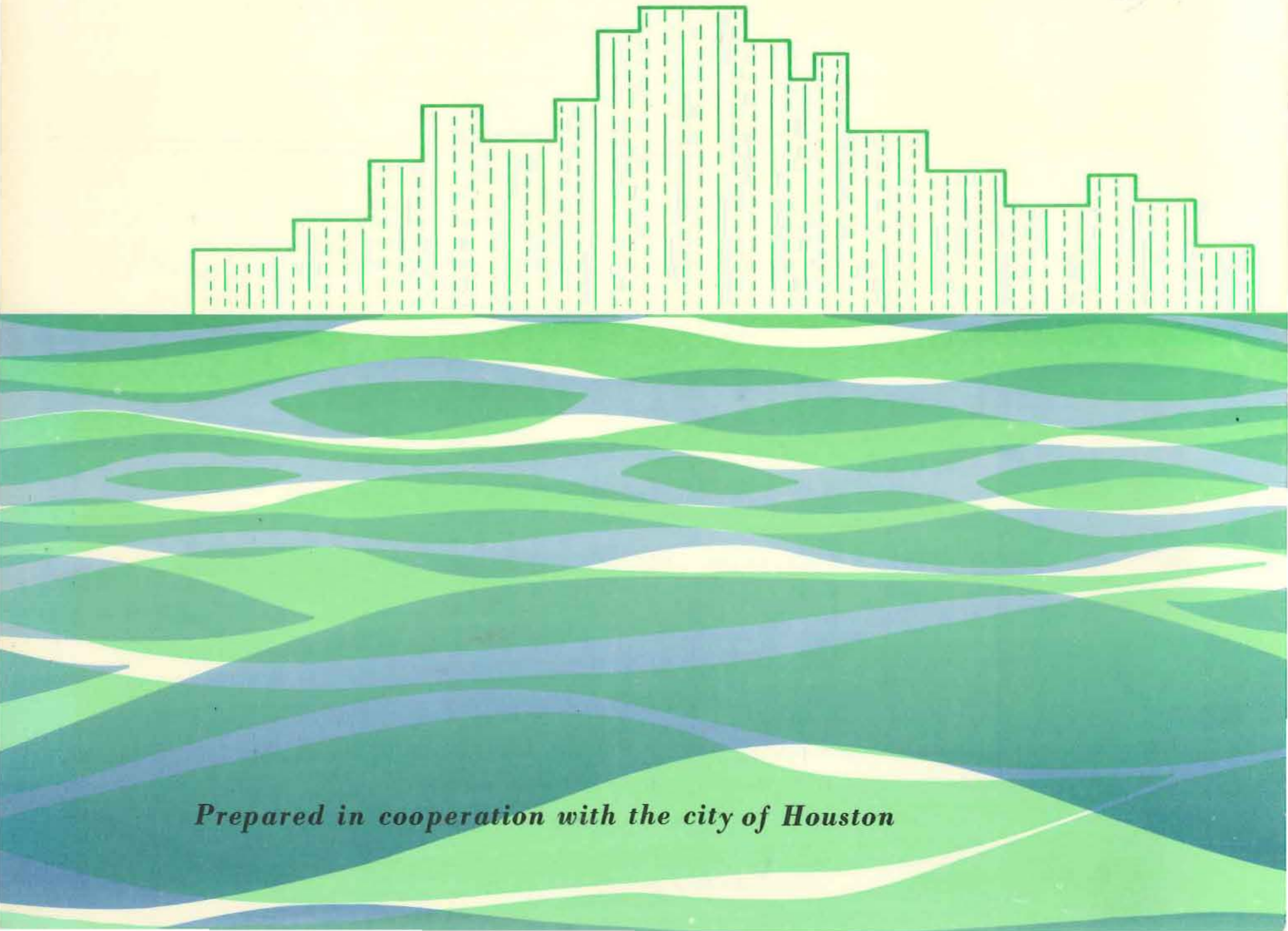
EFFECTS OF URBANIZATION ON FLOODS IN THE HOUSTON, TEXAS METROPOLITAN AREA

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations 3-73



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Rainfall and runoff data from drainage basins in the Houston metropolitan area and a 60-year rainfall record for the National Weather Service station, Houston-City, were used to simulate 60 annual flood peaks at 26 sites. Selected frequency characteristics, based on these simulated annual peaks, are related to drainage area and percentage of impervious area. These relations, which may be used to estimate the flood characteristics at ungaged sites, indicate that in the Houston metropolitan area, complete urbanization increases the magnitude of a 2-year flood nine times and increases the magnitude of a 50-year flood five times.

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APRIL 1973

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EFFECTS OF URBANIZATION ON FLOODS

IN THE HOUSTON, TEXAS, METROPOLITAN AREA

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U.S. Geological Survey

ABSTRACT

This study provides relationships for estimating the magnitudes of annual flood peaks having selected recurrence intervals ranging from 2 to 100 years on streams in the Houston metropolitan area. Data on the size of the contributing watershed and the percent of impervious surface within the watershed are required for use of the relationships, which were defined by analyses of the flood peaks and watershed characteristics for 26 sites.

In the analyses, a 60-year rainfall record was used in a rainfall-runoff model that had been calibrated for each site from a 4 to 10-year period of concurrent rainfall and runoff observations. Flood characteristics for each site were then determined from a frequency analysis of the 60-year synthesized flood record and related by multiple regression to the characteristics of each watershed.

The relationships indicate that as urbanization increases the impervious surface from 1 to 35 percent, the magnitude of a 2-year peak is increased by a factor of 9 and the magnitude of a 50-year peak is increased by a factor of 5. Other analyses indicate that urbanization also significantly increases the magnitude of annual runoff.

INTRODUCTION

Purpose and Scope of this Report

A program to define the effects of urban development on flood characteristics in the Houston metropolitan area was begun in 1964 by the U.S. Geological Survey in cooperation with the city of Houston. Data on flood volumes, flood peaks, and related rainfall were collected at 23 stations established for the urban study and from 10 continuous-record gaging stations in operation prior to 1964 (fig. 1). In addition, data from six supplemental rainfall stations established by the U.S. Geological Survey and from 11 National Weather Service stations were used in this study.

A relation between rainfall and the resulting peak discharge was defined from the records at each station. These relations were then used with the 60-year rainfall record for the National Weather Service station, Houston-City, to synthesize a 60-year flood-peak record for each of 26 sites. These synthesized peaks were the basis for frequency curves that describe the flood-peak characteristics for the basin conditions existing since about 1964. The degree of urbanization in the gaged basins ranges from near zero to virtually complete; consequently, general relations of flood-peak characteristics to drainage area and to an index of urbanization were defined. These latter relations can be used to show the effect of varying degrees of urbanization on flood peaks and to estimate flood-peak characteristics at ungaged sites in the area.

The first detailed analysis of the effects of urbanization on storm runoff in the Houston metropolitan area was made by Van Sickle (1962), who related lag time to basin parameters. His relationships were based on data from the larger basins in Houston and on data from other locations. Espey and Winslow (1968) made a similar investigation that related unit-hydrograph properties to basin parameters by using data from selected gaged basins in Houston together with data from other locations.

The analysis given in this report is based on much more data than were the earlier ones.

Physical Setting

The Houston metropolitan study area (fig. 1), which includes about 1,000 square miles, is in Harris County about 45 miles from the Gulf of Mexico.

Soils in the area are predominantly clays, clay loams, and fine sandy loams that have low to very low permeabilities. Soils in the area north of Buffalo Bayou (fig. 1) are composed of fine sand loams and clays. South of Buffalo Bayou, the soils consist of clay loams (Beaumont Clay) and are treeless in their natural state.

FIGURE 1.- Location of stream-gaging stations

The climate of the Houston area is characterized by mild winters, hot summers, and a high relative humidity throughout most of the year. The lowest temperature recorded was 5°F (-15°C), and the maximum recorded was 108°F (42°C). The mean annual temperature (1931-60) is 69.2°F (20.7°C). The prevailing winds are from the southeast.

The 60-year average (water years 1910-69) rainfall at the National Weather Service station (formerly U.S. Weather Bureau), Houston-City, is 44.44 inches, which is distributed fairly uniformly throughout the year. The maximum rainfall for Houston during this period was 75.46 inches in 1919, and the minimum was 22.26 inches in 1917. During the period 1965-69, the annual rainfall ranged from 30.17 inches to 53.98 inches and averaged 39.68 inches. Storm rainfalls of up to 7 inches in 3 hours have occurred.

Drainage

The Houston metropolitan area is part of a nearly level, almost featureless plain that increases in altitude from about 35 feet above mean sea level in the southeast to about 135 feet in the northwest. The major stream draining the area is Buffalo Bayou (fig. 1), a tributary to the San Jacinto River.

Buffalo Bayou is regulated by the Barker and Addicks floodwater-retarding structures near the western limits of the area. From these structures, Buffalo Bayou meanders eastward through Houston to the Houston Ship Channel, 5 miles east of the downtown area. The main tributaries to Buffalo Bayou are Whiteoak, Brays, Sims, Hunting, and Greens Bayous.

Excluding the drainage area above the floodwater-retarding structures, the drainage area of Buffalo Bayou at the mouth is 767 square miles. Except for a reach above the station Buffalo Bayou at Houston (08074000), all of the major streams have had channel improvements, including some concrete lining.

Because of the relatively flat land-surface slopes (3 to 8 feet per mile), few basin divides are accurately defined by natural features. Basin exchange, which is runoff flowing to or from an adjacent basin, often results from heavy rainfall. Interconnection of adjacent basins by ditches is used to relieve poorly-drained areas, and in instances of unevenly distributed rainfall, the exchange can move in either direction, depending on which drainage system is more loaded.

The magnitude and frequency of flooding also is affected by the hydraulics of the drainage system. Open-street ditch drainage is common in the Houston area and varies from well-maintained grass linings with clean driveway culverts to weedy debris-laden ditches with partially obstructed culverts. Changes in the capacity of the main channel and the outfall conditions of the downstream channel, either by improvement or by channel restrictions, such as growth of vegetation, have considerable effect on floodflows. Espey and Winslow (1968, p. 55), in an analysis of unit hydrographs, found that heavy vegetation doubled the time of rise, and that the unit-peak discharge for channels with light vegetation was 20 percent higher than the unit-peak discharge for channels with heavy vegetation.

Unit hydrographs derived from selected storms at Stoney Brook Street Ditch gaging station (fig. 2) show a progressively decreasing unit-peak discharge as runoff increases. This nonlinear relationship is characteristic of areas with inadequate channel capacity.

Insufficient channel capacity was discussed by Turner and Collie (1961, p. 34) in a preliminary study on drainage in Harris County. They stated that the maximum effect on peak discharge may occur prior to full residential or commercial development. After a certain point of development, the peak discharge at a given point will not increase, although the peak runoff rate will be maintained longer.

Turner and Collie (1961, p. 36) stated that to provide adequate drainage, the water surface should be kept below the top of the channel bank so that the lateral slope from the water surface to the edge of the basin will not be less than 0.05 percent and in most cases not less than 0.1 percent.

Street storage is also used to control floodwaters in Houston and is sometimes designed as a part of the drainage system. A considerable volume of water can be stored in the streets for a short time, thereby reducing the needed capacity of the primary drainage system. Street storage is accomplished by cutting the street grade below the natural ground level and by placing the excavated material on the adjacent lots. Street storage is now utilized in Stoney Brook Street Ditch Basin and in other parts of the city.

