplied by their respective velocities to obtain total flow. The results indicated 185.91 ft^3/s at the upstream station and 183.70 ft^3/s at the downstream station, or a loss between the stations of 2.21 ft^3/s of flow [0.8 $(ft^3/s)/mi$]. The wetted perimeter of the cross section of the canal is 36 ft. Calculating the infiltration per unit area gives:

$$\frac{2.21 \text{ ft}^3/\text{s} \times 86,400}{2.7 \times 5,280 \times 36} = 0.37 \ (\text{ft}^3/\text{ft}^2)/\text{d}$$

or 0.37 ft of infiltration per day from the wetted area of the canal in the measured reach. Evaporation was estimated at 0.01 ft. The figure, corrected for evaporation, agrees reasonably well with the value of 0.345 ft/d reported by Frogge (1978, p. 2) for the Farwell area, and the values of 0.40 to 0.54 ft/d determined as infiltration from undisturbed surface impoundments at the Aurora site.

Reuse Pits in Hamilton County

Staff gages were installed in 11 reuse pits in the vicinity of the Aurora recharge site (fig. 37) to measure infiltration from pits in the area. The staff gages were read daily, when possible, during periods when there was no surface inflow or outflow from the pits. Rain gages were installed near the pits to check the areal uniformity of rainfall and readings were correlated with the continuous record of rainfall at the Aurora recharge site. The record of evaporation at the recharge site was used in estimating evaporation from the reuse pits.

Infiltration rates from the pits differed widely within short distances (table 8). For example, pits G and H are only 1 mi apart, yet the average infiltration rate of pit H was more than 50 times that of pit G (1.60 versus 0.03 ft/d). The reason most of the values shown in table 8 are low is because the pits with high infiltration rates were

