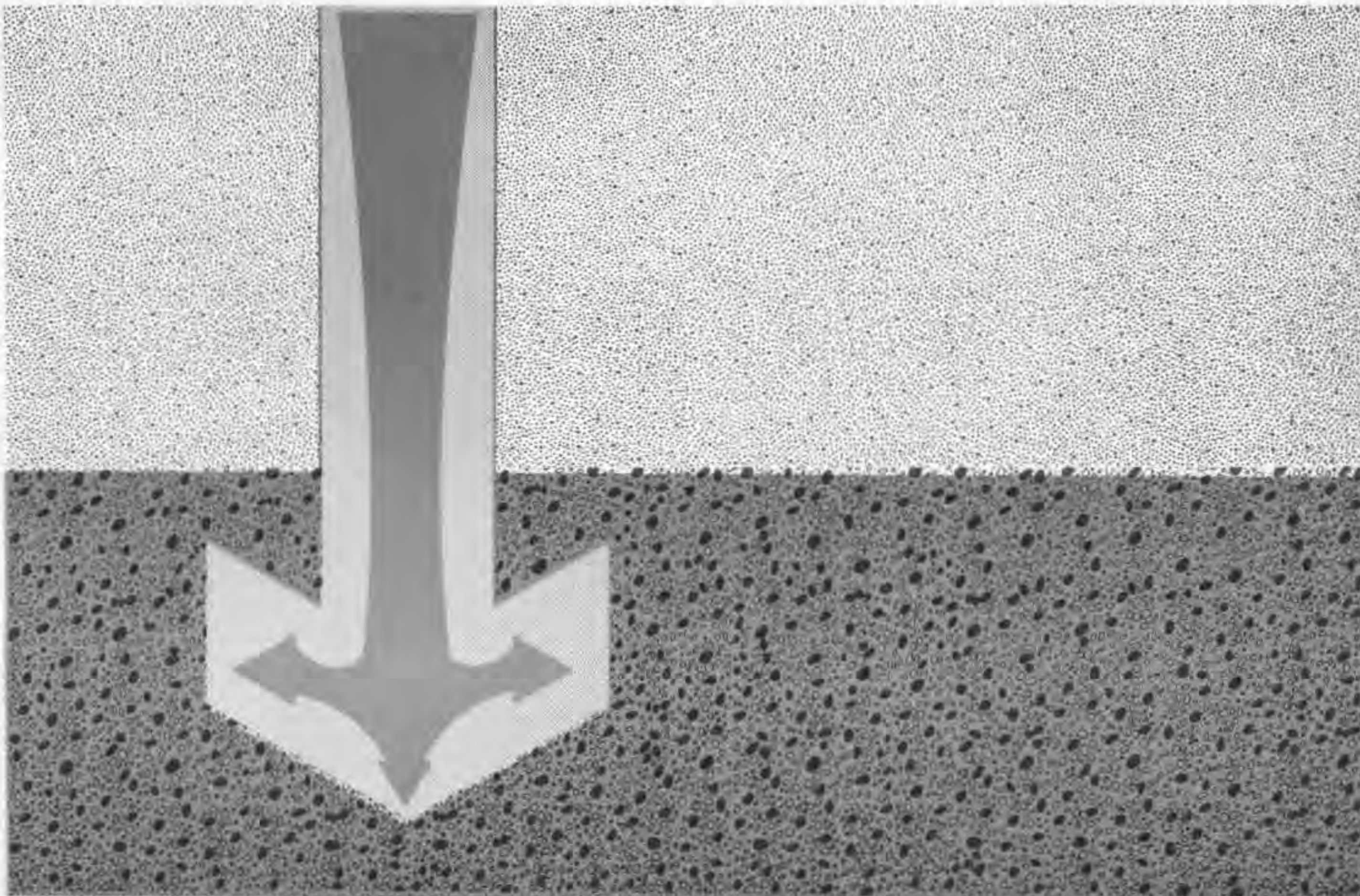
ARTIFICIAL-RECHARGE EXPERIMENTS AND OPERATIONS ON THE SOUTHERN HIGH PLAINS OF TEXAS AND NEW MEXICO



U. S. GEOLOGICAL SURVEY

Water-Resources Investigations 10-73

BIBLIOGRAPHIC DATA SHEET	1. Report No.	2.	3. Recipient's Accession No.

4. Title and Subtitle ARTIFICIAL-RECHARGE EXPERIMENTS AND OPERATIONS ON THE SOUTHERN HIGH PLAINS OF TEXAS AND NEW MEXICO	5. Report Date May 1973 6.
7. Author(s) Richmond F. Brown and Donald C. Signor	8. Performing Organization Rept. No. WRI 10-73
9. Performing Organization Name and Address U.S. Geological Survey Water Resources Division Federal Building, 300 East 8th Street Austin, TX 78701	10. Project/Task/Work Unit No. 11. Contract/Grant No.
12. Sponsoring Organization Name and Address U.S. Geological Survey Water Resources Division Federal Building, 300 East 8th Street Austin, TX 78701	13. Type of Report & Period Covered 14.

15. Supplementary Notes

16. Abstracts

Experiments using highly turbid water from playa lakes for injection into the Ogallala Formation have resulted in greatly decreased yield of the recharge wells. Recharge of ground or surface water of good quality has indicated, however, that injection through wells is an effective method of recharging the aquifer. Water that is slightly turbid can be successfully injected for a period of time, but generally results in constantly declining yields and capacity for recharge. Redevelopment through pumping and surging significantly prolongs the life of recharge wells under some conditions. Surface spreading is little practiced on the High Plains, but locally may be a feasible means of artificial recharge.

17. Key Words and Document Analysis. 17a. Descriptors

*Artificial recharge/ *ground-water recharge/water spreading/ irrigation practices/ injection wells/ playas

17b. Identifiers/Open-Ended Terms

Ogallala Formation

17c. COSATI Field/Group

18. Availability Statement No restrictions on distribution	19. Security Class (This Report) UNCLASSIFIED	21. No. of Pages 59
	20. Security Class (This Page UNCLASSIFIED	22. Price

ARTIFICIAL-RECHARGE EXPERIMENTS AND OPERATIONS ON THE SOUTHERN HIGH PLAINS OF TEXAS AND NEW MEXICO

By Richmond F. Brown and Donald C. Signor

U. S. GEOLOGICAL SURVEY
Water-Resources Investigations 10-73

MAY 1973

UNITED STATES DEPARTMENT OF THE INTERIOR

Rogers C. B. Morton, Secretary

GEOLOGICAL SURVEY

V. E. McKelvey, Director

FOR ADDITIONAL INFORMATION WRITE TO:

U.S. GEOLOGICAL SURVEY
WATER RESOURCES DIVISION
FEDERAL BUILDING
300 EAST 8TH STREET
AUSTIN, TX 78701

MAY 1973

CONTENTS

ILLUSTRATIONS

TABLES

ARTIFICIAL-RECHARGE EXPERIMENTS AND OPERATIONS ON THE SOUTHERN HIGH PLAINS OF TEXAS AND NEW MEXICO

By

Richmond F. Brown and Donald C. Signor
U.S. Geological Survey

ABSTRACT

The Southern High Plains of Texas and New Mexico is an area where ground water is being mined for irrigation, municipal supply, and industrial use. Artificial-recharge experiments and operations have been undertaken to develop methods to supplement the declining ground-water supplies in the Ogallala Formation, a sand and gravel aquifer of Tertiary age.

Experiments using highly turbid water from playa lakes for injection into the Ogallala Formation have resulted in greatly decreased yield and limited life for the recharge wells. Recharge of ground water and surface water of good quality have indicated, however, that injection through wells is an effective method of recharging the aquifer.

Water that is slightly turbid can be injected into wells successfully for a period of time, but in most experiments, the use of turbid water resulted in constantly declining yields of the wells and constantly declining capacities for recharge. Redevelopment of wells through pumping and surging will remove some of the sediment under certain conditions and significantly prolong the life of the recharge wells. Surface spreading is little practiced, but locally may be a feasible means of artificial recharge.

INTRODUCTION

This report is the result of an expanded program of artificial-recharge investigations by the U.S. Geological Survey. A project office for field and laboratory studies was established in Lubbock, Texas, in February 1968. Lubbock was chosen as the project site because of the severe water problem in the region, because of the potential for water management through ground-water storage in the Ogallala Formation, and because of the large amount of data on artificial recharge that is available locally.

The Southern High Plains has a total area of about 32,000 square miles in western Texas and eastern New Mexico (fig. 1). The region is a plateau, bounded on the north by the Canadian River Valley and on the east and west by prominent escarpments rising as much as 300 feet or more above the stream-eroded lowlands. The top of the escarpment is generally capped with caliche, which is known locally as the "caprock". On the south, the Southern High Plains merge without a sharp physiographic break into the Edwards Plateau.

Undrained depressions, locally called playas, ranging from a few feet to 50 feet or more in depth and from a few hundred feet to a mile or more in diameter, are characteristic of the topography of the Southern High Plains. The drainage area of the playas may range from a few square miles to as much as 50 square miles, and during periods of heavy rainfall, runoff collects in the depressions to form temporary ponds or lakes. Some of the larger and deeper playas impound "alkali" or "saline" lakes. The high mineral content of the water results from the concentration of salts by evaporation.

Purpose and Scope of this Report

This report presents data on the major artificial-recharge experiments and operations that have been undertaken on the Southern High Plains prior to 1968. The data were obtained from many State and Federal agencies, drillers, farmers, and industrial personnel. Information is included from all known recharge operations that were research projects, and a sampling of data is included on wells that serve or were intended to serve as recharge wells on a continuing basis.

In general, recharge operations by farm operators, which generally are designed to drain playa lakes to increase farm areas, have not been documented sufficiently to determine the reason for success or failure. However, the reported long-term successes of some of these efforts indicate a need for a more rigorous examination of recharge operations of this type.

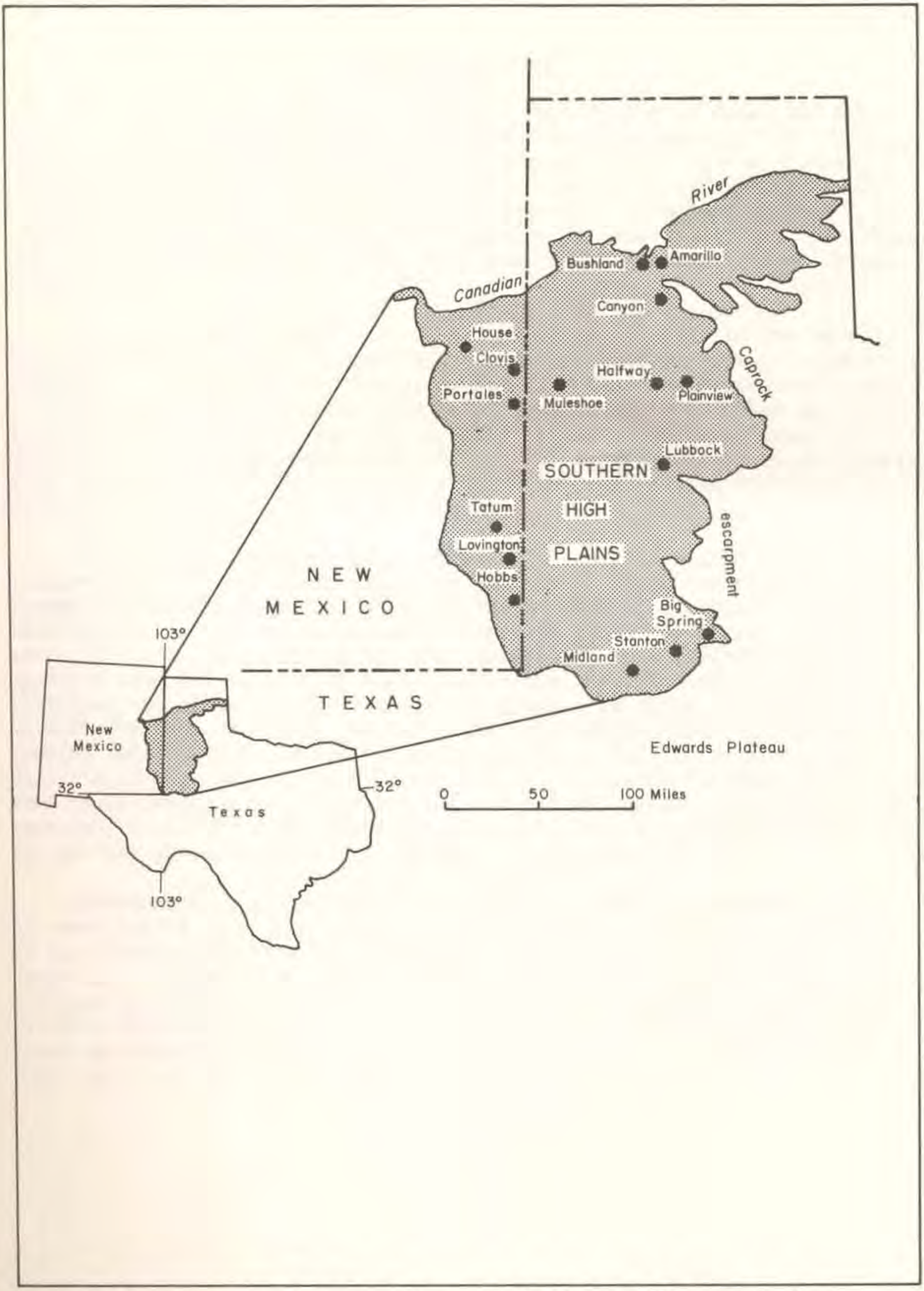


FIGURE 1.-Location of the Southern High Plains of Texas and New Mexico

The Water Problem

Water for irrigation on the Southern High Plains of Texas and New Mexico is available principally from ground-water storage, supplemented by minor amounts of surface water in temporary storage in playa lakes. The decrease in the saturated thickness of the Ogallala Formation caused by ground-water use is resulting in a progressive reduction in yield from individual wells in many areas. The average decline in water levels throughout the area has been more than 1 foot per year since about 1945 (Cronin, 1964, p. 49).

Typical average annual water-level declines in wells in the heavily irrigated parts of the Southern High Plains of Texas are given in table 1. Pumpage for all uses on the Southern High Plains of New Mexico has resulted in water-level declines of as much as 25 feet during 1940-60 in the Tatum-Lovington-Hobbs area; 50 feet during 1932-60 in the Portales area; 20 feet during 1950-60 in the House area; and 34 feet during 1954-60 in the Clovis area (Borton, 1967). The water-level decline in a well at Plainview in Hale County, Texas, is shown on figure 2.

Predictions of ground-water depletion usually have been based on an assumption of uniform permeability of the entire thickness of the Ogallala Formation (see Cronin, 1964, sheet 4) and a constant decrease in yield under conditions of constantly decreasing saturated thickness. In some areas, the effects of declining water levels are more serious than are apparent from examination of maps showing the saturated thickness of the Ogallala. Locally, the permeability is greater in the middle part of the formation than in the lower part (Rettman and Leggat, 1966, p. 19; and Cronin, 1964, p. 32). Where the permeability in the lower part of the Ogallala is very low, a constant decrease in saturated thickness will result in a rapid decrease in yield when the water level reaches the base of the permeable zone. When the water table is at that level, the formation will not produce adequate quantities of water for irrigation.

Development of ground water for irrigation and the resulting decline in water levels have taken place largely since 1943. In the south half of the Southern High Plains, irrigated acreage reached a maximum in 1965 (fig. 3a). In the north half (fig. 3b), the irrigated acreage in 1964 was exceeded in 1968, but only by about 3.4 percent. The data indicate that ground-water development for irrigation in the Southern High Plains of Texas may have reached a peak (Gillett and Janca, 1965; Keese, 1965; Lyle, 1966, 1967; and New, 1968, 1969).

