THE EFFECTS OF URBANIZATION ON FLOODS IN THE AUSTIN METROPOLITAN AREA, TEXAS

By Jack E. Veenhuis and David G. Gannett

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METRIC CONVERSIONS

The inch-pound units of measurements used in this report may be converted to metric units by using the following conversion factors:

Multiply	By	To obtain
inches (in.)	25.4	millimeters (mm)
feet (ft)	0.3048	meters (m)
miles (mi)	1.609	kilometers (km)
square miles (mi^2)	2.590	square kilometers (km^2)
feet per mile (ft/mi)	1.89	meters per kilometer (m/km)
cubic feet per second (ft^3/s)	0.02832	cubic meters per second (m^3/s)

Temperature in degrees Fahrenheit (°F) can be converted to degrees Celsius (°C) as follows:

$$°F = 1.8°C + 32$$
$$°C = 5/9(°F - 32)$$

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ABSTRACT

The effects of urbanization on flood peaks in streams in the Austin metropolitan area were studied in two separate analyses. In the first analysis, annual peak discharge records at 13 streamflow-gaging sites were used to compute a recorded flood frequency relation for each site. Rainfall and streamflow data for 10 to 20 storms for each of these sites were used to calibrate a rainfall-runoff model in which a 55-year rainfall record was used to simulate 55 annual peak discharges. These simulated discharges also were used to develop a flood-frequency relation at each site. The flood-frequency relations from recorded and generated data were then combined by weighting the recorded flood frequency by the years of record at each site to produce a combined (or weighted) flood frequency at each site. Flood frequencies for all 13 sites were subsequently regressed against basin characteristics at each site to determine possible effects of urbanization.

The regression analysis of the combined flood-frequency data for the 13 sites yielded an equation for estimating floods of a given recurrence interval at ungaged sites in the Austin area as a function of the contributing drainage area, the total impervious area percentage, and basin shape. The regression equation estimates that a near fully developed hypothetical drainage basin (impervious area percentage, 45) would have discharges for the 2- and 100-year recurrence interval that are 99 percent and 73 percent greater, respectively, than discharges for those frequencies from a rural drainage basin (impervious percentage, 0).

In the second analysis, records at one streamflow-gaging site on Waller Creek were analyzed for changes in rainfall-runoff and flood-frequency relations due to urbanization. Annual peak discharges from 1956 to 1980 and data from a total of 80 storms at the Waller Creek site were analyzed.

Both analyses showed increases comparable to those predicted using the equations developed from the 13-station analysis. The last 14 years of record (the near fully developed land-use stage for the Waller Creek analysis) at the two sites on Waller Creek were part of the 13-station analysis.

INTRODUCTION

The U.S. Geological Survey, in cooperation with the Texas Department of Water Resources began limited investigations of urban watersheds in Austin in 1954, with the installation of two streamflow-gaging stations and three recording rain gages in the Waller Creek watershed. In 1963, a streamflow gage and three recording rain gages were installed at Wilbarger Creek watershed, a rural area just north of Austin. In cooperation with the City of Austin, the urban study was expanded in 1975 to include additional streamflow and rainfall gaging stations and the collection of surface water-quality data. The number of streamflow-gaging stations increased from 2 to 25 and the number of recording rain gages increased from 3 to 31.

Acknowledgments

The authors gratefully acknowledge the personnel in the Austin Field Headquarters and Raymond M. Slade, Jr. for the collection and assistance in interpretation of the discharge data, Bernard C. Massey for his advise in the flood-freqency analysis, and Gary D. Tasker for assistance in generalized least-square regression. Also, the authors wish to thank the personnel of the Watershed Management Section of the City of Austin Public Works Department for their help in obtaining engineering records of the study areas.

Purpose and Scope

The purpose of this report is to provide a technique for estimating the magnitude and frequency of flood-peak discharges at ungaged sites and to estimate the effects of changes in urbanization on flood peaks. The scope of this study is limited to unregulated streams in the Austin area.

Previous Investigations

The flood data used in this study are available in several reports. From 1961-74, annual reports presenting the data for Waller and Wilbarger Creeks were prepared. Beginning in 1975, the urban study was expanded and a report entitled "Hydrologic data for urban studies in the Austin, Texas, metropolitan area" has been prepared annually. These reports present the hydrologic and rainfall data collected each year.

A regional study of flood frequency for Texas was conducted by Schroeder and Massey (1977) for estimating magnitudes of flood peaks for natural and unregulated drainage basins. The study developed equations for estimating flood peaks based on drainage area and main channel slope. A Hydrologic Investigations Atlas describing the flood of May 24-25, 1981, in Austin was also prepared (Massey and others, 1982); the atlas presents the areal boundaries of the flood on Shoal, Little Walnut, and Walnut Creeks. The peak disharges for those creeks, as well as incremental rainfall and the areal distribution of the total rainfall are also presented.

Location and Description of the Area

The Austin metropolitan area is located in Travis County approximately 150 miles northwest of the Gulf of Mexico in south-central Texas. The altitude of the area ranges from about 400 feet above mean sea level at the downstream end of Boggy Creek to about 1,100 feet above mean sea level at the headwaters of Williamson Creek. Stream slopes of the seven drainage basins used in this study ranged from 20 to 50 feet per mile.

The study area extends from the Hill Country at the eastern edge of the Edwards Plateau across the Balcones Escarpment to the Blackland Prairie of Texas (fig. 1). Soils are generally thin over hard limestone in the western part of the study area. Soft limestones and shales are found in the vicinity of the Balcones fault zone, and soils 12 inches or more in thickness over shales are found in the eastern part of the region. Generally, the soils are predominately clay or silty clays of low permeability, except along the flood plain and alluvial terraces of the Colorado River where soils are thicker, more sandy, and higher in permeability. The geology of the Austin area is presented by Garner and Young (1976). Detailed information concerning soils in the area is presented by the U.S. Department of Agriculture (1974).

The climate in Austin is characterized by short mild winters, long moderately hot summers, moderately high humidity, and southerly winds. Mean-annual temperatures, based on the period 1941-70, is 70.6°F (21.5°C); the mean maximum temperature for July is 95°F (35.0°C); and the mean minimum temperature for January is 41°F (5.0°C). The average growing season is 270 days.

Mean annual precipitation, based on the National Weather Service gage in Austin is about 32 inches, ranging from about 11 inches to as much as 51 inches per year. Rainfall is distributed fairly evenly throughout the year with slightly more occurring in the spring and early fall months. Individual storm rainfall as well as annual total rainfall can vary areally within the study area. For example, the total rainfall for the 1981 water year (October 1, 1980 to September 30, 1981) ranged from 22.86 to 56.09 inches and the mean of all U.S. Geological Survey rain gages was 46.89 inches. The National Weather Service gage at the Austin Municipal Airport recorded 43.52 inches for the 1981 water year. Mean annual pan evaporation from the National Weather Service is 73.82 inches for the period 1916-79.

The Colorado River flows through several man-made lakes, including Town Lake, located near the middle of downtown Austin (fig. 1). Lake Austin located upstream from Town Lake, and the Colorado River downstream from Town Lake compose the receiving waters for the urban streams studied in this report. The major streams in the study area that are tributary to the Colorado River are Onion, Barton, Walnut, Bull, Shoal, Williamson, Slaughter, Bear, and Waller Creeks. Major flooding on several of these streams during the storm of May 23-24, 1981, caused considerable damage to life and property. Rainfall and runoff data for this storm are presented by Massey and others (1982) and Slade and others (1983). Other large storms in the Austin area which produced major flooding occurred in 1919, 1921, 1923, 1929, and 1935. Information concerning historic floods in the Austin area are available at the Austin-Travis County Collection of the Austin Public Library.

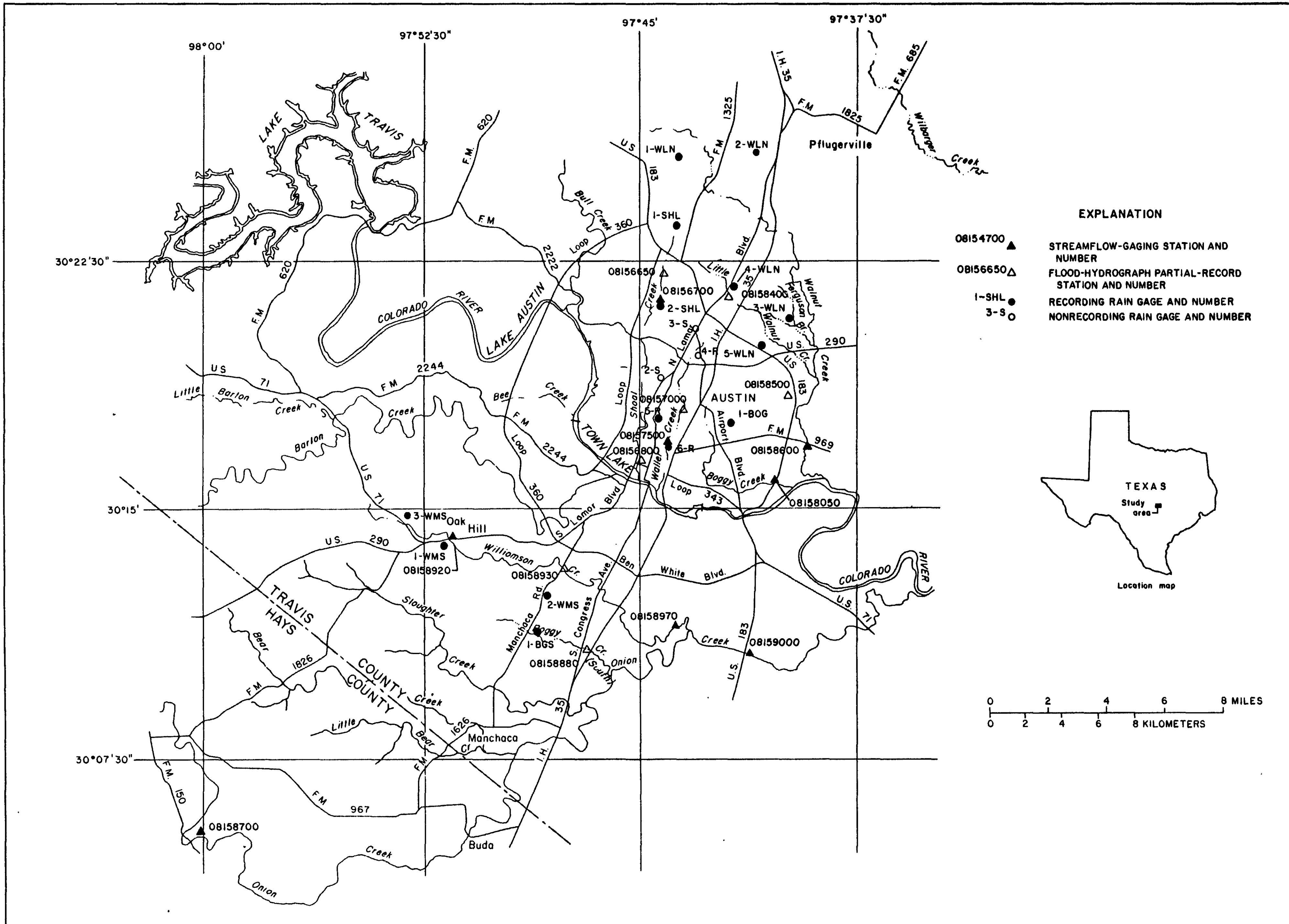

Figure 1.--Location and designation of hydrologic-instrument installations in the Austin urban study area used in this report.

Methods of Investigation

Two methods of investigation were used in this study. In the first method, records were analyzed from 13 streamflow-gaging sites located on 7 streams in the Austin metropolitan area (figs. 2 to 7). Simulated and recorded flood-frequency estimates were developed and combined for each site. Using T-year recurrence-interval flood estimates as dependent variables, multiple regression analysis was used to develop equations to predict flood peaks at ungaged sites from independent basin characteristics.

In the second method, data from 80 storms during a 25-year period when urban development was occurring were analyzed for changes in runoff characteristics at 1 of the 13 sites. In addition, flood-frequencies for several subperiods were compared at one site to determine the influence of increased urban development.

The approach for the two methods of investigation are summarized below:

A. Analysis of 13 urban drainage basins.
   1. Collect and compile a short-term hydrologic data base for basins representing a variety of basin characteristics, including a range in the degree of urban development. Describe the basin characteristics in numerical terms, including characteristics for urban development.
   2. Calibrate a rainfall-runoff model for each streamflow-gaging site and use the calibrated model with long-term rainfall data to simulate annual peak discharges for the period of record of the historical rainfall.
   3. Develop flood-frequency relations for each site using the simulated long-term data and log-Pearson type III analytical procedures as described in Carrigan and others (1977).
   4. Develop flood-frequency relations for each site using recorded annual peak discharge and log-Pearson type III analytical procedures. Weigh recorded flood-frequency estimates by the number of years of record, and combine the two estimates of flood frequency for each site to obtain a combined flood-frequency relation.
   5. Use multiple-regression analysis with recurrence interval floods as dependent variables and the basin characteristics as independent variables to develop mathematical equations for estimating flood peaks for selected frequencies, taking into account possible cross-correlation of the variables at some of the sites.
   6. Assess the mathematical expressions to describe the effects that are characteristic of urban development on peak discharge.

B. Waller Creek Analysis.
   1. Collect and compile a long-term hydrologic data base for two sites on an urban stream that is undergoing increases in development.
   2. Monitor changes in land use as a result of urbanization for the two sites over the period of record.
   3. Analyze changes in individual storm statistics relative to changing urban development.
   4. Calibrate a rainfall-runoff model for one site for two subperiods and use the model with long-term rainfall data to estimate

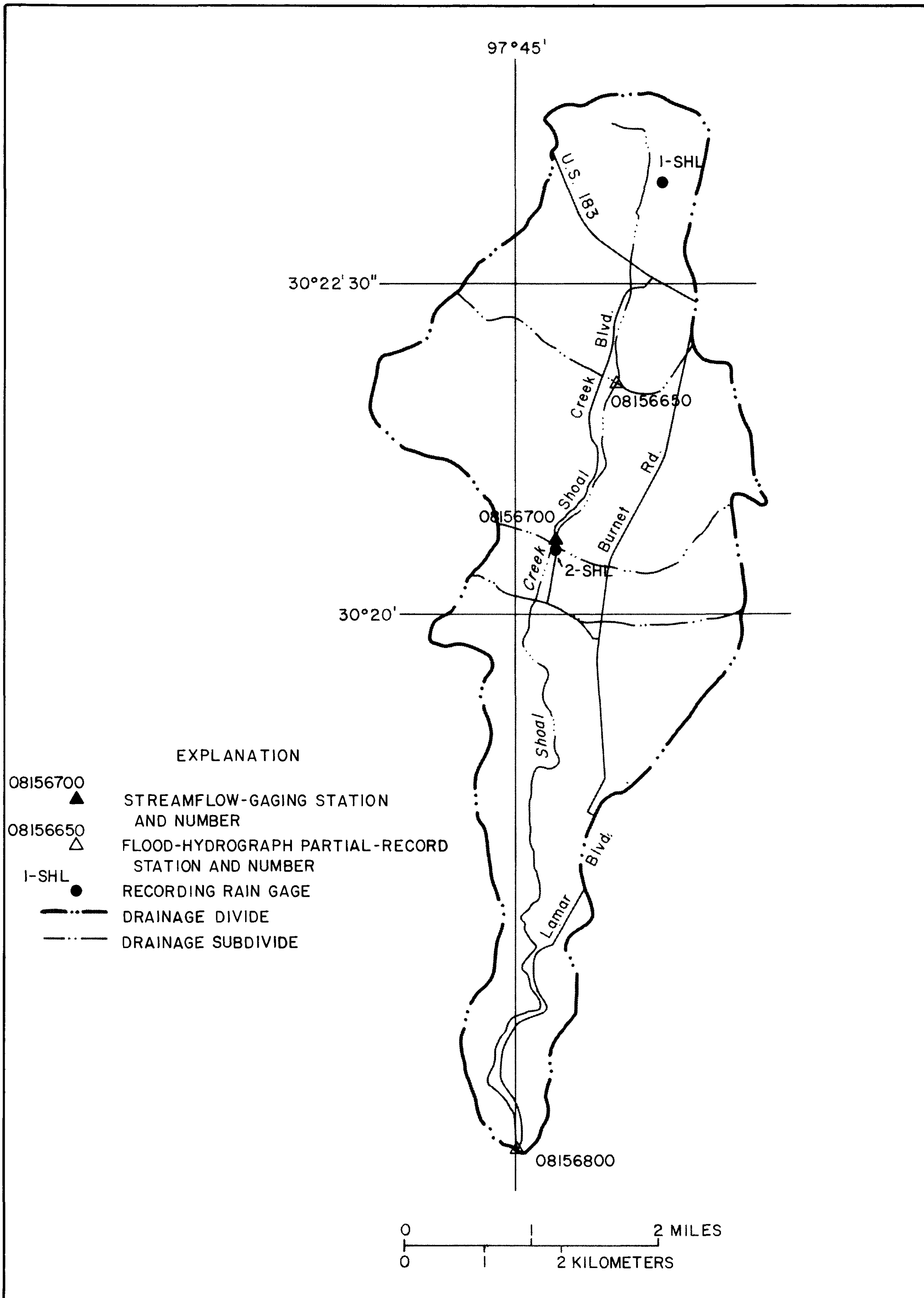

Figure 2.--Shoal Creek study area showing location of streamflow stations and recording rain gages.

