AQUIFER CHARACTERISTICS FROM WELL-FIELD PRODUCTION RECORDS
EDWARDS LIMESTONE, SAN ANTONIO AREA, TEXAS

by

Sergio Garza

A Thesis Submitted to the Faculty of the

GRADUATE COMMITTEE ON HYDROLOGY AND WATER RESOURCES

In Partial Fulfillment of the Requirements
For the Degree of

MASTER OF SCIENCE

In the Graduate College

THE UNIVERSITY OF ARIZONA

1968

STATEMENT BY AUTHOR

This thesis has been submitted in partial fulfillment of requirements for an advanced degree at the University of Arizona and is deposited in the University Library to be made available to borrowers under rules of the Library.

Brief quotations from this thesis are allowable without special permission, provided that accurate acknowledgment of source is made. Requests for permission for extended quotation from or reproduction of this manuscript in whole or in part may be granted by the head of the major department or the Dean of the Graduate College when in his judgment the proposed use of the material is in the interests of scholarship. In all other instances, however, permission must be obtained from the author.

SIGNED: Sergio Garza

APPROVAL BY THESIS DIRECTOR

This thesis has been approved on the date shown below:

Eugene S. Simpson
E. S. Simpson
Professor of Hydrology

2 May 1968
Date

ACKNOWLEDGMENTS

The author wishes to express his appreciation and thanks to Professors E. S. Simpson, H. K. Qashu, and D. D. Lewis for their guidance and encouragement throughout the course of this study and in the preparation of this thesis.

The author also wishes to acknowledge the staff of the U. S. Geological Survey, Water Resources Division, Austin, Texas, for their help in making available previously published illustrations for reproduction and inclusion as part of this thesis.

Much of the study for this thesis is the outgrowth of extensive hydrologic work done by the author, under the U. S. Geological Survey, in the Edwards limestone aquifer in the San Antonio area, Texas. All work completed in these investigations has been published by the Texas Water Development Board in cooperation with the Edwards Underground Water District and the City of San Antonio.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS--Continued

ABSTRACT

The Edwards limestone aquifer, the main source of water to the San Antonio area of south central Texas, has been the subject of numerous hydrologic investigations. The most comprehensive studies have related changes in aquifer head and storage to the differences between recharge and discharge. Projections of future demands from the aquifer are used to predict future aquifer heads, but these are limited to year-end estimates and do not include maximum summertime drawdowns.

The Theis nonequilibrium formula, with a modification introduced by Stallman for continuously varying discharge, was used with well-field production records to determine apparent values of aquifer characteristics. Although the aquifer model does not strictly apply to the mathematical model imposed by the formula, useful approximations of the coefficients of transmissivity (12 million gallons per day per foot) and storage (0.6×10^{-4}) were derived. Testing the coefficients with independent historical data gave some credence to the magnitude of the above results. These apparent coefficients were used with projected aquifer demands and year-end aquifer heads to predict maximum possible summertime drawdowns in a key well for 1970-2000. The 2000 summertime head was projected to be 100 feet lower than the record summertime low of 1956.

CHAPTER 1

INTRODUCTION

Purpose and Scope

The Edwards limestone aquifer in the San Antonio area of south central Texas is the most important water-supply aquifer in the area. Early immigrants to the area settled in the vicinity of the springs which issue from the aquifer. As the area developed, wells were drilled into the aquifer to supply most of the water for municipal, military, industrial, irrigation, domestic and stock needs. Because of its importance, the aquifer has been studied extensively, particularly since the early nineteen fifties, when the effects of a prolonged drouth and an increase in water use resulted in a continued drop of aquifer head.

The quantitative studies to date have involved treatment of the aquifer as though it were a surface-water reservoir, in which balances were established among inflow , outflow, and changes in storage both on a monthly and on an annual basis. A basic result of these studies has been definition of storage changes throughout the period of record. This determination plus annual projections of recharge and discharge have been used to estimate future annual changes in storage and aquifer head. However, prediction of maximum summertime drawdowns, which are most important to the water users, remains unresolved.

The purpose of this thesis is to examine a technique for estimating the maximum possible summertime drawdowns at the largest well field tapping the Edwards aquifer. This well field, which is located in central Bexar County, is referred to as the San Antonio well field because it includes the City of San Antonio, the chief user of water in the area. Well-field production records are used to determine average monthly pumping rates which are used as "stimulus" pulses at a theoretical line sink. These are then related to observed drawdowns ("response" pulses) through a modified form of the Theis nonequilibrium equation in order to calculate aquifer characteristics. Results of these calculations, called apparent aquifer characteristics in this study, may be used to predict aquifer performance. Therefore the historical records from past studies are examined, and in the process much of the results of these previous works is presented. The computed results of the aquifer analyses are compared with other determinations and are tested with independent data. Limitations in the use of these results and a specific application also are presented.

Location and Extent of Area

The term "San Antonio area" has been used in many hydrologic investigations of the Edwards aquifer to indicate the areal extent of the aquifer which is the source of water for the City of San Antonio and its vicinity. The hydraulic boundaries of this area of the Edwards aquifer are the boundaries of the San Antonio area, which includes the Nueces, San Antonio, and Guadalupe River basins (Figure 1). Also shown in figure 1 are observation wells and precipitation and streamflow-gaging stations in the San Antonio area.

The boundary of the San Antonio well field is not easy to define. The well field is roughly circular in shape and about 15 miles in diameter, and the center of the field is near the center of Bexar County. Observation well 26, which was used to monitor changes in aquifer head, is near the center of the well field. Several hundred large-capacity wells are contained within the field.

Previous Work in Area

The Edwards aquifer in the San Antonio area has been the subject of numerous geologic and hydrologic investigations since about 1929. The basic objectives of most of these investigations have been to determine the occurrence, availability, quantity, quality, and use of the water in the aquifer. Some of the early investigations reporting on the general occurrence and availability of water in the area were those by Livingston and others (1936), Sayre (1936), and by Sayre and Bennett (1942). Descriptions of the general geology and hydrology of county areas within the San Antonio area have been published as individual county reports. (See List of References for reports on

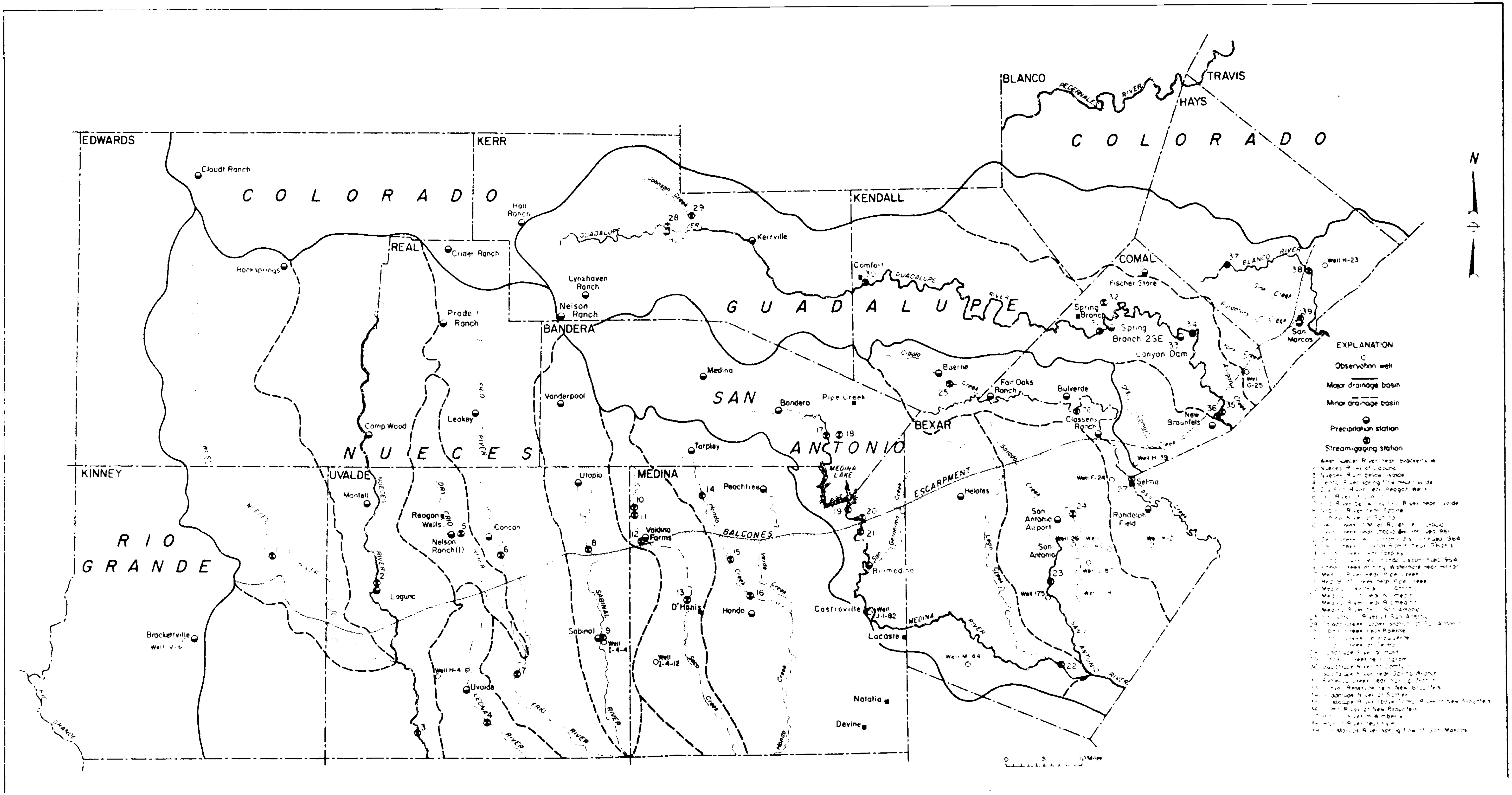

Figure 1. Locations of Observation Wells, Drainage Basins, Precipitation Stations, and Stream-Gaging Stations in the San Antonio Area.

Source: Garza, 1966, Figure 1.

counties of Bexar, Comal, Hays, Medina, Uvalde, and Kinney). Lowry (1955) was one of the first to make estimates of regional recharge to the Edwards aquifer. Reports by Petitt and George (1956) and by Garza (1962, 1966) included comprehensive studies of the regional recharge, discharge, and storage changes in the aquifer throughout the period of record.

CHAPTER 2

THE EDWARDS AQUIFER

General Geologic and Water-Bearing Properties

The Edwards aquifer in the San Antonio area lies within two physiographic sections, the Edwards Plateau to the north and northwest and the West Gulf Coastal Plain to the south and southeast. The Balcones escarpment, a fault scarp in the Balcones fault zone, separates the two physiographic sections and lies in the middle of the east-west trending outcrop of the Edwards aquifer (Figure 1). This area of outcrop is about 180 miles long and about 5 to 40 miles wide within and adjacent to the Balcones fault zone.

The Edwards aquifer has been referred to in many hydrologic reports as the Edwards and associated limestones in the San Antonio area. Geologically, the aquifer is formed by the Comanche Peak, Edwards, and Georgetown limestones of Cretaceous age, but differentiation of these units is difficult in drilled cuttings. Hydrologically, these units form one aquifer, and as such the whole system has been called the Edwards and associated limestones or simply the Edwards aquifer. The strike of the aquifer parallels the Balcones fault zone, and the dip is about 100 feet per mile.

In surface exposures, the units of the aquifer constitute dense, hard, crystalline limestones, but the rocks become extensively honeycombed and cavernous on weathering. Fractures and solutional cavities form more or less linear channels associated with and parallel to faults. These conditions appear to be most favorable for direct infiltration of water, particularly from streams cutting across the outcrop area of the aquifer.

The thickness of the Edwards aquifer at all places is not known, but results from the great number of drilled wells indicate an average thickness of about 500 feet (Petitt and George, 1956). Most of the large wells (10 to 30 inches in diameter) penetrate the entire thickness of the aquifer, and the well yields usually are large to very large.

