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ARTIFICIAL-RECHARGE EXPERIMENTS AT MCDONALD WELL FIELD, AMARILLO, TEXAS

By

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United States Geological Survey

Prepared in cooperation with the Geological Survey,
United States Department of the Interior,
and the
City of Amarillo

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ABSTRACT

The need for large water-storage facilities close to the city to supply peak demands for the municipal water supply of Amarillo, Tex., has become apparent as the population has increased at a rapid rate. The high cost of conventional storage reservoirs prompted the city to consider storing water in natural underground reservoirs. This investigation was made to determine the hydraulic feasibility of such a venture, as its results would be applicable not only to Amarillo but also to many other areas of similar conditions.

The city's McDonald well field, near the southwest edge of town, was selected for the experiments. The chief water-bearing formation in the area is the Ogallala formation of Pliocene age which is described adequately in several previous publications of the Texas Board of Water Engineers. Field studies included 2 pumping tests and a 4-month recharge test using 2 of the city's production wells and 6 observation wells drilled specifically for the tests.

The investigation showed that, although the ground-water reservoir has no physical lateral boundaries within the area of investigation, water moves laterally from an injection well so slowly that about 80 percent of the recharge water injected during the winter months may be recovered by pumping during the remainder of the year. It also showed that water could be injected by gravity flow at rates exceeding 1,000 gallons per minute per well. Wells more than half a mile from the point of injection benefit very little from the recharge operations over a period of a year.

The investigation revealed that the McDonald wells had high specific capacities, indicating excellent well development. Little or no clogging of the perforations in the well casings or formation was encountered during the recharge tests and, because of the excellent well development, no serious clogging should occur during a recharge program extending for many years.

INTRODUCTION

Purpose and Scope

The increasing demand for water has caused the city of Amarillo, Texas, to locate some of its well fields several miles from the city limits (see fig. 1). Because it became apparent that large storage facilities close to town were necessary to meet peak seasonal demands which exceed proposed pipeline capacities, the city requested the Texas Board of Water Engineers and the United States Geological Survey to investigate the hydraulic feasibility of using natural underground reservoirs near the city of Amarillo for temporary storage of water. Tests were made to determine the following: (1) The practicability of recharging the underground reservoir through wells; (2) the recharge-head relationship of injection wells; (3) the storage and transmitting properties of the aquifer; (4) the effect on water levels in the vicinity of supply and injection wells; and (5) the percentage of recharge water that may be recovered by pumping. The McDonald well field was selected as the test site because it is near the city and convenient to existing distribution facilities. The results of the tests will be applicable, at least in part, to similar problems elsewhere.

Storage underground in the McDonald well field has several advantages. The chief advantage is that pipelines to the new distant well fields or to possible future surface sources may be made smaller than would be necessary if the lines were needed to meet peak seasonal water demands. Pumping the distant wells throughout the year at a fairly constant, but lower than maximum, rate would supply the city's winter demands and provide a surplus for storing in the McDonald field. Summer demands in excess of the pipeline capacity from the distant fields could be met by pumping the stored water from the McDonald field. Other advantages of underground storage over surface storage are: (1) No losses by evaporation (a major item in surface reservoirs); (2) virtually no construction costs in preparing the reservoir for storage; and (3) utilization of equipment at the distant well fields, which otherwise would stand idle during the winter months.

The investigation, which was started in September 1954, was made on a cooperative basis between the U. S. Geological Survey, the city of Amarillo, and the Texas Board of Water Engineers. The authors wish to acknowledge the assistance of H. R. Smith, Superintendent of Public Works of Amarillo, and W. C. Roberts, pump attendant at the Amarillo city water department.

The field work was done and the report prepared under the immediate supervision of J. G. Cronin, area engineer, and R. W. Sundstrom, district engineer in charge of ground-water investigations by the Geological Survey in Texas, and under the general direction of A. N. Sayre, chief of the Ground Water Branch, Geological Survey.

Physiography and Geology

The McDonald well field is about 5 miles southwest of the Amarillo post office in section 29, block 9, BS&F Survey, Randall County (see fig. 1). The site is near the northern edge of the Llano Estacado which is bounded by the Canadian River Valley on the north, the Pecos River Valley in New Mexico on the west, and an abrupt escarpment on the east, and passes southward without sharp physiographic break to the Edwards Plateau. The part of the Llano Estacado which is in Texas is referred to locally as the "South Plains."

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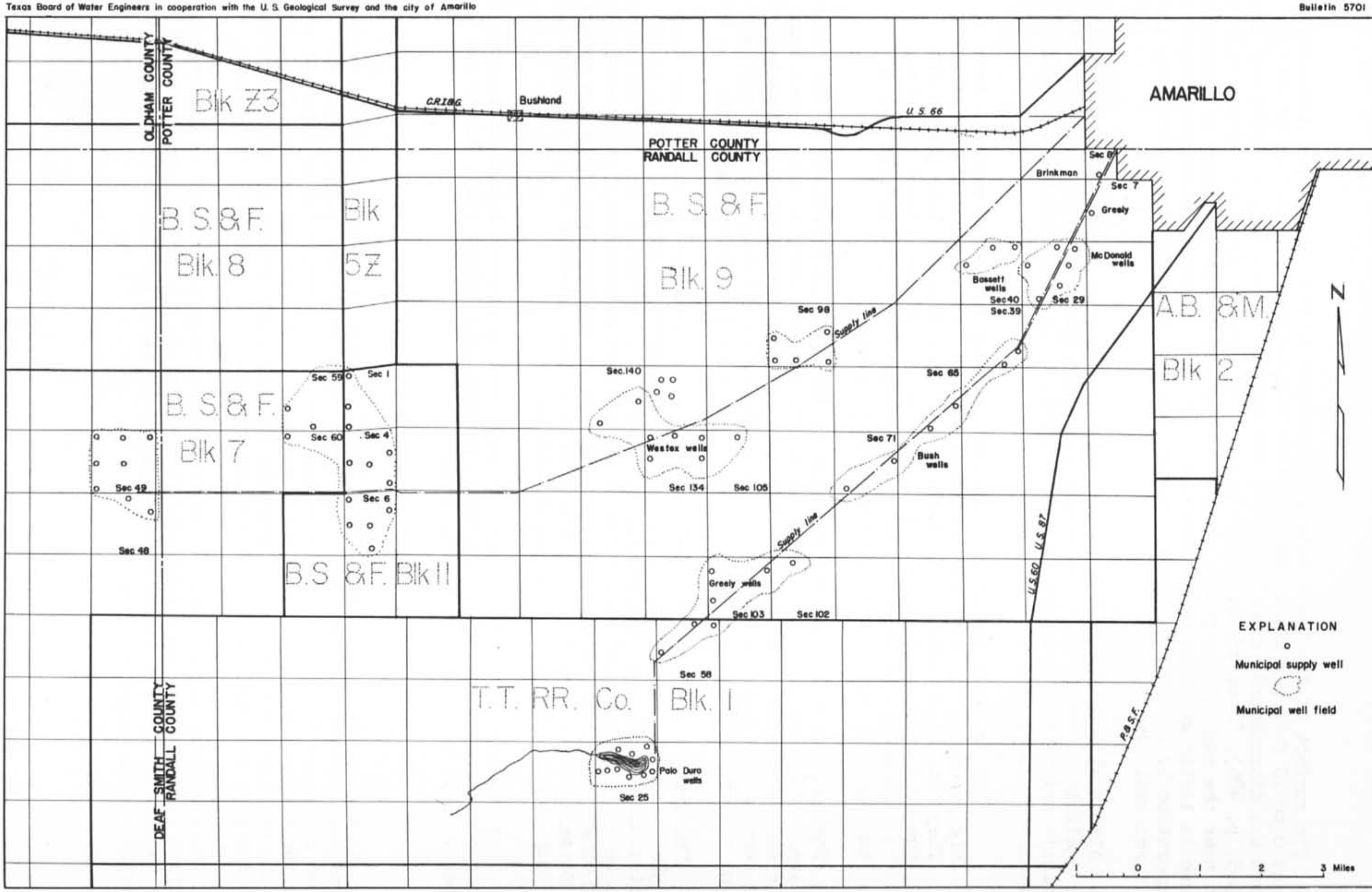

FIGURE 1.-Map showing location of well fields owned by city of Amarillo, Tex.

The surface of the Llano Estacado generally is flat and slopes southeastward about 8 to 10 feet per mile. Many shallow basin-shaped depressions of various sizes are distributed irregularly over the surface. According to Evans and Meade (1945, p. 486), "None of the basins have outlets except along the stream valleys and near the edge of the plains where a few are in the early stages of dissection." There is little drainage development; the overland runoff is dissipated rapidly by evaporation or infiltration. Some runoff reaches the numerous depressions, where it forms small lakes.

Almost all of the potable ground water in the area investigated occurs in the Ogallala formation of Pliocene age which overlies the uneven surface of the Triassic red beds. Alexander and Dante (1946, p. 1) described the Ogallala formation in this area as follows:

> The Ogallala deposits consist principally of eroded material from high areas to the west and northwest brought in and deposited by streams. They consist of sand, silt, gravel, and clay, which in some places are cemented by calcareous material. In common with most stream deposits, the thickness and gradation of the water-bearing sands and gravels in the Ogallala varies widely from place to place.

The only source of natural recharge to the Ogallala formation in the Llano Estacado is precipitation. As pointed out by Barnes (1949, p. 1), it has long been recognized that the Ogallala formation has been hydrologically isolated from the surrounding region by erosion. The escarpments and river valleys that surround the area exclude the possibility of recharge from adjoining areas.

The driller's log of well B-28 shows the depth to the top of the red beds as 326 feet. The logs of wells in section 29 suggest a lack of continuity of individual beds through the section (see table 2). Assuming that the top of the red beds in the McDonald well field is at 326 feet as reported in the driller's log of well B-28, there was more than 110 feet of the Ogallala formation saturated in November 1954. The logs indicate that more than one-half of this thickness is composed of sandy water-bearing materials.

The geology of the High Plains is discussed in greater detail in several of the reports listed in the bibliography, particularly Baker, 1915, Barnes and others, 1949, and Evans and Meade, 1945.

Water-supply Statistics

Water is supplied to the city of Amarillo from 70 wells tapping the Ogallala formation southwest of the city. The location of wells and supply lines are shown in figure 1. The average discharge per well is about 600 gallons per minute, and the maximum capacity of all wells is about 60,000,000 gallons per day. Most of the wells are equipped with deep-well turbine pumps driven by electric motors. The capacity of overhead and underground storage tanks is 23,500,000 gallons.

In addition, water rights to several thousand acres of land in Carson and Hartley Counties have been purchased by the city of Amarillo. Development of the Carson County well field, which is about 20 miles northeast of Amarillo, was started in the summer of 1955.

History of the McDonald Well Field

The well field closest to the city of Amarillo is the McDonald well field. The first five wells in the field were drilled by D. L. McDonald in 1929. In 1931, the city of Amarillo purchased the wells and the section of land in which they were drilled. The sixth well in the field was drilled in 1947 by H. H. Heiskell.

Since 1931 an estimated 16 billion gallons of water have been withdrawn from the McDonald wells. In addition, large quantities of water have been withdrawn from other municipal and private wells within a few miles of the well field. These heavy withdrawals of water from the Ogallala formation have created a basin-shaped depression in the water table which appears to be centered at well B-25 (see fig. 2).

Records of water levels in wells indicate that the water table has declined 17 feet in the northwest quarter of Randall County and 53 feet in the McDonald well field since 1931.

The wells in the McDonald field were drilled with a rotary drilling rig and have an average depth of 291 feet. The first five wells have 18-inch casing and the sixth has 16-inch casing. The casings are perforated throughout the saturated section of the Ogallala formation penetrated by the wells, and all the wells are "gravel packed." Each well is equipped with a deep-well turbine pump driven by a 75-horsepower electric motor.

TESTING PROGRAM

Wells B-25 and B-26, in the lowest part of the cone of depression, were selected as recharge wells. All the wells in the McDonald field were idle from September 10 to October 22, 1954, except when they were pumped for short periods to obtain water samples. Water samples were taken every other day from 36 wells in and near the McDonald well field from September 10 to September 28. The samples were analyzed by the Geological Survey to determine the average chloride content of the native ground water. More complete analyses were made of water samples from a few wells to compare the chemical character of the water from wells in and near the McDonald field with the recharge water (see table 3).

The city installed flow meters and other equipment necessary to measure and supply the recharge water to the wells. To avoid the expense of removing the pumps, water was recharged through the pump columns. A schematic diagram of the installation is shown in figure 3.

Brine-injection equipment was installed at well B-25 by Survey personnel after the recharge test was in progress. The brine increased the chloride content of the recharge water so that it could be distinguished from the native ground water. The brine was prepared periodically by mixing sodium chloride and water in a tank inside the pump house. The tank was filled from the recharge line with the fresh-water pump which had a capacity of 60 gallons per minute (see fig. 4). Careful measurements of weight and volume were made to maintain a constant concentration of chloride. An inexpensive brine pump (capacity 7 gallons per minute) was used in conjunction with a constant-flow orifice to avoid the expense of proportioning equipment and to keep the brine in the tank circulating. A total of 23,896 pounds of pure sodium chloride was added to about 90 million of the total of 240.7 million gallons of recharge water during the period December 6, 1954 to February 28, 1955.