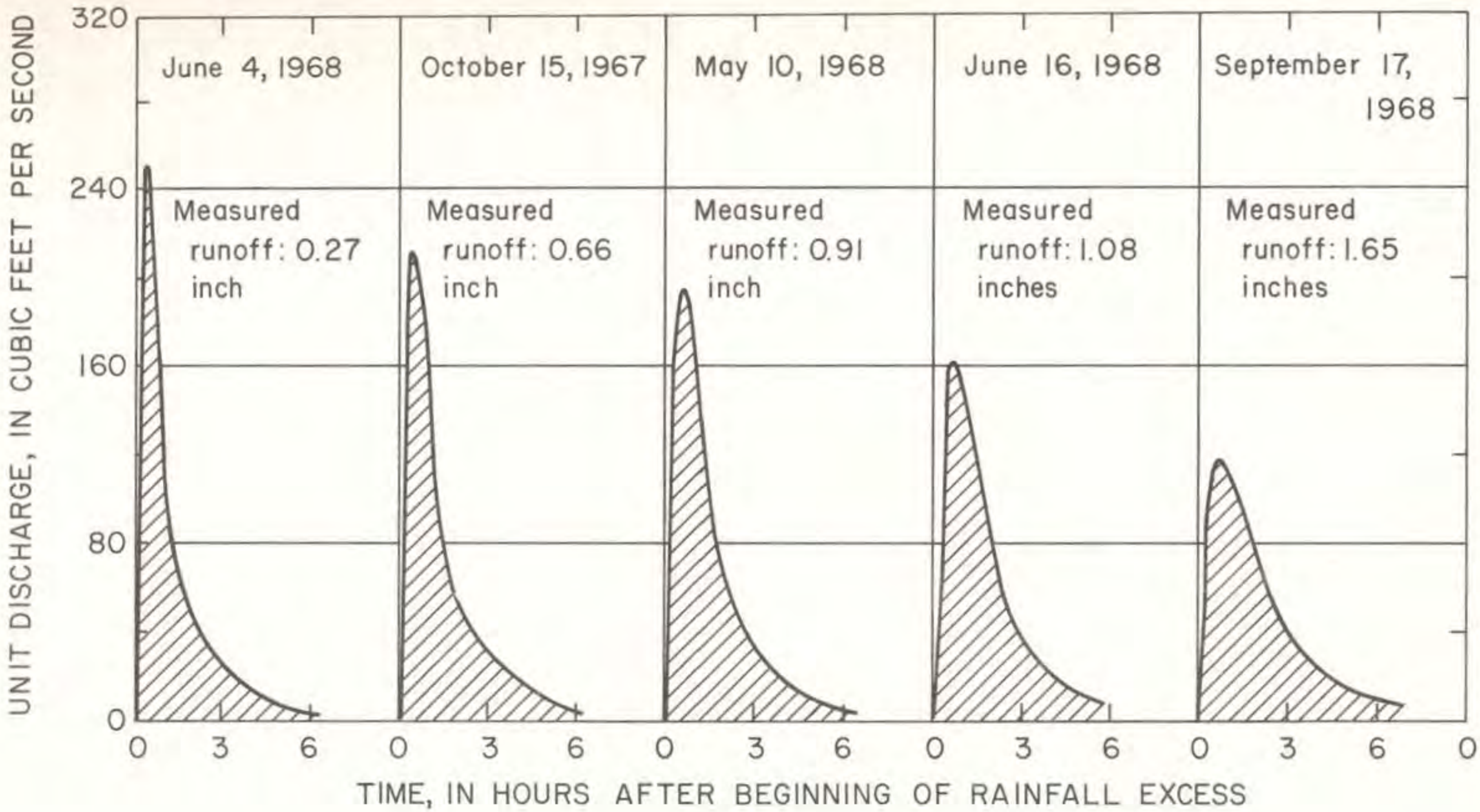

FIGURE 2.-Thirty-minute unit hydrographs for Stoney Brook Street Ditch

Data-Collection Methods

Ten gaging stations (table 1), with drainage areas ranging from 24.7 to 358 square miles, were in operation prior to 1964. Twenty-three additional stations (table 1), with drainage areas ranging from 0.50 to 35.5 square miles were established in 1964. Seven of the 23 additional stations were equipped with continuous recorders; the other 16 were equipped with flood-hydrograph recorders that obtain data only during times of storm runoff.

All of the 23 new sites were instrumented to obtain a continuous rainfall record. Six additional recording rain gages were established (table 2). Data from these rain gages were supplemented with data from 11 stations (table 2) operated by the National Weather Service.

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RELATION OF PEAK DISCHARGE TO RAINFALL AT GAGING STATIONS

Definition of flood-frequency characteristics at a site is usually based on records for 20 or more years. But this approach is not feasible in urban studies because (1) an answer is needed in a short time and (2) basin conditions in an urban area rarely remain stable for more than a few years. The approach used in this report relates concurrent rainfall and flood-peak data collected for a few years at a site, and then uses this relation and a long rainfall record to estimate annual flood peaks that would have occurred at that site under the conditions existing at the time the concurrent rainfall and flood-peak data were collected.

This section of the report describes development of relations of flood peaks to causative rainfall and to antecedent conditions. Data used are in table 3 and the regression model is:

$$\log Q_p = \log a + b_1 \log P + b_2 \log D + b_3 \log M$$

where

Q_p = peak discharge, in cubic feet per second;
P = the Theissen-weighted storm rainfall, in inches;
D = storm duration, in hours, during which 85 percent of the rainfall (P) occurred; and
M = a soil-moisture index, described subsequently.

An equivalent form of this model is $Q_p = a(P^{b_1})(D^{b_2})(M^{b_3})$.

Table 1.--Stream-gaging and rainfall stations in the Houston metropolitan area
C Continuous
F Flood-hydrograph
R Recording rain gage

Station No.	Station Name	Drainage area (sq mi)	Percentage impervious area	Type of station	Beginning of record d/
08069000	a/ Cypress Creek nr Westfield	285	c/	C	1945
08073500	a/ Buffalo Bayou near Addicks	293	c/	C	1946
08073700	a/ Buffalo Bayou at Piney Point	317	c/	C	1964
08073750	Stoney Brook Street Ditch	.50	34.9	F-R	1967
08073800	Bering Ditch at Woodway Drive	2.74	24.1	F-R	1965
08074000	a/ Buffalo Bayou at Houston	358	c/	C	1937
08074100	Cole Creek at Guhn Road	7.05	4.1	F-R	1965
08074150	Cole Creek at Deihl Road	8.81	4.1	C-R	1965
08074200	Brickhouse Gully at Clarblak St.	2.05	3.5	F-R	1965
08074250	Brickhouse Gully at Costa Rica St.	10.5	10.5	C-R	1965
08074500	Whiteoak Bayou at Houston	84.7	9	C	1937
08074780	Keegans Bayou at Keegan Road	5.77	1.9	F-R	1965
08074800	Keegans Bayou at Roark Road	9.28	2.1	C-R	1965
08074850	Bintliff Ditch at Bissonnet St.	4.29	25.8	F-R	1969
08074900	Willow Waterhole Bayou at Landsdowne Street	11.2	6.0	F-R	1965
08075000	Brays Bayou at Houston	88.4	15	C	1937
08075300	Sims Bayou at Carlsbad Street	4.99	4.2	F-R	1965
08075400	Sims Bayou at Hiram Clarke St.	20.2	5.3	C-R	1965
08075500	Sims Bayou at Houston	64.0	11	C	1953
08075550	Berry Bayou at Gilpin Street	3.26	12.0	F-R	1965
08075600	Berry Bayou tributary at Globe St.	1.58	15.2	F-R	1965
08075650	Berry Bayou at Forest Oaks Street	11.1	14.5	C-R	1965
08075700	Berry Creek at Galveston Road	4.86	9.0	F-R	1965
08075750	b/ Hunting Bayou tributary at Cavalcade Street	1.03	28.0	F-R	1965
08075760	Hunting Bayou at Falls Street	3.42	21.0	F-R	1965
08075770	Hunting Bayou at U.S. Hwy 90-A	14.4	14.8	C-R	1965
08075780	Greens Bayou at Cutten Road	8.73	1.9	F-R	1965
08075900	b/ Greens Bayou at U.S. Hwy 75	35.5	1.1	C-R	1966
08076000	Greens Bayou near Houston	72.7	3	C-R	1953
08076200	Halls Bayou at Deertrail Street	6.31	3.6	F-R	1965
08076500	Halls Bayou at Houston	24.7	7	C	1953
08077000	a/ Clear Creek near Pearland	38.8	c/	C	1948
08077100	Clear Creek tributary at Hall Rd.	1.33	8.5	F-R	1965

a/ Not used in analysis
b/ Not used in regionalization analysis
c/ Not determined
d/ First complete year of record

Table 2.--Supplemental rainfall stations in the Houston metropolitan area

R Recording rain gage
S Nonrecording rain gage

Station* No.	Station* Name	Type of station	Beginning of record a/
11-R; 14-R	Linder Lake; Sayers Street	R	1965
12-R	Houston-City b/	R	--
13-S	Houston-Independence Heights b/	S	--
21-R	Brittmore	R	1965
22-R	Houston-Satsuma b/	R	--
23-S	Houston-North Houston b/	S	--
24-S	Houston-Spring Branch b/	S	--
25-R; 26-R	Jones Road; Louedda Street	R	1966
31-R	Stafford	R	1965
32-R	Houston-Alief b/	R	--
33-R	Houston-Addicks b/	R	--
34-S	Clodine b/	S	--
35-S	Houston-Westbury b/	S	--
36-S	Sugarland b/	S	--
39-S	KHTV	S	1968
41-R; 44-R; 45-R	Gulf Palms; Almeda-Genoa; Minnesota	R	1965
42-S	Houston-FAA Airport b/	S	--

* Multiple names and numbers indicate a station that was moved during the period.

a/ First complete year of record for those stations operated by U.S.G.S.
b/ National Weather Service (formerly U.S. Weather Bureau)

Table 3.--Peak discharge and climatic parameters, by stations

Station	Storm date	Peak discharge (cfs) *	Precip-itation (inches)	Storm duration (hours)	Soil-mois-ture index (inches)
08073750	June 1, 1967	128	1.50	1.7	0.73
Stoney Brook Street	Aug. 24, 1967	110	1.10	.8	.12
Ditch	Sept. 21, 1967	145	2.56	2.8	.51
	May 10, 1968	160	1.80	.7	1.31
	June 4, 1968	61	.83	.5	.47
	June 16, 1968	163	1.43	.5	.05
	June 21, 1968	138	1.77	3.5	1.29
	June 23, 1968	192	3.00	3.0	2.01
	July 2, 1968	185	2.70	1.0	.18
	Sept. 5, 1968	133	2.00	4.0	.16
	Sept. 14, 1968	247	3.92	1.5	.17
	Sept. 15, 1968	115	.57	.6	2.01
	Sept. 17, 1968	175	1.84	.7	.89
	Nov. 30, 1968	134	1.70	2.5	.35
	Sept. 19, 1969	144	2.01	.8	.23
08073800	Dec. 10, 1964	91	3.45	24.0	.28
Bering Ditch at	Mar. 28, 1966	682	1.20	1.0	1.03
Woodway Drive	Apr. 14, 1966	712	4.50	6.0	.72
	May 18, 1966	724	2.25	1.4	1.18
	Apr. 13, 1967	336	1.48	1.3	.67
	June 1, 1967	283	1.50	1.7	.74
	Aug. 24, 1967	234	1.34	1.8	.12
	Sept. 21, 1967	535	2.46	2.7	.51
	May 10, 1968	934	1.90	.8	1.31
	June 23, 1968	1,140	3.00	3.0	2.01
	July 2, 1968	660	2.20	1.5	.18
	Sept. 5, 1968	400	1.95	3.5	.16
	Sept. 14, 1968	1,570	3.82	1.5	.17
	Nov. 30, 1968	694	1.72	2.8	.34
	Feb. 14, 1969	380	1.50	3.0	1.00
	Apr. 12, 1969	348	1.48	5.2	1.67
	Sept. 19, 1969	386	1.74	1.1	.23

Table 3.--Peak discharge and climatic parameters, by stations--Continued

Station	Storm date	Peak discharge (cfs) *	Precipitation (inches)	Storm duration (hours)	Soil-moisture index (inches)
08074100 Cole Creek at Guhn Road	Feb. 16, 1965	266	1.87	6.0	1.06
	Nov. 4, 1965	213	2.46	3.5	.58
	Apr. 14, 1966	744	4.38	6.5	.68
	Apr. 13, 1967	79	1.89	1.7	.65
	Sept. 21, 1967	100	2.58	3.0	.30
	May 10, 1968	484	4.29	7.7	.96
	May 12, 1968	433	2.44	4.0	2.01
	June 23, 1968	365	2.20	6.0	1.16
	Feb. 21, 1969	708	3.93	7.0	1.93
	Oct. 23, 1970	488	3.30	1.5	1.30
08074150 Cole Creek at Deihl Road	Feb. 16, 1965	338	1.84	5.9	1.07
	Apr. 14, 1966	850	4.57	6.5	.68
	Apr. 13, 1967	152	1.91	1.7	.64
	May 29, 1967	160	1.70	2.1	.31
	May 10, 1968	810	4.35	7.8	.96
	May 12, 1968	554	2.24	4.5	2.01
	June 23, 1968	447	2.36	6.0	1.16
	Nov. 30, 1968	250	1.74	8.0	.69
	Feb. 21, 1969	966	3.73	6.7	1.93
08074200 Brickhouse Gully at Clarblak Street	May 10, 1968	328	4.68	7.6	1.08
	May 12, 1968	175	2.54	4.0	2.01
	June 23, 1968	180	2.55	8.0	1.33
	Feb. 21, 1969	294	3.57	6.7	2.01
	July 21, 1970	169	2.35	1.0	.06
	May 1, 1970	150	3.10	3.8	.34
	Oct. 11, 1970	177	2.40	3.0	.68
	Oct. 23, 1970	346	3.25	1.5	1.37