Recharge, Discharge, and Movement of Water

Recharge to the Edwards aquifer occurs primarily by transmission losses from streams crossing the outcrop of the aquifer in the Balcones fault zone and, to a lesser extent, by direct infiltration of rainfall.

Estimates of recharge were made by Lowry (1955) and by Petitt and George (1956) for the period 1934-53. The estimates of Petitt and George were later revised and extended through 1964 by Garza (1966). (See Table 1.) The method employed by these investigators to estimate recharge is basically the same, and the differences between the

Table 1. Estimated Annual Recharge to the Edwards Aquifer, 1934-64.

Source: Garza, 1966, Table 3.

Year	Recharge (Thousands of Acre-Feet)	Year	Recharge (Thousands of Acre-Feet)
1934	179.6	1950	200.2
1935	1258	1951	139.9
1936	909.6	1852	275.5
1937	400.7	1953	167.6
1938	432.7	1954	160.9
1939	399.0	1955	192.0
1940	308.8	1956	43.7
1941	850.7	1957	1143
1942	557.8	1958	1711
1943	273.1	1959	690.4
1944	560.9	1960	824.8
1945	527.8	1961	717.1
1946	556.1	1962	249.4
1947	422.6	1963	170.7
1948	178.3	1964	411.2
		Total	15,420
1949	508.1		
		Average	497.4

results of duplicated estimates usually were small. Recharge for each stream basin is the difference between total surface inflow above the recharge zone and the total surface outflow below the recharge zone. Gaging stations are employed in the measurements above and below the recharge areas along each stream. Unit runoff values derived from the upper gaging station have been used to estimate the runoff increment on the outcrop of the aquifer. Evapotranspiration losses per unit area in the outcrop zone are assumed to be the same as the losses in the area above the outcrop. The total inflow is the runoff above the outcrop plus that runoff on the outcrop itself, and the total outflow is measured by the lower gage. Apparently, the method is satisfactory when the variables are averaged over long periods of time, when errors tend to balance out (Garza, 1966). The estimates probably are best for periods of low recharge, when infiltration on the outcrop zone is small, and the bulk of the recharge is determined directly from the streamflow records.

Most of the discharge from the aquifer during the period 1934-64 was from springs, but the discharge from wells increased appreciably during the latter half of this period (Figure 2). In fact, the annual well discharge for the periods 1954-57 and 1963-64 exceeded the annual spring discharge. These periods were below average in annual rainfall, and the result was an increase in well withdrawals and a decrease in springflow. The average annual precipitation at San

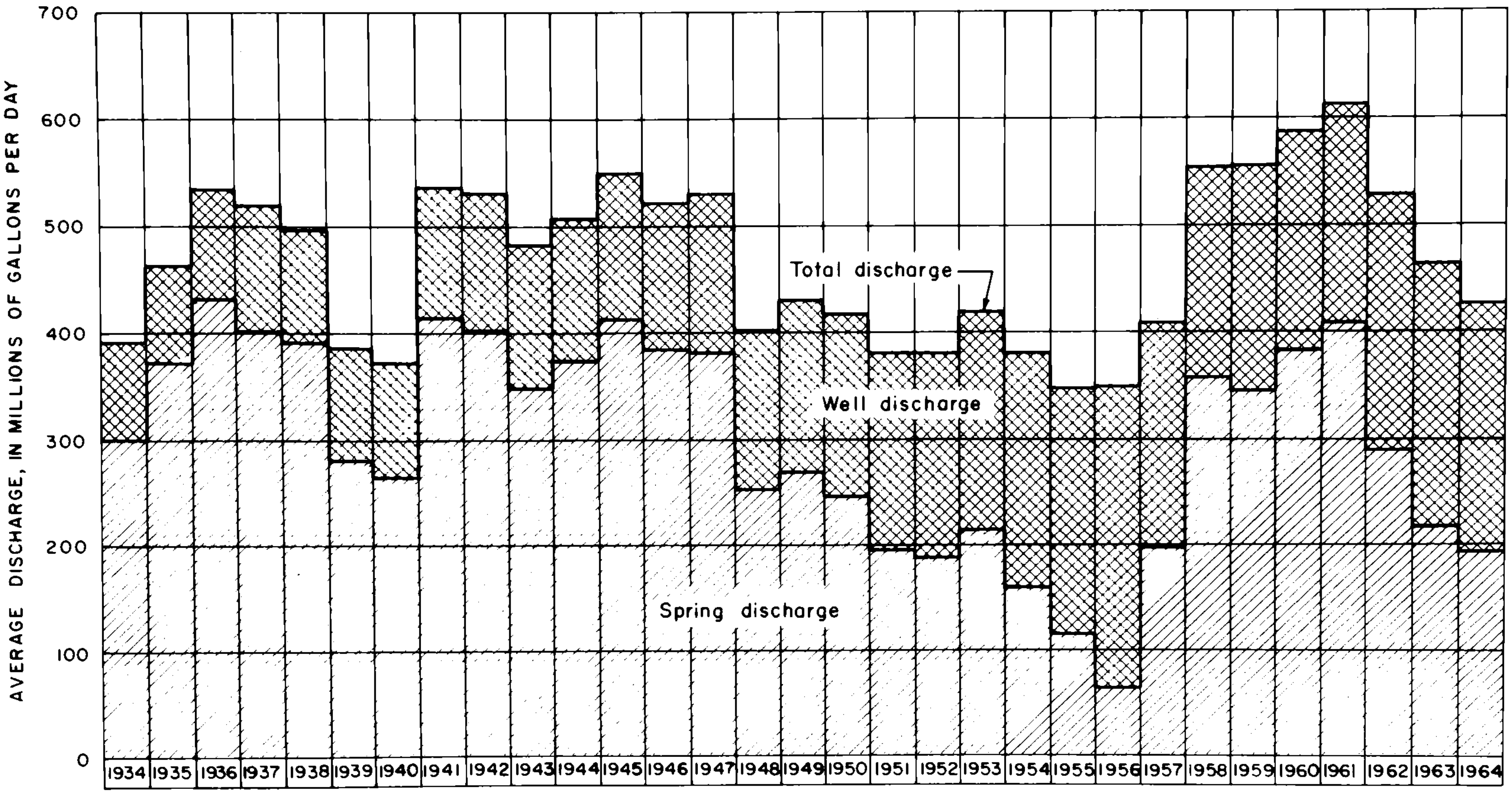

Figure 2. Discharge from Springs and Wells in the Edwards Aquifer

Source: Garza, 1966, Figure 3.

Antonio for 91 years is 27.5 inches (Garza, 1966). When precipitation is above average, such as during the 1957-61 period, the opposite is true.

The springs that issue from the Balcones fault zone between Del Rio and Austin, Texas are among the largest in the United States (Meinzer, 1927). Others west of Del Rio, such as Goodenough Springs and the Devils River Springs, discharge large quantities of water from the part of the Edwards which is west and contiguous to the aquifer under investigation in the San Antonio area. In the San Antonio area, the principal springs are the Leona River Springs near Uvalde, San Antonio and San Pedro Springs at San Antonio, Comal Springs at New Braunfels, and San Marcos Springs at San Marcos (See Figure 3).

During the period 1955-64, more than one-half of the annual well discharge (269,000 acre-feet) was for municipal and military use, and 90 percent of this was in Bexar County. More than one-half of the remaining well discharge was for irrigation, mainly in Uvalde, Bexar, and Medina Counties. The rest of the well discharge was used for industrial, domestic, and stock purposes. During 1955-64, about 75 to 85 percent of the annual well discharge took place in Bexar County, which is the area of the large pumping well field (San Antonio well field) employed in this study for the aquifer analyses.

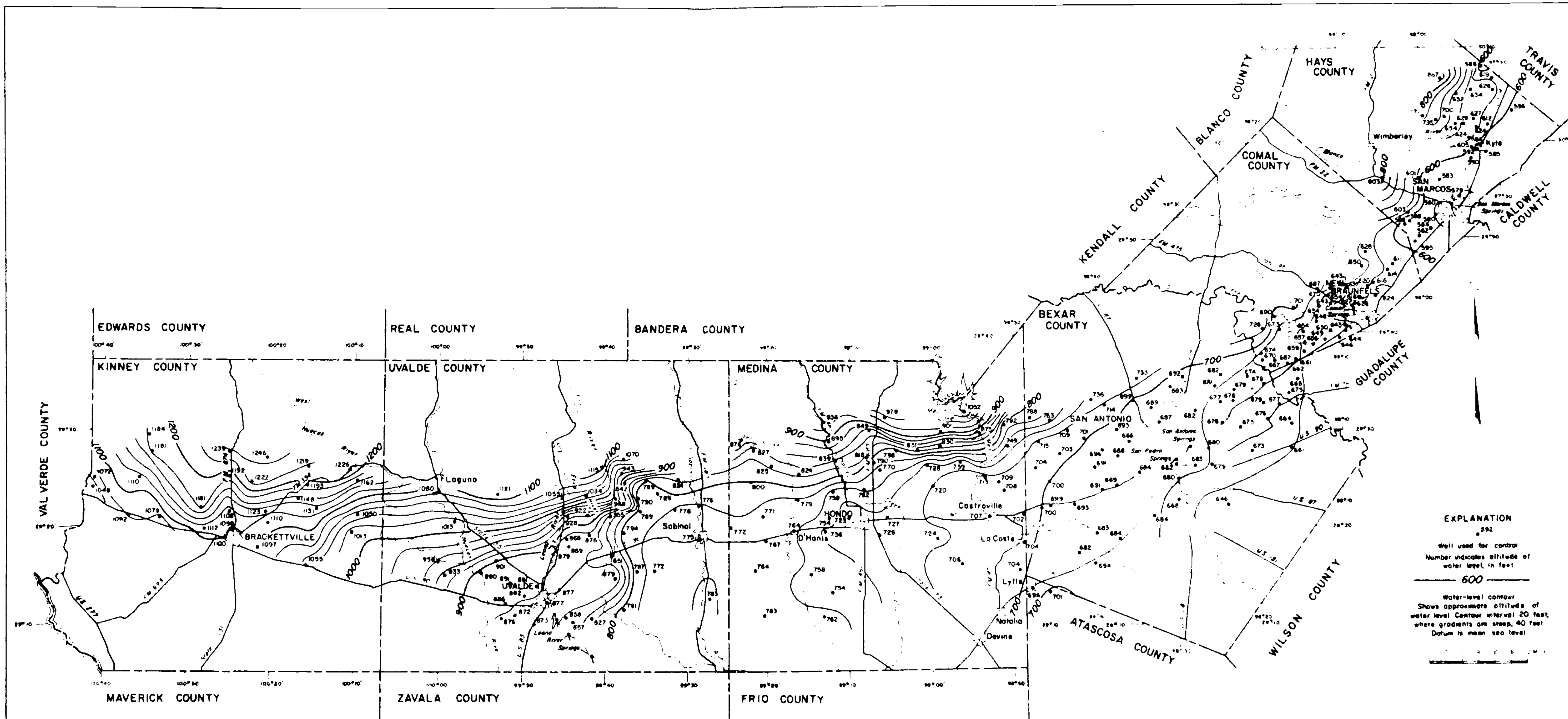

Figure 3. Approximate Altitude of the Water Table and Piezometric Surface of the Edwards Aquifer in January, 1961.

Source: Garza, 1966, Figure 3.

Figure 3 shows the approximate altitude of the water table and piezometric surface of the Edwards aquifer in January, 1961. The general movement of the ground water is in the direction of the hydraulic gradient, and only general direction of movement can be inferred from this map. Water moves southward and southeastward from the water table region (outcrop) towards the artesian part of the aquifer, and then it moves eastward and northeastward towards the large springs (Comal and San Marcos). Ground-water divides in central Kinney County and in the northeastern part of Hays County represent the western and eastern hydraulic boundaries, respectively, of the Edwards aquifer in the San Antonio area.