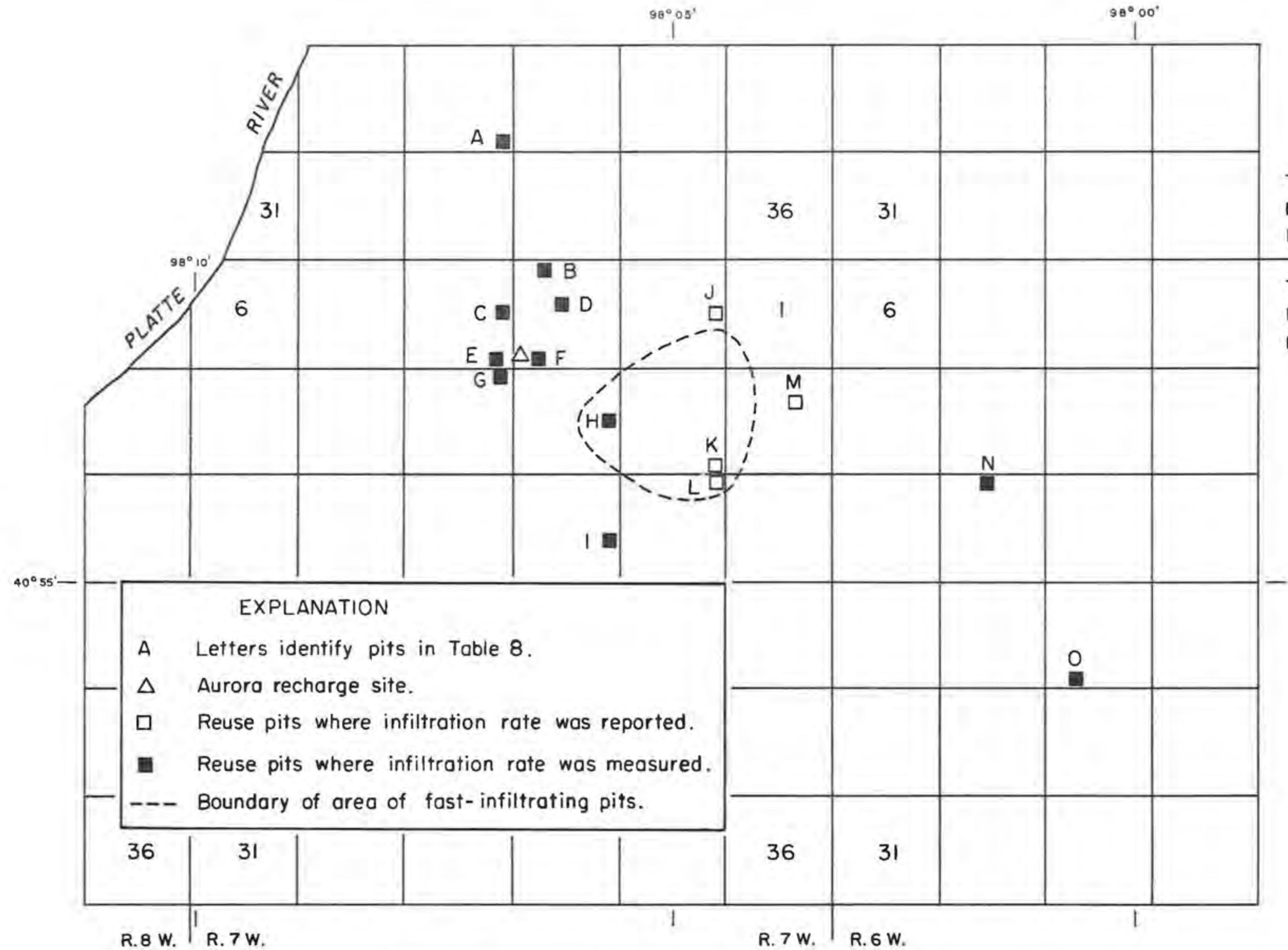

Figure 37.--Locations of reuse pits from which data were collected in the Aurora recharge-site area.

Table 8.--Average infiltration rates from reuse pits near Aurora recharge site

Pit	Infiltration rate (feet per day)	Period measured
A	0.03	July 18-23, 1979
B	.04	May 26 to June 29, 1978
C	.15	May 19 to June 30, 1978
D	.01	May 26 to June 30, 1978
E	.11	May 25 to June 29, 1978
F	.03	May 26 to June 30, 1978
G	.03	May 26 to June 27, 1978
H	1.60	August 21-23, 1979
I	.02	June 2-29, 1978
J	.04	June 3-15, 1978
K	.01	June 3-28, 1978

dry most of the time so the rates could not be measured. During times of steadily declining water levels in the pits, the infiltration rate also declined (fig. 38). However, the rate did not approach zero as the depth of water in the pit approached zero, as would be expected if the layer controlling the rate of infiltration were a layer of negligible thickness at the land surface at the bottom of the pit. The relationship between infiltration rate and depth of water in a typical pit is shown in figure 39. Extending the line depicting the decline of infiltration rate versus depth of water in the pit to its intercept with the zero rate of infiltration line indicates (neglecting hydraulic head loss and lateral spreading of the water mound on the restricting layer) that the restricting layer controlling infiltration from pit C is about 10 ft below the bottom of the pit or 25 ft below the surrounding land surface. Hydraulic head loss and lateral spreading of the mound on the restricting layer probably are significant factors that cannot be neglected in assigning a depth to the restricting layer, but the graph indicates that the layer is below the bottom of the pit and probably at a depth of approximately 10 ft. As the surface altitude at pit C is about 5 ft lower than at the test site, this depth is the approximate position of the Sangamon fossil soil zone (fig. 5). Analyses of data from other pits in the area with similar infiltration rates indicated similar conditions.