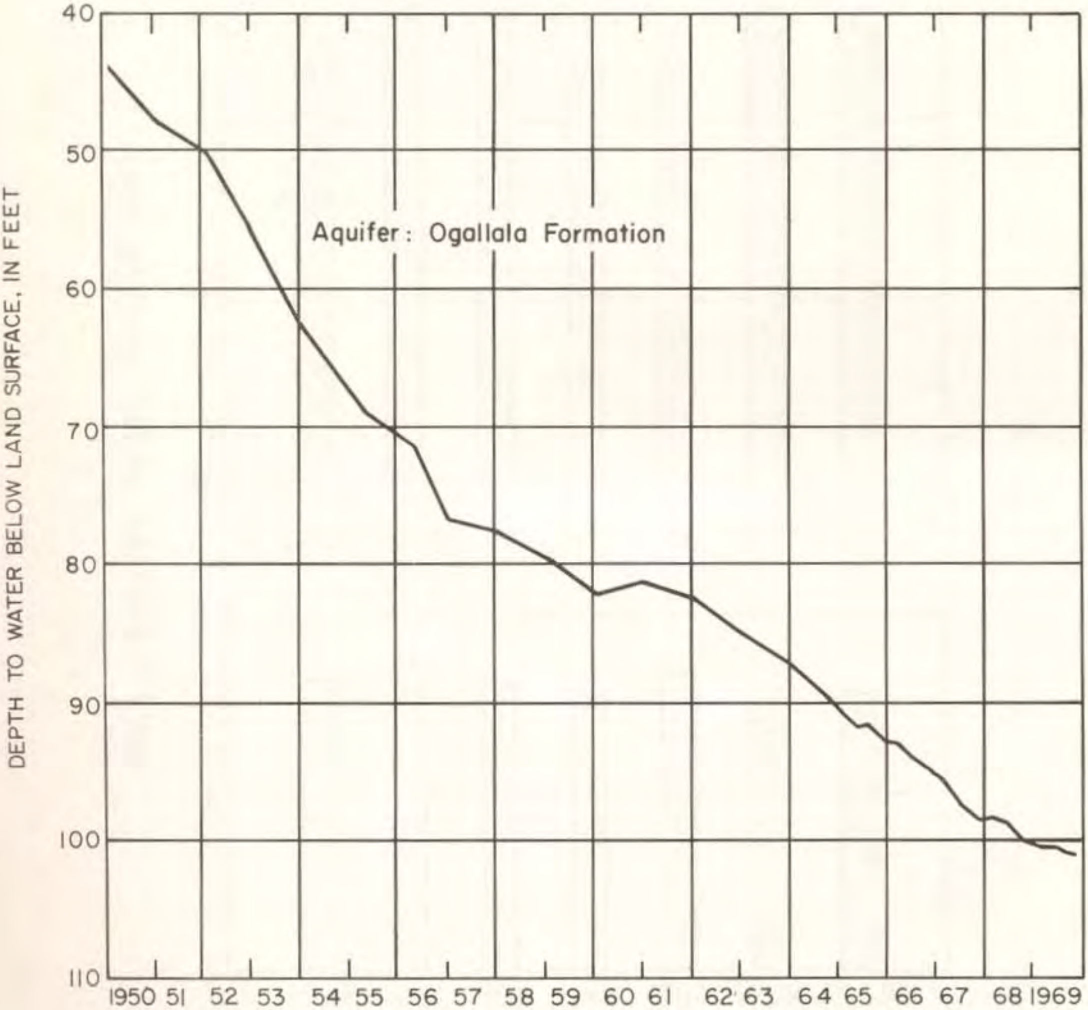


FIGURE 2.-Hydrograph of water levels in an observation well at Plainview, Hale County, Texas

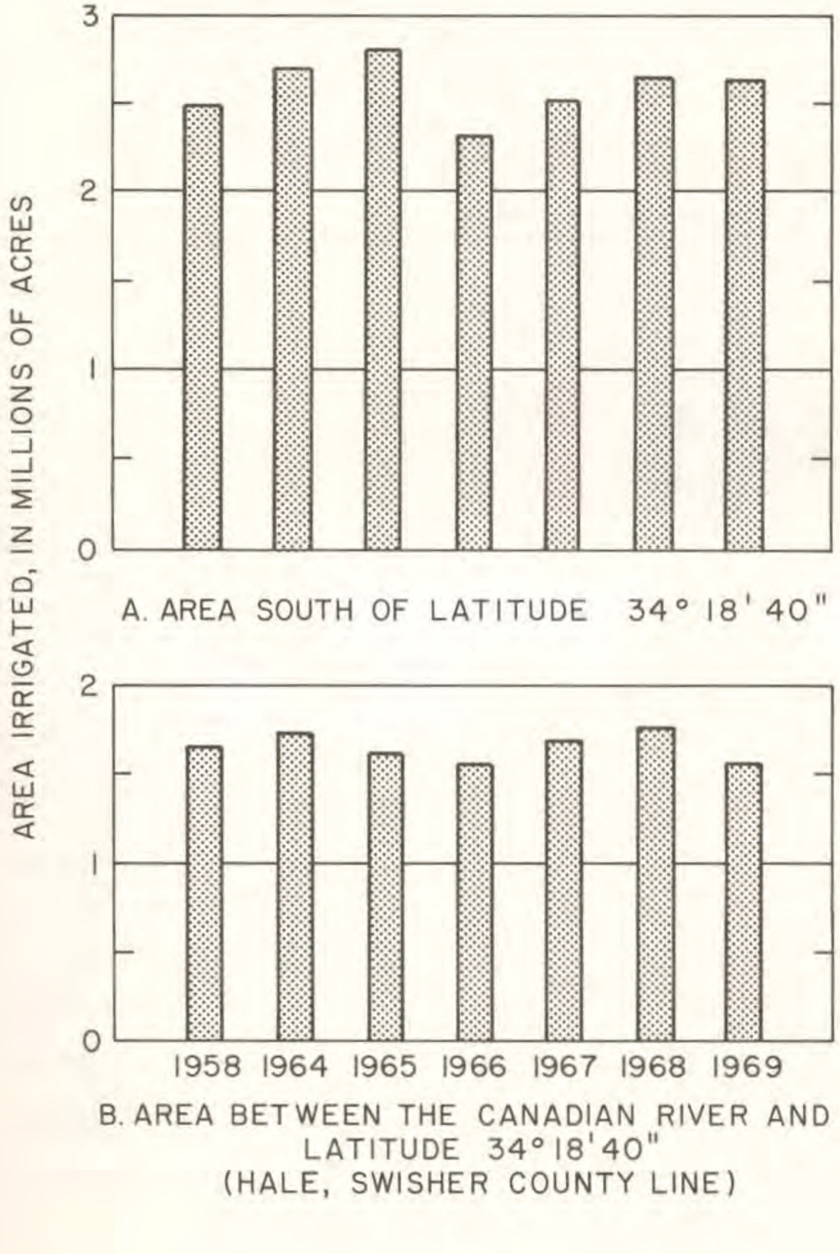


FIGURE 3.-Irrigated acreage on the Southern High Plains of Texas

Table 1.--Water-level declines in the heavily irrigated parts of the Southern High Plains of Texas (Rayner, 1968)

County	Average annual water-level decline in feet, 1962-68
Armstrong	2.26
Bailey	1.63
Castro	3.59
Cochran	2.06
Deaf Smith	3.45
Floyd	4.47
Hale	3.97
Hockley	1.74
Lamb	2.68
Lubbock	2.53
Lynn	1.37
Parmer	4.39
Potter	3.68
Randall	2.42

About 288,200 acres were irrigated on the Southern High Plains of New Mexico in 1961 (Borton, 1967). The total diversion of ground water for irrigation was about 563,900 acre-feet, and depletion was about 355,300 acre-feet. More than 50 percent of the irrigated area is in declared underground-water basins regulated by the New Mexico State Engineer Office; therefore, the amount of irrigated acreage is assumed to be fairly stable.

Annual precipitation and its distribution with time during the growing season affects the need for irrigation water; therefore, annual requirements may vary significantly. Water availability from precipitation and its distribution with time and space are shown on figures 4, 5, and 6.

Above-normal precipitation may occur frequently, but records of the National Weather Service (formerly the U.S. Weather Bureau) indicate that predominantly wet or dry conditions usually prevail for 15 years or more. The importance of annual variations in rainfall is particularly significant on the Southern High Plains because in wet years (maximum of 40 inches of precipitation) little or no irrigation water is used, but in dry years (maximum of 10 inches of precipitation) water application may exceed 2 acre-feet per acre.

Surface storage of water results in a relatively high loss through evaporation. The 1940-65 average gross lake-surface evaporation on the Southern High Plains of Texas and New Mexico was 72 to 80 inches per year (fig. 7). During dry years, such as 1950-56, the annual gross lake-surface evaporation on the Southern High Plains of Texas ranged from 80 to 90 inches (Kane, 1967).

Subsurface storage eliminates evaporation losses, but extensive use of the ground-water reservoir for storage of water recharged by other than natural processes involves complicated technical and economic problems. These problems include the cost of operation and maintenance of recharge facilities, the cost of repumping the water, water-quality problems caused by suspended sediment and other pollutants, and problems of geologic conditions that affect water movement and recoverability.

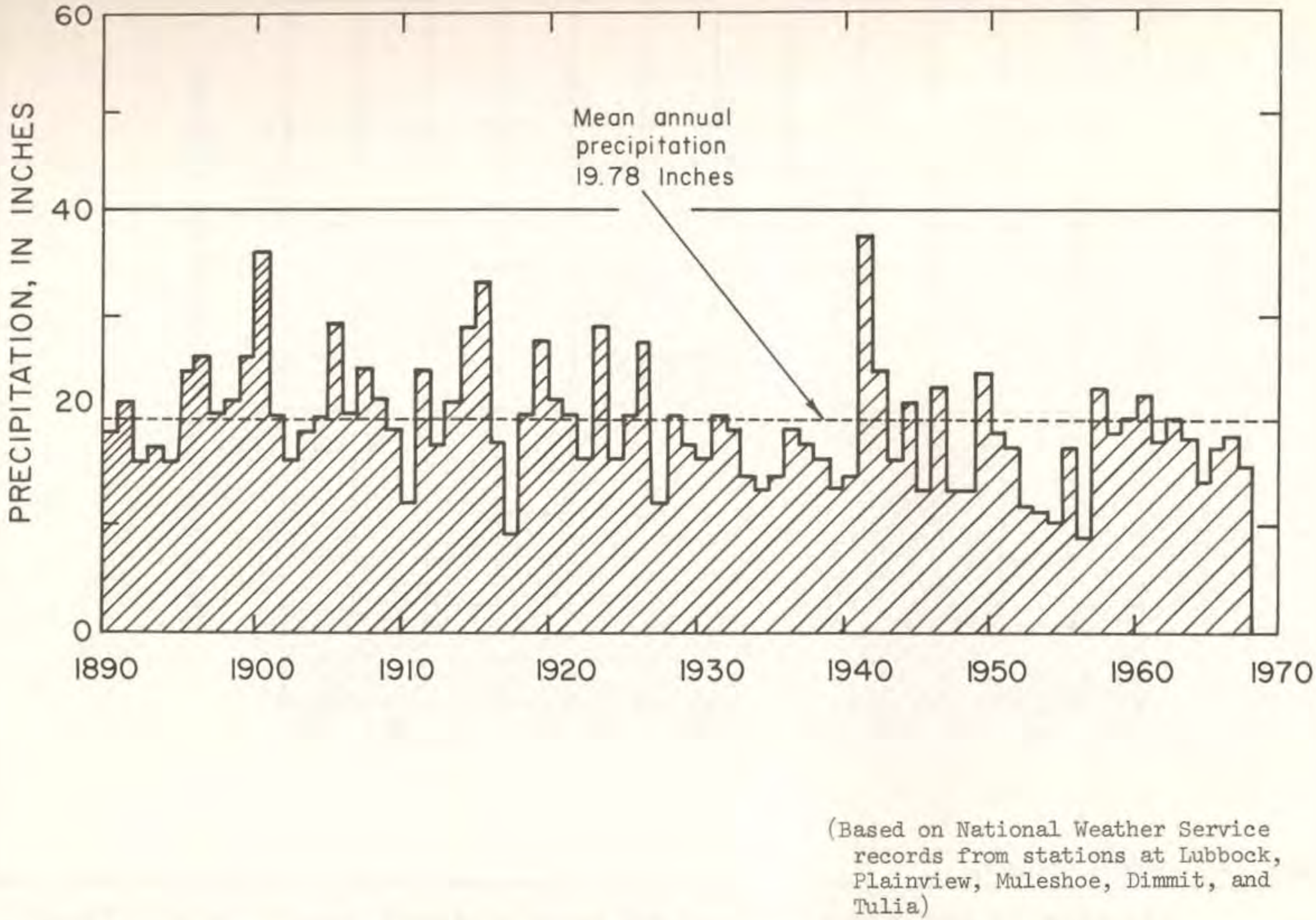


FIGURE 4.-Average annual precipitation on the Southern High of Texas, 1890-1970

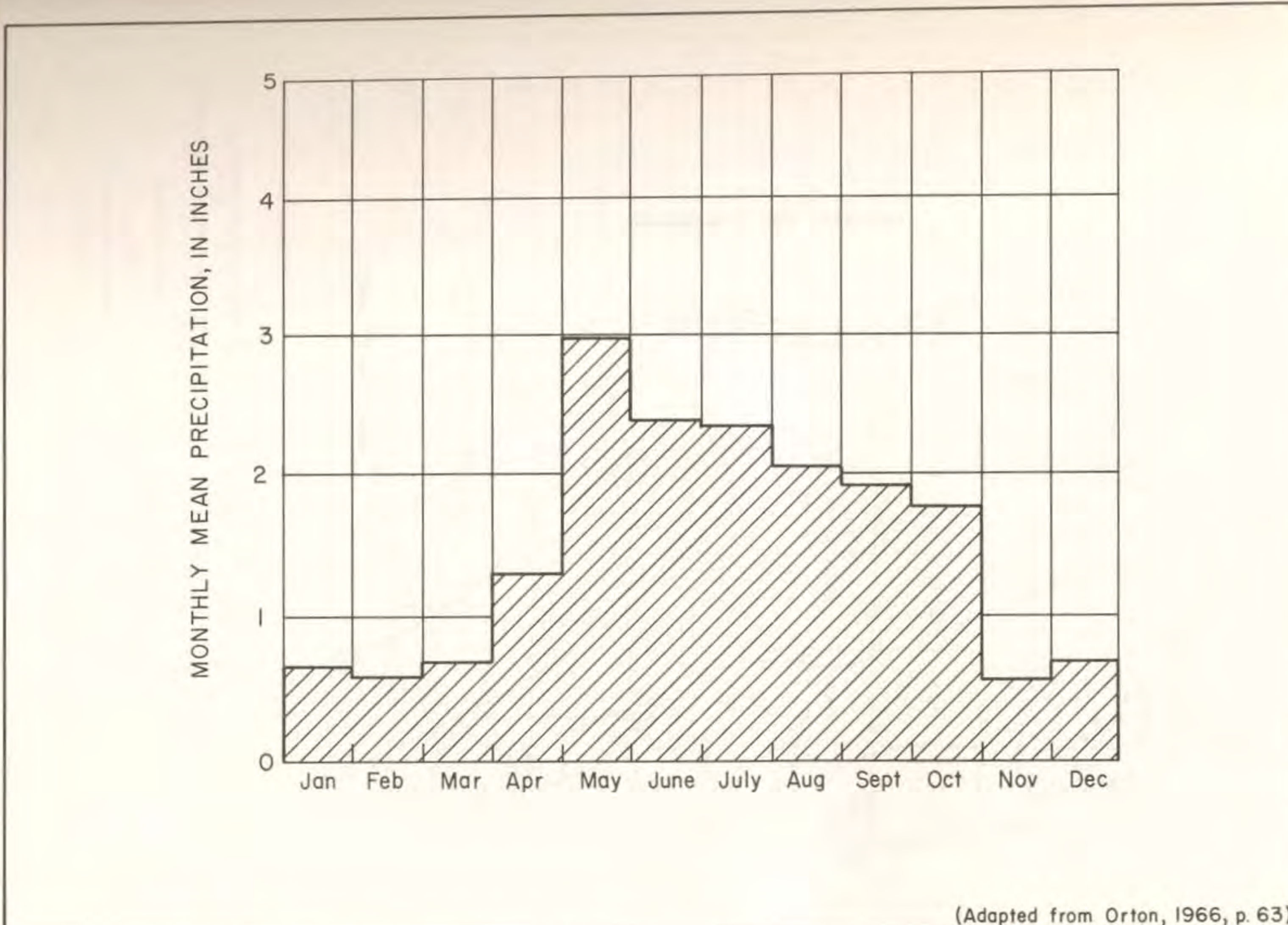


FIGURE 5.-Monthly mean precipitation on the Southern High Plains of Texas and New Mexico, 1931-60

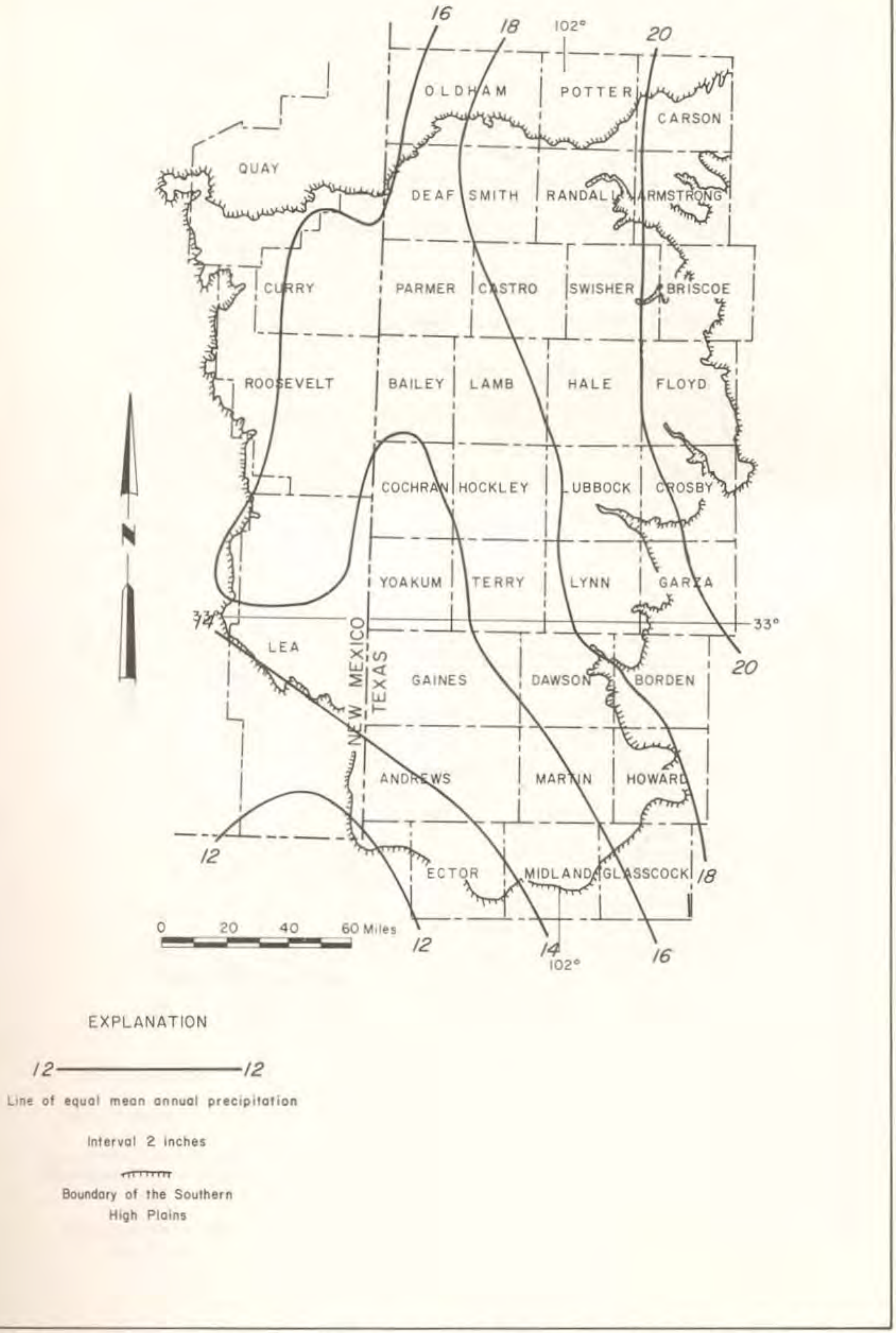


FIGURE 6.-Mean annual precipitation on the Southern High Plains of Texas and New Mexico, 1931-60