Changes in Aquifer Storage

Figure 4 shows discharge from Comal Springs, water level in Bexar County Well 26, and accumulated deviation from average precipitation at Boerne, Texas. (See Figure 1 for location of well 26 in Bexar County; Boerne, Texas is in Kendall County north of Bexar County.) Also included is a comparison of accumulated recharge and discharge. The graphs show clearly the response of aquifer head and spring discharge to precipitation or lack of precipitation in the area. According to Garza (1966), the decrease in aquifer storage during the drouth period 1947-57 was more than 2 million acre-feet, and the

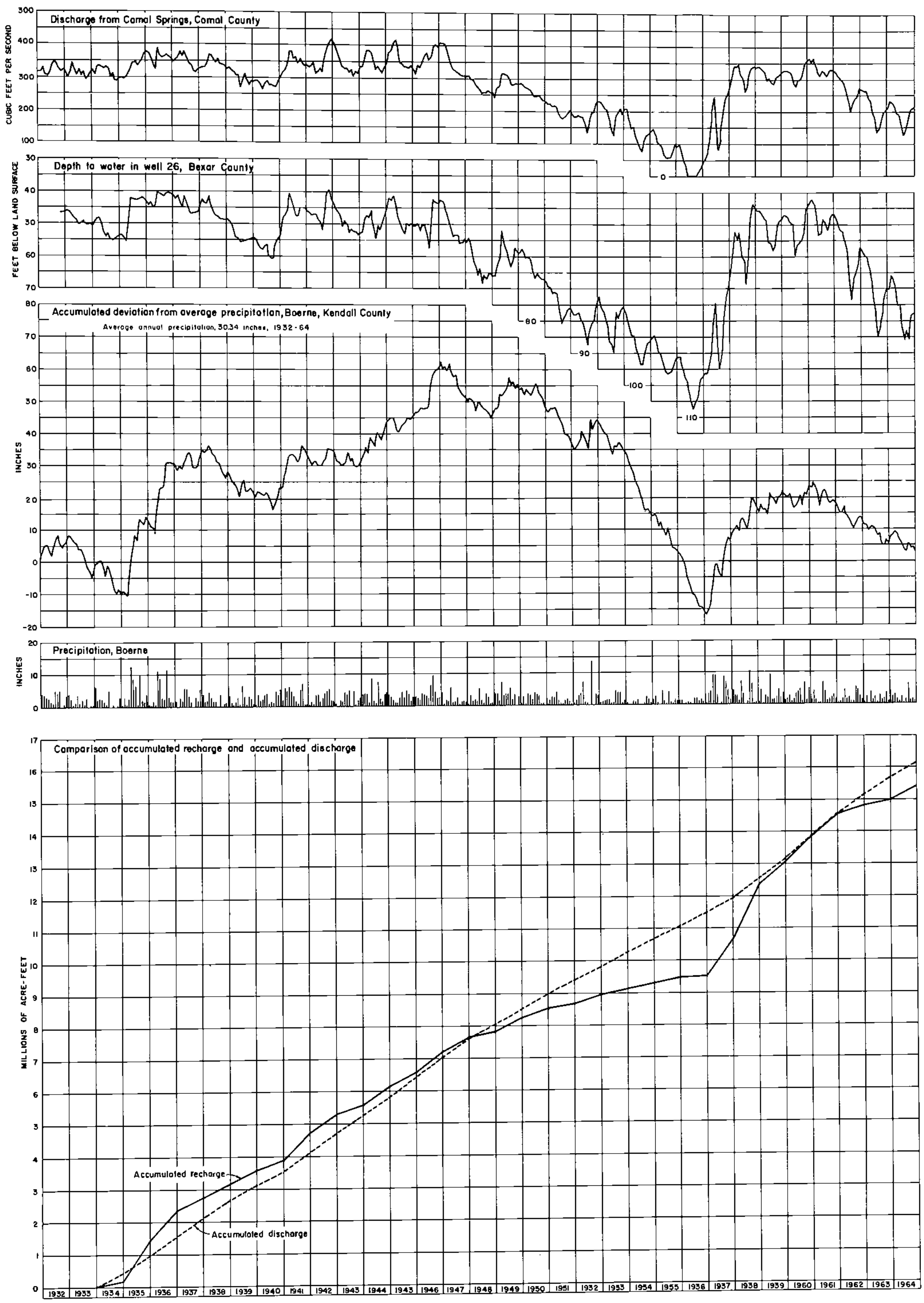

Figure 4. Springflow, Aquifer Head, Precipitation, and Accumulated Recharge and Discharge in the Edwards Aquifer

Source: Garza, 1966, Figure 7.

accretion to aquifer storage during the wet period 1957-61 nearly matched the decrease.

Garza (1966) also related changes in storage with water level in well 26, using the records for 1946-64, which covered a cycle of near-maximum water-level fluctuation (Figure 5). The curve of relation shown in figure 5 is nearly but not quite a curve of best fit. Points above the curve represent relatively wet periods when recharge was predominant; points below the curve represent relatively dry periods when discharge was greater than recharge. Points near the curve may represent water-level conditions such that recharge and discharge were nearly equal. The relative differences between points also may represent other factors difficult to evaluate and which may be related to pumping effects near well 26.

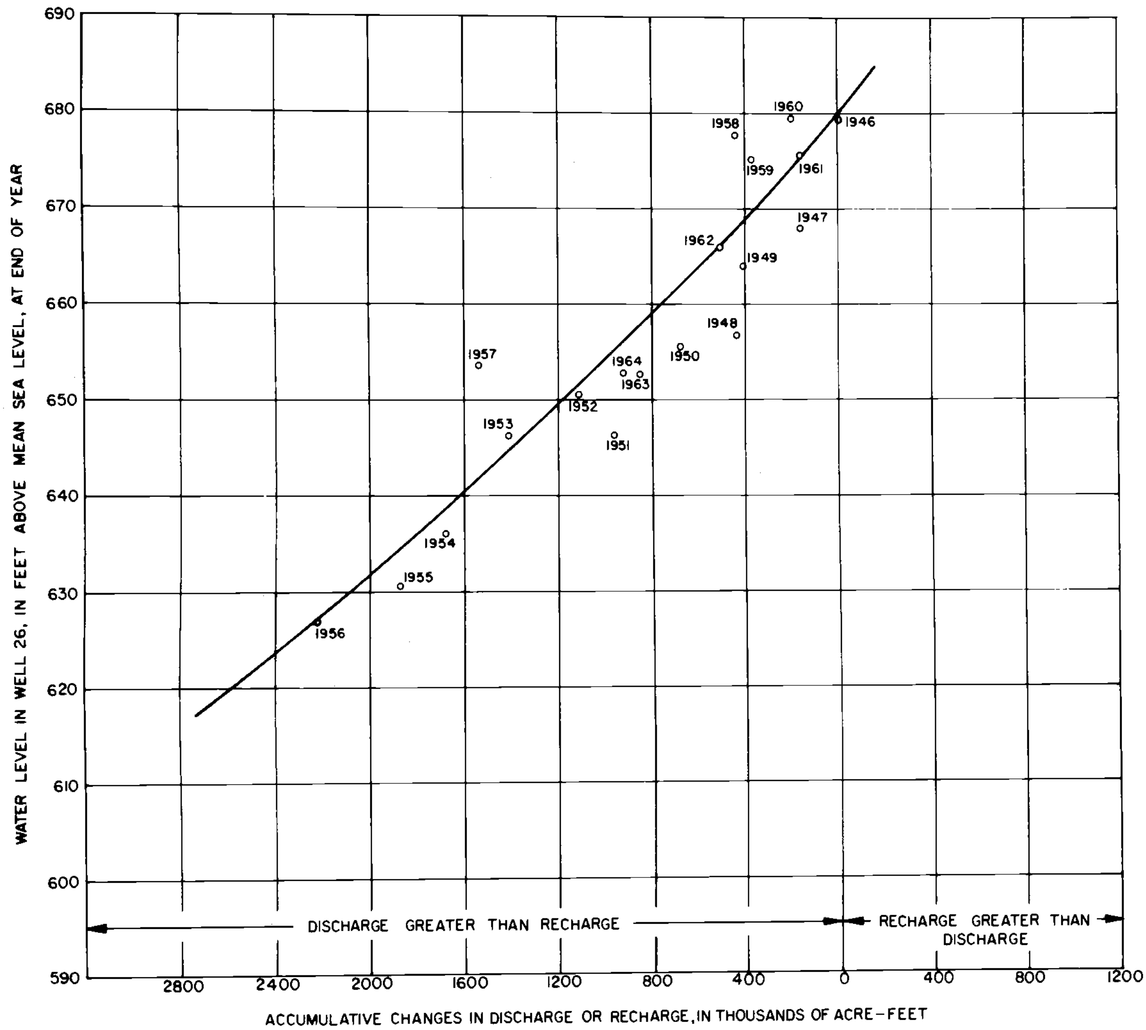

Figure 5. Relation Between Water Level in Well 26 and Accumulated Differences Between Recharge and Discharge in the Edwards Aquifer

Source: Garza, 1966, Figure 9.

CHAPTER 3

APPARENT AQUIFER CHARACTERISTICS AT WELL FIELD

General Theory of Aquifer Tests

The value of an aquifer as a source of water supply is related to its properties to transmit and to store water. The coefficient of transmissivity is a measure of the transmissive property and the coefficient of storage is a measure of the storage property. An aquifer may be tested by pumping a well or well field, and the relation between time, drawdown, and discharge may be used to determine these two aquifer characteristics. The basic theory and assumptions of the principal methods in common use are presented by Ferris and others (1962). For purposes of this thesis, the Theis (1935) nonequilibrium formula, with the modification introduced by Stallman (Ferris and others, 1962) for continuously varying discharge, was employed as the method of analysis.

It is recognized that the limestone aquifer does not exactly fit the mathematical model imposed by the Theis formula. However, under certain assumptions and limitations, useful approximations of what may be termed average values of apparent aquifer characteristics may be derived. These characteristics may be tested for validity by comparing calculated aquifer response with the historical record.

Some of the more important assumptions and limiting factors in the application of the Theis technique to the Edwards aquifer are as follows:

1. Total monthly discharge from the San Antonio well field in Bexar County was used as a varying pumping pulse in the aquifer, and the area encompassing the well field was assumed to have a theoretical line sink. All of the discharge is assumed to be concentrated at the line sink.

2. Hydraulic boundaries exist at the outcrop and toward the saline-water zone downdip in the artesian part of the aquifer, but for purposes of this study the aquifer was assumed infinite.

3. In spite of the relatively large average pore diameter, flow in the saturated regions of the aquifer is slow, and Darcy's law is assumed to apply.

4. The bulk of the flow is assumed to be horizontal and radial toward the theoretical line sink.

5. Although the aquifer is heterogeneous, the size of area influenced by the San Antonio well field in the artesian part of the aquifer is so large that the average flow may be considered irrotational. Hence, the computed coefficients are averages for the entire well field.

Technique Employed

In applying the Theis nonequilibrium formula, the method suggested by Stallman (Ferris and others, 1962, pp. 118-122) was used to construct type curves for analyzing the observed drawdowns caused by the variable pumping rates in the San Antonio well field of the Edwards aquifer. The variable rate is transformed into steps of average discharge, and the total drawdown, s, in an observation well at distance r from the theoretical center of pumping is the sum of the drawdowns caused by each of the steps. ($s = s_1 + s_2 \ldots . s_n$; Equation 44 in Ferris and others, 1962, p. 120). The symbols used for the coefficients of transmissivity and storage are T and S, respectively. (See Appendix for other definitions of symbols in the equation.) The following is from the above reference:

> Applying the Theis nonequilibrium formula to define each of the drawdown components given in equation 44, there follows,

$$s = \frac{114.6}{T} \left[\Delta Q_1 W(u)_1 + \Delta Q_2 W(u)_2 + \Delta Q_3 W(u)_3 \ldots .. + \Delta Q_n W(u)_n \right] . \qquad (45)$$

> The corresponding u values are

$$u_1 = \frac{1.87 r^2 S}{T(t-t_1)}; \quad u_2 = \frac{1.87 r^2 S}{T(t-t_1)}; \quad u_3 = \frac{1.87 r^2 S}{T(t-t_3)}; \quad \ldots\ldots;$$

$$u_n = \frac{1.87 r^2 S}{T(t-t_n)} \qquad (46)$$

Therefore,

$$u_2 = u_1 \frac{t-t_1}{t-t_2}; \qquad u_3 = u_1 \frac{t-t_1}{t-t_3}; \; \ldots . ;$$

$$u_n = u_1 \frac{t-t_1}{t-t_n} \qquad (47)$$

Inspection of equations 46 and 47 should indicate that virtually an infinite number of type curves can be constructed for solving equation 45. For practical purposes, however, only a family of curves need be constructed.