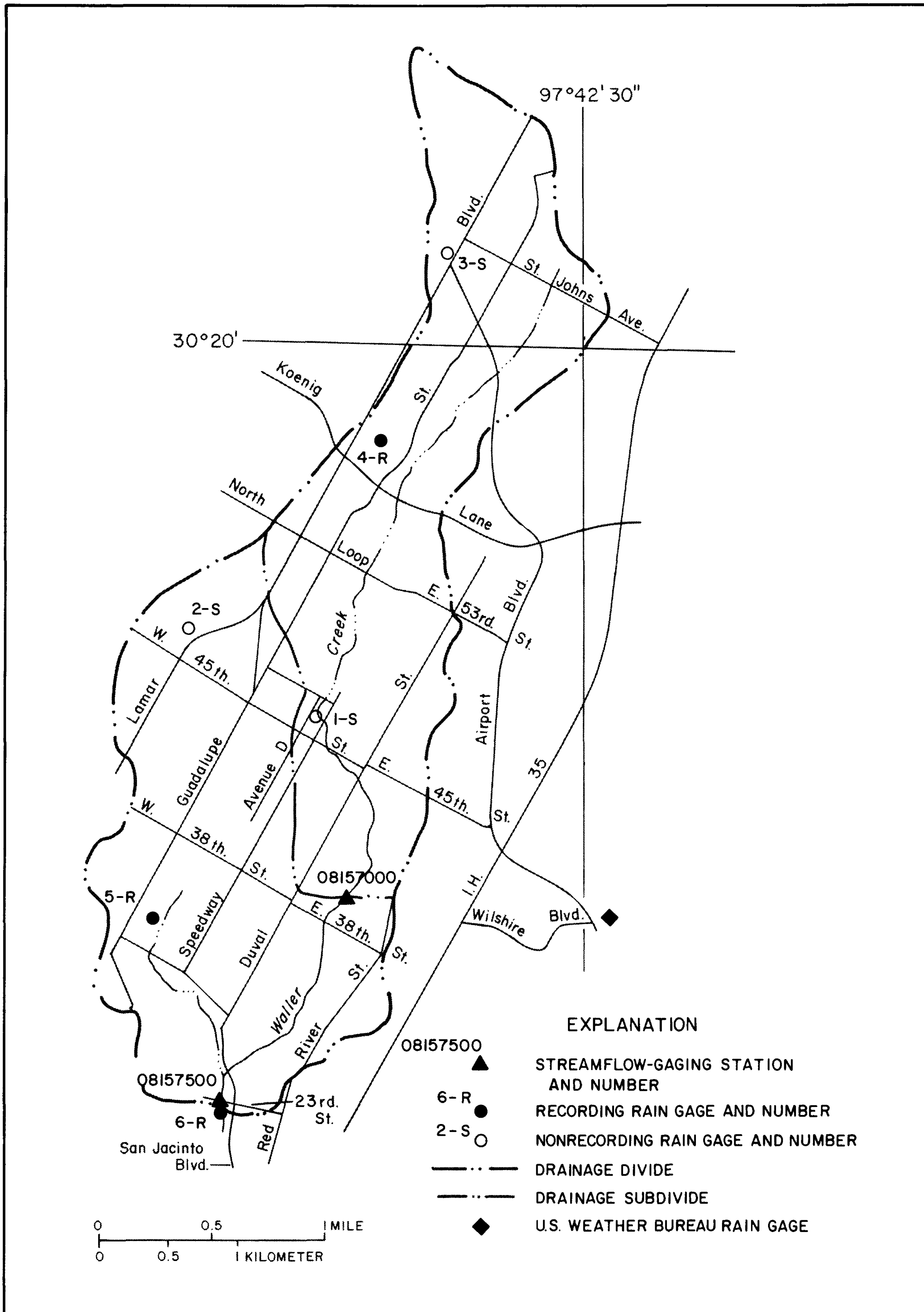

Figure 3.--Waller Creek study area showing location of streamflow stations and recording and nonrecording rain gages.

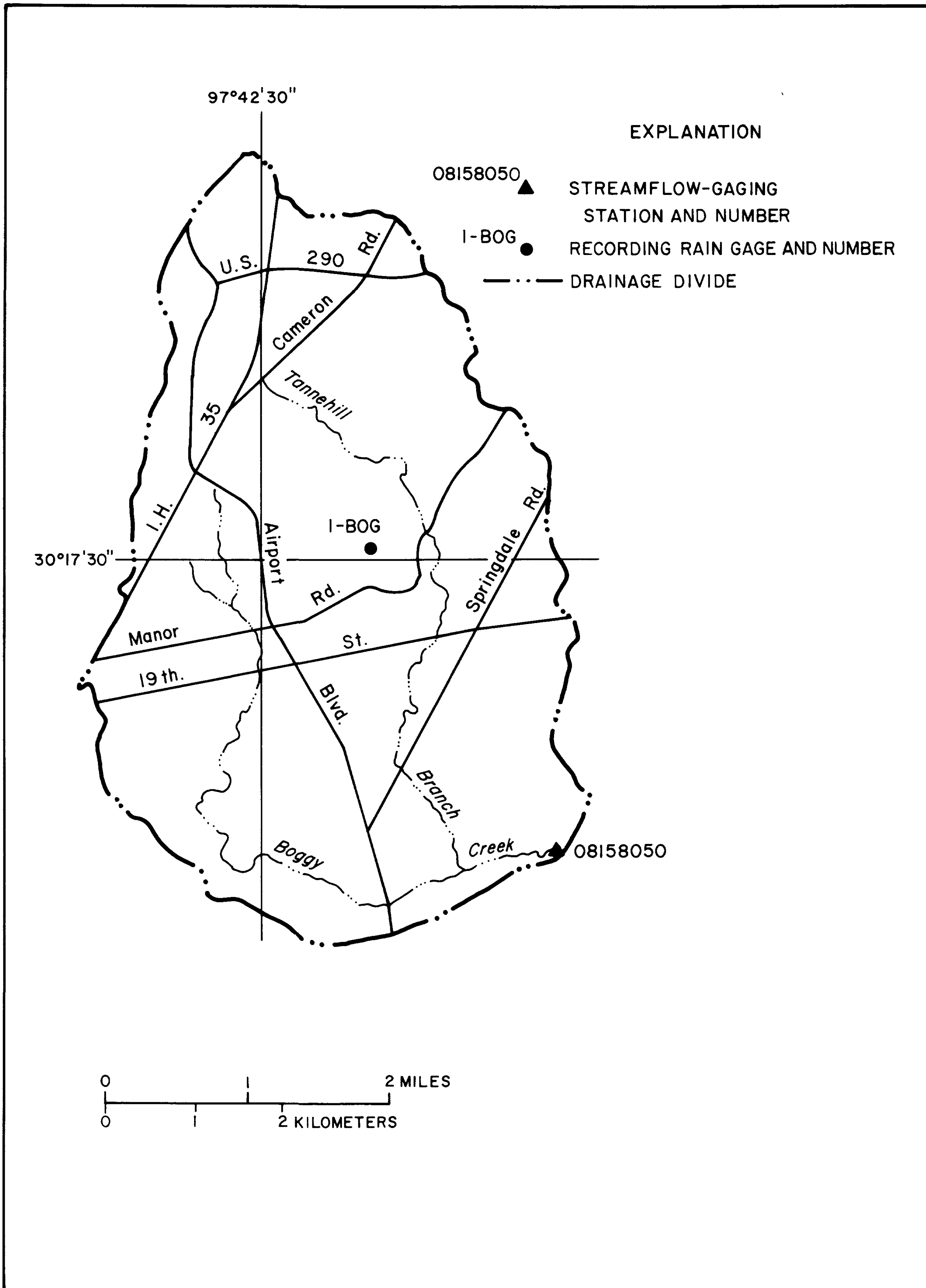

Figure 4.--Boggy Creek study area showing location of streamflow stations and recording rain gages.

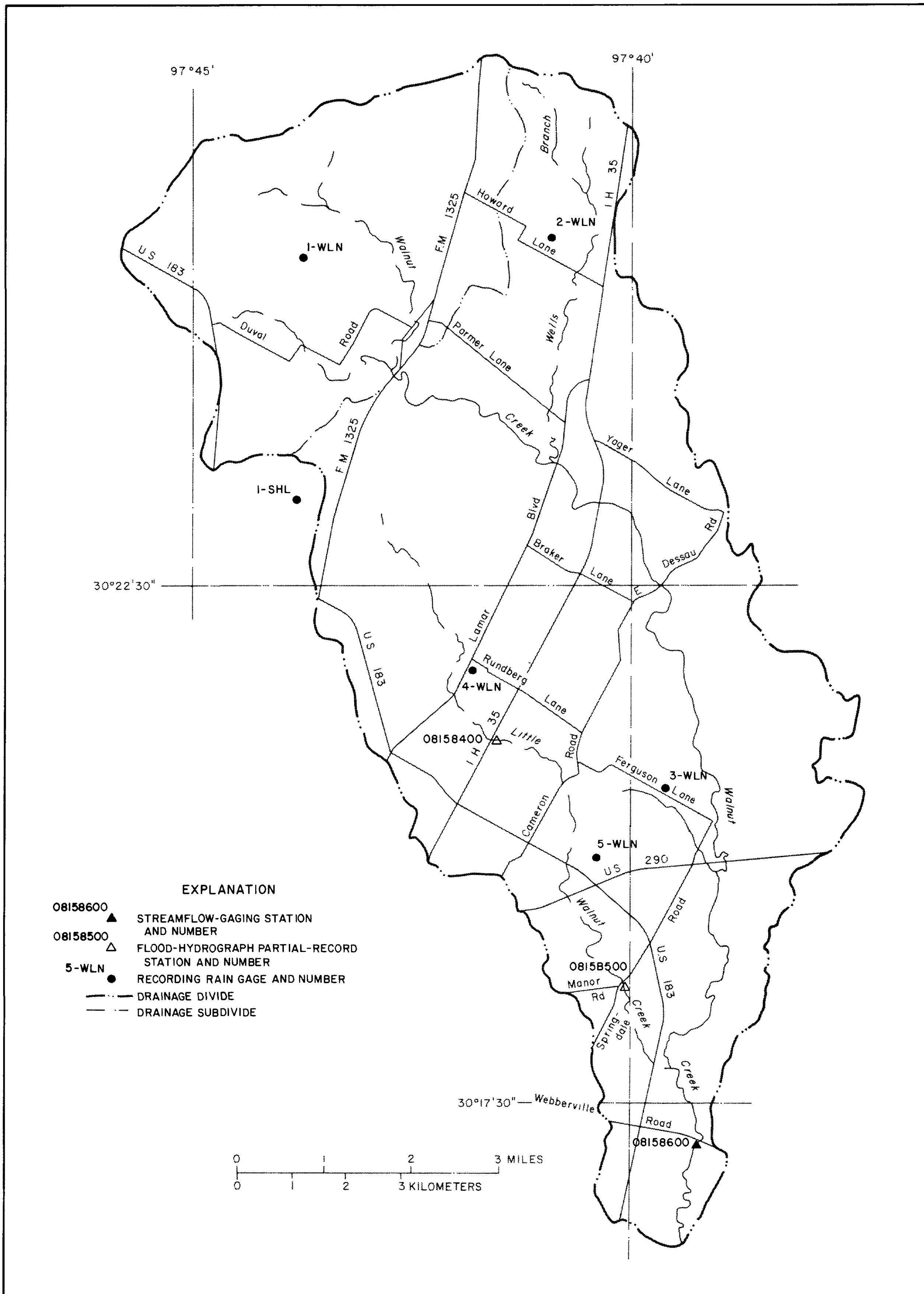

Figure 5.--Walnut Creek and Little Walnut Creek study areas showing location of streamflow stations and recording rain gages.

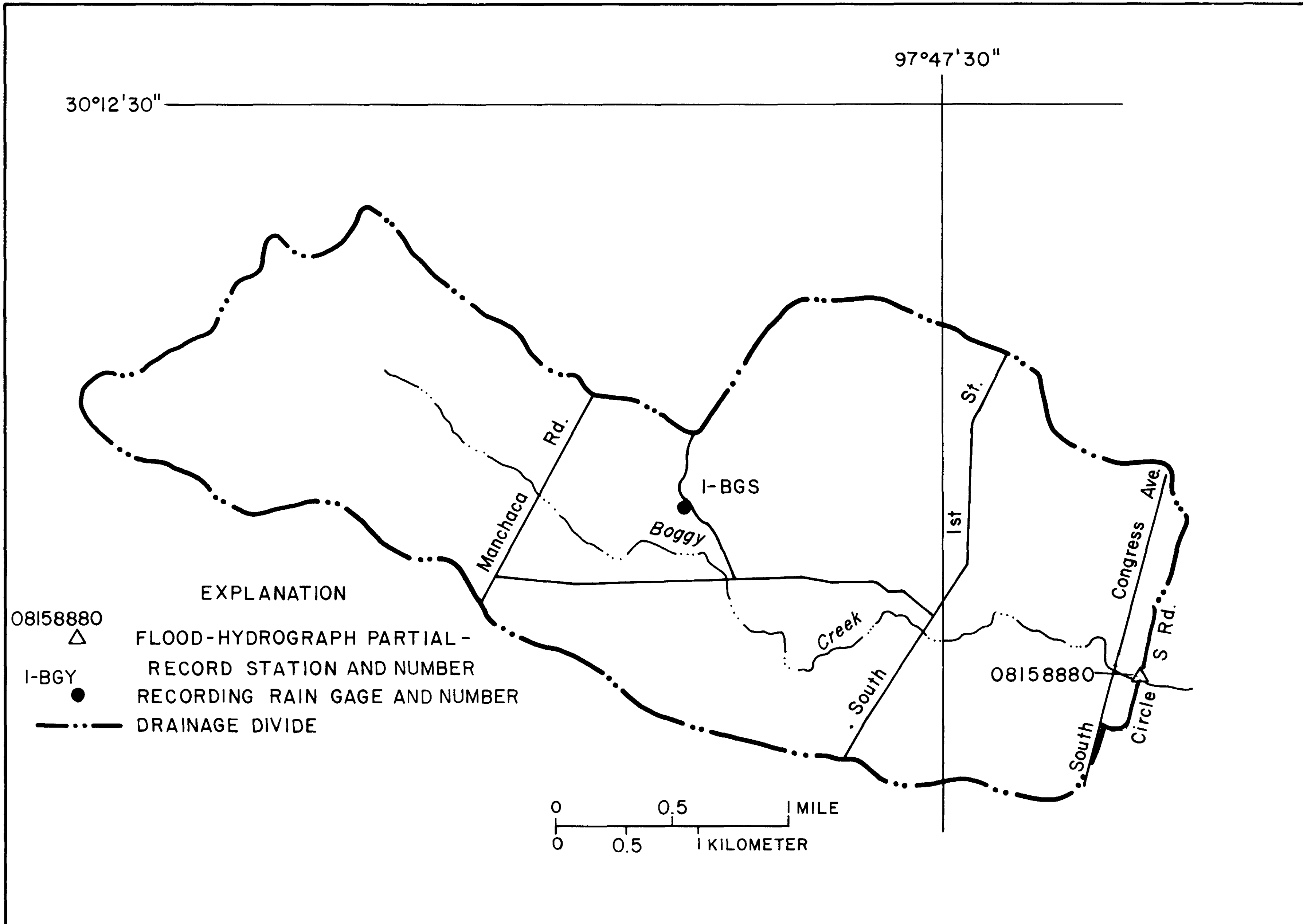

Figure 6.--Boggy Creek (south) study area showing location of streamflow station and recording rain gages.

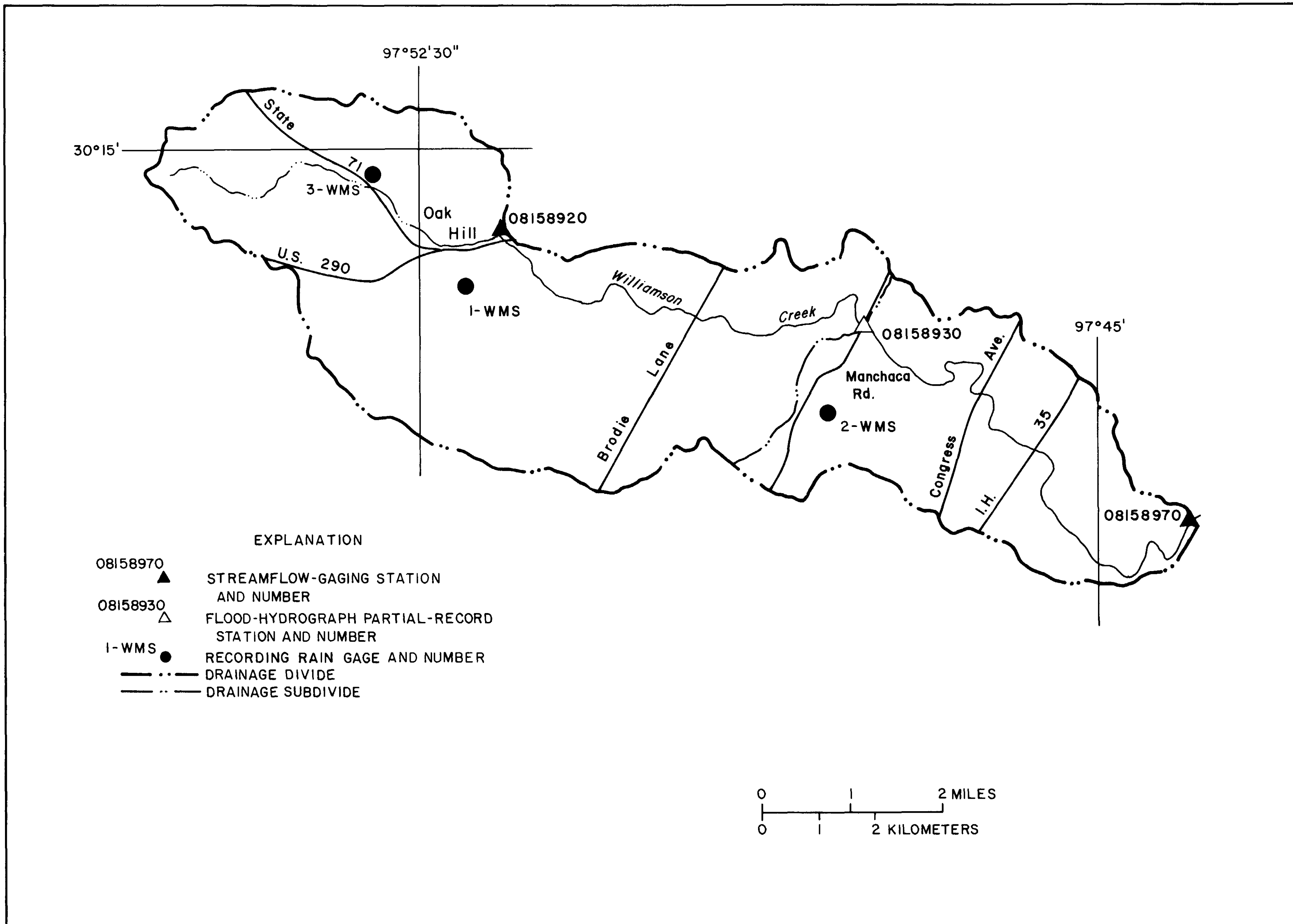

Figure 7.--Williamson Creek study area showing location of streamflow stations and recording rain gages.

annual peak discharges for the period of record of the historical rainfall.

5. Develop flood-frequency relations for each subperiod using simulated long-term data and log-Pearson Type III analytical procedures. Determine the recorded flood frequency for the two different subperiods and weigh, by length of record, those with the simulated frequencies to determine a combined flood frequency at the site.
6. Evaluate flood peaks for selected frequencies at one site for the two different subperiods and relate any difference in flood peaks to changes in urban characteristics.

DATA

Hydrologic Data

In the Austin urban program since 1974, runoff data have been collected on 33 gaging sites having various size drainage areas and degrees of urban development. In addition, runoff data have been collected on Waller Creek for 25 years (1955-80) for two sites. Precipitation data associated with these gaging sites have been collected at 31 recording rain gages. In addition, three storage nonrecording rain gages were operated within the Waller Creek watersheds along with the three recording rain gages (fig. 3). Several storms were analyzed yearly for each basin by tabulating and compiling the time distribution of runoff and associated rainfall. Daily-mean discharges were computed at the continuous-record streamflow stations. The flood-hydrograph streamflow stations recorded those discharges higher than a predetermined magnitude at each site. About half of all the sites were continuous-record sites and half were flood-hydrograph stations.

The hydrologic data required for the calibration of the rainfall-runoff model consist of incremental values of storm discharge and concurrent rainfall for the rain gages within the basin, daily rainfall for one representative rain gage, and daily values of pan evaporation. For this analysis, 13 gaging sites on 7 streams were selected because of the unchanging land use for the period of record, good streamflow gaging records, and ideally a minimum of about 10 storms during the period of record that had uniformly distributed rainfall. A list of the streamflow-gaging stations and rainfall gages used in this analysis is presented in table 1.