Table 3.--Peak discharge and climatic parameters, by stations--Continued

Station	Storm date	Peak discharge (cfs) *	Precip-itation (inches)	Storm duration (hours)	Soil-mois-ture index (inches)
08074250 Brickhouse Gully at Costa Rica St.	Feb. 16, 1965	253	1.70	6.7	0.96
	May 28, 1965	340	1.51	3.7	.57
	Apr. 14, 1966	1,040	3.95	7.0	.62
	May 18, 1966	296	1.45	1.5	.63
	May 10, 1968	2,280	5.35	8.0	1.03
	May 12, 1968	792	1.73	5.2	2.01
	Sept. 5, 1968	431	2.18	2.8	.15
	Sept. 14, 1968	450	2.18	1.6	.02
	Sept. 17, 1968	439	1.23	.7	.56
	Feb. 21, 1969	1,370	2.89	7.5	1.79
08074500 Whiteoak Bayou at Houston	Sept. 22, 1965	2,390	1.30	3.0	2.01
	Apr. 14, 1966	8,320	4.45	9.0	.68
	Apr. 13, 1967	1,500	1.75	1.0	.54
	Sept. 21, 1967	3,330	2.86	4.0	.34
	May 10, 1968	9,120	4.43	8.0	.98
	June 24, 1968	2,930	1.74	6.0	1.19
	Sept. 14, 1968	2,820	1.65	2.0	.02
	Sept. 17, 1968	3,390	1.48	1.0	.43
	Nov. 6, 1968	3,720	2.33	1.0	.10
	Feb. 21, 1969	8,760	3.17	7.0	2.01
	Apr. 12, 1969	2,220	1.54	4.0	1.15
	May 1, 1970	3,650	3.10	4.0	.36
	May 15, 1970	3,750	3.71	6.0	.41
08074780 Keegans Bayou at Keegan Road	Dec. 10, 1964	94	3.40	25.0	.30
	Feb. 16, 1965	66	2.11	6.5	1.24
	Feb. 28, 1966	105	1.58	.8	.93
	Apr. 14, 1966	208	4.63	8.2	.82
	Apr. 17, 1966	46	.97	2.5	2.01
	May 13, 1966	78	1.75	1.0	1.08
	May 18, 1966	147	2.11	1.8	1.27
	Jan. 19, 1968	85	1.91	5.5	.72
	June 23, 1968	192	3.25	4.0	.85
	Feb. 21, 1969	136	2.73	5.0	2.01
	May 3, 1969	114	2.40	1.0	.83

Table 3.--Peak discharge andclimatic parameters, by stations--Continued

Station	Storm date	Peak discharge (cfs) *	Precip-itation (inches)	Storm duration (hours)	Soil-mois-ture index (inches)
08074800	Dec. 10, 1964	140	3.35	24.5	0.25
Keegans Bayou at	Feb. 16, 1965	127	2.10	6.0	1.06
Roark Road	Feb. 9, 1966	238	2.19	16.0	1.44
	Apr. 14, 1966	588	5.08	8.5	.83
	Apr. 17, 1966	89	.95	2.2	2.01
	May 13, 1966	241	1.89	1.0	1.04
	May 18, 1966	231	1.91	1.8	1.31
	Aug. 30, 1966	203	1.75	1.0	.62
	June 4, 1968	119	1.68	.7	.85
	June 23, 1968	352	2.92	4.0	.97
	Sept. 14, 1968	165	1.69	2.0	.02
	Feb. 21, 1969	268	2.53	6.2	2.01
	May 3, 1969	659	3.10	1.0	.69
08074850	Sept. 5, 1968	547	1.80	2.5	.75
Bintliff Ditch at	Sept. 14, 1968	1,030	3.29	1.3	.02
Bissonnet St.	Sept. 15, 1968	294	.62	.6	1.90
	Sept. 17, 1968	926	2.14	1.2	.73
	Nov. 30, 1968	478	1.87	8.2	.32
	Feb. 14, 1969	575	1.48	2.7	.85
	Feb. 21, 1969	726	2.18	6.2	2.01
	Apr. 12, 1969	510	1.53	6.0	1.37
	May 3, 1969	646	1.57	1.0	.72
	Sept. 15, 1969	928	2.04	1.3	.60
	Sept. 19, 1969	846	2.58	.5	.36
08074900	Dec. 9, 1964	350	3.82	24.5	.16
Willow Waterhole at	Feb. 9, 1966	345	2.17	16.0	1.53
Landsdowne St.	Mar. 28, 1966	490	1.44	.8	1.25
	Apr. 14, 1966	1,300	5.23	7.0	.81
	Aug. 6, 1966	204	1.76	1.1	.10
	Aug. 25, 1967	450	1.99	1.0	.35
	Sept. 21, 1967	314	2.93	3.3	.21
	July 25, 1968	448	1.63	1.7	.23
	Sept. 14, 1968	450	2.16	1.1	.03
	Sept. 17, 1968	589	1.63	.7	.47
	Feb. 21, 1969	884	2.13	4.2	2.01
	May 16, 1969	414	1.33	1.8	1.52

Table 3.--Peak discharge and climatic parameters, by stations--Continued

Station	Storm date	Peak discharge (cfs) *	Precip-itation (inches)	Storm duration (hours)	Soil-mois-ture index (inches)
08075000 Brays Bayou at Houston	Dec. 10, 1964	3,160	2.41	20.0	0.09
	Feb. 16, 1965	2,900	1.26	4.0	.91
	Dec. 18, 1965	3,200	1.88	18.0	1.89
	Feb. 9, 1966	5,170	2.27	16.0	1.69
	Mar. 28, 1966	6,140	2.08	6.0	.79
	Apr. 14, 1966	9,400	4.71	8.0	.84
	May 13, 1966	6,140	1.83	1.0	1.13
	Apr. 13, 1967	4,420	1.55	2.0	1.16
	Aug. 25, 1967	4,350	1.56	2.0	.45
	Sept. 21, 1967	4,730	2.76	3.0	.25
	Jan. 21, 1968	3,620	.96	10.0	2.01
	June 16, 1968	11,500	2.99	4.0	2.01
	June 23, 1968	5,100	1.66	1.0	.17
	Sept. 14, 1968	8,000	2.11	1.0	.03
	Sept. 17, 1968	9,120	1.52	1.0	.43
	Jan. 16, 1969	5,900	1.34	3.0	.71
	Feb. 21, 1969	9,240	2.15	4.0	2.01
	May 3, 1969	8,600	2.19	1.0	.75
	May 21, 1970	11,500	4.15	6.0	1.16
08075300 Sims Bayou at Carlsbad St.	June 17, 1965	108	2.52	5.2	.06
	Feb. 10, 1966	190	1.27	3.0	1.91
	Apr. 14, 1966	314	4.94	6.5	.76
	May 20, 1966	146	1.61	4.0	2.01
	Aug. 25, 1967	232	1.96	.8	.55
	Sept. 21, 1967	314	3.10	3.2	.25
	June 23, 1968	455	2.65	4.0	1.12
	Sept. 17, 1968	214	1.43	.5	.39
	Feb. 21, 1969	220	2.11	4.5	2.01
08075400 Sims Bayou at Hiram Clarke St.	Dec. 9, 1964	960	4.11	22.5	.20
	Feb. 10, 1966	960	1.44	4.0	1.86
	Apr. 14, 1966	2,280	4.48	7.0	.69
	May 20, 1966	1,600	2.12	3.0	1.70
	June 23, 1968	2,140	2.70	3.5	1.44
	Feb. 21, 1969	2,130	2.46	4.7	2.01
	May 3, 1969	1,020	2.73	1.2	.50
	May 21, 1970	2,320	4.45	6.5	1.24
	Oct. 11, 1970	2,230	4.20	9.0	.13

Table 3.--Peak discharge and climatic parameters, by stations--Continued

Station	Storm date	Peak discharge (cfs) *	Precip- itation (inches)	Storm duration (hours)	Soil-mois- ture index (inches)
08075500	Dec. 10, 1964	3,800	4.30	20.0	0.19
Sims Bayou at	May 22, 1965	1,500	1.43	3.0	1.82
Houston	Dec. 19, 1964	1,730	.80	10.0	2.01
	Feb. 10, 1966	2,850	2.89	17.0	1.50
	Apr. 14, 1966	5,820	4.37	8.0	.73
	Apr. 17, 1966	1,730	1.10	2.0	2.01
	May 20, 1966	6,700	2.55	2.0	2.01
	Sept. 10, 1966	2,370	1.71	1.0	.15
	Apr. 13, 1967	1,260	1.60	2.0	1.38
	Jan. 19, 1968	2,490	2.33	8.0	1.55
	Apr. 9, 1968	1,730	1.73	6.0	.66
	May 10, 1968	4,680	4.02	8.0	.81
	June 21, 1968	2,690	1.93	7.0	.78
	Jan. 16, 1969	3,630	1.75	6.0	.63
	Feb. 21, 1969	7,720	2.63	5.0	2.01
	Mar. 15, 1969	2,610	1.31	2.0	2.01
	Apr. 12, 1969	1,870	1.79	6.0	1.20
	May 3, 1969	2,530	2.08	1.0	.63
	May 21, 1970	8,800	4.40	6.0	1.28
08075550	Feb. 9, 1966	607	2.97	2.7	1.68
Berry Bayou at	Feb. 10, 1966	319	.89	2.0	2.01
Gilpin St.	Apr. 14, 1966	544	4.14	8.0	.90
	June 19, 1966	463	1.94	1.3	1.00
	Aug. 20, 1966	190	2.40	9.0	.01
	Sept. 9, 1966	291	2.32	1.5	.07
	Apr. 8, 1968	348	2.48	8.0	.70
	May 10, 1968	738	7.28	8.0	.73
	May 11, 1968	434	.86	2.4	2.01
	May 12, 1968	509	.93	6.0	2.01
	June 21, 1968	450	3.20	6.0	.77
	June 23, 1968	628	2.10	2.7	2.01
	June 23, 1968	628	4.15	10.5	2.01
	Sept.17, 1968	187	1.36	.4	.31
	Oct. 9, 1968	302	1.69	1.0	.54
	Feb. 14, 1969	332	1.45	2.4	.89
	Feb. 21, 1969	535	2.50	4.0	2.01
	Mar. 15, 1969	331	1.85	3.5	2.01
	Apr. 12, 1969	530	2.15	5.3	1.54

Table 3.--Peak discharge and climatic parameters, by stations--Continued

Station	Storm date	Peak discharge (cfs) *	Precip-itation (inches)	Storm duration (hours)	Soil-mois-ture index (inches)
08075600	May 22, 1965	114	2.12	4.2	1.28
Berry Bayou tributary	June 6, 1965	87	2.00	2.1	.23
at Globe St.	Feb. 9, 1966	308	3.86	2.8	1.79
	Feb. 10, 1966	119	1.14	3.0	2.01
	Apr. 14, 1966	254	4.10	7.5	.87
	May 20, 1966	218	2.30	2.8	1.37
	June 19, 1966	172	1.80	1.3	.76
	May 11, 1968	127	.95	2.0	2.01
	May 12, 1968	162	.87	4.7	2.01
	May 26, 1968	182	2.28	.5	.61
	June 21, 1968	170	3.20	6.0	.82
	June 22, 1968	284	2.30	1.5	2.01
	Feb. 21, 1969	198	2.50	4.0	2.01
	Apr. 12, 1969	166	1.97	4.8	1.46
08075650	June 6, 1965	706	2.03	2.1	.18
Berry Bayou at	Feb. 9, 1966	2,630	3.29	3.0	1.64
Forest Oaks St.	Apr. 14, 1966	2,180	4.32	8.0	.91
	Aug. 20, 1966	906	2.56	8.5	.01
	Oct. 5, 1966	624	1.90	1.2	.01
	Apr. 13, 1967	886	1.48	1.3	1.60
	Apr. 8, 1968	1,100	2.40	8.0	.67
	May 10, 1968	3,110	6.50	8.5	.70
	May 26, 1968	1,620	2.29	.7	.60
	June 21, 1968	1,620	3.20	6.0	.85
	Sept. 17, 1968	608	1.41	.5	.35
	Feb. 21, 1969	1,410	2.66	4.0	2.01
	Mar. 15, 1969	886	1.75	3.0	2.01
	Apr. 12, 1969	1,050	2.24	5.0	1.33

Table 3.--Peak discharge and climatic parameters, by stations--Continued

Station	Storm date	Peak discharge (cfs) *	Precip- itation (inches)	Storm duration (hours)	Soil-mois- ture index (inches)
08075700 Berry Creek at Galveston Road	Dec. 10, 1964	280	4.99	21.0	0.21
	Apr. 14, 1966	607	4.83	7.5	.87
	May 20, 1966	533	3.29	2.5	1.41
	Aug. 20, 1966	182	2.64	8.0	.02
	Apr. 11, 1967	208	1.95	2.3	.46
	Jan. 19, 1968	403	3.16	9.0	1.85
	May 10, 1968	789	6.50	8.5	.90
	May 26, 1968	440	2.20	.7	.61
	June 21, 1968	540	3.22	6.0	.91
	June 22, 1968	480	1.84	1.2	2.01
	Sept. 17, 1968	230	1.60	.6	.34
	Oct. 9, 1968	209	1.53	1.2	.48
	Feb. 14, 1969	283	1.73	2.4	.94
	Feb. 21, 1969	644	2.86	4.0	2.01
	Mar. 15, 1969	295	1.40	2.0	2.01
08075750 Hunting Bayou tributary at Cavalcade St.	May 18, 1965	49	2.60	5.0	.18
	Sept. 18, 1965	49	1.90	1.0	.01
	Sept. 22, 1965	109	3.10	2.0	.27
	Oct. 18, 1965	67	2.80	1.5	.01
	Mar. 28, 1966	90	1.60	1.0	1.02
	Apr. 14, 1966	119	3.60	8.0	.81
	Oct. 5, 1966	140	3.07	1.5	.70
	Apr. 13, 1967	67	1.50	1.6	.34
	May 29, 1967	95	1.60	.8	.71
	Sept. 21, 1967	132	3.50	4.0	.10
	Jan. 19, 1968	62	2.50	9.0	1.93
	May 10, 1968	149	2.55	.7	.88
	May 11, 1968	56	.60	1.8	2.01
	May 12, 1968	64	.75	2.0	2.01