It can be seen from equations 46 that the relation between the _u_ values is dependent on the value of _t_ selected. For any given value of _t_, the values of _u_ are proportional to the constant $1.87r^2S/T$. Therefore the family of curves must be constructed using _t_ and $1.87r^2S/T$ as independent variables and $\Sigma \Delta QW(u)$ as the dependent variable. This is accomplished by first assuming several values of $1.87r^2S/T$ for a particular value of _t_. Values of u_1 are then computed for that _t_ for the assumed values of $1.87r^2S/T$ using the first of equations 46. Equations 47 are then used to compute values of u_2, $u_3 .. u_n$ for each assumed value of $1.87r^2S/T$. These in turn determine (see table 2)[1] the corresponding W(u) values, which are used to compute the quantity in brackets (the sum of all the $\Delta QW(u)$ terms) in equation 45. Thus a set of values is produced for the sum of the $\Delta QW(u)$ terms, corresponding with the assumed values of $1.87r^2S/T$ and all are related to one assumed value of _t_. This computing procedure is repeated for each value of _t_ in a whole set of _t_ values selected to span a time range that will permit drawing the family of curves ...., through the same time interval covered by the drawdown observations in the aquifer. The field-data plot of log _s_ versus log 1/t is superposed on the family of type curves, taking care that the logarithmic time scales of the two graphs are exactly matched. The data plot

1. Table 2 in Ferris and others (1962) shows the W(u) for values of _u_ between 10^{-15} and 9.9 for use with Theis' nonequilibrium formula.

is then shifted along the $\Sigma\Delta QW(u)$ axis until the position is found where the curvature of the data plot is identical with an underlying type curve or with an interpolated type curve position. It follows that this serves to identify the data curve with a specific value of $1.87r^2S/T$. Values of $\underline{s}$ and $\Sigma\Delta QW(u)$ are read from a point common to both graphs and entered in equation 45 to solve for T. The computed value of T can then be used with the value of $1.87r^2S/T$ to solve for S.

Results

The years 1953, 1954, 1962 and 1963 were selected for analysis because these years represented conditions of relatively small recharge (Table 1); also, the aquifer head at the beginning of each of these years was near the storage relation curve of figure 5. Bexar County well 26 was used to monitor changes in aquifer head within the San Antonio well field. Figures 6 and 7 show the average well discharge at the well field and the actual and assumed water-level trend in well 26 for each of the years selected. The assumed water level trend for each of these years resulted from the "base" of the minimum discharge from the well field. The seasonal stepped increases in discharge are regarded as departures from this minimum for these years. The rate of recharge during these years was small and was assumed to balance the well-field discharge rate during the winter months. As previously stated, the well discharge varies almost continuously, but in figures 6 and 7 the discharge was averaged in a series of stepped pumping rates over the periods indicated.

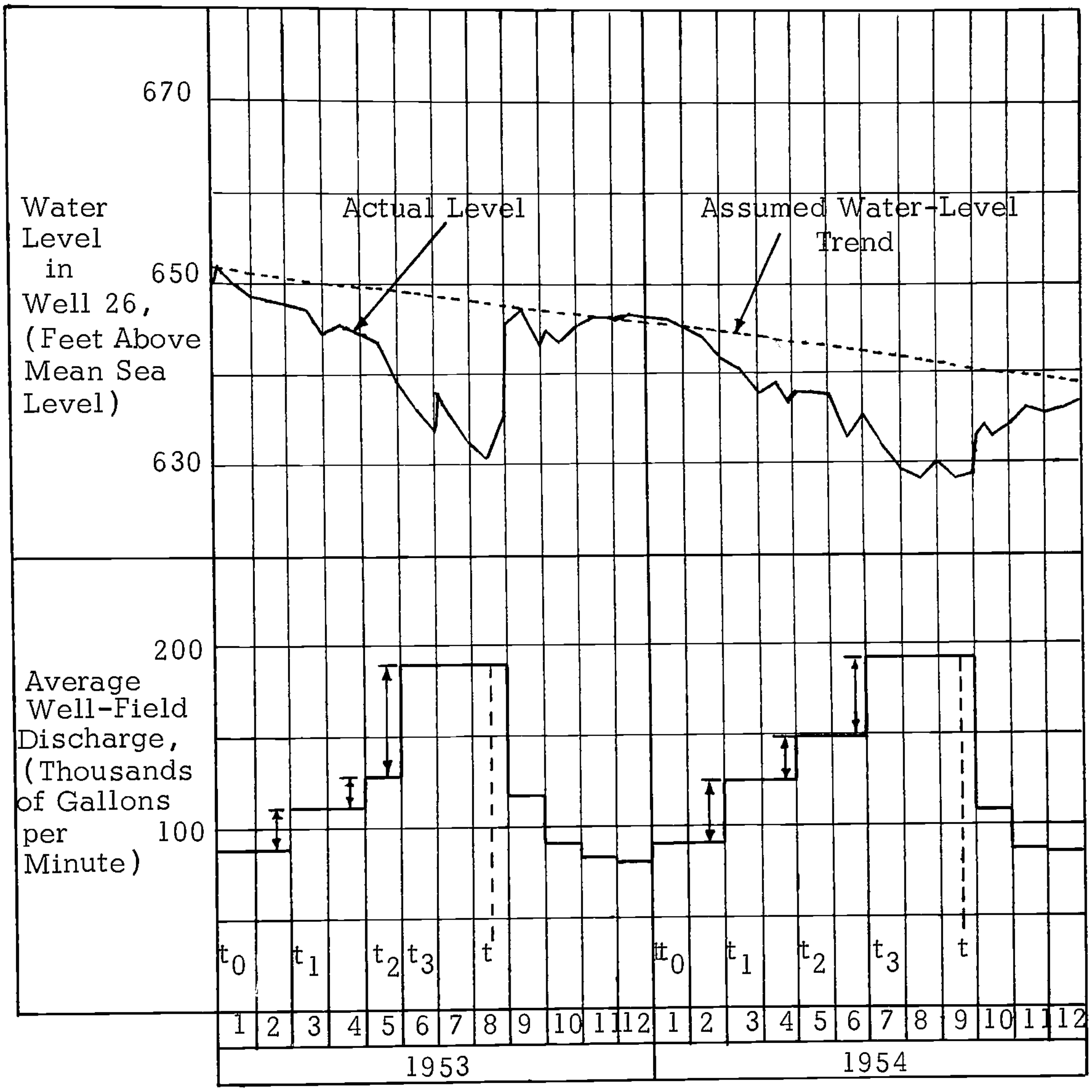

Figure 6. Altitude of Water Level in Well 26 and Average Well Discharge at San Antonio Well Field, 1953 and 1954.

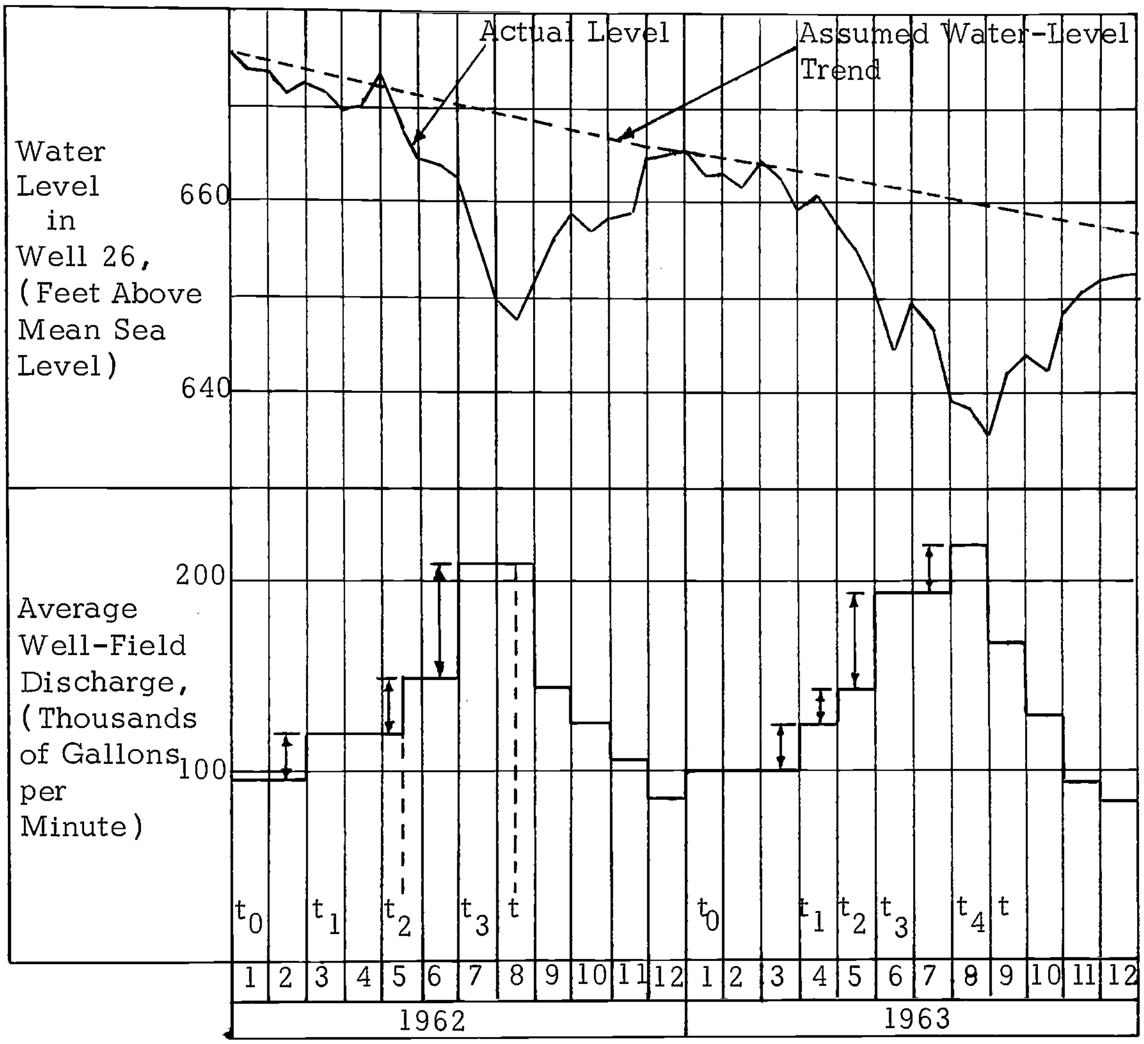

Figure 7. Altitude of Water Level in Well 26 and Average Well Discharge at San Antonio Well Field, 1962 and 1963.

Figures 8, 9, 10, and 11 show the family of type curves for the analyses of 1953, 1954, 1962, and 1963, respectively. These were calculated according to the method given by Stallman and quoted above. Figures 12, 13, 14, and 15 show the type curve of best fit for each respective set of data points. The apparent coefficients of transmissivity thus determined were 12.2, 13.2, 10.1, and 12.6 million gallons per day per foot, respectively. A good fit was found for each of the field-data plots among its respective family of type curves except for 1962 (Figures 10 and 14). Only one of the field-data points for this year appeared to be unrelated, but a fit was found with the remaining three.