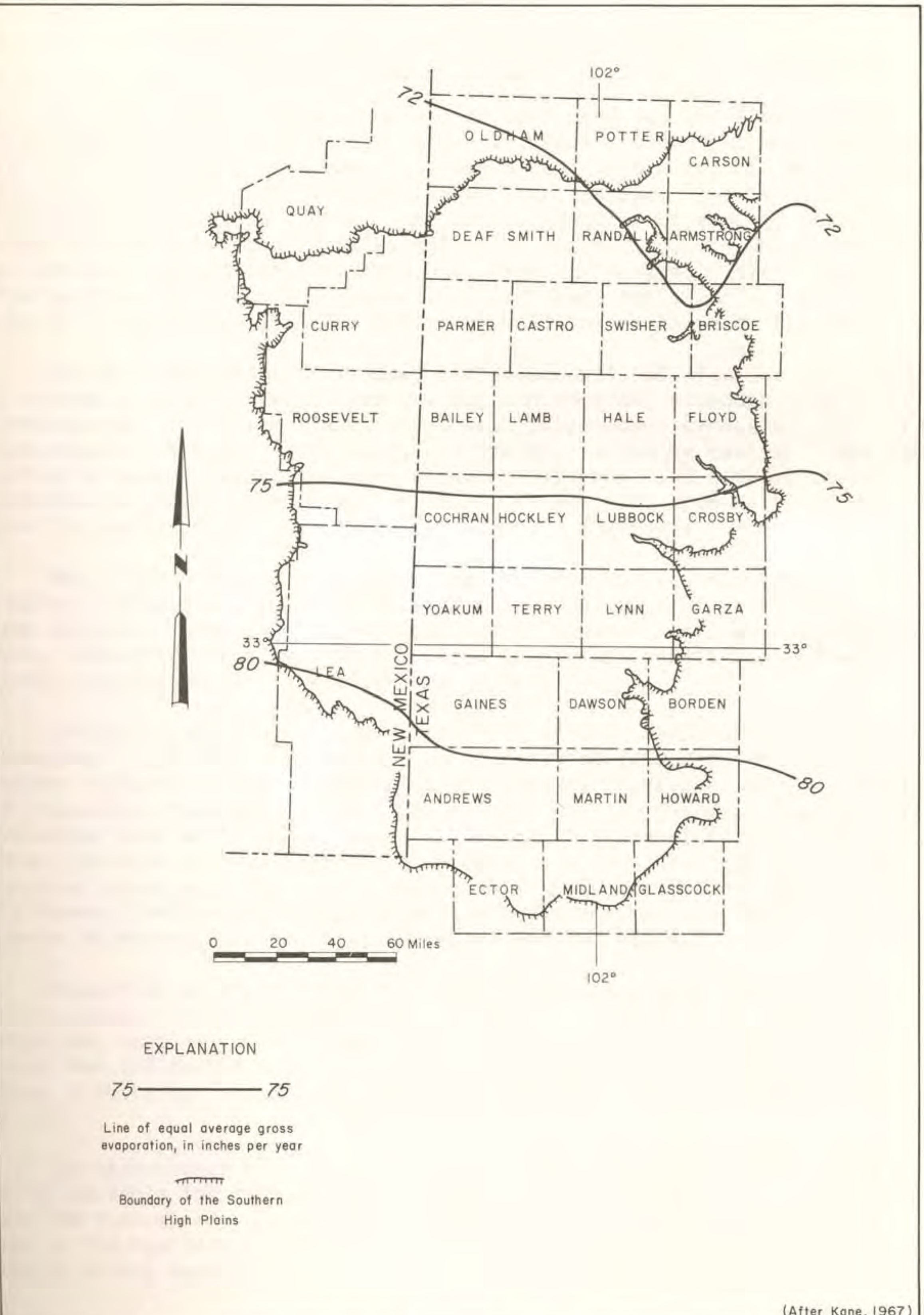


FIGURE 7. - Average annual gross lake-surface evaporation 1940-65

GENERAL GEOLOGY AND HYDROLOGY OF THE AREA

Geologic and Hydrologic Units

The rate at which an aquifer can be recharged and the flow patterns established as a result of recharge operations are dependent upon the hydraulic characteristics of the aquifer. The principal aquifer of the Southern High Plains is the Ogallala Formation of Tertiary age. The formations underlying the Ogallala generally do not yield water of good quality, and except locally as in the Portales Valley of New Mexico, the units overlying the Ogallala are not saturated and have very low permeabilities. The stratigraphic units and their water-bearing characteristics are given in table 2. The geology of the Southern High Plains is shown on figure 8.

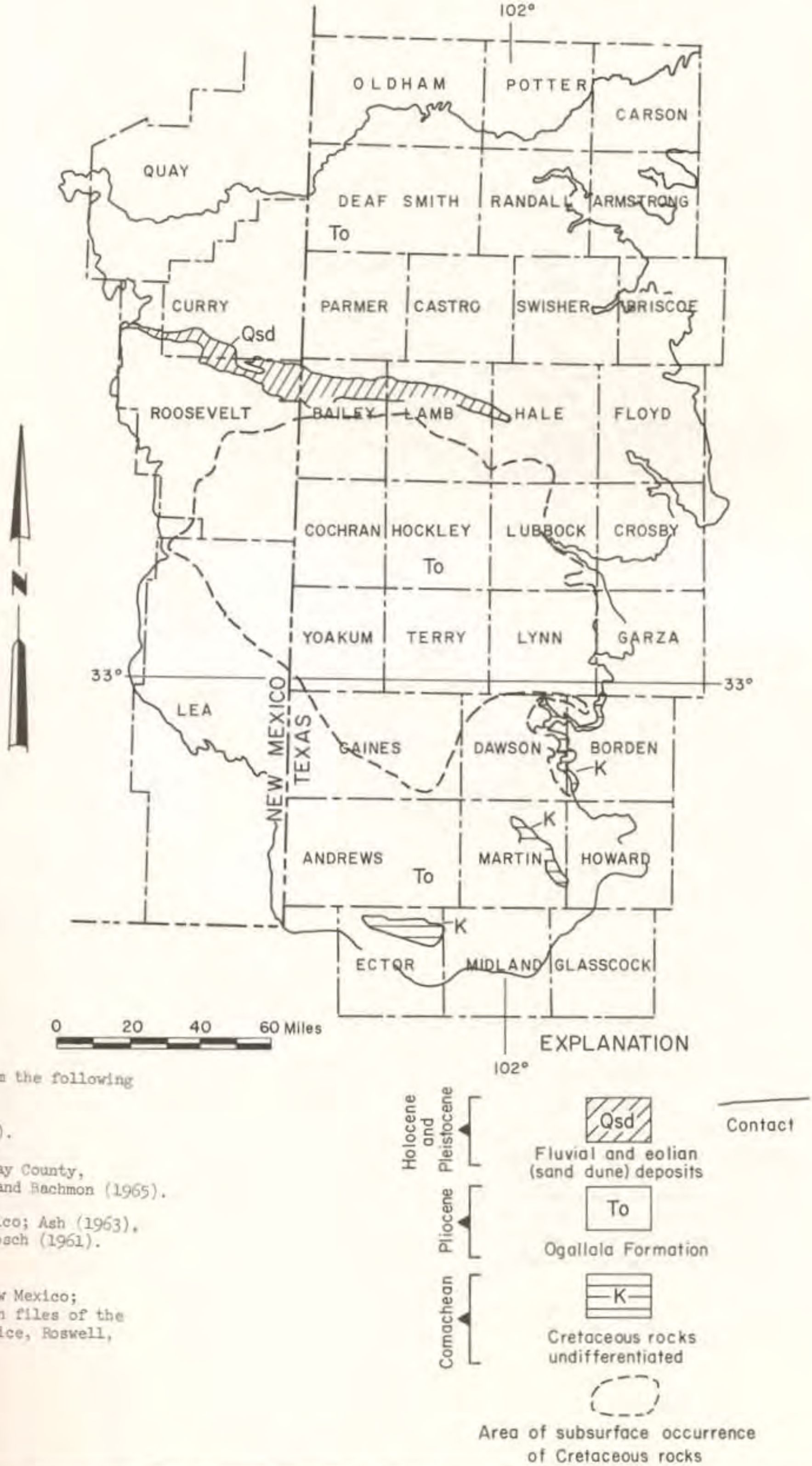
The Ogallala Formation is composed principally of alluvium deposited by streams flowing eastward from the Rocky Mountains, although locally it contains some lacustrine (lake) and eolian (windblown) deposits. The formation consists of clay, silt, sand, and gravel, capped by caliche. The sand is fine to medium quartz, in part silty, calcareous, and clayey; it is indistinctly bedded to massive, in places crossbedded, generally unconsolidated to weakly cohesive, and locally contains quartzite lenses.

The silt and clay are reddish brown to pink and contain some caliche nodules. The gravel, which is present only locally, is mostly quartz with some quartzite, sandstone, limestone, chert, igneous rock, and metamorphic rock. Characteristically, the fluvial deposits are stratified and well sorted locally, but are heterogeneous regionally.

Caliche layers and zones cemented with calcium carbonate occur randomly throughout the formation, possibly as a result of ground-water movement and surface evaporation that occurred at the time of deposition or as a result of evaporation from an aggrading eolian soil profile (Brown, 1956, p. 1-15). Throughout much of the High Plains, a "caprock" layer of caliche, ranging from a few feet to tens of feet in thickness, occurs near the top of the Ogallala Formation. The continuity of this unit has not been determined, but Havens (1961) found in one area of New Mexico that the caprock, although present elsewhere, was generally absent under the playas.

Deposition of the Ogallala Formation apparently took place initially in the valleys of the major streams and continued until the interstream areas were mantled by alluvium. The thickness of the sediments generally range from 100 to 200 feet; although east of Amarillo in Carson County, Texas, a thickness of more than 900 feet has been reported (Long, 1961, p. 16).

The approximate thickness of the Ogallala Formation that is assumed to be available for ground-water storage is shown on figure 9. This thickness was determined by combining a map showing the configuration of the base of the Ogallala (fig. 12) with a generalized topographic map of the loci of points approximately 50 feet below the land surface.



Geology adapted from the following sources:

Texas; Cronin (1964).

Curry County and Quay County, New Mexico; Dane and Bachmon (1965).

Lea County, New Mexico; Ash (1963). Nicholson and Clebsch (1961).

Roosevelt County, New Mexico; maps and records in files of the State Engineer Office, Roswell, New Mexico.

FIGURE 8.-Geology of the Southern High Plains

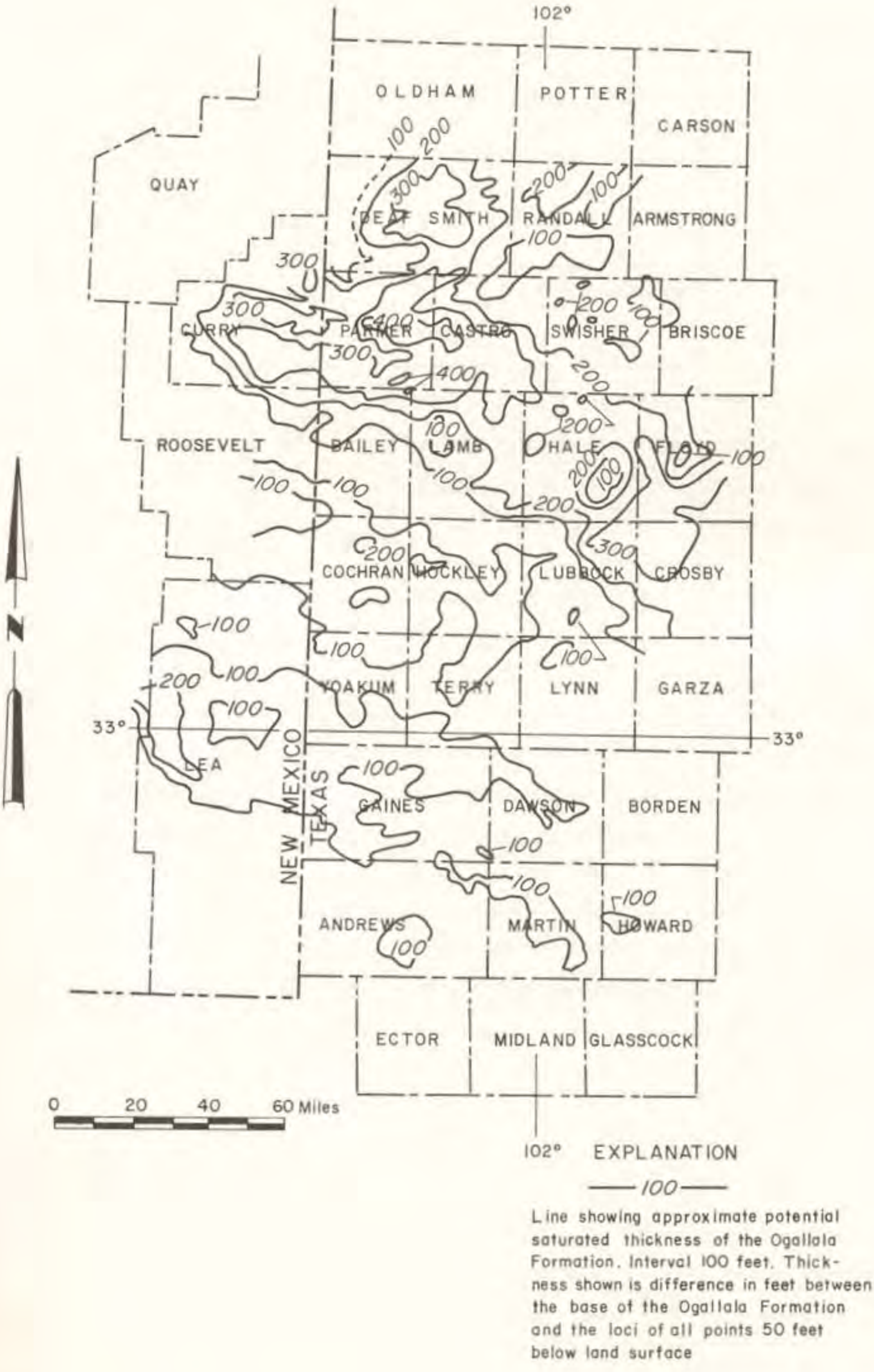


FIGURE 9.-Ground-water storage potential of the Ogallala Formation

Table 2.--Stratigraphic units and their water-bearing characteristics

System	Series	Formation or group	Approximate maximum thickness (feet)	Lithologic description	Water-bearing characteristics [1]
Quaternary	Holocene		15	Chiefly windblown sand and silt.	Yields no water to wells.
	Pleistocene		144	Sand, clay, diatomaceous earth, volcanic ash, and limestone.	Mostly above the water table, does not yield large quantities of water except locally.
Tertiary	Pliocene	Ogallala Formation	900	Fine to coarse sand and gravel; clay, silt, and caliche.	Yields large quantities of water throughout the Southern High Plains.
Cretaceous	Comanchean	Washita, Fredericksburg, and Trinity Groups	200	Fine to coarse sandstone and conglomerate, limestone, shale, and clay.	Locally important as a source of small quantities of water.
Triassic		Dockum Group: Tecovas Formation, Santa Rosa Sandstone, and Chinle Formation equivalent.	1,800	Shale and sandy shale, crossbedded sandstone, and conglomerate.	Probably capable of yielding small to moderate quantities of water, most of which is at least slightly saline.
Permian			8,000	Soft red sandstone, shale, clay, gypsum, and dolomite.	Not known to yield water to wells; water is probably saline.

[1] Yields of wells: Small, less than 100 gpm (gallons per minute); moderate, 100-1,000 gpm; large, more than 1,000 gpm.