Table 3.--Peak discharge and climatic parameters, by stations--Continued

Station	Storm date	Peak discharge (cfs) *	Precip-itation (inches)	Storm duration (hours)	Soil-mois-ture index (inches)
08075760 Hunting Bayou at Falls St.	Sept. 18, 1965	90	1.94	1.5	0.01
	Sept. 22, 1965	236	2.67	4.2	.25
	Oct. 18, 1965	112	2.50	1.5	.01
	Mar. 28, 1966	250	1.65	1.0	1.01
	Apr. 14, 1966	485	3.81	8.0	.81
	Oct. 5, 1966	399	2.98	1.4	1.35
	Sept. 21, 1967	315	3.35	3.9	.10
	May 10, 1968	445	3.69	7.6	.89
	May 11, 1968	101	.56	1.8	2.01
	May 12, 1968	173	.75	2.0	2.01
	June 21, 1968	225	1.70	4.0	1.05
	Sept. 8, 1968	325	1.94	.5	.20
	Sept. 17, 1968	333	1.92	.8	.36
	Nov. 5, 1968	284	2.41	.8	.07
	Feb. 14, 1969	170	1.75	2.5	1.15
	Apr. 12, 1969	270	1.95	9.0	1.09
08075770 Hunting Bayou at U.S. 90A, Houston	Dec. 10, 1964	355	3.36	21.0	.15
	Feb. 10, 1966	730	1.36	3.0	2.01
	Apr. 14, 1966	1,150	3.80	8.0	.73
	May 13, 1966	640	1.32	1.1	.95
	Oct. 5, 1966	920	4.41	3.0	.01
	Sept. 21, 1967	601	2.78	2.8	.11
	May 10, 1968	1,460	3.81	8.0	.83
	June 21, 1968	702	1.84	4.0	.87
	June 23, 1968	1,450	3.28	18.0	2.01
	Sept. 17, 1968	652	1.79	.7	.47
	Nov. 5, 1968	536	2.41	1.1	.03
	Feb. 14, 1969	504	1.68	2.5	.97
	Feb. 21, 1969	1,050	2.08	10.2	2.01
	Apr. 12, 1969	830	2.25	9.0	1.20

Table 3.--Peak discharge and climatic parameters, by stations--Continued

Station	Storm date	Peak discharge (cfs) *	Precip-itation (inches)	Storm duration (hours)	Soil-mois-ture index (inches)
08075780 Greens Bayou at Cutten Road	Feb. 9, 1966	199	2.05	16.0	1.46
	Apr. 14, 1966	514	4.54	7.5	.58
	May 18, 1966	414	3.48	2.0	1.66
	Sept. 21, 1967	468	6.84	4.2	.03
	Jan. 19, 1968	130	1.15	7.0	1.28
	Sept. 17, 1968	104	1.67	.7	.39
	Nov. 5, 1968	250	3.50	1.2	.20
	Nov. 30, 1968	235	2.25	7.0	.95
	Feb. 21, 1969	508	3.15	6.8	1.92
08075900 Greens Bayou at U.S. 75 near Houston	Feb. 9, 1966	710	2.05	16.0	1.50
	Apr. 14, 1966	2,730	4.63	7.5	.54
	May 13, 1966	1,330	2.79	1.2	.60
	Sept. 21, 1967	2,060	7.27	4.8	.03
	May 10, 1968	760	3.08	5.5	.72
	June 23, 1968	862	2.94	20.0	.67
	Nov. 5, 1968	1,370	3.13	1.2	.10
	Nov. 30, 1968	802	1.95	8.0	.59
	Feb. 21, 1969	2,600	3.68	6.8	1.94
08076000 Greens Bayou near Houston	Dec. 18, 1965	2,060	2.15	15.0	1.98
	Feb. 10, 1966	2,500	2.26	17.0	1.47
	Apr. 14, 1966	5,360	4.69	8.0	.54
	May 13, 1966	2,320	2.17	1.0	.70
	May 10, 1968	2,050	3.04	9.0	.66
	June 24, 1968	2,580	3.29	15.0	1.01
	Nov. 6, 1968	1,430	1.22	1.0	.08
	Feb. 22, 1969	4,000	3.52	11.0	2.01
	May 1, 1970	2,200	3.40	7.0	.36
	May 15, 1970	3,600	4.60	9.0	.37
	May 31, 1970	2,250	2.70	4.0	.83

Table 3.--Peak discharge and climatic parameters, by stations--Continued

Station	Storm date	Peak discharge (cfs) *	Precip- itation (inches)	Storm duration (hours)	Soil-mois- ture index (inches)
08076200	Dec. 18, 1965	140	1.70	5.0	2.01
Halls Bayou at	Feb. 9, 1966	250	2.18	16.0	1.46
Deertrail St.	Apr. 14, 1966	614	4.81	7.0	.64
	Aug. 25, 1967	195	2.72	1.6	.14
	Sept. 21, 1967	710	10.20	5.5	.11
	Apr. 10, 1968	318	3.60	8.0	.40
	Sept. 17, 1968	121	1.30	.7	.67
	Oct. 6, 1968	260	1.85	1.0	.07
	Nov. 5, 1968	200	2.15	1.2	.06
	Feb. 21, 1969	596	3.37	7.1	2.01
08076500	June 26, 1960	2,230	5.00	6.0	2.01
Halls Bayou at	Sept. 12, 1961	3,400	8.00	30.0	.11
Houston	Dec. 18, 1965	1,250	2.20	12.0	2.01
	Feb. 9, 1966	1,730	2.27	16.0	1.39
	Apr. 14, 1966	2,640	4.49	8.0	.56
	Sept. 21, 1967	1,100	4.50	5.0	.11
	Jan. 19, 1968	838	1.77	8.0	1.39
	May 10, 1968	2,340	3.15	8.0	.57
	June 23, 1968	2,060	3.24	20.0	1.42
	Nov. 30, 1968	1,090	1.62	8.0	.39
	Feb. 21, 1969	2,500	3.32	7.0	2.01
	Apr. 12, 1969	960	1.62	9.0	1.22
08077100	June 19, 1966	111	2.36	1.5	.52
Clear Creek	Aug. 20, 1966	100	3.73	5.7	.03
tributary at	Oct. 4, 1966	88	3.20	.8	.01
Hall Road	Apr. 13, 1967	132	2.00	1.4	2.01
	Jan. 19, 1968	118	3.06	8.3	2.01
	Apr. 8, 1968	113	3.40	8.0	.80
	May 10, 1968	390	4.31	1.5	1.06
	Feb. 14, 1969	123	2.10	2.4	.97
	Feb. 21, 1969	215	2.90	4.0	2.01
	Mar. 15, 1969	120	1.70	3.5	2.01
	Apr. 12, 1969	125	1.74	4.2	1.37
	May 3, 1969	294	2.80	.7	.77

* Peak discharge resulting from indicated precipitation.

Rainfall that preceded any storm by a period of at least 6 hours was considered to be related to peak discharge only by its effect on antecedent soil-moisture conditions. Rainfall that occurred after the time of peak discharge was not considered if it was separated by a 6-hour period without rainfall.

The soil-moisture index M, was obtained by a modification of the method of Linsley, Kohler, and Paulhus (1958, p. 171-174). The formula used is:

$$M = (M_o + P_o)\, k^t$$

where

- M = the soil-moisture index, in inches, for the day in question;
- M_o = the last computed soil-moisture index, in inches, which happened t days preceding M;
- P_o = the precipitation, in inches, on the day of the last computed soil-moisture index;
- k = the soil-moisture depletion factor dependent upon season; and
- t = the number of days since last computed soil-moisture index.

Instead of using a constant k (soil-moisture depletion factor) for the entire year and adjusting the computed antecedent-precipitation index for each season of the year, k was varied throughout the year. The computation of M involved the following:

1. M values were computed three times, using a different value of k within a seasonal range for each computation.

2. The best seasonal distribution of k values was determined for each basin by graphically relating peak discharge to precipitation, storm duration, and to one of the three computed M values.

3. The range of k values for each basin was investigated to determine if there were any regional trends such as distinct seasonal values for basins north and south of Buffalo Bayou.

4. Because no regional trends were found, an average seasonal k value was used for the final computation of M.

Figure 3 shows the variation of the soil-moisture depletion factor (k) throughout the year compared with the average monthly temperatures at Houston. It is apparent from this graph that the depletion factor is inversely related to the mean monthly temperature.

The soil-moisture index M, was assumed to be zero on October 1, 1964. Subsequent to that date, the weighted-mean rainfall was computed for all storms for use in computing M. The first storm used in the analysis occurred on December 9, 1964. Therefore, no significant error was introduced by the zero assumption for October 1, 1964.

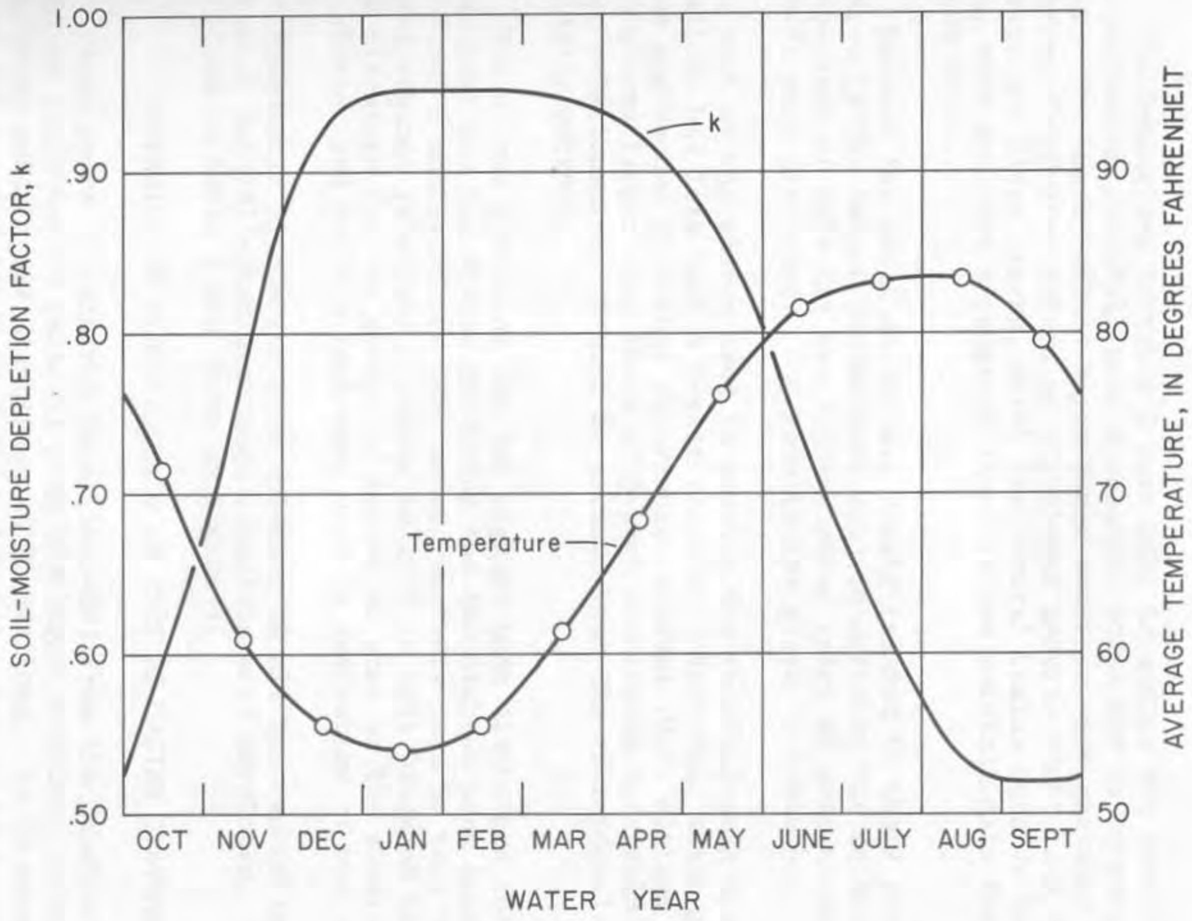

FIGURE 3.-Seasonal variation in soil-moisture depletion factor (k) and the average monthly temperature at Houston

A preliminary analysis showed that an increase in the soil-moisture index above 2 inches had no further relation to the flood peak. It was assumed, therefore, that a soil-moisture index of 2 inches indicated soil saturation. All soil-moisture indices were increased by 0.01 inches to permit taking logarithms of those indices that would have otherwise been zero.