Long-Term Rainfall and Evaporation Data

The long-term daily precipitation, evaporation, and incremental-precipitation data that are used with the calibrated rainfall-runoff model are from the National Weather Service rain gage, now located at the Austin Municipal Airport. Records of monthly total rainfall in Austin are available from various cooperative sources since 1856, and records of daily rainfall for Austin are available since 1898. Data for incremental values of rainfall are available since 1926, when the National Weather Station was established in Austin. The data consist of detailed rainfall rates for all short-duration storms that exceeded a specified intensity for each duration.

Since its establishment, the National Weather Service rain gage has been

Table 1.--Streamflow and rainfall gages with period of record of storms used to calibrate the rainfall-runoff model

Streamflow station number and name		Rain gages identification	Period of record for storms used
08156650	Shoal Creek at Steck Avenue, Austin, Texas	(1-SHL)	1976-82
08156200	Shoal Creek at Northwest Park, Austin, Texas	(1-SHL) (2-SHL)	1976-82
08156800	Shoal Creek at 12th Street, Austin, Texas	(1-SHL) (2-SHL)	1976-82
08157000	Waller Creek at 38th Street, Austin, Texas	(4R) (5R)	1956-80
08157500	Waller Creek at 23rd Street, Austin, Texas	(4R) (5R) (6R)	1956-80
08158050	Boggy Creek at US Hwy. 183, Austin, Texas	(1-BOG)	1976-79
08158400	Little Walnut Creek at IH-35, Austin, Texas	(1-SHL) (4-WLN)	1976-81
08158500	Little Walnut Creek at Manor Rd., Austin, Texas	(1-SHL) (4-WLN) (5-WLN)	1976-81
08158600	Walnut Creek at Webberville Road, Austin, Texas	(1-WLN) (2-WLN) (3-WLN) (4-WLN) (5-WLN)	1976-82
08158800	Boggy Creek (south) at Circle S Rd., Austin, Texas	(1-BGS)	1977-82
08158920	Williamson Creek at Oak Hill, Texas	(1-WMS) (3-WMS)	1978-82
08158930	Williamson Creek at Manchaca Road, Austin, Texas	(1-WMS) (2-WMS) (3-WMS)	1976-82
08158970	Williamson Creek at Jimmy Clay Rd., Austin, Texas	(1-WMS) (2-WMS) (3-WMS)	1976-81

located at four sites before being moved to its present location at the Austin Municipal Airport in 1942. Standardization of specification for rainfall measurement was established in 1947, thus any recorded rainfall prior to that date may be inconsistent with data collected since 1947. Also, because the gage has been at many different locations, areal variation that may occur in the Austin area may be reflected in the recorded data. The annual rainfall, maximum monthly rainfall, and maximum daily rainfall for the different periods of record were compared statistically by the Cramer-von Mises test (Conover, 1971). All data except data prior to 1898 were found to be from the same statistical population distribution.

The 3 to 5 largest 2-day storm rainfall totals for each year were selected from Austin long-term daily rainfall records. For these storms, 5-minute rainfall data were compiled. However, because this study includes some drainage basins less than 3 square miles in area, and maximum runoff may occur during short-duration storms of high intensity, the 3 to 5 largest 2-day storms may not cause the annual flood peak. For this reason, the storm data were supplemented with additional shorter-duration high-intensity storm data that may cause the annual flood peak for these small drainages.

The major storms from 1928-82 recorded at the National Weather Service gage in Austin are presented in table 2. A plot showing 55 annual maximum 60-minute rainfalls compared to 3 locally accepted rainfall frequency-duration curves is shown in figure 8. The long-term rainfall for the 60-minute duration conformed with the 3 more commonly used frequency-duration curves from the U.S. Weather Bureau (1955, 1961) and Carter (1975), the latter found in Annex A of the City of Austin Drainage Design Manual. Other long-term rainfall for the durations from 30 to 180 minutes also conformed with the 3 accepted frequency-duration curves. The 55 annual maximum rainfalls in this plot are 60-minute rainfalls recorded at fixed 5-minute intervals, whereas the 3 plotted frequency curves are true intervals from the beginning of the 60-minute maximum rainfall to the finish. The difference in measurement intervals could cause an average of 2 percent less 60-minute maximum precipitation for the 55-year annual maximums, compared to the other 3 curves for 60-minute durations.

Another problem associated with using the existing incremental rainfall record for annual peak discharge simulation is that the rainfall used may be from a site that is not in the path of some of the high-intensity storms. In the Austin area, 5 of the 26 U.S. Geological Survey rain gages recorded greater 120-minute rainfall during the May 25, 1981, flood than the Austin Weather Service gage has recorded for the entire 55-year period of record. This is mostly attributed to the much denser network of rain gages in and around the Austin area (31 gages in the Austin urban study versus 1 National Weather Service gage) and the resulting higher probability of a high-intensity storm occurring over a gage.

According to a report by the National Weather Service (Grice and Maddox, 1985), the May 25, 1981, storm does not appear to be an unusual event when considering the entire South Texas area. Because of the small areal coverage, the chance for an individual site being hit by a storm of such magnitude during only 6 years of operation is less probable. The Austin Weather service

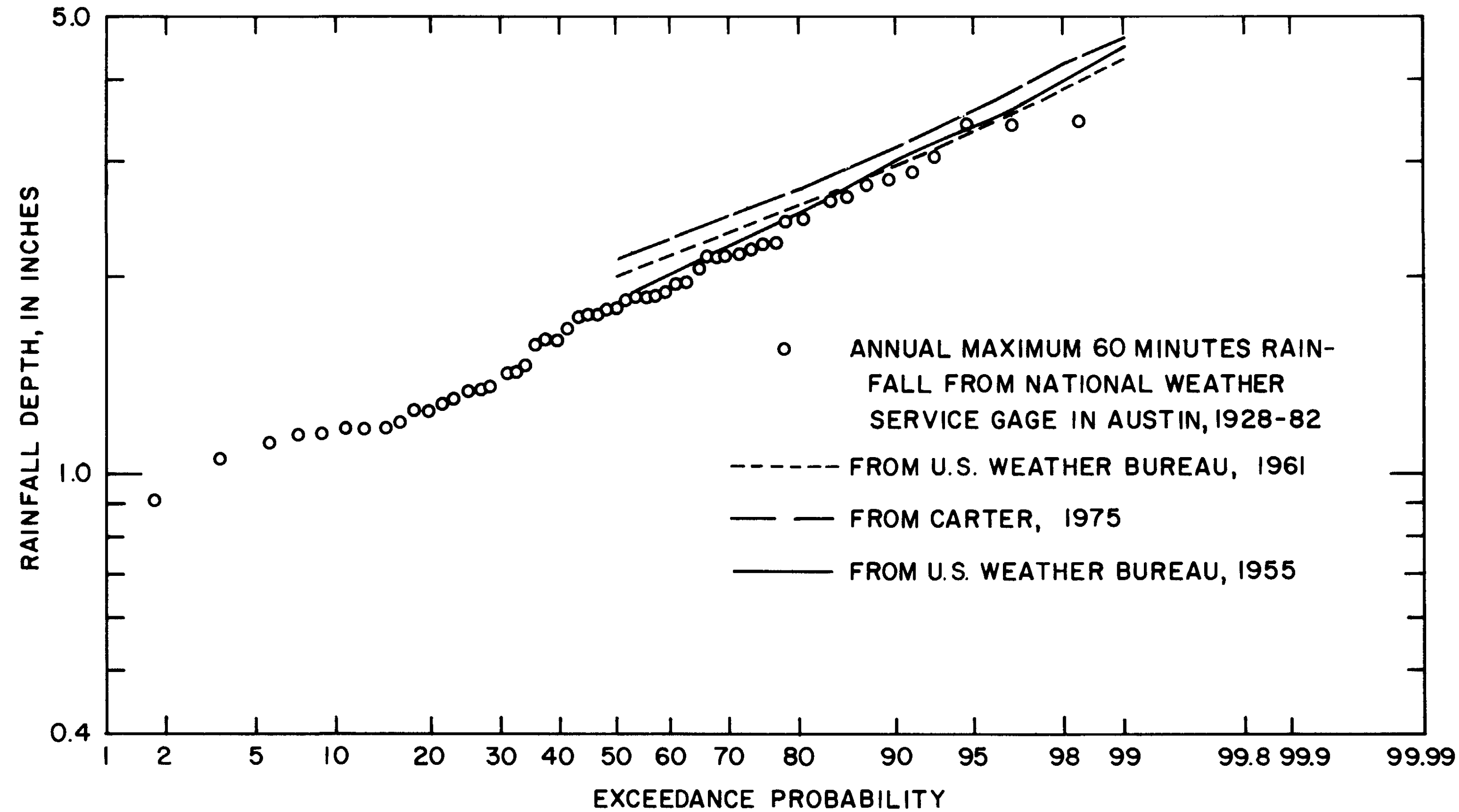

Figure 8.—Rainfall depths and probabilities for 60-minute rainfall duration.

Table 2.--Major storms from 1928-82 recorded at the National Weather Service gage in Austin

Water year	Storm date		Maximum 60-minute accumulated rainfall (inches)	Total rainfall (inches)
1928	Oct.	1	1.17	3.12
	Dec.	28	1.02	1.79
	Feb.	21	1.11	2.05
1929	May	26	1.11	2.02
	Sept.	14	1.46	2.01
1930	May	6	1.83	1.96
1931	Dec.	4	1.58	3.13
	Feb.	22	1.66	2.04
	Apr.	29	1.76	2.88
	July	15	1.74	1.75
1932	Aug.	18	1.42	1.88
	Sept.	3	.95	1.83
1933	July	30	1.05	4.93
1934	Oct.	26	1.87	1.95
	Jan.	27	.82	3.12
1935	May	18	1.62	2.60
	June	1	3.41	4.91
1936	July	16	2.23	5.07
	Aug.	30	1.85	1.86
1937	Aug.	24	1.40	3.02
	Sept.	3	1.86	2.11
1938	Jan.	23	.97	2.02
	June	17	1.11	1.11
	Sept.	14	1.20	1.36
1939	June	25	1.67	1.71
1940	Apr.	6	1.16	2.59
	June	28	1.47	2.94
1941	June	6	3.43	7.14
1942	Oct.	23	1.40	1.76
	Apr.	8	1.95	4.93
	Sept.	3	1.72	1.74
1943	Mar.	24	1.21	2.34
	Apr.	8	2.41	2.60
1944	May	1	2.45	2.84
	Sept.	6	3.41	3.87
1945	Dec.	4	1.93	3.22
	Mar.	30	1.49	1.50
	Apr.	23	1.25	1.25
	Aug.	29	1.58	3.94
1946	Apr.	22	1.83	3.29
	May	15	2.19	2.19
	Sept.	1	1.64	2.50
1947	Nov.	3	2.89	4.01
	May	16	.97	1.35
1948	May	6	1.26	1.27
	May	11	1.03	1.65
	July	4	1.33	1.33
1949	Sept.	9	2.16	3.22
1950	Apr.	23	1.90	2.37
	Sept.	10	1.22	2.04
1951	June	3	1.58	3.79
	June	12	2.17	2.32
	Sept.	9	1.34	1.97
1952	May	27	.80	1.41
	June	5	1.18	1.20
1953	Apr.	29	1.25	1.37
1954	Oct.	23	3.04	4.08
	May	25	1.18	1.63
1955	Feb.	4	.65	1.45
	May	19	.91	2.21
1956	Feb.	8	1.20	1.44
	May	1	1.20	2.08
1957	Apr.	26	1.67	2.12
	May	26	1.58	3.25
	June	12	2.14	3.03
	Sept.	22	1.38	2.55

Table 2.--Major storms from 1928-82 recorded at the National Weather Service gage in Austin--Continued

Water year	Storm date	Maximum 60-minute accumulated rainfall (inches)	Total rain-fall (inches)	Water year	Storm date	Maximum 60-minute accumulated rainfall (inches)	Total rain-fall (inches)
1958	Oct. 15	1.23	2.07	1970	Dec. 5	0.50	2.40
	July 6	1.97	2.32		Feb. 6	.60	2.10
					May 15	1.05	3.65
1959	Sept. 23	2.46	2.56		May 26	1.15	1.55
1960	Oct. 4	.80	3.22	1971	Oct. 5	1.35	1.70
					Aug. 4	1.34	3.03
1961	Oct. 29	2.63	7.22				
				1972	Nov. 18	1.18	1.42
1962	June 3	1.53	1.53		May 2	2.17	3.12
	Aug. 25	1.96	4.74				
				1973	Sept. 26	1.79	6.72
1963	Apr. 4	1.18	2.22				
				1974	Oct. 11	2.22	4.56
1964	June 16	1.60	6.75		Apr. 23	--	1.30
	Sept. 16	1.40	2.75		May 9	1.12	3.33
	Sept. 27	.90	2.45				
				1975	Nov. 23	1.10	5.09
1965	Oct. 26	1.30	3.45		Apr. 28	1.13	2.57
	Jan. 21	.80	3.45		May 23	2.78	4.94
	Feb. 16	.40	2.00				
	May 16	2.80	3.20	1976	Apr. 18	.84	3.53
	Sept. 22	1.15	3.60		June 26	--	2.58
					Sept. 2	1.14	1.70
1966	Dec. 2	.35	2.55				
	Apr. 24	.70	2.75	1977	Apr. 15	1.10	3.29
	Aug. 11	1.75	2.75		Sept. 13	1.29	1.60
					Sept. 19	1.00	1.40
1967	May 20	.90	1.50				
	Aug. 17	1.25	1.35	1978	May 2	1.86	1.99
					May 26	1.27	1.76
1968	Oct. 15	1.30	2.75				
	Nov. 9	.70	2.70	1979	May 21	1.89	5.81
	Dec. 15	1.30	1.75		July 19	2.70	4.81
	Jan. 20	.55	1.90				
	May 10	1.20	1.75	1980	Mar. 27	1.07	2.66
	May 17	1.20	2.00		Apr. 25	1.18	1.59
	May 27	1.13	1.23		Sept. 25	.85	1.95
	July 9	1.60	2.50				
				1981	Mar. 3	.51	1.63
1969	Nov. 30	.25	1.60		May 24	2.07	4.64
	Apr. 12	.45	2.40		June 13	1.89	11.42
	June 24	1.25	1.65				
	Aug. 14	2.65	2.85	1982	May 13	1.04	3.37
	Aug. 25	.85	1.90				

record, from which all three plotted rainfall-frequency curves are derived, as well as the long-term record for this analysis, may be slightly biased towards smaller storms.

Basin Characteristics

Selected characteristics of the 13 drainage basins, including Waller Creek for two periods and conditions of urbanization, are presented in table 3. These basin characteristics have been used in other investigations and are considered to be potentially significant factors affecting peak discharge. Several additional physical basin characteristics and several different indicators of basin urban development that are variations of those listed in table 3 are described below.

The basin characteristics used in the analysis of the 13 stations are:

1. Contributing drainage area--The drainage area (in square miles) of the basin at the gaging site. Values for drainage areas of basins in the Austin area ranged from 2.31 to 51.3 square miles.
2. Stream channel length--Stream length (in miles) measured along the main channel from the gage to the basin divide.
3. Main channel slope--The slope (in feet per mile) of the main channel, between points, 10 and 85 percent of the stream length upstream of the the gage.
4. Basin shape--The square of the stream channel length divided by the drainage area.
5. Geologic factor--The percentage of each watershed underlain by several local geologic formations with a special emphasis in ascending order on the Cretaceous--Glen Rose Formation, Edwards Limestone, and Georgetown Formation. The percentage of drainage area underlain by the Edwards and Georgetown Formations and the percentage of drainage area underlain by the Glen Rose, Edwards, and Georgetown Formations were compared with observed flood-frequency statistics (table 7); the former comparison was used because it had the highest correlation with the standard deviation of the flood frequencies. Geologic information was taken from a map prepared by Garner and Young, 1976.
6. Mean channel elevation--The mean channel elevation (in feet above mean sea level) between points, 10 and 85 percent of stream length upstream from the gage.
7. Length-slope ratio--Length (in miles) divided by the square root of the slope in feet per mile.
8. Total percentage of impervious cover--The percent of the total contributing drainage area that is impervious, including those areas that are covered by streets, buildings, and parking lots. The values of impervious cover were determined from estimates of various land uses in each basin except in the case of Waller Creek where four different determinations of impervious percentage were determined by field and grid method from 1955-80.
9. Total impervious drainage area--Total percentage of impervious cover multiplied by the contributing drainage area.
10. $1 + \frac{\text{total percentage of impervious cover}}{100}$--Similar to the use of the

coefficient of imperviousness by Carter (1961).

11. Urbanization index--A variable defined by Sauer and others (1983) to describe a generalized technique for estimating the magnitude and frequency of floods in urban areas. The urbanization index is used to more accurately quantify the degree of urbanization by incorporating the factors of storm sewers, curbs and gutters, and channel modifications. The index is developed by considering these alterations in the upper, middle, and lower third of the drainage basin. Land and others (1982) modified the index to be a function of the percentage of each factor in each one-third of the basin. Each factor carries an equal weight regardless of the location within the subbasin. The values of each factor range from 1 to 4, based on the degree of development. The sum of the 9 factors can range from 9 to 36 and presents the value of the urbanization index.

The factor values and corresponding percentages of the subbasin affected are:

Percent	Value
0- 24	1
25- 49	2
50- 74	3
75-100	4

The following example of Waller Creek at 38th Street for the 1966-80 period is given to illustrate the determination of the urbanization index:

Subarea	Factors			Total
	Storm sewers	Curb and gutters	Channel rectifications	
Upper	4	4	2	10
Middle	3	4	1	8
Lower	3	4	1	8
Urbanization index				26

The values of each basin characteristic for each stream are given in table 3.

During the period of record, only slight increases in development were noted for several of the basins and except for the two sites on Waller Creek, all were judged to be suitable for model calibration. Urban development in the Waller Creek basin has increased since the gages were installed in 1955. The percentage of impervious cover, a common indicator of urban development, was measured by field survey in 1954, and by grid-sampling method in 1962, 1966, and

Table 3.--Selected characteristics of the study basins

[L^2/A = (stream channel length)^2/contributing drainage area]

Station number	Period of record	Contributing drainage age (square miles)	Stream channel length (miles)	Main channel slope (feet per mile)	Basin shape (L^2/A)	Geologic factor	Impervious cover (percent)	Urbanization factor
08156650	--	2.79	2.62	48	2.46	54	28	19
08156700	--	6.52	4.11	33	2.59	51	38	22
08156800	--	12.3	10.1	32	8.29	31	41	24
08157000	1956-62	2.31	4.17	48	7.53	0	17 a/	--
08157000	1966-80	2.31	4.17	48	7.53	0	37 a/	26
08157500	1956-62	4.13	5.21	49	6.57	0	25 a/	--
08157500	1966-80	4.13	5.21	49	6.57	0	38 a/	27
08158050	--	13.1	7.07	35	3.82	0	40	26
08158400	--	5.57	3.94	31	2.79	0	42	23
08158500	--	12.1	8.00	35	5.29	0	37	20
08158600	--	51.3	19.5	20	7.41	17	17	14
08158880	--	3.58	4.28	44	5.12	0	12	14
08158920	--	6.30	4.87	50	3.76	2	5	12
08158930	--	19.0	10.3	38	5.58	42	10	13
08158970	--	27.6	17.5	27	11.1	28	18	14

a/ Average value for period of record (table 6).