Ground-Water Storage

The specific yield of the Ogallala, which is the amount of water released from storage by a unit decline in head, has been estimated at 15 percent (Cronin, 1964, p. 42). Estimates for the entire saturated section, however, range from 9 percent (Moulder and Frazor, 1957, p. 15) to more than 20 percent (Havens, 1966, p. F24). Field measurements of specific yield by the neutron method at Bushland, Texas (near Amarillo), gave an average value for a 12-foot section of 22 percent after pumping for 11 days (Jones and Schneider, 1969). Values of specific yield determined from laboratory studies of formation samples and from water-level decline data in northern Lea County, New Mexico, ranged from 24 to 38.4 percent. The New Mexico State Engineer uses a specific yield of 20 percent for Lea County (Havens, 1966, p. F24).

Under natural conditions, the amount of water in storage is nearly constant, increasing slightly in wet years and decreasing in dry years. Because recharge is so slight, natural changes in storage are relatively unimportant. The decrease in storage resulting from pumping is relatively so large that it masks any natural changes that may occur. In some areas, most of the water that was in storage has been removed from permeable rocks by pumping. In other areas, the saturated sediments, particularly those in the lower part of the Ogallala, have very low permeabilities and will not yield a significant quantity of water to wells (Rettman and Leggat, 1966, p. 19). Most of this water probably will remain in storage permanently.

Recharge, Movement, and Discharge of Ground Water

Natural recharge to the aquifer system is insignificant in relation to total pumpage, but the amount of recharge can be computed by assuming equilibrium conditions under which down-gradient flow toward the eastern escarpment is equal to natural recharge. This flow, which should correspond to natural discharge along the escarpment, can be computed from assumed values for the transmissivity and the regional hydraulic gradient.

Assuming a transmissivity of 2,000 feet squared per day (probably a lower limit) and a gradient of 10 feet per mile (fig. 10), each section of the aquifer 1 mile in width would discharge 20,000 cfd (cubic feet per day). Assuming uniform recharge along a 150-mile strip, 1-mile wide from the western to the eastern edge of the Southern High Plains, recharge of about 0.002 foot per year would be required to maintain a discharge of 20,000 cfd. If the assumed transmissivity is 6,000 feet squared per day (probably an upper limit), the required recharge would be 0.006 foot per year.

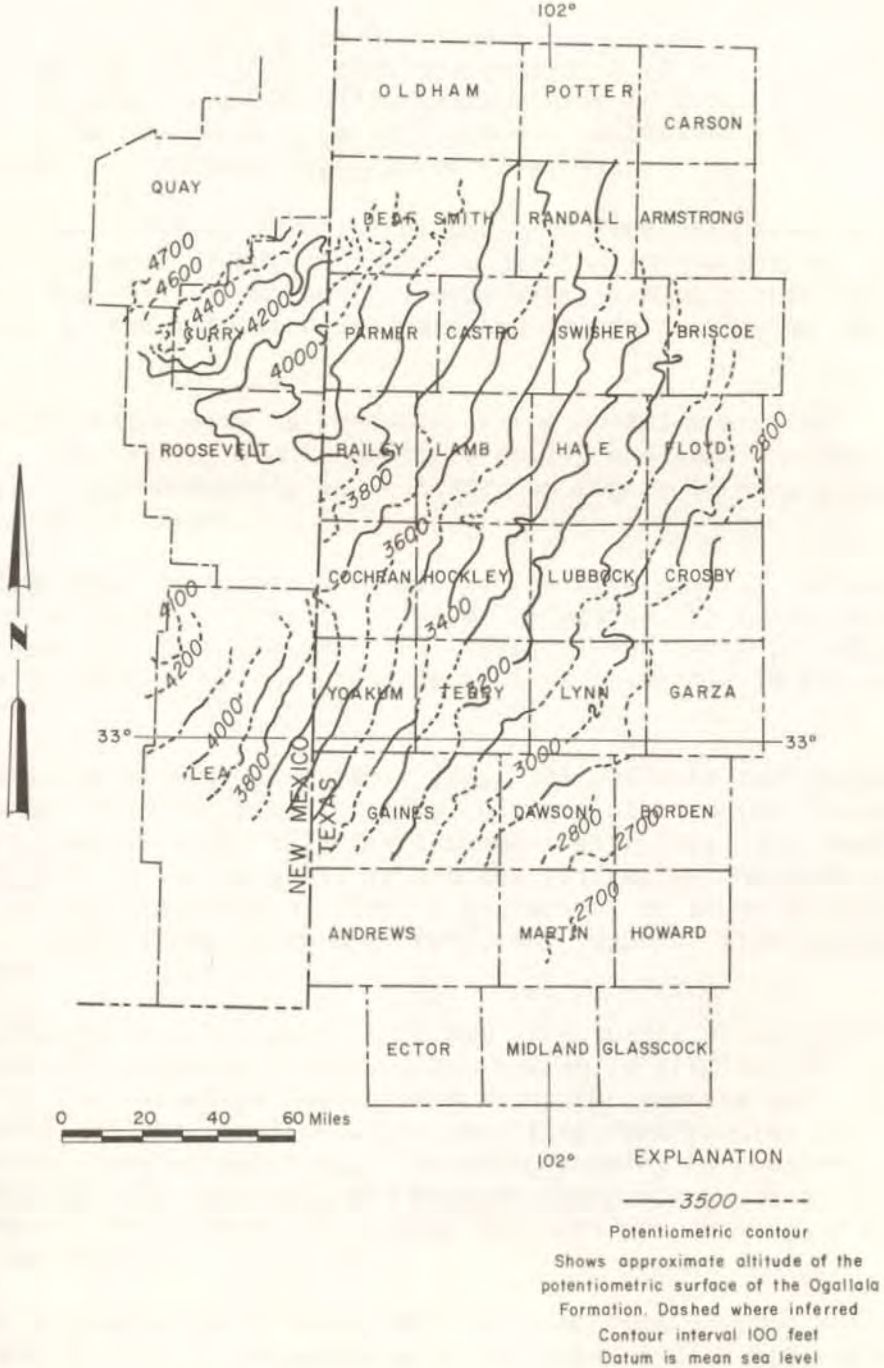


FIGURE 10.-Approximate altitude of the potentiometric surface in the Ogallala Formation

On other evidence, Theis (1937, p. 565) suggested that the average recharge from precipitation was about 0.5 inch per year or less. Probably, the average recharge is about 0.007 foot per year or 0.08 inch per year. Greater rates of recharge occur locally, particularly in areas of very sandy soils and in the sand-dune area that extends southeastward through the central part of the Southern High Plains (fig. 8).

Ground water moves slowly through the aquifers from northwest to southeast. Typically, the rate of movement may be about 2 inches per day (Cronin, 1964, p. 44); but the rate of movement is dependent primarily upon the hydraulic gradient in the saturated zone and the transmissivity of the aquifer.

The highest transmissivity is probably in the Portales area of Roosevelt County, New Mexico, and in northern Bailey and Lamb Counties, Texas. This higher transmissivity is indicated on figure 10 by a trough in the potentiometric surface.

The lower transmissivities in much of the southern part of the area (fig. 11), is due at least in part to a lesser saturated thickness of the aquifer. Also, logs of wells (Rettman and Leggat, 1966, table 3) indicate that locally the lower part of the Ogallala is less permeable in the southern part of the area.

The configuration of the water table (fig. 10) reflects the composite effects of recharge from precipitation (fig. 6), the altitude of the base of the Ogallala Formation (fig. 12), the transmissivity (fig. 11), and the pumpage. The surface of the water table and the surface of the bedrock are nearly parallel in the direction of flow at a gradient of about 10 feet per mile. Locally, gradients may be much steeper, but regional flow patterns are still apparent.

Natural discharge from the aquifer occurs principally as springflow and seeps along the escarpments. Because the hydraulic gradient is to the southeast, most of the discharge takes place along the eastern and southeastern escarpments. Water-level declines resulting from pumping tend to decrease the natural rate of discharge. However, pumping is greatest where the saturated thickness is greatest, and because these areas are remote from the escarpments, the effects of pumping have not yet diminished the natural rate of discharge.

Most of the discharge since about 1940 has been from pumping wells. Annual pumpage during 1940-70 ranged from an estimated 4 to 8 million acre-feet, depending on the amount of precipitation during the irrigation season. Water-level declines exceeding 100 feet have occurred locally, and declines of more than 40 feet have occurred throughout most of the irrigated area north of Lubbock. Pumping for irrigation is stopped by most operators when the saturated thickness of permeable material is less than 20 feet.

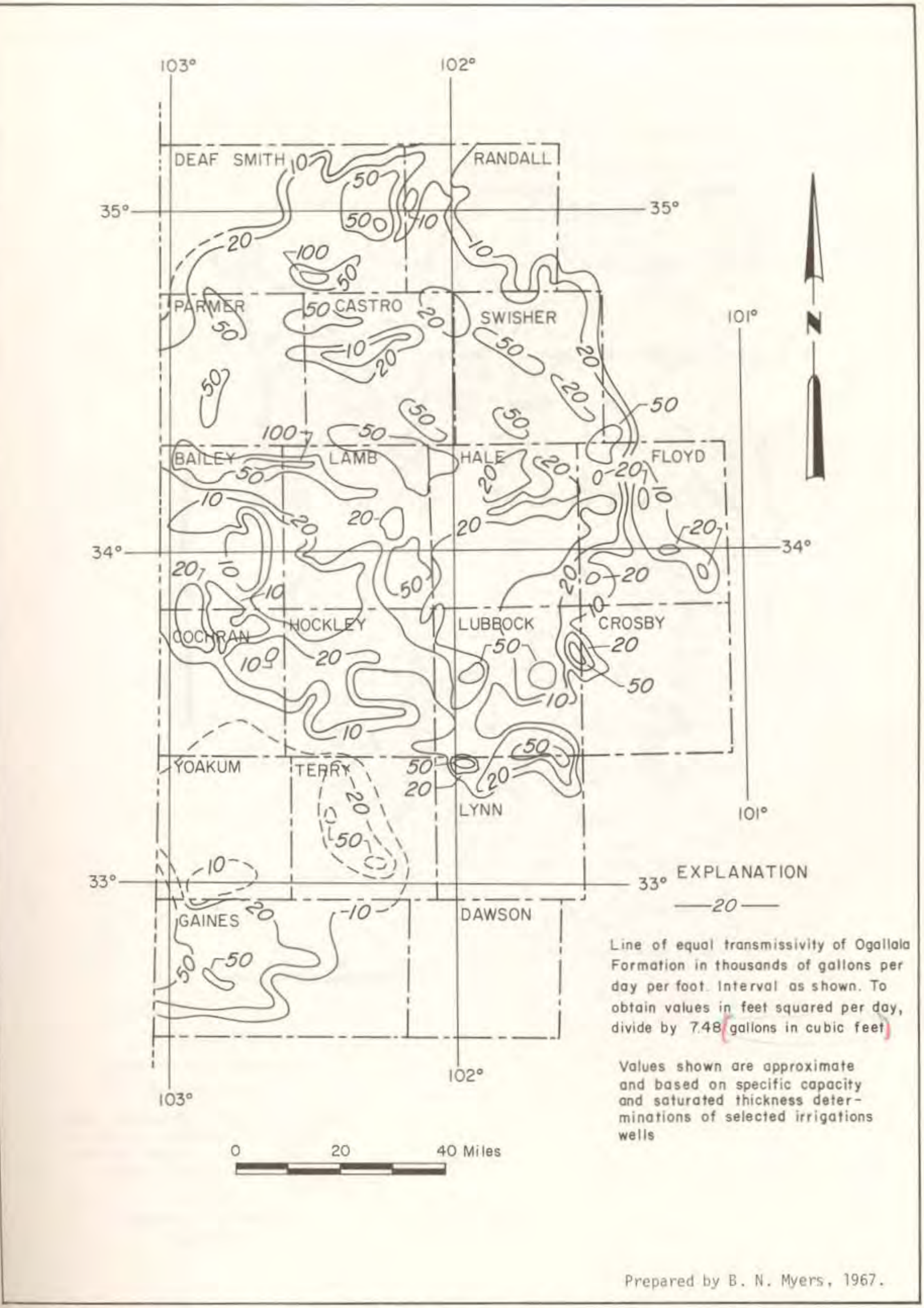


FIGURE 11.-Transmissivity of the Ogallala Formation, based on saturated thichness in 1965

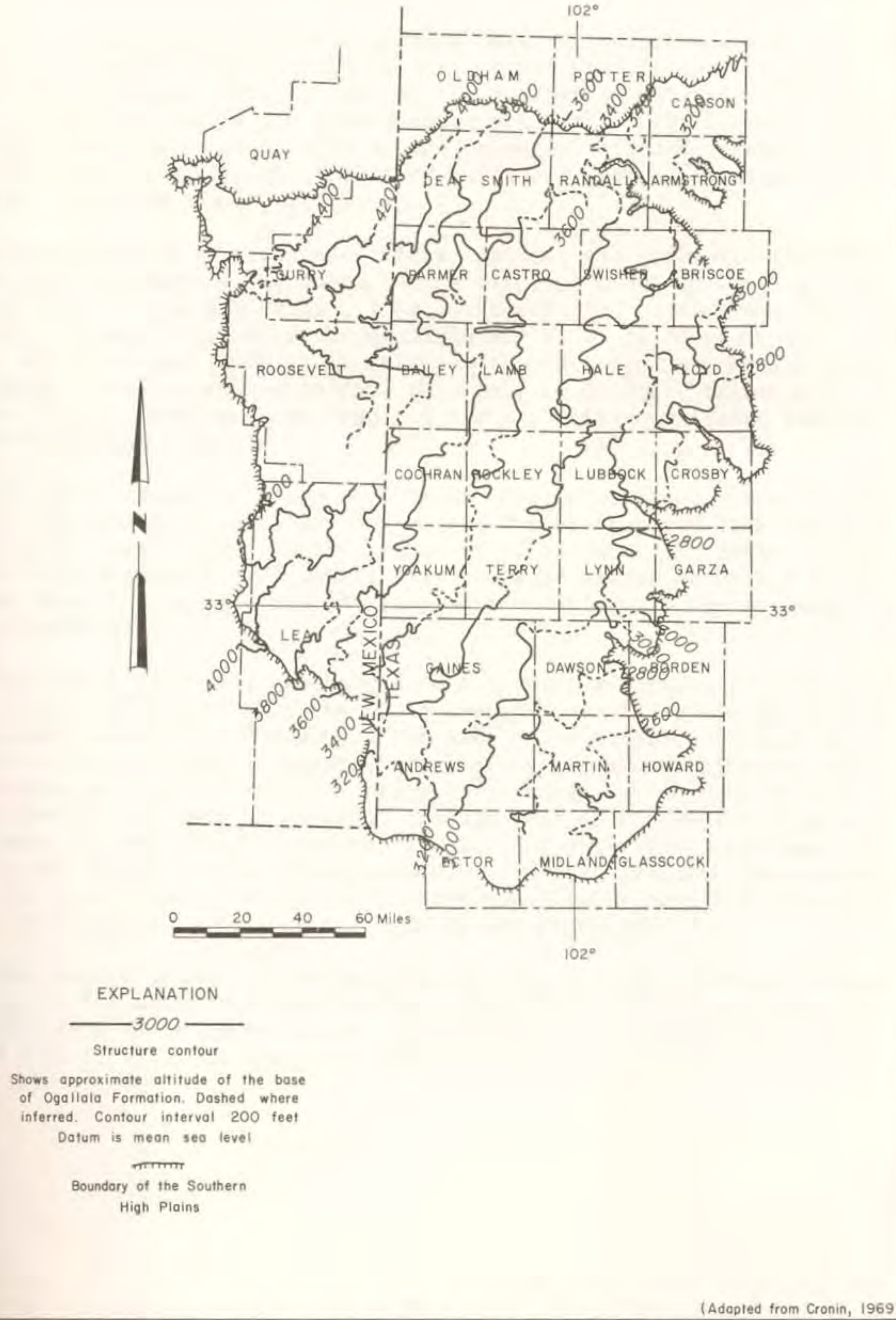


FIGURE 12.-Approximate altitude of the base of the Ogallala Formation

ARTIFICIAL-RECHARGE EXPERIMENTS AND OPERATIONS

Some of the proposals for importing water to the Southern High Plains incorporate ground-water storage as an integral part of the operation. Under other proposals, only a part of the average annual water requirements would be stored in the ground-water reservoir. If, however, the Ogallala Formation is to be used as the principal storage reservoir for imported water, a sufficient saturated thickness must be re-established to permit economic pumping rates.

Depending upon the economics of irrigation, the saturated thickness of the Ogallala must be increased to a minimum of about 30 feet at each pumping site (Hughes and Harman, 1969). Recent studies indicate that the porosity of some sections of the Ogallala may be 32 to 36 percent by volume (Jones and Schneider, 1969). To increase the saturated thickness uniformly by 10 feet, from an assumed initial thickness of 20 feet, recharge of about 3 acre-feet per acre would be required for the entire irrigated part of the Southern High Plains.

The total volume of water that might theoretically be stored in the Ogallala Formation in Texas and New Mexico can be computed from the data on figure 9. Assuming a specific yield of 15 percent, the total volume of recoverable water that theoretically could be stored between a level 50 feet below the surface and the base of the Ogallala would be about 400 million acre-feet.