The data given in table 3 were used to define the coefficients in the regression (rainfall-peak discharge) model and to compute the standard error. The three Buffalo Bayou Basin stations were excluded because upstream floodwater-retarding structures provide controlled discharge. Cypress and Clear Creeks, which drain rural basins outside the metropolitan area, were excluded because of insufficient rainfall data for calibration of the model.

Because the small storms are poorly related to their resulting flood peak, only the larger storms were used in defining the relationships. Due to the lack of data for the 1965-69 water years at some sites, data for 1970-71 were also used. The results are given in table 4.

Most of the storms used to develop the rainfall-peak discharge relations had less than a 5-year recurrence interval, although some conditions approached a 10-year recurrence interval (U.S. Weather Bureau, 1955). When storms larger than those of 5-year recurrence intervals are applied to these relationships, it must be assumed that the extrapolation is hydrologically correct.

The storms producing the two highest peak discharges for the 1970 water year and the storms producing the two highest peak discharges for the first 6 months of the 1971 water year were used to test the rainfall-peak discharge relations. Storms in 1970 or 1971 produced the maximum peak discharge for the period of record at some of the stations. None of the storms used in this test were used in derivation of the relations.

Reasonable discharges were obtained at all but two of the stations for which rainfall-peak discharge relations were developed. The results are given in table 5 and shown on figure 4.

EXTENSION OF FLOOD RECORDS IN TIME AT GAGING STATIONS

Sixty years of rainfall data (1910-69) from the Houston-City station provided input to the rainfall-peak discharge relations of table 4 for simulating annual peak discharges at 26 stations. It is assumed that the record for precipitation at the Houston-City station is a representative sample that could have occurred anywhere in the Houston metropolitan area.

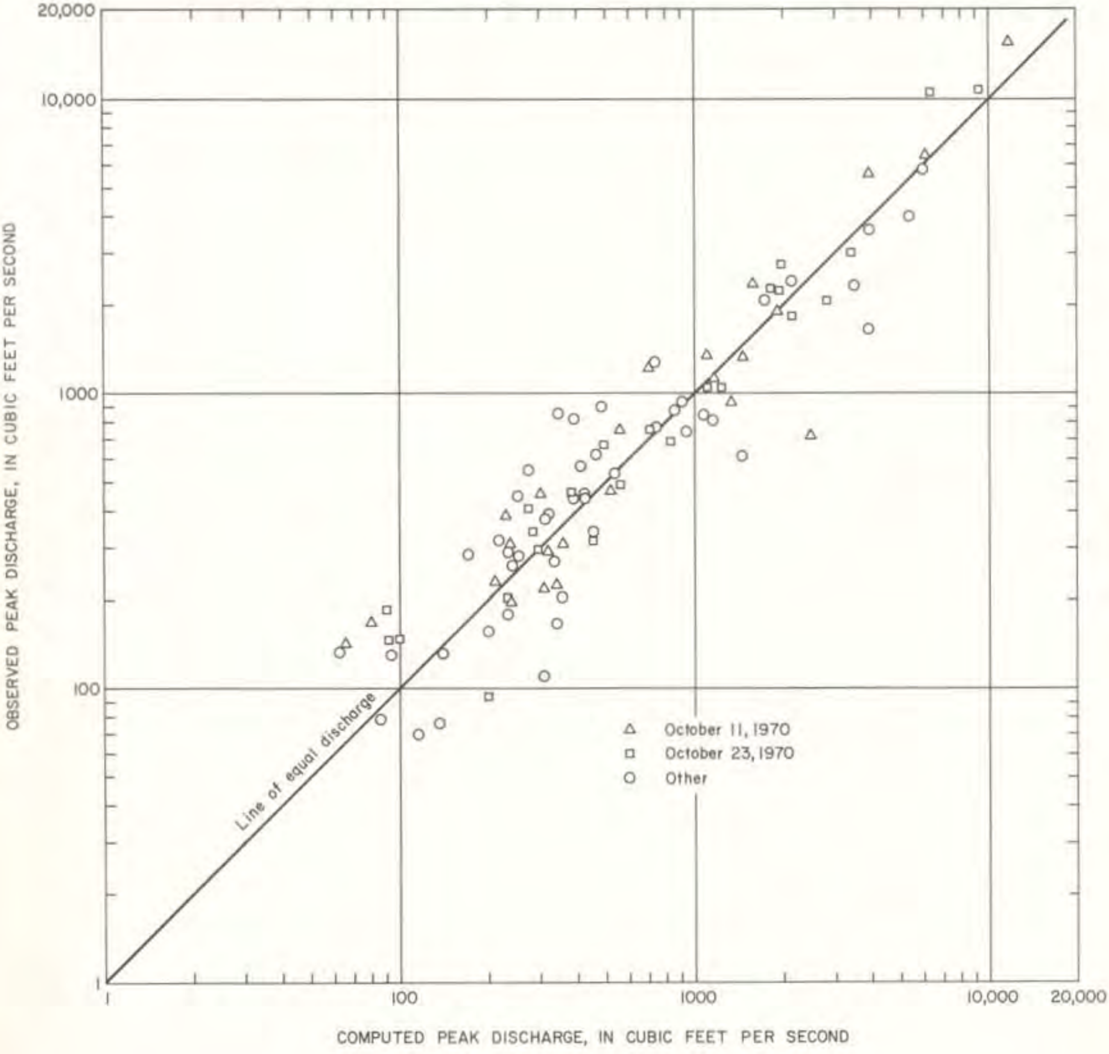

FIGURE 4.-Relationship between observed peak discharges and simulated peak discharges for the 1970-71 water years

Table 4.--Summary of rainfall-peak discharge relations $Q_p = a(P^{b1})(D^{b2})(M^{b3})$

Station Number	Station Name	Constant (a)	Exponent for: P	Exponent for: D	Exponent for: M	Standard error log units	Standard error percent
08073750	Stoney Brook Street Ditch	108	0.60	-0.11	.03	.089	21
08073800	Bering Ditch at Woodway Dr.	402	1.28	- .72	.12	.187	44
08074100	Cole Creek at Guhn Rd.	72.5	1.48	--	.79	.152	36
08074150	Cole Creek at Deihl Rd.	130	1.29	--	.51	.093	22
08074200	Brickhouse Gully at Clarblak St.	78.9	1.23	- .25	.14	.082	19
08074250	Brickhouse Gully at Costa Rica St	294	1.64	- .33	.24	.152	36
08074500	Whiteoak Bayou at Houston	1600	1.03	--	.05	.149	35
08074780	Keegans Bayou at Keegan Rd.	49.6	1.23	- .20	.15	.096	22
08074800	Keegans Bayou at Roark Rd.	97.2	1.42	- .24	.07	.153	36
08074850	Bintliff Ditch at Bissonnet St.	421	.93	- .13	.06	.062	15
08074900	Willow Waterhole Bayou at Landsdowne Street	324	1.15	- .30	.28	.151	35
08075000	Brays Bayou at Houston	4850	.84	- .26	.11	.123	29
08075300	Sims Bayou at Carlsbad St.	153	.98	- .27	.24	.143	34
08075400	Sims Bayou at Hiram Clarke St.	690	.90	- .03	.24	.164	39
08075500	Sims Bayou at Houston	1560	1.06	- .10	.17	.167	40
08075550	Berry Bayou at Gilpin St.	321	.40	--	.21	.090	21
08075600	Berry Bayou tributary at Globe Street	119	.63	- .15	.39	.092	21
08075650	Berry Bayou at Forest Oaks St.	483	1.23	- .12	.10	.075	17
08075700	Berry Creek at Galveston Rd.	199	.96	- .18	.23	.088	20
08075750	Hunting Bayou tributary at Cavalcade Street	72.6	.69	- .26	.15	.102	24
08075760	Hunting Bayou at Falls St.	176	.98	- .18	.23	.099	23

Table 4.--Summary of rainfall-peak discharge relations $Q_p = a(P^{b1})(D^{b2})(M^{b3})$--Continued

Station Number	Station Name	Constant (a)	Exponent for: P	Exponent for: D	Exponent for: M	Standard error: log units	Standard error: percent
08075770	Hunting Bayou at U.S. Hwy 90-A	436	1.31	-0.25	0.28	.120	28
08075780	Greens Bayou at Cutten Rd.	80.5	1.31	--	.25	.075	17
08075900	Greens Bayou at U. S. Hwy. 75	265	1.62	- .13	.23	.200	48
08076000	Greens Bayou near Houston	1270	.89	- .08	.08	.100	23
08076200	Halls Bayou at Deertrail St.	115	.91	--	.04	.145	34
08076500	Halls Bayou at Houston	665	.87	--	.15	.123	29
08077100	Clear Creek tributary at Hall Road	74.4	1.09	- .32	.23	.106	25

Table 5.--Test results of basin rainfall-peak discharge relation using 1970-71 data

Station No. Name	Storm date	Precipitation (inches)	Duration (hours)	Soil-moisture index (inches)	Peak discharge, in cfs Observed	Peak discharge, in cfs Computed
08073750 Stoney Brook Street Ditch	May 21, 1970	3.64	4.5	1.18	157	200
	Sept. 16, 1970	2.00	3.5	.33	133	140
	Oct. 11, 1970	3.44	2.0	1.20	230	212
	Oct. 23, 1970	3.50	1.0	1.85	202	233
08073800 Bering Ditch at Woodway Drive	May 21, 1970	3.72	4.5	1.18	1,280	740
	Aug. 30, 1970	1.62	2.5	.32	859	348
	Oct. 11, 1970	3.50	2.0	1.20	1,900	1,920
	Oct. 23, 1970	3.50	1.0	1.85	1,830	2,150
08074100 Cole Creek at Guhn Road	May 1, 1970	3.38	4.5	.40	321	217
	May 15, 1970	3.64	6.0	.39	293	238
	Oct. 11, 1970	3.72	9.0	.55	290	320
	Oct. 23, 1970 a/	--	--	--	--	--
08074150 Cole Creek at Diehl Road	May 1, 1970	3.38	4.5	.40	442	392
	May 15, 1970	3.64	6.0	.39	453	424
	Oct. 11, 1970	3.72	9.0	.55	470	525
	Oct. 23, 1970	3.32	1.5	1.37	762	716
08074200 Brickhouse at Clarblak Street	May 1, 1970 a/	--	--	--	--	--
	July 21, 1970 a/	--	--	--	--	--
	Oct. 11, 1970 a/	--	--	--	--	--
	Oct. 23, 1970 a/	--	--	--	--	--

a/ Storm used in regression analysis to develop basin regression equation.

Table 5.--Test results of basin rainfall-peak discharge relation using 1970-71 data--Continued

Station No.	Station Name	Storm date	Precipitation (inches)	Duration (hours)	Soil-moisture index (inches)	Peak discharge, in cfs Observed	Peak discharge, in cfs Computed
08074250	Brickhouse Gully at Costa Rica Street	May 1, 1970	3.07	3.8	0.34	925	916
		July 21, 1970	2.12	1.0	.05	898	488
		Oct. 11, 1970	3.72	3.0	.68	2,330	1,600
		Oct. 23, 1970	3.29	1.5	1.37	2,760	1,980
08074500	Whiteoak Bayou at Houston	May 1, 1970 a/	--	--	--	--	--
		May 15, 1970 a/	--	--	--	--	--
		Oct. 11, 1970	3.80	9.0	.59	6,400	6,160
		Oct. 23, 1970	3.92	7.5	.65	10,800	6,400
08074780	Keegans Bayou at Keegan Road	May 15, 1970	3.56	16.0	.33	70	115
		May 21, 1970	2.18	6.0	1.31	128	94
		Oct. 11, 1970	4.22	4.0	1.70	201	239
		Oct. 23, 1970	3.58	8.0	.06	146	99
08074800	Keegans Bayou at Roark Road	May 15, 1970	3.70	7.5	.34	206	356
		May 21, 1970	2.78	6.0	1.42	547	276
		Oct. 11,1970	4.22	4.0	1.69	751	561
		Oct. 23, 1970	3.58	8.0	.06	305	295
08074850	Bintliff Ditch at Bissonnet Street	May 1, 1970	3.58	12.0	.37	741	940
		May 21, 1970	3.60	4.5	1.20	808	1,150
		Oct. 11, 1970	3.20	2.0	1.41	1,120	1,160
		Oct. 23, 1970	3.10	1.0	1.45	1,040	1,230

a/ Storm used in regression analysis to develop basin regression equation.