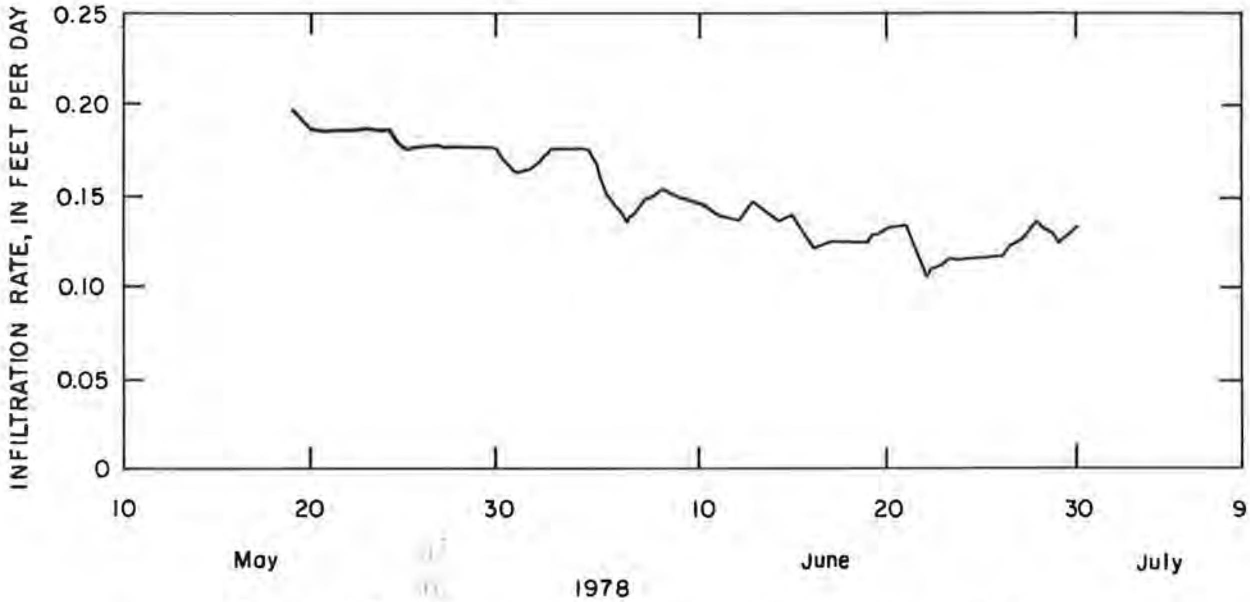

Figure 38.--Changes in infiltration rate in reuse pit C.

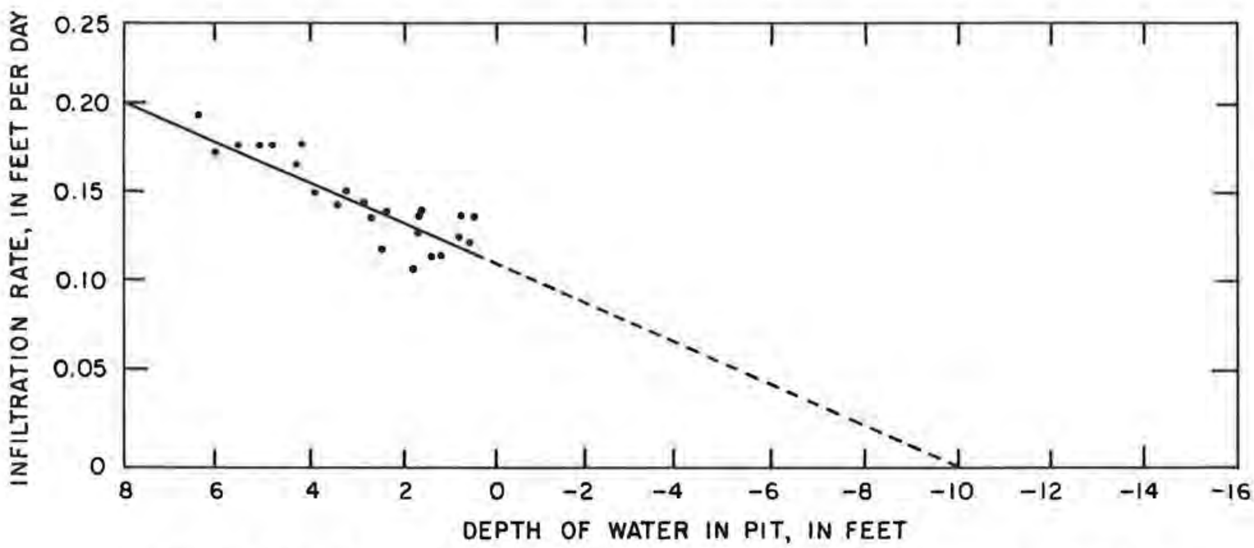

Figure 39.--Changes in infiltration rate with changes in depth of water in reuse pit C.

Although it is commonly said that pits tend to silt up with time and have a reduced rate of infiltration, time and silting do not appear to be the dominant factor causing the infiltration rates to vary in pits G and H. Both pits are excavated to about the same depth in the same kind of material (loess), have been used for many years, and are about the same age. The runoff waters entering the two pits are similar in sediment load and chemical composition, and their topographic locations are similar. In short, there is no apparent surface cause why the infiltration rate from pit H should be so much greater than that for pit G. The owner of pit H reported that in his opinion the infiltration rate from his pit had actually increased slightly from what it was when the pit was first excavated. The owner of pit G reported that the infiltration rate from his pit had not changed appreciably after the second year of the pit's existance. Examination of the top foot of surface material at the bottom of the pits after pits G and H had become dry revealed no significant difference in composition.

