RELATION OF PRECIPITATION TO ANNUAL GROUND-WATER RECHARGE IN THE EDWARDS AQUIFER, SAN ANTONIO AREA, TEXAS

UNITED STATES DEPARTMENT OF THE INTERIOR

Geological Survey

Prepared by the U.S. Geological Survey in cooperation with the city of San Antonio and the Texas Water Development Board

OPEN-FILE REPORT 75-298

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RELATION OF PRECIPITATION TO ANNUAL GROUND-WATER RECHARGE IN THE EDWARDS AQUIFER, SAN ANTONIO AREA, TEXAS

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ABSTRACT

Annual recharge data obtained from historical records and mean-annual precipitation data computed from rainfall records were used to develop simple linear-regression equations for use in estimating annual recharge for seven subbasins in the San Antonio area. Adjustments were made to the precipitation parameter to account for the effects of year-end storms. The standard errors of estimate of the regression equations ranged from 26 percent for the Blanco River basin to 45 percent for the area between the Sabinal and Medina River basins.

Annual-recharge estimates computed by use of the regression equations compared favorably with estimates made on the basis of observed streamflow and precipitation data.

The report includes a brief review of the geology and hydrology of the Edwards aquifer, a discussion of the preparation and evaluation of the precipitation data used in the regression analyses, and a brief summary of the method previously used to estimate recharge.

INTRODUCTION

Estimates of annual recharge to the Edwards aquifer in the San Antonio area have been made by several investigators who used data collected from a network of streamflow stations (Petitt and George, 1956; Garza, 1962, 1966; Rettman, 1966-70; Puente, 1971). The collection of data is part of the program of hydrologic investigations by the U.S. Geological Survey in cooperation with the Edwards Underground Water District, the Texas Water Development Board, and the city of San Antonio.

The principal objective of this report is to examine the relationship between annual precipitation and annual recharge to the Edwards aquifer by development of simple linear-regression equations. The regression equations may then be used as an alternate method for rapidly computing recharge to the Edwards aquifer by using only the weighted mean-annual precipitation as adjusted to account for year-end storm effects.

The study area covers approximately 6,730 square miles (17,431 km^2) and includes all or parts of Kinney, Uvalde, Medina, Bexar, Comal, and Hays Counties in south-central Texas (fig. 1). Most of the area is within the Nueces and Guadalupe River basins, but includes the following subbasins: (1) West Nueces; (2) Frio-Dry Frio; (3) Sabinal; (4) the area between the Sabinal and Medina Rivers; (5) the area between the Medina River and the Cibolo Creek; (6) the Cibolo Creek and the Dry Comal Creek areas; and (7) the Blanco River basin and adjacent areas.

In the Medina River subbasin, the Edwards aquifer is recharged to some extent by infiltration from Medina Lake. However, data from this subbasin and from the Guadalupe River subbasin were not included in the regression analyses because the amount of net recharge to the aquifer from these sources is very small.

For those readers interested in using the metric system, the metric equivalents of English units of measurements are given in parentheses. The English units used in this report may be converted to metric units by the following factors:

From		Multiply by	To obtain	
Unit	Abbreviation		Unit	Abbreviation
acre-feet	--	1233	cubic metres	m^3
inches	--	25.4	millimetres	mm
miles	--	1.609	kilometres	km
square miles	--	2.590	square kilometres	km^2

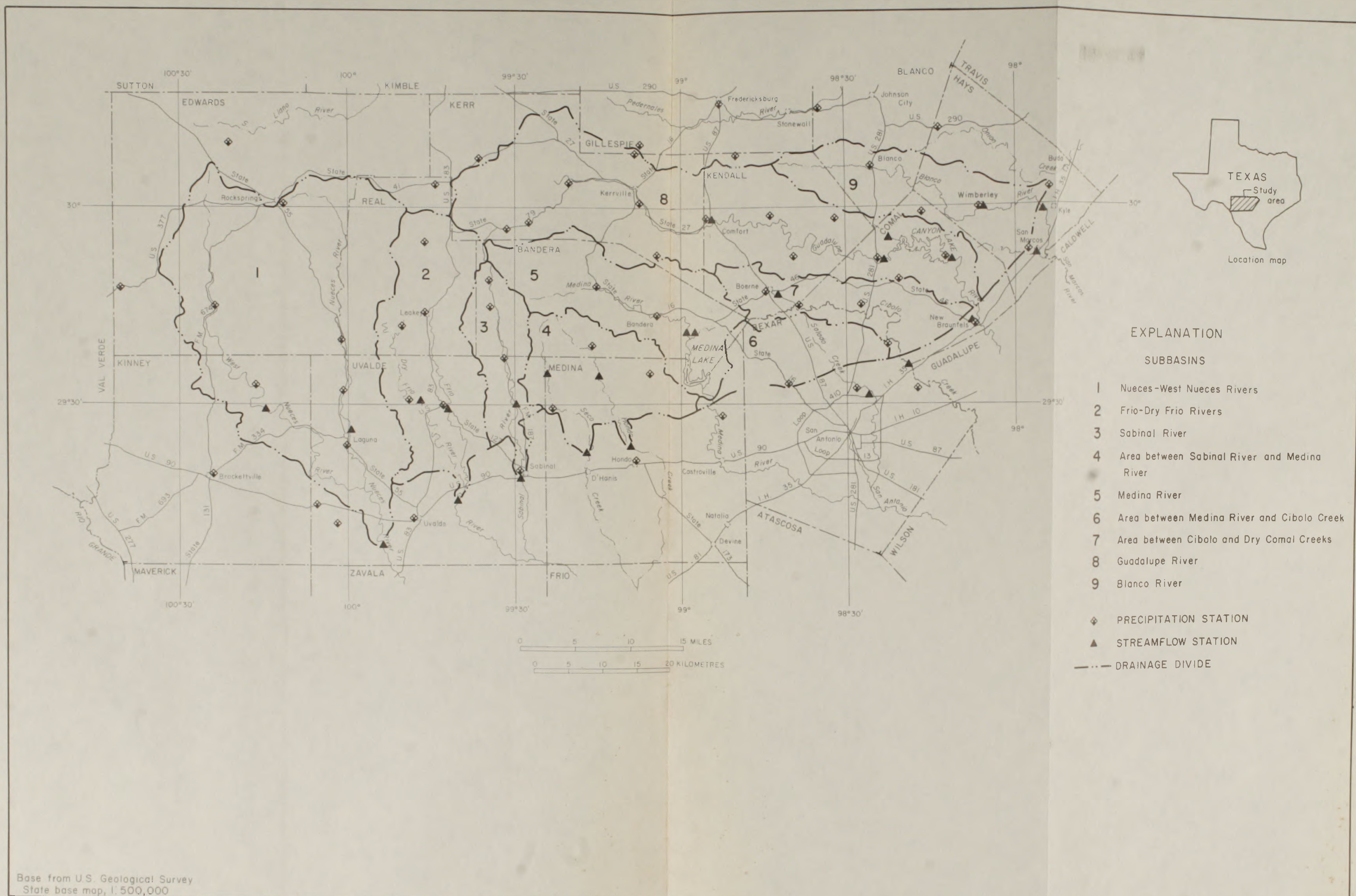


FIGURE 1.-Drainage basins and data-collection sites in the San Antonio area

GEOLOGY AND HYDROLOGY

The regional geology and hydrology of the Edwards aquifer in the San Antonio area have been studied by Petitt and George (1956) and Garza (1962, 1966). The drainage areas affecting the Edwards aquifer are within two physiographic regions, the Edwards Plateau and the Gulf Coastal Plain, which are separated by an intensely faulted area known as the Balcones Fault Zone (Maclay, 1973, p. 2). The flat uplands of the Edwards Plateau are deeply dissected along the plateau margin, and narrow canyons are cut into the Glen Rose Limestone along the southern margin of the plateau.

The areal extent of the part of the outcrop area of the Edwards aquifer under study is delineated on figure 2. The boundaries consist of the outcrop or infiltration area at its northern limits, ground-water divides in Kinney County to the west and in Hays County to the east, and the zone of inferior water (locally known as the "bad-water line") as its southern limits in the artesian area. The aquifer is about 180 miles (290 km) long and ranges in width from about 5 to 40 miles (8 to 64 km).

The Edwards aquifer is composed of the Georgetown, Edwards, and Comanche Peak Limestones, which are considered as a single hydrologic unit of Early Cretaceous age (Petitt and George, 1956). In general, the geologic units are composed of fine grained to dense limestone having well developed secondary porosity along bedding planes and fractures and are locally called Edwards and associated limestones. The Del Rio Clay overlies the aquifer and forms the upper confining bed. The Glen Rose Limestone, a unit of shaly limestone and shale, forms the lower confining bed.

The Balcones Fault Zone is the dominant structural feature in the area (fig. 2). Fault displacements vary greatly; the major faults are not single breaks but a series of closely spaced step faults. In general, the intensity of faulting increases from Uvalde County to Bexar County, which is a factor in accounting for the increased permeability of the aquifer in the San Antonio area.

Most of the catchment area that contributes recharge to the Edwards aquifer is on the Edwards Plateau. The base flow of the streams that drain the plateau is sustained by springflow from a water-table aquifer (plateau aquifer). This base flow and a part of the flood flow are lost by infiltration where the streams cross the outcrop of the Edwards aquifer at the Balcones Fault Zone. Recharge to the aquifer is derived mainly from infiltration of streamflow, but some recharge is derived from direct infiltration of precipitation on the outcrop.

FIGURE 2.-Geologic and hydrologic features in the San Antonio area

EVALUATION OF BASIC DATA

Precipitation

Annual precipitation data were compiled from records of the U.S. Geological Survey, the National Oceanic and Atmospheric Administration, and the International Boundary and Water Commission. Approximately 60 stations were used to define precipitation patterns in the study area (fig. 1). Precipitation maps were prepared for each year from 1954 to 1970. Weighted mean-annual precipitation for one of the subbasins was computed by using both the isohyetal and Thiessen methods. Because the difference between the two methods was found to be small, the Thiessen method was adopted for use in all subbasins because of the ease of calculation once the rain-gage network was established.

The precipitation data were evaluated for inconsistencies by use of double-mass curves. The theory of the double-mass curve is based on the fact that a plot of the cumulation of one quantity against the cumulation of another quantity during the same period will be a straight line if the data are proportional; the slope of the line will represent the constant of proportionality between the quantities. A break in the slope of the double-mass curve indicates a change in the constant of proportionality. This test of consistency was applied mainly to detect any large breaks in slope that probably are caused by changes in gage location and exposure or to observational discrepancies. The double-mass curves that were analyzed indicated a fair degree of consistency.

Recharge

The basic methods of estimating recharge to the Edwards aquifer were developed by Lowry (1955) and Petitt and George (1956) and refined by Garza (1962, 1966). The estimates of recharge are based on balancing the water budget, wherein recharge in each subbasin is the difference between total inflow above and total outflow below the infiltration area plus direct infiltration from precipitation. Inflow is measured by stream-gaging stations along the upper edge of the infiltration area, and outflow is measured by stations along the lower edge. Direct infiltration is estimated on the basis of unit runoff from the catchment area. An assumption is made that the stream losses due to evapotranspiration are proportionately the same for both the infiltration area and the catchment area.

In the Nueces-West Nueces, Frio-Dry Frio, Sabinal, and Blanco basins, streamflow stations are located above and below the infiltration area. Streamflow stations have been established in parts of the area between the Sabinal and Medina basins, in the area between the Medina and Cibolo basins, and in the Cibolo and Dry Comal subbasin. (See fig. 1.) Medina Lake and a downstream reservoir, which are located within the infiltration area, lose considerable quantities of water by infiltration to the aquifer. Water-balance analyses for these reservoirs have resulted in correlation curves relating reservoir stage to recharge (Lowry, 1955). These curves are used to estimate the recharge contributed from the reservoirs. Streamflow records for the Guadalupe River in the infiltration area indicate that gains and losses are insignificant; therefore, recharge from the Guadalupe River is considered negligible.