Inspection of the values of $1.87r^2S/T$ for each analysis indicates that the center of the well field apparently changes from analysis to analysis. This is perhaps to be expected, in view of the fact that many pumping stations, each with several wells among the many in the well field, pump at various times and rates to meet the changing demands for water throughout the area. The City of San Antonio develops new stations from time to time, and others are taken out of production. For example, in the early fifties, two pumping stations, Brackenridge station (1 mile west of well 26) and Market Street station (4 1/2 miles southwest of well 26), pumped over 50 percent of the needs of the City of San Antonio. In the sixties, Basin station (3 miles northwest of

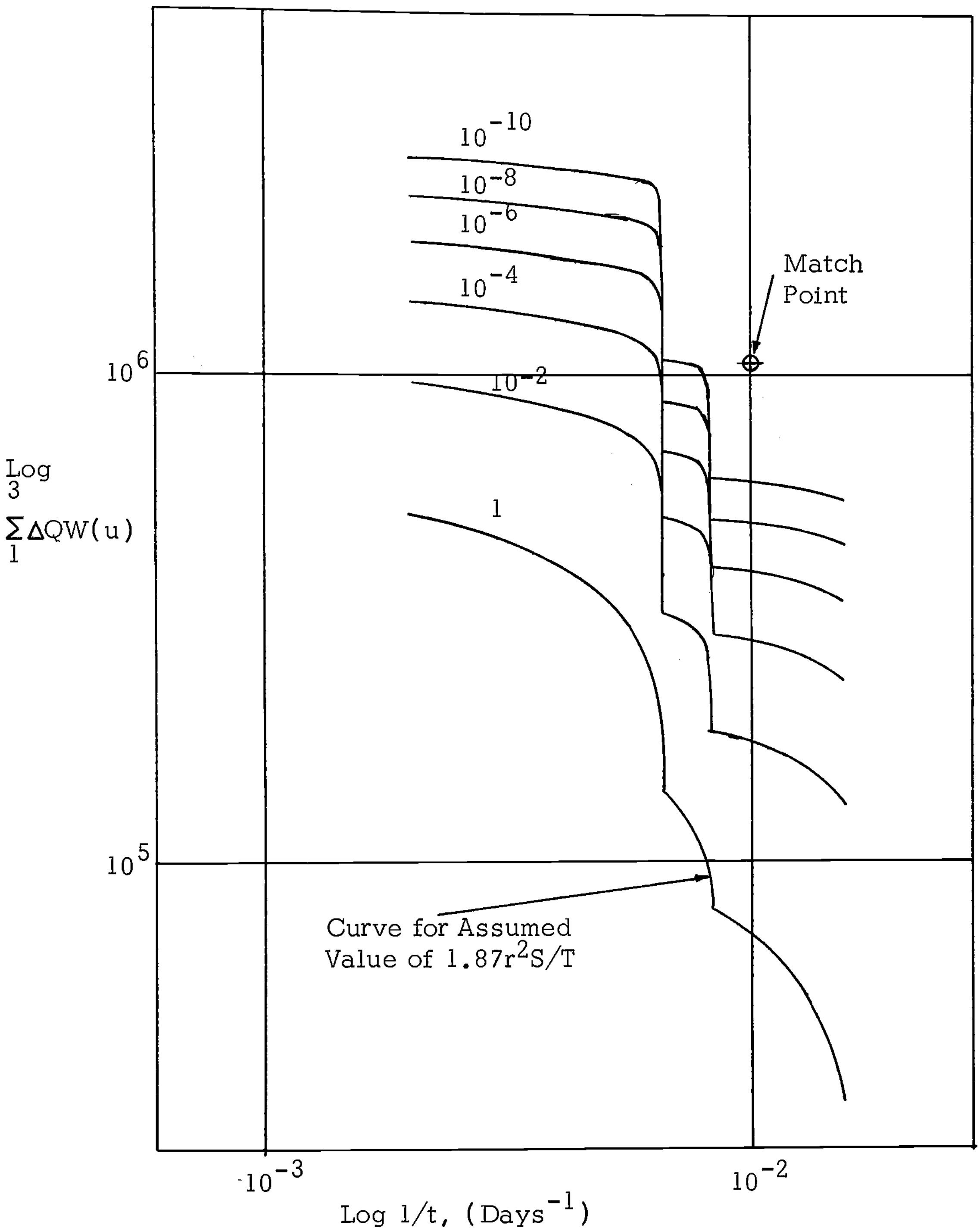

Figure 8. Family of Type Curves for Analysis of Edwards Aquifer in the San Antonio Area, Texas, 1953.

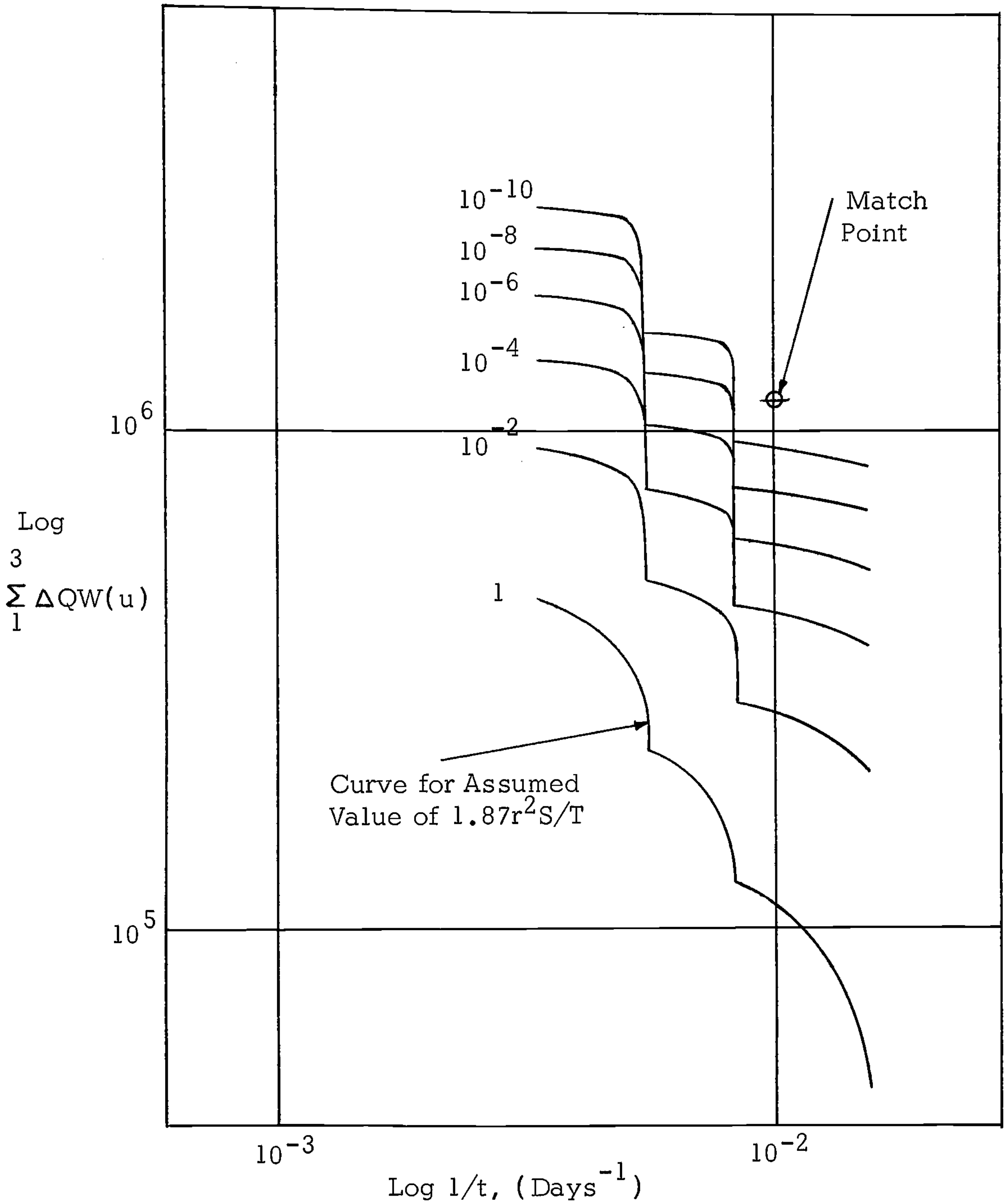

Figure 9. Family of Type Curves for Analysis of Edwards Aquifer in the San Antonio Area, Texas, 1954.

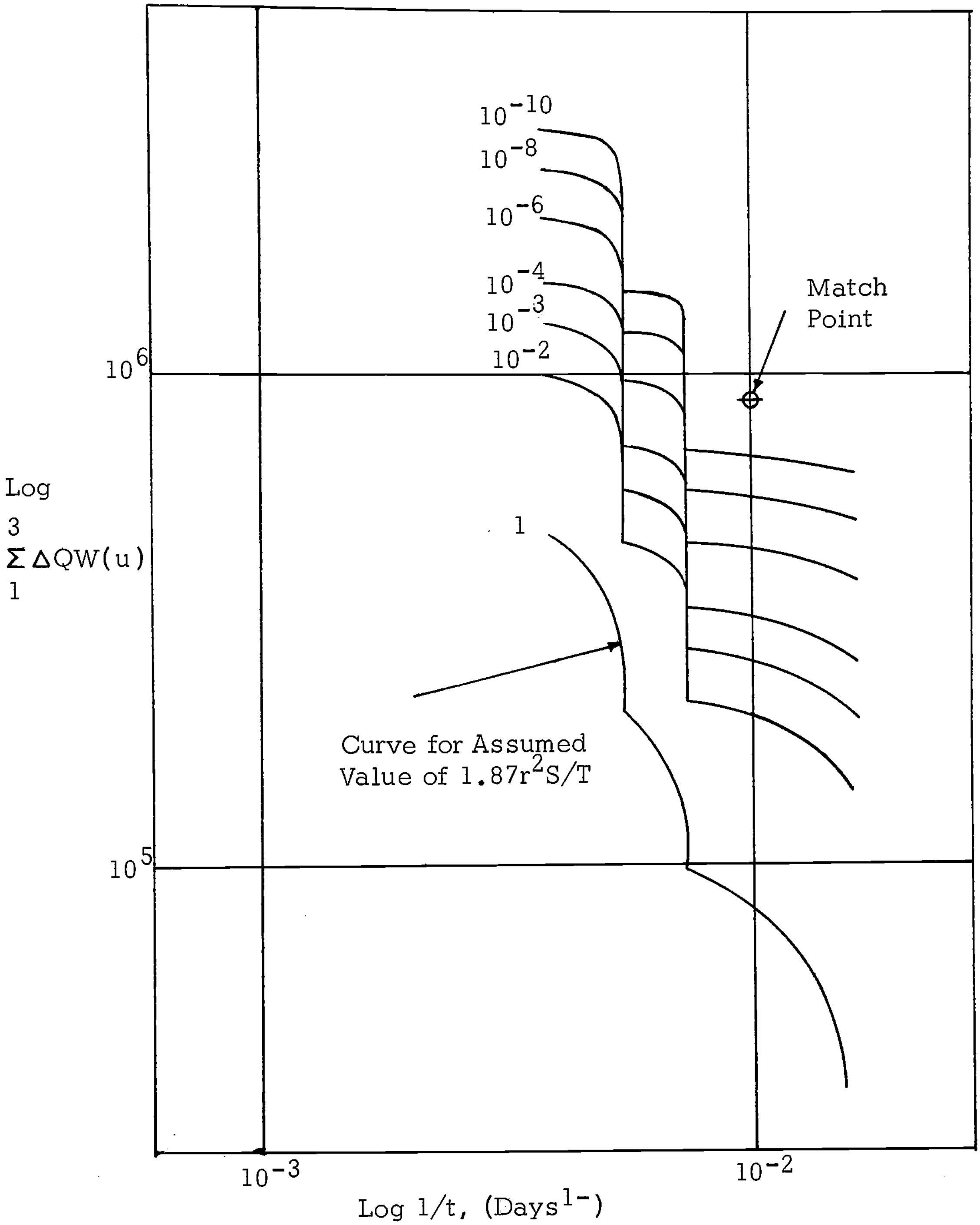

Figure 10. Family of Type Curves for Analysis of Edwards Aquifer in the San Antonio Area, Texas, 1962.