1980. Figure 9 and table 4 show that rapid development occurred in the basin above the 38th Street gage during 1962-66, while the intervening area between the two gages was unchanged for this period. For this reason, periods prior to and after 1962-66 were chosen for comparison. Estimates of land use for 1962 and 1980 are listed in table 4 for the two gages at different time periods.

RAINFALL-RUNOFF SIMULATIONS

Rainfall-Runoff Models

The rainfall-runoff models used in this analysis were the urban and rural versions of a bulk-parameter model developed by the Geological Survey (Dawdy, Lichty, and Bergmann, 1972; Boning, 1974; and Carrigan, Dempster, and Bower, 1977). The model approximates the physical laws that govern antecedent soil moisture, infiltration, and runoff. Table 5 gives the parameters for both models and their function in the modeling process. The model was designed specifically for flood-hydrograph simulation of small drainage areas, and has been extensively used to estimate long-term flood peaks based on a relatively short-term discharge record. The model requires daily evaporation and rainfall data, and selected incremental rainfall and discharge data for calibration. The data required for simulation include daily evaporation and rainfall, incremental rainfall for the largest storms each year of the long-term rainfall record, and the parameter values determined in the calibration process. The model operates on two different time modes--first, a daily accounting of antecedent moisture during nonstorm days, and second, a 5-, 10-, 15-, 30-, or 60-minute time increment for storm-simulated days.

For the purposes of this study, both rural and urban versions of the rainfall-runoff model were used. The rural version of the model was used for drainage basins having a relatively homogeneous land use and only one rain gage. The urban version of the model was used for drainage basins having as many as 5 rain gages with land use and area distributed by rain gage subareas and 20 time-distance zones. Impervious area percentage is estimated for each land use subarea and the time-distance zones are delineated on the basis of flood-wave travel time along the stream. Figure 10 shows a typical basin configuration.

The calibration phase of the model optimizes the model parameter values within predetermined ranges of values until the computed values of runoff volumes and runoff peaks best match recorded values. This is accomplished in three successive steps: Step one involves adjustment of soil infiltration and antecedent moisture conditions to obtain the best possible relation between observed and simulated runoff volumes, step two optimizes routing parameters to best simulate runoff hydrograph shape, and step three readjusts infiltration and antecedent moisture parameters to best relate simulated peak discharges to observed peak discharges. In addition, the rural version optimizes the effective impervious area percentage for the period of calibration. Effective impervious area is that part of the total impervious area that drains directly to the drainage system (creek, channel, pipe, etc.). Noneffective impervious area is that part of the total impervious area that drains to pervious surfaces and is not hydraulically connected to the drainage system.

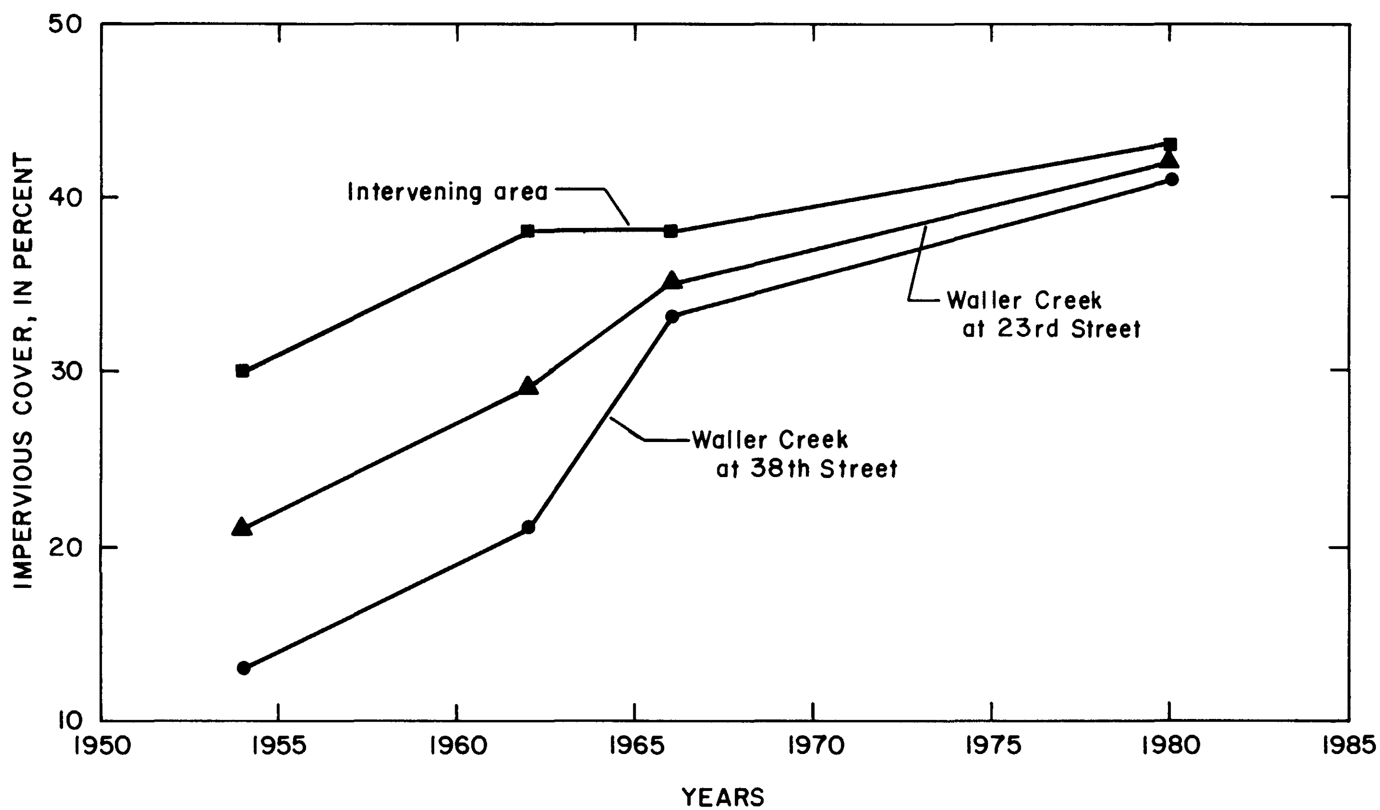

Figure 9.--Impervious cover for the Waller Creek basin, 1954-80.

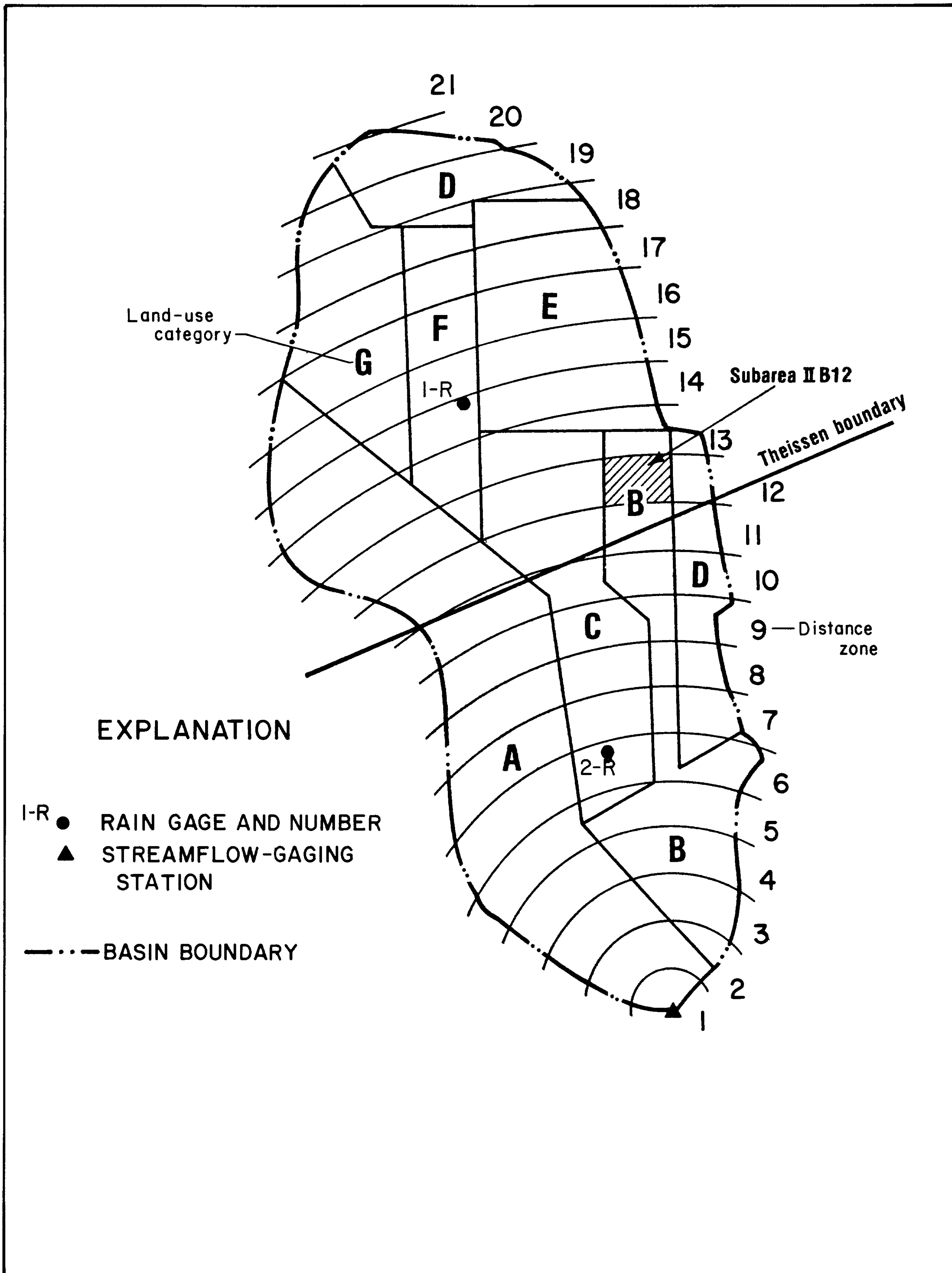

Figure 10.--Sketch showing division of a hypothetical basin into subareas according to location of rain gages, land use, and time of travel.

Table 4.--Characteristics of urban development in the Waller Creek basin, 1954-80

Station	Impervious cover (percent)				Land use estimates (percent)		
	1954	1962	1966	1980		1962	1980
Waller Creek at 38th Street	13	21	33	41	Residential	62	65
					Commercial	10	25
					Undeveloped	28	10
Intervening area	30	38	38	43			
Waller Creek at 23rd Street	21	29	35	42	Residential	67	71
					Commercial	6	23
					Undeveloped	27	6

Table 5.--Model components and parameters

Components	Parameters	Unit of measurement	Definition and function
Antecedent-moisture accounting	EVC	--	Coefficient to convert pan evaporation to potential-evapotranspiration values.
	RR	--	Proportion of daily rainfall that infiltrates the soil.
	BMSM	Inches	Soil-moisture storage volume at field capacity.
	DRN	Inches per hour	Drainage value for redistribution of soil moisture (fraction of KSAT).
Infiltration	PSP	Inches	Product of moisture deficit and suction at the wetted front for soil moisture at field capacity.
	KSAT	Inches per hour	The minimum (saturated) hydraulic conductivity used to determine infiltration rates.
	RGF	--	Ratio of the product of moisture deficit and suction at the wetted front for soil moisture at wilting point to that at field capacity.
Routing	KSW	Hours	Time characteristic for linear reservoir routing.
	TC	Minutes	Length of the base of the triangular hydrograph.

Model Calibration

Three streamflow-gaging sites having only one rain gage within their drainage basins were simulated with the rural version of the rainfall-runoff model. The additional 10 streamflow-gaging sites were simulated using the urban version of the model so that rain variation within the basin and land use and drainage area could be represented within the time-distance zones. Each rain gage subarea was determined by the Theissen polygon method and impervious values for each land-use designation were estimated from values of total and effective impervious percentages for different types of land use (Alley and Veenhuis, 1979).

After data for storms for each basin were screened for errors in rainfall distribution and discharge, the calibration process began and the soil parameter values for DRN and EVC (table 5) were kept constant because of their insensitivity and interaction with other parameters. Several simulations were attempted with the saturated conductivity KSAT set at 0.05, 0.10, 0.20, and 0.30 because of its interaction with PSP.

The rural model calculated an optimum effective impervious percentage for the entire watershed for each simulation. The optimum percentage of effective impervious area generally affects the runoff-volume simulation of the smaller storms, and the saturated conductivity of the soil generally has more affect on the larger storms. A comparison of a best fit between the simulated and recorded volumes determined the optimal values of KSAT and the corresponding effective impervious area for the final calibration. Data for each rain gage in drainage basins with multiple rain gages were used for an initial rural-model calibration to check the data and optimize effective impervious area. A Theissen-weighted effective impervious percentage for the entire basin was estimated from these single rain-gage rural model calibrations to allow the larger, more complex urban model to be calibrated in one or two simulations. The final parameter values for each basin are tabulated in table 6.

The overall success of the model was judged by comparing the base 10 logarithms of recorded and simulated peak-discharge values. The correlation coefficients ranged from 0.898 to 0.984 with a median of 0.963, while the root mean square error ranged from 13.8 to 29.7 percent with a median of 21.6 percent. The calibration statistics and calibration errors are listed in table 5. Plots of the simulated and observed flood-peak discharges from final calibrations are shown in figures 11-15. Comparison of these figures and the calibration errors listed in table 6 indicate that the model was fairly well calibrated for all 13 sites.

Estimation of Flood-Peak Discharges

Rainfall and evaporation data from the National Weather Service gage at the Austin airport were used with the calibrated model to compute simulated long-term peak discharges for each site. The basin model representation for both rural and urban model long-term simulation was similar to the calibration phase except for the use of only one rainfall record for the entire drainage basin. Thus, the long-term flood simulation creates the same effect as if the rainfall occurred uniformly over the entire basin. An annual flood series was developed for each gaging site from the simulated peak discharges.

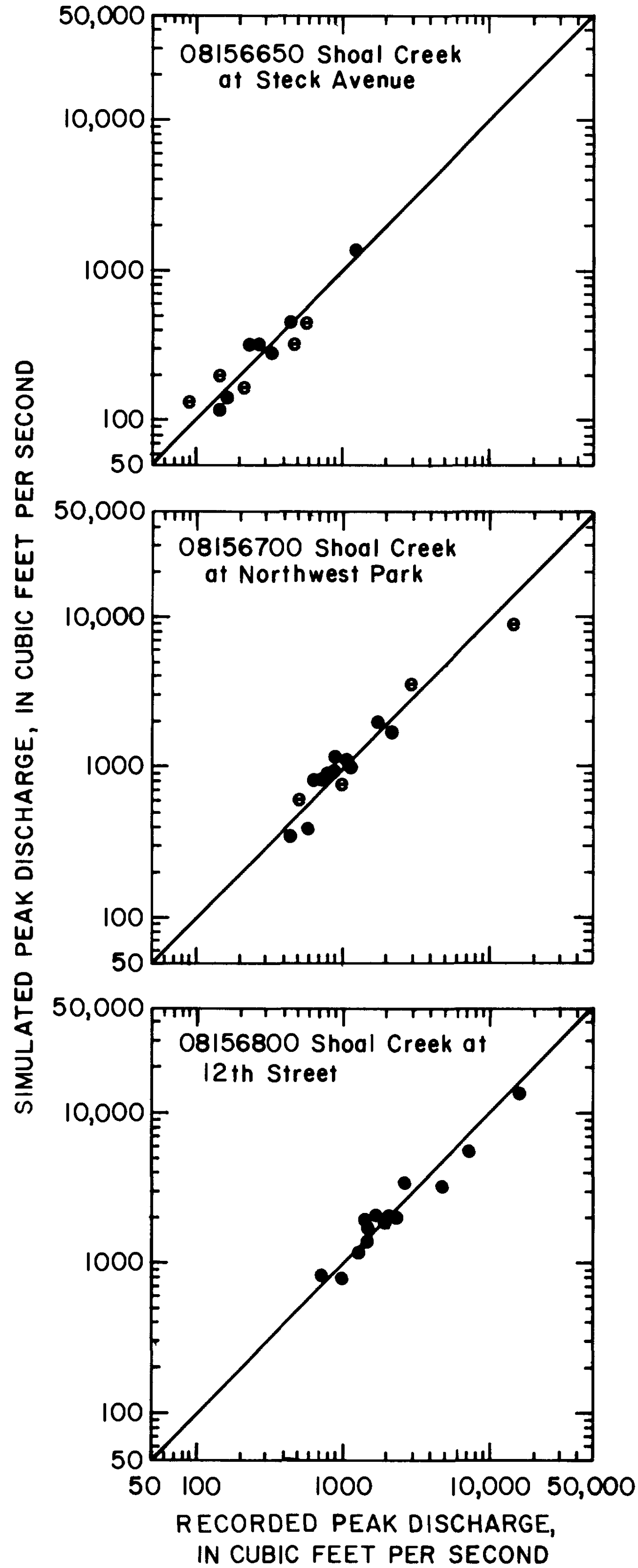

Figure 11.--Recorded and simulated flood-peak discharges from model calibration for streamflow-gaging stations 08156650, 08156700, and 08156800.

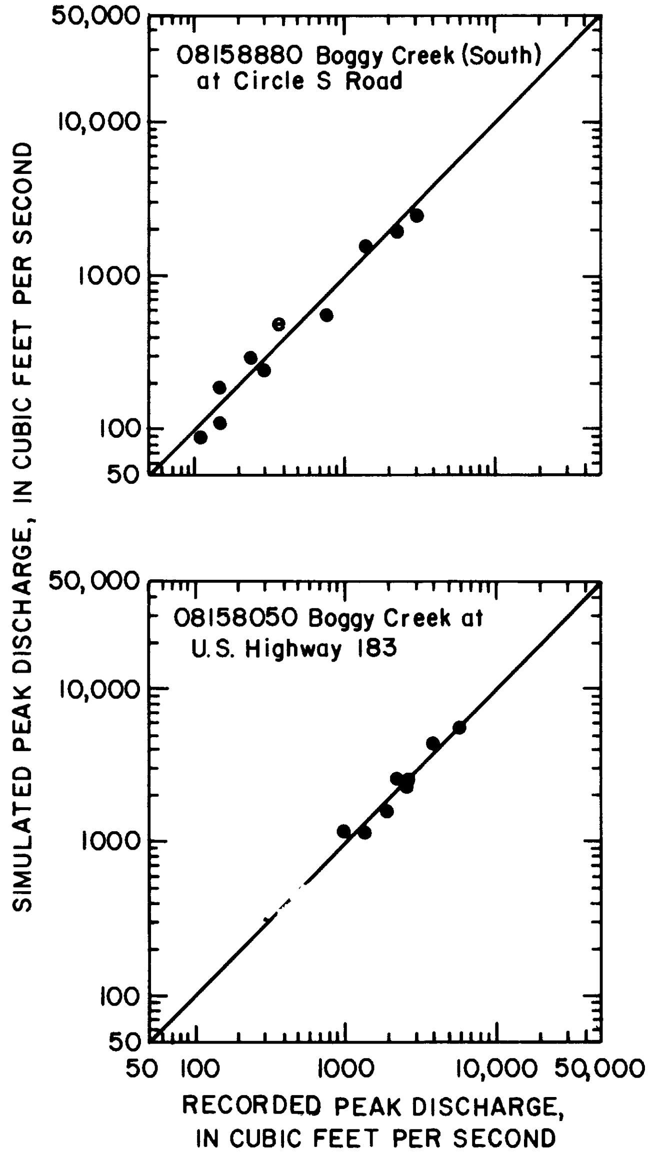

Figure 12.—Recorded and simulated flood-peak discharges from model calibration for streamflow-gaging stations 081588050, and 08158880.