Errors in the historical estimates of annual recharge could be due to inaccuracies in streamflow measurements in gaged areas and to discrepancies in runoff estimates in ungaged areas. The errors in streamflow measurement are minor because most of the records in the San Antonio area are regarded by the U.S. Geological Survey as "excellent", which means that about 95 percent of the daily discharges are accurate within 5 percent. Some estimates of runoff in ungaged areas may have large errors for individual storms. The long-term average estimate of recharge, however, is probably representative of the true average because the averaging procedure of many estimates tends to cancel out the major errors.

REGRESSION ANALYSES

Adjustment of Precipitation Data

The initial study of the relation between the weighted mean-annual precipitation and annual recharge was made graphically. The plots showed a considerable variation of points from the line of regression, especially for those years affected by storms late in the year. The late fall storms affect the recharge for the following year, and a calendar-year correlation does not account for these antecedent conditions. Part of the precipitation in the catchment area is temporarily stored in the plateau aquifer and is discharged at a later time as the base flow of the streams. Because some of the precipitation at the end of a year contributes to the base flow in the following years, the weighted annual precipitation data were adjusted to account for antecedent effects.

To develop a relation that can be used to adjust the precipitation data without the benefit of streamflow records, the relationship between streamflow and precipitation was defined as follows:

1. Streamflow hydrographs constructed from records of gaging stations at the upstream edge of the infiltration area were used to trace the year-end storms and the ensuing recession into the following years.

2. Figure 3 is a hypothetical hydrograph that illustrates the graphical separation of the various streamflow components and their relation to the year-end storms. The flood-flow or surface-flow component C is separated from the base flow, which is further separated into current-year component A and following-year component B. B is the base flow that would be discharged during the last part of the streamflow recession were it to continue uninterruptedly into the following year. The total storm runoff, SR, is the sum of A, B, and C.

3. The total Thiessen-weighted storm precipitation, SP, includes the major and minor daily-precipitation values (R_i) during the year-end storm period:

$$SP = \sum_{i=1}^{n} R_i = R_1 + R_2 + R_3 + \ldots\ldots R_n \qquad (1)$$

The proportional part of SP that accounts for B is termed PA, which may be readily determined through the equivalence of the streamflow ratio B/SR and the precipitation ratio PA/SP:

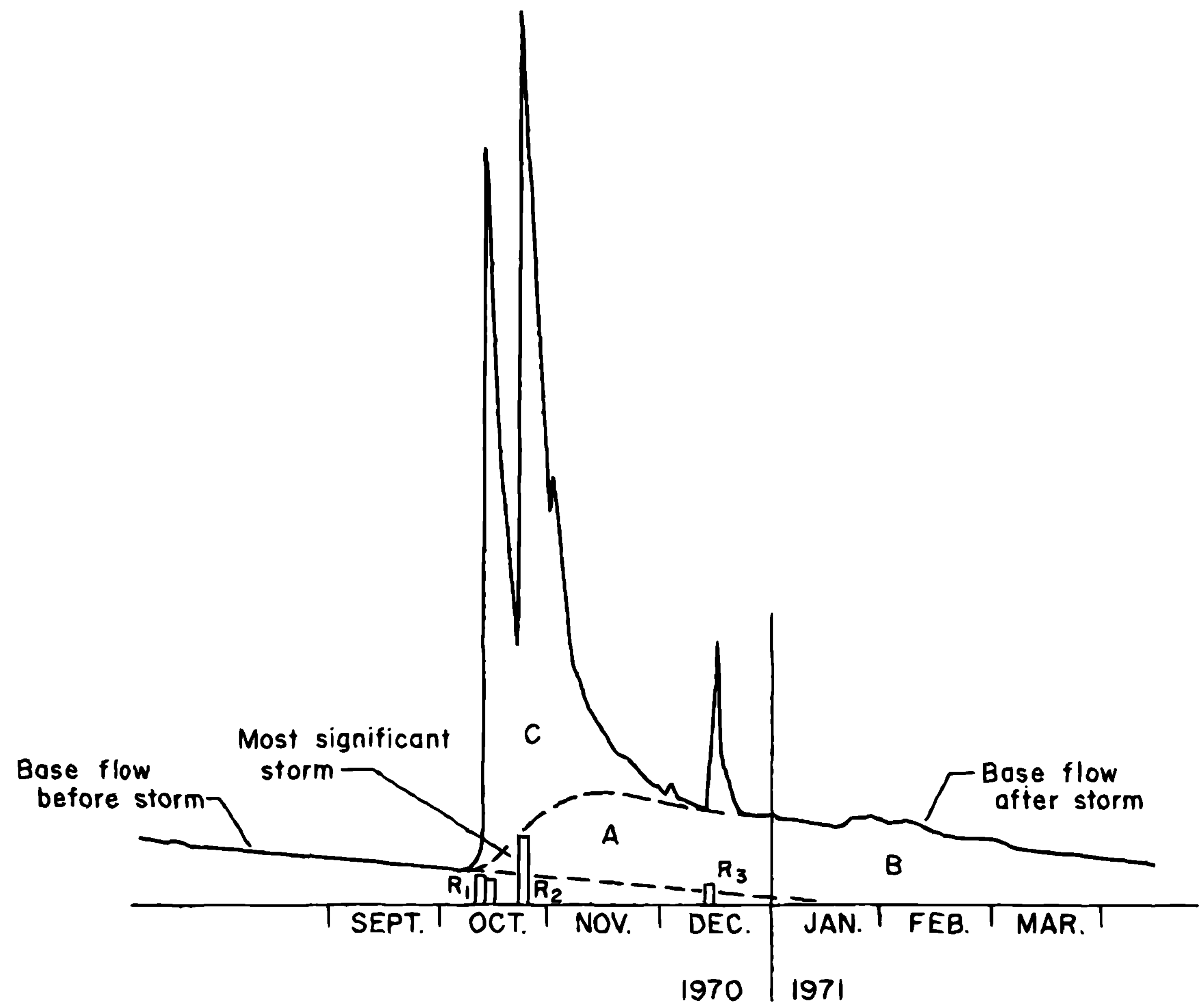
$$B/SR = PA/SP \qquad (2)$$

$$PA = (B/SR)(SP) \qquad (3)$$

The precipitation adjustment for year-end storms with antecedent-precipitation effects is made by adding PA to the following-year precipitation and subtracting PA from the current-year precipitation.

The historical values of PA and SP were used to develop a relation to determine PA without the use of streamflow data. Precipitation from a year-end storm and the date of its occurrence is related to the ratio PA/SP. The greater the amount of storm precipitation and the closer the incidence of the storm to the end of the year, the larger the value of PA/SP.

Historical values of this ratio (PA/SP), termed as Y and arbitrarily called the rainfall-adjustment factor, were plotted against the date (X number of days to end of year) of the most significant year-end storm. A regression analysis was applied to the plot to determine the relation between Y (dependent variable) and X (independent variable). The historical values of the data used in the analysis are from all seven subbasins and therefore represent the regional precipitation and average hydrograph-recession characteristics. Figure 4 shows the linear relationship between X and Y and the resultant regression equation: $Y = 0.93 - 0.0066X$. The standard error of estimate for this equation is 0.11, and the correlation coefficient is 0.86.



Note: See page 16 for explanation of symbols

FIGURE 3.-Graphical separation of a hypothetical hydrograph for distributing year-end storm precipitation

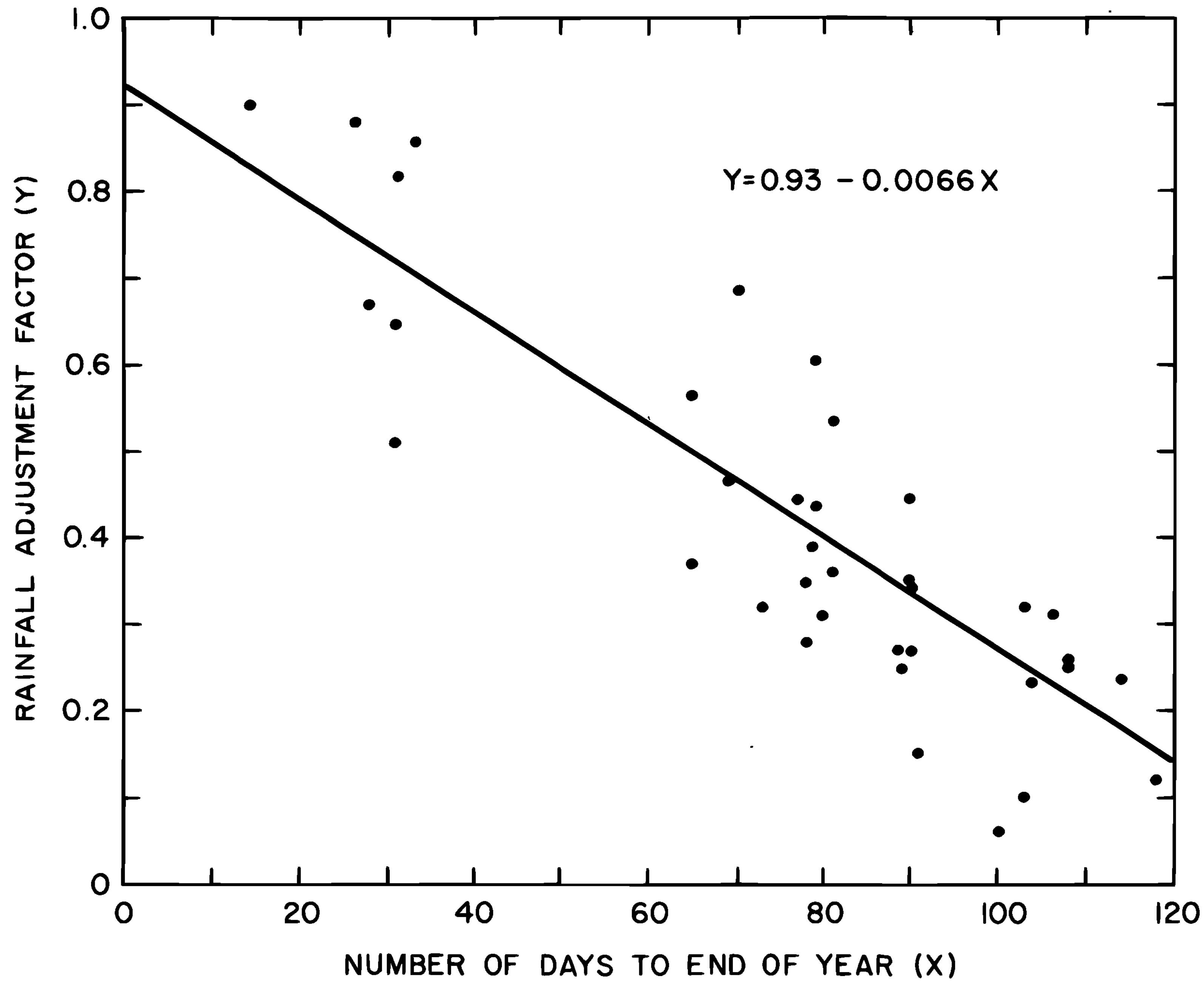


FIGURE 4.-Relationship between rainfall-adjustment factor and date of most significant year-end storm

When several consecutive storms occurred at the end of a year, the selection of the date for the most significant storm posed a difficulty in developing the relation between X and Y and poses the same problem in the use of the regression equation. However, it is not a serious problem as long as the precipitation adjustments are made on an annual basis, which minimizes the errors reflected in the rainfall-adjustment factor. Consideration of the total precipitation, areal distribution, intensity, and duration is used to determine the date of the most significant storm that occurred nearest the end of the year. The data used in the relation are from all seven subbasins, and this tends to regionalize the precipitation; the inherent assumption is that the runoff characteristics of all subbasins are the same. Sufficient data were unavailable to develop a relation for each subbasin.