Project resources did not permit test drilling to determine the character of the material between the bottom of pits and the aquifer, but it appears that the controlling factor governing infiltration is the deeper material rather than clogging of the bottom bed of the pits. A hypothesis is proposed that one or more relatively impermeable layers similar to the perching layer discovered at the surface-impoundment site exists not far below pit G and other so-called "slow-infiltrating" pits and that these layers are absent under pit H and other "fast-infiltrating" pits. The area where fast-infiltrating pits were detected or reported is outlined in figure 37. Further study of infiltration rates from reuse pits could aid in the assessment of areas where surface spreading might be a feasible method of artificial recharge.

The principal conclusions to be drawn from the surface-spreading test conducted during the project are: (1) Detailed knowledge of the permeability of all the strata from the land surface to the top of the aquifer is necessary before the feasibility of surface spreading as an artificial-recharge method in a given area can be assessed, (2) infiltration rates obtained from short-term or small-scale tests will not necessarily apply to long-term or large-scale operations, and (3) an area was detected in the Big Blue River basin where large quantities of water could probably be recharged through surface-spreading methods.

CRITERIA FOR SUCCESSFUL ARTIFICIAL RECHARGE

Several criteria must be met if artificial recharge is to be successful: (1) The recharge site must be underlain by permeable material that holds or is capable of holding water; (2) the aquifer must have unused storage capacity 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.

There must be permeable strata present capable of accepting, storing, and yielding economically significant quantities of water. What is economically significant 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.

If an aquifer is over-developed and artificial recharge is needed to prevent excessive depletion or unacceptably low pumping levels, then unused storage capacity will be available in the dewatered part of the aquifer. Unused storage capacity also can be available in aquifers that are not over-developed; however, the recharged water may be lost to natural discharge if not used soon after injection.

Artificial recharge is not feasible 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 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 it. Water that is of a poorer quality than native water may restrict its use for some purposes. 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 also may cause clogging. Water can be treated to make it acceptable for recharge, but extensive treatment is expensive and may render artificial-recharge operations economically infeasible. The degree of treatment economically feasible may depend on the value placed on the recharged water.

Through Wells

The four general criteria listed above for successful artificial recharge apply to artificial recharge through wells. Criterion (4), that recharge water be of suitable quality, is especially important because rehabilitation of a clogged well is usually expensive. 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. Passing turbid recharge water through a filter of several feet of sand and gravel before injection generally will reduce 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. This, of course, will reduce the average flow of the river. 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) generally 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 stringent and capital costs may be high.

Through Surface Spreading

The four general criteria listed previously for successful artificial recharge 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 significant quantities of water to percolate to the aquifer. A minimum infiltration rate of 0.5 ft/d generally is considered essential to most 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 commonly is 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 in some situations. 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.

AREAS IN NEBRASKA POTENTIALLY SUITABLE FOR ARTIFICIAL RECHARGE

Many areas in Nebraska potentially are suitable for artificial recharge. Most of the State is underlain by aquifers that could accept and store large quantities of water. The range of yields of wells in Nebraska is shown in figure 40. Yields of 500 gal/min or more can be obtained, in most areas, indicating that under favorable conditions, practical rates of recharge are possible. Thus, the first criterion is met in most of Nebraska.

Areas where unused storage capacity existed in Nebraska aquifers in 1978 are indicated in figure 41, which shows the change in ground-water levels between 1950 and 1978. Areas where large water-level declines have occurred generally have large unused storage capacity, thus meeting the second criterion. Also these areas generally have the greatest need for artificial recharge. Other areas also may have unused storage capacity; but if the aquifers are in hydrologic equilibrium, the recharged water would discharge naturally unless withdrawn promptly.