Table 5.--Test results of basin rainfall-peak discharge relation using 1970-71 data--Continued

Station No.	Station Name	Storm date	Precipitation (inches)	Duration (hours)	Soil-moisture index (inches)	Peak discharge, in cfs Observed	Peak discharge, in cfs Computed
08074900	Willow Waterhole Bayou at Landsdowne Street	May 1, 1970	3.83	12.0	0.35	535	540
		May 21, 1970	4.18	6.0	1.42	844	1,090
		Oct. 11, 1970	4.10	4.0	1.15	1,350	1,120
		Oct. 23, 1970	1.91	1.5	.72	496	558
08075000	Brays Bayou at Houston	May 1, 1970	3.17	12.0	.37	5,800	6,000
		May 15, 1970	3.16	17.0	.45	4,000	5,400
		May 21, 1970 a/	--	--	--	--	--
		Oct. 11, 1970	3.89	3.5	1.40	15,500	11,500
		Oct. 23, 1970	2.38	1.5	1.29	10,800	9,300
08075300	Sims Bayou at Carlsbad Street	May 15, 1970	4.10	17.0	.45	180	234
		May 21, 1970	4.10	6.0	1.65	342	427
		Oct. 11, 1970	5.00	7.0	.20	454	300
		Oct. 23, 1970	1.88	1.0	.24	94	200
08075400	Sims Bayou at Hiram Clarke Street	May 15, 1970	3.48	17.0	.32	613	1,470
		May 21, 1970 a/	--	--	--	--	--
		May 11, 1970 a/	--	--	--	--	--
		Oct. 23, 1970	1.82	1.0	.23	690	832
08075500	Sims Bayou at Houston	May 15, 1970	3.86	17.0	.28	1,650	3,900
		May 21, 1970 a/	--	--	--	--	--
		Oct. 11, 1970	4.34	10.0	.10	5,750	3,960
		Oct. 23, 1970	2.22	1.0	.22	2,090	2,820

a/ Storm used in regression analysis to develop basin regression equation.

Table 5.--Test results of basin rainfall-peak discharge relation using 1970-71 data--Continued

Station No. Name	Storm date	Precipitation (inches)	Duration (hours)	Soil-moisture index (inches)	Peak discharge, in cfs Observed	Computed
08075550 Berry Bayou at Gilpin Street	Oct. 30, 1969	2.44	2.8	0.01	285	171
	May 21, 1970	1.27	4.0	.49	110	304
	Oct. 11, 1970	3.82	13.0	.14	303	360
	Oct. 23, 1970	2.37	1.0	.11	339	284
08075600 Berry Bayou tributary at Globe Street	May 21, 1970	1.65	3.5	1.03	76	136
	May 31, 1970	.97	4.0	.79	79	86
	Oct. 11, 1970	3.83	13.0	.11	169	80
	Oct. 23, 1970	2.37	1.0	.12	186	90
08075650 Berry Bayou at Forest Oaks St.	May 21, 1970	.99	3.5	.55	816	390
	May 31, 1970	1.09	4.0	.42	564	416
	Oct. 11, 1970	3.82	13.0	.10	1,310	1,460
	Oct. 23, 1970	2.37	1.0	.12	1,060	1,130
08075700 Berry Creek at Galveston Road	May 21, 1970	2.82	3.5	1.19	441	430
	May 23, 1970	.95	.5	2.01	280	252
	Oct. 11, 1970	3.82	13.0	.05	349	230
	Oct. 23, 1970	3.37	1.0	.12	370	279
08075760 Hunting Bayou at Falls Street	May 15, 1970	3.50	9.5	.35	377	315
	Sept. 1, 1970	3.08	6.0	.14	261	244
	Oct. 11, 1970	3.38	8.5	.11	297	237
	Oct. 23, 1970	3.40	1.5	.73	666	495

Table 5.--Test results of basin rainfall-peak relation using 1970-71 data--Continued

Station No.	Station Name	Storm date	Precipitation (inches)	Duration (hours)	Soil-moisture index (inches)	Peak discharge, in cfs Observed	Peak discharge, in cfs Computed
08075770	Hunting Bayou at U.S. Highway 90-A	May 15, 1970	3.26	9.5	0.35	880	872
		Sept. 1, 1970	2.97	6.0	.20	768	740
		Oct. 11, 1970	3.62	8.5	.09	1,210	703
		Oct. 23, 1970	3.53	1.5	.86	2,260	1,960
08075780	Greens Bayou at Cutten Road	May 15, 1970	3.88	9.5	.26	168	339
		May 30, 1970	3.45	3.6	.47	268	336
		Oct. 11, 1970	4.45	12.0	.09	217	311
		Oct. 23, 1970	4.30	6.8	.48	318	454
08076000	Greens Bayou near Houston	May 15, 1970	4.87	10.0	.38	3,600	3,950
		May 30, 1970	3.58	4.0	.84	2,350	3,490
		Oct. 11, 1970	3.36	12.0	.08	720	2,480
		Oct. 23, 1970	3.80	7.0	.56	3,000	3,410
08076200	Halls Bayou at Deertrail Street	May 1, 1970	3.29	6.5	.37	393	327
		May 15, 1970	4.94	2.0	.38	618	473
		Oct. 11, 1970	3.62	12.0	.07	222	334
		Oct. 23, 1970	3.90	6.8	.56	451	388
08076500	Halls Bayou at Houston	May 1, 1970	3.69	7.0	.33	2,080	1,750
		May 15, 1970	4.47	8.0	.40	2,340	2,140
		Oct. 11, 1970	3.32	12.0	.11	930	1,340
		Oct. 23, 1970	3.45	6.8	.66	2,290	1,840

Table 5.--Test results of basin rainfall-peak relation using 1970-71 data--Continued

Station No. Name	Storm date	Precipitation (inches)	Duration (hours)	Soil-moisture index (inches)	Peak discharge, in cfs Observed	Computed
08077100 Clear Creek tributary at Hall Road	Oct. 12, 1969	2.50	2.5	0.12	132	63
	May 21, 1970	4.16	4.0	1.57	450	251
	Oct. 11, 1970	3.34	13.0	.07	142	66
	Oct. 23, 1970	1.88	1.0	.12	145	91

From the Houston-City rainfall record, all storms that could possibly have produced an annual peak discharge were selected and listed in table 6. Storm precipitations and durations for the 1910-69 period were determined by the methods previously defined; but only the 31-day antecedent precipitation was used to compute the soil-moisture index.

The three climatic factors for each storm in table 6 were used in each of the rainfall-peak discharge relations of table 4 to produce 119 flood peaks at each station. The 60 annual peaks at each station were selected from these and were fitted to a log-Pearson Type III frequency curve as recommended by the U.S. Water Resources Council (1967). The coordinates of the fitted frequency curves and the statistics of the data are given in table 7. These frequency curves reflect basin conditions that existed during the calibration period.

REGIONALIZATION OF FLOOD-PEAK CHARACTERISTICS

The frequency curves of table 7 differ among basins even after the effect of drainage-area size is removed. Much of this remaining variability is due to differences in the degree of urbanization. To put a number on the effect of urbanization and to define the flood characteristics at ungaged sites in the Houston area, selected flood characteristics were related to basin characteristics. The flood characteristics used were the peak discharges at 2, 5, 10, 25, 50, and 100-year recurrence intervals as shown in table 7.

The basin characteristics (parameters) considered are those listed in table 8 and described as follows:

Drainage area (A).--Total contributing area in square miles.

Developed area (Ad).--The area in the basin within 200 feet of streets, roads, parking lots, and industrial sites and drained by open street ditches or storm sewers. This area also includes roads in rural basins.

Impervious area (Ai).--Area in square miles, of buildings, streets, and paved parking lots within a given basin. To aid in determining Ai, a sampling procedure to determine the average impervious area for a residence was made. The representative average value was multiplied by the total number of residences determined from the Census Bureau data (1960) and from aerial photographs taken in 1964 and 1969.

Storm-sewered area (As).--Total area in square miles in the basin served by storm sewers. It includes all of the area within 200 feet of a storm sewer, or a street or parking lot drained by a storm sewer.

Table 6.--Climatic parameters for selected storms from 60 years of data at the Houston-City station

Storm date	Precipitation (inches)	Duration (hours)	Soil-moisture index (inches)
Oct. 31, 1910	3.84	1.5	0.13
Dec. 29, 1910	2.05	.7	1.60
Apr. 25, 1911	3.56	9.0	1.89
Apr. 16, 1912	4.70	4.5	1.24
May 5, 1912	3.60	10.0	1.02
Dec. 3, 1912	2.21	6.0	1.55
Sept. 7, 1913	4.55	1.9	.12
Oct. 1, 1913	7.17	32.0	.65
May 12, 1914	5.27	9.0	.49
May 12, 1914	3.96	1.9	.49
Dec. 1, 1914	7.55	9.0	2.01
Aug. 28, 1915	3.88	2.0	.18
Dec. 6, 1915	3.08	5.0	.30
July 18, 1916	2.85	.6	.14
Dec. 25, 1916	2.09	4.7	.41
July 20, 1917	2.08	1.4	.23
Apr. 29, 1918	2.67	10.0	2.01
July 2, 1918	4.36	1.7	.11
Oct. 7, 1918	4.92	3.0	.11
June 15, 1919	8.39	24.0	.84
Oct. 4, 1919	3.60	5.5	.11
Jan. 23, 1920	4.48	13.0	1.06
Aug. 24, 1920	2.48	1.5	.97
Oct. 23, 1920	2.73	.5	2.01
Nov. 1, 1920	3.54	5.0	1.02
Jan.12, 1921	3.04	28.0	1.12
June 22, 1921	3.13	2.3	.42
Mar. 25, 1922	7.36	7.0	1.62
Apr. 12, 1923	4.04	7.5	2.01
June 28,1923	2.98	1.2	.54
Dec. 10, 1923	4.41	1.3	1.76
Apr. 28, 1925	1.85	.6	.23
May 4, 1925	1.31	1.6	1.76
Aug. 22, 1925	3.44	6.0	.11
Nov. 5, 1925	5.22	6.1	.36

Table 6.--Climatic parameters for selected storms from 60 years of data at the Houston-City station--Continued

Storm date	Precipitation (inches)	Duration (hours)	Soil-moisture index (inches)
Aug. 11, 1926	2.72	0.4	0.11
Oct. 29, 1926	1.98	6.5	.21
Jan. 19, 1927	1.58	5.5	1.39
June 5, 1927	1.85	2.0	.11
Dec. 6, 1927	2.36	2.0	.47
Sept. 21, 1928	2.64	3.8	.13
Apr. 13, 1929	6.43	4.7	1.13
May 12, 1930	2.60	2.1	.42
Oct. 6, 1930	4.42	2.0	.31
Feb. 20, 1932	2.96	11.5	1.90
Mar. 5, 1933	2.18	.8	1.51
July 22, 1933	3.96	21.0	.14
Jan. 26, 1934	2.21	4.1	2.01
Mar. 1, 1934	3.22	21.0	2.01
May 2, 1935	1.88	.8	1.40
July 23, 1935	2.36	1.3	.13
Dec. 7, 1935	5.42	18.5	.28
May 24, 1936	3.96	7.0	.87
Aug. 23, 1936	2.46	.7	.12
Dec.9, 1936	1.68	3.4	1.21
Sept. 25, 1937	1.70	1.0	.11
May 6, 1938	5.91	1.9	1.07
July 11, 1939	8.27	27.0	.57
Feb. 16, 1940	1.47	1.7	.80
June 18, 1940	3.02	1.7	.24
Nov. 24, 1940	4.70	18.0	1.12
June 11, 1941	3.29	1.3	1.46
Oct. 30, 1941	4.59	20.0	.22
July 4, 1942	3.32	7.5	1.01
July 27, 1943	7.26	27.0	.17
Nov. 1, 1943	10.83	7.0	.35
May 21, 1945	5.38	4.00	.37
Aug. 27, 1945	9.28	15.0	.11
May 19, 1946	4.48	1.2	1.80
June 8, 1946	5.54	9.1	2.01

Table 6.--Climatic parameters for selected storms from 60 years of data at the Houston-City station--Continued

Storm date	Precipitation (inches)	Duration (hours)	Soil-moisture index (inches)
May 20, 1947	4.17	4.7	2.01
Dec. 12, 1947	1.59	7.8	1.10
May 18, 1948	1.92	.7	.70
Nov. 16, 1948	3.03	1.7	.38
Feb. 22, 1949	1.96	.8	1.83
July 14, 1949	2.94	2.5	.17
July 16, 1949	2.04	1.8	1.59
Oct. 7, 1949	7.64	12.6	.54
Jan. 1, 1950	3.12	2.7	2.01
Mar. 26, 1951	2.24	15.0	.61
July 26, 1951	2.35	.6	.27
Feb. 1, 1952	3.22	15.0	.83
Apr. 12, 1952	2.04	2.4	1.38
Nov. 9, 1952	3.37	5.6	.18
May 18, 1953	2.58	3.0	2.01
Nov. 18, 1953	3.36	3.0	.13
July 29, 1954	5.59	23.0	.11
Feb. 4, 1955	2.11	1.8	2.01
Feb. 5, 1955	2.39	10.0	2.01
July 22, 1955	2.19	1.0	.42
May 1, 1956	1.65	1.2	.61
Mar. 17, 1957	2.57	6.5	1.42
Sept. 3, 1957	3.20	1.3	.34
Oct. 15, 1957	3.00	1.7	1.88
Oct. 10, 1958	3.01	1.0	.11
May 23, 1959	3.99	9.0	.58
July 25, 1959	5.31	25.0	.15
June 24, 1960	7.29	29.0	.12
June 25, 1960	14.25	42.0	.12
June 26, 1960	6.96	6.0	2.01