The use of figure 4 involves a determination of Y, from a selection of X. By knowing SP, PA can be determined from Y and can then be used to make the precipitation adjustment. Figure 4 was used to adjust the annual weighted precipitation data used in the regression analyses.

Regression Equations

Regression analyses between the annual values of the adjusted weighted mean-annual precipitation and annual recharge were made for seven subbasins within the San Antonio area through programs designed for use on the electronic digital computer IBM-370 system. Regression analysis involves the relation between a set of independent variables and a dependent variable. The end product of the analysis is a regression equation that may be used to estimate values of a dependent variable when values of the independent variables are known (Riggs, 1968, p. 6). Annual recharge (R) was treated as the dependent variable and the adjusted weighted mean-annual precipitation (P) was treated as the independent variable.

A simple linear-regression analysis was made for each of the seven subbasins using the following model:

$$\text{Log } R = \text{Log } C + a \text{ Log } P, \qquad (4)$$

which is readily converted to the power-form equation,

$$R = CP^a, \qquad (5)$$

where R is the annual recharge in thousands of acre-feet (millions of cubic metres), P is the adjusted weighted mean-annual precipitation in inches (millimetres), C is the regression constant, and a is the regression coefficient.

Table 1 shows the regression equations and their standard errors of estimate for the seven subbasins in the San Antonio area. The first equation for each subbasin is in English units and the second one is in metric units. Figures 5 through 11 are log-log plots showing the relationship between annual recharge and the adjusted weighted mean-annual precipitation for each of the subbasins in the study area; these can be used in place of the equations.

The regression constants in most of the equations are very small. By manipulating the plotting reference point, the equations were forced through the origin, but no significant improvement was noted. Therefore, the original constants are those given in table 1.

The standard error of estimate is a measure of the reliability of an equation and can be used to estimate the reliability of dependent-variable estimates made from the regression equation (Riggs, 1968, p. 15). It is also a measure of the variation or scatter of points about the line of regression. About 68 percent of the data points will plot within ±1 standard error of estimate if they are normally distributed about the line of regression. When a logarithmic transformation is applied to an equation, the standard error is commonly expressed as a constant percentage of the curve value of the dependent variable, throughout its range.

Figures 12 through 18 are graphs showing the comparisons of the observed and computed annual recharge in the major river basins in the study area. The observed recharge is the historical record of estimated recharge, and the computed recharge is the recharge as determined by use of the regression equations. The comparisons are made for 1954-70 in all subbasins except the Sabinal which is made for 1957-70, and the Cibolo-Dry Comal which is made for 1956-70; some of the earlier recharge data for these two subbasins are unreliable because of discrepancies in part of the streamflow records.

The graphs show that the computed values are in reasonable agreement with the observed values. Large discrepancies between the computed and observed recharge may occur for some years in most of the basins, but the general comparisons are good. On the basis of long-term averages for the periods considered, the difference between the average observed and computed values of recharge for each basin is not large.

Figure 19 is a graph showing the comparison of the observed and computed annual recharge for the entire San Antonio area. This graph indicates that the computed annual-recharge values for the entire area are in better agreement with the observed annual-recharge values than for any of the individual basins. The difference between the average observed total annual recharge and the average computed total annual recharge was less than 1 percent of the observed average.

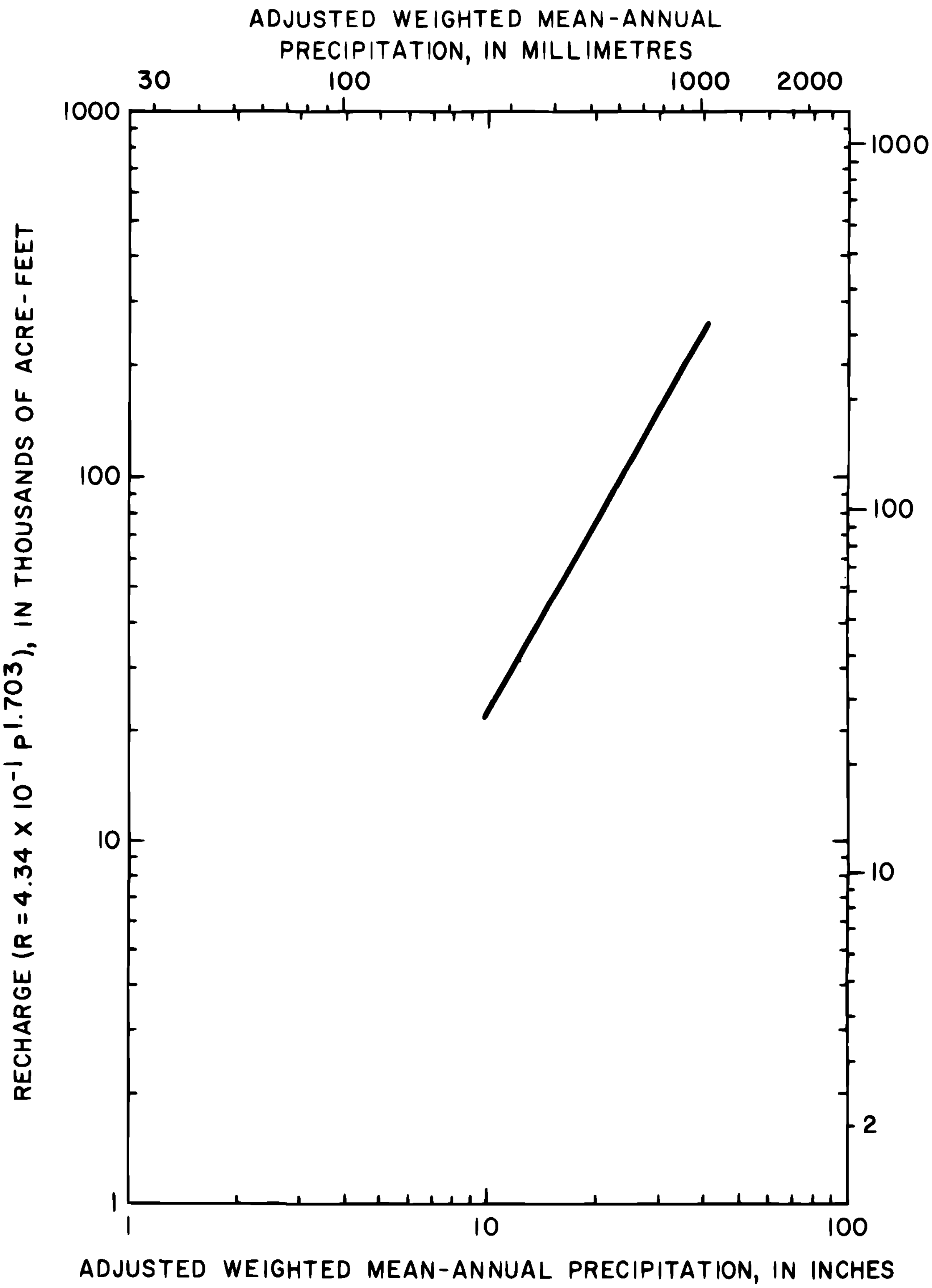


FIGURE 5.-Relationship between annual recharge and precipitation in the Nueces-West Nueces River basin

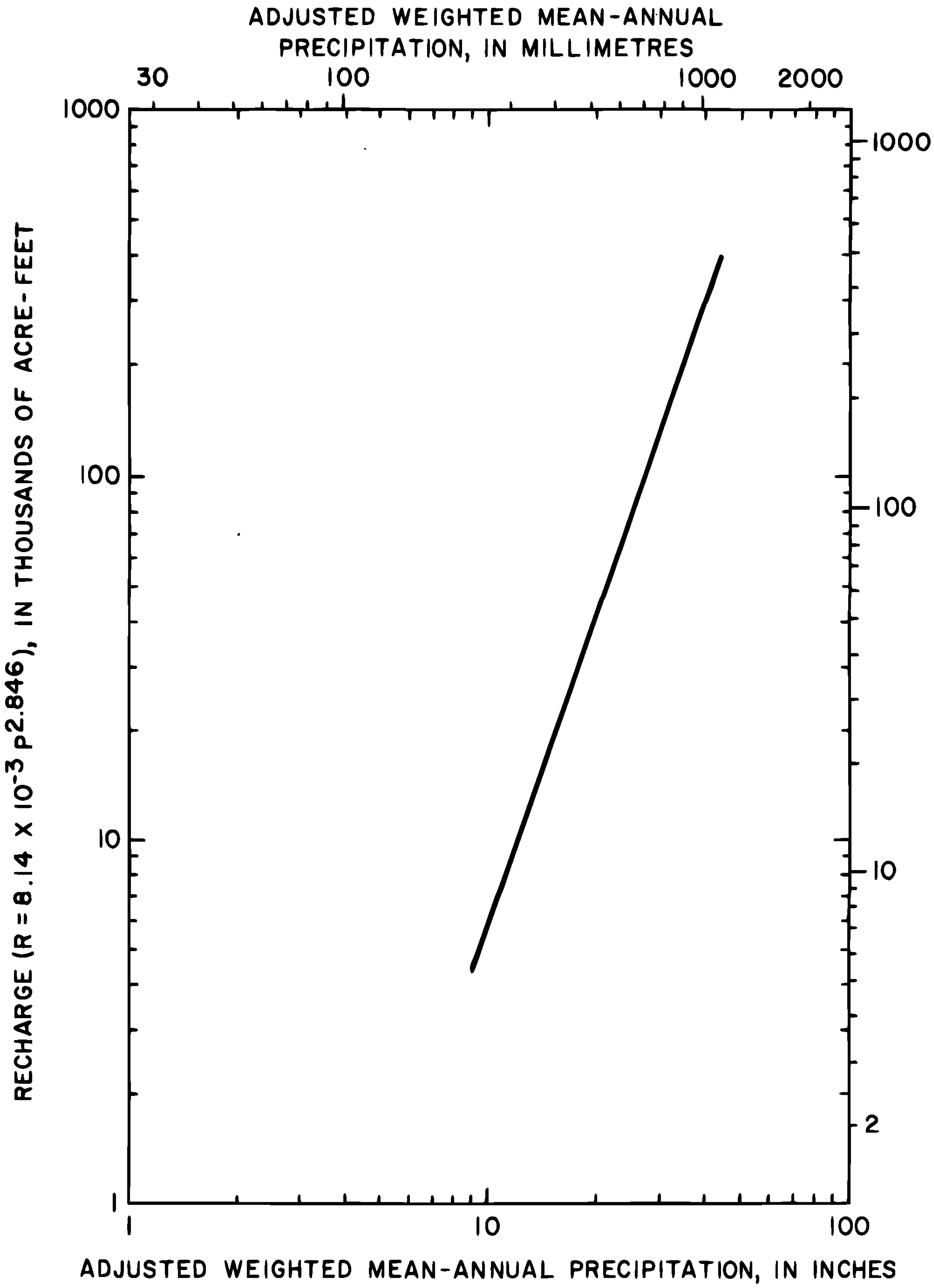


FIGURE 6.-Relationship between annual recharge and precipitation in the Frio-Dry Frio River basin