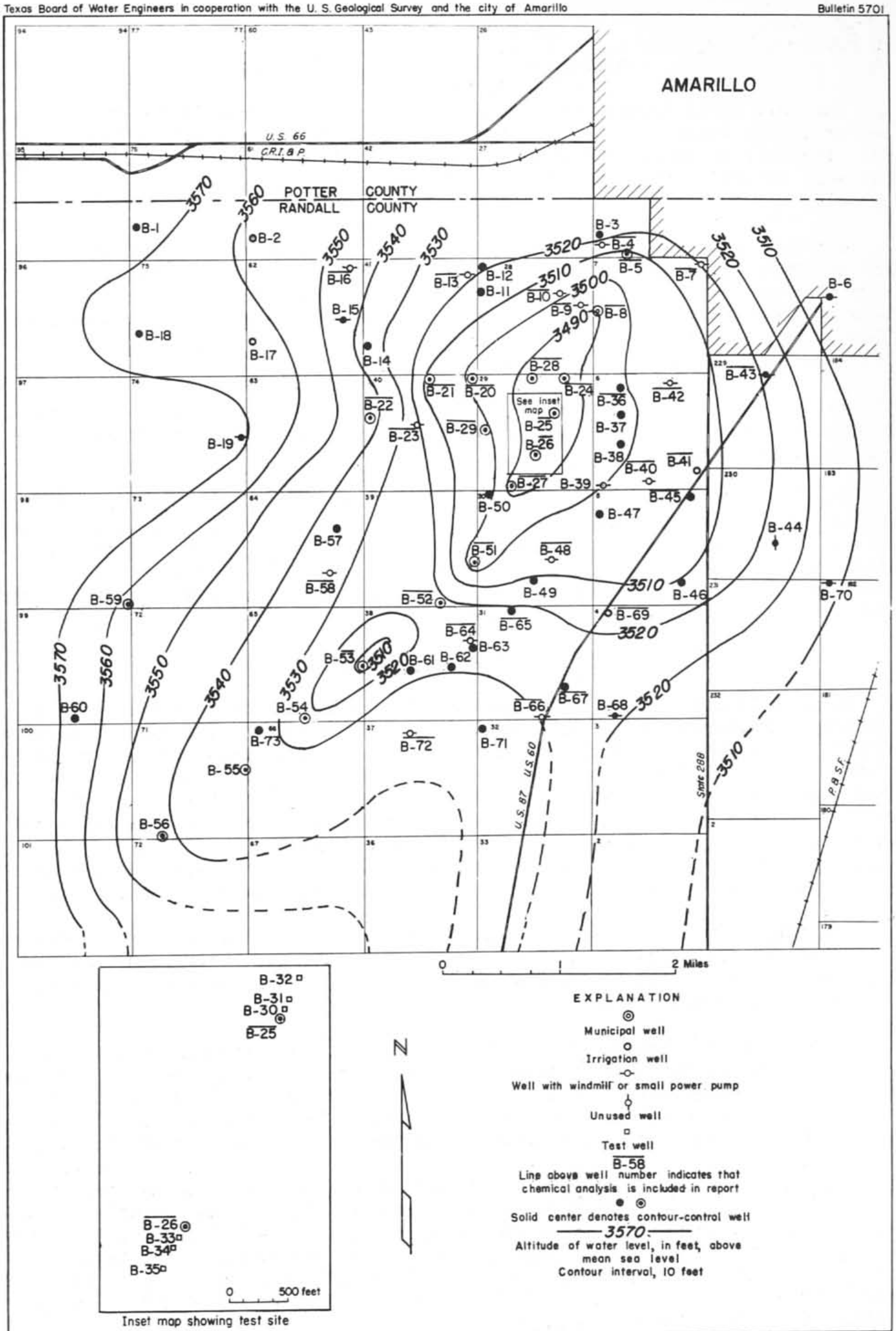

FIGURE 2.-Map showing test site, well locations, and water-table contours on October 25, 1954, for area southwest of Amarillo, Tex.

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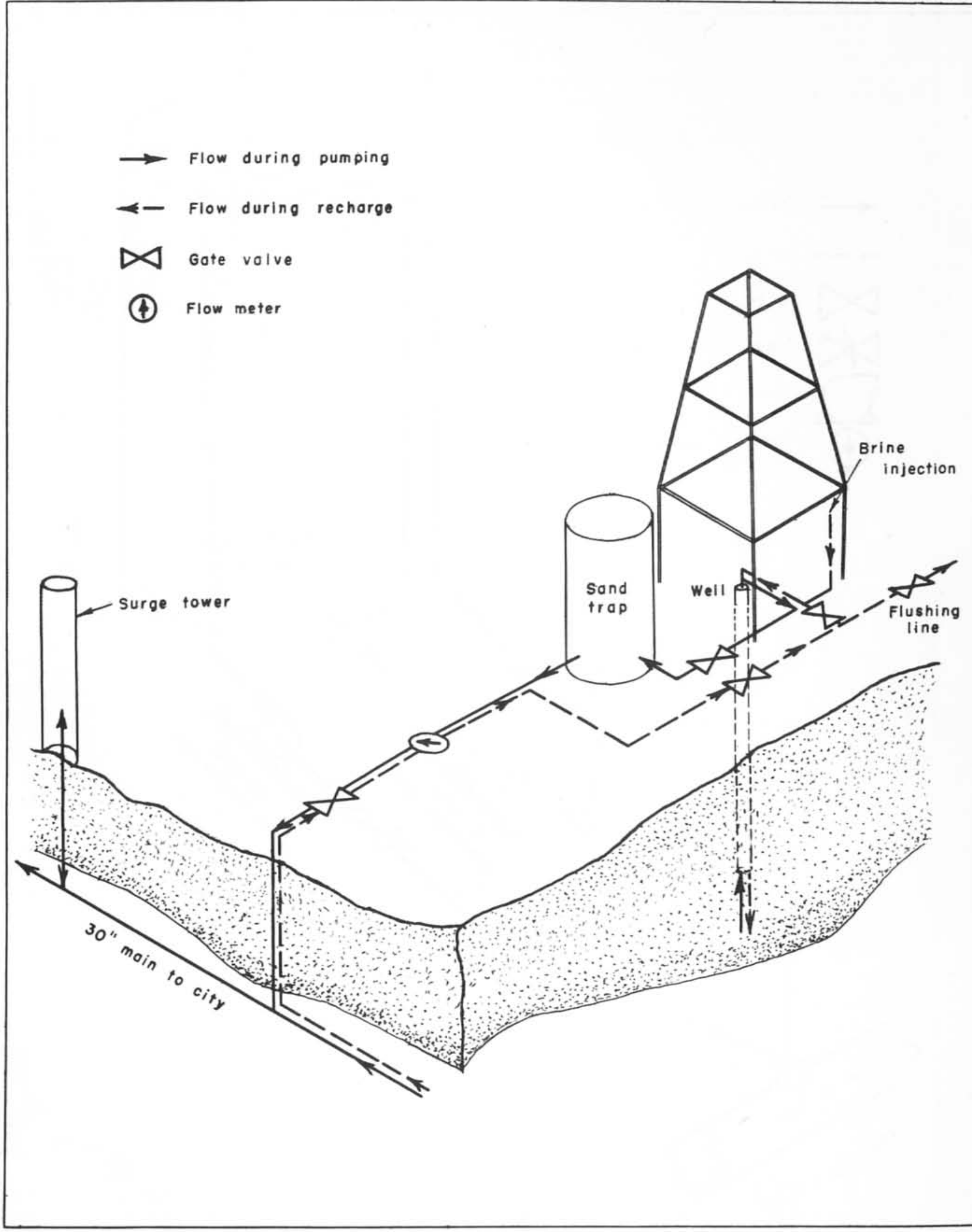


FIGURE 3.-Schematic drawing of distribution lines at recharge well.

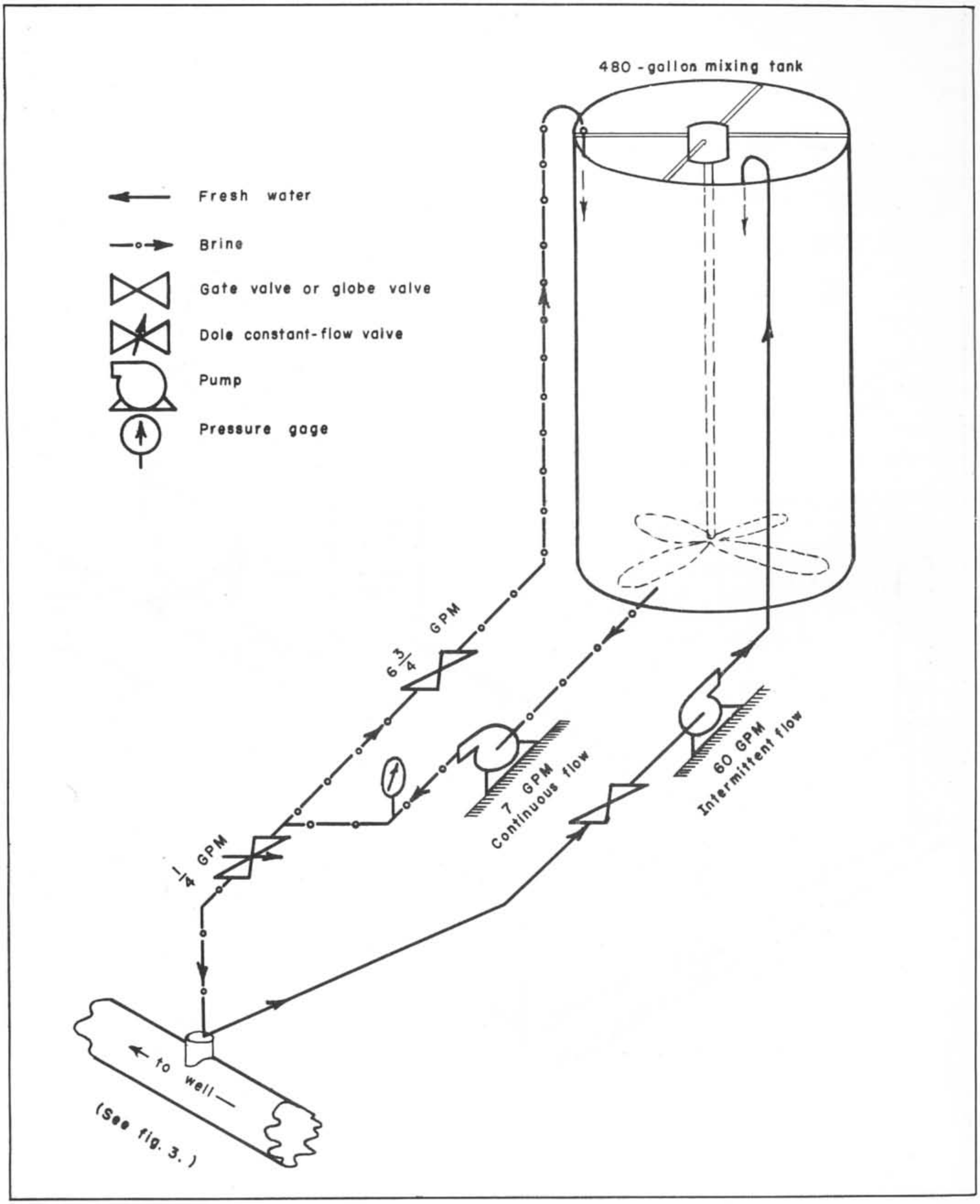


FIGURE 4.-Schematic drawing of brine-injection equipment.

Six observation wells were drilled--three near each recharge well and spaced 100, 200, and 400 feet, respectively, from the well (see inset, fig. 2). The observation wells were drilled to an average depth of 236 feet and were cased with 4-inch casing, the lower 63 feet being slotted. The drillers' logs for these wells are given in table 2. An automatic water-level recorder was installed on well B-30 to obtain a continuous record of water-level changes.

Within a radius of 3 miles of the test site, 55 wells were inventoried and the altitude of the reference point of each well was determined by instrumental leveling (see table 1). A water-table contour map was prepared using water-level measurements made in most of these wells on October 25, 1954 (see fig. 2).

The recharge equipment at each injection well was tested for one hour on October 22, 1954, by injecting water at various rates up to 1,000 gallons per minute. Observations made at this time indicated what measures should be taken to insure smooth operations during the final test.

The wells were idle from October 22 to October 27, 1954, when well B-25 was pumped for about 2 days. Well B-26 also was pumped for 2 days starting October 28, 1954. The purpose of the pumping was to collect data on well and aquifer characteristics which could be compared with similar data to be collected after the recharging period.