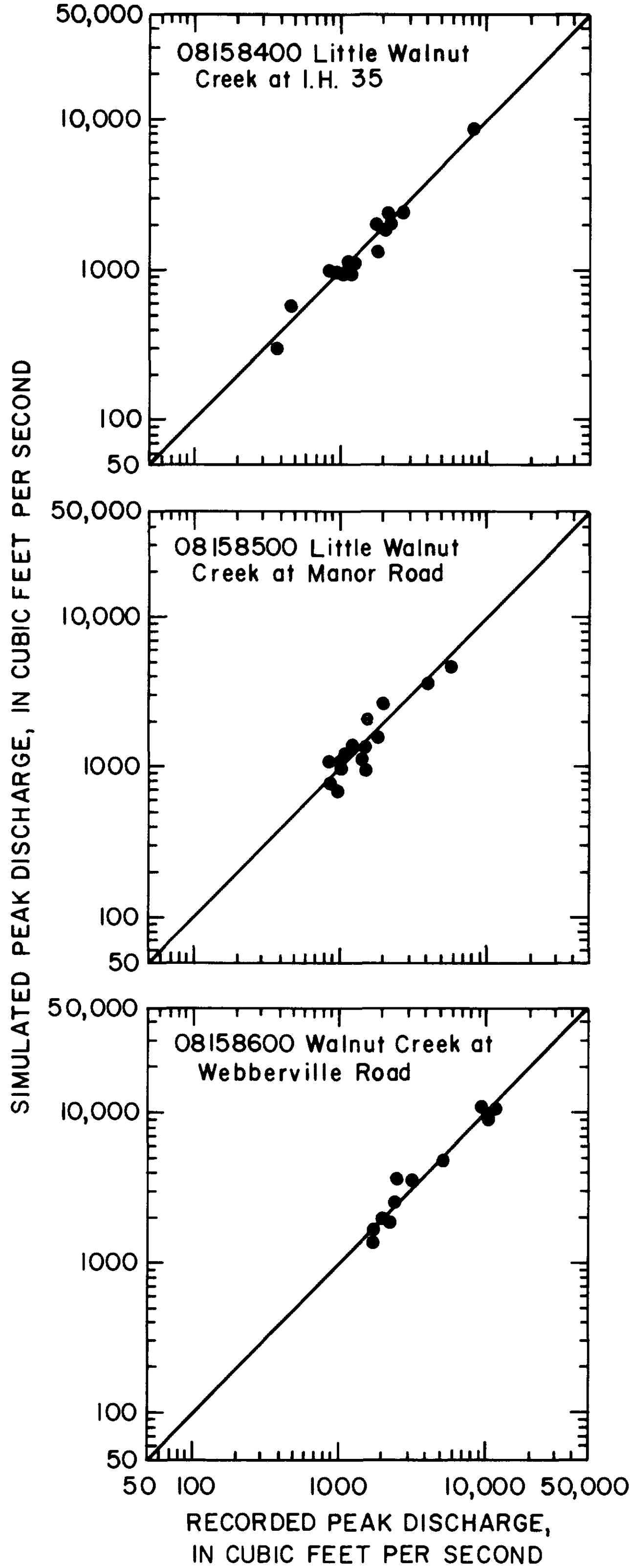

Figure 13.—Recorded and simulated flood-peak discharges from model calibration for streamflow-gaging stations 08158400, 08158500, and 08158600.

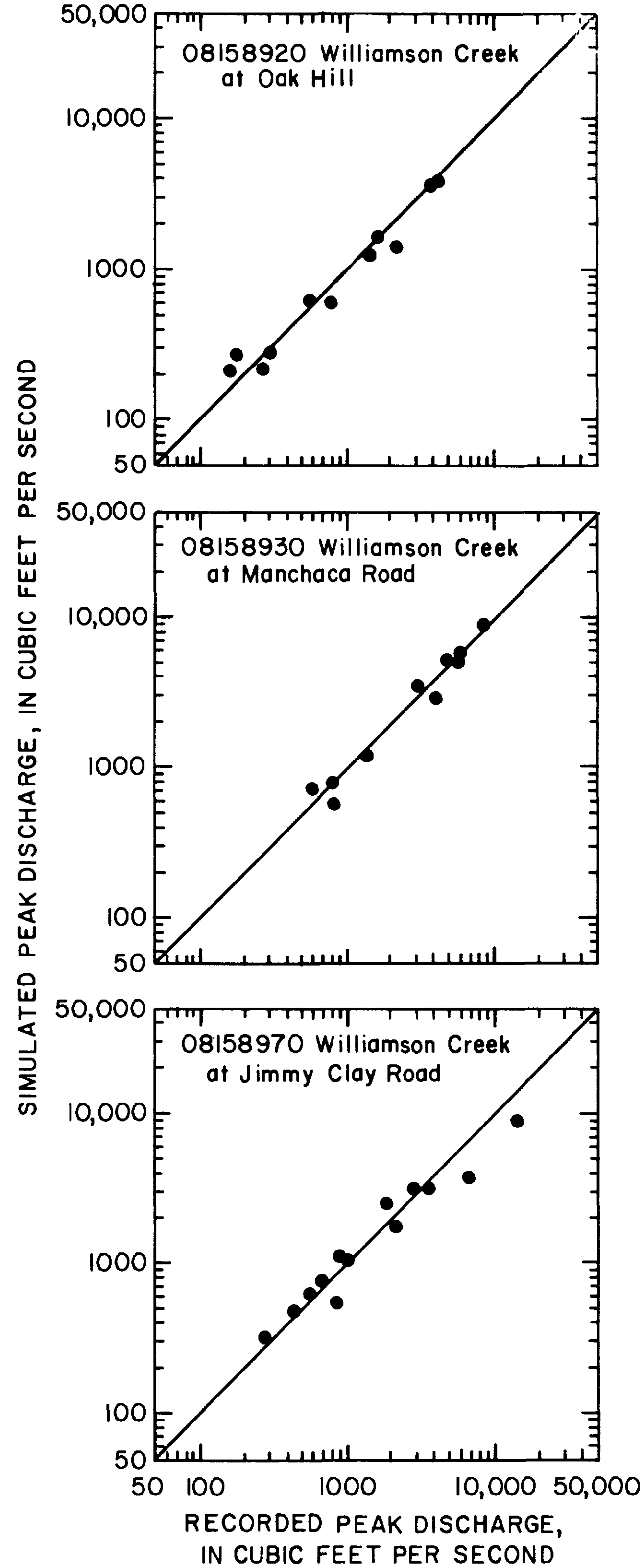

Figure 14.—Recorded and simulated flood-peak discharges from model calibration for streamflow-gaging stations 08158920, 08158930, and 08158970.

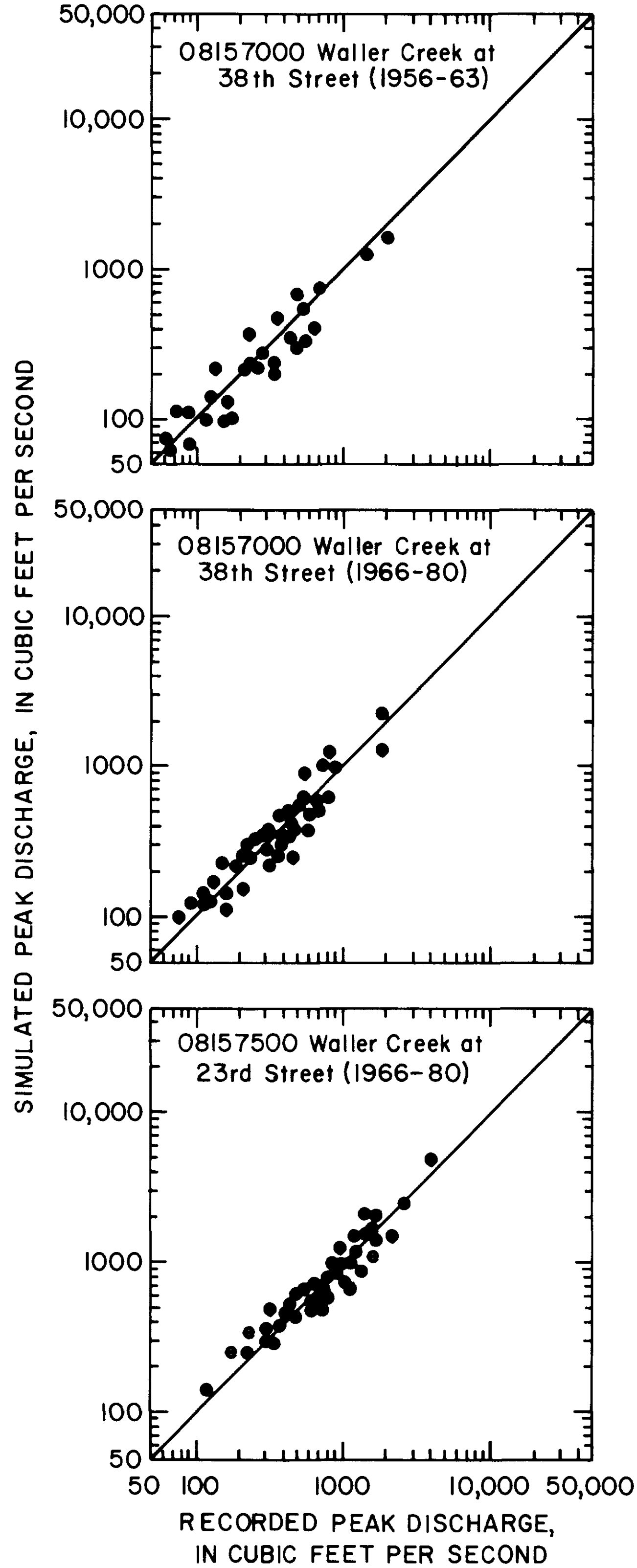

Figure 15.--Recorded and simulated flood-peak discharges from model calibration for streamflow-gaging stations 08157000 for the earlier period (1956-62) and 08157000 and 08157500 for the later period (1966-80).

Table 6.--Values for model parameters and selected calibration statistics

(RMSE, root-mean square error; ft^3/s, cubic feet per second)

Station number	PSP	KSAT	DRN	RFG	BMSM	EVC	RR	KSW	TC	Correlation coefficient (R)	RMSE (percent)	Range in recorded peak discharge (ft^3/s)	Number of peaks
08156650	1.93	0.20	1.00	10.5	12.2	0.70	0.72	0.80	48.2	0.939	25.4	90- 1,240	12
08156700	2.42	.10	1.00	12.1	8.59	.70	.77	1.77	74.6	.963	22.3	435-14,600	16
08156800	1.91	.10	1.00	11.2	6.85	.70	.71	1.79	117.1	.971	18.8	732- 7,310	13
08157000	3.21	.20	1.00	10.8	2.49	.70	.92	.70	78.1	.934	26.1	75- 1,810	42
08157000	1.97	.20	1.00	17.4	3.04	.70	.88	1.01	81.0	.984	29.7	42- 1,970	30
08157500	3.25	.20	1.00	12.9	2.33	.70	.88	.74	69.5	.947	22.9	124- 2,620	42
08158050	2.24	.20	1.00	10.1	1.82	.70	.95	1.12	88.4	.975	13.8	1,000- 5,630	8
08158400	1.82	.10	1.00	10.2	3.50	.70	.99	1.08	86.4	.976	13.8	374- 4,530	18
08158500	3.58	.10	1.00	9.48	9.77	.70	.96	2.05	123.3	.898	24.9	862- 5,640	16
08158600	3.49	.10	1.00	11.9	2.65	.70	.89	4.79	173.2	.976	16.7	1,720-11,700	12
08158880	2.08	.10	1.00	11.4	5.20	.70	.95	1.09	60.7	.982	23.5	109- 2,920	10
08158920	1.96	.20	1.00	12.3	3.29	.70	.98	1.98	97.2	.982	21.4	159- 4,170	11
08158930	1.54	.20	1.00	11.3	3.47	.70	.83	2.42	188.8	.984	18.2	590- 8,530	11
08158970	2.09	.20	1.00	10.3	2.90	.70	.89	4.72	240.8	.974	23.6	281-14,140	11

FLOOD FREQUENCY ANALYSIS

Thirteen Sites

Flood frequency at each of the 13 sites was calculated by two different methods--from 55 years of simulated annual-peak discharges as mentioned above, and from recorded annual-peak discharges. These flood frequencies were calculated by fitting the base 10 logarithm values of each series of annual peaks to a log-Pearson Type III distribution (U.S. Water Resources Council, 1981) by the equation:

$$\log Q_T = M + KS \qquad (1)$$

Where: Q_T = The peak discharge, in cubic feet per second, for a selected recurrence interval (T), in years;
M = the mean of the logarithms of the annual peaks;
K = a Pearson Type-III coefficient, expressed as a function of selected exceedance probability and the skew coefficient (g); and
S = the standard deviation of the logarithms of the annual peaks.

Frequency curves for the simulated series of annual peaks used skew coefficients that were computed from these data. Also, when possible, skew coefficients that were computed from the recorded annual peak data were used for the recorded frequency curves. Table 10 located in the supplemental data section at the end of this report presents recorded annual peak discharges for the 13 sites. The large recorded annual peaks that occurred at many of the sites during May and June 1981, caused many of the skews from the recorded data to be unreasonable, particularly because of the short period of record. As a result, several of the flood-frequency curves for recorded data were weighted with the regional skew in proportion to their mean square error which is consistent with the method presented by the Water Resources Council (1981). Both the simulated and recorded flood-frequency curves were visually compared to the plotted recorded annual peaks for consistancy and agreement. The flood frequency characteristics for the simulated and recorded data are presented in table 7. The flood frequencies for the two Waller Creek sites are for the period 1966-80.

A comparison of the simulated and recorded flood frequency for the 13 sites shows that the simulated flood frequencies tend to have flatter slopes or smaller values of standard deviation (table 7) than the recorded flood frequencies. This effect has been noted in other studies utilizing this model for long-term annual peak simulation and has been termed the "model-smoothing effect" by researchers familiar with the technique (Kirby, 1975). The recorded flood frequencies for most of these sites were influenced by large storms occurring in 1981. Several sites experienced rainfall accumulations that exceeded those recorded during 55 years of records at the National Weather Service gage. For these sites, large storms combined with the relatively short period of record resulted in steeper recorded frequency curves than simulated curves.

Because the frequency curves derived from the two different methods were not in complete agreement, a technique was needed to combine the two frequencies

Table 7.--Summary of flood characteristics for the 13 streamflow-gaging stations

Station number	Source	Recorded annual peaks used (years)	T-year discharges (cubic feet per second) Q2	Q5	Q10	Q25	Q50	Q100	Statistical values: Mean of logs (M)	Standard deviation (S)	Skew (g)
08156650	Simulated		756	1430	1980	2800	3500	4280	2.876	0.310	-0.052
	Recorded	1975-82	620	1490	2380	3980	5590	7610	2.804	.442	.154
	Combined		715	1450	2100	3150	4130	5280			
08156700	Simulated		1,690	3,190	4,400	6,160	7,630	9,230	3.219	.323	-.137
	Recorded	1976-84	1,490	3,580	5,770	9,720	13,700	18,800	3.186	.442	.185
	Combined		1,620	3,330	4,890	7,440	9,820	12,700			
08156800	Simulated		2,920	5,220	7,030	9,610	11,700	14,000	3.460	.287	-.102
	Recorded	1975-84	2,690	5,980	9,140	14,500	19,500	25,600	3.436	.407	.088
	Combined		2,820	5,540	7,920	11,700	15,000	18,800			
08157000 a/	Simulated		732	1,240	1,650	2,250	2,760	3,320	2.871	.252	.142
	Recorded	1966-80	654	1,070	1,420	1,980	2,490	3,090	2.839	.236	.601
	Combined		686	1,150	1,520	2,100	2,610	3,190			
08157500 a/	Simulated		1,420	2,390	3,160	4,290	5,230	6,280	3.158	.264	.132
	Recorded	1966-80	1,290	2,080	2,680	3,540	4,250	5,020	3.116	.242	.129
	Combined		1,350	2,220	2,900	3,880	4,690	5,590			
08158050	Simulated		4,270	7,160	9,380	12,500	15,100	17,800	3.630	.267	-.004
	Recorded	1975-84	2,880	4,880	6,320	8,230	9,690	11,200	3.447	.284	-.281
	Combined		3,690	6,190	8,090	10,700	12,900	15,100			
08158400	Simulated		2,760	4,300	5,390	6,830	7,940	9,080	3.437	.232	-.111
	Recorded	1975-82	2,200	3,890	5,610	8,740	12,000	16,300	3.389	.269	1.061
	Combined		2,590	4,180	5,460	7,400	9,160	11,200			
08158500	Simulated		2,480	4,480	6,110	8,500	10,600	12,800	3.396	.303	.031
	Recorded	1976-82	2,900	6,760	10,500	16,900	23,000	30,300	3.463	.437	.009
	Combined		2,560	4,940	6,990	10,200	13,100	16,300			
08158600	Simulated		5,370	9,960	13,700	19,300	24,000	29,100	3.728	.321	-.040
	Recorded	1966-84	4,650	8,860	12,100	16,400	19,900	23,400	3.646	.353	-.374
	Combined		4,930	9,280	12,700	17,500	21,500	25,600			
08158880	Simulated		1,370	2,280	2,960	3,880	4,600	5,360	3.130	.269	-.131
	Recorded	1977-84	1,500	2,240	2,710	3,290	3,700	4,060	3.160	.221	-.387
	Combined		1,400	2,270	2,910	3,760	4,420	5,100			
08158920	Simulated		1,020	2,050	2,930	4,250	5,390	6,660	3.001	.360	-.115
	Recorded	1978-84	1,080	2,130	3,200	5,160	7,200	9,880	3.073	.324	.735
	Combined		1,030	2,070	2,980	4,430	5,750	7,300			
08158930	Simulated		2,610	4,870	6,710	9,410	11,700	14,200	3.421	.315	-.054
	Recorded	1975-84	2,260	4,940	7,420	11,400	15,000	19,200	3.359	.402	-.033
	Combined		2,460	4,900	7,010	10,200	13,100	16,300			
08158970	Simulated		2,370	4,710	6,980	10,600	13,800	17,500	3.344	.383	-.058
	Recorded	1975-82	2,840	8,030	13,400	22,800	31,800	42,500	3.440	.549	-.215
	Combined		2,510	5,510	8,910	14,300	19,200	25,000			

a/ For period, 1966-80.

into a single curve for each site. Other studies have either averaged the two curves as in the Houston study area (Liscum and Massey, 1980), weighted them on the basis of the length of record as in a similiar study in the Dallas area (Land and others, 1982), or weighted the two frequency curves on the basis of error analysis (Clement, 1983). After a thorough comparison of all methods, the length of record effect at the 13 sites in the Austin area was determined to be the most important factors in combining flood frequency curves. As a result, the weighting curve that was used in the Dallas study (Land and others, 1982), was used to compute a combined flood-frequency curve for each site.