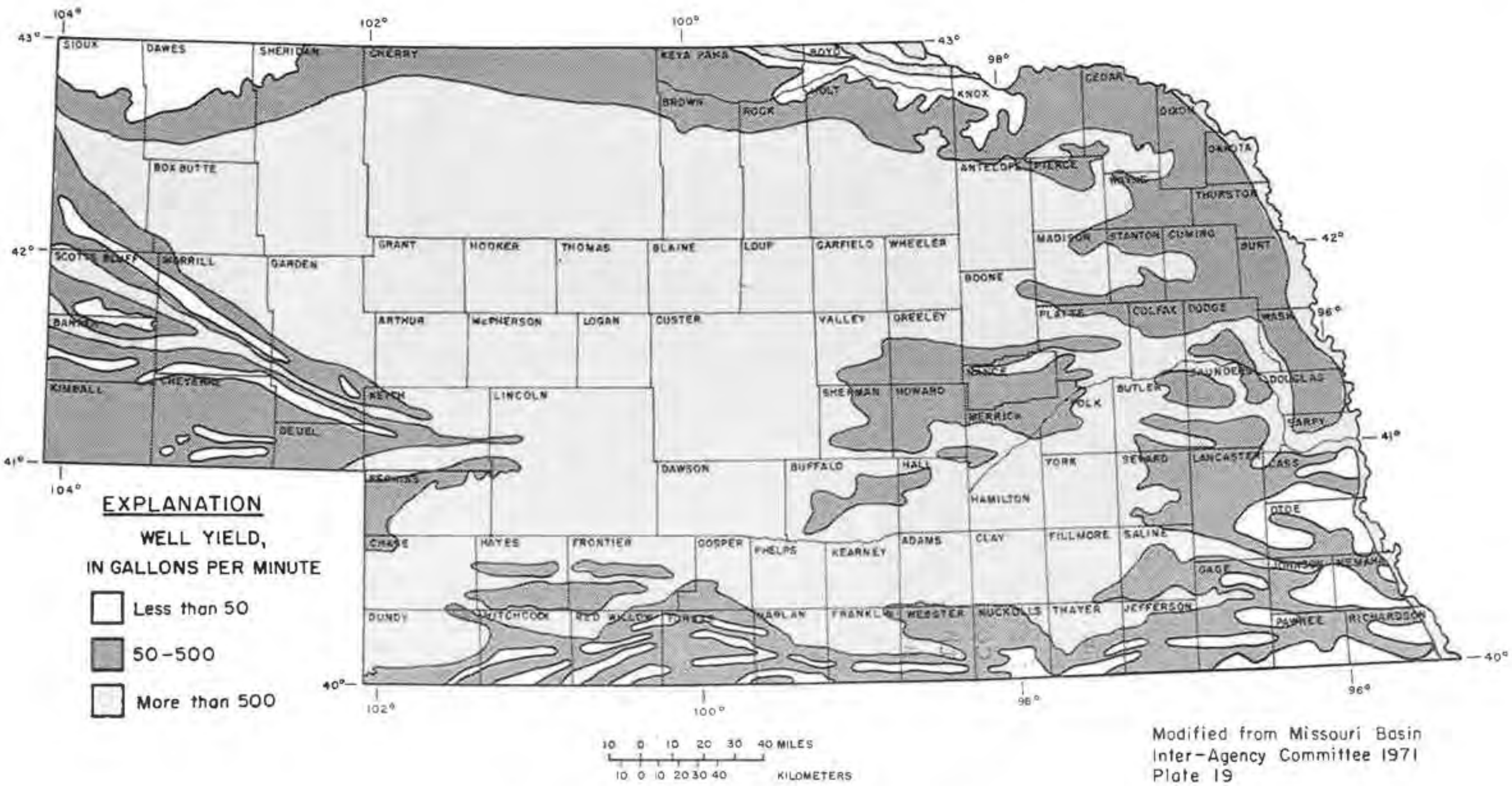

Figure 40.--Yields of wells in Nebraska.