The wells were idle from October 30 to November 8, 1954. The recharge test on well B-25 was started November 8, 1954, and was discontinued March 3, 1955; the test on well B-26 was started November 10, 1954, and discontinued March 1, 1955. Wells in the Palo Duro well field (see fig. 1) supplied the recharge water. Brine injection at well B-25 started December 6, 1954, and was discontinued on February 28, 1955. A total of 132,541,800 gallons of water was injected into well B-25 and 115,314,200 gallons into well B-26.

The wells in the McDonald field were idle for several days after recharging was discontinued. Pumping was started at well B-26 on March 8, 1955, and at well B-25 on March 11. Records of daily pumpage were kept for both wells, and daily water samples were taken from well B-25.

Water-level measurements were made periodically in wells B-25, B-26, B-30, B-31, B-32, B-33, B-34, B-35, and B-39 throughout the entire investigation (see figs. 5 and 6). The measurements in well B-39 were made to determine the effects of recharging outside of the well field.

INTERPRETATION OF TEST DATA

Definitions

The following glossary describes the terms used in this report.

The field coefficient of permeability (P_f) is defined (Wenzel, 1942, p. 7) as the number of gallons of water a day that percolates under prevailing conditions through each mile of water-bearing bed under investigation (measured at right angles to the direction of flow) for each foot of thickness of the bed and for each foot per mile of hydraulic gradient.

The unit of permeability used in this report is:

$$P_f = \frac{1 \text{ gallon}}{(\text{day})\ (\text{ft}^2)\ (1 \text{ ft } H_2O/\text{ft})} = \text{Gallons per day per ft}^2$$

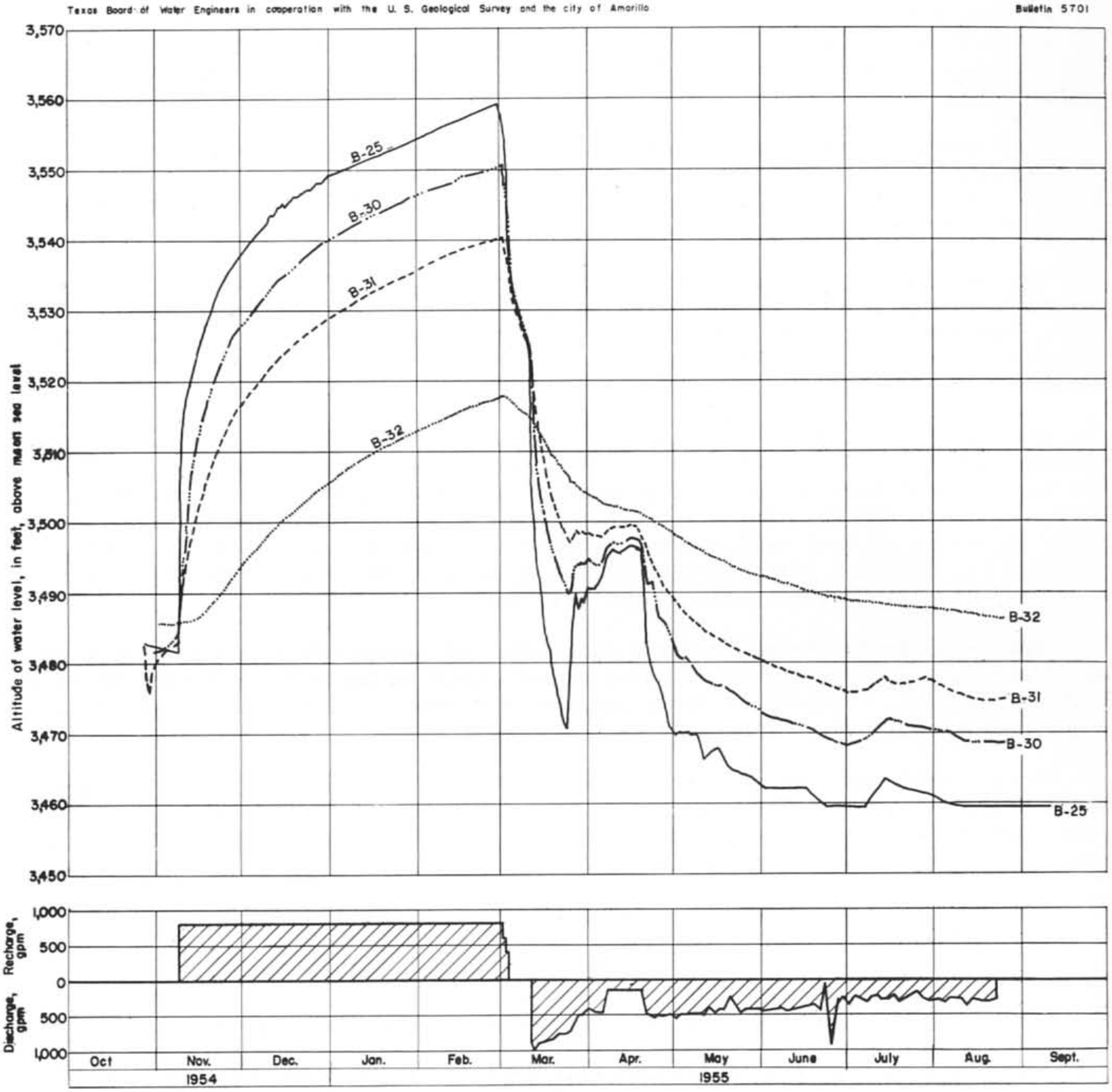


FIGURE 5.-Hydrographs for wells B-25, B-30, B-31, and B-32 and recharge and discharge rate for well B-25.

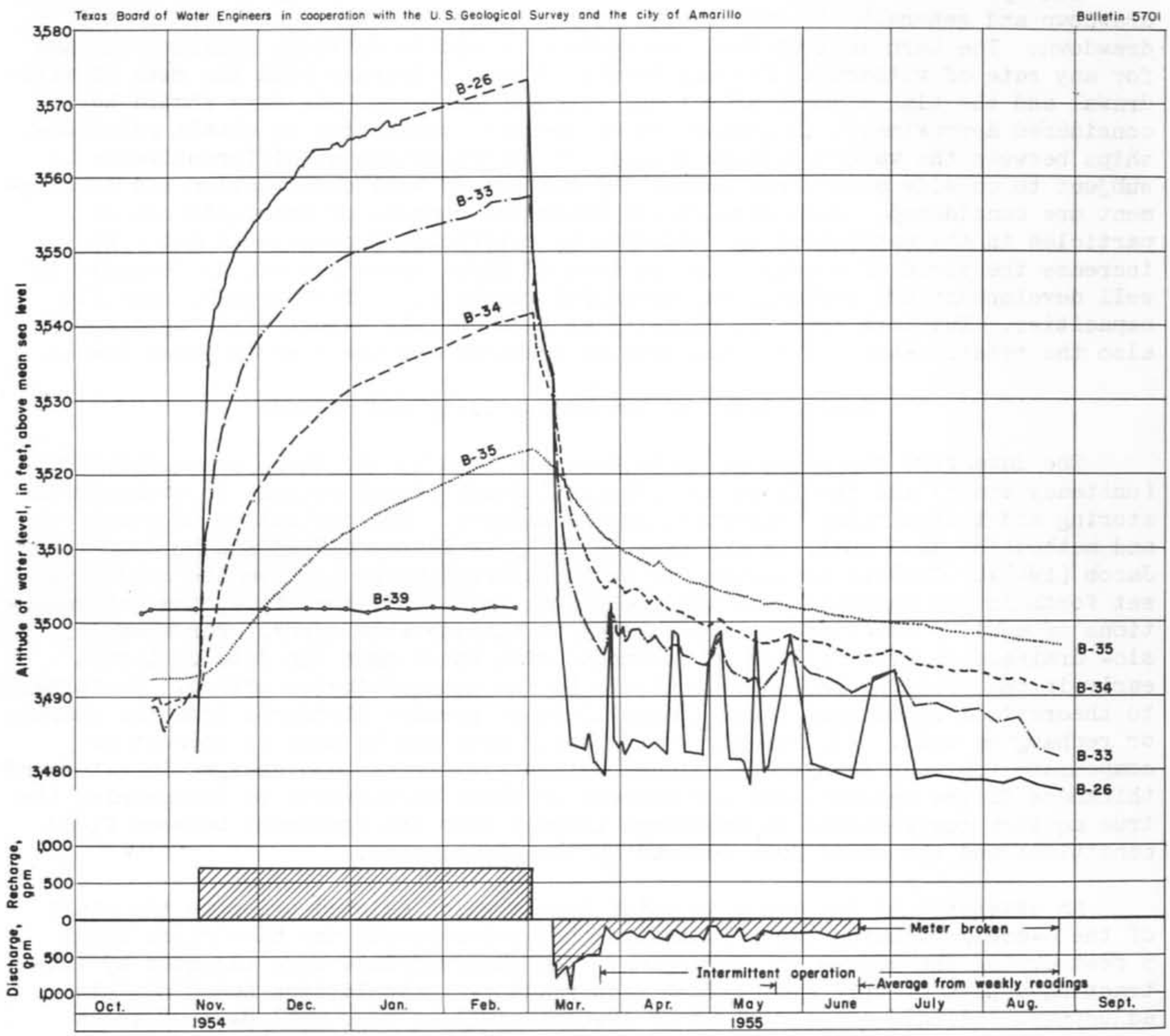


FIGURE 6.-Hydrographs for wells B-26, B-33, B-34, B-35, and B-39, and recharge and discharge rate for well B-26.

The coefficient of transmissibility (T) is the product of the field coefficient of permeability and the thickness of the aquifer in feet and is expressed in gallons per day per foot.

The coefficient of storage of an aquifer (S) is the volume of water it releases from or takes into storage per unit surface area of the aquifer per unit change in the component of head normal to that surface. It is dimensionless.

The specific capacity is used to indicate the relationship of well yield to drawdown and generally is expressed in terms of gallons per minute per foot of drawdown. The term implies that the ratio of yield to drawdown remains constant for any rate of withdrawal for any length of time. Because both the rate of withdrawal and the time element affect the specific capacity, the term should be considered approximate. A comparison of specific capacities to obtain relationships between the water-yielding ability of the formation at different wells is subject to considerable error unless the factors of well construction and development are considered. Well development means the removal or reorientation of particles in the water-bearing formation by artificial processes in order to increase the yield of a well. In the area of this investigation, differences in well development are probably the principal causes for differences in specific capacities. The term specific capacity as used in this report will represent also the relationship between the rate of recharge and the rise in water levels.

Coefficients of Transmissibility and Storage

The data from the recharge tests were analyzed by the Theis nonequilibrium (unsteady state) and the Thiem equilibrium (steady state) methods to estimate the storing and transmitting properties of the aquifer. The derivation of equations and methods of data analysis are treated fully by Wenzel (1942) and by Cooper and Jacob (1946). Conditions during the tests departed markedly from the conditions set forth in the derivation of the analytical equations; therefore, the determinations of aquifer coefficients are subject to considerable error. For example, slow drainage or slow filling of sediments with water made the data collected early in the tests unusable for analysis by the nonequilibrium method. Conformance to theoretical conditions takes longer times at greater distances from the pumping or recharging well. Adjustments to the basic data may be made to correct or compensate for such things as regional water-level trends and changes in saturated thickness of the aquifer, but the success of these adjustments in determining the true aquifer coefficients is dependent largely upon the agreement between field conditions and the conditions assumed by the adjustments.

An extension of the trend in water levels which existed prior to the start of the 4-month recharge tests indicates that water levels may have risen about 5 feet during the course of recharging. The observed data were adjusted by subtracting a part of this amount from each reading. Calculations based on this adjustment indicate a coefficient of transmissibility near well B-25 of about 7,500 gallons per day per foot as compared to about 6,400 gallons per day per foot for unadjusted data (see figs. 7 and 8). Insufficient data are available to adjust water-level records for wells B-31, B-32, B-34, and B-35.