The use of this weighting curve assumes that: (1) Gaged records of less than 6 years are not adequate for computing flood frequencies, giving the observed flood frequency a weight of zero; (2) the simulated and recorded flood-frequency curves have equal weight for a station with 12 years of recorded data; and (3) the recorded flood-frequency curve has a 75-percent weight for a 36-year period of record. The weighting curve is shown in figure 16. The weighted combinations of the model simulated and recorded flood frequencies are given in table 7.

The combined flood-frequency curves tend to balance the short record (which is influenced by the occurrence of a greater than 50-year recurrence interval storm at most sites) with the much longer model-smoothed record (simulated from a long-term rainfall that does not have recorded maximum rainfall intensities nearly as high as several of the basin rain gages). While both simulated and recorded flood-frequency curves may reflect the above mentioned bias, the combined flood-frequency curves are thought to be the most representative of the streamflow sites studied. The combined flood-frequency curves for 11 of the 13 sites excluding the two Waller Creek sites are presented in figures 17-19.

Waller Creek

Flood-frequency curves were developed for one of the Waller Creek sites for two different periods of record representing different degrees of urbanization (table 4). Simulated and recorded flood-frequency curves were developed for one site for the earlier period 1956-62 and for the later period 1966-80. The combined flood-frequency curves for each period for Waller Creek at 38th Street site are presented in figure 20. Only the combined flood-frequency curve for Waller Creek at 23rd Street for the later period of record (1966-80) is presented. Comparison of flood-frequency curves for the two different periods was not possible because the magnitude of the differences expected was overshadowed by gaging inaccuracies before 1964.

MULTIPLE-REGRESSION ANALYSIS

Multiple-linear regression techniques were used to develop a regional relationship for predicting the discharges for selected recurrence intervals for ungaged sites in the Austin area. The recurrence-interval discharges are used as the dependent variables (table 7) and the basin-characteristic data are used as the independent variables (table 3). The regression model used in this analysis is of the form:

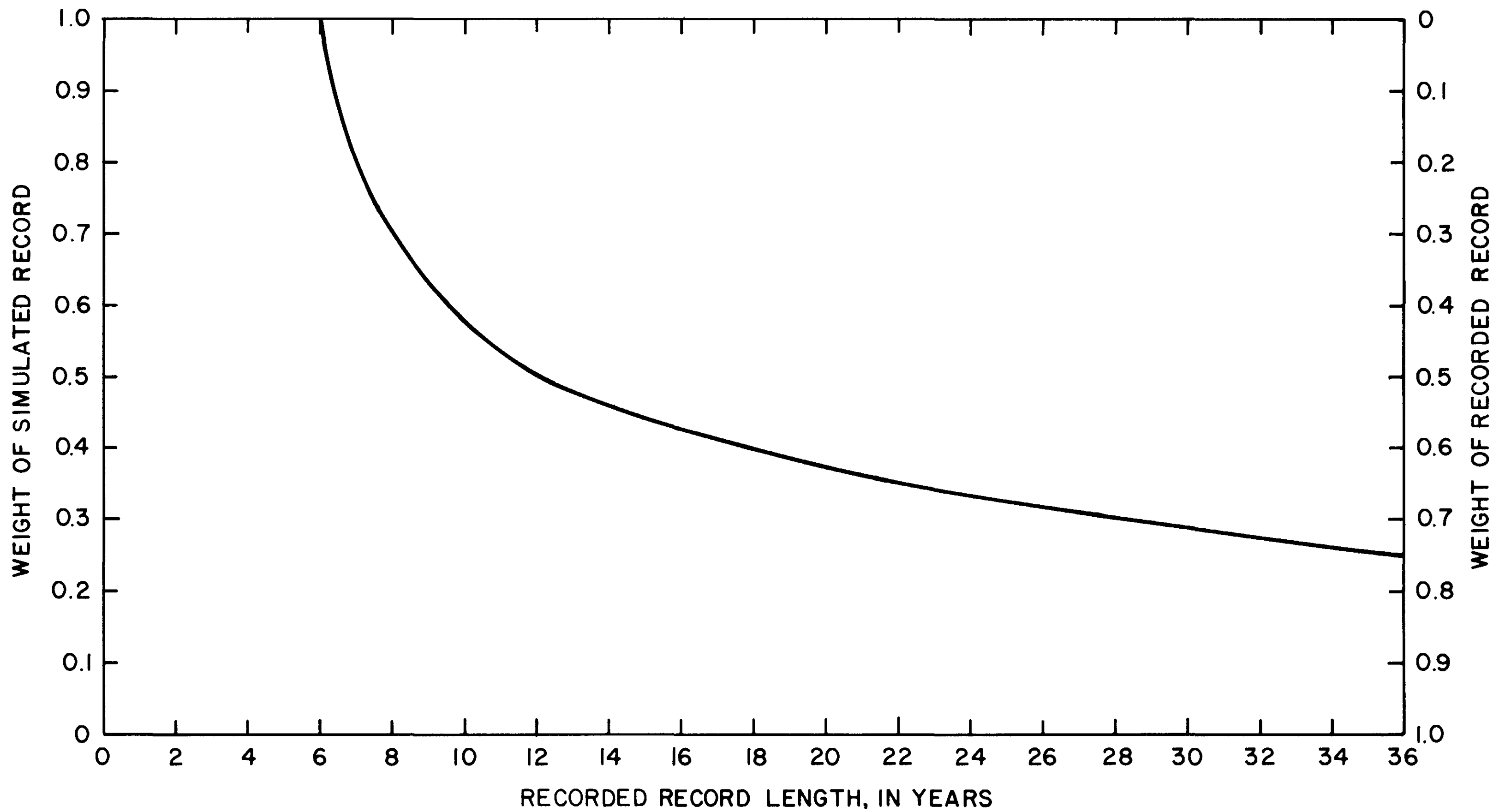

Figure 16.--Weighting of recorded and simulated T-year discharges.

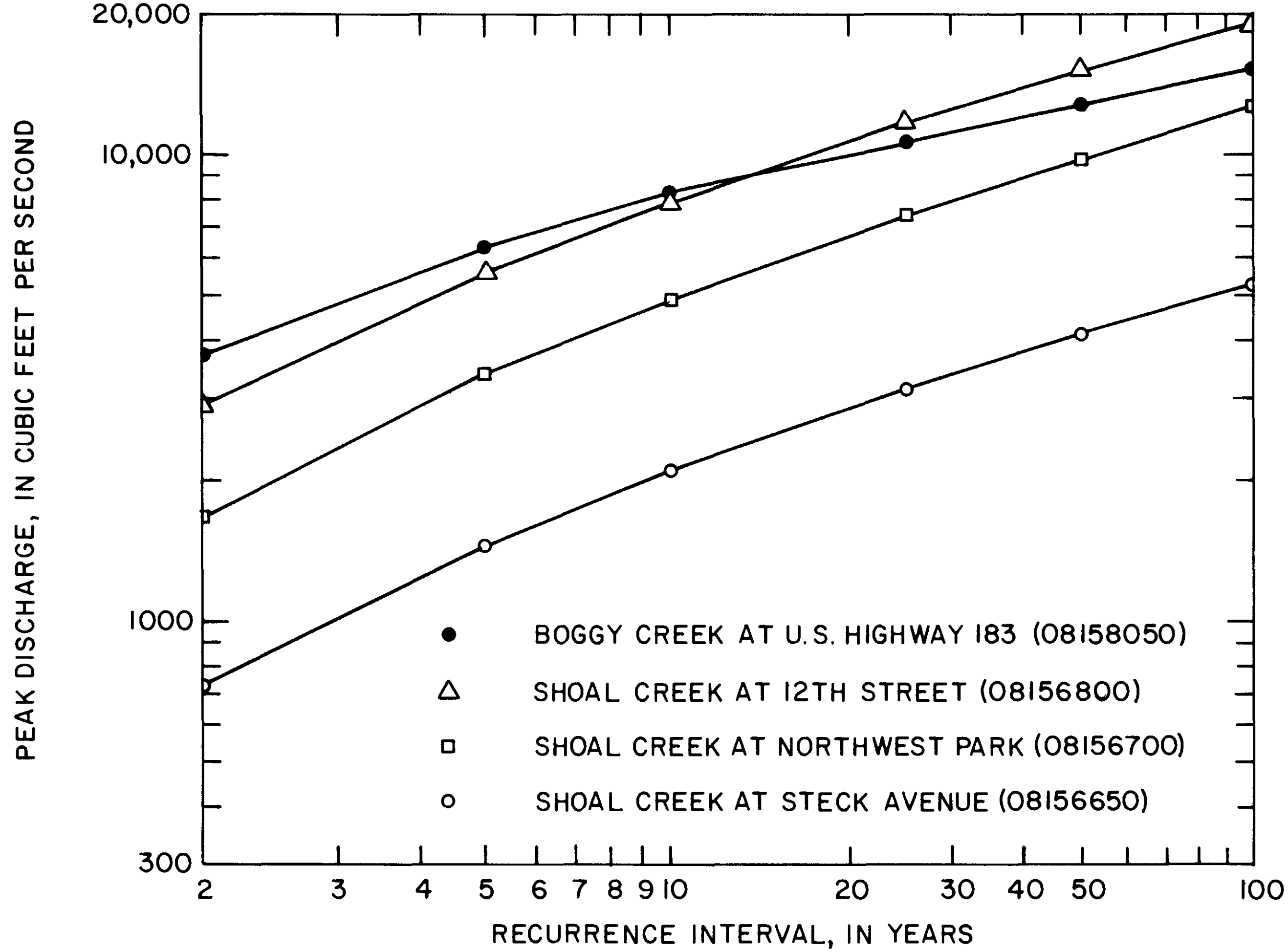

Figure 17.--Combined flood frequencies for streamflow-gaging stations 08156650, 08156700, 08156800, and 08158050.

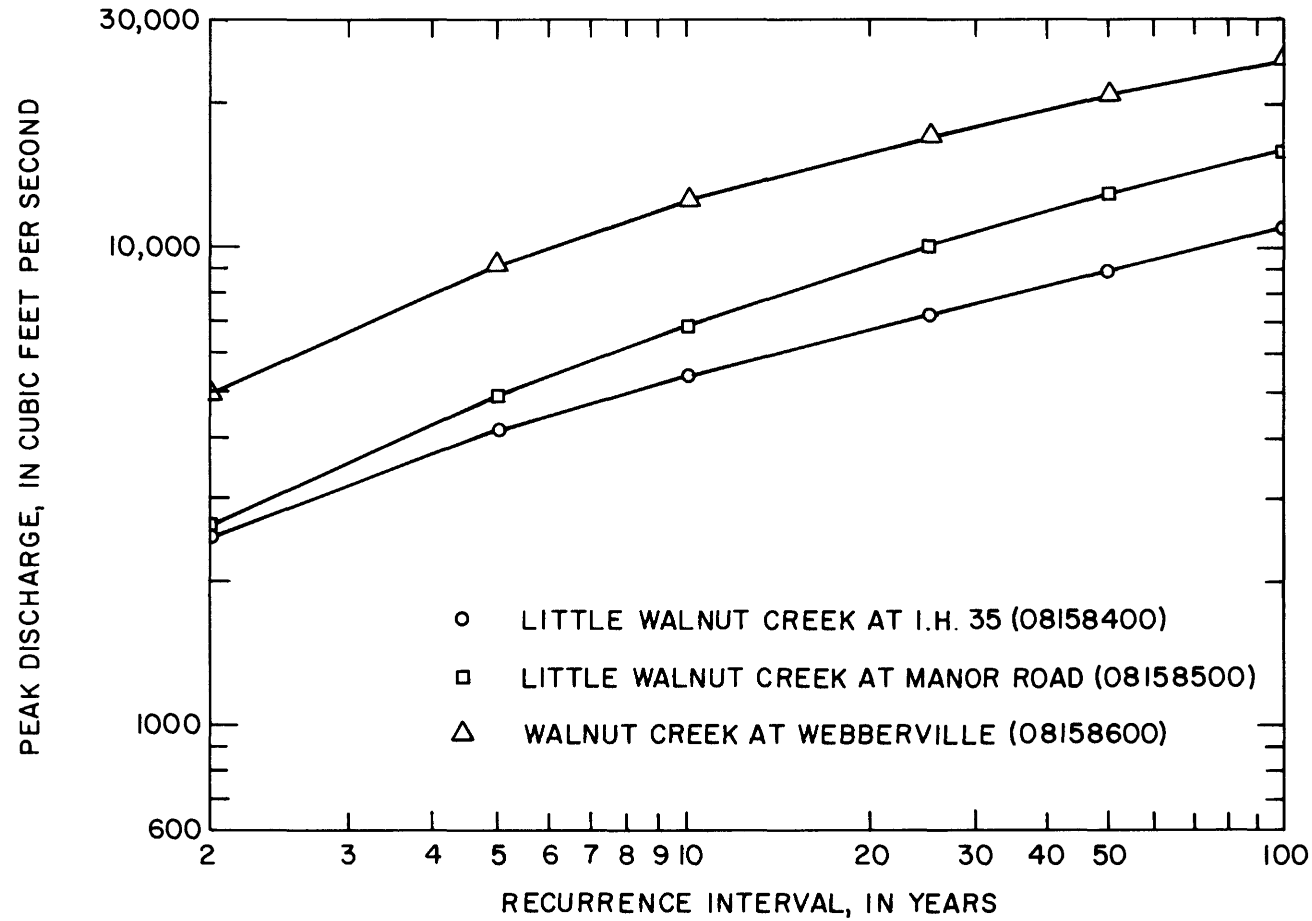

Figure 18.--Combined flood frequencies for streamflow-gaging stations 08158400, 08158500, and 08158600.

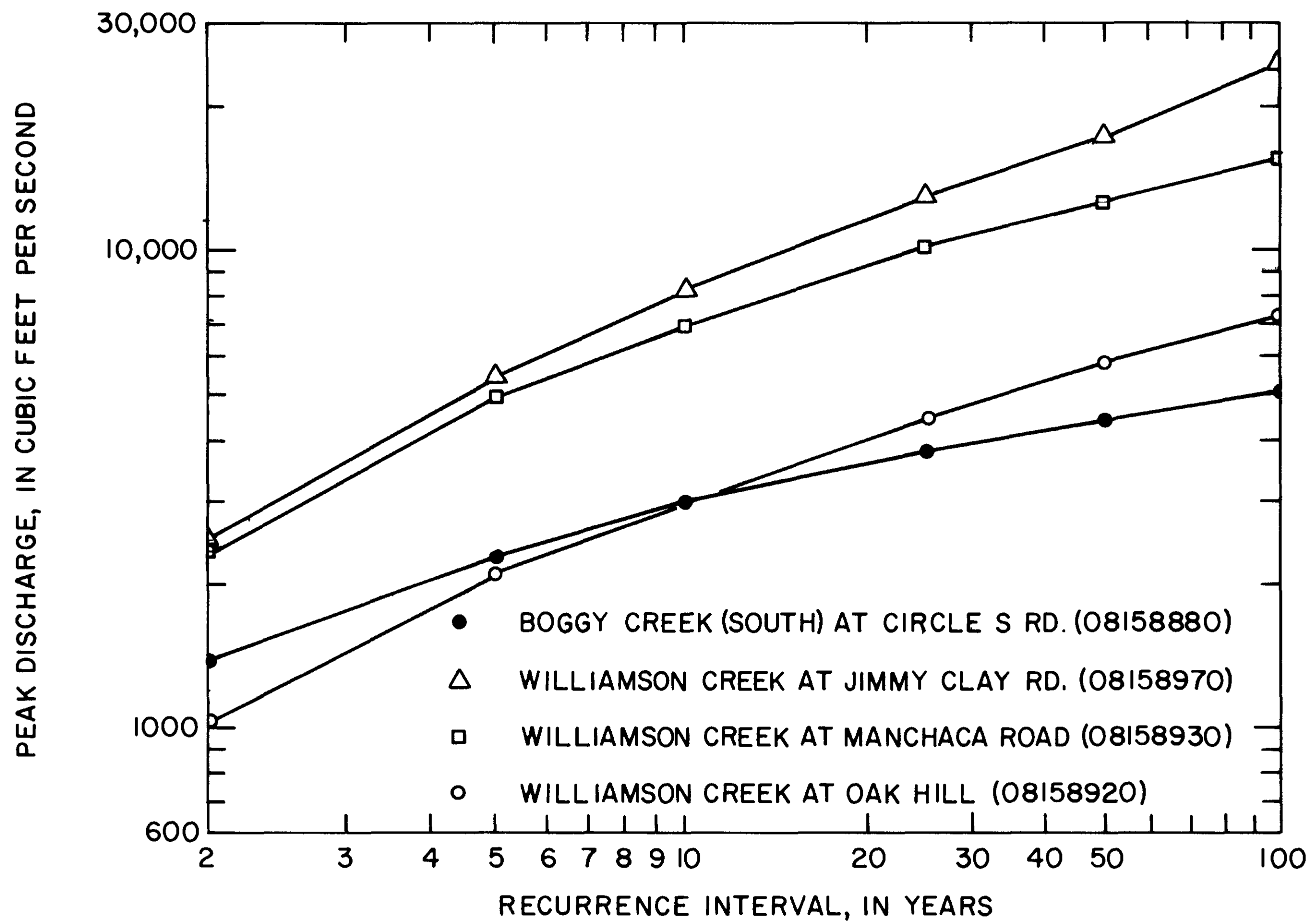

Figure 19.--Combined flood frequencies for streamflow-gaging stations 08158880, 08158920, 08158930, and 08158970.