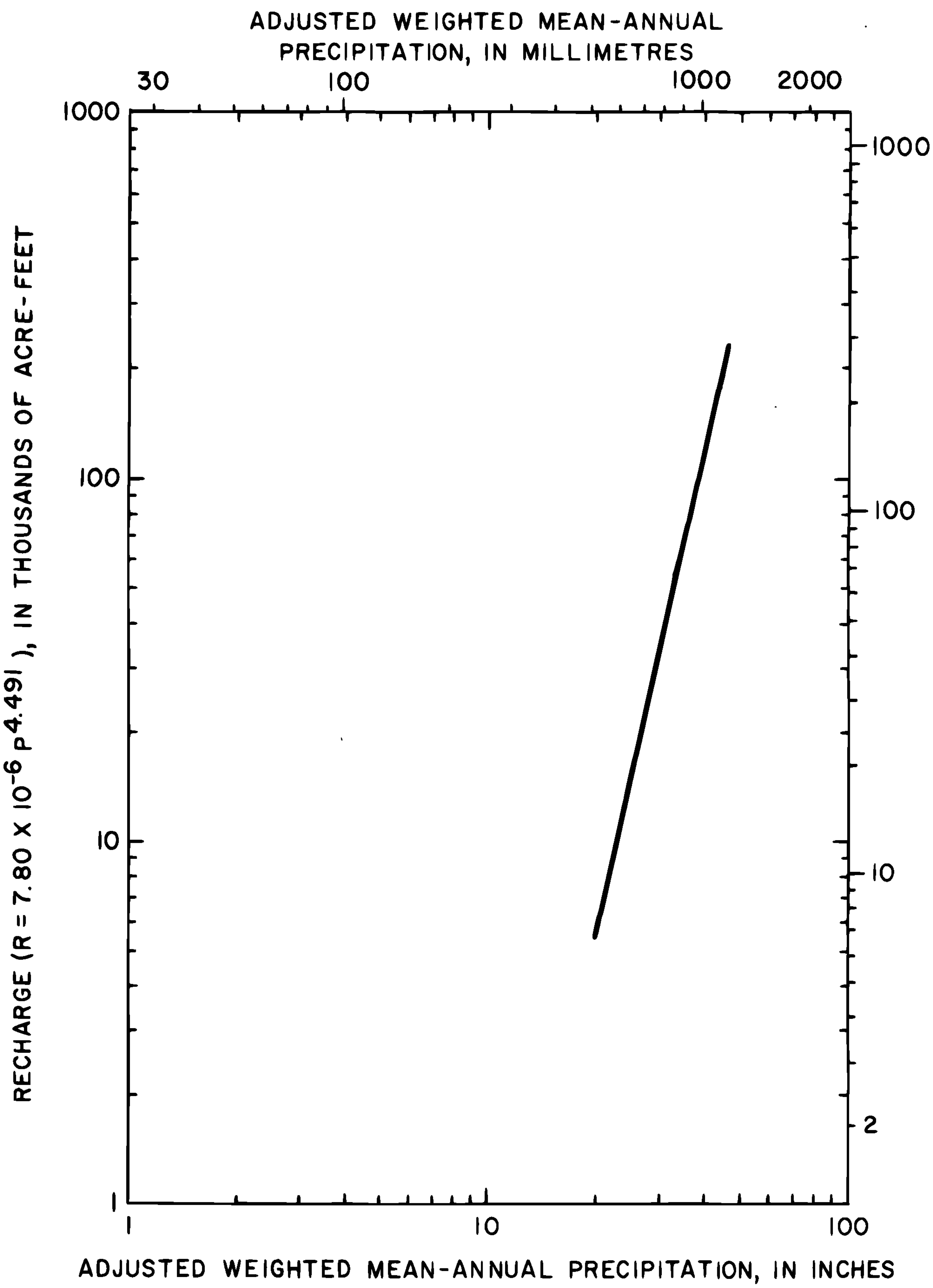


FIGURE 7.-Relationship between annual recharge and precipitation in the Sabinal River basin

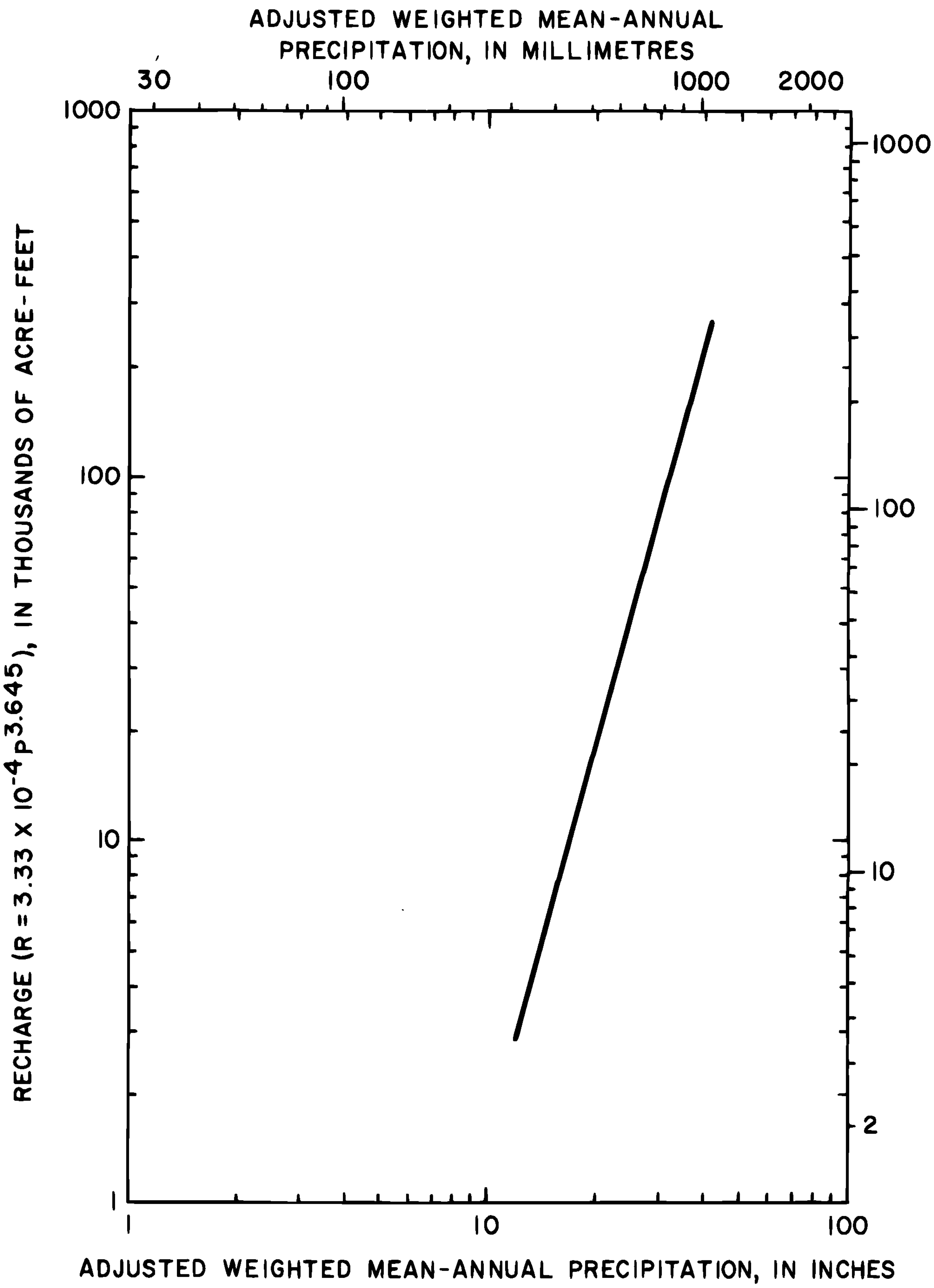


FIGURE 8.-Relationship between annual recharge and precipitation in the area between the Sabinal and Medina River basins

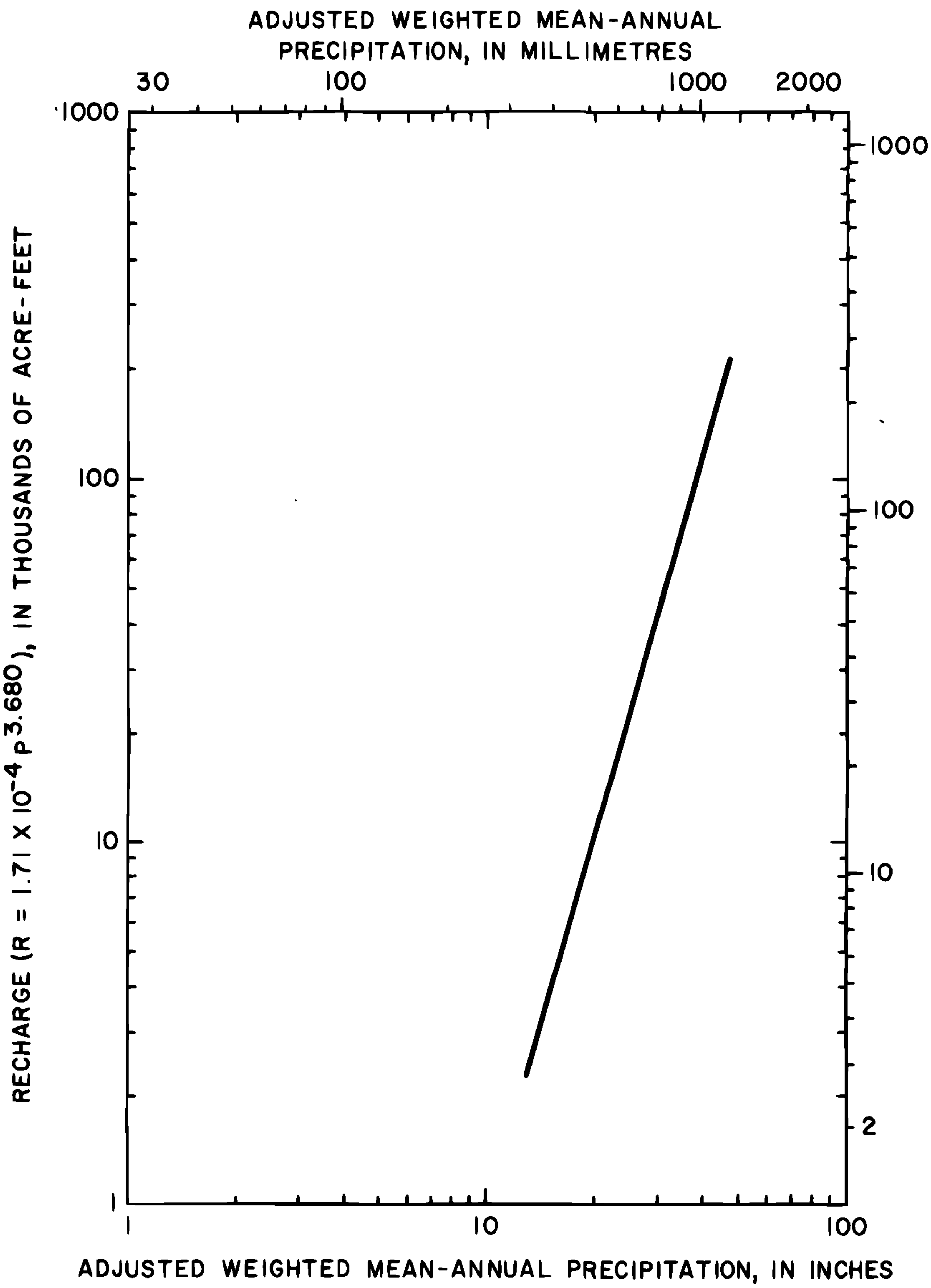


FIGURE 9.-Relationship between annual recharge and precipitation in the area between the Medina River and Cibolo Creek