By adjusting the data for a change in saturated thickness, the adjusted curves do not conform to the theoretical curves and the suggested coefficient of transmissibility averages less than half of that calculated from unadjusted data. Analytical examination of all the basic data strongly suggests that the adjustment for the change in saturated thickness is not warranted during the recharge tests. Examination of the drillers' logs of wells B-31 and B-32 shows a

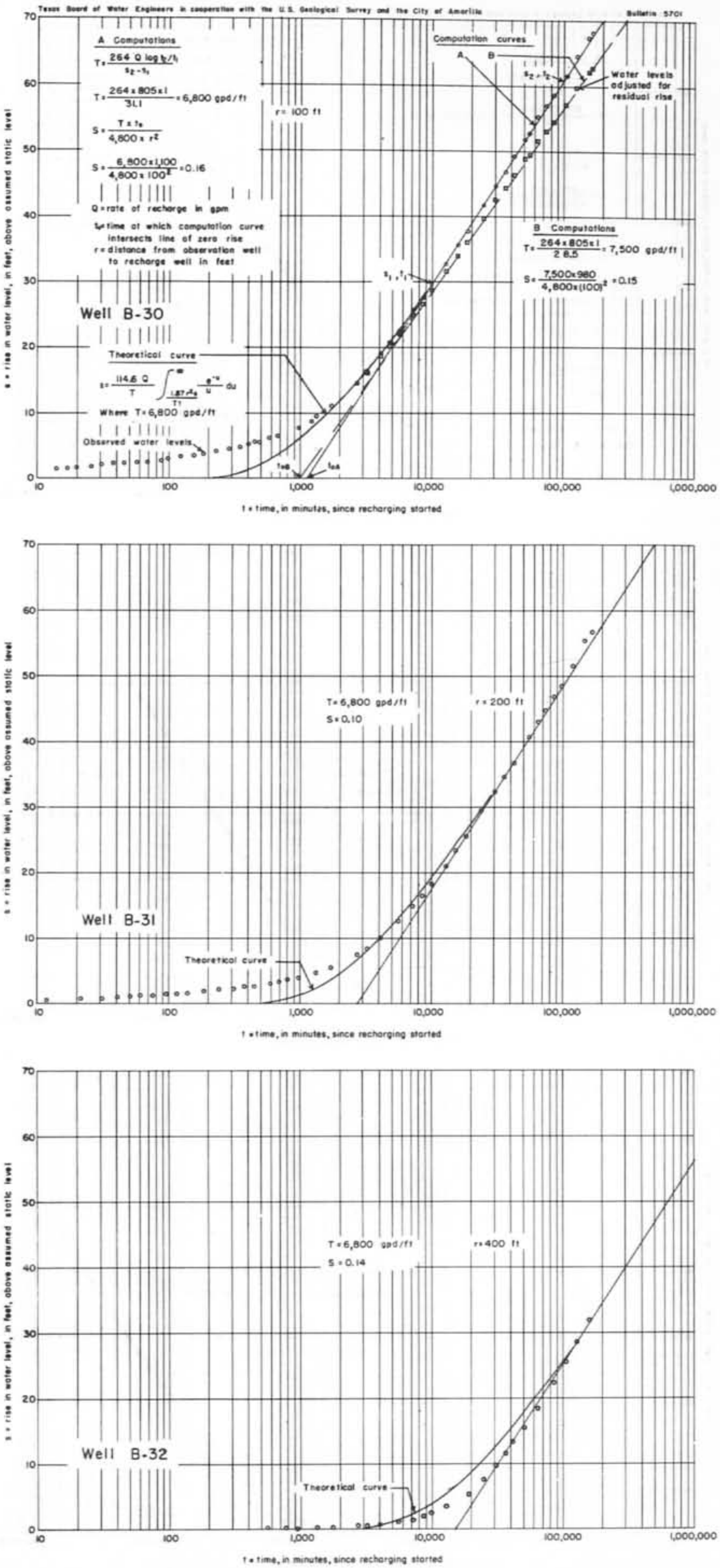


FIGURE 7.- Analysis of unadjusted recharge data for wells B-30, B-31, and B-32 and of adjusted recharge data for well B-30 by the nonequilibrium method.

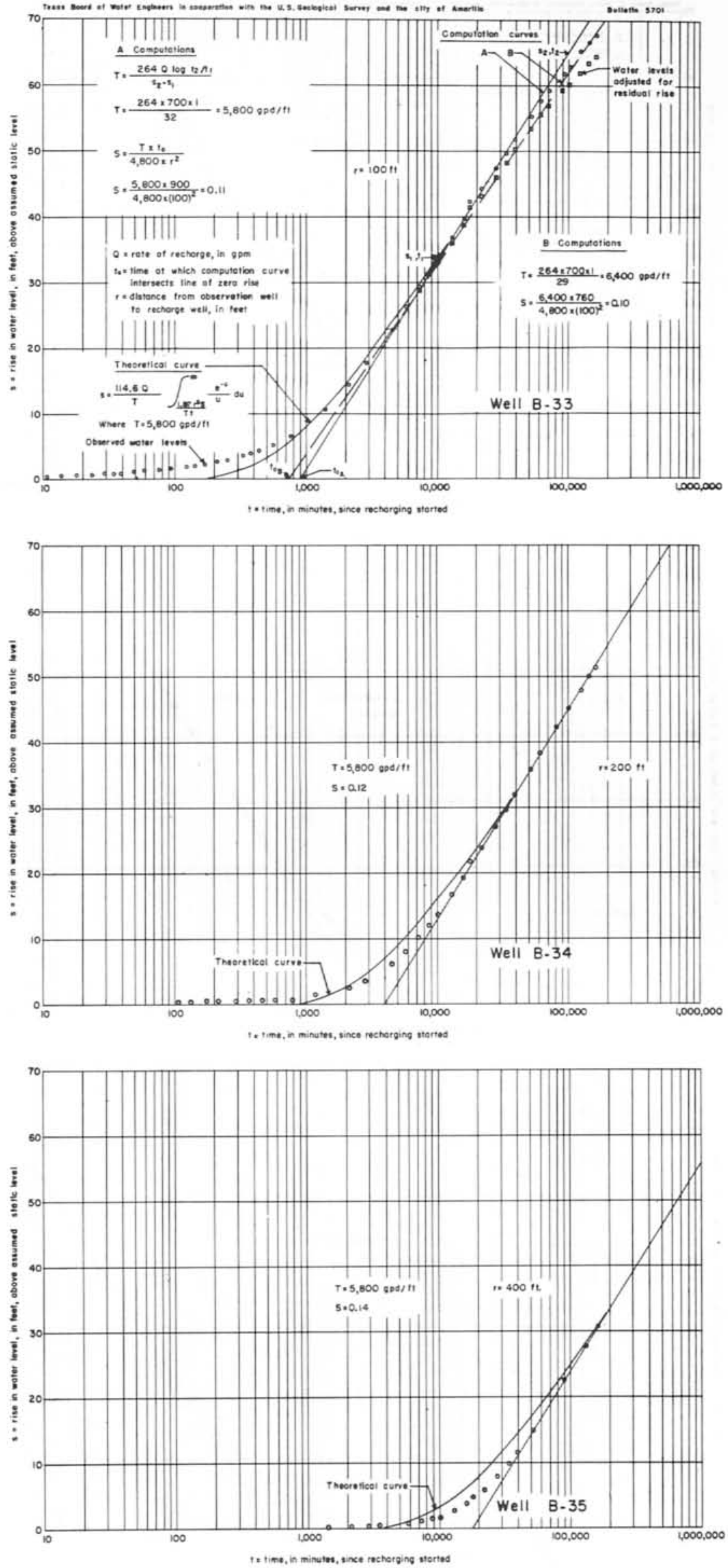


FIGURE 8.-Analysis of unadjusted recharge data for wells B-33, B-34, and B-35 and of adjusted recharge data for well B-33 by the nonequilibrium method.

thick layer of material composed principally of clay extending from the surface to a depth of about 200 feet. Although the magnitude of the calculated storage coefficients (figs. 7 and 9) suggests that the clayey layer becomes saturated to a level coincident with the piezometric surface after an extended period of recharging, probably most of the lateral movement of water away from the well is confined principally to a section below this layer. Thus the water seems to be confined during the recharge cycle, and, hence, the adjustment is not needed. Similar conditions prevail near well B-26, and the data show similar results.

Changes in rate of discharge during the pumping period preclude the use of drawdown data for a positive check of aquifer coefficients. Data from well B-30 adjusted for the residual water-level trend are shown in figure 10. Calculations based on the data for the period 70-110 days after pumping started indicate an apparent coefficient of transmissibility of about 5,000 gallons per day per foot as compared to about 3,700 gallons per day per foot for unadjusted data. Applying the adjustment for change in saturated thickness to drawdowns where the depth to water exceeds 200 feet, the apparent transmissibility is calculated to be about 7,300 gallons per day per foot. Thus, it appears that the drawdown data roughly confirm the validity of the conditions assumed in analyzing the recharge data. It is concluded, therefore, that the coefficient of transmissibility of the aquifer is about 7,000 gallons per day per foot near well B-25 and about 6,000 gallons per day per foot near well B-26. The calculated values for storage coefficient ranged from 0.09 to 0.16. The period of pumping at a constant rate was insufficient to make drawdown data from other observation wells comparable.

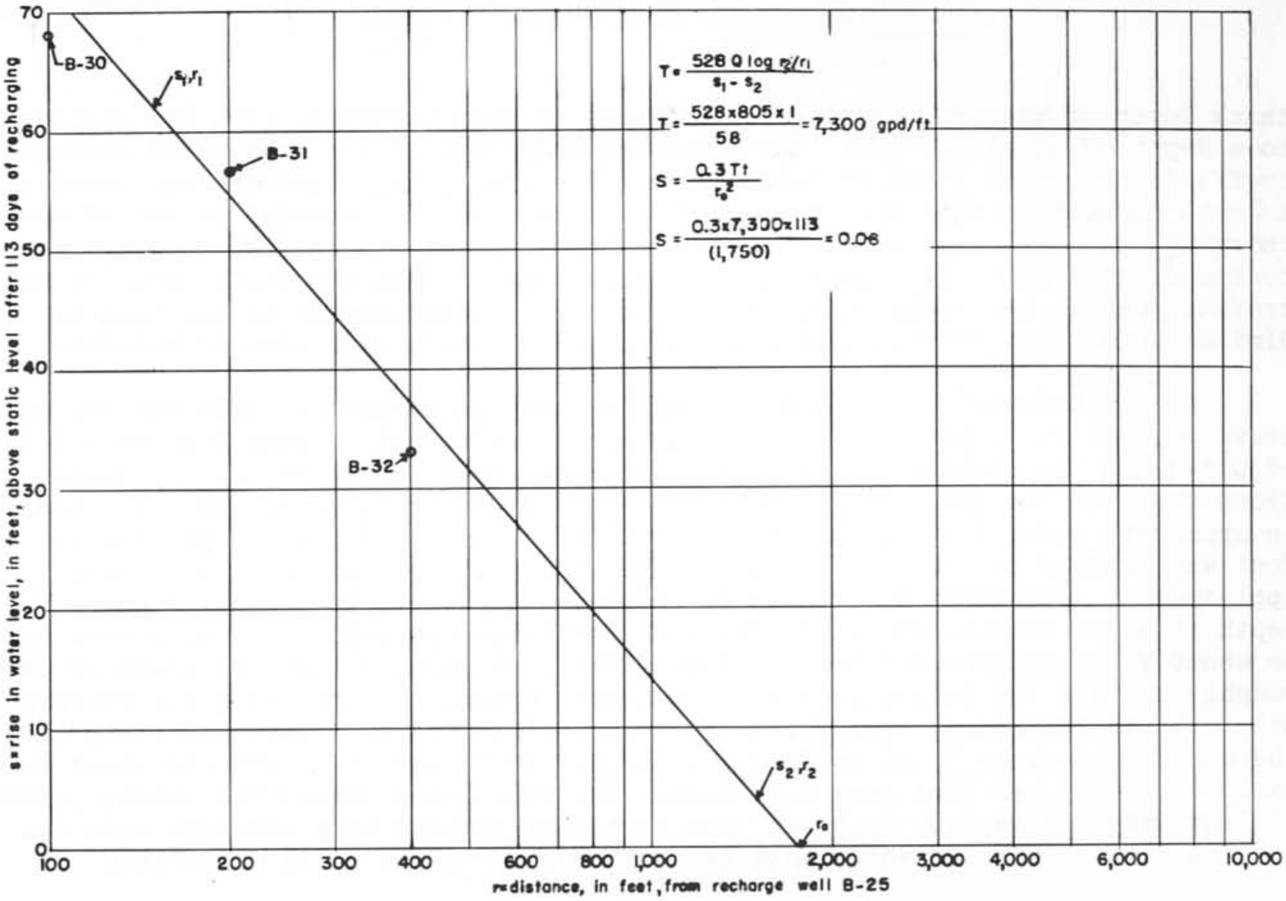
The indicated coefficient of transmissibility for this area is much smaller than the average (about 50,000 gallons per day per foot) previously assumed in the High Plains (Barnes and others, 1949, p. 36). This may be due, in part, to the fact that the saturated thickness of water-bearing materials in the McDonald well field is less than the average at the other sites.

Well-field Characteristics

Water in the Ogallala formation is moving, but the horizontal component of movement is extremely small where there are no withdrawals from wells. The reservoir beneath the McDonald well field has virtually no physical boundaries to prevent movement in a lateral direction, but under natural gradients the horizontal movement is less than 100 feet per year. The principal factors that tend to localize water injected into wells in the McDonald field are the depressions in the water table caused by pumping, the resistance to flow through the materials of the formation, and the ability of these materials to store water.

The profile of the water table in the McDonald field during various phases of the pumping-recharging cycle is shown in figure 11. Because the movement of water is controlled by the gradient of the water table, all injected water is trapped within the large basin-shaped depression shown in figures 2 and 11.

The water levels in wells outside the section of land containing the McDonald wells were not affected appreciably by the pumping and recharging of wells B-25 and B-26. Measurements of water level in well B-39 (fig. 6) show that at 0.6 mile from well B-26 no effects from the recharging were apparent. Measurements of water levels in wells B-24 and B-27 suggest that throughout the recharging and pumping program the effects on water levels at a distance of a quarter of a mile were less than 5 feet.