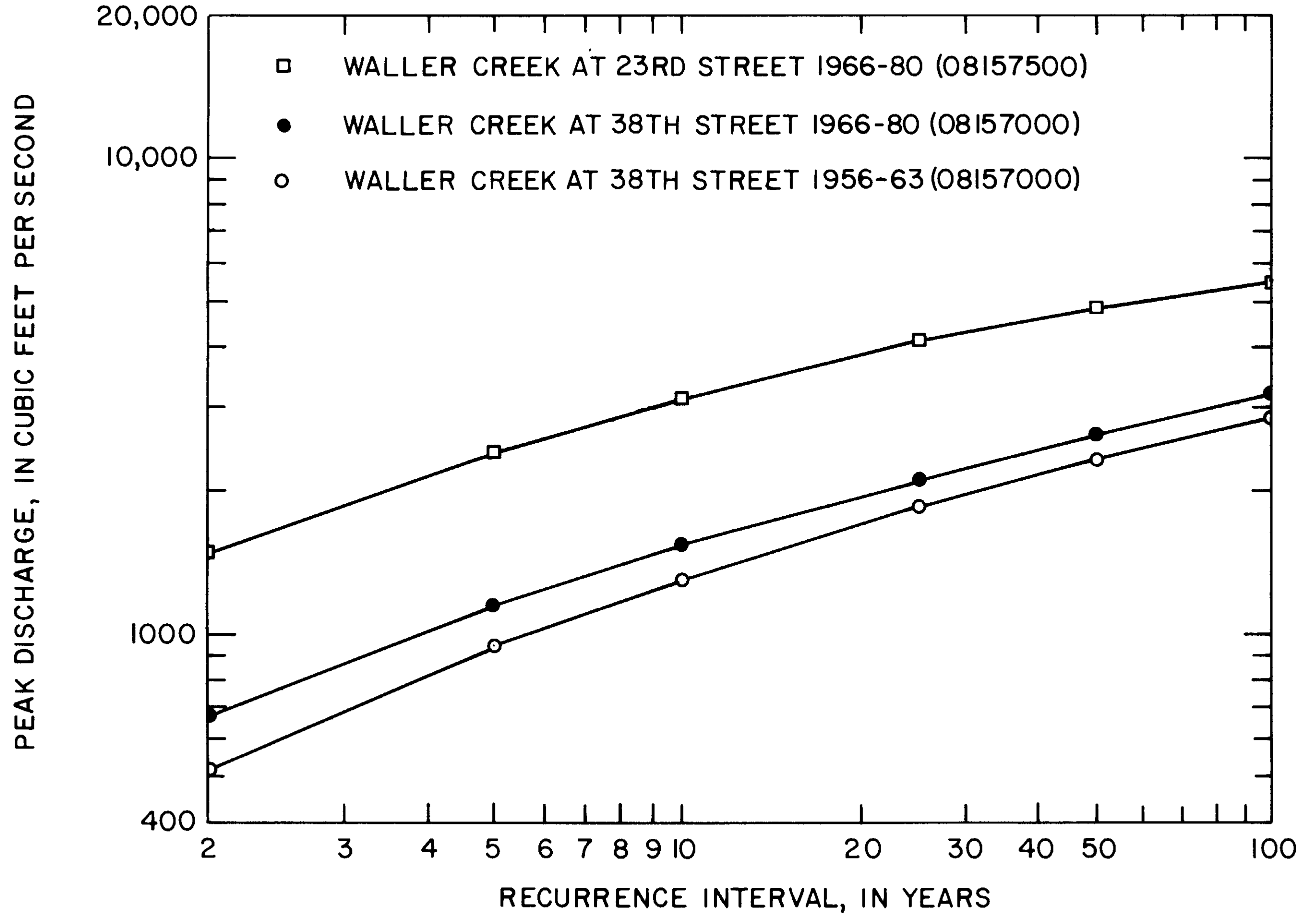

Figure 20.--Combined flood frequencies for streamflow-gaging stations 08157000 for the earlier period (1956-62), and 08157000 and 08157500 for the later period (1966-80).

$$Q_T = aB_1^{b_1} B_2^{b_2} B_3^{b_3} \ldots \quad (2)$$

Where: Q_T = Discharge at a given (T) recurrence interval;
a = regression constant;
b_1, b_2, b_3 = coefficients defined by regression; and
B_1, B_2, B_3 = basin characteristics.

The dependent and independent variables were transformed to base 10 logarithms prior to analysis and the equation becomes linear.

All independent variables previously defined in the basin characteristics section were tested for significance in estimating flood magnitudes in the Austin area. Drainage area was the most significant basin characteristics. Channel length was too highly correlated with drainage area to be included in the regression analyses. Mean basin elevation, channel slope, and geologic factor were found to have no significant effect on flood peaks. Basin shape was found to be statistically significant at the 0.10 level for only the 25-, 50-, and 100-year recurrence intervals.

Of tle four measures of urbanization that were investigated, $1 + \frac{\text{total impervious percentage}}{100}$ and urbanization index were the independent variables that most highly correlated with flood magnitudes after contributing drainage area was already included in the equation. These two indices of urbanization were compared, and because the regression equations with the variable $1 + \frac{\text{total impervious percentage}}{100}$ had lower average standard errors of estimates, they were chosen to represent the degree of urbanization.

Impervious area is most commonly cited as one of the main causes of changes in runoff characteristics from an urban basin whereas the urbanization index is more a measure of the structural management of those changes. Although impervious area may be more difficult to measure, the urbanization index is probably more subjective and may not reflect as much cause and effect relationship. Contributing drainage area was the most significant explanatory independent variable for estimating discharge for selected recurrence intervals, while the statistically independent variable representing total impervious cover was also significant for all recurrence intervals.

After the most significant independent variables were determined, a stepwise regression was used to determine the preliminary flood-frequency equations represented by

$$Q_T = a\,(CDA)^{b_1}\,(1 + \frac{TIMP}{100})^{b_2} \quad (3)$$

where: Q_T = Discharge for a given (t) recurrence interval;
a = regression constant;
b_1, b_2 = coefficients defined by regression;
CDA = contibuting drainage area; and
TIMP = total impervious percentage.

A two-parameter model was chosen as the best representation of the 13 basins because of the small number of sites in this analysis and marginal significance of any additional variables. At this point in the analysis, the regression process was continued using generalized least-squares instead of ordinary least-squares.

Stedinger and Tasker (1984) stated that differences in the length of record at stream-gaging stations included in regression analysis may make generalized least-square analysis more preferable to ordinary least-squares stepwise analysis. In addition, whenever several sites are located fairly close to each other, the individual site data may be highly correlated. This may be caused by the contributing drainage area of one site being completely contained within the drainage area of another site, as characteristic of this study. It may also be caused by the proximity of the gages which would tend to make them show the same storms and thus have highly correlated concurrent flows. The fact that simulated flood-frequency curves were generated using the identical long-term rainfall record also compounds this cross-correlation problem. Therefore, after initial ordinary least-square regression, the generalized least-squares method was used for the final analysis, resulting in slightly different equations with reduced standard errors. The final regional equations and an error analysis are given in table 8.

Use of Equations for Ungaged Sites

The equations developed by multiple-regression analysis can be used to estimate peak discharges for selected recurrence intervals for ungaged drainage basins in the Austin area. The user must determine the contributing drainage area at the point of interest, and estimate the total impervious percentage from air photos or land-use maps. The equation for the recurrence interval of interest can then be used to estimate magnitude of the flood peak at this site.

Limitations of Equations

Users of the flood-frequency equations developed in this report should use some judgement and consider the limitations that apply. The equations are general and do not apply to basins with unusual or special characteristics, such as large flood detention structures or diversions. The values of independent variables should be within the range of values used to develop the equations, and the equations should only be applied to small basins in the Austin metropolitan area. The equations were developed for basins with drainage areas ranging from 2.31 to 51.3 square miles. The total impervious percentage ranged from 5 to 42 percent, but because most of the highly developed sites are less than 15 square miles, the equations should only be used for basins with drainage areas that range from 2.0 to 20 square miles.

The flood-frequency equations for each site were derived by combining a relatively short-term series of annual peak data weighted with a 55-year series of model-generated annual peaks. Considerable subjective judgement was used in the choice of specific model-calibration storms, the development of the recorded flood frequency that consisted of at least one large flood at most of the sites, the choice of the significant independent variables related to urbanization, and the weighting of the flood-frequency estimates from the two separate techniques.

Independent parameters for the following typical basins in the Austin area were used for prediction by two methods and then compared. The hypothetical 5- and 100-year floods were predicted from the equations for a rural condition (0 percent impervious area) and a near fully developed basin (45 percent impervious area) and compared to the corresponding (rural) floods predicted by the regional analysis in the report by Schroeder and Massey (1977).

Site for which basin characteristics are used	Peak discharge at 5-year recurrence interval (ft^3/sec)			Peak discharge at 100-year recurrence interval (ft^3/sec)		
	45-percent impervious (fully urbanized)	0-percent impervious (rural)	Schroeder and Massey, 1977 (rural)	45-percent impervious (fully urbanized)	0-percent impervious (rural)	Schroeder and Massey, 1977 (rural)
08156800 Shoal Creek at 12th Street	5,380	2,960	2,890	14,700	8,520	8,860
08157500 Waller Creek at 23rd Street	2,650	1,460	1,590	7,030	4,070	4,640
08158880 Boggy Creek (South) at Circle S Rd.	2,420	1,330	1,420	6,380	3,690	4,090
08158920 Williamson Creek at Oak Hill, Texas	3,490	1,920	2,070	9,360	5,410	6,250

There is an increase in 5-year recurrence-interval floods from 67 to 86 percent when using the basin characteristics of the four sites shown, and an increase in the 100-year recurrence interval floods from 50 to 66 percent when comparing the near fully urbanized condition predicted by using the equation from this study to the rural equation used by Schroeder and Massey. These increases are comparable to the increases determined from the analysis of the equation discussed earlier in this section of this report.

Indications from Waller Creek

An independent assessment of the effects of urbanization on floods can be made by analysis of the 25 years of streamflow-gaging record at Waller Creek at 38th Street. This assessment is made by studying (1) the difference in flood frequency between earlier and later periods representing different degrees of urbanization and (2) the differences in storm peak discharge over the 25 years of record as explained by increased impervious cover. These two analyses can be called independent of the 13 station analysis because they analyze the record at one site that underwent changes in development during the period of record while the 13-station regression equation represents all 13 sites, each with a constant degree of development. It should be noted that only the later period (1966-80) on both Waller Creek sites was included in the 13 station regression equations.

Flood Frequencies

Flood discharges at selected recurrence intervals for the Waller Creek at 38th Street basin are presented in table 9 for the two periods of record representing different degrees of urbanization (table 4). The percentage increase from the earlier to the later period for each recurrence interval flood is presented in table 9. In addition, the flood discharges at selected recurrence intervals using the basin characteristics for the Waller Creek at 38th Street drainage basin in the 13-station regression equation are presented in table 9. Average impervious areas of 17 and 37 percent were used to calculate these recurrence-interval floods for the earlier (1956-62) and later (1966-80) periods respectively and the percentage increases for each recurrence interval.

The recurrence-interval floods, predicted using the 13-station regression equation, are larger throughout the range, although the increases from the earlier to the later periods are comparable for the shorter recurrence intervals using both techniques. The recurrence-interval floods from the combined flood-frequency for the two periods are smaller, probably because of the effect of undersized storm sewers in the older residential neighborhoods in the Waller Creek basin above 38th Street, which would affect the longer recurrence-interval floods the most. The recurrence interval of floods predicted from the 13-station regression equation on the other hand is influenced by all 13 stations, and the Waller Creek at 38th Street flood-frequency data, although valid for that site, showed the largest deviation from the 13-station regression model. In summary, the increases in combined flood-frequency discharges from the earlier to the later period independently support the finding from the 13-station regression equation. The predicted recurrence-interval floods reflect the "average" of the 13-station flow conditions whereas the combined recurrence-interval floods from the individual site reflect its characteristic flow conditions that can, as in this case, reduce the magnitude of all corresponding return interval floods.

Table 8.--Flood-frequency equations

Equation for indicated T-year flood discharge (cubic feet per second)	Average standard error of prediction (percent)	Correlation coefficient (R)	
$Q_2 = 332\ (CDA)^{0.607}\ (1 + \frac{TIMP}{100})^{1.854}$	30.1	0.912	(4)
$Q_5 = 581\ (CDA)^{0.649}\ (1 + \frac{TIMP}{100})^{1.607}$	27.0	.950	(5)
$Q_{10} = 780\ (CDA)^{0.663}\ (1 + \frac{TIMP}{100})^{1.526}$	26.0	.961	(6)
$Q_{25} = 1{,}064\ (CDA)^{0.674}\ (1 + \frac{TIMP}{100})^{1.476}$	25.6	.963	(7)
$Q_{50} = 1{,}299\ (CDA)^{0.677}\ (1 + \frac{TIMP}{100})^{1.475}$	25.7	.961	(8)
$Q_{100} = 1{,}554\ (CDA)^{0.678}\ (1 + \frac{TIMP}{100})^{1.474}$	25.9	.955	(9)

Where: Q_T = Discharge, at given (T) recurrence interval, in cubic feet per second;
CDA = contributing drainage area, in square miles; and
TIMP = total impervious percentage.

EFFECTS OF URBANIZATION

Indications from the 13 Sites

The effects of urbanization on floods can be hypothetically estimated by assigning the total impervious area percentage of 0 for an undeveloped site and 45 for an urban site. These values slightly exceed the range of impervious area cover (5 to 42 percent) represented by the sites used in this study. While the other independent variables were kept constant, the impervious area percentage was increased from 0 to 45. The corresponding change in recurrence interval floods were noted in the table below.

Recurrence interval in years	Hypothetical ratio of flood peak (urban condition) to flood peak (rural condition)
2	1.99
5	1.82
10	1.76
25	1.73
50	1.73
100	1.73

Table 9.--Comparison of changes in flood frequencies at Waller Creek at 38th Street computed by combined simulated and recorded data and 13 station regression equations

Recurrence interval, in years	Peak discharge (ft^3/s) Earlier period 1956-62	Peak discharge (ft^3/s) Later period 1966-80	Percent increase
Combined (simulated and recorded) flood frequency			
2	514	686	33
5	940	1,150	22
10	1,300	1,520	17
25	1,850	2,100	14
50	2,340	2,610	12
100	2,890	3,190	10
Predicted flood frequency using the 13 station regression equation			
	TIMP = 17	TIMP = 37	
2	738	989	34
5	1,290	1,660	29
10	1,730	2,200	27
25	2,360	2,980	26
50	2,890	3,640	26
100	3,460	4,360	26

Peak Discharges of Floods

The peak discharges for all 80 storms for the Waller Creek at 38th Street site were related to rainfall and degree of development at the time of the storm by multiple-regression analysis. The resulting equation was:

$$Qp = 31.1\,(I60)^{0.906}\,(RN)^{0.663}\,(API)^{0.140}\,(TIMP)^{0.580} \qquad (10)$$

$$SE\ percent = 35.3 \qquad R = 0.909$$

where: Qp = the peak discharge for the storm;
I60 = the maximum 60 minute rainfall depth for the storm;
RN = the total rainfall for the storm;
API = the antecedent precipitation index for the storm as taken from Linsley and others, 1975; and
TIMP = the total impervious percentage.

The 80 storm peaks used in the development of this equation ranged from 30 to 1,970 cubic feet per second and a median of 359 cubic feet per second. The I60 ranged from 0.40 to 2.61 inches for the period and RN ranged from 0.56 to 7.44 inches. API ranged from 0 to 5.04 inches and TIMP ranged from 15 percent for the first storm analyzed to 41 percent in 1980.

This equation, developed from statistical analysis of 80 individual storms applies only to the Waller Creek at 38th Street site. However, the equation can be used to estimate the effects of changes in total impervious percentage on peak discharge for any particular storm within this basin. To compare the statistical equation prediction with the results with the previous assessment, the increase in peak discharge was determined for identical storms with total impervious covers of 17 and 37 percent. The equation predicts a peak discharge increase of 57 percent. This is a larger percentage increase than that predicted by either the Waller Creek flood frequency analysis for the two periods of record, or the increase predicted by the 13-station equation. However, the above equation is heavily weighted by a large number of storms having less than the 2-year recurrence interval which is the shortest recurrence interval reported by the two other methods presented earlier in this section. With this consideration, the 57-percent increase is reasonable for an average small storm and generally supports the results presented earlier.

SUMMARY AND CONCLUSIONS

Streamflow and rainfall data in the Austin metropolitan area collected from 1966-82 were used for estimating the magnitude and frequency of floods for ungaged basins, and the effects of impervious cover on flood peaks. In addition, analyses of recorded peak discharges for a basin with a long period of record (1956-80) and changing impervious cover were used to substantiate estimated changes in flood peaks.

The selected procedure for making the flood-frequency estimates included the use of rainfall and runoff data with a rainfall-runoff simulation model. The simulation model was calibrated with incremental rainfall and runoff data for 13 streamflow-gaging sites, each representing various degrees of urban development. Rainfall records collected over a 55-year period were used to simulate annual peak discharges at the 13 sites. The simulated annual peaks and the recorded annual peak discharges were analyzed separately by log Pearson type III frequency analysis. The resulting relations were weighted based on the length of record at each site to produce a combined flood frequency. These combined flood-frequency relations were subsequently regressed against basin characteristics to develop an equation for estimating flood peaks of selected recurrence intervals at ungaged sites. Using the equations, a basin that hypothetically changed from a rural condition (total impervious area percentage = 0) to a near fully developed condition (total impervious area percentage = 45), has a 99-percent increase in the 2-year recurrence-interval flood and a 73-percent increase in the 100-year recurrence-interval flood.

The storm data and annual peak-flow data for a streamflow-gaging site on Waller Creek were analyzed for two periods of relatively stable land use to estimate the effect of differences in impervious cover on flood peaks. The change in impervious cover at the Waller Creek site accounted for increased flood peaks of selected recurrence intervals that were comparable to the change in flood peaks predicted by the regional equations. In addition, analysis of data from 80 storms recorded at this site yielded a statistical equation that can be used to predict peak discharge for any given rainfall and total impervious percentage.

SELECTED REFERENCES

Alley, W. M., and Veenhuis, J. E., 1979, Determinations of basin characteristics for an urban distributed routing rainfall-runoff model, in Stormwater Management Model (SWMM) Users Group Meeting, Montreal, Canada, May 24-25, 1919, Preceedings: Washington, D.C., U.S. Environmental Protection Agency, Miscellaneous Reports Series, EPA 600/9-79-026, 27 p.

Benson, M. A., 1964, Factors affecting the occurrence of floods in the Southwest: U.S. Geological Survey, Water-Supply Paper 1980-D, 72 p.

Boning C. W., 1974, Users guide for a U.S. Geological Survey rainfall-runoff model and associated data files: U.S. Geological Survey, Open-File Report 74-33, 234 p.

Carrigan, P. H., Jr., 1973, Calibration of U.S. Geological Survey rainfall--for peak flow synthesis--natural basins: U.S. Geological Survey, Open-File Report, 109 p.

Carrigan, P. H., Dempster, G. R., and Bower, D. E., 1977, User's guide for U.S. Geological Survey rainfall-runoff model--revison of Open-File Report 74-33: U.S. Geological Survey, Open-File Report 77-884, 273 p.

Carter, C. K., 1975, Analysis of extreme rainfall events occurring at Austin, Texas in Austin, Texas Comprehensive Drainage Plan and Study, CIP Project No. 70290, 13 p.

Carter, R. W., 1961, Magnitude and frequency of floods in suburban areas: U.S. Geological Survey, Professional Paper 424-B, p. B9-B11.

Conover, W. J., 1971, Practical nonparametric statistics: John Wiley and Sons, New York, p. 314-316.

Clement, R. W., 1983, Improvement of flood-frequency estimates for selected small watersheds in eastern Kansas using a rainfall-runoff model: U.S. Geological Survey Water Resources Investigations Report 83-4110, 22 p.

Dawdy, D. E., Lighty, R. W., and Bergmann, J. M., 1972, A rianfall-runoff simulation model for estimation of flood peaks for small drainage basins: U.S. Geological Survey, Professional Paper 506-B, 28 p.

Dempster, G. R., Jr., 1974, Factors influencing the occurrence of floods in the Dallas, Texas, metropolitan area: U.S. Geological Survey, Water Resources Investigations Report 60-73, 50 p.

Draper, N. R., and H. Smith, 1981, Applied regression analysis: John Wiley and Sons, New York, Second edtion, 709 p.