Table 6.--Climatic parameters for selected storms from 60 years of data at the Houston-City station--Continued

Storm date	Precipitation (inches)	Duration (hours)	Soil-moisture index (inches)
Apr. 29, 1961	2.78	1.7	0.42
June 18, 1961	4.75	2.0	.47
Nov. 12, 1961	8.29	12.5	.26
Nov. 13, 1961	3.76	5.5	1.34
June 4, 1962	3.45	2.0	.82
Nov. 27, 1962	3.12	3.8	.32
Jan. 17, 1963	2.39	4.5	2.01
May 22, 1963	3.10	1.3	.20
Mar. 19, 1964	1.76	2.6	.75
Dec. 9, 1964	3.45	20.5	.29
Sept. 22, 1965	3.14	1.6	.28
Apr. 14, 1966	3.52	7.0	.70
May 13, 1966	2.74	1.6	1.20
Oct. 4, 1966	2.79	1.2	.11
Feb. 6, 1967	1.11	8.0	.91
May 10, 1968	5.89	7.0	.94
May 10, 1968	2.62	.7	.94
Jan. 16, 1969	2.60	2.1	2.01
Feb. 20, 19, 1969	1.89	28.0	.66

Table 7.--T-year peaks by stations and log-Pearson Type III analysis statistics

Station no.	Q_2 (cfs)	Q_5 (cfs)	Q_{10} (cfs)	Q_{25} (cfs)	Q_{50} (cfs)	Q_{100} (cfs)	Skew coefficient	Mean logs	Standard deviation logs
08073750	205	250	278	310	340	360	0.171	2.316	0.099
08073800	1,100	1,600	1,910	2,270	2,510	2,730	-.519	3.021	.214
08074100	455	910	1,310	1,910	2,420	3,000	-.158	2.640	.378
08074150	625	1,120	1,530	2,120	2,630	3,190	.020	2.797	.302
08074200	275	400	510	640	745	850	.103	2.445	.202
08074250	1,520	2,610	3,490	4,790	5,890	7,110	.129	3.188	.274
08074500	6,450	9,920	12,600	16,300	19,300	22,600	.222	3.817	.216
08074780	185	275	345	440	520	600	.136	2.267	.210
08074800	460	740	950	1,260	1,520	1,790	.185	2.672	.237
08074850	1,200	1,650	1,970	2,380	2,700	3,040	.188	3.083	.162
08074900	900	1,330	1,650	2,090	2,450	2,830	.231	2.961	.197
08075000	10,400	13,300	15,200	17,400	19,100	20,700	.019	4.016	.128
08075300	350	500	600	730	840	950	.228	2.562	.167
08075400	1,980	2,870	3,510	4,370	5,050	5,750	.149	3.302	.188
08075500	5,160	7,670	9,510	12,100	14,100	16,300	.200	3.719	.199
08075550	520	630	700	780	830	880	-.049	2.714	.101
08075600	205	280	325	380	420	460	-.166	2.309	.161
08075650	2,040	3,210	4,110	5,380	6,430	7,570	.196	3.317	.228
08075700	505	710	860	1,060	1,210	1,370	.217	2.710	.172
08075760	460	650	790	970	1,120	1,270	.217	2.668	.176
08075770	1,570	2,480	3,180	4,190	5,020	5,930	.211	3.204	.230
08075780	325	530	695	935	1,140	1,360	.167	2.635	.278
08076000	3,600	5,000	6,000	7,290	8,310	9,370	.207	3.562	.165
08076200	390	570	710	890	1,040	1,200	.250	2.600	.190
08076500	2,020	2,910	3,550	4,410	5,080	5,790	.172	3.311	.184
08077100	190	275	330	410	470	530	.166	2.289	.179

Table 8.--Basin parameters by station

Station no.	A	Ad	Ai	As	I	Sc	H	Sf	Lb	Dd	U	Si
08073750	0.50	0.44	0.17	0.42	34.9	3.1	1.8	4.1	0.8	2.70	1.00	0.20
08073800	2.74	2.73	.66	1.86	24.1	3.5	7.0	1.7	3.7	3.20	1.00	.20
08074100	7.05	2.47	.29	.02	4.1	5.3	14.5	1.6	3.1	.86	1.60	2.00
08074150	8.81	3.02	.36	.18	4.1	5.9	24.3	.8	4.9	.86	2.20	2.00
08074200	2.05	.71	.07	.07	3.5	4.8	9.0	1.0	2.6	1.11	1.90	2.00
08074250	10.5	6.41	1.10	2.09	10.5	7.4	36.0	1.6	6.1	1.49	1.40	2.00
08074500	84.7	38.3	7.62	15.2	9.0	4.9	79.0	.9	20.0	1.40	1.90	2.00
08074780	5.77	1.21	.11	.02	1.9	2.5	11.0	.9	5.8	1.38	1.00	.20
08074800	9.28	2.44	.19	.61	2.1	3.0	16.5	.9	9.9	.54	1.50	.20
08074850	4.29	3.87	1.11	3.58	25.8	3.9	7.3	2.8	2.5	3.24	1.10	.20
08074900	11.2	3.07	.67	1.55	6.0	5.0	18.0	1.9	5.1	.99	3.30	.20
08075000	88.4	39.4	13.3	28.7	15.0	3.6	50.0	1.2	17.2	1.75	2.10	.20
08075300	4.99	1.49	.21	.02	4.2	5.5	13.3	1.9	3.2	.70	1.60	.20
08075400	20.2	8.17	1.07	1.70	5.3	5.2	25.7	2.8	6.6	1.33	1.90	.20
08075500	64.0	32.12	7.04	15.4	11.0	3.2	42.0	1.3	15.3	1.35	1.30	.20
08075550	3.26	1.89	.39	.88	12.0	3.9	7.5	3.3	2.0	1.53	1.40	.20
08075600	1.58	1.22	.24	.40	15.2	3.9	4.6	2.0	1.7	1.27	1.50	.20
08075650	11.1	8.09	1.61	2.69	14.5	8.5	31.0	2.1	4.6	1.81	1.30	.20
08075700	4.86	2.94	.44	.86	9.0	6.0	18.0	.7	3.0	2.11	1.50	.20
08075760	3.42	3.28	.72	.87	21.0	8.8	9.0	2.7	1.3	2.61	1.00	2.00
08075770	14.4	12.0	2.13	2.00	14.8	3.2	13.5	1.7	5.0	1.99	.80	1.30
08075780	8.73	2.13	.17	.02	1.9	5.1	18.0	2.2	4.2	.51	1.00	2.00
08076000	72.7	19.1	2.18	.78	3.0	4.4	69.0	1.1	17.3	1.07	1.40	2.00
08076200	6.31	1.92	.23	.31	3.6	6.8	22.0	2.1	4.3	1.29	2.30	2.00
08076500	24.7	14.9	1.73	1.19	7.0	4.5	41.0	1.9	8.2	1.34	1.70	2.00
08077100	1.33	1.09	.11	.40	8.5	5.0	8.5	2.6	1.5	2.56	1.00	.20

Percentage impervious area (I).--Percentage of a basin that is impervious (I = 100Ai/A).

Channel slope (Sc).--The slope, in feet per mile, between the points at 10 percent and 85 percent of the distance along the main channel from the gage to the edge of the basin.

Channel rise (H).--The altitude difference in feet, between the 10 percent and 85 percent points along the length of the main channel from the gage to the edge of the basin.

Shape factor (Sf).--The drainage area (A) divided by the square of the distance along the main channel from the gage to a point on the channel nearest the centroid of the basin.

Basin length (Lb).--The distance along the channel from the gage to the head of the basin, in miles.

Drainage density (Dd).--The length of storm sewers and drainage channels (including the main channel) divided by the drainage area (in miles per square mile). To simplify the procedure, only storm sewers 36 inches in diameter or more were considered in the determination. In determining the length of all ditches and channels, drainage-system maps of various organizations were used. Generally, all ditches and channels shown on topographic maps and those maintained by the Harris County Flood Control District were included in the calculation of lengths.

Urban-location ratio (U).--The distance along the main channel from the gage to a point on the channel nearest the centroid of the basin (Lca) divided by the distance from the gage to the centroid of the urban area (Lcua) (U = Lca/Lcua).

Soil index (Si).--The maximum permeability of the natural soil, in inches per hour, based on the latest U.S. Department of Agriculture soil survey (1970).

Selection of the most useful independent variables (basin characteristics) to define the regional variation in flood-peak characteristics involved many preliminary trial-and-error procedures. The regional model selected as the most useful used only drainage area (A) and percentage impervious area (I) in a linear relation of the logarithms of the variables.

The regional relations are given in table 9. The independent variables are statistically significant at the 1-percent level.

Table 9.--Regional relations for T-year flood events

$$Q_T = a(A^{b_1})(I^{b_2})$$

Recurrence interval T, in years	Constant (a)	Exponent for: A	Exponent for: I	Standard error log units	Standard error percent (average)
2	38.8	0.86	0.62	0.111	26
5	62.7	.87	.57	.119	28
10	82.0	.87	.54	.129	30
25	109	.88	.50	.141	33
50	132	.88	.48	.150	35
100	156	.89	.45	.159	37

It is desirable to have a set of prediction equations that have a minimal standard error of estimate and have continuity between the regression coefficients in successive T-year events. In table 9, the exponents for I get smaller as the recurrence interval increases. This indicates that urban development has proportionally less effect on large floods than on small ones. The exponents for A increase as the recurrence interval increases. The uniformity of variation in the constant and exponents (table 9) indicates both consistency and continuity in the relationships.

ESTIMATION OF FLOOD-PEAK CHARACTERISTICS AT UNGAGED SITES

From the defined relationships (table 9), flood-peak characteristics may be estimated at ungaged sites. Use of the relationships should be helpful in designing drainage systems and in determining right-of-way requirements.

The drainage area A, and the percentage of impervious area I, should be measured on the most detailed maps and the latest aerial photographs available. For totally rural basins, the percentage of impervious area should be assumed to be 1 percent so that a zero value will not be used in the equation. The effect of a 1-percent impervious area on the drainage characteristics of a basin is very slight, and any error resulting from the 1-percent assumption will be nominal.

Estimation of impervious area without adequate knowledge will usually result in values that are too high. A combination of direct measurement and estimation for calculation of large impervious areas will result in more accurate results. A basin should be divided into sections and the impervious area of each section computed separately.

An approximation of the percentage of impervious area of a basin may be made from the following. The percentage of impervious area in fully developed residential subdivisions will normally average 30 to 40 percent but will vary depending on the size of lots, houses, driveways, and streets. Suburban areas with 1-acre lots will have a much lower percentage of impervious area, about 5 to 10 percent. Garden apartment complexes will have percentage of impervious area of about 60 to 100 percent, depending on density and lawn area.

The regional relations are presented in nomographic form in figure 5. The nomograph provides a graphical method for determining design discharges without having to make mathematical calculations.

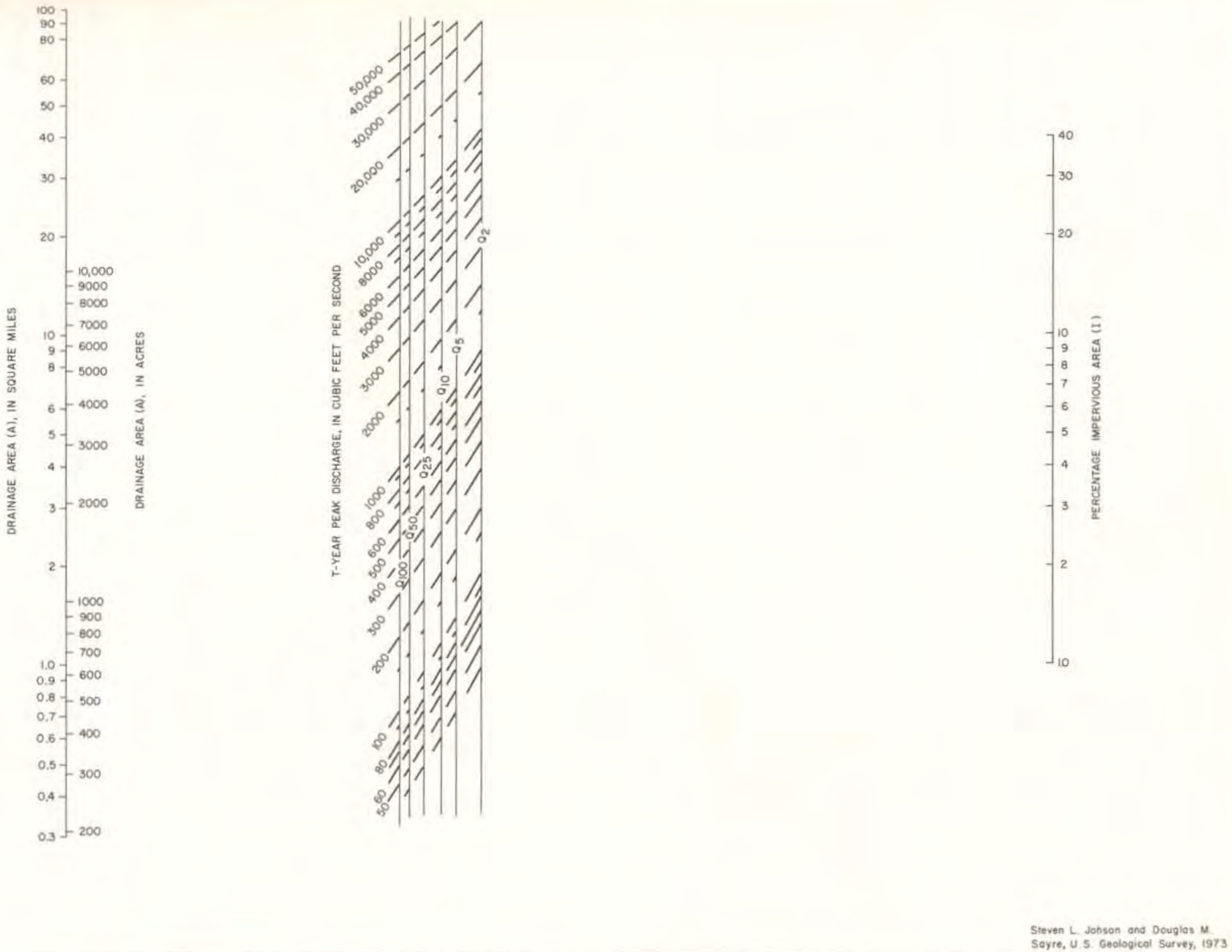

FIGURE 5.-Nomograph for determining design discharges for various recurrence intervals

For example, in a 500-acre (0.78 square mile) area to be developed for a residential subdivision, the peak discharge at the 50-year recurrence interval is desired for planning purposes. Assuming 35 percent impervious area for the residential area when fully developed, the nomograph can be used by laying a straightedge between 500 acres on the A scale and 35 percent on the I scale. A peak discharge of 580 cfs (cubic feet per second) is obtained from the intersection of the straightedge and the scale for Q_{50}.