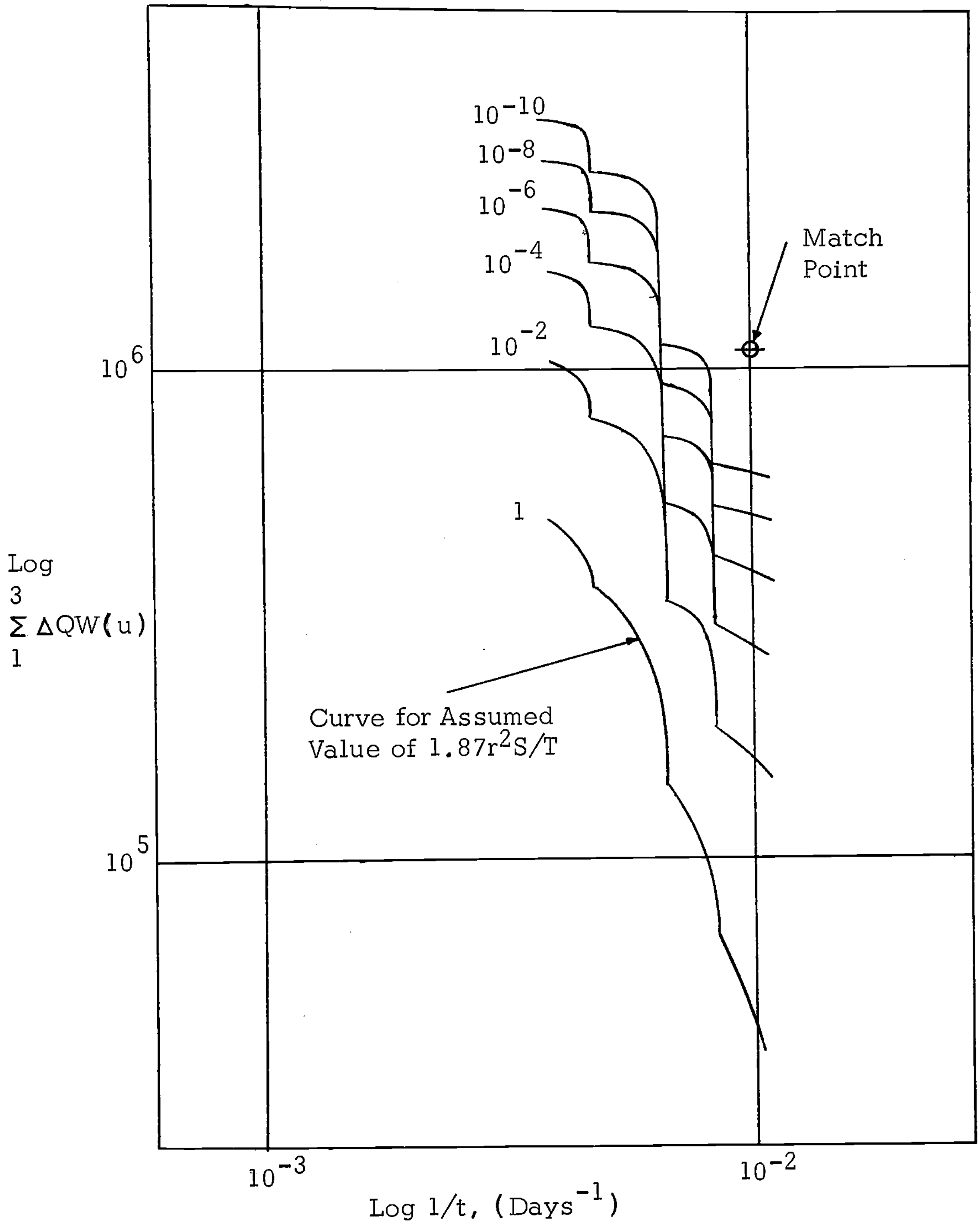

Figure 11. Family of Type Curves for Analysis of Edwards Aquifer in the San Antonio Area, Texas, 1963.

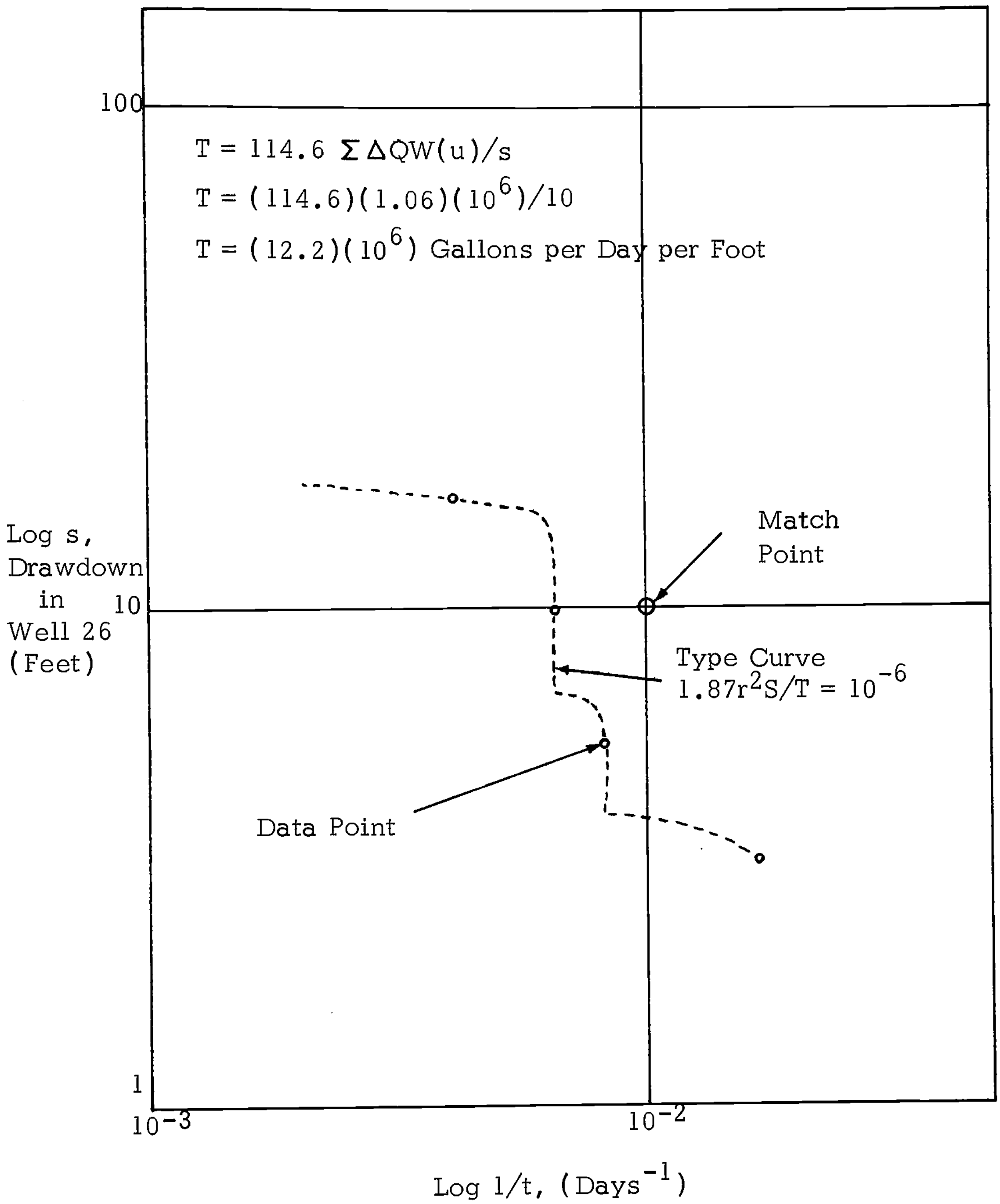

Figure 12. Well-Field Data for Drawdown-Time Relation for Analysis of Edwards Aquifer, San Antonio Area, Texas, 1953.

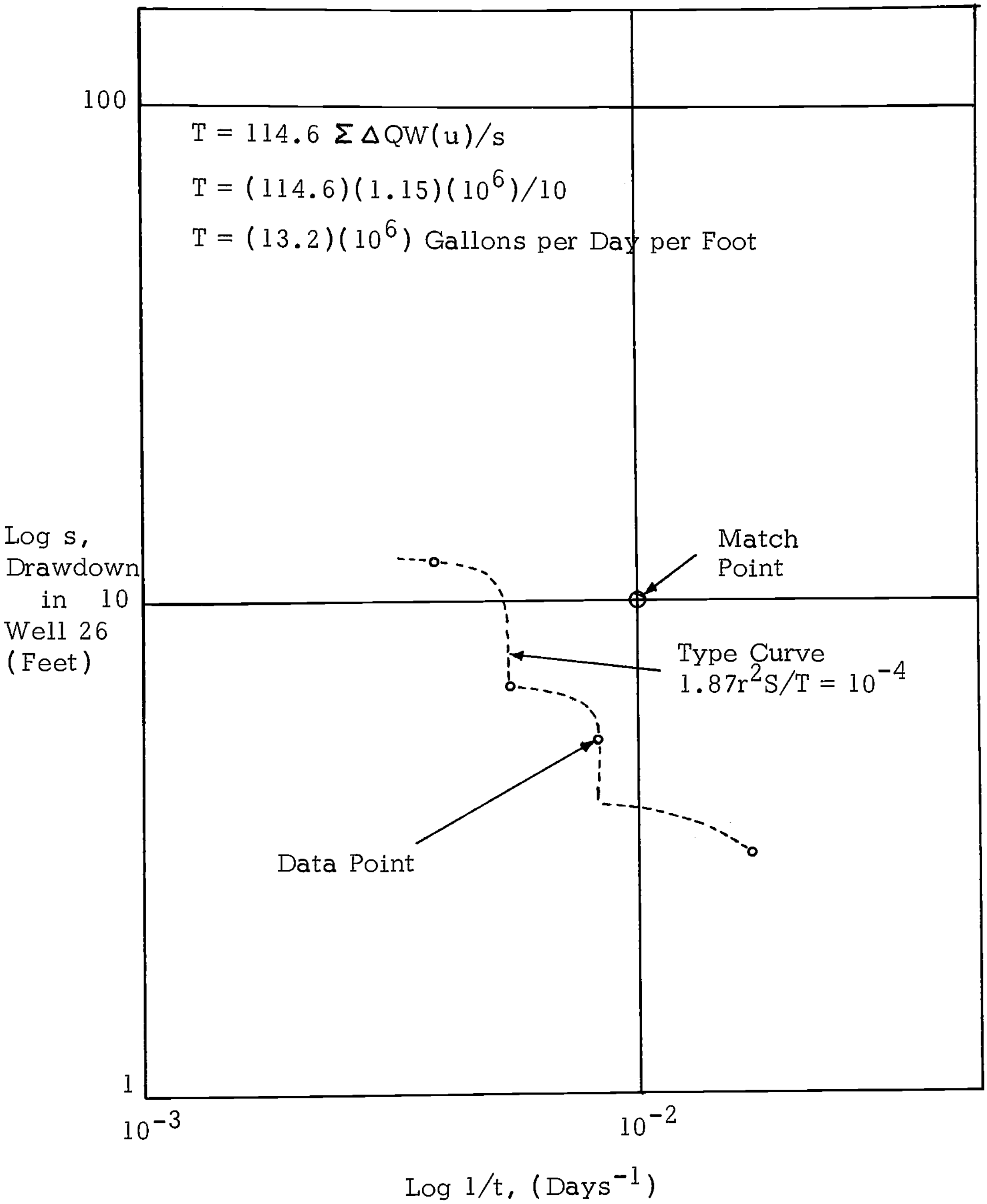

Figure 13. Well-Field Data for Drawdown-Time Relation for Analysis of Edwards Aquifer, San Antonio Area, Texas, 1954.