Farnsworth, R. K., 1982a, Evaporation Atlas for the contiguous 48 United States: U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Weather Service, Technical Report 33, 26 p.

________ 1982b, Mean monthly, seasonal, and annual pan evaporation for the United States: U.S. Department of Commerce, NOAA Technical Report, National Weather Service 34, 82 p.

Garner, L. E., and Young, K. P., 1976, Environmental geology of the Austin area: An aid to urban planning: University of Texas at Austin, Bureau of Economic Geology, Report of Investigations 86, 39 p.

Grice, G. K., and Maddox, R. A., 1985, The setting of the meteorological stage for the Austin, Texas flash flood in 14th Conference on severe local storms, October 19-November 1, 1985: American Meteorological Society, Indianopolis, Indiana, p. J36-J42.

Hardison, C. H., 1969, Accuracy of streamflow characterisitics, in Geological Survey Research 1969: U.S. Geological Survey, Professional Paper 650-D,

p. D210-D214.

________ 1971, Prediction error of regression estimates of streamflow characteristics at ungaged sites: U.S. Geological Survey, Professional Paper 750-C, p. C228-C236.

Hershfield, D. M., 1961, Rainfall frequency atlas of the Unites States for durations from 30 minutes to 24 hours and return periods from 1 to 100 years: U.S. Weather Bureau Technical Report 40.

Johnson, S. L., and Sayre, D. M., 1973, Effects of urbanization on floods in the Houston, Texas, metropolitan area: U.S. Geological Survey, Water Resources Investigations 3-73, 50 p.

Kirby, W. H., 1975, Model smoothing effect diminishes simulated flood peak variance: American Geophysics Union Transactions, June 18, 1975, v. 56, no. 6, p. 361.

Kohler, M. A., Nordenson, T. J., and Baker, D. R., 1959, Evaporation maps for the United States: U.S. Department of Commerce, Weather Bureau Technical Paper 37, 13 p.

Land, L. F., Schroeder, E. E., and Hampton, B. B., 1982, Techniques for estimating the magnitude and frequency of floods in the Dallas-Fort Worth metropolitan area, Texas: U.S. Geologial Survey, Water Resources Investigations 82-18, 55 p.

Lichty, R. W., and Liscum, Fred, 1978, A rainfall-runoff modeling procedure for improving estimates of T-year (annual) floods for small drainage basins: U.S. Geological Survey, Water Resources Investigations 78-7, 49 p.

Linsley, R. K., Jr., Kohler, M. A., and Paulhus, J. L. H., 1975, Hydrology for engineers, Second edition: New York, McGray Hill Series, p. 265-266.

Liscum, Fred, and Massey, B. C., 1980, Techniques for estimating the magnitude and frequency of floods in the Houston, Texas, metropolitan area: U.S. Geological Survey Water Resources Investigations 80-17, 29 p.

Massey, B. C., Reeves, W. E., and Lear, W. A., 1982, Flood of May 24-25, 1981, in the Austin, Texas, metropolitan area: U.S. Geological Survey, Hydrologic Investigations Atlas HA-656.

Massey, B. C., and Schroeder, E. E., 1977, Application of a rainfall-runoff model in estimating flood peaks for selected small natural drainage basins in Texas: U.S. Geological Survey, Open-File Report 77-792, 23 p.

Rawls, W. J., Stricker, V. A., and Wilson, K. V., 1980, Review and evaluation of urban floodflow frequency procedures: U.S. Department of Agriculture, Bibliographies and Literature of Agriculture No. 9, 62 p.

Riggs, H. C., 1968a, Some statistical tools in hydrology: U.S. Geological Survey, Techniques of Water-Resources Investigations, Book 4, Chapter A1, 39 p.

________ 1968B, Frequency curves: U.S. Geological Survey, Techniques of Water-Resources Investigations, Book 4, Chapter A2, 15 p.

________ 1973, Regional analyses of streamflow characteristics: U.S. Geological Survey, Techniques of Water-Resources Investigations, Book 4, Chapter B3, 15 p.

________ 1976, Accuracy in equivalent years: Water Resources Division Bulletin, July-September 1976, p. 25-27.

Sauer, V. B., Thomas, W. O., Stricker, V. A., and Wilson, K. V., 1983, Flood characteristics of urban watersheds in the United States: U.S. Geological Survey, Water-Supply Paper 2207, 63 p.

Schroeder, E. E., and Massey, B. C., 1977, Technique for estimating the magnitude and frequency of floods in Texas: U.S. Geological Survey, Water-Resources

Investigations 77-110, 22 p.

Slade, R. M., Jr., Veenhuis, J. E., Dorsey, M. E., Gardiner, Heather, and Smith, A. E., 1983, Hydrologic data for urban studies in the Austin, Texas, metropolitan area, 1981: U.S. Geological Survey, Open-File Report 83-44, 293 p.

Stedinger, J. R., and G. D., Tasker, 1984, Regional hydrologic analysis 1--ordinary, weighted, and generalized least squares compared: American Geophysical Union, Water Resources Research, volume 21, number 9, p. 1421-1432.

Tasker, G. D., 1980, Hydrologic regression and weighted least squares: American Geophysical Union, Water Resources Research, volume 16, number 6, p. 1107-1113.

Theissen, A. H., 1911, Precipitation for large areas: Monthly Weather Review, volume 39, p. 1082-1084.

Thomas, D. M., and Benson, M. A., 1970, Generalization of streamflow characteristics from drainage-basin characteristics: U.S. Geological Survey, Water-Supply Paper 1975, 55 p.

Thomas, W. O., Jr., 1980, Comparison of procedures for weighting flood-frequency curves: Water Rsources Division Bulletin, April-June 1980, p. 23-30.

________ 1980, Determining the equivalent years of record of flood-frequency estimates based on rainfall-runoff modeling: Water Resources Division Bulletin, July-December 1980, p. 56-61.

________ 1982, Equivalent years of record--revisited: Water Resources Divison Bulletin, January-April 1982, p. 17-19.

U.S. Department of Agriculture, 1974, Soil Survey of Travis County Texas: U.S. Department of Agriculture, 123 p.

U.S. Water Resources Council, 1977, Guidelines for determining floodflow frequency: Washington, D.C., U.S. Water Resources Council, Hydrology Committee, Bulletin 17B, 28 p.

________ 1981, Guidelines for determining floodflow frequency (Errata corrections included through March 1982): Water Resources Council, Bulletin 17B, 183 p.

U.S. Weather Bureau, 1955, Rainfall intensity--duration--frequency curves for selected stations in the United States, Alaska, Hawaiian Islands, and Puerto Rico: U.S. Weather Bureau, Technical Paper No. 25.

________ 1961, Rainfall frequency atlas of the United States: U.S. Department of Commerce Technical Paper no. 40, 61 p.

S U P P L E M E N T A L   D A T A

Table 10.--Recorded annual-peak discharges for the streamflow-gaging stations

[ft^3/s, cubic feet per second]

08156650 SHOAL CREEK AT STECK AVENUE, AUSTIN, TX
(Flood-hydrograph partial-record gage)

LOCATION.--Lat 30°21'55", long 97°44'11", Travis County, on downstream side of bridge on Steck Avenue, 0.5 mi west of the intersection of Burnet Road and Steck Avenue, and 6.3 mi north of the State Capitol Building in Austin.

Annual peak data

Water year	Date	Discharge (ft^3/s)	Water year	Date	Discharge (ft^3/s)
1975	11-23-74	824	1979	7-19-79	561
1976	4-18-76	369	1980	5-12-80	463
1977	4-15-77	198	1981	5-24-81	5,100
1978	5-11-78	282	1982	5-13-82	1,200

Note: Gage discontinued at the end of the 1982 water year.

Table 10.--Recorded annual-peak discharges for the streamflow-gaging stations--Continued

08156700 SHOAL CREEK AT NORTHWEST PARK, AUSTIN, TX

LOCATION.--Lat 30°20'50", long 97°44'41", Travis County, at Northwest Park in Austin 400 ft (122 m) upstream from Shoal Creek Boulevard bridge, 0.5 mi (0.8 km) west of intersection of Burnet Road and Justin Lane, and 5.0 mi (8.0 km) north of State Capitol Building in Austin.

Annual peak data

Water year	Date	Discharge (ft^3/s)	Water year	Date	Discharge (ft^3/s)
1976	4-18-76	1,060	1981	5-24-81	14,600
1977	4-15-77	580	1982	5-13-82	2,920
1978	5-11-78	978	1983	8-8-83	1,670
1979	7-19-79	2,110	1984	7-24-84	497
1980	5-12-80	1,060			

Note: Gage discontinued at the end of the 1984 water year.

Table 10.--Recorded annual-peak discharges for the streamflow-gaging stations--Continued

08156800 SHOAL CREEK AT 12th STREET, AUSTIN, TX
(Flood-hydrograph partial-record gage)

LOCATION.--Lat 30°16'35", long 97°45'00", Travis County, at downstream side of bridge on 12th Street and 0.6 mi (1.0 km) west of the State Capitol Building in Austin.

Annual peak data

Water year	Date	Discharge (ft^3/s)	Water year	Date	Discharge (ft^3/s)
1975	11-23-74	4,800	1980	5-12-80	1,900
1976	4-18-76	1,670	1981	5-24-81	16,000
1977	4-15-77	999	1982	5-13-82	7,310
1978	5- 2-78 5-11-78	1,470	1983	8- 8-83	1,980
			1984	10- 9-83	893
1979	5-21-79	4,970			

Table 10.--Recorded annual-peak discharges for the streamflow-gaging stations--Continued

08157000 WALLER CREEK AT 38TH STREET, AUSTIN, TX

LOCATION.--Lat 30°17'49", long 97°43'36", Travis County, on right bank 200 ft (61 m) upstream from bridge at East 38th Street in Austin, 1.1 mi (1.8 km) upstream from West Branch of Waller Creek, and 3.3 mi (5.3 km) upstream from Colorado River.

Annual peak data

Water year	Date	Discharge (ft^3/s)	Water year	Date	Discharge (ft^3/s)
1957	5-26-57	618	1969	8-14-69	361
1958	10-13-57	535	1970	5-15-70	444
1959	9-23-59	479	1971	8- 4-71	587
1960	10- 4-59	251	1972	5- 2-72	1,400
1961	10-29-60	1,970	1973	9-26-73	830
1962	6-10-62	1,420	1974	10-11-73	1,810
1963	6-18-63	263	1975	11-23-74	892
1964	9-27-64	1,340	1976	5-25-76	657
1965	5-16-65	805	1977	12-10-76	379
1966	8-11-66	618	1978	5- 2-78	531
1967	4-23-67	604	1979	5-21-79	1,830
1968	10-15-67	745	1980	5-12-80	327

Note: Gage discontinued at end of 1980 water year.

Table 10.--Recorded annual-peak discharges for the streamflow-gaging stations--Continued

08157500 WALLER CREEK AT 23D STREET, AUSTIN, TX

LOCATION.--Lat 30°17'08", long 97°4'01", Travis County, on San Jacinto Boulevard, 50 ft (15 m) upstream from bridge on East 23d Street in Austin, and 2.1 mi (3.4 km) upstream from Colorado River.

Annual peak data

Water year	Date	Discharge (ft^3/s)	Water year	Date	Discharge (ft^3/s)
1951 a/	6-12-51	2,010	1968	5-27-68	1,220
1955	5-18-55	1,520	1969	5- 8-69	1,350
1956	5- 1-56	615	1970	5-15-70	610
1957	6-12-57	1,540	1971	6-21-71	1,560
1958	4-26-58	1,570	1972	5- 2-72	2,160
1959	9-23-59	1,740	1973	9-26-73	1,460
1960	10- 4-59	726	1974	10-11-73	4,020
1961	10-29-60	3,710	1975	5-23-75	1,660
1962	6- 3-62	2,270	1976	5-25-76	979
1963	6-18-63	1,070	1977	4-15-77	641
1964	9-27-64	2,280	1978	5- 2-78	1,280
1965	5-16-65	2,320	1979	5-21-79	2,620
1966	8-11-66	1,680	1980	3-27-80	520
1967	4-23-67	900			

Note: Gage discontinued at end of 1980 water year.

a/ Historic peak observed before gage was installed.

Table 10.--Recorded annual-peak discharges for the streamflow-gaging stations--Continued

08158050 BOGGY CREEK AT U.S. HIGHWAY 183, AUSTIN, TX

LOCATION.--Lat 30°15'47", long 97°40'20", Travis County, on U.S. Highway 183, 1.6 mi (2.6 km) south of the intersection of Webberville Road and U.S. Highway 183, and 4.1 mi (6.6 km) east of the State Capitol Building in Austin.

Annual peak data

Water year	Date	Discharge (ft^3/s)	Water year	Date	Discharge (ft^3/s)
1975	5-23-75	6,100	1980	3-27-80	1,990 b/
1976	4-18-76	2,490	1981	5-24-81	5,760 b/
1977	4-19-77	1,560	1982	5-13-82	4,580 b/
1978	5- 2-78	1,920	1983	5-20-83	2,500
1979	5-21-79	5,630	1984	3-12-84	872

b/ Revised maximum discharge for water year.

Table 10.--Recorded annual-peak discharges for the streamflow-gaging stations--Continued

08158400 LITTLE WALNUT CREEK AT INTERSTATE HIGHWAY 35, AUSTIN, TX
(Flood-hydrograph partial-record gage)

LOCATION.--Lat 30°20'57", long 97°41'34", Travis County, on downstream frontage road bridge on Interstate Highway 35 and 5.9 mi north of State Capitol Building in Austin.

Annual peak data

Water year	Date	Discharge (ft^3/s)	Water year	Date	Discharge (ft^3/s)
1975	11-23-75	2,700	1979	5-21-79	2,090
1976	5-25-76	1,990	1980	5-12-80	1,780
1977	4-19-77	1,200	1981	5-24-81	7,900
1978	5- 2-78	1,500	1982	5-13-82	4,530

Note: Gage discontinued at end of 1982 water year.

Table 10.--Recorded annual-peak discharges for the streamflow-gaging stations--Continued

08158500 LITTLE WALNUT CREEK AT MANOR ROAD, AUSTIN, TX
(Flood-hydrograph partial-record gage)

LOCATION.--Lat 30°18'34", long 97°40'04", Travis County, on downstream side of bridge on Manor Road and 4.9 mi northeast of the State Capitol Building in Austin.

Annual peak data

Water year	Date	Discharge (ft^3/s)	Water year	Date	Discharge (ft^3/s)
1976	5-25-76	1,940	1980	3-27-80	1,520
1977	4-19-77	1,010	1981	5-25-81	14,500
1978	5- 2-78	1,180	1982	5-13-82	6,020
1979	5-21-79	5,640			

Note: Gage discontinued at end of 1982 water year.

Table 10.--Recorded annual-peak discharges for the streamflow-gaging stations--Continued

08158600 WALNUT CREEK AT WEBBERVILLE ROAD, AUSTIN, TX

LOCATION.--Lat 30°16'59", long 97°39'17", Travis County on left bank 190 ft (58 m) downstream from bridge on Farm Road 969, 0.8 mi (1.3 km) downstream from Little Walnut Creek, 2.8 mi (4.5 km) upstream from Colorado River, and 5.2 mi (8.4 km) east of the State Capitol Building in Austin.

Annual peak data

Water year	Date	Discharge (ft^3/s)	Water year	Date	Discharge (ft^3/s)
1966	8-11-66	2,750	1976	5-26-76	5,140
1967	9- 4-67	303	1977	4-20-77	2,520
1968	1-21-68	5,640	1978	6- 7-78	1,760
1969	2-14-69	1,050	1979	5-21-79	12,400
1970	5-15-70	6,020	1980	9-25-80	3,400
1971	10-23-70	3,740	1981	5-25-81	14,300
1972	6-16-72	4,580	1982	5-13-82	9,540
1973	9-27-73	5,140	1983	5-11-83	3,100
1974	10-11-73	10,400	1984	7-24-84	916
1975	11-23-74	12,600			

Table 10.--Recorded annual-peak discharges for the streamflow-gaging stations--Continued

08158880 BOGGY CREEK (SOUTH) AT CIRCLE S ROAD, AUSTIN, TX.
(Flood-hydrograph partial-record gage)

LOCATION.--Lat 30°10'50", long 97°46'55", Travis County, on downstream side of bridge on Circle S Road and 7.0 mi south of the State Capitol Building in Austin.

Annual peak data

Water year	Date	Discharge (ft^3/s)	Water year	Date	Discharge (ft^3/s)
1977	9-19-77	1,670	1981	6-13-81	2,920
1978	5- 2-78	360	1982	5-13-82	1,360
1979	2-23-79	1,940	1983	8- 8-83	1,740
1980	5- 8-80	--	1984	11- 5-84	797

Table 10.--Recorded annual-peak discharges for the streamflow-gaging stations--Continued

08158920 WILLIAMSON CREEK AT OAK HILL, TX

LOCATION.--Lat 30°14'06", long 97°51'36", Travis County, on downstream side of bridge on U.S. Highway 290 in Oak Hill, 0.8 mi (1.3 km) east of the intersection of U.S. Highway 290 and State Highway 71, and 7.7 mi (12.4 km) southwest of the State Capitol Building in Austin.

Annual peak data

Water year	Date	Discharge (ft^3/s)	Water year	Date	Discharge (ft^3/s)
1978	6- 6-78	890	1982	5-13-82	1,580
1979	5-21-79	2,130	1983	8- 8-83	756
1980	5-12-80	696	1984	11- 6-83	497
1981	6-11-81	4,170			

Table 10.--Recorded annual-peak discharges for the streamflow-gaging stations--Continued

08158930 WILLIAMSON CREEK AT MANCHACA ROAD, AUSTIN, TX
(Flood-hydrograph partial-record gage)

LOCATION.--Lat 30°13'16", long 97°47'36", Travis County, on downstream side of bridge on Manchaca Road, 0.7 mi south of the intersection of Ben White Boulevard and Manchaca Road, and 4.9 mi southwest of the State Capitol Building in Austin.

Annual peak data

Water year	Date	Discharge (ft^3/s)	Water year	Date	Discharge (ft^3/s)
1975	5-23-75	5,900	1980	5-12-80	1,000
1976	4-18-76	2,960	1981	6-11-81	8,490
1977	4-15-77	764	1982	5-13-82	3,900
1978	5- 2-78	551	1983	8- 8-83	1,670
1979	5-22-79	5,560	1984	11- 5-84	1,320

Table 10.--Recorded annual-peak discharges for the streamflow-gaging stations--Continued

08158970 WILLIAMSON CREEK AT JIMMY CLAY ROAD, AUSTIN, TX

LOCATION.--Lat 30°11'21", long 97°43'56", Travis County at Jimmy Clay Road, 0.5 mi (0.8 km) southeast of the intersection of Jimmy Clay and Nuckles Crossing Roads, and 5.9 mi (9.5 km) south of the State Capitol in Austin.

Annual peak data

Water year	Date	Discharge (ft^3/s)	Water year	Date	Discharge (ft^3/s)
1975	11-23-74	10,100	1980	5-12-80	737
1976	4-18-76	3,490	1981	6-11-81	14,100
1977	9-19-77	891	1982	5-13-82	2,830
1978	2-12-78	428	1983	5-20-83	617
1979	5-22-79	6,740	1984	11- 5-83	485