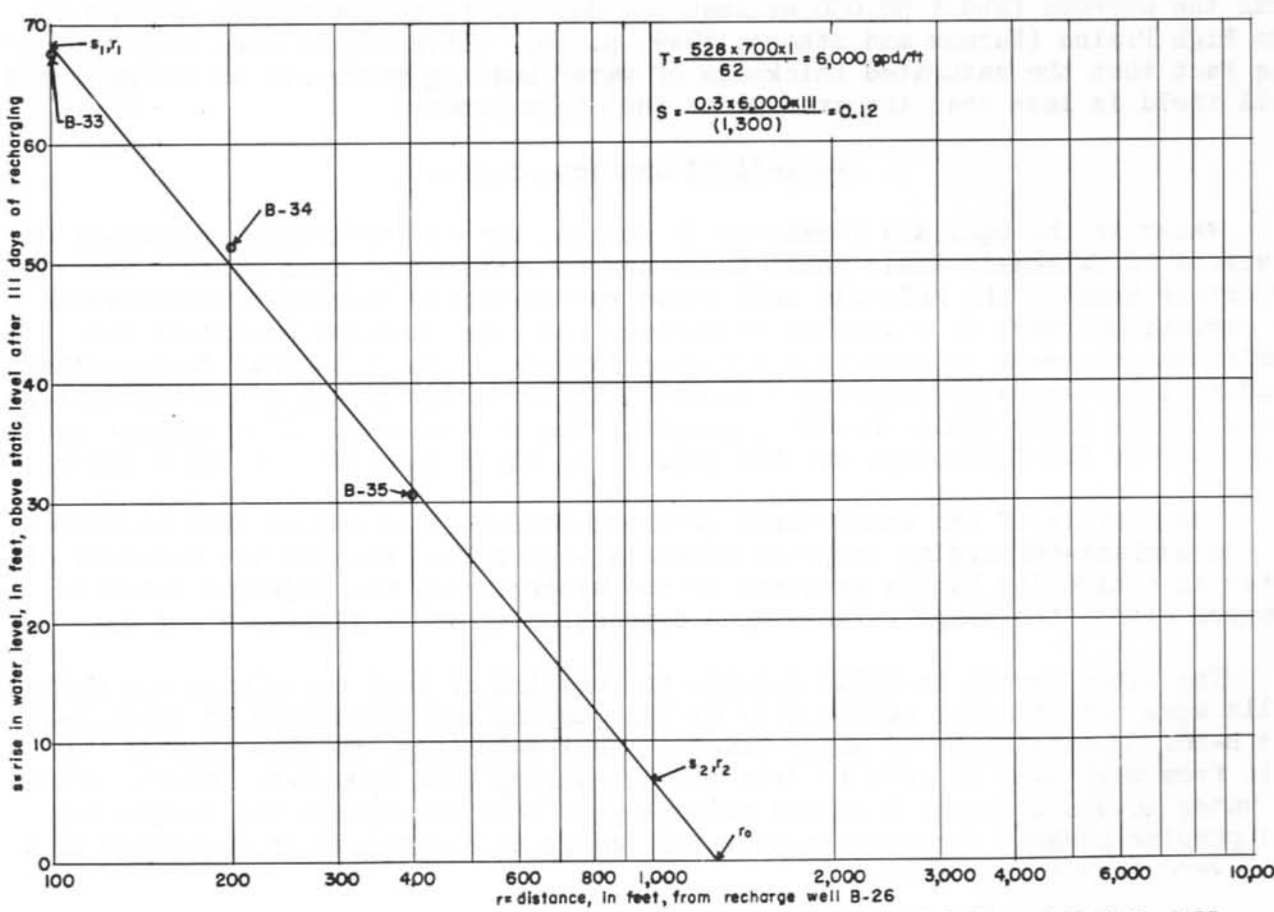


FIGURE 9.-Analysis of unadjusted recharge data by equilibrium method, wells B-25, B-26, and B-30 to B-35.

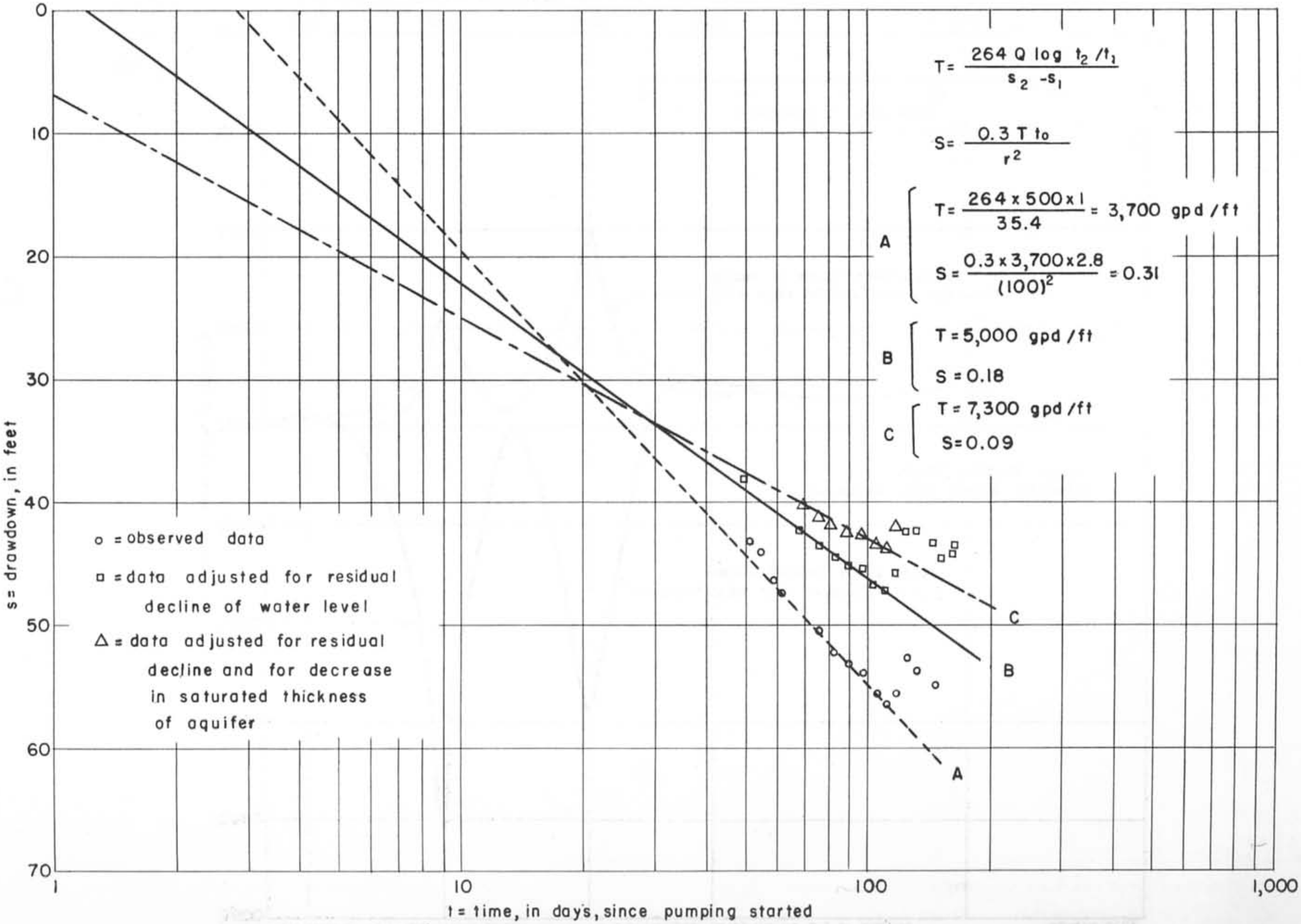


FIGURE 10.-Comparison of adjusted and observed drawdown data, well B-30.

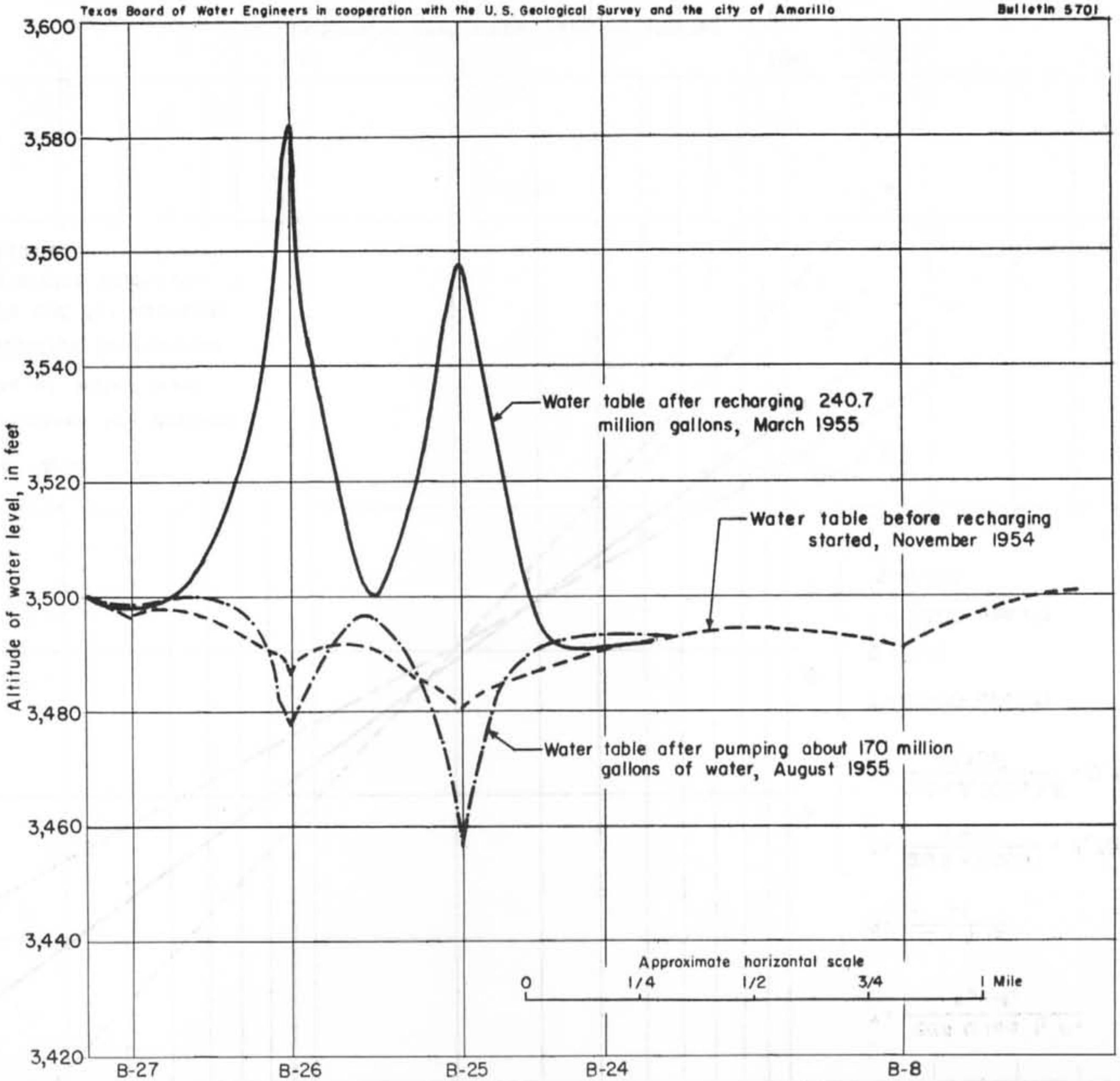


FIGURE 11.-Cross-sectional view of water table in the vicinity of the test sites, based on observed water-level measurements.

Well Characteristics

The ability of a well to accept or yield water is affected by the size, shape, arrangement, and composition of the material near the well. The properties of the materials surrounding the wells in the McDonald field appear to be very favorable to the performance of the wells.

The wells perform much better than would be expected considering the apparent coefficient of transmissibility of the aquifer. Measurements of the water levels were made in wells B-25 and B-26 ten days after each had started recharging about 800 gallons per minute (gpm). The observed specific capacities were 18 gpm per foot and 12.5 gpm per foot, respectively. The theoretical values for specific capacity computed by the Theis nonequilibrium method, assuming a coefficient of transmissibility of 7,000 gallons per day per foot and a coefficient of storage of 0.15, are less than half the observed values. If the assumed values, which were based on the assumption that no appreciable flow occurs through the newly saturated clayey deposits, are of the correct order of magnitude, it appears likely that the principal cause for the high specific capacities is well development.

Excellent well development is also suggested by the history of the wells in the McDonald field which reportedly have yielded large quantities of sand since they were drilled. The wells were constructed with a gravel wall around the inner well casing, and as the gravel slumped into cavities formed by the removal of sand during the initial development and subsequent pumping, additional gravel was added. The permeability of the water-bearing material probably was increased far beyond the radial limit of the gravel envelope as very fine particles of sand, silt, and clay migrated toward the well and were discharged.