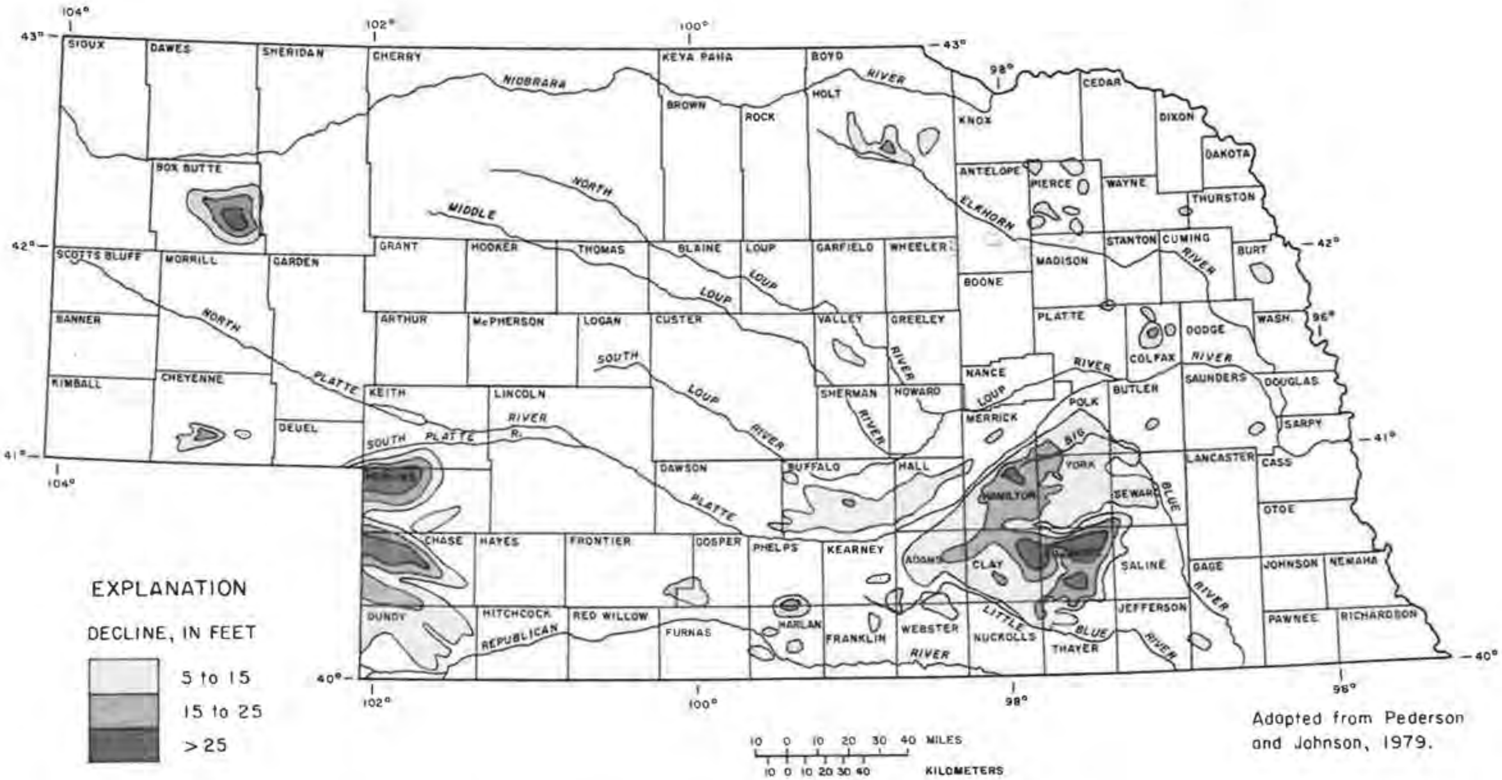

Figure 41.--Areas of unused storage capacity as indicated by decline in ground-water levels from 1950 to 1978.

Where there is a reasonably accessible source of recharge water to meet the third criterion, is more difficult to assess. Reasonably accessible sources of recharge water probably are not as plentiful in Nebraska as are the needs for artificial recharge. The Platte River is a large source of surface water within the State; however, there are many demands for its water.

Approximately 7 million acre-ft of water leaves the State in an average year from the Platte River. Much of this water could possibly be captured and stored underground for later use. However, most of the water is in the eastern part of the State; whereas, because of decreasing rainfall from east to west, the need for irrigation is greater in the western part. The cost of transporting water long distances tends to reduce the economic feasibility of artificial recharge.

Many smaller streams in Nebraska also are potential sources of recharge water; however, ground water and surface water in Nebraska usually are interconnected and care must be taken in assessment of water resources that the same resource is not counted twice. In other words, if the ground water that was maintaining the flow of a stream is intercepted by pumping before it reaches the stream, then the streamflow will not be available to recharge the aquifer when pumping exceeds natural recharge.

The Missouri River is a large potential source of recharge water; but as it forms the eastern boundary of the State, water would have to be pumped long distances uphill to most of the areas of extensive ground-water decline (fig. 41).

In addition to surface sources of water for artificial recharge, ground water, in certain circumstances, might be used. However, unless the ground-water reservoir is replenished by or contributes water to a surface-water source, it probably would be more efficient to use the water directly from the source.

Possible sources of artificial-recharge water in Nebraska are not delineated in this report because the practicality depends on many considerations, including: (1) Whether the water is considered surplus in the area of origin by the decision makers; (2) the value placed on the water and the cost of artificial recharge in relation to that value; (3) legal restraints on the transport of water; (4) the dependability of the supply. These types of considerations were not a part of this investigation. They would have to be studied in detail for each situation before the feasibility of artificial recharge in a given area could be determined.

In regard to criterion (4), the natural chemical quality of the water in most streams in Nebraska is suitable for most uses and, in general, is compatible with the ground water. In some areas, farming, return of irrigation water, industry and waste disposal may have contaminated some waters.