As another example of the use of the nomograph, assume that it is desired to determine at what stage of development the 25-year recurrence interval flood will exceed the channel capacity on a hypothetical basin. Assume the drainage area (A) is 15 square miles and the existing channel capacity is 2,500 cfs. Using the nomograph, place a straightedge across the A scale at 15 square miles and the Q_{25} scale at 2,500 cfs. The value of 4.7 percent is read on the percentage of impervious-area scale. When development increases beyond that point, adequate drainage at the 25-year recurrence interval will no longer exist. Of course, improvement of channels within the basin and/or lowering the water surface in the receiving channel would provide the needed drainage.

The relations of table 9 were defined by data from basins having drainage areas ranging from 0.50 square mile to 88.4 square miles and having percentages of impervious areas less than 35 percent. Results using values outside of these ranges probably will be less reliable than indicated by the standard errors.

The estimated T-year discharges from the relationship are design values. Sufficient channel capacity must be provided or inundation, resulting from temporary ponding, will occur in parts of the basin. Unless adequate channel capacity is provided, flooding can occur at low points along the channel as a result of channel flooding or at street intersections and grade separations that cannot be adequately drained.

Because the discharges are design values, they should not be used to predict water-surface elevations along a channel that has a capacity less than the selected T-year discharge indicated by the relation.

For basins with flood-detention reservoirs, the relations should be used only for that part of the basin that is uncontrolled.

The relations are based on the assumption that urban development, whatever the stage, is homogeneous throughout the basin. Urbanization concentrated in the upper or lower part of a basin probably would produce different flood characteristics than those resulting from uniform urbanization throughout; however, the degree of this effect is unknown.

The relationships should apply to coastal areas other than the Houston area if those areas have similar rainfall-frequency curves, land slopes, and soils.

EFFECT OF URBAN DEVELOPMENT ON STREAMFLOW

Flood Peaks

The effect of urbanization on peak discharges is considerable at all recurrence intervals. On the basis of the regional relation, changing a rural basin ($I \simeq 1\%$) to a fully developed ($I \simeq 35\%$) urban basin will increase the magnitude of the 2-year flood about nine times and the magnitude of the 50-year flood about five times.

Annual Runoff

The effects of urbanization on total annual runoff can be demonstrated by comparing the runoff from a relatively undeveloped basin to the runoff from a developing basin. Figure 6 is a double-mass curve showing the relation between total runoff from Brays Bayou at Houston (developing basin) and Cypress Creek near Westfield (undeveloped basin). Development in the Brays Bayou Basin has increased rapidly in the past 15 years. Impervious area in this basin was about 2 percent in 1945, 4 percent in 1955, and 15 percent in 1969. Figure 6 shows that the runoff of Brays Bayou increased progressively with time, relative to Cypress Creek, presumably due to the increased urban development.

Figure 7 shows the effect of urban development, as measured by the percentage of impervious area, on total runoff for a dry year (1967) and a relatively wet year (1968). The two curves for 1968 are indicative of differences in the soil types north and south of Buffalo Bayou.

Maps prepared by the U.S. Department of Agriculture (1970) show that the soils north of Buffalo Bayou are more permeable than those south of the Bayou. During dry years, however, the type of soil has very little effect on infiltration because cracks will open in both soil types and infiltration and depression storage will be very high; this premise is supported by the data for 1967 (fig. 7) which show no differences north and south of Buffalo Bayou.

SUMMARY AND CONCLUSIONS

Rainfall and storm runoff data were collected for 5 years or more at 23 sites in the Houston metropolitan area. Streamflow data at 10 additional sites were available from other programs. These data were used to define, at each site, a relation between flood peak and the causative rainfall.

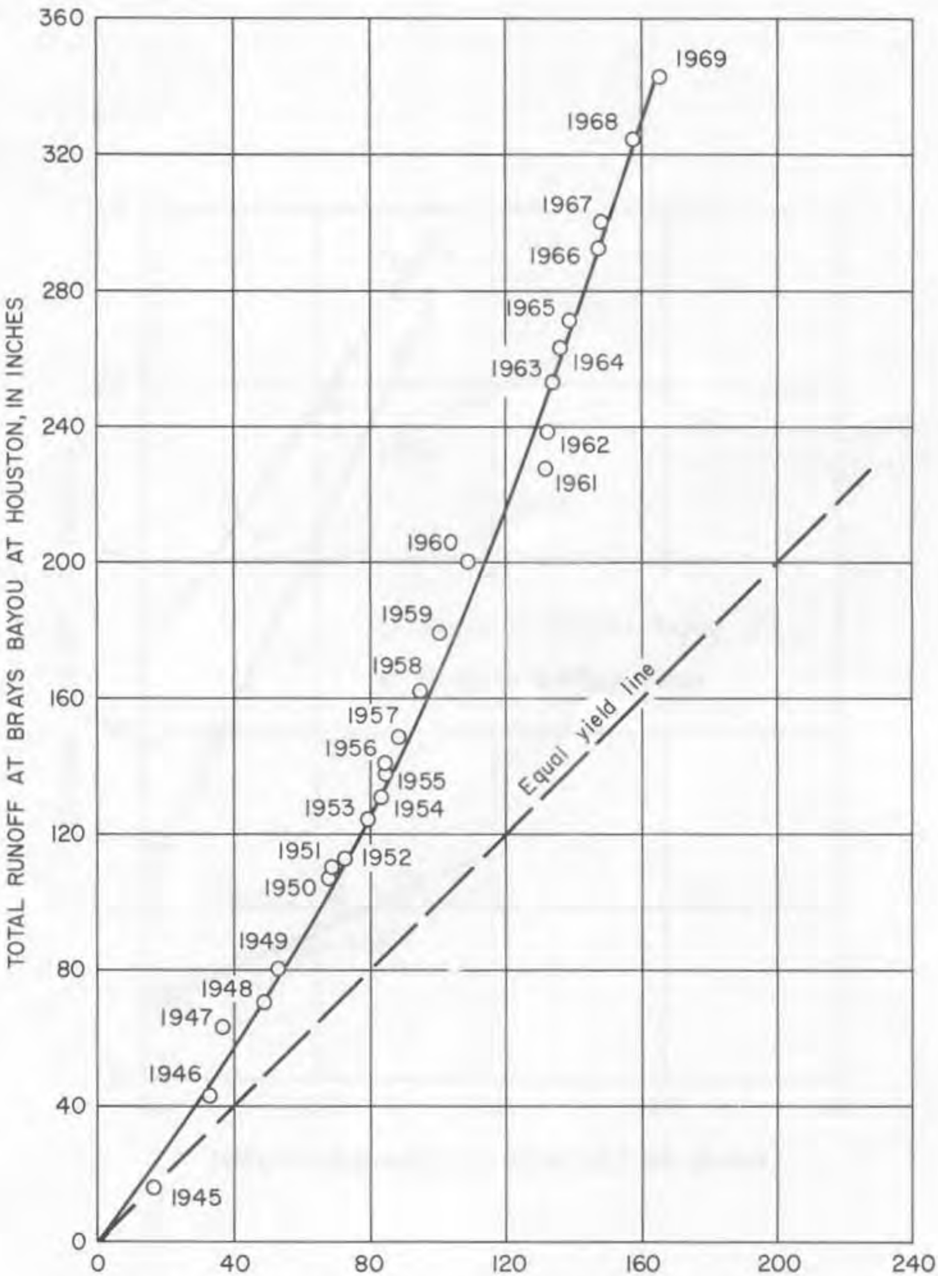

FIGURE 6.-Double mass curve of cumulative runoff for Brays Bayou at Houston and Cypress Creek near Westfield, 1945-69

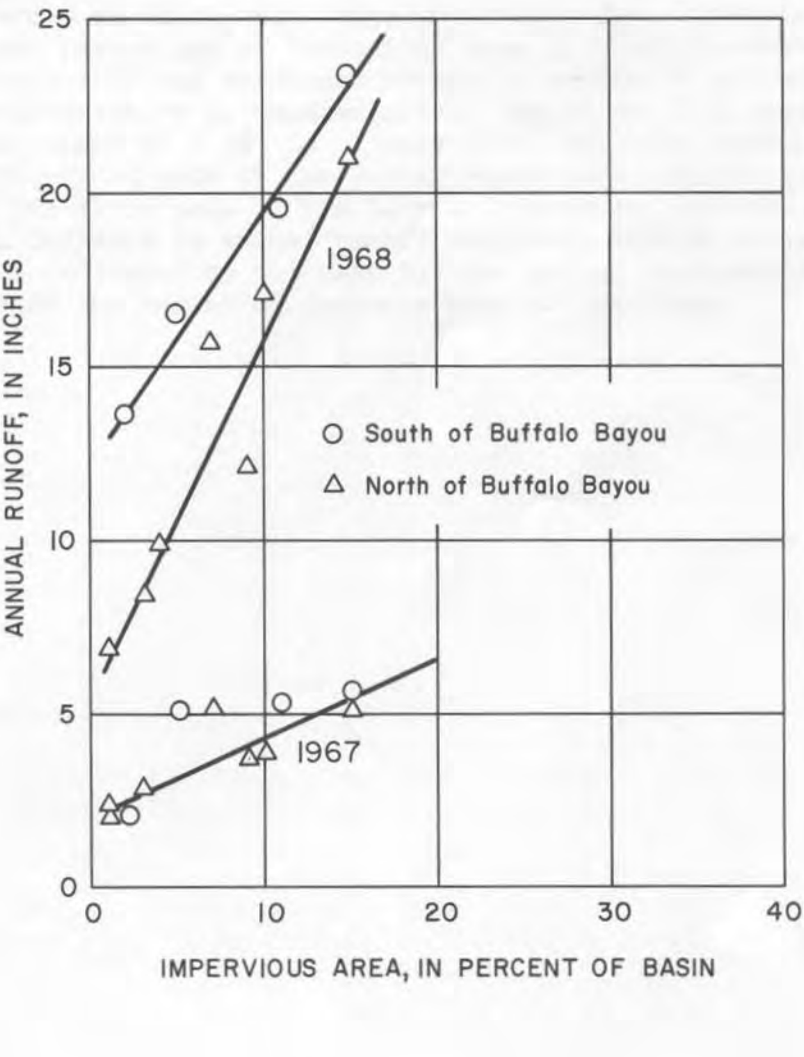

FIGURE 7.-Relationship between percentage of impervious area and runoff

The rainfall-runoff relations were used with a 60-year record of rainfall to simulate 60 annual peak discharges for each site. Frequency curves were prepared from these peak discharges and from these the discharges corresponding to recurrence intervals of 2, 5, 10, 25, 50, and 100 years were obtained.

The discharges at these recurrence intervals were related to drainage area and percentage of impervious area by multiple-regression techniques. These regional relations provide a method of estimating the flood-peak characteristics at ungaged sites. Based on these analyses, changing a rural basin ($I \simeq 1\%$) to a fully developed urban basin ($I \simeq 35\%$) will increase the flood peak at the 2-year recurrence interval by about nine times and the flood peak at the 50-year recurrence interval, by about five times. An increase in annual runoff resulting from an increase in urbanization was indicated by the data for two gaging stations; however, methods to predict the amount of increase were not developed.

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