Water that is locally recharged to a formation creates a mound on the water table. Dissipation of the mound depends upon the geologic and hydrologic conditions within and around the area of injection. Lateral movement of water away from a recharge area, after the mound dissipates, will approximate the rate of movement prior to recharge, or about 2 inches per day. Probably the rate of movement through most of the Ogallala is within this order of magnitude, therefore, a volume of water recharged along a line or at a point in the formation would move down gradient (southeast) about 60 feet a year. Nearly all the recharged water could be recovered from a point on the same acre on which it was injected.

The largest presently available local source of water for artificial recharge is the water contained in the playa lakes. The amount of water available from these lakes has not been determined, but estimates range from 1.8 to 5.7 million acre-feet annually (Hauser and Lotspeich, 1967, p. 11-15).

The quality of water in the playa lakes is very poor for artificial recharge operations because of the high concentration of suspended sediments. Hauser and Signor (1967, p. 7) found 210 mg/l (milligrams per liter) suspended sediment (0.3 ton per acre-foot) in a playa lake near Bushland, Texas. Clyma (1964, p. 3) reported that lake-water sediments in Hockley County near Levelland ranged from 370 to 1,800 mg/l (0.5 to 2.5 tons per acre-foot). Hauser and Lotspeich (1967, p. 11) sampled 11 lakes near Amarillo in 1965 and found that suspended sediment ranged from 200 to 1,000 mg/l.

The feasibility of artificial recharge on the Southern High Plains can be best evaluated by an analysis of recharge projects that have been conducted or that are in operation. To a large degree, these experiments and operations are the first efforts to artificially recharge the Ogallala Formation and probably do not represent the eventual success that could be attained at a given site. In addition, the test sites were not systematically selected on the basis of detailed hydrologic data, and therefore may not represent typical conditions for a regional project.

Recharge Experiments

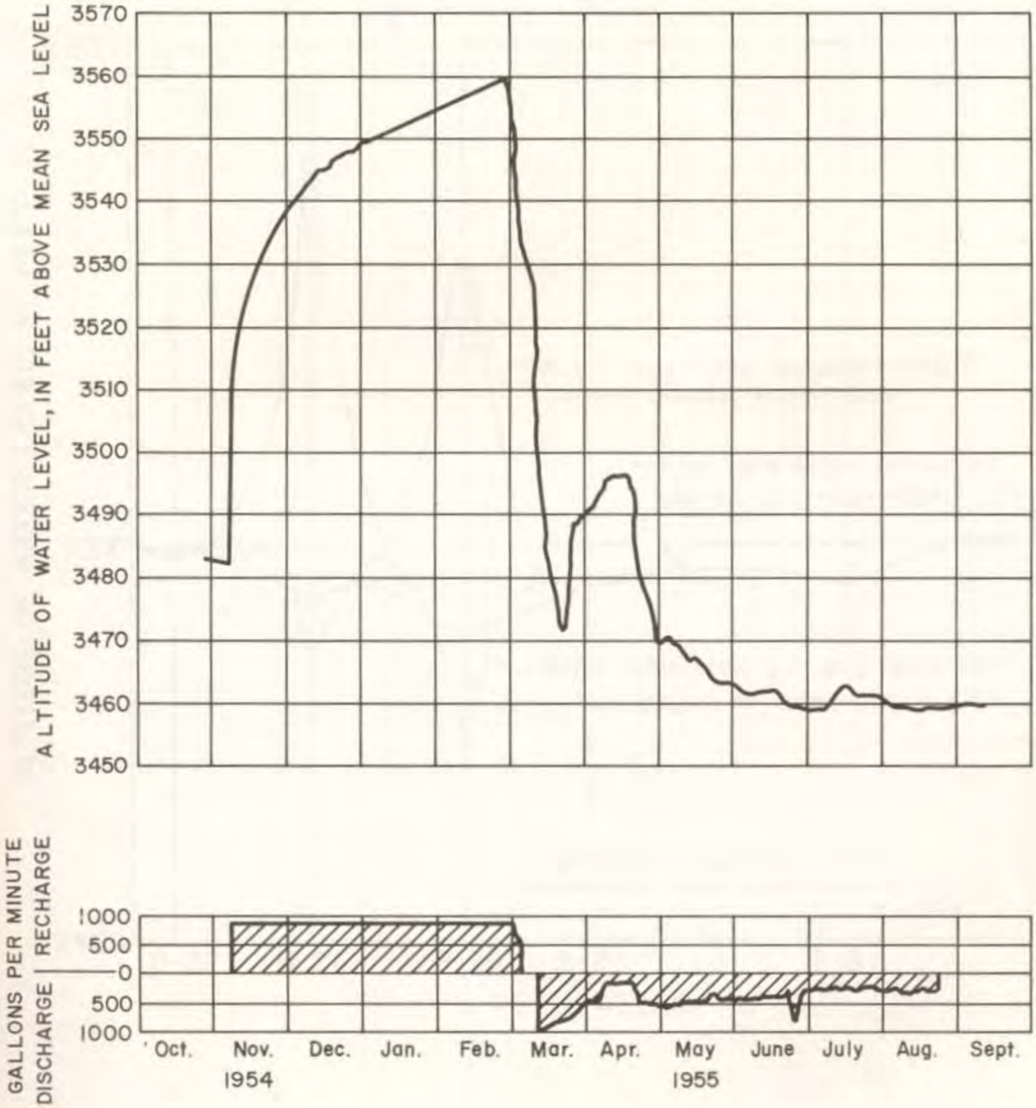
Amarillo, Texas

In 1954-55, a 4-month recharge test was conducted in the McDonald well field 2 miles southwest of Amarillo (Moulder and Frazor, 1957). Water was injected into two wells, (B-25 and B-26), from the Palo Duro well field, which is about 16 miles southwest of Amarillo.

These wells had specific capacities of 18 and 12.5 gpm (gallons per minute) per foot, and the calculated transmissivity was 940 feet squared per day for one well and 800 feet squared per day for the other. The saturated thickness was more than 110 feet, so the average hydraulic conductivity was about 8 feet per day. The storage coefficients were calculated to range from 0.09 to 0.16. The average depth of the wells below land surface was about 290 feet.

The water used for recharge was a composite of water from the Palo Duro well field, which in turn was obtained from induced infiltration of water from a small lake. A total of 407 acre-feet (132,541,800 gallons) was injected into well B-25, and 354 acre-feet (115,314,200 gallons) was injected into well B-26. A hydrograph and the recharge and discharge rates for well B-25 are shown on figure 13. A cross section of the water table before and after recharge (Moulder and Frazor, 1957) is shown on figure 14.

No significant difficulties were encountered during the recharge operations. The water was free of sediment and chemically compatible with the native water. Maximum rates of recharge were about 1,000 gpm, and rates of about 2,000 gpm were estimated to be attainable. Approximately 1,600 to 3,200 acre-feet per year could theoretically be injected through similar wells on a sustained basis.



(After Moulder and Frazor, 1957, p. 18)

FIGURE 13.-Water levels and recharge and discharge rates for well B-25, McDonald well field, Amarrillo, Texas

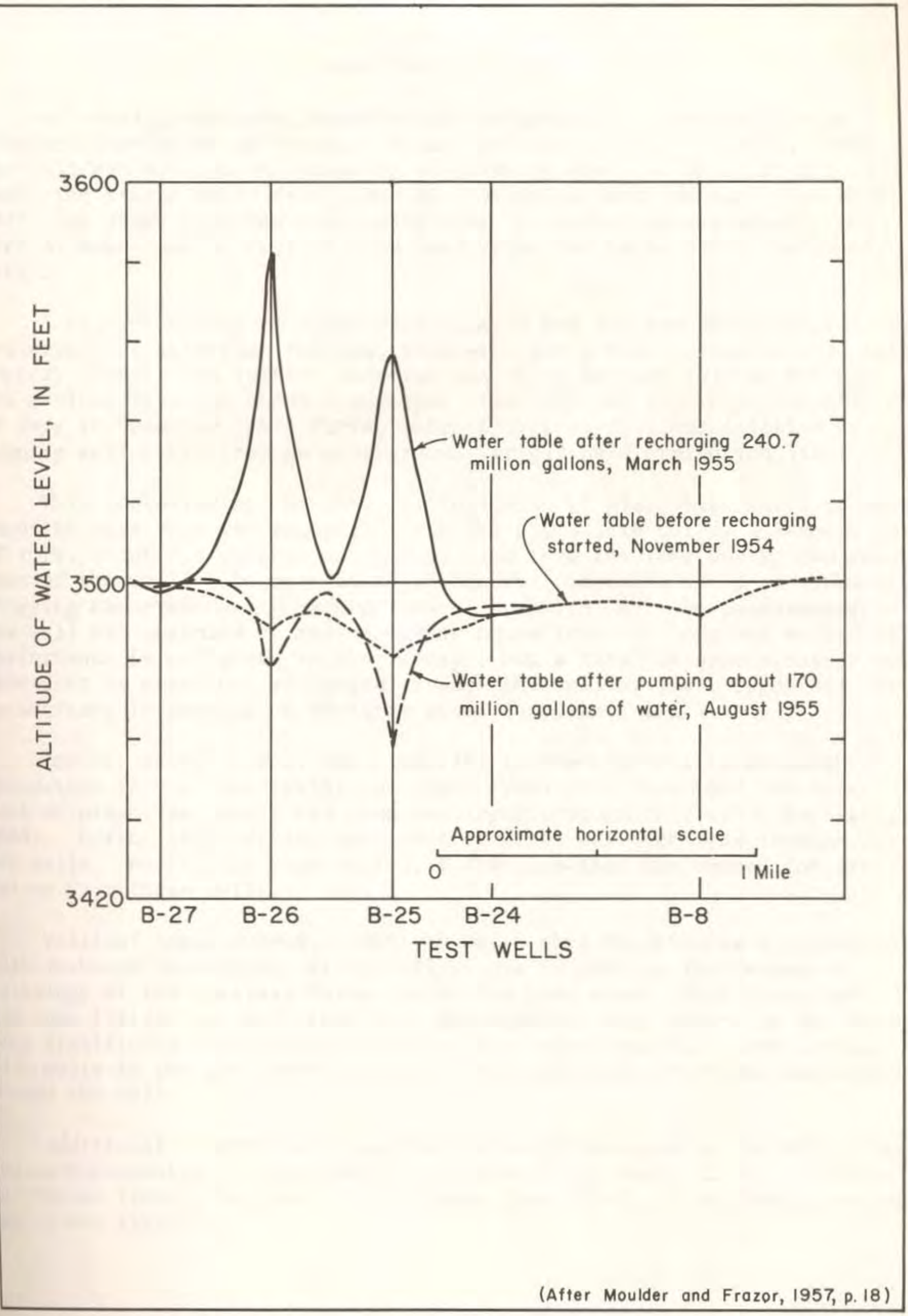


FIGURE 14.-Water levels resulting from recharge and pumping in McDonald well field, Amarillo, Texas

Hale County, Texas

A recharge well was installed on the grounds of the High Plains Research Foundation at Halfway, Texas, in 1957 (Myers in Cronin, 1964). The well was drilled to sediments of Triassic age (red beds) at 320 feet; the static water level was 110 feet below land surface. The driller's log shows that the well penetrated 30 feet of coarse gravel, 40 feet of sand, and 35 feet of find sand below the water table (Valliant, 1962).

A transmissivity of 5,000 feet squared per day was estimated for the recharge-well site from the transmissivity for a similar nearby well site (Myers, 1969). The initial recharge was at an average rate of 800 gpm; the maximum rate was about 1,200 gpm. The test was run intermittently for 18 days in December 1957, during which 63.7 acre-feet was injected by pumping well water from an underground irrigation-distribution line.

This installation was used for injection of playa-lake water in 1959. About 68 acre-feet was recharged from the playa lake during a 1-month period. Of this, about 7 acre-feet was pumped back into the lake during redevelopment of the well. The rate at which the well accepted water remained high. Clogging occurred during each period of recharge, but the performance of the well was restored by redevelopment operations. A complete record of performance is not given in the reports, but a total of approximately 300 acre-feet of water was recharged through the well by 1961, reportedly with no decrease in pumping or recharge rates (Valliant, 1961).

Another recharge well was installed at the High Plains Research Foundation in May 1961 (Valliant, 1963, 1965). By June 1962, 68 acre-feet of playa-lake water had been recharged through this well (Valliant, 1963). During 1959-64, 499 acre-feet of water was recharged through the two wells. During the same period, 1,788 acre-feet was pumped for irrigation from these wells.

Valliant (oral commun., 1968) believes that the success experienced with recharge through the first well is due in part to the favorable lithology of the Ogallala Formation in the test area. This first well and some irrigation wells that have subsequently been tested in the area, pump significant quantities of sand during redevelopment. Some irrigation wells in the area have pumped so much sand that cratering has occurred around the well.

Additional information regarding recharge research at the High Plains Research Foundation is available in reports by Cullinan (1959), Cullinan and Reeves (1961), Valliant (1960, 1964, 1965, 1967), Winn (1960), and Winn and Reeves (1961).

To facilitate construction of a pipeline, the Pioneer Natural Gas Company constructed a well in southeastern Hale County in 1957 to drain a playa lake (Broadhurst, 1957b). The well was drilled to 400 feet, and the log shows saturated fine sand from 100 to 200 feet. The lower 200 feet is saturated coarse sand and gravel.

The well was cased with 15-inch steel gas-line pipe perforated from 200 to 400 feet with 1/4-inch slots 12-inches in length. Water flowed from the lake into the open end of the well casing at about 2,000 gpm from June 1-7, 1957. Later, the casing height was extended, and a pump was installed to put water into the well and to permit cleaning the well by pumping. After installation was completed, the well was pumped 30 to 60 minutes each day. Intermittent recharge was continued from June 24 to July 12, 1957. The rate of acceptance decreased from 2,000 gpm to an average rate of 1,100 gpm. Recharge operations were terminated on July 12.

Floyd and Lubbock Counties, Texas

Recharge experiments have been conducted by the High Plains Underground Water Conservation District No. 1 in several irrigation wells. One well in southwestern Floyd County, about 20 miles northeast of Lubbock, was drilled to a depth of 377 feet in 1953 and equipped with a 12-inch casing perforated with 1/2-inch slots from a depth of 130 feet to the bottom.

This well was recharged with playa-lake water in 1955 at an initial rate of 1,050 gpm (Broadhurst and Willis, 1955). After 8 days of continuous recharge, 13 acre-feet of water and about 300 cubic feet of sediment had been injected into the aquifer. The well bore was reported almost completely plugged with silt, and the final acceptance rate of recharge was less than 200 gpm. After 4 hours of test pumping at 1,000 gpm, sufficient silt and sand were removed to restore the well to its original specific capacity.

In 1957, the playa lake was again filled and recharge rates for a 4-day period ranged from 1,700 gpm to 620 gpm, averaging 920 gpm (Broadhurst, 1957a). The aquifer was recharged through the well until the lake was drained. The well was redeveloped by pumping at 1,000 gpm for approximately 1 hour after each day of recharge.

Approximately 10 acre-feet was recharged in 1959, and 33 acre-feet was recharged in 1960. More water was available in 1960, but the well would neither accept or produce water. Following redevelopment, a total of approximately 150 acre-feet was recharged to the aquifer before the well failed.

The Earl Weaver well in eastern Lubbock County, which was constructed as a dual-purpose well, was recharged with playa-lake water in 1960 by the High Plains Underground Water Conservation District No. 1 (Broadhurst, 1960). The well depth was 203 feet; the saturated thickness was 133 feet; and the well diameter was 16 inches. The well was equipped with a torch slotted screen. Turbid lake water was recharged at a maximum rate of 500 gpm and at an average rate of 390 gpm for 49 hours. A total of 3.5 acre-feet was recharged. Data are not available on further operations at this well.

Hockley and Potter Counties, Texas

The Agricultural Research Service (ARS), U.S. Department of Agriculture, at Bushland, Texas, in cooperation with the High Plains Underground Water District No. 1, made recharge tests on a well in Hockley County between 1958 and 1960 (Jensen and Clyma, 1959; Clyma 1964). Several tests were made during which turbid water from a playa lake entered the well by gravity flow for 24 hours. Flow was then stopped and the well was pumped for one hour to remove accumulated sediment. About 90 percent of the injected sediment remained in the well after pumping. During injection of a total of 17 acre-feet of turbid water, the specific capacity of the well decreased from 20 gpm per foot to 2 gpm per foot.

During the experiment, about 4 acre-feet of water treated with an organic flocculant was injected. The treatment with flocculant, which was accomplished by dusting the lake from an airplane, reduced the clay and silt content of the lake water by about 30 percent.

A total of almost 11,000 pounds of clay and silt remained in the well after three of the recharge-pumping cycles that were conducted in 1958 and 1960, during which 7.65 acre-feet of water was recharged. Extending this rate of suspended-sediment injection to the total of 17 acre-feet that was recharged during the experiment, more than 12 tons of silt and clay remained in the well after recharge and pumping. Through subsequent redevelopment with acids, detergents, tetrasodium pyrophosphate, and surging, the specific capacity of the well was finally returned to 6.5 gpm per foot; the total loss in specific capacity was 13.5 gpm per foot.