Water-injection Problems

The injection of water may cause operating difficulties not encountered in pumping. Injected water may carry suspended solids that tend to clog the well screen and formation; the injection of water may reorient the particles in the formation into a denser pattern; or water containing certain dissolved substances may react chemically to form suspended solids. None of these problems were encountered during this investigation. The buildup of head in wells B-25 and B-26 is normal because as shown in figure 12, the plotted points fall along straight lines that slope nearly the same as those for the observation wells given on figures 7 and 8. Clogging would be indicated if the points should form a curve that swings upward. If recharge water from a source other than the Ogallala should be considered, samples should be analyzed to determine whether chemical treatment would be necessary to prevent clogging. Dual-purpose wells recharged by water from the Ogallala should not clog because the small amount of suspended solids that may collect in the formation during the recharging period probably will be removed during the pumping period.

The changes in water levels in the injection wells are related to the injection rates, and the specific capacity expresses the relationship. The specific capacity will decrease markedly if the injection rate becomes great enough to cause turbulence. Water was injected into and pumped from wells B-25 and B-26 at several different rates between 200 and 1,000 gpm. Turbulence was not encountered at either well and the specific capacities for each well at the different rates were about the same. Figure 13 shows the relationship of specific capacity to time for wells B-25 and B-26. The rise in water level accompanying any injection rate up to 1,000 gpm may be determined by dividing the proposed injection rate by the specific capacity for the proposed period of injection selected from figure 13.

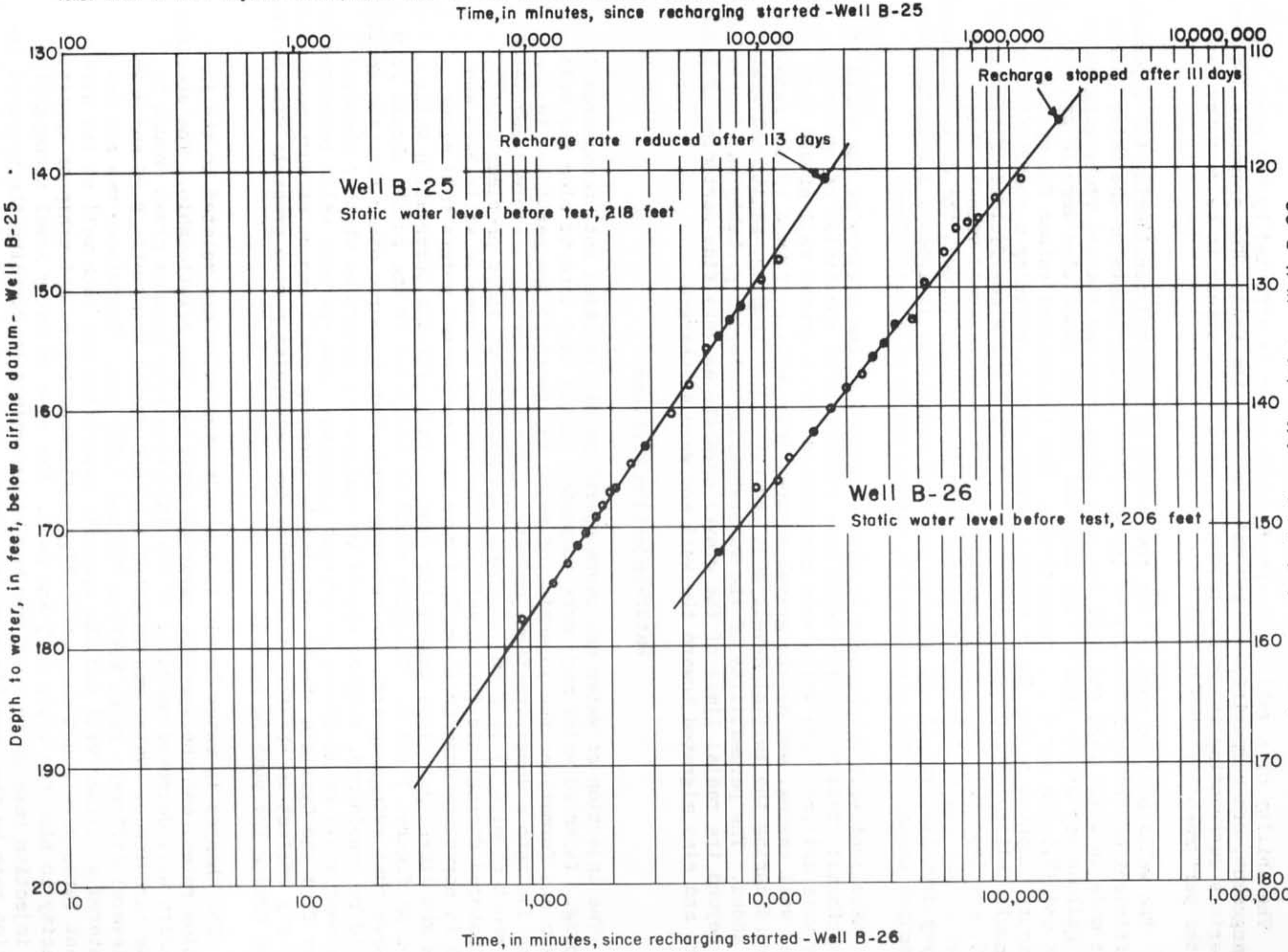


FIGURE 12.- Graph of build up of water levels in wells B-25 and B-26.

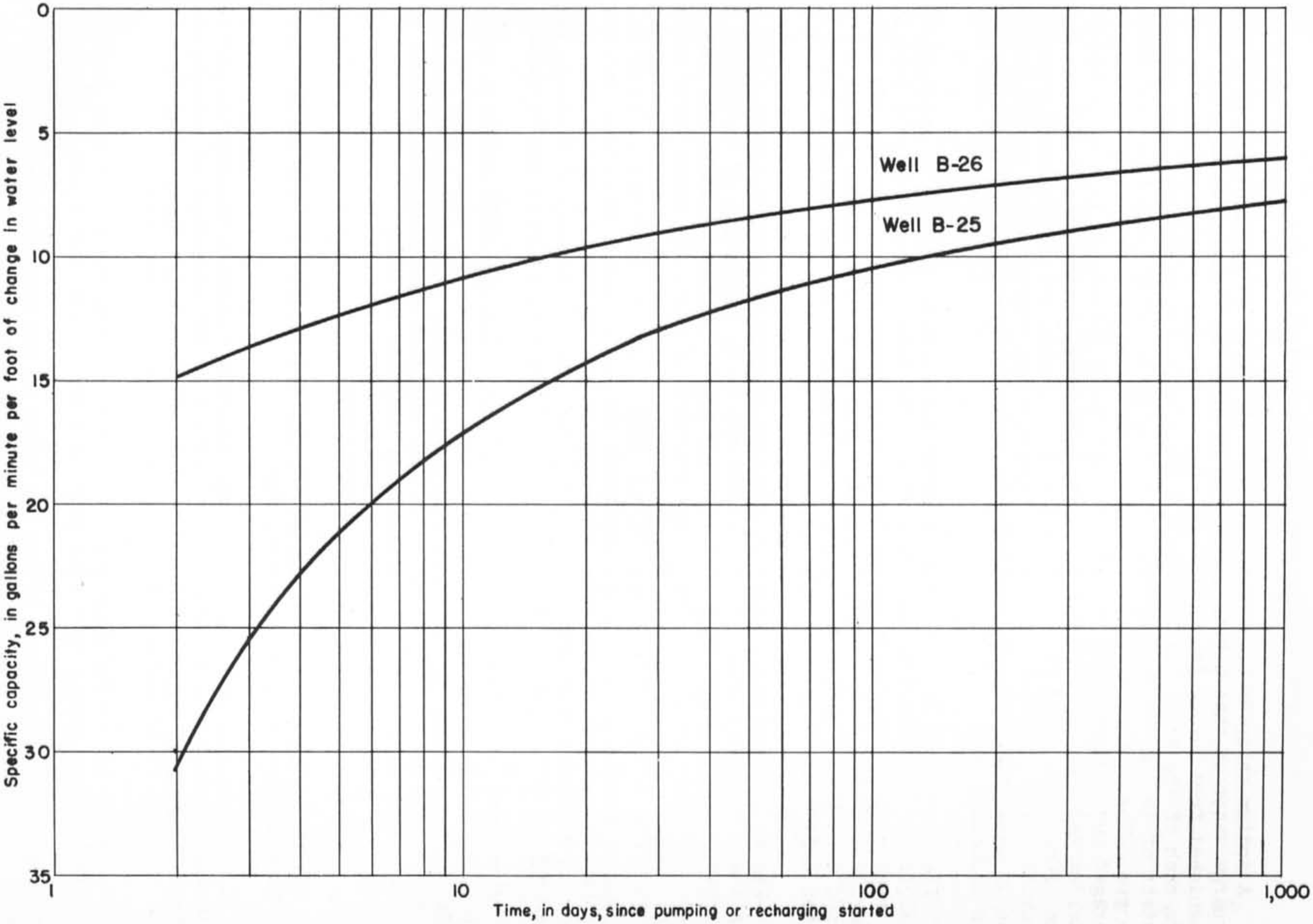


FIGURE 13.-Graph showing variations of specific capacity with time in wells B-25 and B-26 for pumping or recharging rates up to 1,000 gallons per minute.

Recovery of Recharge Water

A sodium chloride brine was injected into about 90 million gallons of the recharge water so that during subsequent pumping the recharge water could be distinguished from the native water. Samples of the native water were collected from each of the wells in the McDonald field prior to recharging. The chloride content of 30 samples ranged from 6.5 to 9.8 parts per million (ppm) and averaged 8.4 ppm. The content of samples from well B-25 ranged from 7.0 to 9.8 ppm and averaged about 9 ppm. The chloride content of 29 samples of the raw recharge water ranged from 6.0 to 8.0 ppm and averaged about 7 ppm. The 90 million gallons of recharge water into which brine was injected had a calculated average chloride content of 26.4 ppm. Brine injection was started after 34,360,500 gallons of water had been recharged and was stopped after 125,414,000 gallons had been recharged.

The percentage of brine-treated water recovered by pumping is approximately equal to the percentage of salt recovered. The water pumped from well B-25 after the recharging period was a mixture of brine-treated recharge water, raw recharge water, and native water. The 100 million gallons of water pumped probably contained very little native water, however, because of the raw recharge water injected before the brine was injected.

Figure 14 shows the changes in chloride content as pumping progressed. The data that plot above 26.4 ppm of chloride may be an indication of variations in the rate of brine injection in the recharge water. Figure 15 shows two curves representing the cumulative percentage recovery of salt; the upper curve assumes no native water in the mixture and the lower curve assumes no raw recharge water. The curves show that after pumping a quantity of water approximately equal to the amount recharged since brine injection started at least 78 percent but not more than 90 percent of the water recharged to the aquifer was recovered. The upper curve should represent closely the true rate of recovery of recharge water because most of the pumped water probably contained very little native water.

A recharge experiment in El Paso, Texas, (Sundstrom, 1952) showed a similar rate of recovery and showed that essentially all of the recharge water was recovered after pumping nearly three times the quantity recharged. The similarity to the results of the experiment in El Paso suggests that continued pumping of well B-25 also would result in essentially complete recovery.

CONCLUSIONS

The following conclusions pertain to the feasibility of temporarily storing water underground near Amarillo, Tex.:

1. The unsaturated deposits of the Ogallala formation beneath the section of land occupied by the McDonald wells contain 10,000 acre-feet of storage space between the present water table and a level 100 feet below the land surface, the level to which it is assumed that the aquifer could be saturated.

2. Wells in the McDonald well field may be recharged at rates up to about 1,000 gallons per minute each with present distribution facilities. By removing the pumps from the wells, the injection rate could be increased to perhaps 2,000 gallons per minute. If each of the six wells in the McDonald field were recharged at an average rate of 1,000 gallons per minute, it would take about a year to store 10,000 acre-feet of water.