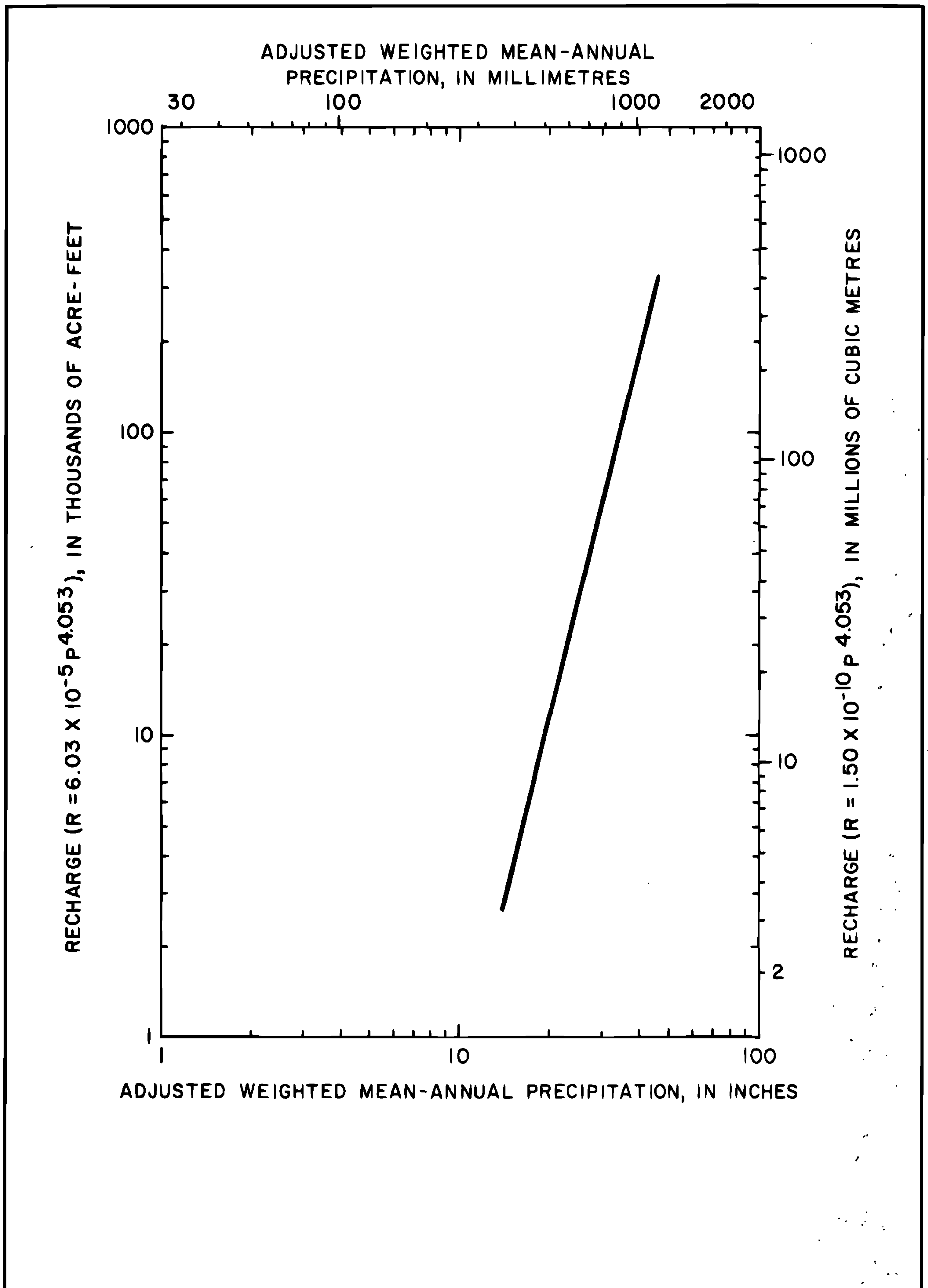


FIGURE 10.-Relationship between annual recharge and precipitation in the Cibolo Creek and Dry Comal Creek basins

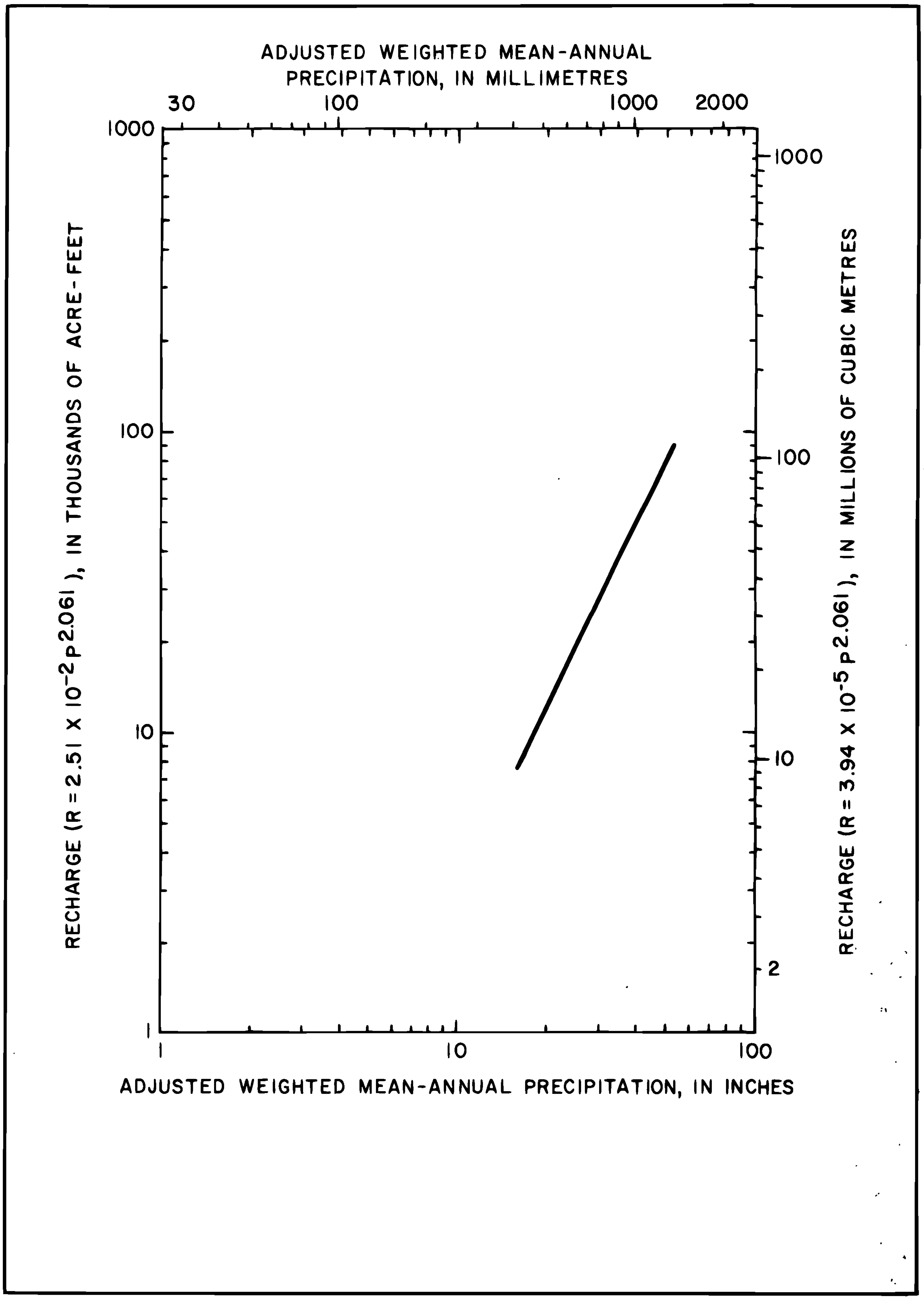


FIGURE 11.-Relationship between annual recharge and precipitation in the Blanco River basin

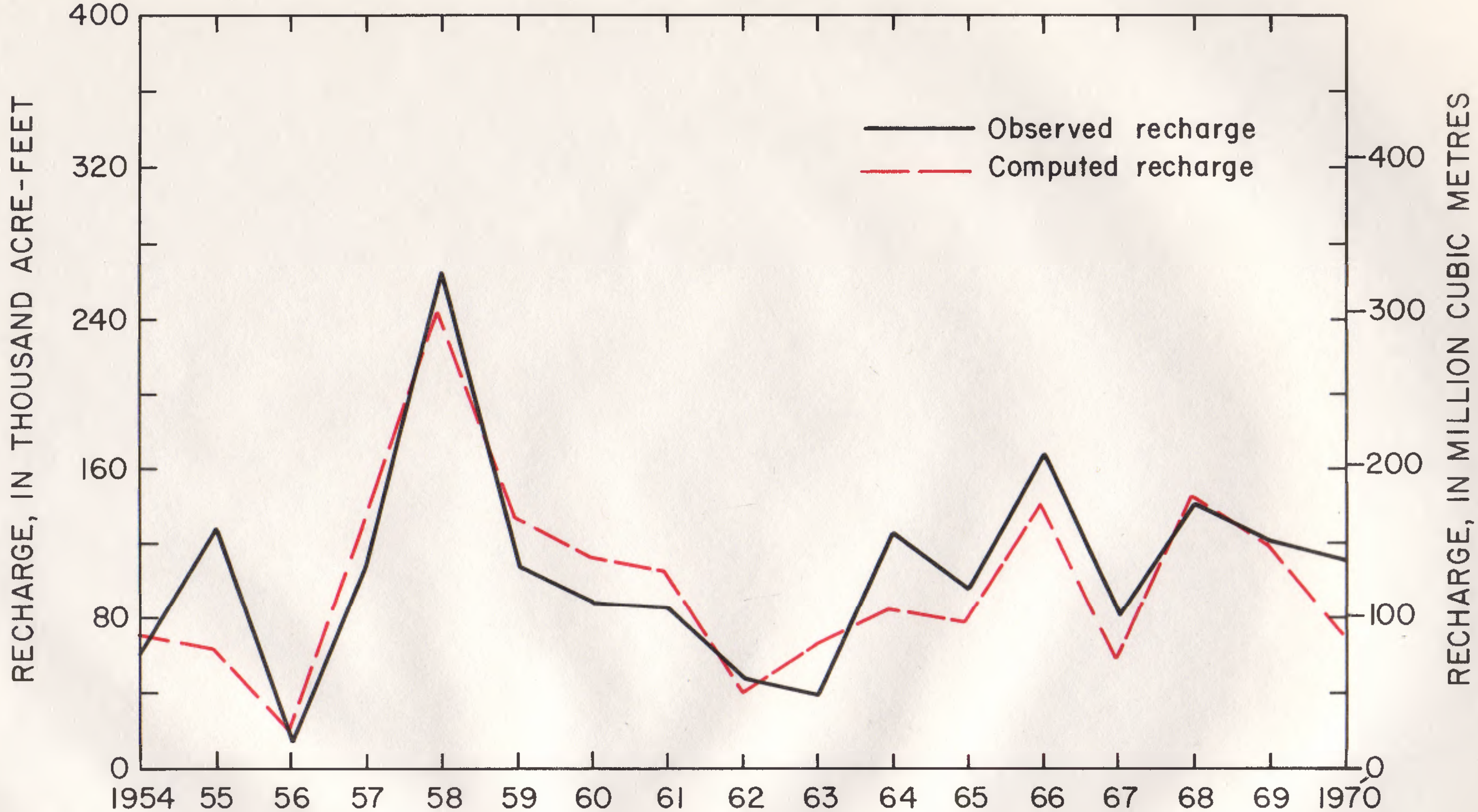


FIGURE 12.-Comparison of observed annual recharge and computed annual recharge for the Nueces-West Nueces River basin