Several experimental recharge projects have been undertaken at the Southwestern Great Plains Research Center, Bushland, as a part of the research effort by the ARS. Through the use of polyelectrolyte polymers and alum to flocculate and precipitate suspended solids in playa-lake water, the suspended sediment load of the lake water was lowered by more than 90 percent. The initial suspended-sediment concentration ranged from 120 to 250 mg/l. After treatment, most samples contained less than 20 mg/l and none exceeded 30 mg/l. (Hauser and Lotspeich, 1967; Rebhun and Hauser, 1967; Hauser and Signor, 1967.) This treated water was used for experimental injection into four wells located at the research center, three 6-inch and one 16-inch.

About 46.6 acre-feet was injected into the three 6-inch wells and 15 acre-feet into the 16-inch well. The residual 20 to 30 mg/l of sediment plugged the wells during recharge. However, redevelopment by bailing was successful in the 6-inch wells, and the 16-inch well was redeveloped by pumping. Approximately 2 cubic yards of sand were removed from one 6-inch well by bailing, and this material contained much of the injected sediment. The successful redevelopment of these wells was probably due in large part to a microfloc which inhibited penetration of the formation by the sediment in the injected water.

Lubbock, Texas

Texas Tech University has conducted several recharge projects in the Lubbock area, and the initial results of some of these experiments have been published. The experiments of Johnson and Crawford (1967) were designed for laboratory determination of the characteristics of clogging by the injection of silt and clay into a sand body. The problem was separated into (1) sand-face plugging and (2) formation sealing by the limiting distance of penetration of silt as related to the velocity of injection.

The initial conclusions from the laboratory tests were that the silt does not create a cover on the face of permeable sand, but that plugging continues for some distance into the formation as silt slowly fills the matrix.

An experimental recharge well was drilled into the Ogallala to a depth of 145 feet and reamed to 20 inches in diameter to a depth of 107 feet. Torch slots were cut in the lower 55 feet of 10 3/4-inch gravel-packed casing. About 11.5 acre-feet of water was injected by gravity flow during the first year of operation, and 6.8 acre-feet was pumped from the well for irrigation and redevelopment. About 20,000 pounds of clay was injected, but less than 9,000 pounds remained in the well after pumping.

Recharge rates declined during the test from 525 gpm to about 40 gpm. An attempt was made to restore recharge capacity through acidizing, but there was no measurable increase in the acceptance rate. A subsequent test using pressure injection recharged 2.86 acre-feet of water and approximately 12,800 pounds (60 cubic feet) of silt and clay in slightly more than 8 hours. Casing-head pressure dropped from an initial 85 to 50 psi (pounds per square inch) to 50 psi while maintaining a constant recharge rate of 1,919 gpm.

Johnson and Crawford (1967, p. 11) concluded that "collodial or suspended material that may deposit in pore openings in porous media will cause an increase in flow velocity of fluids through the reduced size pore openings resulting in fluid erosion to remove the deposited material, or it will cause an increase in pressure to the extent to cause formation particle disturbance by fracturing of the strata."

The results of this short test of pressure injection seem highly favorable. However, the quantity of water injected was relatively small, and additional experimentation is needed to evaluate pressure injection as a recharge technique in the Ogallala Formation.

An evaluation of the effectiveness of near-surface drains was made by William Schwiesow, Department of Agricultural Engineering, Texas Tech University. Sixteen drainage-filtering lines, 600 feet in length and 37 feet apart, were buried 3 to 4 feet below the bottom of a playa lake. Soil, cotton burrs, gin trash, corn cobs, and gravel were used as filter media; the pipes were composed of plastic, bituminous fibers, asbestos cement, and vitrified clay tile. Six pipes were 6 inches in diameter and the others were 4 inches in diameter. These pipes drained into a 16-inch diameter well drilled 150 feet deep.

The initial drainage of the lake was reported to be rapid, and 90 acre-feet of water was collected and recharged through a well during approximately 2 years of tests. Subsequently, deposition of sediment in the lake basin has reportedly reduced vertical permeability and prevented any significant discharge from the drain lines into the well.

Denver City, Texas

The Southwestern Public Service Company began recharging a well at their Denver City, Texas, plant (70 miles southwest of Lubbock) in July 1957. One well in a depleted well field was used to recharge the aquifer at an average rate of 130 gpm from a remote well field in the Ogallala that provided the regular plant supply. The recharge water was largely free of suspended sediment; the well was gravel packed; and no operational or plugging problems were encountered.

After 1 week of the operation, 4.5 acre-feet had been recharged. The original static water level at the well before recharge was 74.1 feet below land surface. During the recharge period, the static level rose to 61.9 feet. A water-stage recorder was installed later in an observation well about 600 feet from the recharge well. At that time, 17.1 acre-feet had been recharged, and the water levels were 5.1 feet and 14.4 feet above their original levels in the observation well and recharge well, respectively. This recharge operation continued for about 1 year.

Because the water in the depleted well field had a high concentration of dissolved solids; it was hoped that the recharged water would provide an emergency supply that would be less salty. However, when the recharged water was repumped, the salt content increased rapidly with time; therefore, the operation was discontinued.

Lea County, New Mexico

Havens (1966) described experiments in three recharge wells in northern Lea County, east of Lovington, New Mexico. Pumps were not provided for cleaning the wells. The wells were equipped with a surface filtering system using a 6-inch annular pack of pea gravel in a 7-foot circular screen. High-test hypochlorite powder was added by hand to the lake water to maintain an approximate chlorine concentration of 2 mg/1 in the recharge water. Water from lakes entered the wells by gravity flow.

"In October 1960, water was injected by gravity flow into the aquifer [through one recharge well]. The initial metered flow ranged from 600 to 750 gpm. Within 2 minutes the water level rose nearly 0.6 foot in an observation well 196 feet southeast of the injection well. As injection continued at lessened rates, the water level in the observation well reflected these changes, but continued to rise. When injection was stopped, the water level in the observation well declined within a few hours to a level of about 0.2 foot above that observed before recharge was started. Because several days were required for the water level in the observation well to decline to that observed before injection began, the build-up and gradual dissipation of a mound of water around the recharge well was indicated" (Havens, 1966, p. F45).

The gravel filters were unsatisfactory because they clogged too rapidly and decreased the flow to the recharge well. Efforts to clean the gravel-pack filters were only partly successful, and the total amount of recharge was estimated to be 180,000 gallons. Although there was no determination of the clogging in the recharge well, the severe problems of clogging in the filter indicated that without the filter, critical plugging of the recharge well would have occurred. No further experiments were made in the well field to determine alternative methods of filtering the water or effectively recharging the well.

Recharge Operations

Midland, Texas

Wells in the McMillen well field, a part of the water-supply system for Midland, Texas, have been used for artificial recharge on three separate occasions. In 1957-58, 335 acre-feet was injected into wells in the central part of the field from wells in the northwest corner. In 1959, 121 acre-feet was injected into the central part of the field from the Paul Davis well field which is 30 miles northwest of the McMillen field. In 1965-66, an additional 1,391 acre-feet was injected from the Paul Davis well field.

According to Reed (1959) the initial operations in 1957-58 were designed to obtain information on the feasibility of recharging the well field. Specifically, the objective was to determine whether the wells would accept and recharge the aquifer with significant volumes of water, and whether the mound created by recharge would stay within the area of the city well field so that the recharged water could be reclaimed.

Prior to recharge, the potentiometric surface contained several drawdown cones in an elongated trough (Reed, 1959), and from 1953 to 1959 water levels declined as much as 34 feet (figure 15).

Two weeks after injection of 335 acre-feet of water during a 107-day period in 1957-58, the altitude of the water table was increased a maximum of about 10 feet above pre-recharge levels. The configuration of the mound, computed by Reed as the difference between normal recovery when pumping ceased and actual recovery from injection, is shown on figure 16. Injection of 1,391 acre-feet into the field in 1965-66 resulted in a more extensive mound (figure 17).

The water was injected through three wells at rates ranging from 121 to 279 gpm during the first operations in 1957-58. In 1965-66, water was injected into 11 wells at an average rate of 265 gpm. The wells were production wells with no modifications. Recharge water was pumped back down the pump column through a closed system from pumping wells in an adjoining field.

Although water-quality data are not available, the proximity of the recharge and supply wells would indicate that the water quality is similar in the two areas. Reed (1959, p. 9) concluded on the basis of the operations that 1,500 acre-feet (500 million gallons) a year could be stored in a 2-square-mile area of the McMillen field. Water from the Paul Davis field was also successfully recharged to the McMillen field in 1966-67 and 1967-68.

Martin County, Texas

The Colorado River Municipal Water District, Big Spring, Texas, began artificially recharging the Ogallala Formation in December 1963. A total of almost 4,000 acre-feet of lake water had been recharged by July 1968, and recharge operations were continuing.

The recharge wells are in Martin County, Texas, and the water supply is from Lake J. B. Thomas, about 28 miles northeast of Big Spring. Water is distributed from the lake by pipeline to municipal and industrial users. Peak-flow demands of the users are greater than the capacity of the pipeline, but during low-demand periods, the pipeline capacity is greater than demand.

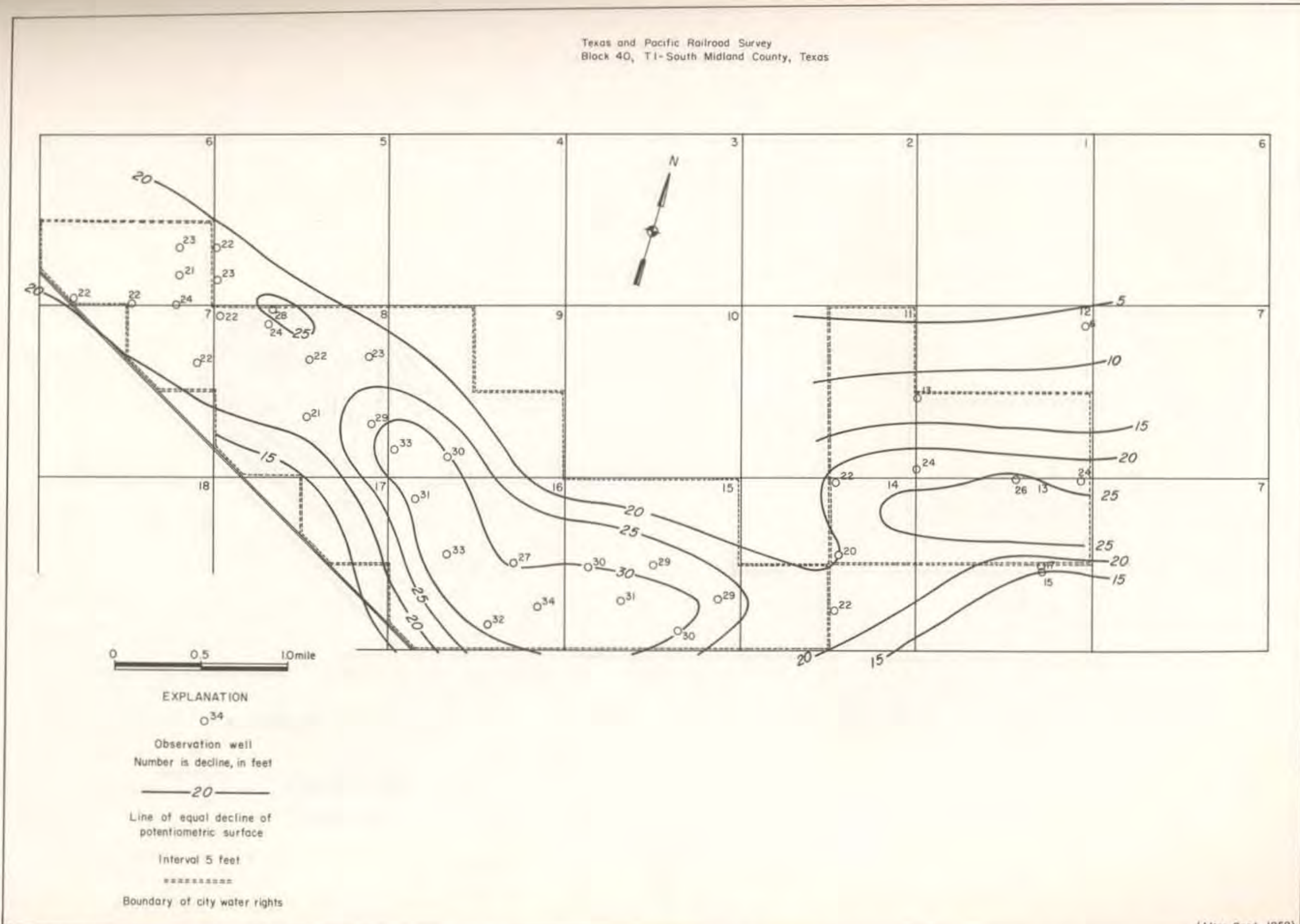


FIGURE 15.-Decline of the potentiometric surface in the McMillen well field, Midland, Texas, 1953-59

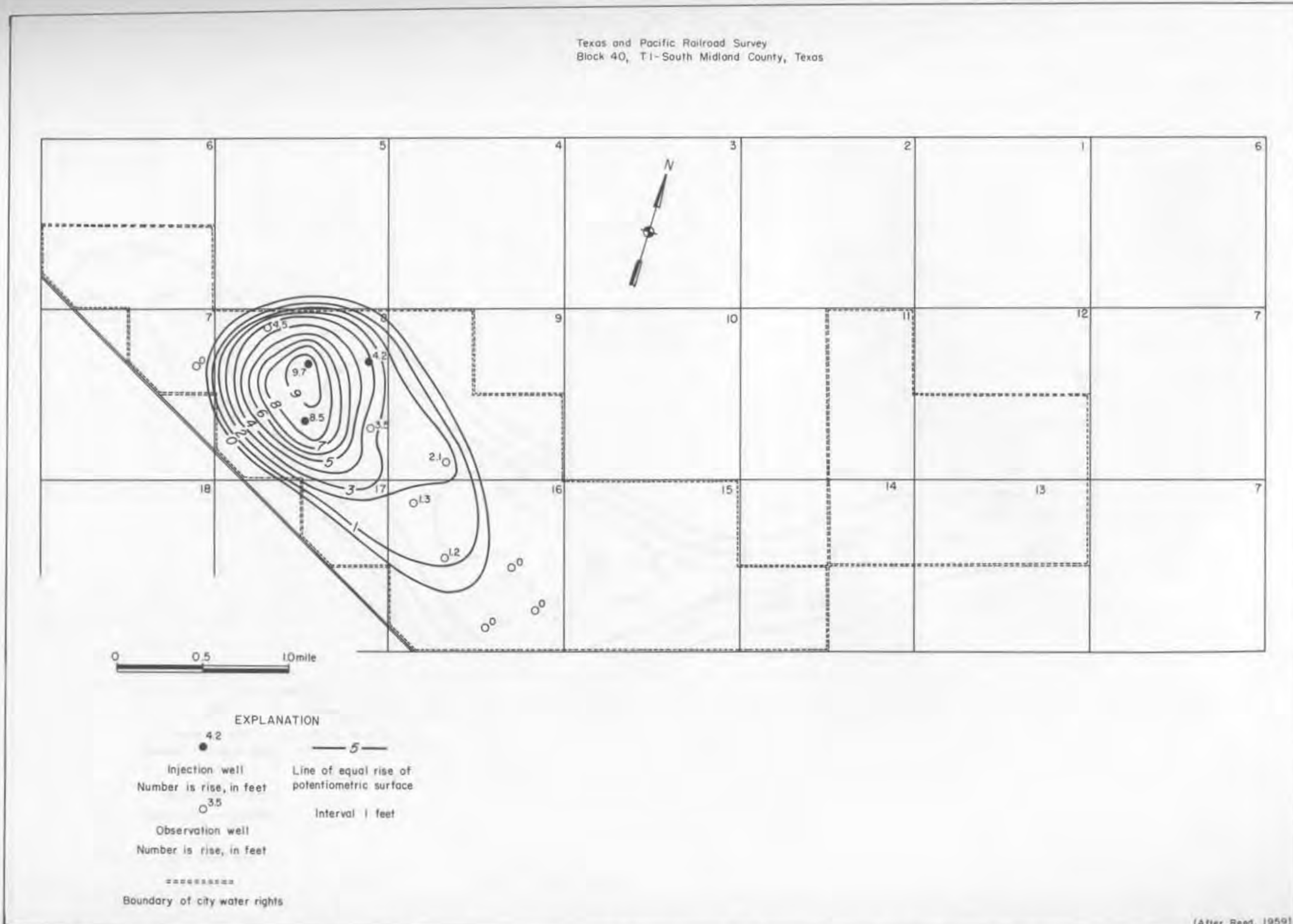


FIGURE 16.-Potentiometric surface of a recharge mound in the McMillen well field, Midland, Texas, 1957-58