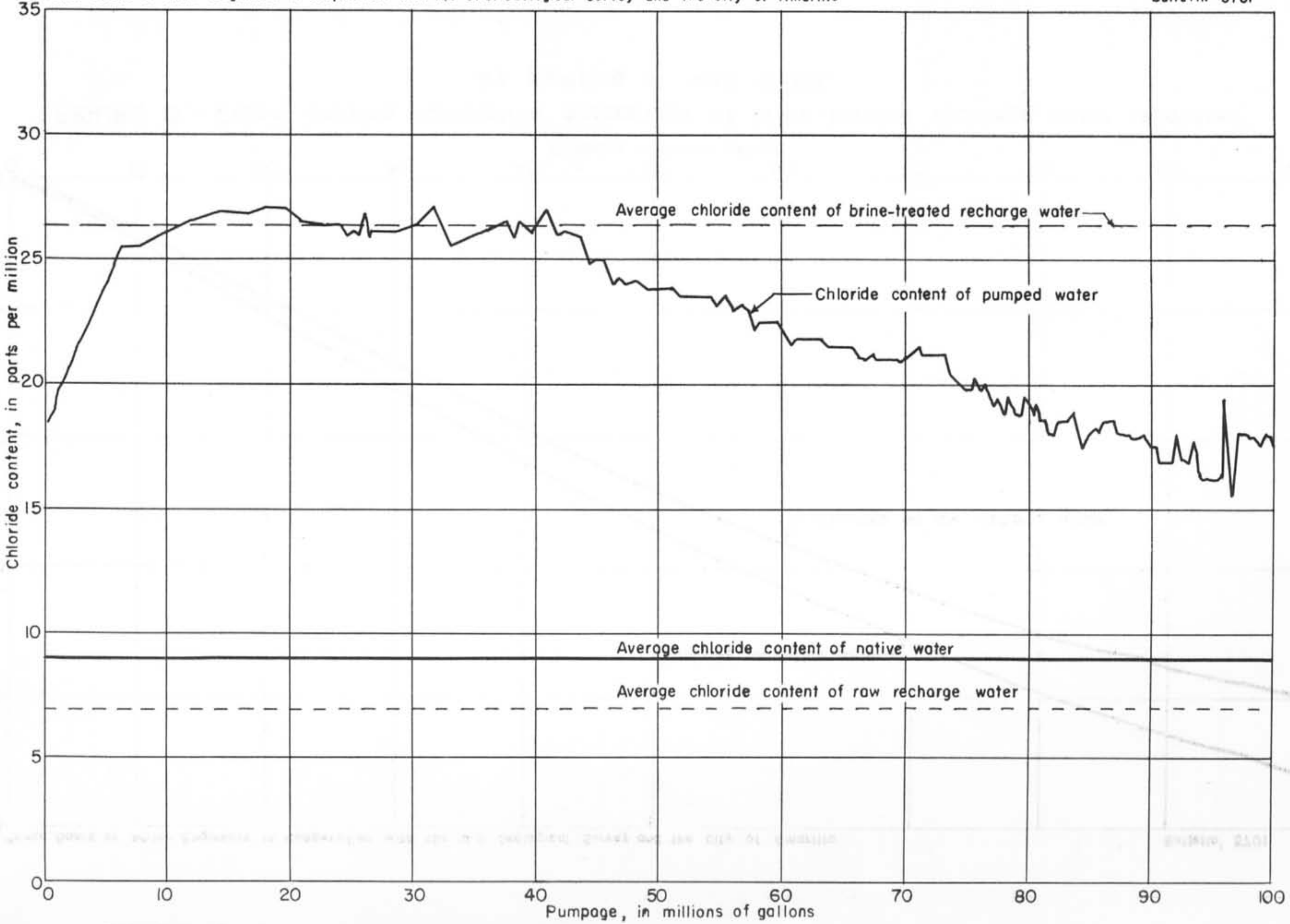


FIGURE 14.-Graph showing chloride content of recharge water recovered by pumping.

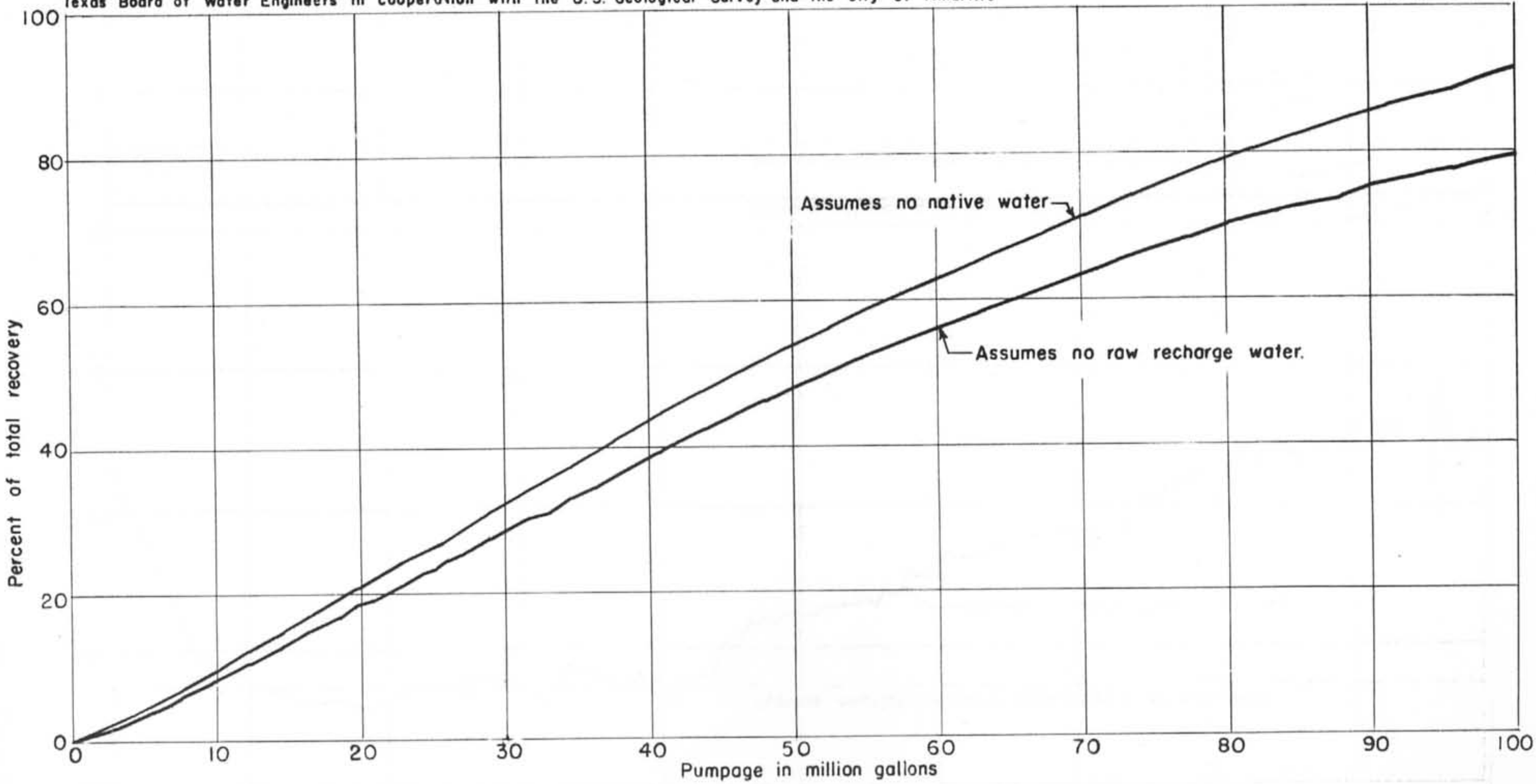


FIGURE 15.- Graph showing cumulative percentage of brine-treated recharge water recovered by pumping at well B-25.

3. Water from any part of the Ogallala formation that has a low content of suspended solids may be injected into the wells in the McDonald field without undue clogging difficulties. Untreated water from other sources may have a chemical reaction with the water in the Ogallala causing injection difficulties.

4. Maximum efficiency is gained by starting pumping operations as soon after recharging as possible.

5. A balanced annual pumping-recharging cycle would halt the decline of pumping levels caused by pumping from wells of the McDonald field.

6. The water table would be affected very little beyond a distance of half a mile from a pumping-recharging well which over a period of a year discharges approximately the same quantity of water that was recharged. However, because no physical boundaries are present in the aquifer nearby wells eventually will benefit from any recharge program. The benefits, however, will decrease with distance from the point of injection.

7. The conclusions for the McDonald well field probably are representative of the other city well fields because subsurface conditions appear to be similar. In the event that additional sources of recharge become available and other well fields are considered for recharging, well-performance figures (pumping rates and drawdown measurements) will indicate the best wells for injecting large quantities of water.

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Table 1.- Records of wells southwest of Amarillo, Randall County, Texas

Method of lift: C, cylinder; T, turbine; E, electric; W, windmill; G, gasoline.
Use of water: D, domestic; Irr, irrigation; P, public supply; S, stock; N, none.

Well	Amarillo well no.	Distance and direction from well B-25 (miles)	Owner	Driller	Date com-pleted	Depth of well (ft.)	Diam-eter of well (in.)	Altitude of land surface (ft.)	Water level, Oct. 25, 1954: Below land-surface datum (ft.)	Water level, Oct. 25, 1954: Altitude (ft.)	Method of lift	Use of water	Remarks
B-1		3.9 NW	O. L. Taylor	W. D. Muncey	1943	278	16	3756.59	181.10	3575.49	T, E	Irr	
B-2		3.0 NW	--	--	--	--	--	3741.44	182.83	3558.61	T, E	Irr	
B-3		1.6 N	-- Watkins	--	1954	--	8	3695.59	171.07	3524.52	T, E	D, Irr	
*B-4		1.5 N	--	--	--	--	--	--	--	--	T, E	D, S	
*B-5	Brinkman 1	1.5 NW	City of Amarillo	H. H. Heiskell	1944	277	16	3690.48	181.90	3508.58	T, E	P	Gravel packed.
B-6		3.0 NE	--	--	--	--	6	3643.96	140.56	3503.40	C, W	D, S	
*B-7		2.7 NE	--	--	--	--	--	--	--	--	C, W	D, S	
*B-8	Greely 6	1.0 NE	City of Amarillo	H. H. Heiskell	1946	271	16	3690.63	199.84	3490.79	T, E	P	Gravel packed.
*B-9		1.0 N	B. M. Puckett	--	--	242	--	--	--	--	T, E	D	
*B-10		1.0 N	do	--	--	--	--	--	--	--	C, W	D, S	
B-11		1.2 NW	do	--	--	--	--	3713.49	199.53	3513.96	T, E	Irr	
B-12		1.4 NW	do	--	--	--	--	3714.76	194.92	3519.84	T, E	Irr	
*B-13		1.4 NW	-- O'Brien	--	--	150	6	--	--	--	C, W	D, S	
B-14		1.7 NW	--	--	--	--	--	3724.73	190.52	3534.21	T, E	Irr	
*B-15		2.0 NW	John Menke	Joe Conner	1923	183	5	--	--	--	C, E	D, S	
*B-16		2.2 NW	--	--	--	--	--	--	--	--	C, W	D, S	
B-17		2.7 W	E. C. Smith	--	--	--	--	3741.90	174.04	3567.86	T, E	Irr	
B-18		3.6 W	Bush Estate	--	--	--	--	3758.87	193.74	3565.13	T, E	Irr	
B-19		2.7 W	M. J. Michaelias	--	1935	200+	4	3736.23	162.34	3573.89	C, W	D, S	
*B-20	Bassett 1	0.8 NW	City of Amarillo	H. H. Heiskell	1947	265	16	3693.97	196.50	3497.47	T, E	P	Gravel packed.
*B-21	Bassett 2	1.1 W	do	do	1947	280	16	3715.42	205.60	3509.82	T, E	P	Do.
*B-22	Bassett 3	1.5 W	do	do	1947	--	16	3719.21	174.12	3545.09	T, E	P	Do.
*B-23		1.2 W	Mrs. F. Bassett	--	1910	200	5	--	---	--	C, W	D, S	
*B-24	McDonald 1	0.3 NE	City of Amarillo	D. L. McDonald	1929	270	18	3694.91	205.37	3489.54	T, E	P	Gravel packed.
*B-25	McDonald 2	--	do	do	1929	270	18	3696.05	215.20	3480.85	T, E	P	Do.
*B-26	McDonald 3	0.3 SW	do	do	1929	270	18	3695.92	205.70	3490.22	T, E	P	Do.
*B-27	McDonald 4	0.7 SW	do	do	1929	322	18	3698.25	209.70	3488.55	T, E	P	Do.
*B-28	McDonald 5	0.3 NW	do	do	1929	336	18	3698.04	211.70	3486.34	T, E	P	Do.
*B-29	McDonald 6	0.6 W	do	H. H. Heiskell	1947	280	16	3689.63	185.50	3504.13	T, E	P	Do.
B-30	Obs 1	100 ft NE	do	do	1954	250	4	3695.30	212.62	3482.68	None	N	Observation well.
B-31	Obs 2	200 ft NE	do	do	1954	240	4	3695.61	213.00	3482.61	None	N	Do.

* Sampled for chloride analysis.