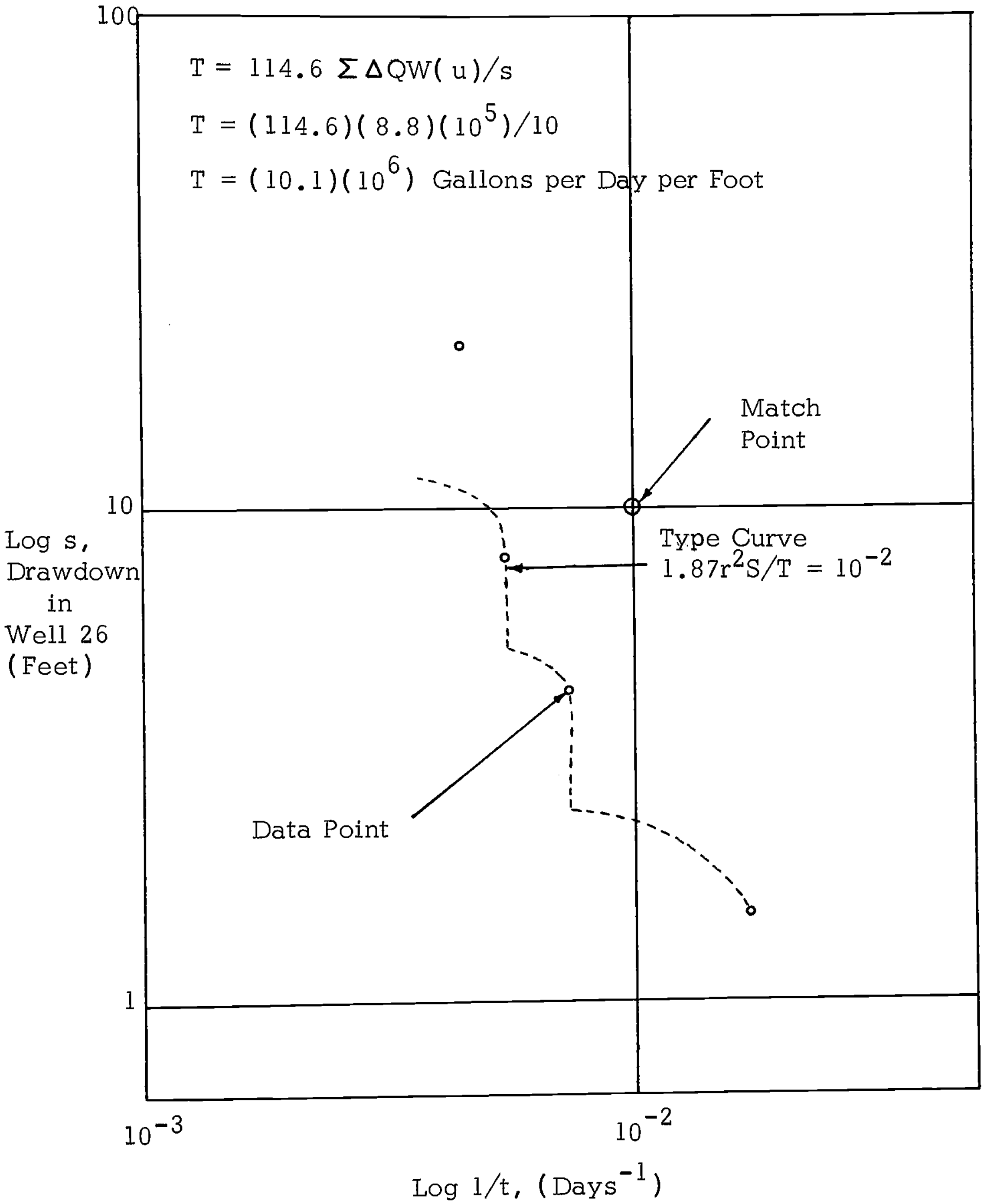

Figure 14. Well-Field Data for Drawdown-Time Relation for Analysis of Edwards Aquifer, San Antonio Area, Texas, 1962.

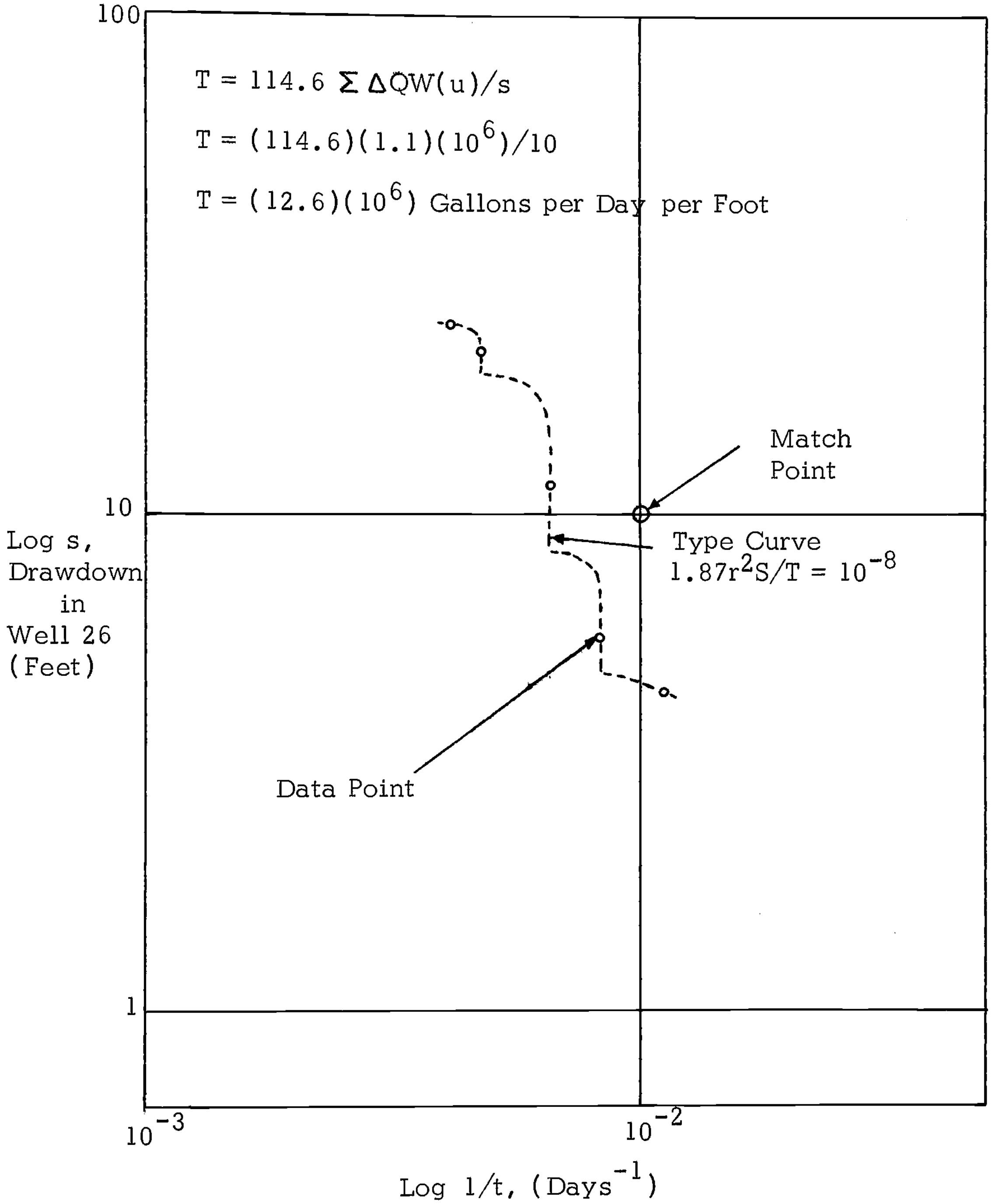

Figure 15. Well-Field Data for Drawdown-Time Relation for Analysis of Edwards Aquifer, San Antonio Area, Texas, 1963.

well 26), Artesian station (2 miles southeast of well 26), and Market Street station supplied over 60 percent of the city's needs.

Sufficient water-level control is not available to determine accurately the distance $\underline{r}$ from well 26 to the theoretical center of the assumed line sink in the pumping well field. Indeed, a point sink as such may not exist. Piezometric maps of summertime levels indicate an apparently flat piezometric surface within the above major pumping stations (Petitt and George, 1956; Garza, 1962).

Although calculation of the location of the theoretical line sink is not needed for determination of transmissivity, $\underline{T}$, it is of interest to do so. By assuming a value for the coefficient of apparent storage, $\underline{S}$, the distance $\underline{r}$ may be calculated. It should be noted that because $\underline{r}$ is not known to begin with, it is not possible to compute $\underline{S}$. The co-efficient of storage, which is a function of the elasticity of the artesian aquifer and the compressibility of water, may be approximated by the following relation expressed by Jacob (1950):

$$S = a\,b\,c\,(d + e/b)$$

where $\underline{a}$ = specific weight of water (62.4 pounds per cubic foot).

$\underline{b}$ = porosity of the aquifer.

$\underline{c}$ = thickness of the aquifer (feet).

$\underline{d}$ = compressibility of water, which is $(3.3)(10^{-6})$ square inches per pound.

$\underline{e}$ = compressibility of the aquifer skeleton.

Assuming _b_ to be 0.05, _c_ to be 500 feet, and _e_ to be 10^{-7} square inches per pound, a value of _S_ of 0.6×10^{-4} was derived. The value of _e_ for a limestone formation was taken from Clark (1966, p. 165). Also, if the average value for the apparent _T_ at the well field is 12 million gallons per day per foot, the distance _r_ for the 1953 analysis would be about 300 feet, that for the 1954 analysis about 3000 feet, that for the 1962 analysis about 30,000 feet, and that for the 1963 analysis about 30 feet. The 1962 analysis gives an apparently unreasonable value for the theoretical _r_; this analysis was the only one that resulted in a relatively poor fit in the preceding analyses for the values of apparent _T_. The other three appear to give reasonable theoretical values for _r_, in view of the variation in the space distribution of changes in the well field.

CHAPTER 4

ANALYSIS AND USE OF RESULTS

Comparison and Verification of Computed Results

The average coefficient for the apparent transmissivity of the San Antonio well field was about 12 million gallons per day per foot, a large value. However, this coefficient is directly dependent on the thickness of the formation, and the value which should be used for comparative purposes is the coefficient of permeability, which is transmissivity per unit thickness of formation. Because the average thickness of the Edwards aquifer is about 500 feet, the average coefficient of apparent permeability is about 24,000 gallons per day per square foot. This value is comparable to results from tests of some of the more permeable formations in the United States. More than a dozen field tests made by the U. S. Geological Survey in different parts of the Biscayne aquifer in southeastern Florida resulted in average permeability values ranging from 50,000 to 70,000 gallons per day per square foot (Parker, 1951). Another way of comparing these aquifers is to examine the yield of large-capacity municipal wells in each of the areas. The Miami Springs-Hialeah well field has wells that produce as much as 6 million gallons per day each (Parker, 1951). Each of many wells of the San Antonio City Water Board can pump from 3 to 12 million gallons per day (personal communication with City Water Board officials, July, 1967).

Application of the computed coefficients of apparent transmissivity to check their usefulness in the Edwards aquifer should involve well-field production records during those periods when recharge is believed to be negligible. Only a few years may approach this criterion and therefore any substantiation of aquifer characteristics with well-field data is limited and only approximate. Nevertheless, an attempt was made to compare computed drawdowns based on pumpage records and the computed aquifer characteristics with the actual drawdowns in well 26. The actual drawdown data was determined with the aid of figure 5. Using an average coefficient of apparent transmissivity of 12 million gallons per day per foot, and assuming a coefficient of apparent storage of 0.6×10^{-4}, the following table was prepared to compare computed and actual drawdowns in well 26 for the selected periods when recharge was relatively small (Values of _r_ used are 100, 1500, and 3000 feet.):

Year	Computed Drawdown (Feet) r = 100	r = 1500	r = 3000	Actual Drawdown (Feet)
1948	19.9	14.7	13.4	19.0
1950	21.9	16.3	14.8	13.0
1951	23.2	17.3	15.7	19.0
1952	23.1	17.2	15.6	20.0
1955	26.8	19.9	18.0	14.0
1956	29.0	21.5	19.5	19.0

Errors in the computed drawdowns may reflect errors in picking the distance $\underline{r}$, the effects of recharge during each of these periods, or errors in the values derived for the apparent aquifer characteristics. If the above table reflects only the errors in picking the distance $\underline{r}$, it appears that the distance between well 26 and the theoretical line sink was between 100 and 1500 feet during 1948, 1951, and 1952. Also, this distance $\underline{r}$ would appear to be slightly larger than 3000 feet in 1950 and 1956 and somewhat larger than 3000 feet in 1955. In spite of the assumed field conditions and the nonideal field data, it appears that the average values for apparent $\underline{T}$ and $\underline{S}$ are approximately in the right order of magnitude.