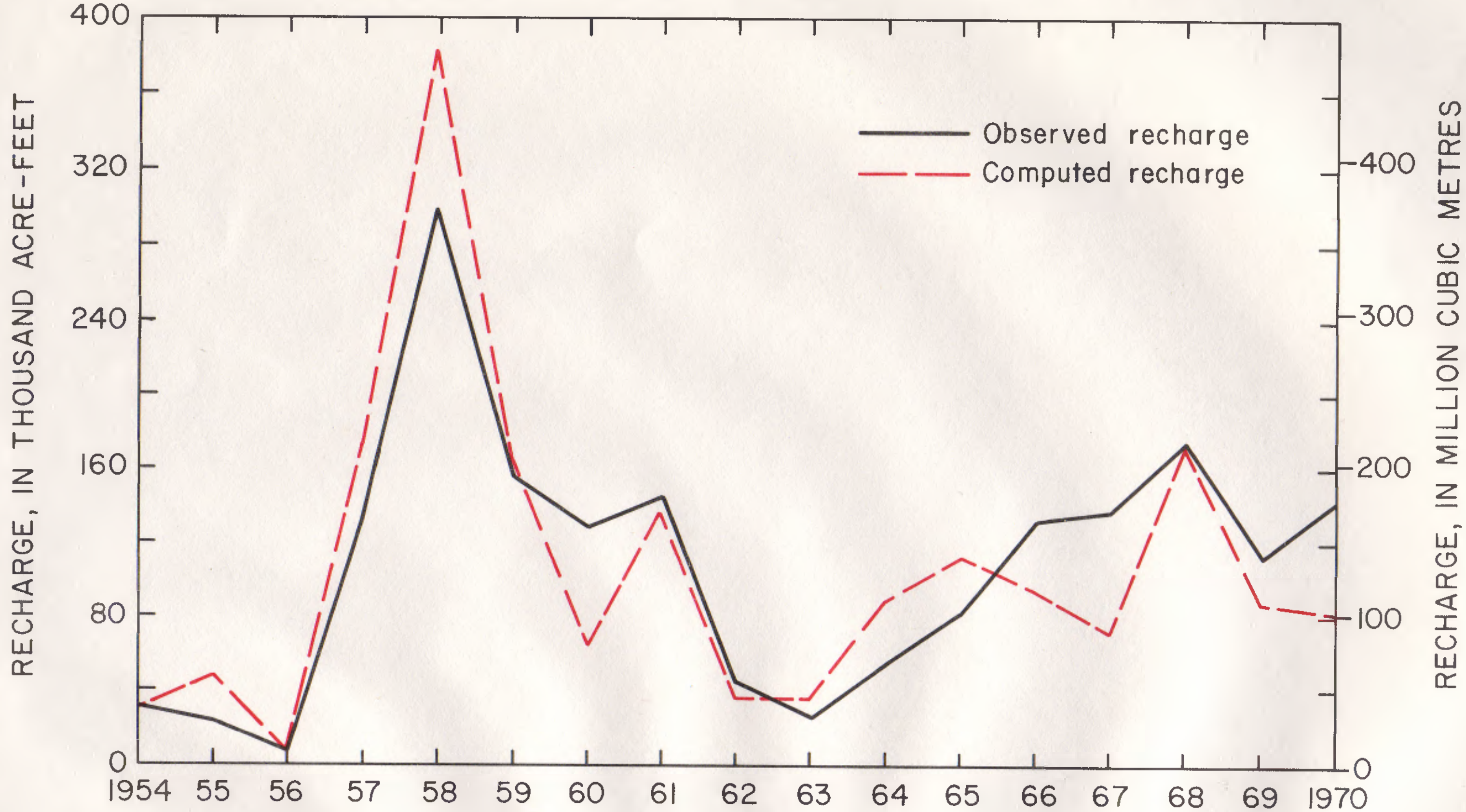


FIGURE 13.-Comparison of observed annual recharge and computed annual recharge for the Frio-Dry Frio River basin

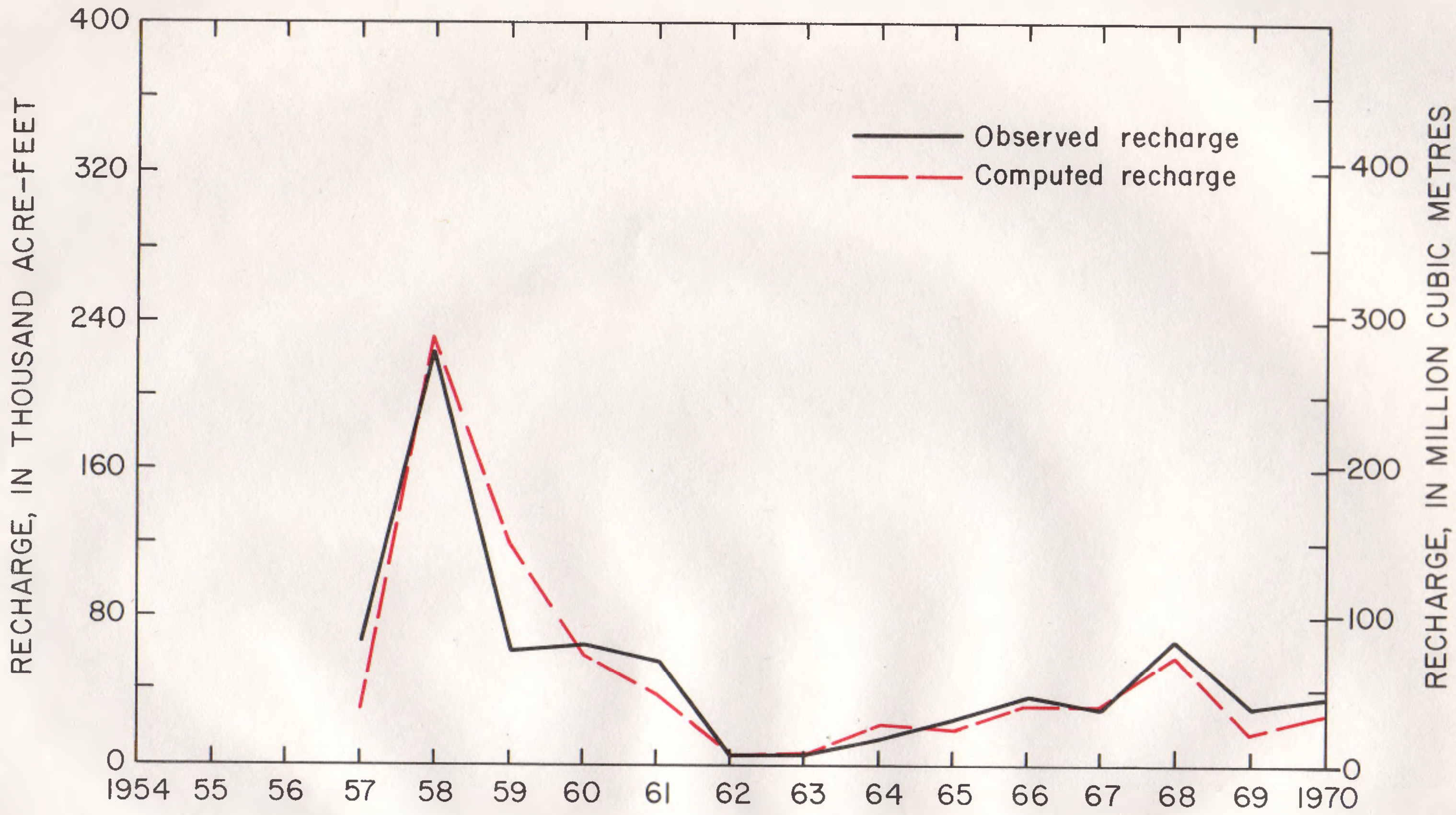


FIGURE 14.-Comparison of observed annual recharge and computed annual recharge for the Sabinal River basin

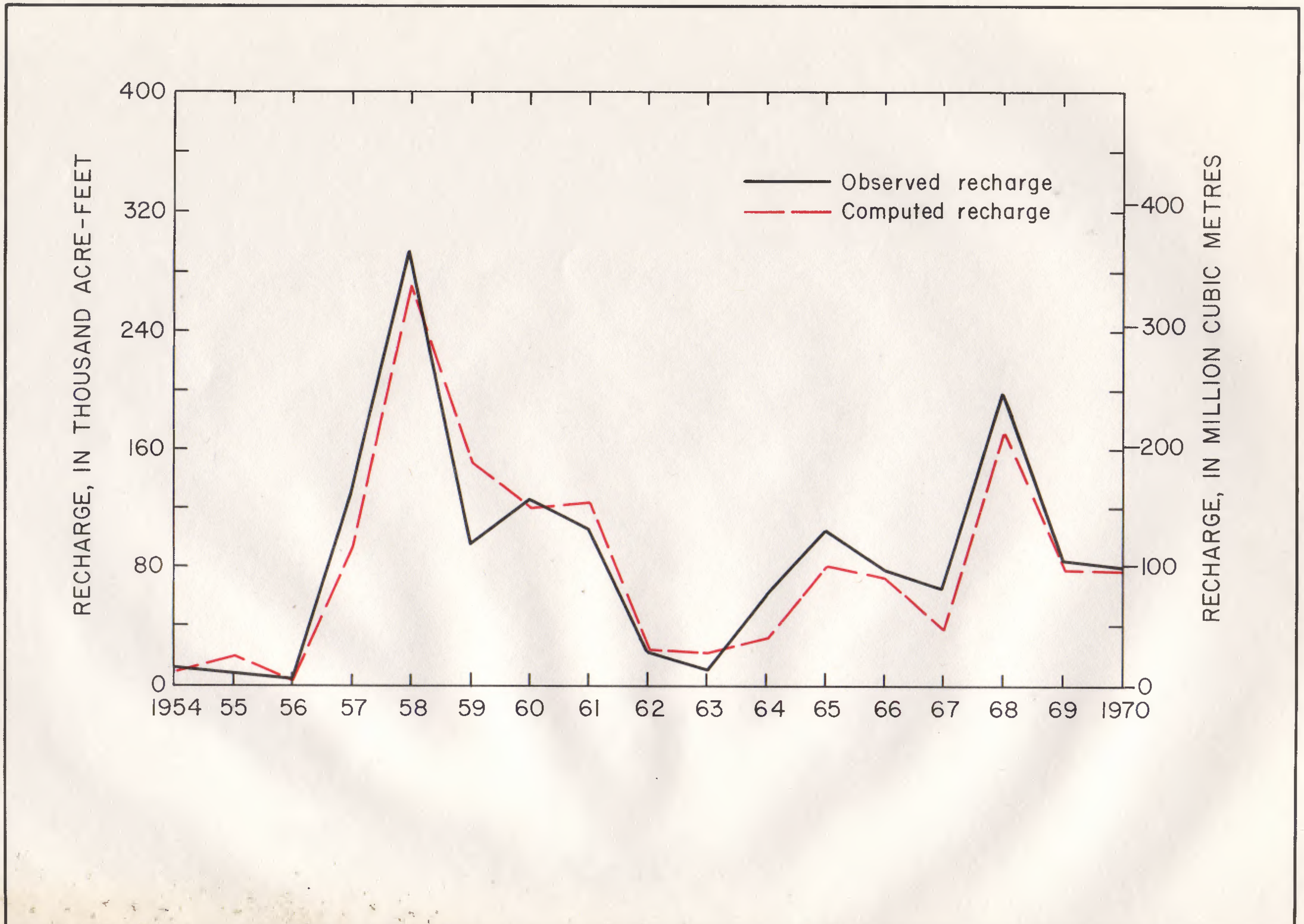


FIGURE 15.-Comparison of observed annual recharge and computed annual recharge for the area between the Sabinal and Medina River basins