Table 1.- Records of wells southwest of Amarillo, Randall County--Continued

Well	Amarillo well no.	Distance and direction from well B-25 (miles)	Owner	Driller	Date com-plet-ed	Depth of well (ft.)	Diam-eter of well (in.)	Altitude of land surface (ft.)	Water level Oct. 25, 1954: Below land surface datum (ft.)	Water level Oct. 25, 1954: Altitude (ft.)	Method of lift	Use of water	Remarks
B-32	Obs 3	400 ft NE	City of Amarillo	H. H. Heiskell	1954	230	4	3695.83	210.85	3484.98	None	N	Observation well.
B-33	Obs 4	0.3 SW	do	do	1954	236	4	3695.38	205.63	3489.75	None	N	Do.
B-34	Obs 5	0.3 SW	do	do	1954	236	4	3695.68	205.20	3490.48	None	N	Do.
B-35	Obs 6	0.3 SW	do	do	1954	236	4	3695.84	204.03	3491.81	None	N	Do.
*B-36		0.6 E	C. S. Lambie	D. L. McDonald	1943	250	16	3686.25	186.06	3500.19	T, E	Irr	
B-37		0.6 E	do	do	1946	240	12	3686.22	193.74	3492.48	T, E	Irr	
B-38		0.8 SE	do	do	1946	250	16	3686.55	191.38	3495.17	T, E	Irr	
B-39		0.8 SE	Geo. Barnard	--	1938	212	--	3686.68	184.88	3501.80	T, E	D	
*B-40		1.0 SE	--	--	--	--	--	--	--	--	C, W	D	
*B-41		1.3 SE	Richard Massey	--	--	230	--	--	--	--	T, E	Irr, D	
*B-42		1.0 E	C. S. Lambie	--	--	235?	--	--	--	--	T, E	D, S	
*B-43		1.8 E	--	--	--	--	--	--	--	--	C, E	D	
B-44		2.5 SE	R. G. Shaw	--	--	--	6	3617.47	94.08	3523.39	None	N	
*B-45		1.4 SE	Roy Bechtold	--	1946	205	8	3673.50	169.13	3504.37	T, E	Irr, D	Gravel packed.
B-46		2.8 SE	--	--	--	--	--	3673.87	162.84	3511.03	T, E	Irr	
B-47		1.0 SE	--	--	--	--	--	3688.66	185.39	3503.27	T, E	Irr	
*B-48		1.2 S	Glenn L. Casey	--	--	--	--	--	--	--	C, W	D, S	
B-49		1.4 S	do	--	--	--	--	3700.07	189.19	3510.88	T, E	Irr	
B-50		0.8 SW	do	--	--	--	--	3699.03	198.47	3500.56	T, E	Irr	
*B-51	Bush 1	1.4 SW	City of Amarillo	H. H. Heiskell	1943	296	16	3695.06	197.37	3497.69	T, E	P	Gravel packed.
*B-52	Bush 2	1.9 SW	do	do	1944	250	16	3672.51	148.82	3523.69	T, E	P	Do.
*B-53	Bush 3	2.7 SW	do	do	1944	239	16	3682.67	173.68	3508.99	T, E	P	Do.
B-54	Bush 4	3.3 SW	do	do	1943	305	16	3706.88	184.23	3522.65	T, E	P	Do.
B-55	Bush 5	4.0 SW	do	do	1943	263	16	3705.83	172.79	3533.04	T, E	P	Do.
B-56	Bush 6	4.9 SW	do	do	1944	247	16	3697.85	154.53	3543.32	T, E	P	Do.
B-57		2.1 SW	E. T. Brian	--	--	--	--	3723.35	185.80	3537.55	T, E	Irr	
*B-58		2.3 SW	--	--	--	--	--	--	--	--	C, W	D, S	
B-59	Section 98	4.0 SW	City of Amarillo	H. H. Heiskell	1951	252	16	3719.45	161.75	3557.70	T, E	P	Gravel packed.
B-60		3.8 SW	--	--	--	--	--	3724.81	154.99	3569.82	T, E	Irr	
B-61		2.5 SW	Boyd Elliott	--	--	--	--	3695.42	166.57	3528.85	T, G	Irr	
B-62		2.3 S	do	--	--	--	--	3695.70	165.94	3529.34	T, E	Irr	
B-63		2.1 S	-- Coulter	--	--	--	--	3696.90	171.75	3525.15	T, E	Irr	
*B-64		2.1 SW	--	--	--	--	--	--	--	--	C, W	D, S	
*B-65		1.7 S	Bush Estate	-- Fisch	--	263	16	3702.48	180.57	3521.91	T, E	Irr	
*B-66		2.6 S	do	--	--	--	--	--	--	--	C, E	D, S	
*B-67		2.3 S	-- Wheeler	--	1946	240	16	3673.75	148.41	3525.34	T, E	D, S	

Table 1.- Records of wells southwest of Amarillo, Randall County--Continued

Well	Amarillo well no.	Distance and direction from well B-25 (miles)	Owner	Driller	Date com- plet- ed	Depth of well (ft.)	Diam- eter of well (in.)	Altitude of land surface (ft.)	Water level, Oct. 25, 1954		Method of lift	Use of water	Remarks
									Below land-surface datum (ft.)	Altitude (ft.)			
B-68		2.7 S	E. E. Marrs	Joe Curry	1954	200	6	3668.22	146.44	3521.78	T,E	D	
*B-69		1.7 SE	--	--	--	200?	--	--	--	--	T,E	Irr,D	
B-70		3.0 SE	Johnson Estate	--	1920	--	6	3628.65	113.71	3514.94	C,W	D,S	
B-71		2.8 S	--	--	--	--	--	3686.76	150.72	3536.04	T,E	Irr	
*B-72		3.0 SW	--	--	--	--	--	--	--	--	C,W	S	
B-73		4.0 SW	--	--	--	--	--	3711.24	175.41	3535.83	T,E	Irr	

* Sampled for chloride analysis.

Table 2.- Drillers' logs of wells southwest of Amarillo, Randall County, Texas, McDonald well field

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Well B-24					
Owner: McDonald well 1.					
Top soil (clay and sand)-------	4	4	Sandrock ----------	4	186
Caliche ----------------------	8	12	Sand and sand boulders	8	194
Clay, yellow -----------------	58	70	Clay, sandy --------	19	213
Clay, red, sandy -------------	12	82	Sand, red, cavey ---	10	223
Clay, light sandy ------------	13	95	Sand, red, very fine-grained -----	15	238
Sand, gray, clayey -----------	45	140	Clay, white --------	2	240
Clay, soft, red, sandy --------	5	145	Sand, red ----------	11	251
Sandrock, soft, honeycombed ---	18	163	Clay, white --------	3	254
Sand, red, cavey -------------	6	169	Sand, clean, red ---	5	259
Sandrock ---------------------	1	170	Clay, red ----------	11	270
Sandrock, soft, honeycombed ---	12	182			
Well B-25					
Owner: McDonald well 2.					
Soil -----------------------	4	4	Sand, gray, clayey--	14	200
Clay, red ------------------	13	17	Sandrock, soft -----	4	204
Caliche --------------------	4	21	Sand, coarse, and honeycomb sandrock	6	210
Clay, yellow ---------------	47	68	Sandrock, soft -----	7	217
Clay, yellow, sandy --------	19	87	Sand, clean red ----	7	224
Clay, gray, sandy ----------	5	92	Packsand, gray clayey	3	227
Clay, light gray, sandy ----	8	100	Sand, clean red ----	3	230
Clay, soft red, sandy ------	48	148	Clay, red sandy ----	5	235
Sandrock, honeycomb --------	3	151	Sand, red cavey ----	3	238
Sand, dirty gray -----------	9	160	Sand, gray clayey --	8	246
Sand, clean red ------------	3	163	Clay, gray --------	2	248
Sand, gray, clayey ---------	7	170	Sand, clayey -------	6	254
Sand, loose, boulders ------	6	176	Clay, white --------	3	257
Sand, clean red ------------	4	180	Clay, red ----------	13	270
Sand, gray, clayey ---------	3	183			
Sand, gray, sand sandrock --	3	186			

Table 2.- Drillers' logs of wells southwest of Amarillo, Randall County--Continued

McDonald well field

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Well B-26					
Owner: McDonald well 3.					
Soil ----------------------	4	4	Sand, honeycomb ----	6	176
Clay, yellow -------------	46	50	Sandstone, red -----	14	190
Clay, gray sandy ---------	12	62	Sand, red with thin clay strata ------	8	198
Clay, red sandy ----------	45	107	Sand, red cavey ----	10	208
Clay, red sandy, soft ----	43	150	Sand, clayey, gray -	4	212
Sandrock -----------------	4	154	Sand, red caving ---	3	215
Sand, gray and rock ------	2	156	No record ----------	55	270
Sand, coarse and sandrock-	14	170			
Well B-27					
Owner: McDonald well 4.					
Soil ----------------------	3	3	Sand, soft yellow water-bearing ----	15	224
Clay, yellow ------------	47	50	Sand, red and corals with streaks of yellow sandy clay-	31	255
Clay, white sandy -------	15	65	Clay, blue ---------	10	265
Clay, yellow sandy and gravel ----------------	9	74	Clay, red ----------	26	291
Rock --------------------	4	78	Clay, brown --------	21	312
Clay, yellow sand and gravel ----------------	76	154	Sand, red water-bearing ----------	2	314
Sandrock soft water-bearing ---------------	10	164	Clay, red and blue -	8	322
Sand, yellow and white rock	16	180			
Sand, red water-bearing, honeycomb, with corals -	29	209			
Well B-28					
Owner: McDonald well 5					
Soil ----------------------	2	2	Sand, soft loose water-bearing and pebbles -	6	164
Clay, yellow -------------	63	65	Sand, yellow with thin clay streaks --------	30	194
Clay, yellow sandy --------	33	98	Clay, white sandy -----	6	200
Clay, gray sandy ----------	34	132			
Sand, yellow clayey -------	26	158			

(Continued on next page)

Table 2.- Drillers' logs of wells southwest of Amarillo, Randall County--Continued

McDonald well field

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Well B-28--Continued					
Sand, red ----------------	12	212	Sand, red -----------	26	284
Clay, white sandy ---------	3	215	Clay, reddish-brown -	28	312
Sand, red ----------------	31	246	Sand, red -----------	5	317
Sand, red with loose white rock ------------------	9	255	Sand, gray ----------	9	326
Clay, white sandy ---------	3	258	Red beds ------------	10	336
Well B-30					
Owner: Observation well 1.					
Top soil ----------------	2	2	Sand, shells hard --	50	150
Top clay ----------------	28	30	Sand and light shells, soft --------------	85	235
Clay, brown -------------	58	88	Clay, brown ---------	15	250
Shells, hard ------------	12	100			
Well B-31					
Owner: Observation well 2.					
Top soil ----------------	2	2	Clay, sandy and shells	86	200
Clay --------------------	88	90	Sand and light shells	35	235
Shells ------------------	10	100	Clay ---------------	5	240
Clay, sandy -------------	14	114			
Well B-32					
Owner: Observation well 3.					
Top soil ----------------	2	2	Clay, sandy --------	95	195
Clay --------------------	86	88	Sand, light shells --	35	230
Shells, hard ------------	12	100			

Table 2.- Drillers' logs of wells southwest of Amarillo, Randall County--Continued

McDonald well field

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Well B-33					
Owner: Observation well 4.					
Top soil ------------------	2	2	Clay, sandy light shells ------------	100	205
Clay ---------------------	88	90	Sand, shells --------	231	236
Shells and clay -----------	15	105			
Well B-34					
Owner: Observation well 5.					
Top soil -----------------	2	2	Clay,sandy shells ---	110	195
Clay --------------------	83	85	Sand, shells --------	41	236
Well B-35					
Owner: Observation well 6.					
Top soil ----------------	2	2	Clay, sandy shells -	105	200
Clay -------------------	93	95	Sand, shells -------	36	236

Table 3.- Chemical analyses of water from wells southwest of Amarillo, Randall County, Texas

(Analyses in parts per million except specific conductance, pH, and percent sodium)

Well	Owner	Depth of well (ft.)	Date of collection	Silica (SiO_2)	Iron (Fe)	Manganese (Mn)	Calcium (Ca)	Magnesium (Mg)	Sodium and potassium (Na + K)		Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Phosphate (PO_4)	Boron (B)	Dissolved solids	Hardness as $CaCO_3$	Percent sodium	Specific conductance (micromhos at 25°C)	pH
B-9	B. M. Puckett	242	Sept. 14, 1954	48	-	-	53	22	19	-	271	27	4.8	2.0	2.0	-	0.20	328	223	16	491	8.1
B-25	City of Amarillo	270	Nov. 1, 1954	76	0.20	0.00	35	38	24	5.8	307	30	9.0	2.2	3.2	0.00	.20	374	244	17	597	7.9
B-25	do	270	Mar. 11, 1955	74	.02	.00	40	37	34	5.2	319	38	18	3.6	3.8	.00	.48	411	252	22	598	7.9
B-26	do	270	Nov. 1, 1954	77	.04	.00	36	38	28	5.9	308	34	9.0	2.4	2.2	.00	.16	384	246	19	554	7.7
B-26	do	270	Mar. 8, 1955	-	-	-	-	-	-	-	320	-	7.2	-	-	-	-	-	255	-	569	8.4
B-41	Richard Massey	230	Sept. 14, 1954	70	-	-	51	29	18	-	273	28	14	2.0	6.5	-	.22	353	246	14	542	7.9
B-42	C. S. Lambie	235?	do	68	-	-	43	31	22	-	289	26	7.0	2.4	2.0	-	.25	344	235	17	519	7.6
B-45	Roy Bechtold	205	do	66	-	-	39	37	9.0	-	269	25	10	1.6	2.5	-	.05	324	249	7	492	8.2
B-69	--	200?	do	67	-	-	58	24	16	-	284	24	7.5	2.4	4.5	-	.22	352	243	13	516	7.6
Recharge water from Palo Duro well field		-	Nov. 8, 1954	68	.02	.00	38	38	29	4.2	317	34	6.5	5.6	4.1	.04	.18	384	251	20	565	8.0