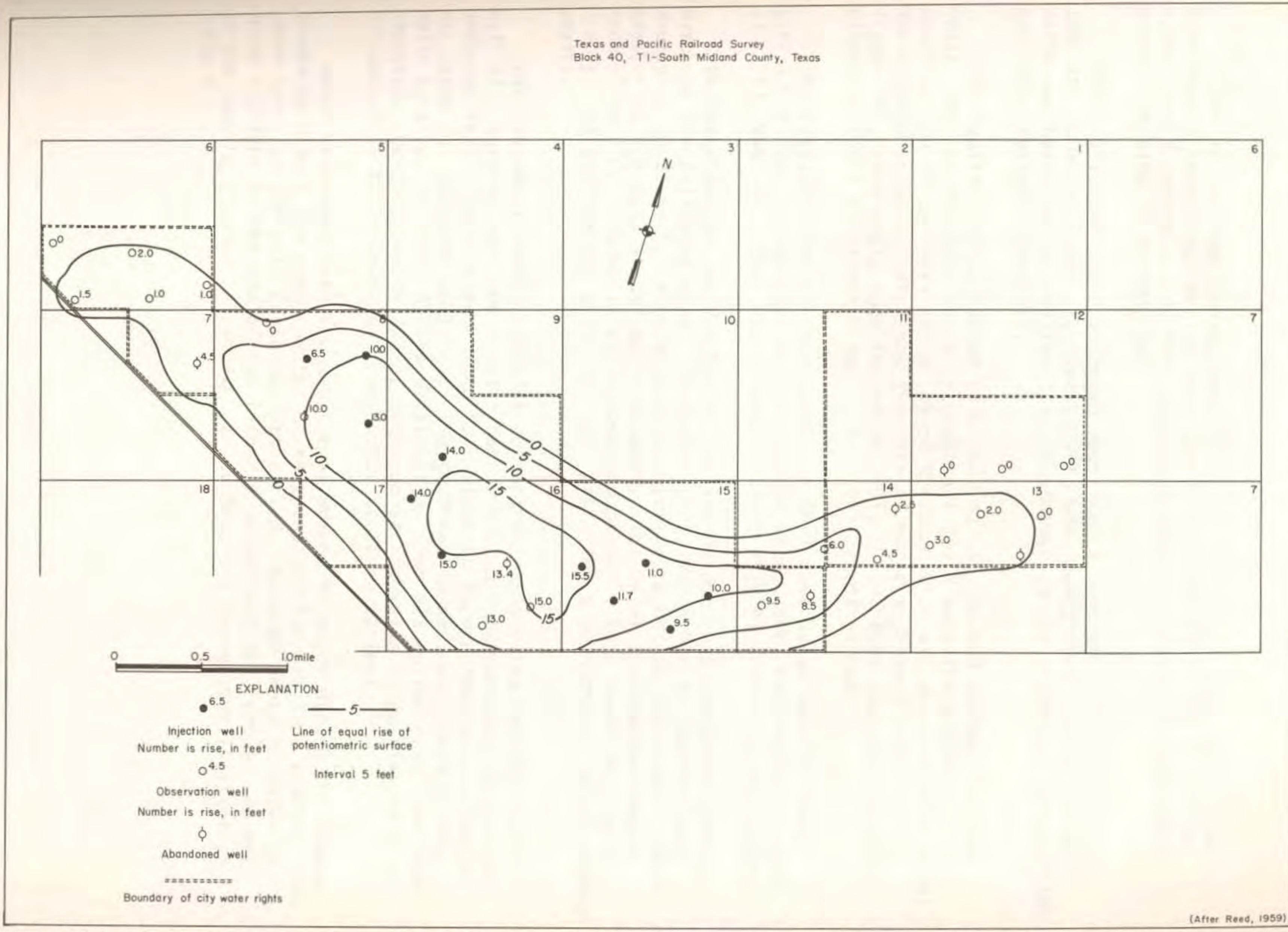


FIGURE 17.-Potentiometric surface of a recharge mound in the McMillen well field, Midland, Texas, 1965-66

Prior to recharge operations, pipeline deliveries from the lake at peak demand were supplemented from ground-water sources, but declining water levels caused a need for additional interim storage of lake water nearer the area of maximum use.

Water-level declines averaged more than 6 feet per year from 1952 to 1963 in the well field. The decision to use underground storage of lake water was based on the availability of storage in the formation and the high cost of a surface reservoir.

The aquifer was recharged each year during 1963-68 through several wells, but the recharge rates through well No. 2 were the highest. The construction of the well and a log of the formation are shown on figure 18. The average recharge rates and quantity of water recharged are shown on figure 19. This well, constructed in 1951, is 205 feet deep and is completed in rocks of Triassic age. It is not gravel packed.

The original static water level was 69.1 feet below land surface, with 134.9 feet of saturation. The static water level measured on January 27, 1963, was 142.8 feet below land surface, with 61.2 feet of saturation.

Recharge to the aquifer begins in late October and continues through March of the following year. The lake water, which has a sediment load averaging 20-25 mg/l, is treated with chlorine to obtain a residual concentration of 1.5 mg/l at the well entrance. The water temperature ranges from 7° to 9°C. The wells are surged and pumped 4 to 5 hours once every 7 days. Water from the wells is very turbid for a few minutes after pumping starts.

The maximum recorded sediment content during surging was 600 mg/l in well 29. Surging was done by alternately pumping and backwashing in each recharge well. Wells were surged four times in 15 minutes, then a sample was taken for sediment analysis. The decrease in sediment yield of the wells is given in table 3. No difficulties from air entrainment have been reported. Depth to water during recharge at the wells is maintained at a minimum of 25 to 30 feet, but ordinarily is 50 to 60 feet.

Water recharged into the aquifer is pumped to users during the summer months in almost the same quantities as recharged the previous winter. The water level in the well field has stabilized. Average depth to water is about 132 feet at the end of the recharge season and 155 feet at the end of the pumping season. A summary of the recharge operations is given in table 4.

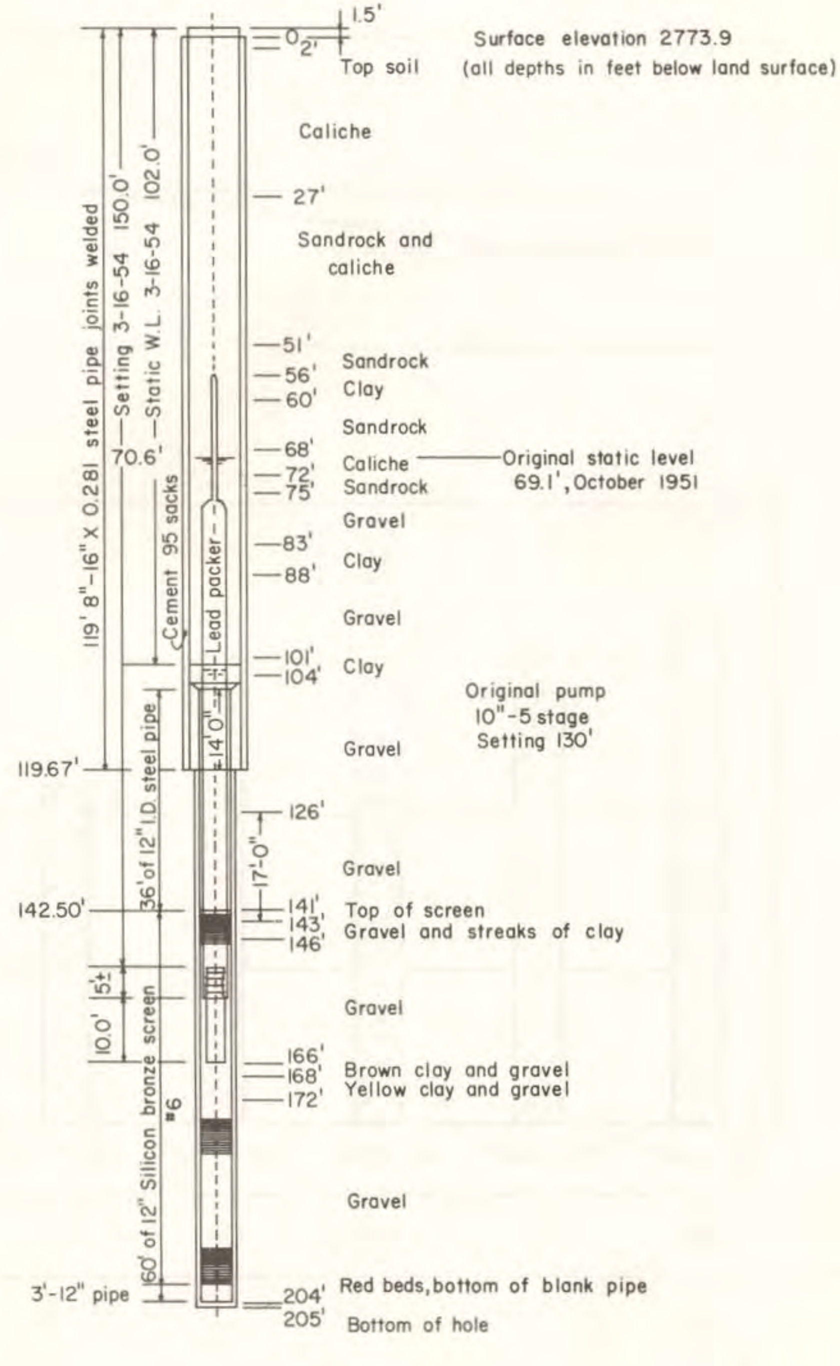


FIGURE 18.-Log and section of the Colorado River Municipal Water District recharge well No. 2, Martin County, Texas

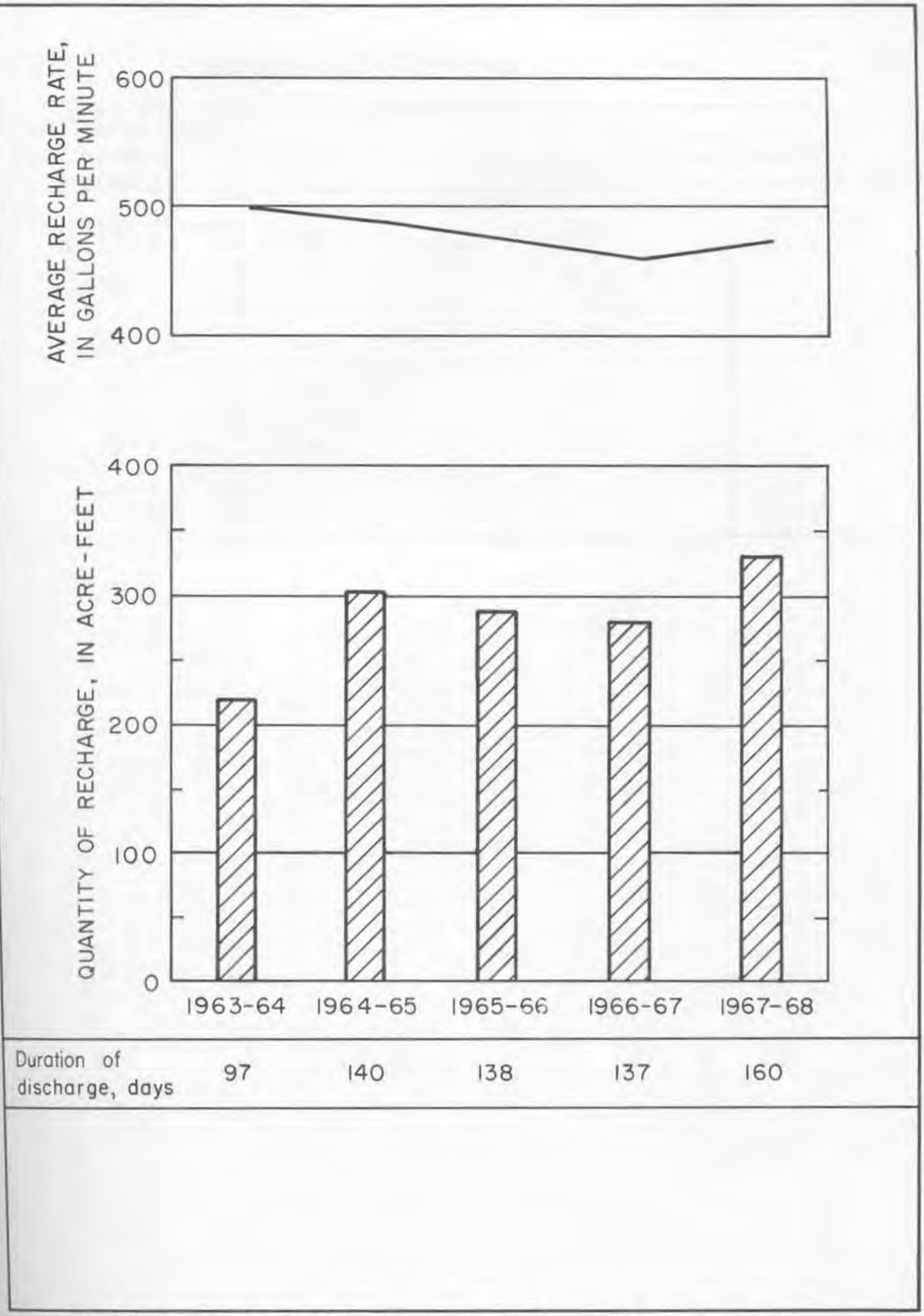


FIGURE 19.-Average recharge rates and quantity of water recharged through the Colorado River Municipal Water District recharge well No. 2, Martin County, Texas

Table 3.--Effect of surging on sediment yield of recharge wells in Martin County, Texas

Cumulative time of surging in minutes	Sample no.	Turbidity in mg/l	
		Well no. 29	Well no. 2
15	1	600	200
30	2	120	80
45	3	60	50
60	4	45	35
75	5	35	30
90	6	35	20

Table 4.--Summary of recharge operations, Colorado River Municipal Water District, 1963-68.

Year	Number of recharge wells	Amount recharged (acre-feet)	Average recharge 1/ rate/well (gpm)
1963-64	3	415.6	425
1964-65	3	536.2	272
1965-66	8	1,065.5	217
1966-67	8	962.3	257
1967-68	5	1,008.8	285

1/ The average is the amount recharged divided by the total time of recharge but does not take into account time or amount of water pumped while the well was being redeveloped.

Stanton, Texas

In 1969, Stanton, Texas, installed an artificial-recharge system under a Federal grant. The purpose of the recharge operation is to decrease the incidence of flooding in Stanton, which is on the edge of a playa-lake basin. The lake occasionally fills to flood levels during periods of heavy rains, causing damage to commercial and residential buildings in the area. The recharge operation is intended to collect flood waters, conduct them through concrete canals to a holding basin, and pump the water from the basin into ground-water storage.

The excavated lake basin has an area of approximately 3 acres and when filled is about 20 feet deep at its deepest point. An intake structure is along one side of the lake. Alum and lime are added to the water in the intake structure and are dispersed by beaters. The water then enters the holding basin where the water is held for 4 hours for precipitation of the sediment.

From the basin, water is pumped to one of three diatomaceous-earth filters, which have a capacity of approximately 2,000 gpm. Water enters under a positive pressure of 35 psi and leaves as gravity flow to the four recharge wells situated around the lake. The driller's log of a typical well is given in table 5.

The recharge wells are 20 inches in diameter and have 40 feet of cemented surface casing. A 10-inch casing is telescoped to the bottom of the hole and the annular space between the 20-inch hole and 10-inch casing is gravel packed. The bottom 40 feet of the 10-inch casing is saw slotted.

The water level is about 110 feet below land surface; therefore, there is approximately 57 feet of saturation. Maximum production from the aquifer before recharge was 75 gpm. The capacity of the pump installed in each well to permit the development and backwashing of the well after recharge operations is 250 gpm. A pipe carries water from the filters to each of the wells and is cut into the inner casing 4 feet below land surface. Water entering the well casing falls free through the inner casing to the water table at a maximum rate of about 400 gpm. Although designed for gravity flow, residual pressure on the effluent side of the filters could be used to raise the head in the recharge well above land surface and cause a more rapid discharge into the wells.

Table 5.--Generalized driller's log of a recharge well at Stanton, Texas

Depth	Material
0 - 10 feet	Top soil
10 - 15 feet	Caliche
15 - 20 feet	Sand
20 - 27 feet	Rock
27 - 40 feet	Sand
40 - 45 feet	Rock
45 - 90 feet	Sand
90 - 100 feet	Sandy shale
100 - 167 feet	Sand, gravel
167 - 177 feet	Red bed

Long-term operation of the plant will be particularly informative because it is the only one known in which water from a playa lake will be recharged with almost zero sediment load to the Ogallala aquifer. Because a chlorine residual of 0.07 to 1.00 mg/l will be carried in the recharge water, the only problem that should be encountered is in chemical compatibility. There is no indication from the short tests that this will be a problem; however, only long-term operation of the plant will prove the success of the system.

Lubbock, Texas

The city of Lubbock has recharged the Ogallala aquifer through municipal wells with treated water from Lake Meredith on the Canadian River. The water is similar in quality to native ground water, but higher in dissolved solids, particularly in chloride. During the period October-December 1968, 300 million gallons of filtered and chlorinated water were recharged through 39 wells.

The water was recharged through existing wells which were a part of the Lubbock municipal water-supply system. The only modifications made were those required to permit water to flow backwards through the discharge pipe. Canadian River water was recharged first through 10 wells in the East Lubbock well field. Subsequently, water was recharged to wells in the Shallowater well field, 1.5 miles northwest of Shallowater, about 15 miles northwest of Lubbock. The maximum rate of recharge through all 39 wells was 2 mgd.

Artificial recharge of Canadian River water was undertaken because the annual allocation of water from the Canadian River pipeline to the city is more than is now being used. The recharge water is refilling partially dewatered well fields that formerly were the principal sources of water for Lubbock. This water will be used to supplement the municipal supply during drought years. The first year of recharge operations was apparently very successful, and the city intends to continue to recharge during those years in which excess water is available.

In another operation, Frank Gray, a farm operator near Lubbock has contracted with the city to purchase sewage effluent that has undergone secondary treatment for use in irrigation. He applies approximately 3.9 feet per year (14 mgd) to 4,000 acres by flood irrigation from underground pipes, or in some areas, by ditches. In 1948 and 1949, he attempted sprinkler irrigation, but found that he could not apply as much water as by the flood and ditch system.