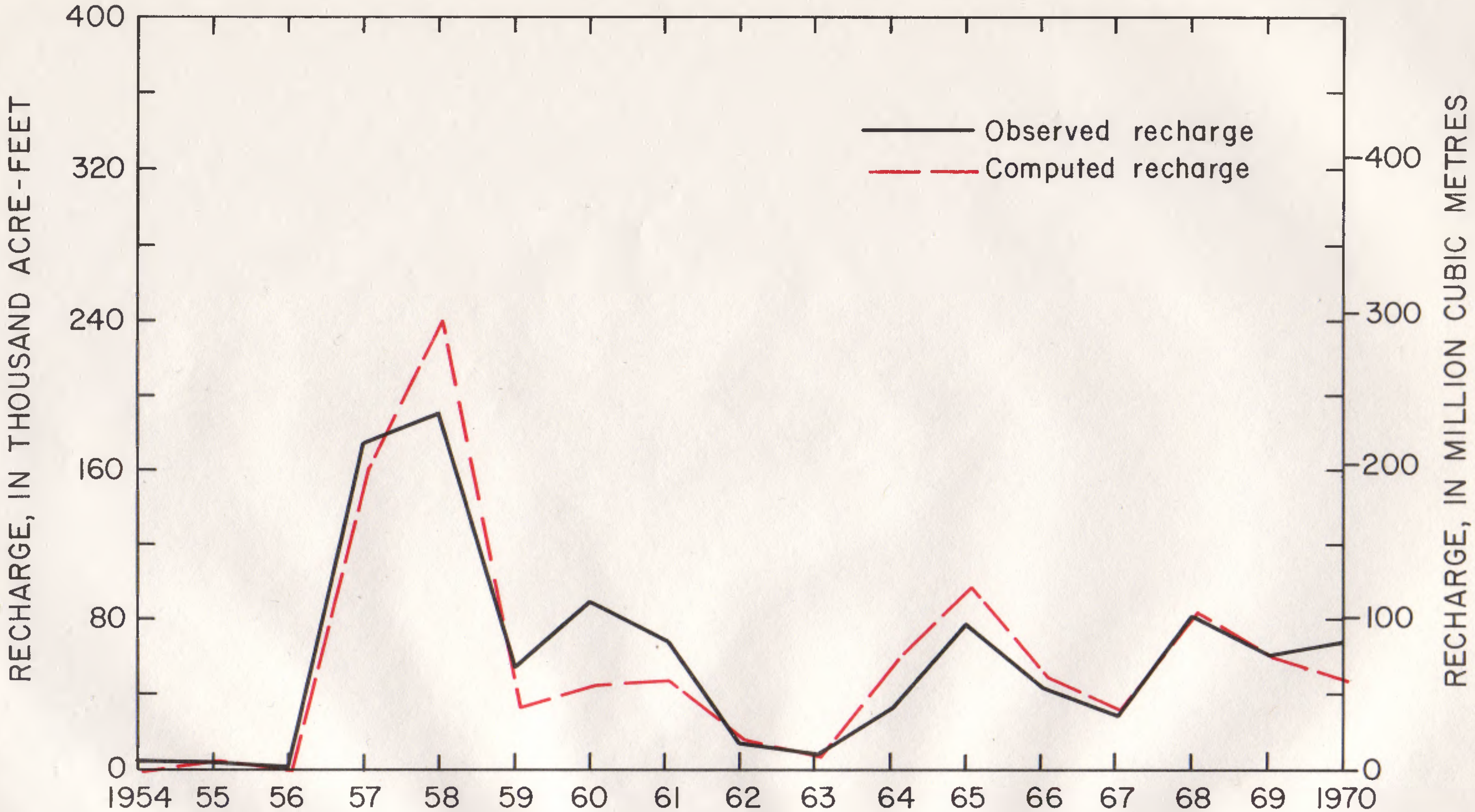


FIGURE 16.-Comparison of observed annual recharge and computed annual recharge for the area between the Medina River and Cibolo Creek

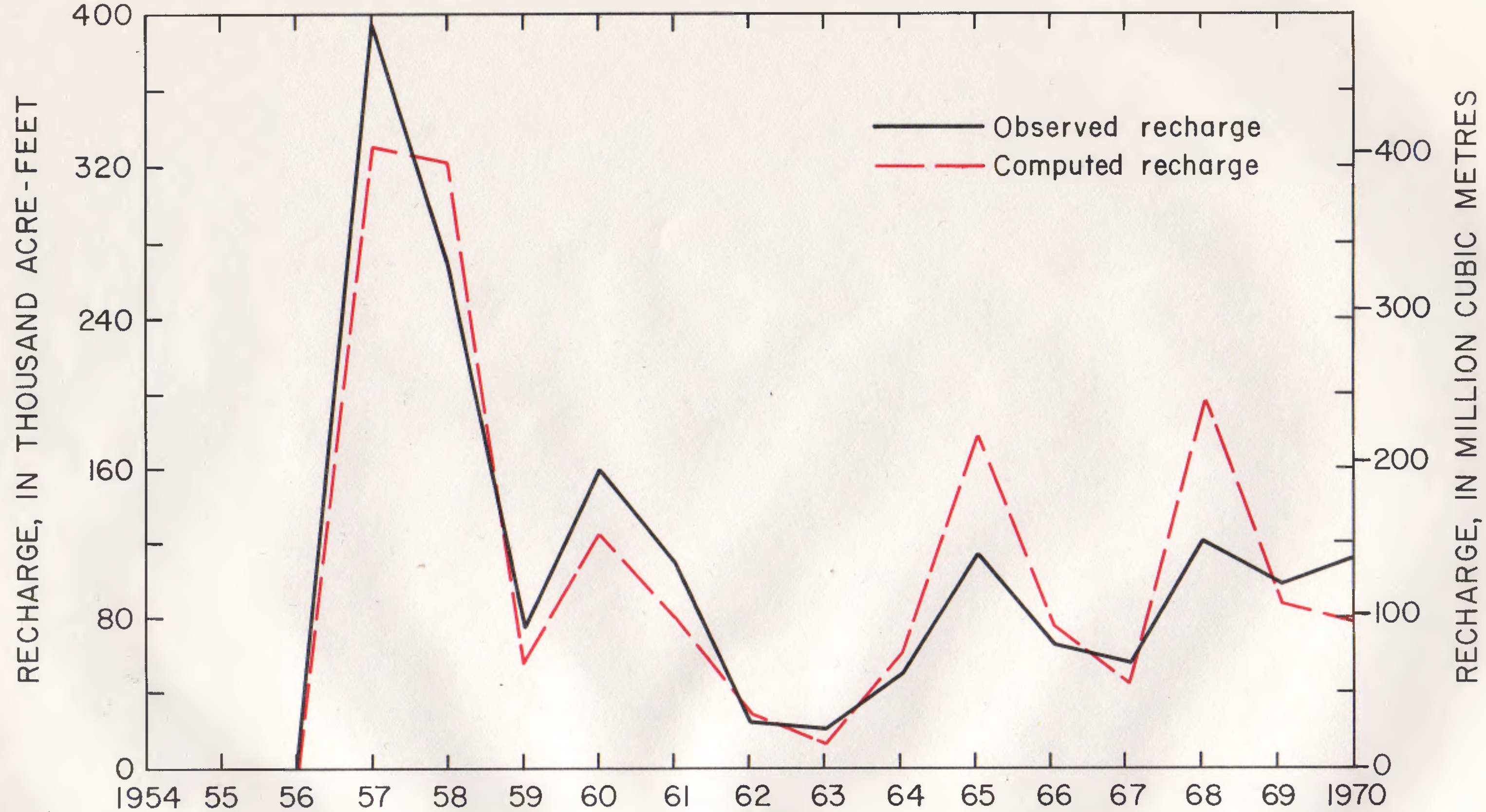


FIGURE 17.-Comparison of observed annual recharge and computed annual recharge for the Cibolo Creek and Dry Comal Creek basins

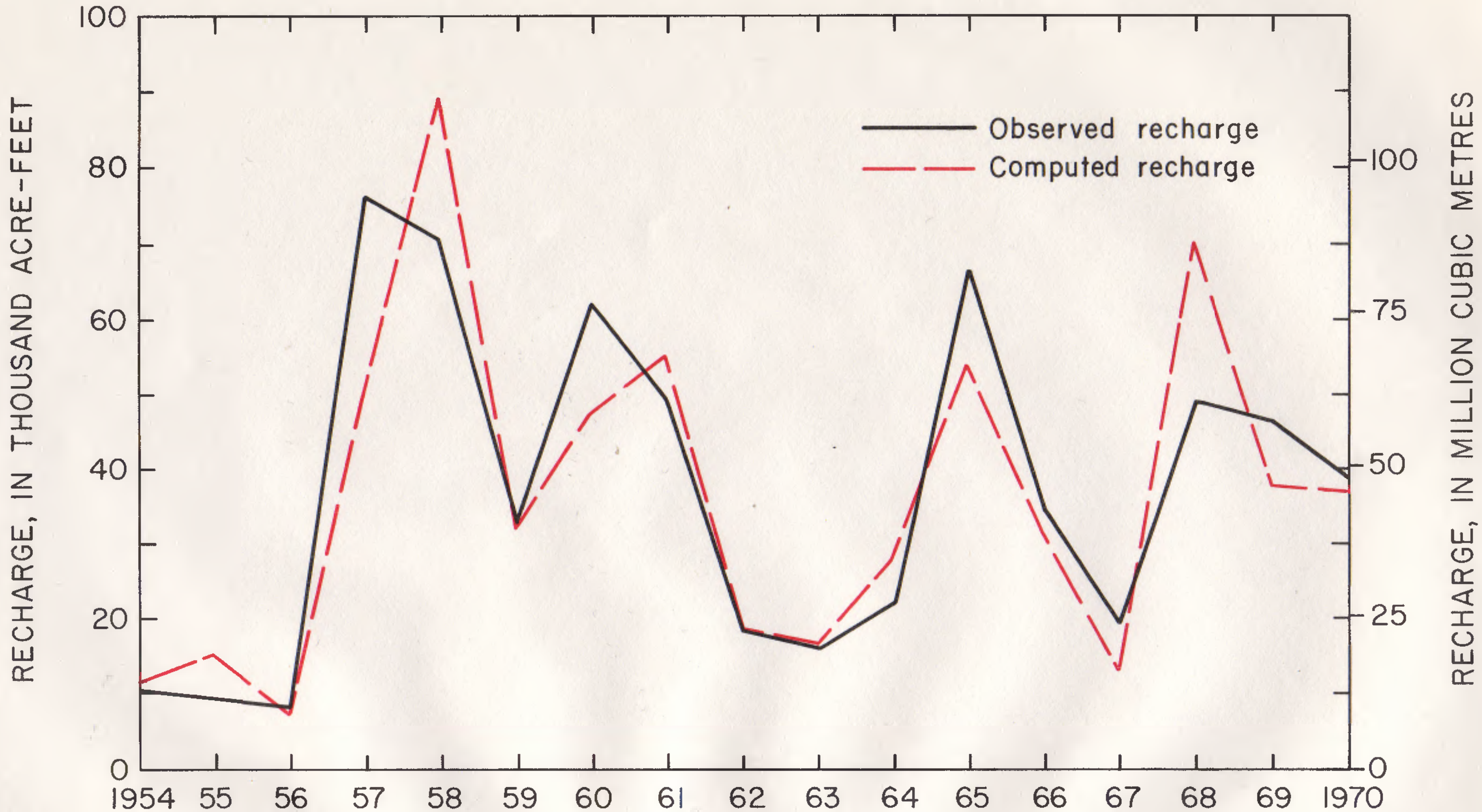


FIGURE 18.-Comparison of observed annual recharge and computed annual recharge for the Blanco River basin