The principal quality-of-water problem in using surface water for direct recharge is suspended sediment, air, and bacteria in the water. This is especially true during times of high flow, which are the times when the most surplus water is available.

Pumping from withdrawal wells developed in an aquifer that is directly connected to a nearby stream can induce stream water to seep toward the well, thereby removing most troublesome impurities. Therefore, the most likely places in Nebraska for successful artificial recharge, especially through wells, are areas, such as the Aurora site, where surface water in contact with extensive deposits of sand and gravel allow development of high-yield supply wells a reasonable distance from the stream. The definition of "reasonable distance" will depend on the character of the sand and gravel; but studies have shown that percolation through as little as 10 ft of sand removes most of the suspended sediment, air, and microbes from water.

Many such areas probably exist along the rivers in Nebraska, but probably not all have been delineated. Consultation with local residents possibly would help to locate favorable deposits.

No attempt was made to evaluate areas that might be suitable for surface-spreading recharge, because tests at the Aurora site showed that infiltration rates can be more than 50 times greater at one point than another in distances of as little as a mile.

Much information on the material overlying aquifers exists in the form of well logs, but most logs are not in sufficient detail to evaluate thin layers of low permeability that could cause perched conditions or water logging. The best way to determine if an individual site would be suitable for surface spreading would be to examine in detail a continuous core from land surface to the top of the aquifer to determine if low-permeability layers exist.

SUMMARY AND CONCLUSIONS

Experiments with artificial recharge of ground water in many parts of the world have shown that the success or failure of artificial recharge depends on many factors that are peculiar to the individual situation. The principal factors are the type and characteristics of the aquifer, the quality of the recharge water, and the characteristics of the material overlying the aquifer. Other criteria necessary for successful artificial recharge are the availability nearby of an adequate supply of water, the absence of legal barriers, and economic feasibility.

An aquifer composed of cavernous limestone is usually less subject to plugging than an aquifer composed of fine sand. Similarly, an aquifer with high transmissivity will usually accept recharge water at a higher rate than will an aquifer with low transmissivity. The probability of successful recharge through wells is enhanced by water containing little sediment, entrained air, and microorganisms, and chemically compatible with the native water and aquifer material. Artificial recharge through surface spreading depends on the absence of relatively impermeable layers between the infiltration surface and the aquifer; however, this is not important for recharge through wells.

Artificial recharge can be by direct or indirect methods. Common direct methods are recharge through wells and surface spreading. Indirect methods usually involve lowering of ground-water levels to induce greater infiltration of surface water.

Only direct methods of artificial recharge were investigated during this project. They included recharge through wells and surface spreading by impoundments, flowing water in canals, and storage in pits.

About 456 million gallons (1,400 acre-ft) of water were recharged to the Pleistocene sand and gravel aquifer through a well at an experimental site near Aurora, in Hamilton County. The water was recharged at an average rate of 732 gal/min for 6 months, September 1977 to April 1978, and for 8 months at an average rate of 730 gal/min, November 1978 to July 1979.

The recharge water was withdrawn from a well near the Platte River in an area where the Platte is in hydrologic connection with the aquifer and where the river has been providing recharge for many years. The water was transmitted 3 miles through a pipeline buried below frostline to a recharge well in an area of the Big Blue River basin where ground-water levels were progressively declining due to heavy withdrawals for irrigation. The recharge water and the native ground water in the vicinity of the recharge well differed in chemical quality; however, the waters were apparently compatible for recharge purposes.

During the first recharge test which lasted 6 months and recharged 207 million gallons of water, the water levels in observation wells as close as 10 ft to the recharge well virtually stabilized within 2 months; whereas, the water level in the recharge well continued to rise. This continuing rise of the water level in the recharge well showed that an increasing gradient was necessary to move a constant quantity of water a constant distance.

The water level in an observation well outside the screen in the gravel pack surrounding the well was identical to the water level in the recharge well. Therefore, the rising water level in the recharge well indicated that a gradual decrease in transmissivity (clogging) was occurring in the aquifer in the immediate vicinity of the recharge well. This slow clogging of the aquifer, which occurred less than 10 ft from the recharge well and probably within 1 or 2 ft of the well, was evidently caused by sediment in the recharge water. Clogging by bacterial growth or air entrainment were discounted because analysis of the recharge water and water in the recharge well showed a very low bacteria count, and analysis of the dissolved-oxygen concentration of the water showed that the positive pressure maintained in the system was effective in keeping entrained air from the well.