Application of Computed Results

William F. Guyton and Associates, consulting ground-water hydrologists for the City of San Antonio, made estimates of future aquifer heads, as represented in well 26, with the use of projected demands to the year 2000 (Guyton and Associates, 1963). The basis for this determination is the water-budget equation, which relates annual changes in aquifer storage to the annual differences between recharge and discharge. The annual storage changes are reflected by the change in the year-end water level in well 26, and the storage curve employed was based on the data for the period 1934-61. Projections of recharge to the year 2000 were made by assuming that the climatic conditions of the period 1934-61, as well as the recharge determinations for this period, were continually recurring. Under these conditions, the year-end water levels in well 26 were predicted to the year 2000 (Guyton and Associates, p. 10, 1963).

The above predictions are limited to year-end aquifer heads, and another technique is needed to predict maximum possible summertime drawdowns. The development of useful aquifer characteristics at the San Antonio well field makes it possible to use the Theis method to estimate these summertime drawdowns in the vicinity of well 26. The determination of these drawdowns under different climatic conditions (non-negligible recharge) is beyond the scope of this presentation, but the maximum drawdowns possible under projected pumping demands may be approximated with the use of the results derived previously.

Figure 16 shows the relation between time, drawdown, and average discharge in the area of the San Antonio well field. It has been assumed that the indicated values for the distance $\underline{r}$ and the coefficients of transmissivity and storage are valid. This relation can be used to estimate drawdowns under predetermined average discharges for any of the periods indicated. These drawdowns would be considered as maximum possible drawdowns in the Edwards aquifer, that is, when recharge is small enough to be neglected.

Table 2 shows the projected maximum possible drawdowns in the San Antonio well field for the period 1970-2000 in five year intervals. The projected average annual pumpage for the aquifer area and the projected depth to water in well 26 at the first of the year are those appraised by Guyton and Associates (1963). Pumpage from the San Antonio well-field area was assumed to be 80 percent of the total pumpage from the aquifer area. The computed drawdowns were estimated through use of figure 16 by applying an average pumping rate for the San Antonio well field for a period of 180 days. The computed drawdowns were added to Guyton's projected water levels to estimate the maximum summertime water levels. The computed maximum water level in well

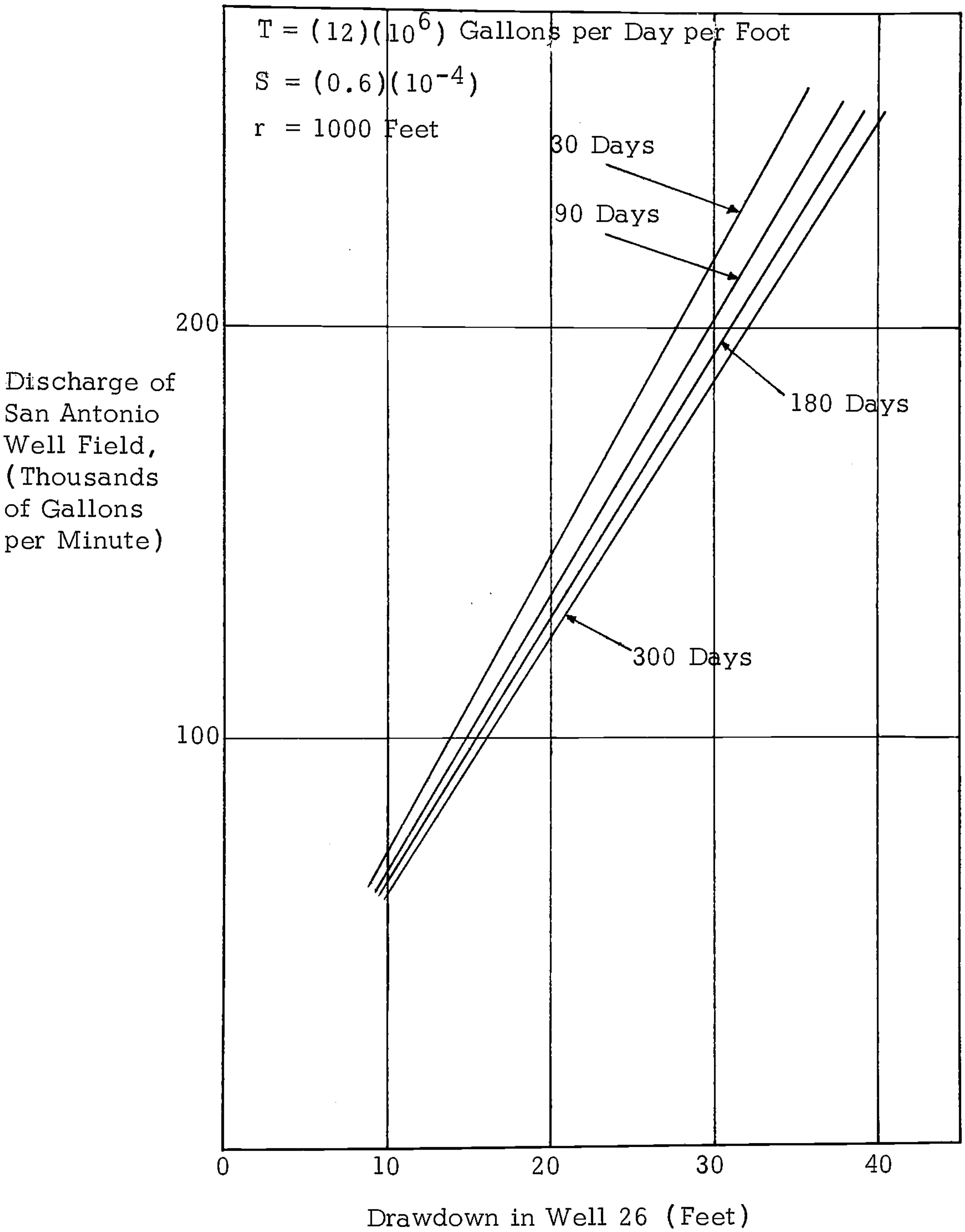

Figure 16. Relation Between Time, Drawdown, and Average Discharge in the San Antonio Well-Field of the Edwards Aquifer.

Table 2. Projected Maximum Possible Drawdowns in the San Antonio Well Field of the Edwards Aquifer, 1970-2000

	Projected Average Annual Pumpage (Thousands of Gallons per Minute)		Computed	Depth to Water in Well 26 (Feet below Land Surface)	
Year	Aquifer Area	San Antonio Well Field	Drawdown (Feet)	First of Year	Summer
1970	190	152	23	97	120
1975	215	172	26	69	95
1980	238	190	29	67	96
1985	267	214	33	87	120
1990	296	237	36	95	131
1995	296	237	37	128	165
2000	296	237	37	174	211

26 in the year 2000 was estimated to be about 100 feet lower than the record low established in 1956 for the period 1934-67.

CHAPTER 5

CONCLUSIONS

The treatment given here to the Edwards limestone aquifer through the use of the Theis nonequilibrium formula in the derivation of apparent aquifer characteristics is not exactly without foundation. However, strict conformance to the idealized conditions imposed by this formula is impossible in a limestone aquifer. This may be true for almost every aquifer, but the degree of inapplicability is most glaring in limestone formations. The underlying base for applying this technique to the Edwards aquifer has been the availability of production records and aquifer heads from a large well field which influences a large artesian part (about 15 miles in diameter) of the aquifer. On a macroscopic basis, the technique becomes more applicable, but the results still should be viewed only as average theoretical approximations. Testing of these results with independent data gave some credence to the usefulness of the derived material in the approximate predictions of aquifer performance. However, these predictions must be within the boundaries and limitations set forth for the well-field area.

APPENDIX

The Theis (1935) nonequilibrium formula is as follows:

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

where

$u = 1.87r^2S/Tt$

s = drawdown, in feet, at any point of observation in the vicinity of a well or well field discharging at constant rate.

Q = discharge of well or well field, in gallons per minute.

T = coefficient of transmissivity, in gallons per day per foot.

S = coefficient of storage (decimal fraction)

t = time in days since pumping started.

r = distance, in feet, from the discharging well (or center of well field) to the point of observation.

The integral above is expressed as W(u), and is called the well function of <u>u</u>.

LIST OF REFERENCES

Arnow, Tec. 1959. Ground-water geology of Bexar County, Texas. Texas Board Water Engineers Bull. 5911.

Bennett, R. R. and Sayre, A. N. 1962. Geology and ground-water resources of Kinney County, Texas. Texas Water Commission Bull. 6216.

Clark, Sydney P., Jr., Editor. 1966. Handbook of physical constants. Geological Society of America, Inc. New York, N.Y.

DeCook, K. J. 1960. Geology and ground-water resources of Hays County, Texas. Texas Board Water Engineers Bull. 6004.

Ferris, J. G. and others, 1962. Theory of aquifer tests. U. S. Geol. Survey Water Supply Paper 1536-E.

Garza, Sergio. 1962. Recharge, discharge, and changes in ground-water storage in the Edwards and associated limestones, San Antonio area, Texas, a progress report on studies, 1955-59. Texas Board Water Engineers Bull. 6201.

_________. 1966. Ground-water resources of the San Antonio area, Texas, a progress report on studies, 1960-64. Texas Water Development Board Report 34.

George, W. O. 1952. Geology and ground-water resources of Comal County, Texas with sections on surface-water runoff, by S. D. Breeding, and chemical character of the water, by W. W. Hastings: U. S. Geol. Survey Water Supply Paper 1138.

Guyton, William F. 1963. Estimates of future water levels in the Edwards limestone reservoir. Consulting Eng. Rept. to San Antonio City Water Board.

Holt, C. L. R., Jr. 1950. Geology and ground-water resources of Medina County, Texas. U. S. Geol. Survey Water Supply Paper 1422.

Jacob, C. E. 1950. Flow of ground water. Chapter 5 in Rouse, Hunter. Engineering hydraulics. John Wiley and Sons, New York, N.Y.

Livingston, Penn, Sayre, A. N. and White, W. N. 1936. Water resources of the Edwards limestone in the San Antonio area, Texas. U. S. Geol. Survey Water Supply Paper 773-B.

Lowry, R. L. 1955. Recharge to the Edwards ground-water reservoir. Consulting Eng. Rept. to San Antonio City Water Board.

Meinzer, O. E. 1927. Large springs in the United States. U. S. Geol. Survey Water Supply Paper 557.

Parker, G. G. 1951. Geologic and hydrologic factors in the perennial yield of the Biscayne aquifer. Journal of the American Water Works Association, Vol. 43: 817-835.

Petitt, B. M., Jr. and George, W. O. 1956. Ground-water resources of the San Antonio area, Texas. Texas Board Water Engineers Bull. 5608.

Sayre, A. N. 1936. Geology and ground-water resources of Uvalde and Medina Counties, Texas. U. S. Geol. Survey Water Supply Paper 678.

Sayre, A. N. and Bennett, R. R. 1942. Recharge, movement, and discharge in the Edwards limestone reservoir, Texas. Am. Geophys. Union Trans., August, pt. 1: 19-27.

Welder, Frank, and Reeves, R. D. 1964. Geology and ground-water resources of Uvalde County, Texas. U. S. Geol. Survey Water Supply Paper 1584.