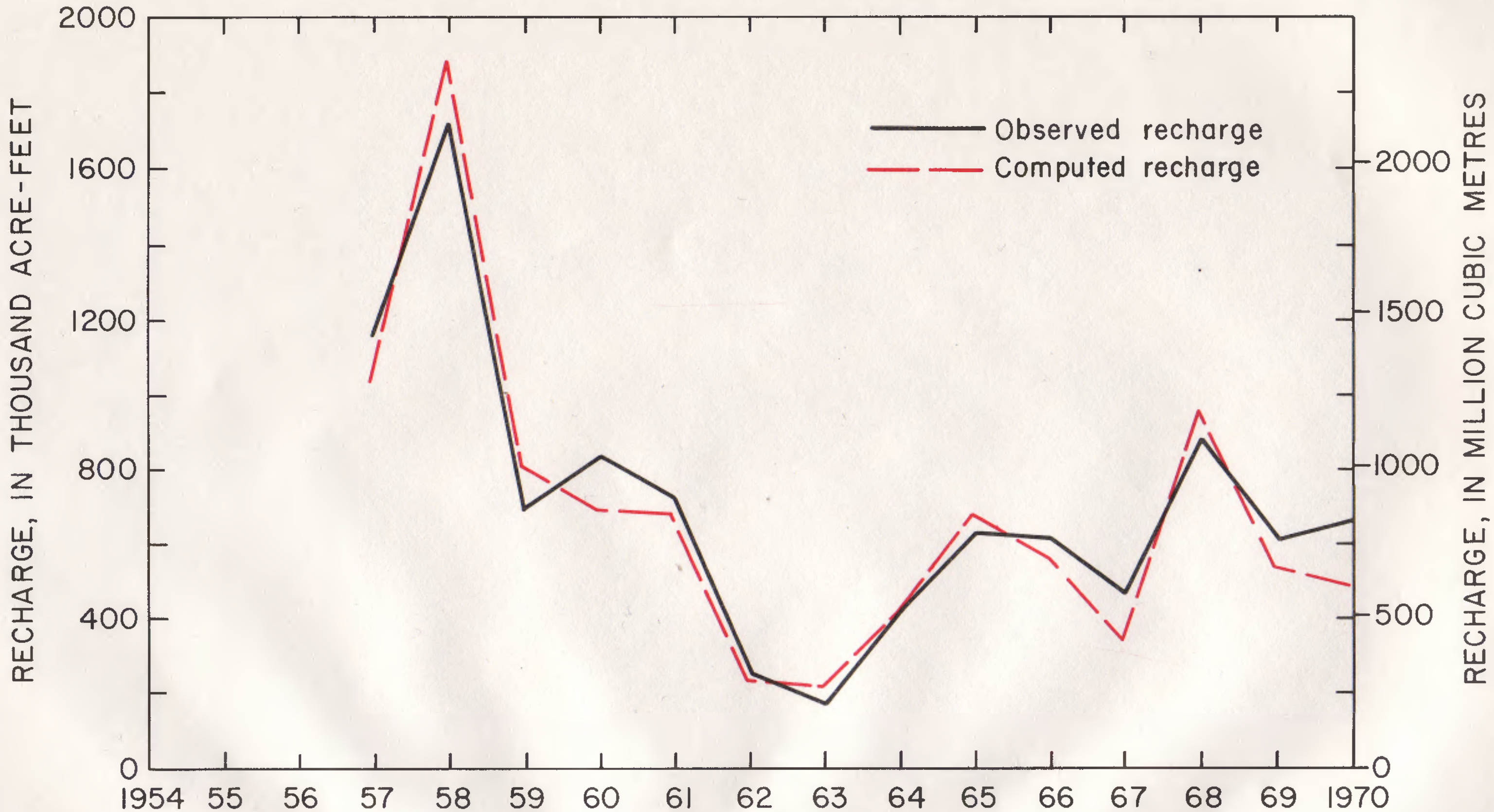


FIGURE 19.-Comparison of observed annual recharge and computed annual recharge for the San Antonio area

Table 1.--Regression equations and standard errors of estimate for the subbasins in the San Antonio area

Subbasin	Regression equation 1/	Standard error (percent)	Range in adjusted weighted mean-annual precipitation	
			Inches	Millimetres
Nueces-West Nueces	$R = 4.34 \times 10^{-1} P^{1.703}$ $R = 2.17 \times 10^{-3} P^{1.703}$	34	10-41	254-1,041
Frio-Dry Frio	$R = 8.14 \times 10^{-3} P^{2.846}$ $R = 1.01 \times 10^{-6} P^{2.846}$	43	9-44	229-1,118
Sabinal	$R = 7.80 \times 10^{-6} P^{4.491}$ $R = 4.72 \times 10^{-12} P^{4.491}$	40	20-46	508-1,168
Sabinal-Medina area	$R = 3.33 \times 10^{-4} P^{3.645}$ $R = 3.11 \times 10^{-9} P^{3.645}$	45	12-42	305-1,067
Medina-Cibolo area	$R = 1.71 \times 10^{-4} P^{3.680}$ $R = 1.42 \times 10^{-9} P^{3.680}$	33	13-47	330-1,194
Cibolo-Dry Comal area	$R = 6.03 \times 10^{-5} P^{4.053}$ $R = 1.50 \times 10^{-10} P^{4.053}$	32	14-46	356-1,168
Blanco	$R = 2.51 \times 10^{-2} P^{2.061}$ $R = 3.94 \times 10^{-5} P^{2.061}$	26	16-53	406-1,346

1/ In the upper equation, R is expressed in acre-feet x 10^3 and in the lower equation, R is expressed in cubic metres x 10^6. P is expressed in inches in the upper equation, and in millimetres in the lower equation.

The occurrence of a large variation between the observed and computed annual recharge for some years may be attributed to two main factors: Discrepancies in the adjusted weighted mean-annual precipitation, and errors in the estimates of observed recharge. Both of these factors are particularly sensitive with regard to storms of short duration and high intensity, which are prevalent during the summer and fall in this area. Errors in the adjustment of the weighted mean-annual precipitation to compensate for antecedent effects may also contribute to the variations shown on the graphs.

Use of the Regression Equations

The use of the regression equations developed in this study is limited to gross estimates of annual recharge to the Edwards aquifer by the use of a single independent variable--adjusted weighted mean-annual precipitation. This procedure does not apply to estimates of recharge in the Medina River basin, which must be determined separately by another method. The equations become more useful if the end product sought is the average annual recharge over an extended period, such as 10 years or more.

The procedure to estimate annual recharge by using the regression equations with records of precipitation as the only data input is outlined as follows:

1. The weighted mean-annual precipitation within a subbasin in both the catchment and infiltration areas is computed by applying the Thiessen method to the precipitation data. Steps 2 through 4 may then be followed if adjustments for year-end precipitation effects are necessary.

2. The date of the most significant year-end storm (X number of days to end of year) is selected from the precipitation data after consideration of the amount, duration, intensity, and distribution of precipitation.

3. The factor Y may be calculated from the equation $Y = 0.93 - 0.0066X$ or from the graph shown on figure 4.

4. The product of Y and the total year-end precipitation (SP) results in the value of PA. The antecedent-precipitation adjustment is made when PA is added to the following-year precipitation and subtracted from the current-year precipitation.

5. The weighted mean-annual precipitation, adjusted for antecedent effects where necessary, may then be applied to the appropriate regression equation to estimate annual recharge for a given subbasin.

CONCLUSIONS

The regression equations presented in this report may be used to make gross estimates of annual recharge to the Edwards aquifer in the seven drainage subbasins in the San Antonio area. The equations provide an alternate method for computing annual recharge by using only the weighted mean-annual precipitation that has been adjusted for year-end antecedent effects. Recharge to the aquifer in the Medina River subbasin is from leakage of Medina Lake, and contributions from the Guadalupe River subbasin are considered negligible; therefore, neither of these two subbasins were analyzed.

The computed recharge values compared favorably with the observed historical estimates of recharge. The differences between the computed and observed values for the long-term averages in the subbasins were small, and the long-term computed average for the total area (seven subbasins) was within 1 percent of the long-term observed average.

This study is an initial attempt, through simple regression analysis, to relate annual recharge to the Edwards aquifer to annual precipitation that has been weighted and adjusted. These equations are preliminary and will be modified as more data become available. The relationships may be further refined through the use of multiple regression analyses that use other parameters, such as water-level data, various basin characteristics, and the number of days between the end of the year and the date of the last most significant storm.

SELECTED REFERENCES

Dalrymple, Tate, 1960, Flood-frequency analyses: U.S. Geol. Survey Water-Supply Paper 1543-A, 80 p.

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, 42 p.

______1963, Records of precipitation, aquifer head, and ground-water recharge to the Edwards and associated limestones, 1960-62, San Antonio area, Texas: Edwards Underground Water Dist. Bull. 3, 7 p.

______1964, Records of precipitation, aquifer head, and ground-water recharge to the Edwards and associated limestones, San Antonio area, Texas, 1963: Edwards Underground Water Dist. Bull. 6, 7 p.

______1966, Ground-water resources of the San Antonio area, Texas, a progress report on studies, 1960-64: Texas Water Devel. Board Rept. 34, 31 p.

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

Maclay, R. W., and others, 1973, Hydrogeology of the Edwards Limestone aquifer: Geol. Soc. of Am. Hydrogeology Field Trip, San Antonio, Texas, 16 p.

Petitt, B. M., and George, W. O., 1956, Ground-water resources of the San Antonio area, Texas, a progress report on current studies: Texas Board Water Engineers Bull. 5608, v. 1, 80 p.

Puente, Celso, 1971, Records of precipitation, water levels, and ground-water recharge to the Edwards and associated limestones, San Antonio area, Texas, 1970: Edwards Underground Water Dist. Bull. 27, 11 p.

Rettman, Paul, 1966, Records of precipitation, aquifer head, and ground-water recharge to the Edwards and associated limestones, San Antonio area, Texas, 1965: Edwards Underground Water Dist. Bull. 12, 8 p.

______1967, Records of precipitation, aquifer head, and ground-water recharge to the Edwards and associated limestones, San Antonio area, Texas, 1966: Edwards Underground Water Dist. Bull. 15, 9 p.

______1968, Records of precipitation, aquifer head, and ground-water recharge to the Edwards and associated limestones, San Antonio area, Texas, 1967: Edwards Underground Water Dist. Bull. 18, 9 p.

______1969, Records of precipitation, aquifer head, and ground-water recharge to the Edwards and associated limestones, San Antonio area, Texas, 1968: Edwards Underground Water Dist. Bull. 21, 9 p.

______1970, Records of precipitation, aquifer head, and ground-water recharge to the Edwards and associated limestones, San Atnonio area, Texas, 1969: Edwards Underground Water Dist. Bull. 24, 11 p.

Riggs, H. C., 1968, Some statistical tools in hydrology: U.S. Geol. Survey Tech. Water-Resources Inv., Book 4, Ch. A1, 39 p.

Searcy, J. K., and Hardison, C. H., 1960, Double-mass curves: U.S. Geol. Survey Water-Supply Paper 1541-B, 66 p.

U.S. Geological Survey, 1973, Water resources data for Texas, part 1, surface water records: U.S. Geol. Survey rept.