The withdrawal well was carefully designed and constructed to yield as sediment-free water as practical. However, apparently even the very low sediment concentration of the recharge water (0.04 mg/L) when multiplied by hundreds of millions of gallons was sufficient to cause slow clogging of the aquifer.

At the rate that clogging was occurring during the first test, recharge could have been continued for several years. Redevelopment of the well would then have been necessary. Simply pumping the well may not restore its initial specific capacity.

During the second recharge test, which lasted 8 months and recharged 247 million gallons, the pattern of water-level rise in the early part of the test was similar to what it was in the first test. During the latter part of the second test, the water-level rise in the recharge well accelerated to 17 times what it was in the middle part of the test. The water level in the gravel pack observation well also rose but not as fast as in the recharge well. Sediment analyses indicate a large increase in sediment concentration of the recharge water. Subsequent down-hole television surveys revealed coarse sand and gravel coating the inside of the screen of the recharge well and a hole in the casing of the withdrawal well. It was estimated that more than 800 lb of sediment had been sucked from the withdrawal well and deposited in the recharge well.

Conclusions reached from the well recharge tests are that under favorable conditions such as existed at the test site, large quantities of water can be recharged through wells. Care must be taken to keep the sediment concentration of the recharge water as low as possible and provision must be made for periodic redevelopment of the recharge well. The measurable effects of recharge extended more than a mile from the recharge well during the 8 months of recharge at 730 gal/min.

The maximum infiltration rate from 24-foot-diameter surface impoundments near Aurora was about 0.5 ft/d over the wetted area of the impoundments. A low-permeability layer 38 ft below the land surface prevented the water from moving directly to the aquifer. The total area that the water spread out on the low-permeability layer is not known. The perched zone of saturation built up 15 ft to within 21 ft of the surface under the impoundment during the 140 days of the experiment and was still rising when freezing weather terminated the experiment. If the impoundment had been larger in area or if the experiment had been of longer duration, the zone of saturation probably would have reached the surface and the infiltration rate would have declined.

Conclusions reached from the surface-impoundment experiments near Aurora are that the success of large-scale surface spreading in the Big Blue River basin is dependent on locating areas where low-permeability layers do not occur between the land surface and the aquifer and where near-surface layers commonly are not the layers controlling long-term or large-scale rates of recharge.

Analysis of infiltration rates from reuse pits in the area of the experimental recharge sites near Aurora show that low-permeability layers do not exist everywhere and that infiltration rates vary nearly two orders of magnitude within a range of a few miles (0.01 to 1.60 ft/d). Although project resources did not permit test drilling at reuse pits, it is likely that low-permeability layers are missing or at much greater depths in the areas of the fast-seepage pits.

At the Tryon experimental site in the Sand Hills region of Nebraska, both the surface and subsurface materials are much more permeable than at the Aurora site. During the second test at the site, which lasted from

September 12 to November 9, 1978, infiltration rates increased from 3.5 ft/d near the start of the test to nearly 11 ft/d. During the third test, which lasted from August 8 to October 19, 1979, infiltration rates increased from 3.1 to nearly 11 ft/d. Neutron-log analyses showed that recharge water percolated to a depth of 85 ft in 58 days. Although no low-permeability layers existed at least to a depth of 85 ft, the material was not completely uniform. Slightly silty sand layers that had lower permeability than the material above and below caused lateral movement of water. Perched zones of saturation formed on these layers and expanded until the buildup of hydraulic head on the layer was sufficient to force water downward at a rate equal to the recharge coming from above.

Conclusions reached from the Tryon experiment are that large quantities of water could be recharged to the aquifer in the Sand Hills region from surface impoundment covering relatively small areas if the sites are similar to the experimental site. In this type of situation, surface spreading would probably be more feasible than well recharge.

Flow measurements made in a canal in the Farwell South Canal in east-central Nebraska indicated that water seeped from the reach of the canal at a rate of 0.36 ft/d. The canal was excavated in loess and the infiltration rate is similar to that for the surface impoundment on loessal soil at the Aurora site. The canal contains water for only 3 months of the year; therefore, water levels have not built up on underlying low-permeability layers to the level of the bottom of the canal. However, water logging of low-lying areas has occurred and caused drainage problems. Conclusions are that the lack of an adequate aquifer above the low-permeability layer prevented the conjunctive use of the seeped water in the Farwell South Canal.

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