The water table in the area in which the effluent is applied has risen from about 120 feet in 1938 when spreading was initiated to within a few feet of land surface in 1968. E. L. Reed (written commun., 1969) estimates that 5 mgd are discharged from the spreading area through seeps and springs. The area is near the valley of the Double Mountain Fork Brazos River and there is a steep water-table gradient from the spreading area to the bottom of the valley. Much of the water is discharged by evapotranspiration from the side of the valley, and the rest presumably augments flow in the river.

This operation has successfully recharged water, but the concentration of nitrate in the ground water has increased because of the high nitrate in the effluent. Apparently, because of the high evaporation and evapotranspiration rate and the high rate of application, the nitrates are concentrated in the soil and only partly consumed by plants. Subsequent applications of effluent wash the concentrated nitrate farther down toward the ground-water body. The sewage effluent has a nitrate concentration of 18 mg/l and the ground water under the farm has a nitrate concentration of 72 mg/l, which may be compared to natural concentrations of 6-8 mg/l (Wells, 1968).

In order to maintain the high infiltration rate, crops in the irrigated area are rotated. Various types of grasses, particularly Bermuda grass, have been used to keep the soil broken up. In addition, a deep chisel plow is used periodically to open the soil to the maximum possible depth. Cash crops are principally cotton, grain sorghum, and wheat.

SUMMARY AND CONCLUSIONS

The Ogallala Formation is the principal source of water in the Southern High Plains of Texas and New Mexico. The continuous decline of water levels and the dependence of the local economy on a continuing supply of water indicate that major operational changes must be made. Water supplies can be increased only by more efficient use of precipitation in the area or by importation of water from outside the region. Any plan that presupposes an increase in available water should also consider storage facilities for this water during periods of relatively low use.

Adequate storage is available in the Ogallala aquifer for water from playa lakes or for imported water that can be recharged by surface spreading or by injection. The recharge method chosen will be determined by the type and quality of water that is available for recharge as well as by the hydraulic characteristics of the Ogallala Formation

Recharge is currently practiced in many places on the Southern High Plains. Some operations have been successful for several years by using high quality, chemically compatible water to recharge the aquifer (table 6). Successful recharge through wells has been achieved by intra-aquifer transfer of water at Amarillo and Midland, Texas; by recharge of water from the Canadian River into well fields at Lubbock; and by recharge of water from Lake J. B. Thomas into well fields between Big Spring and Midland. Although these operations have not been carried on long enough to preclude the possibility of failure from bacterial contamination or slowly occurring chemical changes, the success indicates that there are no short-term difficulties in recharging high-quality water.

Recharge through wells of water from playa lakes has been generally unsuccessful. The water in the playa lakes contains so much suspended sediment that the aquifer is rapidly clogged by the injected material. Problems of chemical incompatibility, bacterial contamination, and air entrainment may complicate recharge experiments using playa lake water; however, the large amount of suspended sediment clogs the pore spaces in the formation so rapidly that it overshadows all other factors. The wells that have operated for a period of years as both recharge and production wells are those which pump a great deal of sand, and thus remove a large part of the aquifer material and the injected sediment during redevelopment.

The most successful approach to recharging playa-lake water through wells has been that of Hauser and Lotspeich (1967), in which surface treatment of the highly turbid water removed 90 percent or more of the suspended material from the water. Even when using water with low concentrations of suspended material, biological plugging may eventually result from a combination of the dissolved organic materials and biota contained in the water.

Recharge from spreading basins, ditches, or vertical shafts has been successfully accomplished and may be feasible over large parts of the Southern High Plains. The most serious problem appears to be the presence of layers of low permeability between the land surface and the water table, which would delay vertical movement of water and prevent utilization of recharge within an acceptable period of time.

Table 6.--Summary of artificial recharge experiments and operations on the Southern High Plains

Recharge through wells

Location	Well No.	Aquifer characteristics			Recharge	
		Transmissivity ($feet^2$/day)	Hydraulic conductivity (feet/day)	Saturated thickness (feet)	Rate (gallons per minute)	Total (acre-feet)
1. McDonald Well Field, Amarillo, Randall County, Texas.	25b	940	8.5	110	800	407
	26b	800	7.3	110	700	354
						761
2. McMillen Well Field, Midland, Midland County. Texas.	2-8 3-8 4-8	2,600	35	77	121-279	335 (1957-58)
	—	—	—	—	—	121 (1959)
	—	—	—	—	265 (average of 11 wells)	1,391 (1965-66)
						1,847
3. Southwestern Public Service Company, Denver City, Yoakum County, Texas.	5	1,200 (estimated)	—	—	130	200 (approximately)
4. Southwestern Great Plains Research Center, Bushland, Randall County, Texas.	13	2,900	20	146	348	15.4

Table 6.--Summary of artificial recharge experiments and operations on the Southern High Plains--Continued

Recharge through wells

Location	Well No.	Aquifer characteristics: Transmissivity (feet^2/day)	Aquifer characteristics: Hydraulic conductivity (feet/day)	Aquifer characteristics: Saturated thickness (feet)	Recharge: Rate (gallons per minute)	Recharge: Total (acre-feet)
5. Colorado River Municipal Water District, Big Spring, Wells located in Martin County, Texas.	1	2,000	48	42	217	197
	2	1,300	21	61	474	1,415
	29	—	—	—	254	710
	39	840	14	59	110	86
	40	1,500 est. from well logs	22	69	120	93
	41	600	7	86	159	328
	42	1,300	13	97	353	729
	43	530	5	104	162	334
	44	530	6	76	123	95
						3,987
6. City of Lubbock, Lubbock County, Texas.	—	—	—	—	2,000,000 gal/day maximum	920 (1968)
						1,840 (1969)
						2,760
7. Southwestern Great Plains Research Center, Bushland, Randall County, Texas.	68	2,900	23	125	200-425	1.2
	72					22.9
	73					22.5
	13				330-425	15.1
						61.7

Recharge through wells

Location	Well No.	Aquifer characteristics			Recharge	
		Transmissivity (feet^2/day)	Hydraulic conductivity (feet/day)	Saturated thickness (feet)	Rate (gallons per minute)	Total (acre-feet)
8. High Plains Research Foundation, Halfway, Hale County, Texas.	—	5,000	25	210	800 (Ogallala) 780-850 (Playa lake)	64 500 564 (through 1964)
9. Huland Moreland well, Hockley County, Texas.	—	—	—	97	500-600	17
10. Pioneer Natural Gas Company, Hale County, Texas.	—	—	—	300	1,100-2,000	212
11. Earl Weaver Well, Lubbock County, Texas.	—	—	—	133	390	3.5
12. Bill Allmon Well, Floyd County, Texas.	—	—	—	240	200-1,050	150
13. Stanton, Martin County, Texas.	—	—	—	35	400/well 2,000 for whole system	—
14. Texas Tech University, Petroleum Engineering Department, Lubbock County, Texas.	—	—	—	—	525-175 (gravity flow) 200- 38 (gravity flow) 1,920 (pressure)	3.1 6.1 2.9 12.1

Table 6.--Summary of artificial recharge experiments and operations on the Southern High Plains--Continued

Recharge through wells

Location	Well No.	Aquifer characteristics			Recharge	
		Transmissivity ($feet^2/day$)	Hydraulic conductivity (feet/day)	Saturated thickness (feet)	Rate (gallons per minute)	Total (acre-feet)
15. U.S. Geological Survey, Lovington, Lea County, New Mexico.	2	13,370	133	100	600-700 (initial)	0.6

Recharge by surface spreading

Description	Spreading area (acres)	Inflow (acre-feet)	Outflow (acre-feet)	Evaporation (acre-feet)	Recharge (acre-feet)
Frank Gray Farm, Lubbock County, Texas.	4,000	42 acre-feet/day (14 mgd application or 3.9 acre-feet per acre, per year)	——	——	——

REFERENCES CITED

Ash, S. R., 1963, Ground-water conditions in northern Lea County, New Mexico: U.S. Geol. Survey Hydrol. Inv. Atlas 62, 2 sheets, 5 figs.

Borton, R. L., 1967, Water resources of New Mexico, occurrence, development and use--Southern High Plains--settlement, development and water use: New Mexico State Engineer Office in cooperation with New Mexico Interstate Stream Comm. and U.S. Geol. Survey, State Planning Office, Santa Fe, p. 58.

Broadhurst, W. L., 1957a, Experiment recharge well taking over one million gallons of water per day: The Cross Section, v. 3, no. 11, p. 3.

______1957b, Another recharge well does the job: The Cross Section, v. 4, no. 2, p. 2-3.

______1960, Recharge well used in conducting flocculating chemical test: The Cross Section, v. 7, no. 2, p. 1.

Broadhurst, W. L., and Willis, G. W., 1955, Rains activate recharge experiment: The Cross Section, v. 1, no. 12, p. 1.

Brown, C. N., 1956, Origin of caliche on the Northeastern Llano-Estacado, Texas: Jour Geology, v. 64, no. 1, 15 p.

Clyma, Wayne, 1964, Artificial ground-water recharge by a multiple-purpose well: Texas Agr. Expt. Sta. Misc. Pub. 712, 7 p.

Cronin, J. G., 1964, A summary of the occurrence and development of ground water in the Southern High Plains of Texas: U.S. Geol. Survey Water-Supply Paper 1693, 88 p.

______1969, Ground water in the Ogallala Formation in the Southern High Plains of Texas and New Mexico: U.S. Geol. Survey Hydrol. Inv. Atlas, HA-30, 9 p., 4 maps.

Cullinan, T. A., 1960, Preliminary study on the movement of silt and clay in a water-bearing formation: Lubbock, Tex., Texas Tech. College Dept. Geology, unpub. M.S. thesis.

Cullinan, T. A., and Reeves, C. C., Jr., 1961, Aquifer clogging by silt and clay in recharge water: Water Well Jour., v. 15, no. 5, p. 14-15, 26, 51, 56-57, 64-65.

Dane, C. H., and Bachman, G. O., 1965, Geologic map of New Mexico: U.S. Geol. Survey, Washington, D.C.

Gillett, P. T., and Janca, I. G., 1965, Inventory of Texas irrigation, 1958 and 1964: Texas Water Comm. Bull. 6515, 317 p.

Hauser, V. L., and Lotspeich, F. B., 1967, Artificial ground-water recharge through wells: Jour. Soil and Water Conserv., v. 22, no. 1, p. 11-15.

Hauser, V. L., and Signor, D. C., 1967, Water conservation and ground-water recharge research in the Texas High Plains, in West Texas water conf., 5th, Lubbock, Tex., 1967, Proc.: Lubbock, Tex., Texas Tech. College, West Texas Water Inst., p. 41-74; Texas A&M Univ., Texas Agr. Expt. Sta. Misc. Pub. 850, 10 p.

Havens, J. S., 1961, Preliminary results of test drilling in depressions on the High Plains, Lea County, New Mexico, in geological research, 1961: U.S. Geol. Survey Prof. Paper 424B, p. B123-B125.

______1966, Recharge studies on the High Plains in northern Lea County, New Mexico: U.S. Geol. Survey Water-Supply Paper 1819-F, 52 p., 4 pls., 48 figs.

Hughes, W. F., and Harman, Wyatte L., 1969, Projected economic life of water resources, subdivision no. 1, High Plains underground water reservoir: Texas Agr. Expt. Sta., Tech. Monog. 6, 82 p., 11 figs.

Jensen, M. E., and Clyma, Wayne, 1959, What happens to sediments in playa lake water when used for underground recharge in wells: The Cross Section, v. 5, no. 8, p. 2-4.

Johnson, P. W., and Crawford, D. A., 1967a, An investigation of the effect on the mechanism of hydraulic formation fracturing in water injection of a sandface filter cake deposited from waters carrying high colloidal and solid suspensions of organic and/or inorganic origin: Lubbock, Tex., Texas Tech. College, Dept. Petroleum Eng., Research Rept., Research Proj. 191-5408, 71 p., 30 figs.

Jones, O. R., and Schneider, A. D., 1969, Determining specific yield of the Ogallala aquifer by the neutron method: Water Resources Research, v. 5, no. 6, p. 1267-1272.

Kane, J. W., 1967, Monthly reservoir evaporation rates for Texas, 1940 through 1965: Texas Water Devel. Board Rept. 64, 111 p.

Keese, C. W., 1965, High Plains irrigation survey 1965: Agr. Ext. Service, Texas A&M Univ., cooperating with U.S. Dept. Agriculture, 13 p.

Long, A. T., Jr., 1961, Geology and ground-water resources of Carson County and part of Gray County, Texas: Prog. Rept. no. 1: Texas Board Water Engineers, Bull. 6102, 45 p., 11 figs.

Lyle, W. M., 1966, High Plains irrigation survey, 1966: Agr. Ext. Service, Texas A&M Univ., cooperating with U.S. Dept. Agriculture, 13 p.

______1967, High Plains irrigation survey, 1967: Agr. Ext. Service, Texas A&M Univ., cooperating with U.S. Dept. Agriculture, 13 p.

Moulder, E. A., and Frazor, D. R., 1957, Artificial recharge experiments at McDonald well field, Amarillo, Texas: Texas Board Water Engineers, Bull. 5701, 34 p.

Myers, B. N., 1964, Artificial recharge studies <u>in</u> Cronin, J. G., A summary of the occurrence and development of ground water in the Southern High Plains of Texas: U.S. Geol. Survey Water-Supply Paper 1693, 88 p.

______1969, Compilation of results of aquifer tests in Texas: Texas Water Devel. Board Rept. 98, p. 204.

New, Leon, 1968, High Plains irrigation survey, 1968: Agr. Ext. Service, Texas A&M Univ., cooperating with U.S. Dept. Agriculture, 13 p.

______1969, High Plains irrigation survey, 1969: Agr. Ext. Service, Texas A&M Univ., cooperating with U.S. Dept. Agriculture, 13 p.

Nicholson, Alexander, Jr., and Clebsch, Alfred, Jr., 1961, Geology and ground-water conditions in southern Lea County, New Mexico: New Mexico State Bur. Mines and Mineral Resources Ground-Water Rept. 6, 123 p., 2 pls., 30 figs.

Orton, Robert, 1966, The weather and climate of northwest Texas, <u>in</u> West Texas water conf., 4th, Lubbock, Tex., 1966 Proc.: Lubbock, Tex., Texas Tech. College, West Texas Water Inst., p. 55-80.

Rayner, F. A., 1968, The annual water statement, 1967-1968: The Cross Section, v. 14, no. 10, p. 8.

Rebhun, M., Hauser, V. L., 1967, Clarification of turbid water with poly-electrolytes for recharge through wells: Internat. Assoc. Sci. Hydrology Pub. 72, p. 218-228.

Reed, E. L., 1959, City of Midland--artificial recharge project, McMillen Field; report presented to the city of Midland, Tex.: 9 p., 29 pls.

Rettman, P. L., Leggat, E. R., 1966, Ground-water resources of Gaines County Texas: Texas Water Devel. Board Rept. 15, 185 p., 20 figs., 1 pl.

Texas Water Development Board, 1968, The Texas water plan, Texas Water Devel. Board, 215 p., 37 figs., 4 pls.

Theis, C. V., 1937, Amount of ground-water recharge in the Southern High Plains: Am. Geophys. Union Trans, v. 18, p. 564-568.

Valliant, J. C., 1960, Ground-water recharge and soil management: Halfway, Tex., High Plains Research Foundation Rept. 2, 3 p.

______1961, Artificial ground-water recharge: Halfway, Tex., High Plains Research Foundation Rept. 18, 8 p.

______1962, Artificial recharge of surface water to the Ogallala Formation in the High Plains of Texas: Halfway, Tex., High Plains Research Foundation Bull. 1, 17 p.

______ 1963b, Artificial recharge of surface water to the Ogallala Formation in the High Plains of Texas, in Schiff, Leonard, ed., Bienn. conf. on ground-water recharge and ground-water basin management, 4th, Berkeley, Calif., 1963, Proc.: Fresno, Calif., Ground-Water Recharge Center, 7 p.

______1964, Artificial recharge of surface water to the Ogallala Formation in the High Plains of Texas: Ground Water, v. 2, no. 2, p. 42-45.

______1965, Research with multiple-purpose (recharge) wells and artificial recharge of runoff water in the Texas High Plains, in West Texas water conf., 3d, Lubbock, Tex., 1965, Proc.: Lubbock, Tex., Texas Tech. College, West Texas Water Inst., p. 94-96.

______1967, Ground-water recharge research--High Plains Research Foundation in West Texas water conf., 5th, Lubbock, Tex., 1967, Proc.: Lubbock, Tex., Texas Tech. College, West Texas Water Inst., p. 75-78.

Wells, D. M., 1968, Ground-water recharge with treated municipal effluent in Wilson, G. W., and Beckett, F. E., Municipal sewage effluent for irrigation: Louisiana Polytechnic Inst., Agr. Eng. Dept., 169 p., (The Louisiana Tech Alumni Found., Box 1, Tech Station, Ruston, La. 71270).

Winn, R. W., 1960, Clarification of lake water prior to artificial recharge by wells: Lubbock, Tex., Texas Tech. College, Dept. Geology, M.S. thesis, 56 p.

REFERENCES CITED--Concluded

Winn, R. W., and Reeves, C. C., Jr., 1961, Replenishment in the High Plains: Water Well Jour., v. 15, no. 2, p. 6-7, 34-35, 37.